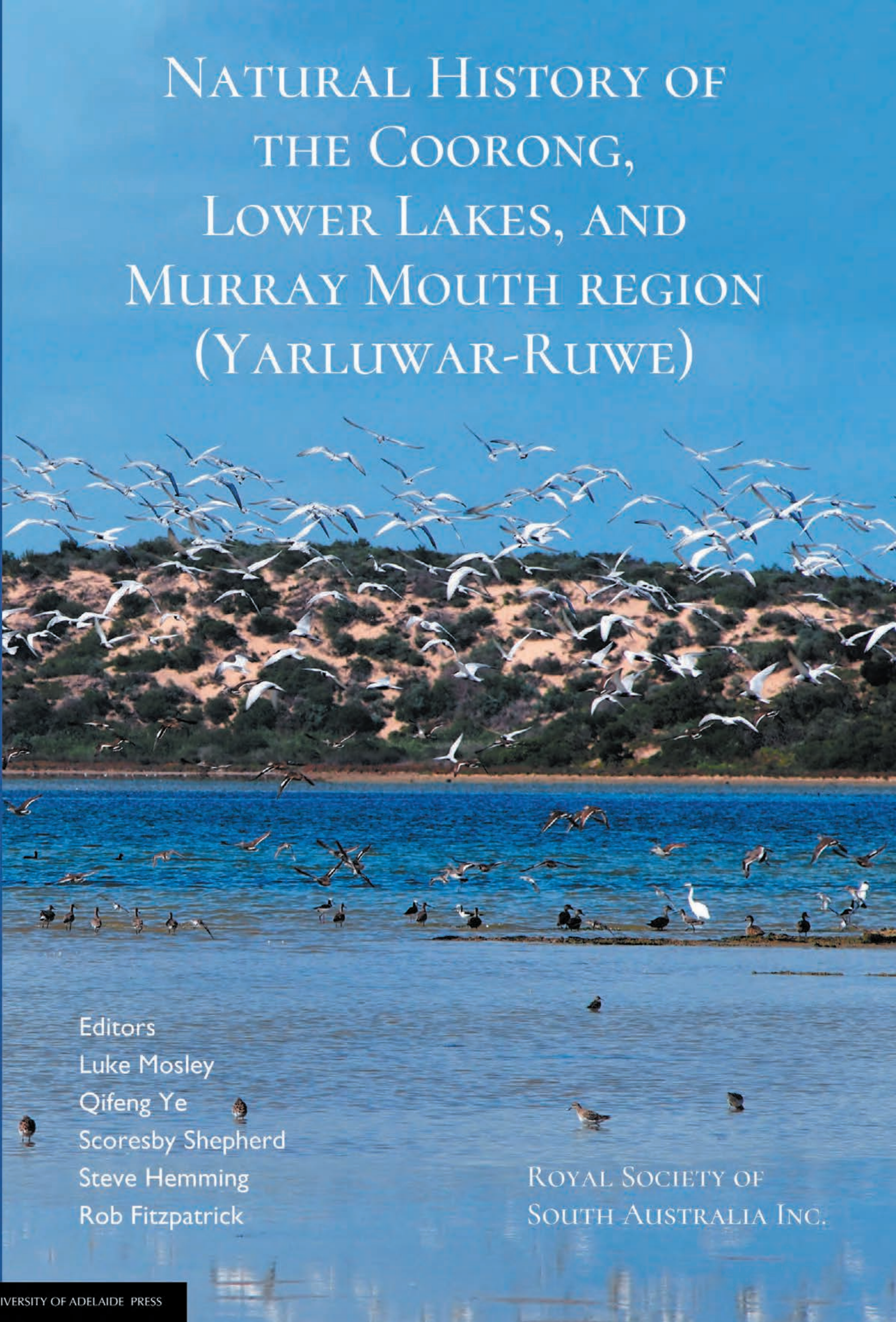

Natural History of the Coorong, Lower Lakes, and Murray Mouth region (Yarluwar-Ruwe)

Editors
Luke Mosley
Qifeng Ye
Scoresby Shepherd
Steve Hemming
Rob Fitzpatrick

Royal Society of South Australia Inc.

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NATURAL HISTORY OF THE COORONG, LOWER LAKES, AND MURRAY MOUTH REGION (YARLUWAR-RUWE)

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ROYAL SOCIETY OF SOUTH AUSTRALIA INC.

This book, a volume in the Natural History Series by the Royal Society of South Australia, explores the natural history of the Coorong, Lower Lakes, and Murray Mouth region (Yarluwar-Ruwe) of South Australia (the CLLMM), a region that has been listed as a Wetland of International Importance under the Ramsar Convention.

The book is divided into four main themes: a historical overview of the region; its physical-chemical nature; its biological systems; and its management, resource use and conservation. The effects of large-scale anthropogenic change, climate change, global warming and sea-level changes are discussed from multiple perspectives, as are the effects of acid sulfate soils and the overall consequences of the Millennium Drought on the CLLMM's water quality, biological life and food web.

The discussion includes information from Ngarrindjeri leaders about the history and culture of the Ngarrindjeri people, the traditional owners of the region's land and waters. The book concludes by establishing the vision and framework required for the important and increasing role that the Ngarrindjeri Nation will play in the shared long-term management of the region.

ISBN 978-1-925261-80-6
90000
9 781925 261806

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Cover design: Emma Spoehr
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Occasional publications of the Royal Society of South Australia Inc.

Ideas & Endeavours: a History of the Natural Sciences in South Australia, published 1986.
Natural History of the Adelaide Region, published 1976, reprinted 1988.
Natural History of Eyre Peninsula, published 1985.
Natural History of the Flinders Ranges, published 1996.
Natural History of Kangaroo Island, second edition, published 2002.
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Natural History of Riverland and Murraylands, published 2009.
Natural History of Spencer Gulf, published 2014.

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UNIVERSITY OF
ADELAIDE PRESS

Published in Adelaide by
University of Adelaide Press
Barr Smith Library
The University of Adelaide
South Australia 5005
press@adelaide.edu.au
www.adelaide.edu.au/press

on behalf of the Royal Society of South Australia Inc.

For the full Cataloguing-in-Publication data please contact the National Library of Australia: cip@nla.gov.au.

ISBN (paperback) 978-1-925261-80-6
ISBN (ebook: pdf) 978-1-925261-81-3

Senior Editor: Rebecca Burton, and the volume editors were assisted by Erinne Stirling.
Book design: Midland Typesetters.
Cover design: Emma Spoehr.
Cover photo: Sabine Dittman, looking across to Ngulung from Tultherang (Pelican Point).

FOREWORD

The Coorong and Lakes Alexandrina and Albert Wetland was designated a Wetland of International Importance under the Ramsar Convention in 1985. The wetland is also one of Australia's most important and unique wetland systems and supports significant ecological, cultural, recreational, heritage and economic values. It is the only estuary within the Murray-Darling Basin and is a designated icon site under The Living Murray initiative. The site supports a vast array of native flora and fauna, including internationally and nationally significant species and communities.

From late 1996 to mid-2010 much of southern Australia, including the Coorong and Lakes region, experienced a prolonged period of dry conditions — the Millennium Drought. This had a devastating impact on the ecology of the Coorong and Lakes and on the wellbeing of our local communities, including the Ngarrindjeri people.

While we are still seeing long-lasting ill effects, particularly within the southern lagoon of the Coorong, the drought brought the plight of the River Murray to the national agenda and helped to highlight the importance of end-of-system flows and water for the environment. The adoption of the Murray-Darling Basin Plan, and corresponding recovery and delivery of water for the environment, have resulted in improvements to the ecology of the Coorong and Lakes Alexandrina and Albert. While many improvements are evident, some aspects of the ecology have experienced sustained change, most notably submergent vegetation communities in the Coorong and some waterbirds, particularly migratory shorebirds, which have not yet recovered to pre-drought levels. Providing the leadership that is required to protect, sustain and revitalise the Coorong is a personal quest which I am determined to advance during my time as South Australia's Minister for Environment and Water.

I would like to acknowledge the dedication of South Australia's scientific community, the members of whom are tireless advocates for this wetland. The long-term data that have been collected by these people and groups have been instrumental in our negotiations to secure water for the environment and in delivering on-ground works to protect the Coorong and Lakes Alexandrina and Albert. The South Australian Government is committed to using the best scientific, cultural and local knowledge to manage this important wetland.

I commend the Royal Society of South Australia for its work to collate decades of monitoring and research data into this important publication on South Australia's most iconic estuary.

David Speirs MP
Minister for Environment and Water
(September 2018)

DEDICATION

This book is dedicated to Tom Trevorrow and Henry Jones.

Thomas Edwin Trevorrow (1954-2013) was renowned and respected for his lifelong commitment to the health of his beloved Ruwe/Ruwar (Country, spirt, body and all living things). Trained by his people as an educator and political leader, he worked closely with Ngarrindjeri and non-Ngarrindjeri to create a healthy future for all, based on respect for the lands, water and all living things. He qualified as a park ranger, but chose instead to work tirelessly for his people across many Ngarrindjeri organisations and committees, including the Ngarrindjeri Regional Authority. As a gifted orator, an educator at Camp Coorong, and a Ngarrindjeri leader, he ensured that the knowledge of his ancestors was valued, understood and respected. This led to the widespread incorporation of Ngarrindjeri understandings of Murrundi (River Murray) and the Lower Lakes and Kurangk (the Coorong) in natural resource management policy and practice. With other Ngarrindjeri leaders, such as George Trevorrow and Matthew Rigney, he negotiated groundbreaking agreements (Kungun Ngarrindjeri Yunnan — listen to Ngarrindjeri people) with non-Indigenous organisations and governments and these have provided the framework for just relationships and a sustainable Coorong, Lower Lakes and Murray Mouth.

Henry Jones (1941-2014) was a fourth-generation fisherman in the Lower Lakes and Coorong and, together with his wife Gloria, a passionate and highly successful advocate for protection of this region. Henry witnessed how declining river flows over many decades had led to poor health of the local environment and fisheries. He became arguably the most influential community person pushing for the implementation of a national plan to save both the environment of the Murray-Darling Basin and, through that, the livelihoods of thousands of people who rely on it. His emotional plea for national reform to save the ailing system, on the lawns of Parliament House (accompanied by his tinnie and barbeque, whilst cooking fish) in Canberra in March 2012, was so powerful that it was credited by politicians of all persuasions as a game-changer in the long fight for River Murray reform. Henry was humble and quietly spoken, but his influence was so great that he was the first person who was called when then Federal Water Minister Tony Burke signed the historic Murray-Darling Basin agreement in November 2012; and he was invited to be present in Parliament with Gloria when the Basin Plan was passed into law in 2013. His numerous other achievements included helping shape a world-first environmental management plan for the fisheries as a whole in the Lower Lakes and Coorong and helping the local fishing community to achieve a Marine Stewardship Council Certification for sustainable fishing practices. Henry was a finalist in the South Australia Senior Australian of the Year Award 2014 for his work in water conservation. His lifelong dedication and fight for protecting the River Murray was recognised in 2013, when he became the first member of the community to receive the River Murray Medal from the Murray-Darling Basin Authority. In 2015, Henry was also posthumously appointed a member of the Order of Australia (AM) for significant service to the conservation of the Lower Murray River and to the community.

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ACKNOWLEDGEMENTS

First, we thank all the authors who have contributed to an excellent series of chapters in this book. We thank the Department for Environment and Water for being a major sponsor of the book, and the South Australian Research and Development Institute (SARDI) and University of Adelaide for providing additional funding support. The Editors also thank the following individuals, who have contributed to the book's development: Andrew Beal, Richard Brown, Jason Higham, Rebecca Quinn, Megan Lewis and Erinne Stirling. We recognise the leadership and partnership of Ngarrindjeri leaders and elders past and present and their commitment to ensuring healthy Ngarrindjeri Ruwe/Ruwar (Country).

INTRODUCTION

The Editorial Committee welcomes you to this *Natural History Series* book, *Natural History of the Coorong, Lower Lakes and Murray Mouth* (CLLMM) region. The book is divided into four main parts, with individual chapters within each part outlined below.

HISTORICAL OVERVIEW (PART 1)

The book begins with Ngarrindjeri leaders such as Tom Trevorrow, George Trevorrow and Matthew Rigney (all deceased) providing a valuable introduction to the history and culture of the Ngarrindjeri traditional owners of the CLLMM land and waters, with a contextual introduction to this Ngarrindjeri account by Steve Hemming (Chapter 1.1). The more recent history of European settlement is then detailed by Valerie Sitters (1.2).

PHYSICAL-CHEMICAL NATURE (PART 2)

The detailed evolution and contemporary geology and geomorphology of the Murray Estuary and Mouth are provided in three chapters by Bob Bourman and co-authors (Chapters 2.1-2.3). Next, Deborah Haynes and co-authors reveal the hydrological and salinity history of the CLLMM based on their studies of diatoms archived in the bottom sediment (2.4). John Cann and Chantelle Lower describe the effects of ice ages, global warming and sea level changes in the formation of the Coorong Lagoon and catchment based on mollusc and other records in sediment cores (2.5). Deirdre Ryan describes the role of historical and current climate in shaping the CLLMM region, including large historical flood events (2.6). The surface water flows and movement within the system, which underpin much of the system function and health, are elaborated by Matt Gibbs and co-authors (2.7). The hydrogeology in the surrounding catchment, and groundwater inflows, are described by Steve Barnett (2.8). The soils in the CLLMM and surrounding catchments are described by Rob Fitzpatrick and co-authors (2.9), with particular emphasis on acid sulfate soils that caused major issues in the Millennium Drought. Finally, in this Part, the water quality of the CLLMM, which is a key driver of ecological health, is then described by Kane Aldridge and co-authors (2.10).

BIOLOGICAL SYSTEMS (PART 3)

Sophie Leterme and co-authors describe the plankton communities that form the base of the food chain and respond to changing hydrology and water quality (Chapter 3.1). The diverse vegetation in and on the edges of the water, and how it responds to changing water levels and quality, is outlined by Jason Nicol and co-authors (3.2). The terrestrial vegetation in the local catchment area, and factors determining its distribution, are described by Sacha Jellinek and co-authors (3.3). The composition of sediment-dwelling invertebrates in the Coorong and Murray Mouth estuary are detailed by Sabine Dittmann (3.4), including how these were severely impacted by the Millennium Drought. Invertebrates in the freshwater Lower Lakes are reviewed by the late Keith Walker (with Peter Goonan, Paul McEvoy and co-authors) (3.5). Chris Bice and co-authors provide a synopsis of the ecology and biology of fishes in the CLLMM (3.6), and how they are influenced by changing flow, water quality and connectivity. David Paton and co-authors present a chapter on waterbirds (3.7), which are a key component of the CLLMM region and one of the main reasons it is listed as a Wetland of International Importance under the Ramsar Convention. The frogs of the CLLMM, including the important, yet vulnerable, Southern bell frog, are presented by Kate Mason and Rebecca Turner (3.8). Lastly for this Part, George Giatas and colleagues describe the Coorong food web (3.9), and how food and 'energy' flows between species to make the system productive and healthy.

MANAGEMENT, RESOURCE USE AND CONSERVATION (PART 4)

Given the large-scale anthropogenic changes in the hydrology of the Murray-Darling Basin, environmental water delivery, guided by legislation, plays a critical role in ensuring the health of the CLLMM system, as described by Adrienne Rumbelow (Chapter 4.1). This includes supporting important local fisheries, which have a long history in the region, as described by Greg Ferguson (4.2). Extreme low flows and water levels in the Millennium Drought created huge management challenges that had never been faced in the CLLMM before, as described by Kerri Muller and co-authors (4.3). Finally, Steve Hemming and co-authors provide two chapters (4.4-4.5) which establish the vision and framework for the important and increasing role that the Ngarrindjeri Nation will play in the shared long-term management of the region (Ngarrindjeri Ruwe/Ruwar).

NOTES TO THE READER

1. For consistency's sake, we have opted for the following usages of upper- and lower-case initials throughout this volume, reflecting common (though not always unvarying) practice in the relevant literature:
    North Lagoon
    South Lagoon
    Lower Lakes
    the Coorong
2. According to the Australian Government's Bureau of Meteorology, the Millennium Drought is defined as having lasted from 1996 to 2010. However, between individual chapters dates given for the drought may vary slightly across this range, depending upon the particular focus of the chapter. For more information, see http://www.bom.gov.au/climate/updates/articles/a010-southern-rainfall-decline.shtml.
3. During the course of preparing this book for publication, the names of some departments within the South Australian Government changed. The Department for Environment and Water (DEW) was first so named in March 2018. References in individual chapters to both the Department for Environment, Water and Natural Resources (DEWNR) and the Department for Water (DEW) are reflective of these changes.

ABBREVIATIONS

AAASS	Atlas of Australian Acid Sulfate Soils
ACT	Australian Capital Territory
AFDM	ash-free dry mass
AHD	Australian height datum
ALoC	Aboriginals learning on Country
AMS	accelerator mass spectrometry
AMTD	adopted middle thread distance
ANZDA	Australia and New Zealand Drought Atlas
ANZECC	Australian and New Zealand Environment and Conservation Council
AOP	annual operating probabilities
APSL	above present sea level
ARI	annual return interval
ARMCAN	Agriculture and Resource Management Council of Australia and New Zealand
ASM	Australian summer monsoon
ASR	aquifer storage and recovery
ASRIS	Australian Soil Resource Information System
ASS	acid sulfate soil
AUS	Australia
AWE	Australian Water Environments
BOM	Bureau of Meteorology
BP	before present (1950)
BPSL	before present sea level
c.	circa (approximately)
cal yr	calendar year
CE	common era (i.e. calendar year)
CEWH	Commonwealth Environmental Water Holder
CEWO	Commonwealth Environmental Water Office
CHM	Cultural Heritage Management
CLLMM	Coorong, Lower Lakes and Murray Mouth
CPS	components, processes and services
CPUE	catch per unit effort
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEH	Department for Environment and Heritage (Government of South Australia)
DENR	Department of Environment and Natural Resources (Government of South Australia)
DEW	Department for Environment and Water (Government of South Australia)
DEWHA	Department for Environment, Heritage and Aboriginal Affairs (Government of South Australia)

DEWNR	Department of Environment, Water and Natural Resources (Government of South Australia)
DO	dissolved oxygen
DOC	dissolved organic carbon
DOM	dissolved organic matter
DON	dissolved organic nitrogen
DOP	dissolved organic phosphorus
DWLBC	Department of Water, Land, Biodiversity and Conservation (Government of South Australia)
E	east
EC	electrical conductivity
ECD	ecological character description
EMLR	Eastern Mount Lofty Ranges
ENSO	El Niño Southern Oscillation
EPA	Environment Protection Authority (Government of South Australia)
EPBC	*Environment Protection and Biodiversity Conservation Act 1999* (Cth)
ES	ecological services
EUFG	estuarine use functional guide
FFG	feeding functional guides
GIS	geographical information system
GWLAP	Goolwa to Wellington Local Action Planning Association
GWLMA	Goolwa Water Level Management Area
I.	island
IBCK	Indigenous Biocultural Knowledge
IBRA	Interim Biogeographic Regionalisation for Australia
ICEWARM	International Centre of Excellence in Water Resources Management
ICIP	Indigenous Cultural and Intellectual Property
IOD	Indian Ocean Dipole
IOS	Indian Ocean Sector
IPCC	Intergovernmental Panel on Climate Change
Is.	islands
ka	kilo annum (1 000 years)
KNY	*Kungun Ngarrindjeri Yunnan* (Listen to what Ngarrindjeri have to say)
KNYA	*Kungun Ngarrindjeri Yunnan* agreement
LAC	limits of acceptable change
LASS	Lake Albert scoping study
LCF	Lakes and Coorong Fishery
LGM	Last Glacial Maximum
LLC	Lower Lakes and Coorong
MA	management action
Ma	mega annum (1 000 000 years)
MBO	monosulfidic black ooze
MDB	Murray-Darling Basin
MDBA	Murray-Darling Basin Authority

MDBC	Murray-Darling Basin Commission
MGL	Murray Group Limestone
MIS	marine isotope stage
MM	Murray Mouth
MSC	Marine Stewardship Council
MSEC	Minister for Sustainability, Environment and Conservation (Government of South Australia)
N	north
NATA	National Association of Testing Authorities
NCC-BOM	National Climate Centre — Bureau of Meteorology
NE	north-east
NL	North Lagoon
NPP	Ngarrindjeri Partnerships Project
NRA	Ngarrindjeri Regional Authority
NRM	Natural Resource Management
NRWG	Ngarrindjeri Ramsar Working Group
NSW	New South Wales
NTU	Nephelometric turbidity units
NW	north-west
NZ	New Zealand
OM	organic matter
OSL	optically stimulated luminescence
PIRSA	Primary Industries and Resources South Australia (Government of South Australia)
POM	particulate organic matter
PS	paddle steamer
QLD	Queensland
RIS	Ramsar Information Sheet
S	south
SA	South Australia
SAM	Southern Annular Mode
SARDI	South Australian Research and Development Institute
SE	south-east
SEDB	South East Drainage Board
SILO	Scientific Information for Land Owners
SIMPROF	similarity profile analysis
SIP	Strategic Implementation Plan
SL	South Lagoon
SOC	Statement of Commitment
SST	sea surface temperature
STR	subtropical ridge
SW	south-west
TACC	total allowable commercial catch
TACE	total allowable commercial effort

TDS	total dissolved solids
TEK	Traditional ecological knowledge
TL	thermoluminescence
TLM	The Living Murray
TN	total nitrogen
TP	total phosphorus
UN	United Nations
USA	United States of America
VEWH	Victorian Environmental Water Holder
W	west
WA	Western Australia
WRT	water residence time
yr	year

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Part 3: Biological Systems

Part 4: Management, Resource Use and Conservation

PART I:

HISTORICAL OVERVIEW

CHAPTER 1.1

NGARRINDJERI NATION YARLUWAR-RUWE PLAN: CARING FOR NGARRINDJERI COUNTRY AND CULTURE:

KUNGUN NGARRINDJERI YUNNAN (LISTEN TO NGARRINDJERI PEOPLE TALKING)

NGARRINDJERI NATION[1] WITH INTRODUCTION AND CONCLUSION
BY STEVE HEMMING[2]

INTRODUCTION

In 2009 the Ngarrindjeri Nation in South Australia (SA) negotiated a formal *Kungun Ngarrindjeri Yunnan* Agreement (KNY — Listen to what Ngarrindjeri have to say) with the State Government that recognised traditional ownership of Ngarrindjeri lands and waters and established a process for negotiating and supporting Ngarrindjeri rights and responsibilities for Country (Rigney et al. 2015). The KNY strategy has provided the framework for the South Australian Government to support Ngarrindjeri to build their core capacity to engage in Caring for Country activities during initiatives such as the *Murray Futures* Coorong, Lower Lakes and Murray Mouth Recovery Project and to become long-term contributors to regional Natural Resource Management (see Hemming et al. 2011; Chapter 4.5). Central to brokering progress in improved Ngarrindjeri engagement with government was the *Ngarrindjeri Nation Yarluwar-Ruwe Plan* ('the plan'), a foundational management planning document prepared by Ngarrindjeri leaders in 2007 on behalf of the Ngarrindjeri Nation to communicate the Ngarrindjeri vision for caring for their lands and waters (Ngarrindjeri Nation 2007). Prior to the plan, Ngarrindjeri had been effectively excluded from regional planning engagements, and their aspirations had been silent in management plans and the implementation of these plans. The plan's vision makes clear the essential link between the wellbeing of Ngarrindjeri individuals, families and communities and the interconnectivity with lands and waters. A key purpose of the plan was to better educate government and non-government agencies, researchers and the wider Australian public on Ngarrindjeri connection to Country and their associated rights and obligations to *Yarluwar-Ruwe*. In doing so, the plan clearly links Ngarrindjeri cultural, social and economic perspectives to the broad Caring for Country vision — which encapsulates *Ruwe*/*Ruwar* — and to goals, strategies and objectives for Ngarrindjeri *Yarluwar-Ruwe*. It is now officially recognised by both state and federal governments and continues to frame Ngarrindjeri negotiations impacting the health of Ngarrindjeri lands and waters. The following chapter reproduces a section from the plan.

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[1] Ngarrindjeri Regional Authority, 50 Princes Highway, Murray Bridge, SA 5253. Email: admin@ngarrindjeri.org.au

[2] Office of Indigenous Strategy and Engagement, Flinders University, GPO Box 2100, Adelaide, SA 5001. Email: steve.hemming@flinders.edu.au

NGARRINDJERI CONCERN FOR COUNTRY

Our Lands, Our Waters, Our People, All Living Things are connected. We implore people to respect our *Ruwe* (Country) as it was created in the *Kaldowinyeri* (the Creation). We long for sparkling, clean waters, healthy land and people and all living things. We long for the *Yarluwar-Ruwe* (Sea Country) of our ancestors. Our vision is all people Caring, Sharing, Knowing and Respecting the lands, the waters and all living things.

> Ngarrindjeri Vision for Country
> Kungun Ngarrindjeri Yunnan
> (Listen to what Ngarrindjeri people have to say)

Our Goals Are:

For our people, children and descendants to be healthy and to enjoy our healthy lands and waters.

To see our lands and waters healthy and spiritually alive.

For all our people to benefit from our equity in our lands and waters.

To see our closest friends — our *Ngartjis* (special animals) — healthy and spiritually alive.

For our people to continue to occupy and benefit from our lands and waters.

To see all people respecting our laws and living in harmony with our lands and waters.

About the *Ngarrindjeri Sea Country Plan*

The *Ngarrindjeri Sea Country Plan* has been prepared by Ngarrindjeri people to help government agencies, natural resource managers, researchers, industry and the wider Australian community to better understand and recognise rights and responsibilities to our *Yarluwar-Ruwe* (Sea Country), including the lower Murray River, Lakes, Coorong and adjacent marine and land areas. Our vision for our Sea Country is based on the relationship between our people and our Sea Country which goes back to Creation. The river, lakes, wetlands/nurseries, Coorong estuary and sea have sustained us culturally and economically for tens of thousands of years.

Owing to the abuse and misuse of Ngarrindjeri lands and waters by non-Indigenous people, and the denial of Ngarrindjeri rights and interests, we now find that, as the Traditional Owners of our lands and waters and all living things, we must stand up and speak out to save our *Ruwe* (Country) before we reach the point of no return.

Part 1 of the *Sea Country Plan* introduces our people and culture and explains our relationship with our Sea Country. Over the last 200 years, there have been attempts to break that relationship with our *Yarluwar-Ruwe* and we continue to feel the pain of these onslaughts.

We have been witnessing the destruction of our precious lands and waters by newcomers who do not understand their new surroundings and who do not or will not respect our rights and obligations to Country.

Part 2 describes the background and processes that led to the development of this *Sea Country Plan*, and outlines the major issues that are addressed later in the document. It explains that this is the second *Sea Country Plan* to be funded by the Australian Government's National

BOX 1.1.1

The Indigenous People of the Lower River Murray, Lakes and Coorong, known as the Ngarrindjeri, first flew and adopted this flag on 21 November 1999 on Kumarangk (Hindmarsh Island).

Figure 1.1.1 Ngarrindjeri Flag. (Designed by Matt Rigney)

The 18 dots represent the 18 Laklinyeris (tribes) that make up the Ngarrindjeri Nation. The spears represent the traditional fishing spears of the Ngarrindjeri. The boomerang is the Sacred Boomerang that, when thrown, circles the Laklinyeris, informing their clan leaders to attend a Nation Meeting called *Tendi* (which makes and interprets Ngarrindjeri Law). The blue represents the waters of Ngarrindjeri Country. The sun gives life. The ochre colour of the boomerang represents our mother — Mother Earth.

Oceans Office[3] as part of the implementation of the *South-east Regional Marine Plan* that was released in 2004.

Part 3 outlines the issues, objectives, strategies and priority actions that we intend to address to realise our vision for the future of our Sea Country. While some of these strategies and actions may challenge existing management arrangements, they are all consistent with our human rights, cultural rights and cultural obligations, and they are laid out here in keeping with our values of caring and sharing that always has been the Ngarrindjeri way.

Part 4 explores opportunities for partnerships for implementing our *Sea Country Plan*. We review other major plans, policies and laws that have been developed for our Sea Country by government agencies and other organisations. We look for areas of common ground and explain how support for our *Sea Country Plan* can assist government agencies and others to

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[3] This office was part of the Department of the Environment and Heritage.

meet their own objectives and commitments, and work towards a more sustainable future for humankind and all living things of creation.

We invite you to read our *Sea Country Plan* carefully and commit yourself to working with us for the benefit of our shared future and for our land and waters upon which we all depend.

NGARINDJERI PEOPLE AND COUNTRY

Ngurunderi and The Creator

A long, long time ago Ngurunderi our Spiritual Ancestor chased *Pondi*, the giant Murray Cod, from the junction where the Darling and *Murrundi* (River Murray) meet. Back then, the River Murray was just a small stream and *Pondi* had nowhere to go (Fig. 1.1.2). As Ngurunderi chased him in his bark canoe he went ploughing and crashing through the land and his huge body and tail created the mighty River Murray. When Ngurunderi and his brother-in-law Nepele caught *Pondi* at the place where the fresh and salt water meet they cut him up into many pieces, which became the fresh and salt water fish for the Ngarrindjeri people. To the last piece Ngurunderi said, ‘You keep being a *Pondi* (Murray Cod)’.

As Ngurunderi travelled throughout our Country, he created landforms, waterways and life. He gave to his people the stories, meanings and laws associated with our lands and waters of his creation. He gave each *Lakalinyeri* (clan) our identity to our *Ruwe* (country) and our *Ngarjtis* (animals, birds, fish and plants) — who are our friends. Ngurunderi taught us how to hunt and gather our foods from the lands and waters. He taught us, don’t be greedy, don’t take any more than what you need, and share with one another. Ngurunderi also warned us that if we don’t share we will be punished (see *Thukeri* story below).

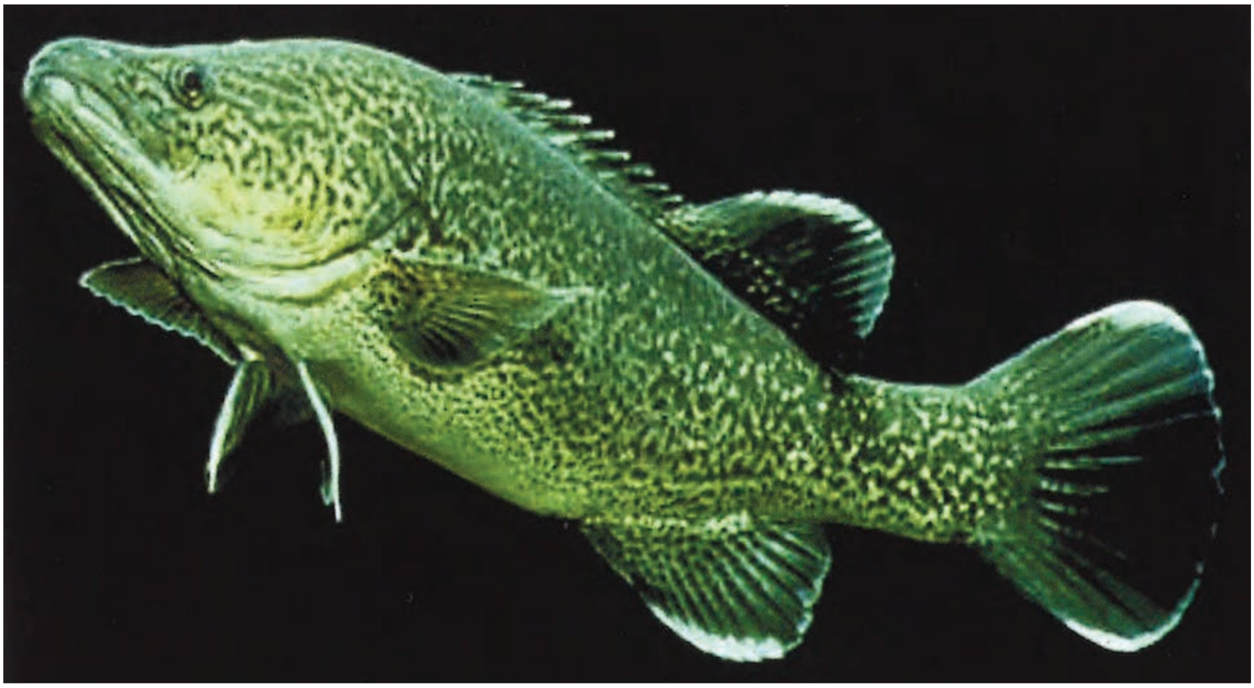

Figure 1.1.2 *Pondi* (Murray Cod). (From Ngarrindjeri Nation (2007), courtesy of Ngarrindjeri Regional Authority)

Thukeri (Bony Bream) Story

A long time ago two Ngarrindjeri men went fishing in a bay near Lake Alexandrina to catch the *thukeri mami* (bream fish) (Fig. 1.1.3). They set off in their bark canoe to catch the big fat *thukeri*. They fished and fished until their canoe was over full and they said we have plenty of *thukeri* we will paddle to shore before we sink. As they paddled to shore they saw a stranger coming towards them so they covered up the *thukeri* with their woven mats they said this man might want some of our *thukeri*, when they approached the shore the stranger said to them hey brothers I'm hungry have you got any fish to share, but the two Ngarrindjeri men said no we haven't got many fish we only have enough to feed our families. So the stranger began to walk away then he turned and said you have plenty of fish and because you are greedy and don't want to share you will not enjoy the *thukeri* fish ever again. As the stranger walked away the two Ngarrindjeri men laughed at him. When the two Ngarrindjeri men unloaded the *thukeri* on to the banks to scale and clean them, they saw that their nice big fat *thukeri* were bony and they didn't know what had happened. The two Ngarrindjeri men went home to the campsite in shame and told the Elders what had happened. The Elders were angry and said the stranger was Ngurunderi our Spirit Ancestor and because you two were greedy and would not share with him he has put a curse on our *thukeri mami*. Now all the Ngarrindjeri people will be punished.

Ngarrindjeri respect the gifts of Creation that Ngurunderi passed down to our Spiritual Ancestors, our Elders and to us. Ngarrindjeri must follow the Traditional Laws; we must respect and honour the lands, waters and all living things. Ngurunderi taught us our *Miwi*, which is our inner spiritual connection to our lands, waters, each other and all living things, and which is passed down through our mothers since Creation.

Our Great Grandmothers, Grandmothers and mothers fought to protect our Spiritual waters from desecration when a bridge to *Kumarangk* (Hindmarsh Island) was to be built.

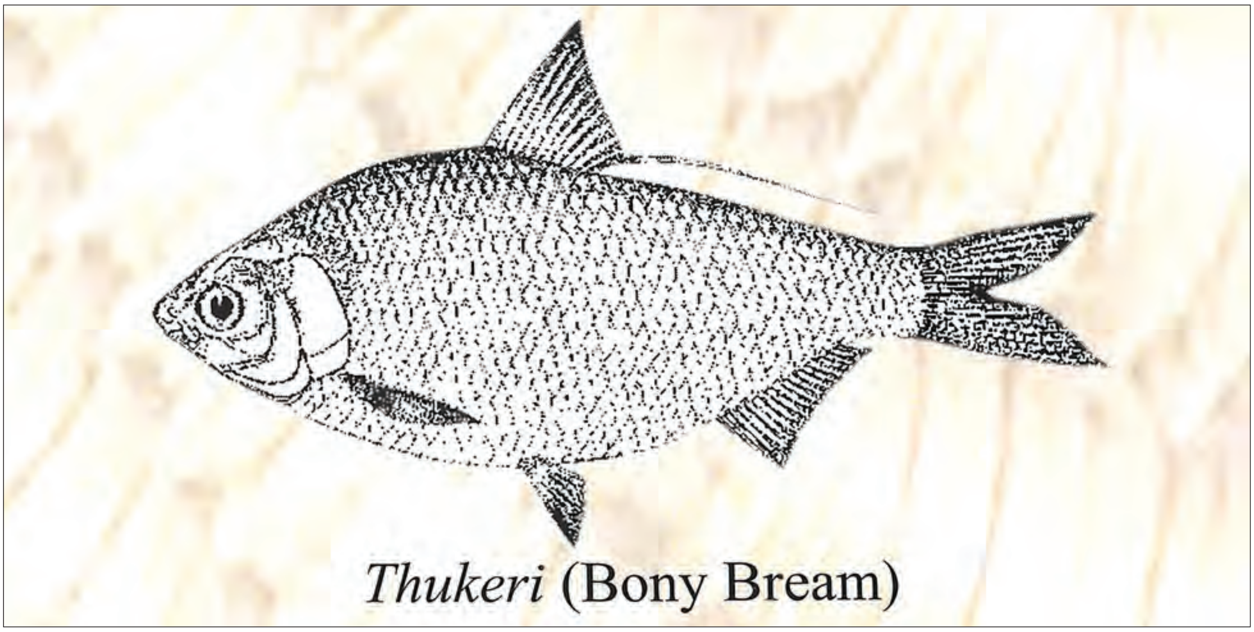

Figure 1.1.3 *Thukeri* (Bony Bream). (From Ngarrindjeri Nation (2007), courtesy of Ngarrindjeri Regional Authority)

Now we fear a new proposal to build a twin lakes system in Lake Alexandrina which would further destroy the creation of our lands and waters (Fig. 1.1.4).

Ngurunderi taught us how to sustain our lives and our culture from what were our healthy lands and waters. Our lands and waters must be managed according to our Laws to make them healthy once again. As the Ngarrindjeri Nation we must maintain our inherent sovereign rights to our *Yarluwar-Ruwe*. Ngarrindjeri people have a sovereign right to make our living from the lands and waters in a respectful and sustainable way (Figs. 1.1.5-1.1.8).

We are asking non-Indigenous people to respect our traditions, our rights and our responsibilities according to Ngarrindjeri laws.

Ngarrindjeri have occupied, enjoyed, managed and used our inhabited lands and waters, since Creation.

We were here when the sea level began rising about 18 000 years ago, and our ancestors watched the sea flooding over our coastal plains (see Fig. 1.1.8). We were here when the sea

Figure 1.1.4 Ngurunderi's Creation Journey. (From Ngarrindjeri Nation (2007), courtesy of Ngarrindjeri Regional Authority)

stabilised at its current level about 5 000 years ago. Our Creation stories record these dramatic changes. We were here when the European invaders began stealing our land and our resources; killing our people and our *Ngartjis*, such as *Kondoli* (whale) and *Paingal* (seal); polluting our rivers, lakes and Coorong; and draining our wetlands/nurseries. And we are still here!

Figure 1.1.5 Pellampellamwallah Ngarrindjeri woman wearing a rush and fibre cloak. She is carrying fire and a bundle of bulrushes — an important food and fibre source. (Artist G.F. Angas, courtesy of South Australian Museum)

Figure 1.1.6 A man of the Milmendura tribe wearing a seagrass cloak. (Artist G.F. Angas, courtesy of South Australian Museum)

Figure 1.1.7 *Ngori* (pelicans). (From Ngarrindjeri Nation (2007), courtesy of David Sjoberg)

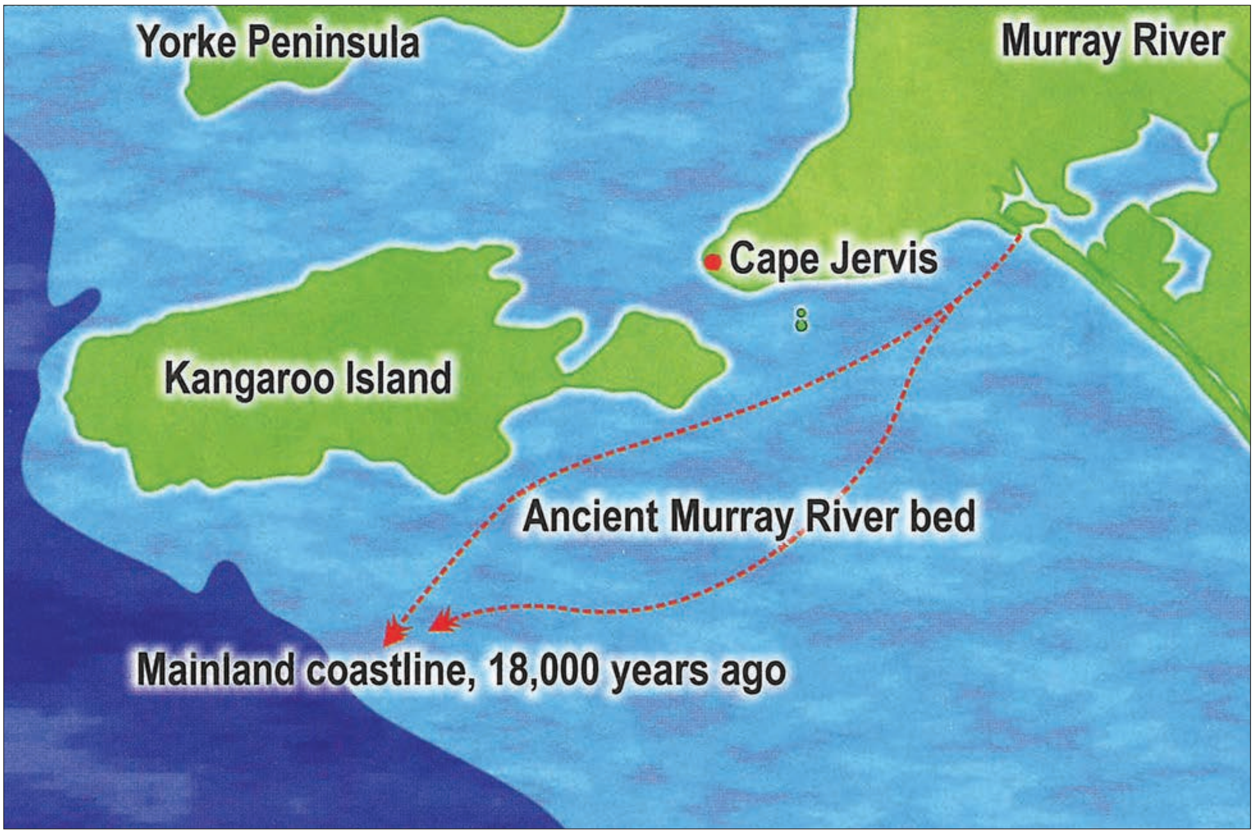

Figure 1.1.8 Changing coastline over 18 000 years. (From Ngarrindjeri Nation (2007), courtesy of Ngarrindjeri Regional Authority)

Because of the richness of our natural resources and our sustainable use and management of them, our Sea Country supported among the highest density of Aboriginal population anywhere in Australia prior to European invasion. Our population at that time has been estimated to be about 6 000 people.

Our culture and economy have always depended on the resources of our *Yarluwar-Ruwe*. We used and continue to use the resources of the land, but it was the saltwater and freshwater environments that provided us with most of our needs. Such was the wealth of sea and marine life such as fish, shellfish, eels, waterbirds and water plants that we have always lived a settled lifestyle. Our knowledge of our Sea Country will continue to underpin our survival and our economy. *Tendi*, our formal governing council, ensured and will continue to ensure our stable and sustainable society, which maintains our obligations to Sea Country.

Our creation stories and oral traditions have been passed down from generation to generation and with them a detailed knowledge of our *Yarluwar-Ruwe*. We developed many tools and other equipment to harvest and process our Sea Country resources, including fish nets, fishing weirs, spears, lines, snare traps, decoys, bark canoes, reed rafts, large floating fishing platforms and woven baskets (Fig. 1.1.9). Our capacity for storing food enabled us to organise large gatherings of Ngarrindjeri people to engage in trade, ceremonies and other social activities with neighbouring nations.

Ngarrindjeri people speak a common Ngarrindjeri language. We comprise several peoples, each with particular knowledge about areas of Ngarrindjeri Sea Country. We are all linked through creation stories, creation trails and sites, ceremonies and sacred places. Central to Ngarrindjeri shared culture is the creator ancestor Ngurunderi whose travels and actions created the River Murray, the Lakes, the Coorong and coastal Hummocks, our lands, waters, fish and resources.

Towards the end of his journey Ngurunderi placed his *Yuke* (canoe) into the dark night sky where it became *Warriewar* (the Milky Way). Like other creation stories, Ngurunderi's journey ended at Kangaroo Island from where he ascended into the sky and became the bright star in *Warriewar*. Ngurunderi's story also refers to the role of ancestral women (in this case Ngurunderi's two wives) in creating the Country we know today.

Both men and women hold special cultural and environmental knowledge and both men and women have always been involved, and continue to be involved, in passing down our knowledge between generations and in decision-making about Ngarrindjeri affairs, land waters and resources (Fig. 1.1.10). Ngarrindjeri people hold cultural and spiritual connections to particular places, to particular species of animals and plants, and all elements of the environment are part of our kinship system. Particular animal and plant species are the *Ngartji* (totem or special friend) of Ngarrindjeri people, who have special responsibility to care for their *Ngartji*. To care for *Ngartji* is to care for country.

The waters of the seas, the waters of the *Kurangk* (Coorong), the waters of the rivers and the lakes are all spiritual waters. The Creation ancestors taught us how to respect and understand the connections between the lands, the waters and the sky. The place where the fresh and salt waters mix is a place of creation where our *Ngarjtis* breed. Our women fought to protect these spiritual waters by objecting to the building of the bridge to *Kumarangk* (Hindmarsh Island). Any future plans affecting these waters must respect our cultural traditions and beliefs.

Figure 1.1.9 Making a fishing net at Encounter Bay in 1844. The seated woman is softening the bulrush-root fibre by chewing it; the man is rolling the fibre to make cord for a net like the one on the roof of the whalebone hut. (Artist G.F. Angas, courtesy of South Australian Museum)

We implore non-Indigenous people to respect the *Yarluwar-Ruwe* as it was created in the *Kaldowinyeri* (the Creation).

Our Old People have rejoiced the return to Ngarrindjeri *Yarluwar-Ruwe* of *Kondoli* our whale ancestors. Some of our *Ngartjis* have not returned to our lands and waters. We mourn the loss of our closest friends. We fear for the animals, fish, birds and all living things in our seas and waterways. We hope that the growing awareness of non-Indigenous people will not be too late. We know that many of our *Ngartjis* travel to other countries during certain times of the year and therefore we have a cultural responsibility to care for each other's *Ngartji*, and to care for each other's lands and waters. We have always recognised our responsibilities and connections to other parts of Australia and to distant lands. In recent times we have learned that our *Ngartjis* travel to places such as Great Turtle Island (North America) and various other countries.

Our Ngarrindjeri Vision for Our Sea Country must remain strong, for the health and survival of our brothers and sisters in distant lands that rely on our *Ngartjis* — birds, fish and other animals — that are nourished by our *Yarluwar-Ruwe* and travel over long distances.

The land and waters are a living body. We the Ngarrindjeri people are a part of its existence. The land and waters must be healthy for the Ngarrindjeri people to be healthy. We say that if *Yarluwar-Ruwe* dies, the waters die, our *Ngartjis* die, then the Ngarrindjeri will surely die.

Figure 1.1.10 Ngarrindjeri rafts with windbreaks and fires (1840). (Artist A.C. Kelly, courtesy of State Library of South Australia)

Figure 1.1.11 Ellen Trevorrow: Ngarrindjeri Basket Weaver. (From Ngarrindjeri Nation (2007), courtesy of Vespa Tjukonai)

We ask non-Indigenous people to respect and understand our traditions, our rights and our responsibilities according to Ngarrindjeri laws and to realise that what affects us, will eventually affect them (Fig 1.1.11).

IMPACT OF EUROPEAN INVASION AND SETTLEMENT

Since European arrival, terrible crimes have been committed against the lands, the waters and all living things, and against the Ngarrindjeri People. Ngarrindjeri are living with the pain and suffering from the acts of terror and violence that were inflicted upon our Old People. This pain has been passed down to us through the generations. Our lands and waters were stolen, our children were stolen and our Old People's bodies were stolen from our burial grounds.

The first Europeans to arrive on our Country were supposed to make Treaties with Ngarrindjeri for the use, purchase and occupation of our lands and waters. The *Letters Patent of 1836* (Fig. 1.1.12) that authorised the British colonisation of the 'Province of South Australia' expressly sought to protect our traditional rights to land and resources in the following words:

> … Provided Always that nothing in those our Letters Patent contained shall affect or be construed to affect the rights of any Aboriginal Natives of the said Province to the actual occupation or enjoyment in their own Persons or in the Persons of their Descendants of any Lands therein now actually occupied or enjoyed by such Natives.

These provisions of the *Letters Patent* were the foundation on which the Ngarrindjeri vision for Sea Country could have been built, but sadly the South Australian Company ignored the written orders from King William IV of England.

In 2003, based on provisions of the *Letters Patent* and similar protections provided in legislation relating to the establishment of the Colony of South Australia, we petitioned the South Australian Government to transfer title of Crown land to Ngarrindjeri people and to negotiate a Treaty with us. So far there has been no response to our genuine request as Traditional Owners of our lands and waters for a Treaty and just settlement (Fig. 1.1.14).

Our contact with Europeans began in about 1810, when sealers operating from Kangaroo Island kidnapped Ngarrindjeri women and introduced venereal diseases. Soon after, other introduced diseases such as smallpox took a heavy toll on our people.

The stealing of our land by the South Australian authorities was illegal according to the instructions of the British Crown. Farmers and other settlers began occupying these stolen lands in about 1840. This was swiftly followed by destructive changes to our environment, the effects of which continue to impact on us today.

In 1840 a party of non-Indigenous survivors from a wrecked brig, the *Maria*, made their way along the *Kurangk* (Coorong) from near present-day Kingston. A year or so earlier another ship wrecked party was safely escorted along the *Kurangk* coast back to Adelaide. Ngarrindjeri stories tell of laws being broken by some members of the *Maria* party and violence occurring leading to the killings of the survivors. In response to the reported killings of the *Maria* survivors, a punitive expedition was sent from Adelaide to the area. Under the leadership of

Figure 1.1.12 *Letters Patent* of 1836 establishing the Province of South Australia. (From State Records South Australia — GRG2/64, courtesy of Government of South Australia).

Major O'Halloran, Ngarrindjeri were shot and several men were summarily hanged. No trial was held and even at the time this was recognised as a serious breach of British justice.

Since the 1860s successive South Australian governments have supported the construction of a huge network of agricultural drains in the south-east of our Country. Water that once brought life to a vast expanse of wetlands was drained into the sea, and the Coorong and

Figure 1.1.13 A large Ngarrindjeri *ngowanthi* (hut) on the hill overlooking Raukkan (Point McLeay Mission) on the shores of Lake Alexandrina in about 1880. The hut is a solid construction, with a timber frame and a windbreak extension. Fishing nets and spears can be seen. (Photographer S. Sweet, courtesy of South Australian Museum)

Figure 1.1.14 Presenting the Ngarrindjeri Petition to the South Australian Governor, Marjorie Nelson-Jackson, in 2003. (From Ngarrindjeri Nation (2007), courtesy of David Sjoberg)

other inland wetlands have been denied their major source of freshwater. As a result of this destructive land management, the Coorong, for thousands of years a major focus of our culture and economy, began to deteriorate and is rapidly dying today. According to recent scientific studies two thirds of the Coorong is irreparably damaged.

From 1935 to 1940 the South Australian Government funded the construction of five barrages at the southern end of Lake Alexandrina for the purpose of preventing the flow of saltwater into Lake Alexandrina and the Murray River (Fig. 1.1.15). Until that time, saltwater mixed with fresh water and sometimes travelled great distances up the river and the ecosystems of the lakes and the river had depended on the mixing of saltwater and freshwater.

The barrages were built at the request of European landowners and without the consent of Ngarrindjeri people. For the last 65 years we have witnessed the decline in the health, wildlife and other resources of the lakes and the river, made worse by the deliberate introduction of exotic species, such as the European Carp and destructive farming practices such as dairy farming, irrigation, land clearing and cattle and sheep grazing.

In 1859 a Christian Mission was established by the Aborigines' Friends Association at Point McLeay (now Raukkan Community), which provided a refuge for some Ngarrindjeri people who had been forced from their lands. However, missionaries such as George Taplin believed that the only way for Ngarrindjeri people to survive was to adopt European traditions and to become Christians. This meant that our language, traditional belief systems, culture and heritage was not valued by the South Australian government and the majority of the non-Indigenous community, and was undermined by the missionaries. We know that in 1836 the British Crown recognised our human rights through the *Letters Patent* and our equitable rights as British subjects. We also recognise that some South Australians have long supported, and continue to support, our human rights.

Threats to our traditional beliefs and sacred places have continued into recent times. The proposal to build a bridge to *Kumarangk* (Hindmarsh Island) during the 1990s directly threatened Ngarrindjeri women's and men's cultural beliefs and cultural sites. The majority of Ngarrindjeri people rejected the unjust outcome of the 1995 Hindmarsh Island Bridge Royal Commission. In 2001, a Federal Court decision by Justice Von Doussa completely contradicted the findings of the Royal Commission, but by then the bridge had been built, our beliefs desecrated and our sites destroyed.

Although Ngarrindjeri have watched the continuing destruction of our lands and waters we will always respect Our Laws of Sharing, Caring and Respect. Because of our knowledge, our inherent rights to our lands and waters, and our Cultural Spiritual responsibility we must be recognised as equal partners in caring and sharing for Country. Until our rights and responsibilities are acknowledged and respected this pain, suffering and continued denial of our inherited rights will be passed down to our children and their children's children.

We seek a just settlement of the past, recognition of our inherent rights in our *Yarluwar-Ruwe* (Our Country), an apology for the pain and suffering inflicted upon us, and compensation that will provide us with the resources to build a healthy future for our children and our grandchildren.

Figure 1.1.15 Tauwitchere Barrage near the Murray River mouth. (From Ngarrindjeri Nation (2007), courtesy of David Sjoberg)

We want to build partnerships, through *Kungun Ngarrindjeri Yunnan* Agreements, on foundations of trust and respect — this is the path our leaders have chosen. We congratulate the vision of the Alexandrina Council in signing the first ever *Kungun Ngarrindjeri Yunnan Agreement* with the Ngarrindjeri Nation which includes a 'sincere expression of sorrow and apology to the Ngarrindjeri people'.

We have long understood that for our rights, culture and heritage to be respected we must actively help the wider community to understand our history, our traditions, our beliefs and way of life. For more than 20 years we have operated a unique residential cross-cultural awareness and education facility at Camp Coorong, near Meningie (Fig. 1.1.16). Many thousands of Australians of all ages and backgrounds have attended courses and workshops at Camp Coorong and we have been encouraged by their willingness to listen to our side of the story and to reassess their own understanding of Australia's history and peoples. To counter ongoing challenges and threats to our cultural beliefs, special places and traditional practices, we will continue to engage in cross-cultural awareness teaching and we look forward to sharing our knowledge of culture and Country with many more Australians and international groups in the years ahead.

Our Old People taught us to Share with others. We invite all who respect us to join with us in our responsibility and duty to Care for Country. Let us walk together to build a healthy future for our children, our grandchildren and all generations to come.

Climate change

Ngarrindjeri have long experience with climate change and sea-level changes. *Kaldowinyeri* stories provide important teachings about the flooding of Ngarrindjeri lands and the changes to rivers and coast lines. Our Old People have watched the impacts of the degradation of their lands and waters since European invasion. Ngarrindjeri today recognise the huge impacts of global warming on their lands and waters and all living things.

In recent years we have observed changes in the local environment that indicates climate change is a reality. We see that the breeding behaviour of birds is changing, and the fruiting and flowering of certain Ngarrindjeri bush foods is changing. We have watched fresh water holes dry up or turn salty and coastal camping places and middens washed away by rising sea levels. When we lose such places we lose not only part of our cultural heritage, but we also lose an irreplaceable record of Ngarrindjeri adaptation to climate change in the past.

We have also noticed that some of their animal and plant species have declined in size and abundance, and some species have disappeared altogether.

We support the Kyoto Protocol, and the Ngarrindjeri Nation is willing to work with all levels of governments to reverse the damage done by industrialisation, bad farming practices and unsustainable lifestyles.

Figure 1.1.16 Tom Trevorrow (Deceased), Ngarrindjeri Elder, teaching Ngarrindjeri traditions on *Ruwe*. (From Ngarrindjeri Nation (2007), courtesy of David Sjoberg)

CONCLUSION

The Ngarrindjeri worldview has gained high-level acceptance in the non-Indigenous context through official State Government recognition of the *Ngarrindjeri Nation Yarluwar-Ruwe Plan* (2007) and the KNY agreement-making strategy. The plan and its vision, which encapsulate the Ngarrindjeri philosophy of being (*Ruwe*/*Ruwar*), have been at the centre of recent Ngarrindjeri interventions in Natural Resource Management, including the successful translation of the plans, goals and objectives into the *Murray Futures* project. The *Yarluwar-Ruwe Plan* is a clear example of Ngarrindjeri speaking as Country (*Yannarumi*) — the right and responsibility to speak as Country. It carries with it reference to Ngarrindjeri law, a Ngarrindjeri assessment of what constitutes wellbeing and guidance on the changes required to achieve Ngarrindjeri the vision for Country. In keeping with this vision, and working within the original intent of the KNY Agreement, Ngarrindjeri have recently further developed the KNY framework to include Speaking as Country agreements, which acknowledge that Ngarrindjeri speak for, control and care for their Country. In signing these agreements, parties commit to listening to Ngarrindjeri 'Speaking as Country' (Rigney et al. 2015). The Ngarrindjeri strategic approach, based on formal agreements and processes, careful planning and funded programs, continues to implement the *Ngarrindjeri Nation Yarluwar-Ruwe Plan* with its long-term vision of securing improved wellbeing for community, family, individuals and lands and waters within the Coorong, Lakes and Lower River Murray Region in South Australia.

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CHAPTER 1.2

EUROPEAN SETTLEMENT ACROSS THE END OF THE RIVER MURRAY

VALERIE SITTERS[1]

INTRODUCTION

The human population of the Murray River, Coorong and Lakes now comprises a diverse region of pastoralists, farmers and vignerons that has sustained European settlement since the 1840s,[2] when the explorers, coming by sea and river, found good pasturage and abundant fresh water. The overlanders, coming from the east with their cattle, found more pastures and another lake. The pastoralists were swift in taking advantage of these discoveries, raising cattle, sheep and horses on the lush fringes of the Lake. Farmers with their families came next, producing grain crops and dairy products; vignerons planted vines; and fishers harvested the rich fishing grounds of the Lakes and Coorong. Towns grew to support these activities and riverboats plied the Murray River with an associated boat-building industry. This chapter summarises European settlement and land use across the end of the River — a tale of diversity, hardship and adaptation.

EXPLORERS AND OVERLANDERS

When Matthew Flinders and Nicholas Baudin explored the southern coast of Australia in 1802 and met at what Flinders subsequently named Encounter Bay, neither noted the Mouth of the River Murray, Australia's longest river. Nor were they impressed by the Coorong shoreline. Baudin, sailing from the east, considered that

> [t]he stretch of coast that we have been following since yesterday consisted entirely of sand dunes … Quite apart from the wretched and unpleasant appearance of this shore, the sea breaks all the way along it with extraordinary force … [T]he lookout men at the mastheads … reported that in the hinterland, as far as the eye could see, there was nothing but arid sand with no vegetation.
>
> (quoted in Fornasiero et al. 2004, p. 153)

Flinders, sailing to the south-east, was similarly unenthusiastic:

> Next morning we again followed the coast at the distance of from five to three miles … [T]he coast is little else than a bank of sand, with a few hummocks on the top, partially covered with small vegetation; nor could anything of the interior country be distinguished above the bank.
>
> (Flinders 1814, p. 197)

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[2] Rob Linn's books 'A Diverse Land: A History of the Lower Murray, Lakes and Coorong' (1988) and 'A Land Abounding: A History of the Port Elliot and Goolwa Region, South Australia' (2001) were invaluable resources in writing this chapter. Tom McCourt's 'The Coorong and the Lakes of the Lower Murray' (1987) is a diverting and more personal account.

Charles Sturt, who navigated the River Murray in 1829-1830 and entered the broad lake at the termination of the river on 9 February 1830, had a more positive view: 'Immediately below me was a beautiful lake, which appeared to be a fitting reservoir for the noble stream that had led us to it' (Sturt 1834, p. 230). Sturt's fear that the lake meant there would be no practical exit to the sea was confirmed when he later examined the Mouth. His question as to whether he had missed another exit to the sea in his journey downstream was answered in 1831 when Captain Collet Barker was sent to explore this possibility. Travelling overland from Gulf St Vincent after having surveyed that coast, Barker showed that the river mouth discovered by Sturt was indeed the only exit to the sea. He also confirmed Sturt's impression of the fertility of the land on the south coast.

Although Sturt had negotiated the Murray and named Lake Alexandrina after the heir-presumptive to the British throne, he was not the first white person to view the Lake. The details of a lake found by sealers were forwarded to the Colonial Secretary in Sydney in a letter dated 20 January 1829 by Captain Forbes of the schooner *Prince of Denmark*. Forbes wrote that some of his sealing gang had 'discovered a very large lake of fresh water. They described it as being very deep and of great extent, as they could not discern the termination of it from the highest land' (Gill 1904-1906, p. 53).

While this letter was delayed in its arrival, a second letter written by Forbes, dated 13 May 1829, did reach Sydney before Sturt departed on his explorations, but it would appear that he saw neither letter.

South Australia was proclaimed and settled on 28 December 1836, in part because of the good reports of the land from Sturt and Barker. In November 1837 Young Bingham Hutchinson and Thomas Bewes Strangways explored south from Adelaide across the ranges towards Encounter Bay, where they borrowed a whaleboat and crew to examine Lake Alexandrina and the Mouth of the Murray. They discovered Currency Creek (named after the whaleboat), traced it to its source and described the 'fertile, well-watered and sheltered spot' (Linn 2001, p. 31). They landed on and named Hindmarsh Island, and also named Points Sturt and McLeay. Captain Blenkinsop's attempt to navigate the Murray Mouth in the whaleboat ended in disaster when it was overwhelmed by the surf and four men drowned. Hutchinson and Strangways reported that there was 'no practicable communication between the Murray and the sea by this entrance' (p. 34).

In December 1837 another small party set out to explore the region of the Lake. Robert Cock, William Finlayson and two others travelled via Mount Barker, discovered the River Bremer and reached the Lake. On the return leg of their journey they discovered the River Angas. Their report also praised the quality of the land.

Charles Bonney overlanded cattle from the Glenelg River in Victoria, leaving on 18 March 1839. In this pioneering journey, men and beasts endured great thirst, only being saved when the cattle, with the 'instinct peculiar to the animal, smelt the water of the lake' and followed their noses to what Bonney then named Lake Albert (South Australian Gazette and Colonial Register 1839, p. 2). He crossed the river near the future Wellington and proceeded to Adelaide with his herd.

Bonney's success encouraged George Hamilton, who left Port Phillip in the middle of 1839. He encountered even drier conditions, and his cattle, crazed with thirst, stampeded as they approached Lake Albert. Hamilton also experienced difficulties at the river crossing when his cattle balked and then bolted into the swamp; a different crossing was then safely negotiated. Other overlanders followed in their tracks and in September, while conducting a Special Survey for Neill Malcolm, Surveyor General E.C. Frome surveyed the whole shoreline of Lake Albert and most of that of Lake Alexandrina. He also made a quick trip along the Coorong as far as Salt Creek, reporting good feed and water and advising that it would make a suitable stock route.

Stock continued to be swum across the Murray until a private ferry was established at Wellington in 1841. Acting for the Secondary Towns Association and believing that a substantial town would develop near the junction of river and lake, John Morphett took out two Special Surveys that encompassed 15 000 acres 'one mile from each bank of the River Murray' (Linn 1988, p. 27). This survey included 'the rights to all of the water front of the Murray, from half a kilometre upstream from Monteith' to reach nearly to Point Pomanda below Wellington (p. 27). Morphett established his station on the Murray and began a ferry service across the river 6 km north of Wellington.

THE PASTORALISTS

The overlanders had shown the potential of the Lakes region and the Coorong. Pastoralists looking for land for their stock quickly followed. Neill Malcolm named his Special Survey Poltalloch, after his Scottish estate. He left the management to his agents in South Australia, Dr D. MacDougall and Samuel Davenport, who stocked it with Durham cattle, which thrived on the water grasses and reeds. Davenport was enthusiastic about the land: 'The Lake country is the best cattle run we have in these southern and eastern parts of the colony' (quoted in Linn 1988, p. 27). The South Australian Company was next to take up land in the district. Their manager, William Giles, investigated the land in September 1843 preparatory to sending 8 000 sheep and 800 cattle. On another scouting trip a few months later, he found that a Mr Johnson had established his sheep station near the junction of river and lake and a Mr Wilson another about 17 km to the south. The South Australian Company had other competitors as well — Duncan MacFarlane took advantage of an error in the company's application for an occupation licence and registered his own. Both moved quickly to get their stock onto the land. While MacFarlane narrowly won, they ended up dividing the Narrung Peninsula between them.

More occupation licences followed: by February 1846, T.G.F. Lang was setting up near Salt Creek and by September of that year Edward Spicer was on the Coorong. Other licences were held for adjoining areas in the Tatiara and north of Morphett's holding on the Murray. By the 1850s pastoralists were well established; some properties remained with the same family for several generations, while others changed hands through the years. Over time the stock changed as well. As pastoralists found that sheep did not thrive along the Coorong — they were affected by coast disease, the result of a copper and cobalt deficiency in the soil that was not resolved until the 1930s — the switch was made to cattle. As well, at Lallawa opposite Magrath Flat, the Dodds ran a successful horse-breeding stud. The family later purchased Mundoo Island and land near Meningie for horse breeding. Hindmarsh Island was leased by Dr John Rankine in 1853 for £10 a year and stocked with cattle, but he lost most of his herd when the Lake and

Lower Murray became saline. He also had land in the Angas River district and at Strathalbyn. Other Strathalbyn settlers grazed their sheep along the river and down to Lake Alexandrina. Charles Price took up land on Hindmarsh Island in 1854 and, fertilising with the bleached bones of Rankine's cattle, established vines that produced particularly tasty grapes. Pastoralism was also established further down the Coorong: John Gall purchased Cantara Station from Peter MacDonald in 1863 and later acquired Tilley's Swamp and Marcollat Station. Gall also secured the mail contract between Meningie and Kingston.

THE ROAD THROUGH THE COORONG

The Coorong was the main route to the south-east and on to Victoria. From a rough overlanding stock route it developed into a road, later the Princes Highway. Hotels sprang up to cater for passing traffic, with relay stations for coaches, and to supply the few locals. William Carter established a hotel and store at Salt Creek in 1847 — the first on the Coorong. The Tam O'Shanter opened at Magrath Flat in 1858, and the Coorong Hotel at Woods Well in 1861. To avoid the Victorian poll tax, Chinese people travelling to the Victorian goldfields at first landed at Port Adelaide and then travelled through the Coorong; later they switched to the new port of Robe. In July 1858 the first telegraph line between Adelaide and Melbourne, running from Goolwa to Pelican Point to Magrath Flat along the Coorong, was opened. The line went underwater from Goolwa to Hindmarsh Island and again to Pelican Point. In 1872 the line was rerouted through Wellington, joining the original line at Magrath Flat, because the Ngarrendjeri feared that the underwater cables would interfere with fish stocks and tried to damage it.

Initially, the Gold Escort route from the Victorian goldfields to Adelaide used the Coorong track but it was not long before a more direct route was surveyed through the Ninety Mile Desert. Sometimes the return trip was through the Coorong, depending on the weather. Coach travel along the Coorong became regular from 1867, with relay stations for the horses at Magrath Flat, Woods Well, Stony Well, Salt Creek, Chinaman's Well, Coolatoo and White Hut. Travellers and mail crossed the Lakes from Milang to Meningie on the Lake Alexandrina Steam Navigation Company's paddle steamer, the *Telegraph*. Later, with the advent of motor traffic, the track was compacted with local limestone and shells. A motor passenger service was operated from the late 1920s by two companies, McGee & Robb and (later) Bond's Buses. The road was officially proclaimed the Princes Highway on 9 February 1922, named after Edward Prince of Wales (1894-1972); it was bituminised in the 1930s.

AGRICULTURE

Pastoralists viewed agriculture as a threat because many of their leases were resumed and the land surveyed for smaller blocks. Surveys around Lake Alexandrina and Wellington were completed by July 1857, and the land released for sale three months later. Farming was labour-intensive and managed by families who frequently lacked the reserves to cope with poor seasons. Settlers of British and German stock had no experience of the drier Mediterranean climate of South Australia. Many were also inexperienced as farmers and either were slow to adapt their methods or failed to do so at all. For a time, wheat farming thrived and flour mills operated at Port Elliot, Goolwa, Hindmarsh Island and Milang, but without fertiliser the land became 'wheat sick'. While superphosphate became available from the 1880s, there was an initial slow uptake because of difficulties in spreading it. New seed drills finally resolved this problem. Many farmers moved to mixed farming. Ploughing competitions led to the formation of the Southern Agricultural Society, which by 1869 was holding annual show days that still operate. While wheat was the major crop, barley, lucerne and potatoes were also grown. In the Bremer River region in 1875 over 25 000 vines produced 500 gallons of wine — an early foray into what are now the Currency Creek and Langhorne Creek wine regions.

Agricultural Bureaus (forerunners of the Department of Agriculture) did not spread to the Lakes district until 1914, when they became a useful medium for discussing farming problems. While an irrigation colony proposed for the Milang district in 1892 did not proceed, the scrub in the area was cleared. Mullenising removed the mallee and the application of superphosphate boosted soil fertility. The railway proved its worth, transporting mallee roots and timber to Adelaide. But mallee stumps also proved useful in preventing soil erosion, with the new shoots burned and the ash distributed as a fertiliser.

With their plumes at the height of fashion, there was a brief foray into ostrich farming, while a duck-canning factory operated during the late 1980s but was abandoned in the mid-1890s on Younghusband Peninsula.

Soldier settlement schemes in the 1920s, together with increased mechanisation, led to a surge in occupation in the Finniss River and Currency Creek regions. But drought years, followed by the Great Depression, drove farmers from the land. Over-cropping and intensive farming methods also led to soil deterioration and erosion. Today there are a much higher use of irrigation and a proliferation of vineyards.

A cheese factory opened on Hindmarsh Island in 1900, using milk from local herds. A butter factory, opened at Milang in the 1880s, produced excellent butter and sent its produce to Adelaide. It closed in June 1904 as farmers sent their product direct to Adelaide, but reopened in 1915, with new owners using cream from Meningie across the Lake.

Early in the 20th century, the Government bought over 3 500 acres of Watson Park, originally established by Dr Rankine of Strathalbyn and Hindmarsh Island. The land was subdivided to become intensive dairy farms, with a Dairymen's Association established after World War II. When bulk handling of milk from the 1960s brought change, with licensing and strict regulations, many dairy farmers sold out, while others changed to crops such as lucerne and potatoes. In 1951 an irrigation settlement in Milang was again investigated but, as before, was not pursued. The only irrigation today is drawn from bores, many of which were sunk at the beginning of the 20th century.

FISHING

Fishing in the Lakes and Coorong includes both salt- and freshwater fish (see Chapter 3.6). Fishermen were recorded at the Murray Mouth in 1846. F.W. Cleland and Co. established a fish-processing plant at the Murray Mouth in 1870 which provided stability for about 30 fishers at Goolwa and Milang. The number of fishers increased during periods of low water in the River as the steamers could not operate, and again during the 1930s Depression, but generally hovered around 40. Milang fishers were more constant at around 11. Licensing was introduced in 1906.

Preserved fishes (smoked or cured) were sent to Port Adelaide for shipment, some to New South Wales and Victoria, and some as far as Mauritius. Mulloway was initially caught solely for the swim bladders that were dried for isinglass used in the brewing industry, but later for the flesh. Commercial fishing did not flourish, however, until the transport infrastructure improved with the railway from Goolwa and Milang in the 1880s and road transport from the late 1930s, although getting the fish fresh to the Adelaide market remained a problem before refrigeration, particularly in the summer. The fishery peaked in 1939 with 1 000 tonnes. Mulloway and yellow-eyed mullet were the main species harvested and they remain so, but quantities are greatly reduced.

Despite protests from fishers, barrages were erected across the Mouth of the Murray, varying Lake Alexandrina from a partially, or at times totally, marine environment to a freshwater system. Fish stocks changed, with numbers of callop and congollis increasing and Murray cod moving further out into the Lake. The barrages are generally believed to have severely impacted the nursery grounds for mulloway. Size limits were set for mulloway in the late 1880s and remain part of the regulations that cover fishing on the Coorong. Flounder became more prevalent after the mid-1970s, and were then the main species caught, giving the mulloway a respite and a chance to recover.

Over the years, commercial fishing has faced numerous threats. When, in the 1870s, fishermen blamed pelicans and shags for a decline in fish stocks, the Government declared a closed season to allow fish stocks to recover, leading to an outcry from fishers, fish mongers and customers. The arguments lasted for four years and the threatened closure only caused further problems. More and more fishers turned to nets rather than line fishing, adding to the over-fishing. By the 1950s the growing number of recreational fishers holidaying in shacks built in the Coorong further increased pressure on fish stocks.

In recent years, as the population of long-nosed fur seals in South Australia has been recovering, interactions with Lakes and Coorong fishers have increased to a level that has impacted the economic viability of gill net fishing methods. Interactions with fur seals are most significant during winter months when many juvenile and sub-adult male fur seals move into coastal waters to forage (see Chapter 3.9).

More positively, in 2015 Goolwa Pipico won a sustainability award, as it supplied a growing demand for the pipi or Goolwa cockle in top restaurants. The Coorong and Lakes fishery now has accreditation from the Marine Sustainability Council.

ACCESS ACROSS THE RIVER AND LAKES

The overlanders had pioneered the five original River Murray crossings — Wellington, Morphett's, Thompson's, Mason's, Edwards. From 1839 a private ferry operated at Wellington, the main crossing point of the Murray. In 1849 the Government took over the ferry's operation, with William Carter the lessee. The ferry was heavily used, and constantly beset with problems. It was later connected to a hawser stretched across the River, and hand-operated for many years before being motorised. Eventually the Colonial Engineer took over management. The stockyards on both sides of the Murray were inadequate for the traffic, and winds sweeping upriver from the Lake meant that the ferry could not always operate. The Victorian Gold Rush increased patronage, and in February 1852 alone 1 200 passengers, nearly 1 300 horses and bullocks, and 164 carriages used the crossing. Indeed, so much traffic used the ferry that the hawser needed replacement. Hailed as 'the most important to traffic of any in the colony' it continued to be plagued with problems (Linn 1988, p. 79); toll evasion was rife and ferryman Carter eventually collapsed from the stress. Even when, in 1879, the Murray was bridged upstream at Edwards crossing, the Wellington ferry continued to operate, and still does.

There were other ways of crossing the Murray. Dr Rankine used his own ferry for moving stock between Hindmarsh Island and his Strathalbyn property. The Dodd brothers daringly swam their stock across the Murray Mouth to the Coorong, but experienced some losses. A ferry operated from Goolwa to Hindmarsh I. from some time in the 1850s; the Council spent £750 on it in 1862, and in 1867 installed a larger ferry to cope with increased traffic. Maintenance of the ferry was a heated issue between the Council of Port Elliot and the Town of Goolwa. In 2001 the Hindmarsh I. Bridge replaced the ferry to service a proposed marina development on the Island. Controversy over traditional Indigenous beliefs and sacred site issues, as well as environmental concerns, delayed construction for many years. Steamer traffic across the Lakes flourished in the years before adequate road infrastructure.

THE MURRAY MOUTH

Charles Sturt's assessment in 1830 that '[t]he mouth of the channel is defended by a double line of breakers amidst which it would be dangerous to venture' (1834, p. 240) was just the first of many negative reports. The work of marine surveyors employed by the Government resulted in accurate charting, but the major problem was the huge movement of sand. Two surveys, in 1839 by W.J.S. Pullen and in 1857 by Bloomfield Douglas, revealed that the Mouth had moved about 500 m south-east. A further survey in 1876 showed that this movement had continued for another 400 m. But by 1914 the Mouth had moved west by 450 m and continued to do so, returning nearly to its original position of 1839. A later survey again revealed an easterly drift.

While this continual movement was not insurmountable, it added to the problem of navigating the Mouth. Various proposals made across the years to deal with this included deep piling to assist in scouring the channel. But the most enduring concept was a canal, either to Port Elliot, instead of the railway, or later to Victor Harbor. Two further proposals were made in 1916. The one favoured was a canal from Goolwa through the Sir Richard Peninsula, which involved cutting through the sand hills to provide a canal with a minimum depth of 7 m and two breakwaters into the sea, one 1 310 m long and the other 2 633 m. Less popular was the proposal for a huge breakwater, 2 520 m long, which curved around to the east across the Mouth. Major Johnston of the United States Corps of Engineers, engaged by the South Australian Government to advise on River Murray navigation improvements, suggested several variations of a canal, as well as reclaiming Lakes Alexandrina and Albert. All these schemes and suggestions, however, were deemed too expensive and were shelved. Today, with the river boat trade long past, dredging in times of low river flow keeps the Murray Mouth open.

PADDLE STEAMERS, TRADE AND THE GROWTH OF TOWNS

From the time Charles Sturt navigated the River Murray it was seen as a highway to the other colonies. At first it was overlanders bringing stock across to Adelaide from Victoria, but when

Governor Sir Henry Fox Young arrived in South Australia in August 1848 he pushed for further use. A commission into ports and harbours emphasised the idea of linking the Murray to a harbour in Encounter Bay by either rail or canal, as Goolwa was within 12 km of a possible location in the Bay. Harbourmaster Thomas Lipson, authorised by Young to survey Encounter Bay for a suitable site, selected Horseshoe Bay over the more exposed Rosetta Head, Victor Harbor. The land between Horseshoe Bay and Goolwa was surveyed in 1849 for a railway but a canal soon gained favour, even though it was seen as an expensive option. But the concept of a canal linking Goolwa to the sea did not die and work began in 1851 on a port at Horseshoe Bay, with a township surveyed in January 1852.

Meanwhile, Governor Young announced a bonus for the first iron steamer on the River Murray. Gumeracha miller William Randell was already working on his paddle steamer (PS) with an eye to delivering flour and other supplies to the Victorian gold fields and had the PS *Mary Ann* on the River in March 1853. But he had a competitor: Francis Cadell negotiated a deal with the Government — £1 000 for reaching the junction of the Darling River, a further £1 000 if he remained trading for a full year, and £500 if he navigated the Murray Mouth. His steamer, the PS *Lady Augusta*, built in Sydney and sailed under jury rig to Encounter Bay, was safely brought through the Mouth. At Goolwa, Cadell collected the locally built barge *Eureka* and, with an official party including a reporter, began the voyage upriver, while Randell had left 10 days previously. The *Lady Augusta* caught up with the *Mary Ann* some days' journey out of Swan Hill, where both vessels arrived on 17 September. After two days, Randell pushed on to Echuca while Cadell turned back to honour a commitment to collect a load of wool. Randell received a bonus of £300; the reward for Cadell was much richer, thanks to his canny negotiations with the Government.

This was the beginning of a lucrative river trade. Paddle steamers plied the Murray for years to come, crossing the Lakes and steaming down the Coorong, and shipbuilding thrived at river ports, including Goolwa and Milang. Cadell had shown that the Murray Mouth could be navigated with due care, and others emulated him in the coming years. Cargo coming down the river was taken by horse-drawn rail, the first iron railway in Australia, to Port Elliot for shipment to Port Adelaide or to the other colonies. Extended to Victor Harbor in 1864 when Port Elliot proved an unsafe harbour, and to Strathalbyn in 1869, the line was connected to Adelaide in 1884 and converted to steam in 1885. The opening of the Adelaide to Morgan railway in November 1878 affected the amount of trade coming downriver and eventually led to the demise of the river towns, Goolwa in particular.

Goolwa was first surveyed in January 1840 as part of the Currency Creek Special Survey, and the first allotments were issued by ballot in 1841. However, it was the birth of the river trade and the railway that brought real growth. A further survey of town allotments was conducted at the same time as the survey for a suitable site for a wharf, the allotments being auctioned on 28 April 1853. Construction of a stone residence for the railway superintendent began in July 1852, and of the wharf in November 1852, with the cargo shed foundations being laid in December 1853. The railway and river trade generated further substantial buildings in the next decade — the Customs House in 1859 after the Port of Goolwa was proclaimed in September 1857, and the railway horse stables in 1862. The wharf was extended in the 1870s, with additional mooring dolphins in the stream; a railway station for passengers erected opposite the post office later proved too small and was relocated and enlarged. A courthouse, an improved police station, churches, a school, a bank building and an Institute followed, and the growing town was declared a municipality at the end of 1872.

Steamers and barges had been built from the 1850s, largely from prefabricated sections shipped out from Scotland, but the Goolwa Iron Works and Patent Slip, subsequently known as Graham's Foundry, opened in 1864. It built 45 steamers and barges from 1864 to 1877, as well as undertaking repair work. The Foundry, employing between 20 and 30 skilled hands, produced a wide range of machinery, including engines and boilers and everything required for the Goolwa Saw Mill. However, by the early 1880s, as the Morgan railway made an impact, Graham's Foundry was forced to close. Although the steamer trade continued, Goolwa's heyday as the premier town on the River Murray was over and it declined, not to begin a recovery until the 1930s with the building of the barrages.

Milang on Lake Alexandrina was surveyed in December 1853, in part as a service town for the farmers of the Hundred of Bremer but also as a port for the new river trade. A 67 m long jetty was built in 1856 and extended three years later to a length of 217 m to allow for the greater number of steamers using it, and to cope with the sometimes shallow water of the Lake. A steel crane mounted at the end of the jetty aided the loading and unloading of cargo. Steamers and barges were built at Milang, together with fishing and sailing boats. A.H. Landseer, a prominent local businessman, commissioned a floating dock from Thomas Smith of Milang. Reputed to cost £1 500 and to be the largest in the southern hemisphere, it was not a success, owing to the shallowness of the Lake, and it was subsequently towed to Mannum to be used as a graving dock.

Landseer, one of the owners of the Lake Alexandrina Shipping Navigation Company, commissioned the building of the PS *Telegraph* in 1866. It carried mail, general cargo and passengers from Milang to Meningie but was replaced by the PS *Despatch* in 1877. Other steamers were built in Milang, but probably the most notable was the PS *Marion*, built in 1897 for Adelaide merchant G.S. Fowler. He died before the boat was completed and it was later acquired by William Bowring of Wentworth. The *Marion* traded successfully for many years and is now a museum exhibit and cruise boat at Mannum.

While shipbuilding was a strong secondary industry in Milang, the town did not suffer the downturn of Goolwa when the river trade declined, as it enjoyed a buoyant cross-lakes trade with both steamers and sailing vessels. Narrung, Point McLeay and Meningie were serviced by these vessels, as well as many of the large pastoral properties, such as Poltalloch and Campbell Park, which had their own jetties. Stock was transferred across the Lakes, and cream from the dairies, and general farm stores. Navigating Lake Alexandrina could be dangerous, as winds whipped up huge waves, and not for nothing was the central region of the Lake noted as an 'open sea'. Road transport eventually destroyed this era of lake traffic and Milang reverted to its agricultural roots.

Across the Lake, Meningie arose on Lake Albert to become part of a better mail and passenger service to the south-east of the colony. The steamers that plied between Milang and Meningie connected with a coach service and cut a large angle off the old route from Wellington. The town was surveyed in May/June 1866 and the first blocks went on sale in August. The post office was opened in 1867, while a jetty was built at the end of the town to accommodate the steamers, as this was considered the best position. A hotel and a store followed within a year. Meningie, developed as a service town for the region, continued to thrive long after the mail service was taken over by the railway through Murray Bridge. It is now the tourism gateway to the Coorong, offering hotels, motels and caravan parks.

An unusual development of the Lakes' steamer traffic was the building of Australia's only inland lighthouse, at Point Malcolm at the Narrung Narrows between Lakes Alexandrina and Albert. Operating from February 1878, it was turned off in September 1931 with the decline of the steamer traffic. A light on a pole next to the lighthouse tower now aids recreational and commercial vessels. As the township grew, the District Council of Meningie was formed in February 1888, and was dominated initially by the pastoralists with concerns over sand drift, the spread of rabbits and noxious weeds, and the perennial issue of the Wellington ferry. As the district expanded, the railway town of Tailem Bend came under Meningie's administration. Because it had an entirely different focus from the pastoral and agricultural land owners of the Lakes and Coorong, there was ongoing dissension and talk of secession by the town's residents. Nevertheless, Tailem Bend remains within the Coorong District Council, formed in 1995 and with offices in Meningie, Tailem Bend and Tintinara.

Wellington was surveyed in 1841 as part of John Morphett's Special Survey, with 700 half-acre town allotments on the west bank and a further 300 on the east bank. Police were stationed there in the same year, but it was some years before an adequate police station was

Figure 1.2.1 At Point Malcolm, at the Narrung Narrows between Lakes Alexandrina and Albert, is Australia's only inland lighthouse. (Photograph reproduced with permission from the State Library of South Australia, SLSA PRG 280/1/4/180, photographer unnamed)

built. The police served a large area around the eastern shore of the Lakes and down into the Coorong. The focus of the town was the ferry, both as an important river crossing for people and stock, and for the trade that this brought to the hotels established on either bank.

LAW AND ORDER

Law and order in the disparate regions of the Coorong and Lower Lakes region began as early as 1841, when police troopers were stationed at Wellington. Goolwa was initially served by a trooper from Port Elliot station, but in 1858 the first police were stationed in the town and a police station and courthouse opened on 27 October 1859. The main focus of policing in the town was petty theft and drunkenness, particularly in the low season when there was an influx of men who worked on the paddle steamers. A police trooper was stationed at Milang in late 1865 after a Memorial was sent to the Governor, seeking police protection against petty theft by unemployed men from the paddle steamers. The Milang Police Station closed in the 1970s. A police station opened at Narrung in October 1853 to deal with the illegal supply of alcohol to the Indigenous population. Meningie Police Station, which was opened in November 1878, had a stop/start history, being closed in September 1894 due to police retrenchments but then reopened in 1907.

Town policing was one thing, policing outside the towns another. Busy ferry town Wellington had police as early as 1841, but it was some years before an adequate police station with accommodation for the troopers was built. Originally on the River's west bank, it was later moved to the east bank, which was more practical given the many emergencies east of the River. The Wellington police oversaw a huge area extending into the Coorong. Everyday occurrences included drunkenness, abusive language, robbery, sheep stealing and the illegal supply of alcohol to the local Indigenous population. However, the lonely reaches of the Coorong were also the scene of some horrific murders, as when, in 1842, George McGrath was killed by his Aboriginal companions. When eventually captured, the leader of the group who killed him pleaded that he and his companions had been forced to travel beyond their tribal boundaries. This was not accepted as a justification for the crime, and he was hanged in 1845. McGrath Flat commemorates this incident.

By far a more horrendous crime, infamous in its time and with modern-day echoes, was the murder of servant Jane Macmenimen at Salt Creek. Jane worked at the Traveller's Rest Inn, owned by Malachi and Catherine Martin. In February 1862 her sister, a frequent correspondent, became suspicious of Jane's absence from her workplace. Martin and his wife gave conflicting accounts of the direction in which Jane had gone, and it was also thought strange that she had not claimed £50 that a Mr Carter in Wellington was minding for her. With these uncertainties, coupled with Martin's poor reputation, the police from Wellington began investigating. Martin was suspected of murdering his wife's first husband, William Robinson, but never charged, and local Aboriginals believed he had killed one of their own. When a trooper sent from Adelaide to assist the investigation passed through McGrath Flat, he was told that Aboriginal people had found a woman's body stuffed down a wombat hole. Although badly battered, the body was readily identified as that of Jane Macmenimen. Martin and his wife attempted to throw suspicion on the Aboriginal people, but the police were not convinced. Evidence of a violent struggle in a room at the inn with a blood-spattered wall hidden behind a cupboard, together with the strong motive that Martin had not paid Jane for two years, was enough to convince the police. Martin was arrested and brought to trial in Adelaide in December 1862, found guilty of murder and hanged at Adelaide Gaol on 24 December 1862. William Wilsen, who claimed to be engaged to Jane, was found guilty of being an accessory to the murder and sentenced to four years' hard labour.

More vicious still was the murder of Trooper Harry Pearce, a case that involved the length of the Lakes and Coorong. Robert Johnston, charged on 11 May 1881 in Wellington for selling alcohol to the local Aboriginal people, failed to appear at the urgently convened court that he had requested because of commitments elsewhere. As he was suspected also of horse theft in South Australia's Mid-North, a warrant for his arrest was issued, and he was taken to Meningie Police Station and from there relayed to Kingston Police. While he was near Salt Creek, Johnston had boasted to a farmer that it would be easy to kill a police trooper when away from a town and its support. He moved on to White Hut, where Kingston police sent Trooper Pearce to arrest him. Johnston went quietly but, dismounting under some pretext on the way to Kingston, stabbed Pearce multiple times, effectively disembowelling him. Johnston turned the police horse loose, disarmed the trooper's weapon and rode away, leaving Pearce to die. Several hours later, a passing rider heard Pearce's faint calls for help. Another passer-by, a drayman, remained with Pearce while the rider returned to Kingston for medical help. Pearce lived long enough to make a dying deposition and to identify Johnston. His parents from Adelaide also had time to reach his side before he died of his wounds on 18 May. Johnston was captured near Naracoorte and his blood-stained clothes and a blood-stained knife found in his swag were strong evidence against him. He was tried for murder at Robe on 21 October 1881, the jury taking only 15 minutes to find him guilty; and he was executed at Mount Gambier Gaol on 18 November 1881. The telegraph played an important role in linking the police stations and widening the search.

TOURISM-LED RECOVERY

The barrage building saw a temporary boom in Goolwa, but after World War II it became a rather bleak and uninspiring country town, at least economically speaking. The river trade had promised, and for a while did offer so much, but that faded with the growing network of railways across the state. The town found a new direction in a slowly growing tourist trade, beginning with pioneering tours to the Murray Mouth conducted during the Depression by the Bedford family. Sports venues were upgraded; then in the 1960s private developers initiated the South Lakes development, turning swamp and sand hills into a 'pleasure resort' that encouraged further developments. As well, Keith Veenstra built and operated boats for guided tours of the Murray Mouth. This highly successful family business, Spirit Australia, still operates, with regular cruises to the Murray Mouth and the Coorong. The Signal Point Riverboat Museum and Interpretive Centre opened in January 1988. Built on Signal Point Hill overlooking the Goolwa Channel and wharf area, it featured the PS *Oscar W*, built in 1908, as a working exhibit. Although Signal Point later closed as unprofitable, *Oscar W* remains at the wharf, lovingly brought to full restoration by a dedicated Friends group. Now owned by the Alexandrina Council, it operates one-hour cruises and full-day charters, while the Signal Point building houses an art gallery and wine-tasting centre. The popular Wooden Boat and Music festival, initiated in 1989, draws enthusiasts and visitors every year from across Australia. Goolwa is also part of the international Cittaslow movement, which aims to promote the cultural diversity and uniqueness of individual towns.

The 1981 census showed that the highest ratio of holiday homes for the state was in the Victor Harbor, Port Elliot and Goolwa districts. The River and Lakes towns have also enjoyed a boom as a 'retirement zone'. Goolwa recognised this early and the Customs House was revamped as the Heritage Club to offer an activity centre for elderly people. Renamed the Centre for Positive Ageing it continues this function, catering for the burgeoning number of retirement communities in the district. Wellington also enjoys this boom in tourism, with the courthouse restored and renovated as a hotel with fine dining, and a new development on the east shore of the River at Wellington Shores.

CONCLUSION

The land across the end of the river, one of the state's most fertile regions, has thrived. In a state as dry as South Australia, the value of the lower River and Lakes was immediately recognised as a source of fresh water for pastoralists and their herds, for farmers and their crops, for vignerons and their grapes, and for fishers with the diversity of fresh- and saltwater fish. Extraction of water upstream, drought and the need for water for environmental purposes are now a grave concern and a focus of debate between South Australia and the upstream states. Over and above these primary industry needs, however, there have always been an appreciation of the natural beauty of the region and a growing enjoyment of the lower river system for recreational purposes.

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PART 2:

PHYSICAL-CHEMICAL NATURE

CHAPTER 2.1

GEOLOGICAL EVOLUTION OF THE RIVER MURRAY ESTUARY REGION, SOUTH AUSTRALIA

ROBERT P. BOURMAN[1], COLIN V. MURRAY-WALLACE[2], DEIRDRE D. RYAN[3] AND ANTONIO P. BELPERIO[4]

INTRODUCTION

The modern River Murray Estuary collectively comprises the predominantly freshwater Lakes Alexandrina and Albert and the saline Coorong Lagoon, with oceanic access via the River Murray Mouth. The estuary is situated in the south-western corner of the greater Murray Basin (Fig. 2.1.1) in close proximity to the Mount Lofty Ranges. Although the Murray Estuary occupies a somewhat subdued topographical setting, investigations of its geology reveal a fascinating evolutionary history, which extends from the Archaean to the present time, albeit with episodes of minimal change. A prolonged period of denudation separated a dramatic episode of mountain building and the passage of a continental ice mass, culminating in the un-roofing of the Encounter Bay Granites, which still influence the morphology of the Estuary. Further landscape lowering and deep weathering followed, all before Australia and Antarctica separated by plate tectonic movements.

The nascent Encounter Bay coastline formed from ~43 Ma ago as the last two continents of Gondwana separated. At this time a low-lying and deeply weathered landscape subject to oceanic ingress heralded the onset of shallow marine deposition in the Murray Basin on a trailing edge, passive continental margin. Continuing tectonism throughout the Cenozoic resulted in uplift of the Mount Lofty Ranges and the Padthaway Ridge, with the Estuary subsiding, allowing multiple marine transgressions into the low-lying continental margin basin. The resulting marine limestones act as useful markers for differential tectonism between the Estuary and the Mount Lofty Ranges.

A combination of subsidence of the Murray Lakes area, uplift of both the south-eastern Coastal Plain and the inland Murray Basin, together with regular sea-level fluctuations throughout the Pliocene and Pleistocene, resulted in the formation of a remarkable sequence of stranded coastlines extending from hundreds of kilometres inland to the modern shoreline.

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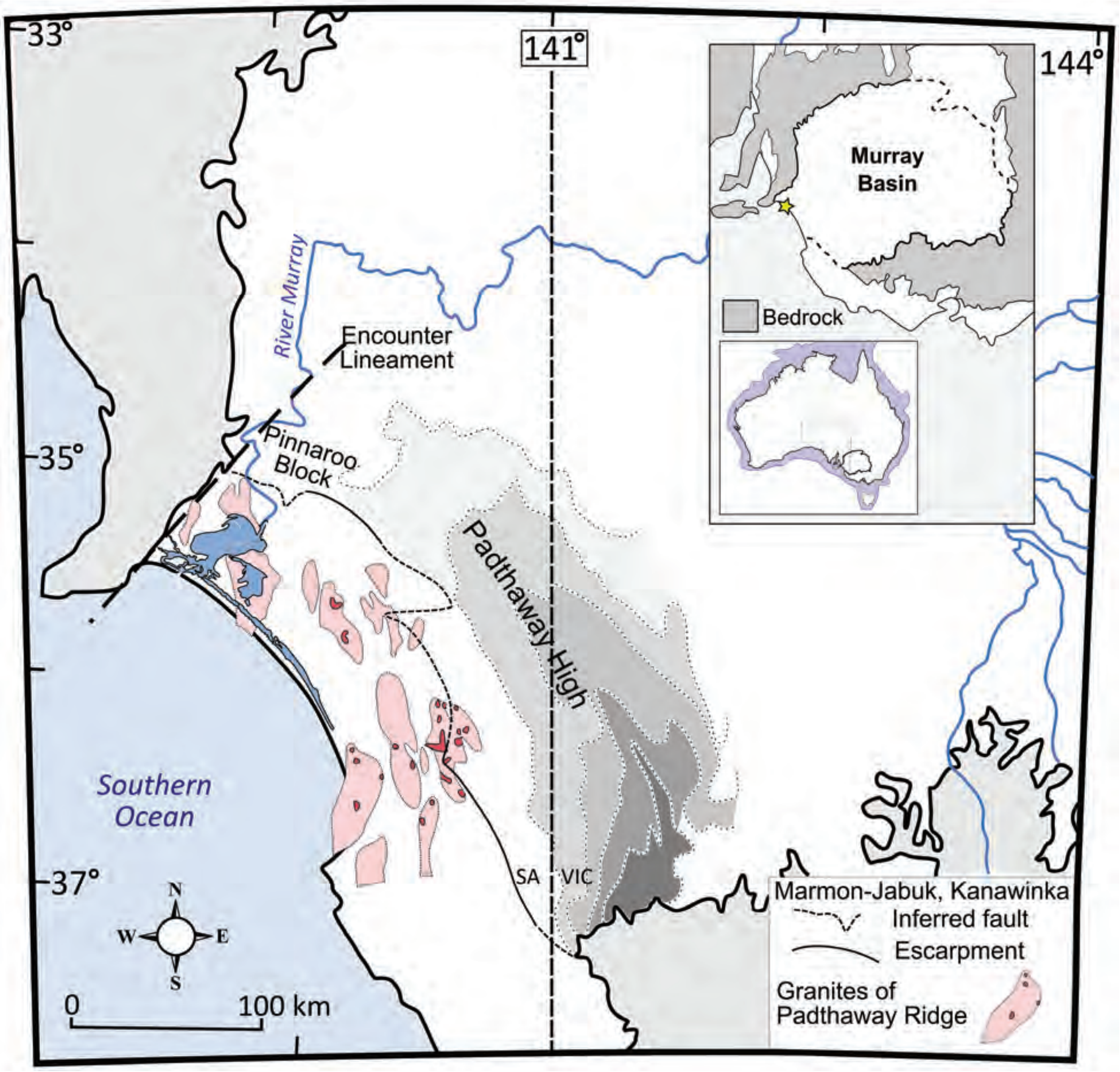

Figure 2.1.1 Location map of the lower River Murray Lakes and the Coorong Lagoon between the Mount Lofty Ranges and the granites of the Padthaway Ridge. Location of Padthaway Ridge granites from Preiss (1995). (Map by Deirdre D. Ryan)

Interdunal corridors, enlarged by erosion of the south-flowing River Murray, formed the template for the freshwater Murray Lakes, while the saline Coorong Lagoon developed between the Last Interglacial shoreline and the modern beach/barrier shoreline of Younghusband Peninsula.

The southerly course of the River Murray is structurally controlled by N-S trending faults and its present-day course was established following the drainage of a huge freshwater lake upstream of Swan Reach about 800 ka ago. Uplift along the Encounter Fault on the eastern side of the Mount Lofty Ranges led to the shedding of river alluvium, which forms river terraces along the streams draining to Lake Alexandrina, while increased river flow, a higher sea level in the mid-Holocene, and enlarged lakes caused deposition of lacustrine sediments around the Lake margins.

The modern landscape reflects the influence of many of the antecedent geological events: sediments derived from the underlying bedrock were incorporated into Permian glacigene sediments, which, in turn, provided the source for many generations of subsequent fluvial, marine and aeolian sediments, as did deeply weathered regolith; the glaciation exposed the granite core of the ~500 Ma old fold mountain range and these granite masses have subsequently influenced the plan form of Pleistocene shorelines, with some of the younger shorelines resting on older ones following tectonic subsidence.

Much of the detailed geology of the Murray Estuary has been covered in the first chapter of the Royal Society publication the 'Natural History of the Riverland and Murraylands' (Bone 2009). This present volume examines the geology primarily in terms of unravelling the geological evolution of the Murray Estuary Region and revealing the impacts that earlier processes and rocks have had on its present-day landscapes. Many of these rocks are found at the surface across Fleurieu Peninsula and at varying depths beneath the Murray Estuary. During the Quaternary, the past 2.6 Ma, the geological features of the estuary are very closely associated with its modern landscapes, as seen in fossil beach/dune barrier ranges and fluvial and lacustrine sediments.

BEDROCK UNDERLYING THE MURRAY ESTUARY

The Murray Estuary is underlain at depth by the Cambrian Kanmantoo Group of metasedimentary and associated igneous rocks, which occur only sporadically at or near the surface. Samples of bedrock encountered in nine drill holes in the vicinity of Lakes Albert and Alexandrina included metasandstone, phyllite, schist, granite and sandy sediments (SADME Petrology Report 21/90 1990), at depths varying between 69.4 and 187.6 m. As well as providing the foundations for the evolution of the Murray Estuary, these rocks have also served as sources for subsequent sedimentation and have influenced the morphology of more recent landforms. The Kanmantoo Group of rocks also comprises the majority of the rocks on the eastern Mount Lofty Ranges and underlies the Murray Basin probably at least as far as the Victorian and NSW borders (Preiss 1987; Belperio et al. 1998).

The Kanmantoo Group was deposited along the eastern margin of the Adelaide Geosyncline, a subsiding rift complex underlain by crystalline Precambrian basement rocks of Archaean to Meso-Proterozoic age (Preiss 1993). These ancient rocks, formerly sedimentary, metamorphic and igneous rocks, were metamorphosed c.1 600-1 550 Ma ago (Belperio et al. 1998), forming the crustal rocks of the supercontinent of Rodinia. Rifting phases affecting Rodinia led to the development of a huge subsiding basin complex, the Adelaide Geosyncline, in which a maximum thickness of 24 km of shallow marine clastic and glacial sediments with associated volcanic deposits accumulated during Neoproterozoic to Middle Cambrian times, 870-c.500 Ma ago (Preiss 1987, 1995; Preiss et al. 2002; Belperio et al. 1998). The Adelaide Geosyncline extended from Kangaroo I. to beyond the North Flinders Ranges and was up to 300 km wide. The Kanmantoo Group comprises the youngest rocks of the Adelaide Geosyncline deposited into the deeply subsiding Kanmantoo Trough from 526 Ma, in an extensional sub-basin, generated by renewed rifting (Belperio et al. 1998).

The entire sequence of ancient basement rocks and Proterozoic and Cambrian rocks was folded and uplifted by compressive forces during the Delamerian Orogeny of Middle to Late

Cambrian age, resulting in the formation of a fold belt of possible Himalayan proportions. Volcanic extrusions and granitic intrusions at a depth in the crust of 10-14 km (Milnes et al. 1977; Sandiford et al. 1992; Foden et al. 2006) accompanied the deformation of these rocks between 510 and 500 Ma ago. The granites are now exposed around Encounter Bay as islands and headlands on the eastern side of the Mount Lofty Ranges, on Kangaroo I., on the margins of Lake Albert and south-east of the estuary, while the extrusives occur largely beneath younger Murray Basin cover in an arcuate magnetic zone, referred to as the Padthaway Ridge, a horst-like structure oriented in a SE-NW direction, 30-60 km inland from the Coorong. As well as granitic emplacement, the Delamerian Orogeny was accompanied by intense compressive folding, thrust faulting and shearing, associated with pervasive, but only low to moderately high-grade metamorphism (Belperio et al. 1998; Jago et al. 2003), as original sedimentary features and fossils can still be recognised in many cases. The intense compressive folding was followed by crustal extension at ~490 to 480 Ma ago (Belperio et al. 1998).

THE PERMIAN GLACIATION (299-290 MA)

Following the Delamerian Orogeny, there is little record of sedimentation in the Murray Estuary Region over the ensuing 200 Ma. Some reworked Devonian spores, identified in Permian glacigene sediments on Yorke Peninsula (Harris & McGowran 1971), were derived from localities to the east and may have originally accumulated in the Murray Basin (Rogers 1995a) or the Mount Lofty Ranges. However, the dominant processes operating on the Delamerides over this vast time span were those of erosion, so that, by the time of the Late Palaeozoic glaciation ~300 Ma, the granite core of the mountains had been exposed. This is shown by the presence of glaciated granite bedrock at Port Elliot (Milnes & Bourman 1972) and the widespread distribution of erratics of Encounter Bay Granites across Fleurieu Peninsula. Even further erosion is shown by the glacial pavements present on Precambrian basement rocks near Little Gorge on Fleurieu Peninsula (Bourman & Milnes 2016).

Sediments from the protracted erosion before the Late Palaeozoic glaciation would have accumulated within and on the margins of the Delamerides, but they were incorporated into Permian deposits as the area was submerged by a continental ice cap up to 1 to 2 km thick, eroding bedrock, while bulldozing and reworking pre-existing deposits.

Even though all the states of Australia were impacted by a continental ice mass during the Late Palaeozoic of the Carboniferous and Permian, the majority of associated glacigene sediments in SA appear to have been deposited during Permian times. Early Permian forams were identified in deglacial sediments in the Troubridge Basin (Ludbrook 1967; Foster 1974), while Early Permian pollen has been recovered from lodgement tills at Hallett Cove and the Murray Basin (see Bourman 1987), thus covering the entire period of the glaciation.

The area occupied by the modern Murray Estuary was transgressed by continental ice moving generally from the south-east to the north-west during Early Permian times 299-290 Ma ago. The north-westerly direction of ice flow is conveniently revealed by the provenance of erratics. For example, granite erratics derived from Dergholm in Victoria (Wells 1956) and erratics of porphyry sourced from the Mount Monster porphyry outcrops in the Southeast of SA have been located in the Mount Lofty Ranges (Thomson & Amtmanis 1971; Webb 1976) and on Yorke Peninsula (Crawford 1965).

At this time the southern continents were welded together with peninsular India to form the supercontinent of Gondwana (Fig. 2.1.2), all of which was impacted by an extensive polar ice cap. In SA the ice mass was temperate and wet-based in character, with the base of the ice mass being near pressure melting point, due to the great weight of overlying ice. Meltwater at the ice base caused relatively rapid and plastic movement of the ice with high erosive potential. There is compelling evidence of this glaciation preserved in the form of glaciated bedrock surfaces, glacial landforms and extensive glacigene sediments throughout the Troubridge Basin (Alley & Bourman 1995; Alley et al. 1995, 2013; Bourman & Milnes 2016) (Fig. 2.1.3), the general boundaries of which reflect relicts of a widespread blanket of glacigene deposits (Wopfner 1970). However, the thickest sequences have been preserved in tectonic and topographic bedrock troughs (Alley & Bourman 1995).

The Permian glacigene sediments (the Cape Jervis Formation) were named after the type section in the cliffs at Cape Jervis (Alley & Bourman 1984). Only 50 m of the Cape Jervis Formation occur in outcrop, but thicknesses of up to 335 m have been proven by drilling at Kingscote (Bourman & Alley 1999). Several workers (e.g. Bowen 1958; Crowell & Frakes 1971a, b; Toteff 1983) have proposed the possibility of multiple Permian glaciations in SA. However, glacigene sediments at the type section record the passage of only a single, wet-based continental-scale glaciation (Alley & Bourman 1984). The earliest recorded sediments in the area were deposited in streams and lakes ahead of the advancing ice. This was followed

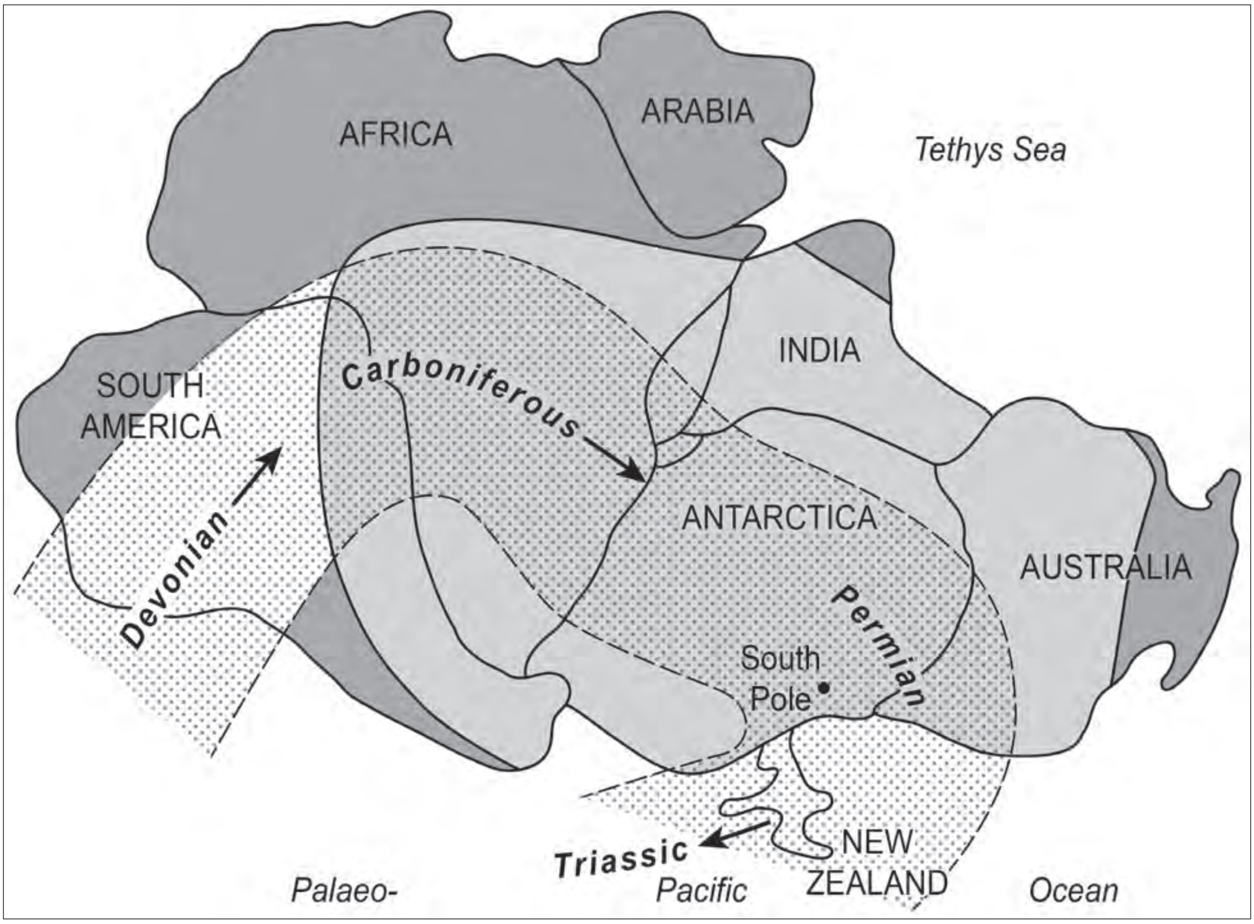

Figure 2.1.2 Supercontinent of Gondwana showing areas covered by Devonian to Permian ice (light grey). (From Alley et al. 1995, reproduced with permission from the Department of Energy and Mining)

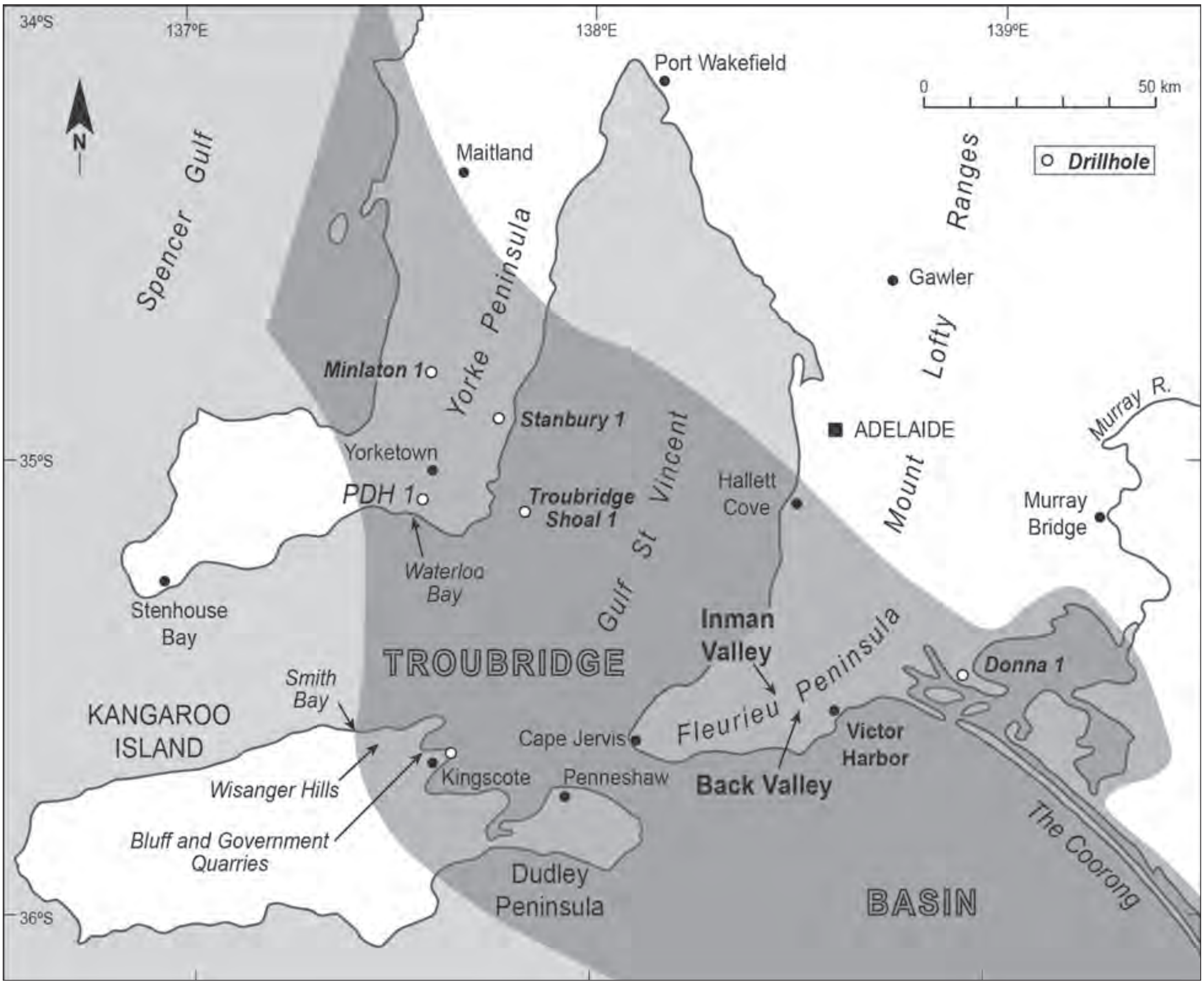

Figure 2.1.3 Location of the Permian Troubridge Basin in dark grey, delineating areas of glacial sedimentation both in outcrop and subsurface. (From Alley et al. 1995, reproduced with permission from the Department of Energy and Mining)

by deposition of a basal lodgement till plastered onto ice-fractured bedrock by the advancing ice mass. Locally sourced pebbles in the lodgement till align with the direction of ice flow. Progressively, this lodgement till was overlain by sediments associated with ice decay, and down wasting; fine-grained glacio-lacustrine sediments were deposited in lakes marginal to the melting ice with dropstones released from melting icebergs. Slippage of accumulated rocks and other sediments from the surface of the melting glacier into the adjacent lakes produced flow tills, which superficially resemble lodgement tills but can easily be distinguished from them as they contain many exotic pebbles with chaotic orientations. Finally, the topmost unit (glacio-marine sediments) accumulated in the sea as the ice melted out rapidly and sea level rose (Alley & Bourman 1984). Although minor fluctuations may have occurred in the position of the ice front, nowhere have genuine interglacial deposits separating genuine lodgement tills been reported from either outcrop or borehole (Alley & Bourman 1995; Bourman & Alley 1999; Alley et al. 2013). Even though there is no convincing evidence for multiple glaciations during the Permian ice age in SA, the glaciation, which we have evidence for, may have destroyed any pre-existing glacial deposits as it ground its way across the Australian continent.

The considerable relief on the Permian bedrock topography underlying the estuary demonstrates extensive glacial erosion, which exposed granites and other bedrock. A substantial glacial trough containing 600-800 m of glacigene sediments underlies Lake Alexandrina, shallowing towards Tailem Bend (SADME Petrology Report 21/90 1990). The Donna Number 1 Well north of Clayton intersected 550 m of sands and clays containing foraminifera of Permian age with glacio-marine affinities, indicating at least partial sedimentation in a deglaciating marine environment (Ludbrook 1967). Both Hossfeld (1950) and O'Driscoll (1960) mapped a steep-sided subsurface bedrock glacial valley following the western edge of the granitic mass of the Padthaway Ridge, into which it is deeply cut, thereby explaining the preponderance of granitic debris in the glacigene sediments (Rogers 1980). It is also possible that this bedrock ridge and valley later impacted on the general trend of Pleistocene shorelines; it aligns with the orientation of the present-day Coorong.

Permian glacigene sediments up to 300 m thick occupy this steep-sided U-shaped bedrock valley, while a series of bedrock highs forms the NE flank of the valley. Granitic bedrock crops out on the eastern shore of Lake Albert, whereas a bore near the centre of Hindmarsh I. intersected 120 m of glacial sediments to a depth of >168 m below sea level without hitting bedrock. The upper surface of the glacigene infill in this valley is also irregular, varying between 23 m in the north to 150 m below sea level in the south (O'Driscoll 1960).

Anomalous Permian fluvioglacial sediments occur on the north shore of Hindmarsh I. at the end of Barker Road at about 1 m above water level in a former slipway operated by the Veenstra family. Mr Jock Veenstra is adamant that the glacigene sediments were not artificially introduced to the site (*pers. com.* 2000), which makes it remarkable in that only about 4 km to the south-southeast, near the Goolwa Channel, and 2.5 km to the east-southeast, the top of Permian sediments occurs at depths of ~150 m (Armond et al. 1999), overlain by Cenozoic limestone and aeolianite.

Bedrock highs occur to the west of the estuary; the Encounter Bay Granites, which possibly formed up to 10 km below the surface, were exposed at Port Elliot by the time of the Permian glaciation, as the granite bedrock carries polished and striated glacial pavements (Milnes & Bourman 1972). These glaciated surfaces were, until recently, covered with glacigene silts and clays, protecting and preserving the glaciated surface for ~300 Ma. At one stage the granite at Port Elliot was also covered by Late Pleistocene aeolianite of the Bridgewater Formation, minor relicts of which remain (Fig. 2.1.4). It is highly likely that the Permian glaciation is also responsible for the general distribution of the igneous rock outcrops that occur in the islands and headlands of Encounter Bay (Bourman & Milnes 2016) and at the southern end and landward of the Coorong Lagoon. More closely jointed igneous rocks were eroded by the advancing ice and spread to the west across Fleurieu Peninsula to Yorke Peninsula and beyond, further demonstrating the general north-westerly ice flow in the area.

These hard rock outcrops have important influences on the configuration of the modern coastline and did so in the past, forming headlands that caused earlier Pleistocene shorelines to converge, merge and overlap (Blackburn et al. 1965). For example, the granite headlands at Port Elliot were largely covered by Pleistocene aeolianite, which is now in the process of being stripped away.

Figure 2.1.4 Granite headland at Knights Beach, Port Elliot. This headland carries glacial striae demonstrating that the granite core of the Delamerides was revealed by Permian times. Remnants of Permian glacigene sediments and Pleistocene Bridgewater aeolianite resting on the granite reveal a complex history of burial and exhumation. These features may be observed on the walking trail across the headland. (Photograph by R.P. Bourman)

POST-PERMIAN MESOZOIC EVENTS

The unconsolidated Permian sediments, which are widespread beneath the Murray Estuary and crop out extensively in the nearby Mount Lofty Ranges, have been an abundant source of sand, clay, boulders and pebbles for reworking and redeposition during the Cenozoic, contributing to subsequent coastal, marine and terrestrial deposits that include alluvial sequences associated with river terraces, several generations of sand dunes and lake sediments.

For ~200 Ma throughout the Mesozoic, following the termination of the Permian glaciation, there is no sedimentary record of geological events in the immediate Murray Estuary area, although sediments of Cretaceous age do occur within the broader Murray Basin in the Renmark Trough, a deep and narrow half graben, which extends up to >3 000 m below present sea level north-west of the junction of the South Australian, Victorian and New South Wales borders (Thornton 1972). Boreholes have intersected up to 440 m of Lower Cretaceous sediments (the Monash Formation) at depths between ~550 m and 990 m, overlying Permian and Devonian deposits (Rogers 1995a). Marginal marine, marine and freshwater environments reflect the transgression and regression of the Lower Cretaceous seas (Thornton 1972).

During the Mesozoic, the subaerially exposed areas of the region were subjected to prolonged weathering and erosion, transforming an irregular, glaciated landscape with steep slopes into one of low relief underlain by folded and intensely weathered bedrock to depths of up to 70 m (Bourman & Milnes 2016). This landscape was probably close to sea level but there is no evidence that it was ever totally submerged (Milnes et al. 1985). Throughout this time Australia was still attached to Antarctica, and it was not until ~43 Ma ago that the two continents separated (Veevers et al. 2009), allowing oceanic access; they were the last two continents of Gondwana to part company, after which time Australia moved rapidly over 3 000 km towards the north.

The weathered zones on the summit surface of Fleurieu Peninsula typically comprise upper-level hematite-rich mottled zones overlying bleached, white-coloured kaolinitic clays. Goethitic, hematitic and maghemitic pisoliths, largely derived from the breakup of mottles exposed at the surface, commonly form a thin surface layer in and below the A-horizon of the modern soil, directly overlying weathered and mottled bedrock (Fig. 2.1.5). Minerals identified in the weathered zones include goethite, quartz, gibbsite, hematite, maghemite, kaolinite, smectite and interstratified clays (Bourman 1989). There have been suggestions that this land surface has been preserved in its original form from some 200 Ma ago to present times (Twidale 1983). Certainly, there are relicts of ancient pre-Jurassic weathering preserved by burial on Kangaroo I. (Daily et al. 1974) and pre-Permian weathering near Yundi on Fleurieu Peninsula (Atlhopheng 2002). However, stratigraphic evidence coupled with oxygen isotope and palaeomagnetic dating reveal that subaerially exposed weathered zones have been subjected to ongoing weathering (Bourman 1993), culminating in the determination of a Pliocene age for the weathering underlying the modern summit surface (Bird & Chivas 1993).

Deeply weathered, partly ferruginised metasandstone of the Kanmantoo Group underlies parts of the Murray Estuary. In particular, numerous drill holes in the Milang and Langhorne

Figure 2.1.5 Road cutting on the Fleurieu Peninsula summit surface exposing part of the underlying iron-mottled deeply weathered zone. Large, dense mottles of iron oxides, consisting primarily of blood-coloured hematite, are surrounded by white clays (mainly kaolinite). Original bedrock structures can be discerned. (Photograph by R.P. Bourman)

Creek area on the western side of Lake Alexandrina reveal up to 20 m of weathered, occasionally ferruginous bedrock, underlying marine Late Eocene Buccleuch Formation sediments at depths of ~100 m (Williams 1978; Lablack 1991). It is likely that the weathered bedrock here is part of a down-faulted slab of the original weathered high summit surface of the adjacent Fleurieu Peninsula, preserved by burial with Buccleuch Formation deposits, beginning in the Late Eocene with clastic sediments derived from the Mount Lofty Ranges (Lablack 1991). On this evidence the buried weathering predates the Late Eocene (Lindsay & Kim 1971), whereas on the exposed summit, surface weathering continued into the Pliocene.

CENOZOIC EVENTS

The Cenozoic (past 66 Ma) geological history of the Murray Estuary region is broadly similar to that of the greater Murray Basin, with localised influences from proximity to the Mount Lofty Ranges to the west and the Padthaway Ridge to the east. The Murray Basin was created as a consequence of the separation of Australia and Antarctica in the Eocene, and the northward drift and relaxation of the Australian platform (Veevers 2000), which allowed increasing oceanic ingress during the Palaeogene, and ultimately initiation of the Leeuwin Current (McGowran et al. 1997). The extra-limital occurrence of the arcoid bivalve mollusc *Anadara trapezia* and the megascopic, benthic foraminifer *Marginopora vertebralis* attests to an enhanced Leeuwin Current during the Last Interglacial, bringing warmer, lower-salinity waters across the Great Australian Bight from Western Australia (Cann & Clarke 1993; Murray-Wallace et al. 2000).

The topographically low-lying and low-gradient setting of the basin throughout the Cenozoic left it prone to partial flooding by shallow epicontinental seas during periods of high relative sea level. Slow subsidence rates, low rates of sediment supply and minimal compaction resulted in Cenozoic sediments reaching a maximum 600 m thickness in the central-western part of the basin, but averaging a thickness of <200-300 m (Brown 1983; Brown & Stephenson 1991). The Cenozoic sequences include Late Palaeocene to Early Oligocene non-marine and marginal marine sediments of the Renmark Supergroup; transgressive Late Eocene to Middle Miocene marine sediments of the Murray Supergroup; Miocene to Late Pliocene marine, estuarine and shoreline deposits of the Loxton-Parilla Sands; and a variety of lacustrine, aeolian and shoreline deposits that reflect increasing aridity through the Quaternary.

Cenozoic uplift of the Mount Lofty Ranges, sagging of the adjacent estuary, and uplift of the southern Coorong Coastal Plain progressively diverted the proto-River Murray to a location similar to that of its modern counterpart. It appears that the Mount Lofty Ranges were uplands throughout the Mesozoic, but further uplift probably began in the Palaeocene (Wellman & Greenhalgh 1988) with some reactivation of Delamerian faults (Preiss 2000), but also with independent neotectonic faulting (Bourman et al. 2010; Jayawardena 2013) related to transpressive forces.

LATE PALAEOCENE TO EOCENE RENMARK SUPERGROUP

The earliest Cenozoic sediments deposited in the Murray Basin were Palaeocene and Eocene alluvial and marginal marine sands and carbonaceous silts of the Warina Sand and Olney Formation (Renmark Supergroup) (Rogers et al. 1995). These grade into more fully marine sediments of the Buccleuch Formation along the Padthaway Ridge and in the Milang, Langhorne Creek and Waitpinga areas (Rogers et al. 1995).

Warina Sand and Olney Formation

The fluvial/lacustrine Warina Sand is known only from deep parts of the basin, such as near Renmark, where it is >300 m deep. However, the Olney Formation is far more widespread and laps the basin margins including the Murray Estuary region in the western part of the basin, where it is of marginal marine character (Rogers et al. 1995). Underlying the Milang-Langhorne Creek plains on the western side of the estuary, the deposition of clastic sediments derived from the Mount Lofty Ranges began in the Late Eocene (Lablack 1991), followed by marine sedimentation with deposition of the Late Eocene Buccleuch Formation, which not only overlies, but in places interdigitates with, the Renmark Supergroup confined aquifer (SADME Petrology Report 21/90 1990). During deposition of the Renmark Supergroup, the Padthaway Ridge formed a laterally extensive high region (see Fig. 2.1.6).

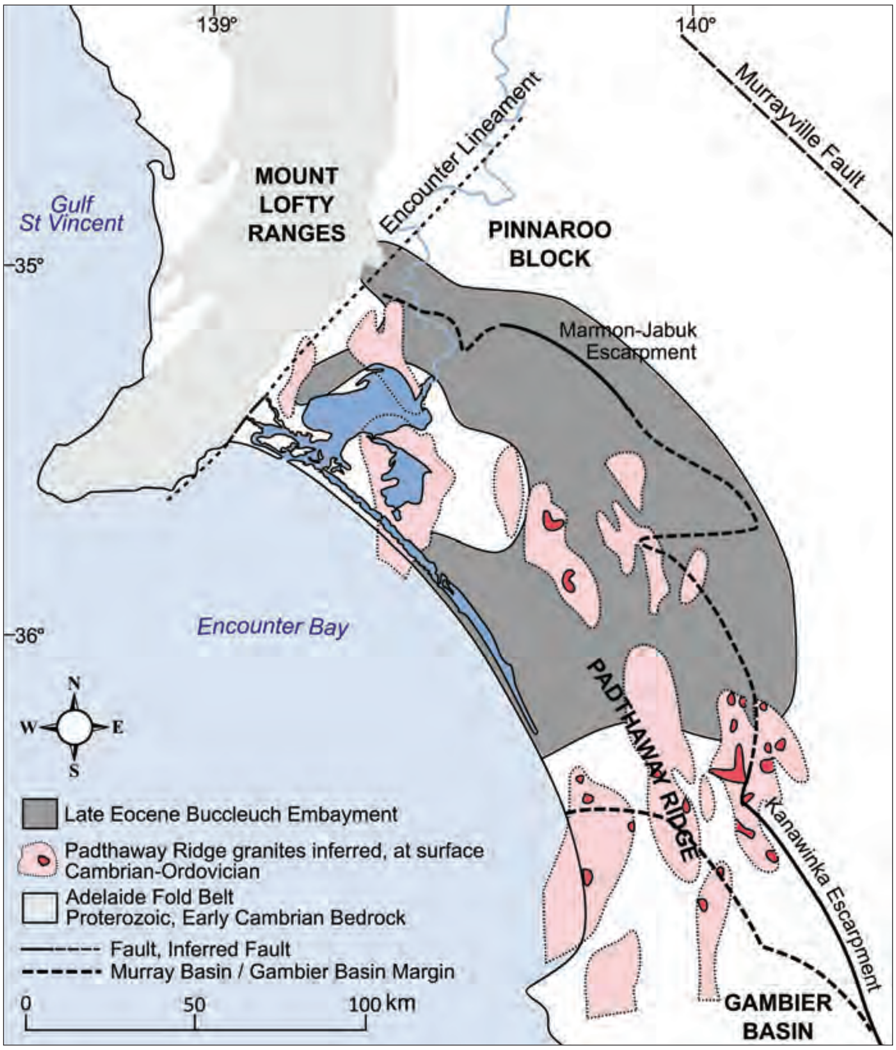

Figure 2.1.6 The Buccleuch Embayment and the Padthaway Ridge. (From Ryan 2015 after Ludbrook 1961 and Brown & Stephenson 1991. Locations of granitoid intrusives from Preiss 1995 and fault locations from Rogers et al. 1995)

Buccleuch Formation

The Late Eocene Buccleuch Formation heralded the first significant marine transgression into the Murray Estuary area; it is equivalent to the Tortachilla Limestone of the St Vincent Basin. The Buccleuch Formation includes bryozoal limestone, glauconitic calcareous and ferruginous clays, bryozoal sand and dark coloured pyritic clay with minor sand (Lablack 1991), along with lignitic sands (Mills 1965). Lablack (1991) recorded a c.20-50 m thickness of the Buccleuch Formation in the Milang-Langhorne Creek area at depths down to 116 m. Ludbrook (1957, 1961) had informally divided the Buccleuch Group into three beds designated 'A', 'B' and 'C', but Lablack (1991) regarded the Buccleuch Formation as a complex of facies rather than separate recognisable units.

An Eocene assemblage of microfossils was identified in a 2.4 m thick limestone intersected by a drill hole 6 km west-southwest of Victor Harbor in the South Mount Lofty Ranges at an elevation of 70 m above present sea level, and may be correlated with the Buccleuch 'A' limestone of the Murray Basin (Bourman & Lindsay 1973). The limestone bed, which rests on metasedimentary rock of the Kanmantoo Group, also contained ferruginous pisoliths, suggesting pre-Eocene weathering of the land surface.

Beds of the Buccleuch Formation, which were deposited in the Buccleuch Embayment, are absent from the palaeo-topographic high of the Padthaway Ridge, which at the time acted as a natural breakwater (O'Driscoll 1960), but now extend landward of the subsequently formed Marmon-Jabuk Scarp (Fig. 2.1.6). The deposition of the Buccleuch Formation ceased with sea-level retreat during the Early Oligocene, the largest in 250 Ma (McGowran et. al. 1997).

MIDDLE OLIGOCENE TO MIDDLE MIOCENE MURRAY SUPERGROUP, 28-11 MA

A substantial rise in global sea level occurred during the Late Oligocene, peaking during the Middle Miocene (Brown 1983), substantially flooding the entire Murray Basin and producing the Murravian Gulf of Sprigg (1952). The Oligocene-Miocene high-stand correlates with a warming phase in an otherwise cooling Cenozoic trend with the peak of the warm phase coinciding with the peak of the marine transgression at ~16 Ma (Fujioka & Chappell 2010; Riordan et al. 2012).

Many members of the Murray Supergroup, the stratigraphic framework of which was established by Ludbrook (1957, 1961), crop out along the banks of the lower River Murray between Tailem Bend and Overland Corner (Bone 2009). The Murray Group of rocks consisted of different limestone units previously named the Mannum Formation, Morgan Limestone and Pata Limestone, but as they are difficult to distinguish lithologically they were incorporated into one unit, the Mannum Limestone (Rogers et al. 1995). Subsequently, the members of the Murray Supergroup were refined by Lukasik and James (1998) into the Ettrick Formation, Mannum Formation (with informal lower and upper members), Swan Reach Dolomite Member within the Mannum Formation, Finniss Formation and the Morgan Group. Gallagher and Gourley (2007) subsequently extended this stratigraphic framework into Victoria, thereby reconciling the outcrop and subsurface Oligo-Miocene marine stratigraphy of the Murray Basin, arriving at a basin-wide correlation.

Ettrick Formation

This Late Oligocene formation disconformably overlies the Buccleuch Formation, with ferruginisation at the top of the Buccleuch Formation beds marking the disconformity in places (Rogers 1980). The Ettrick Formation comprises glauconitic and sandy marls grading to calcarenitic limestone (Ludbrook 1957, 1961; Lindsay & Kim 1971; Lablack 1991), largely described from boreholes, but also recognised in surface exposures immediately south of the Tailem Bend pumping station near river level (Ludbrook 1961), in a road cut near Hartley, in a railway cutting at Monarto and at a bridge crossing of the Bremer River ~1 km north-east of Hartley (Lindsay & Williams 1977). The last three sites are on the western margin of the Murray Estuary as far as 25 km inland along the Bremer River, and record the nearshore depositional onset of an Oligocene marine transgression (Lindsay & Williams 1977), which extended far into the Murray Basin (Ludbrook 1969). The Ettrick Formation in these localities is underlain by the equivalent of the Oligocene Compton Conglomerate, a thin basal unit containing goethitic pisoliths and grits, ferruginous sand, ferruginous casts and bouldery conglomerate (Ludbrook 1961; Lindsay & Williams 1977). The Compton Conglomerate rests on highly weathered, partly ferruginised metasediments of the Cambrian Kanmantoo Group of rocks.

The Padthaway Ridge probably obstructed marine access into the greater Murray Basin during the Oligocene marine transgression (Brown & Stephenson 1991), but when the majority of the Padthaway Ridge was largely inundated it became an archipelago of granitic islands in a shallow sea (Rogers 1995a).

Mannum Formation

The early Miocene Mannum Formation is predominantly composed of yellow to brown sandy bryozoal limestone, rich in echinoid fragments. It is widespread in the Murray Basin and it forms river bluffs considerable distances up the River Murray; its type section is at the Mannum pumping station (Ludbrook 1961). In the Murray Estuary area, it is largely only known from boreholes and it generally displays conformable relationships with the Ettrick Formation. However, where exposed near Hartley, the Mannum Formation is revealed to disconformably overlie the Ettrick Formation (Lindsay & Williams 1977). Furthermore, a high-energy, near-shore and shallow marine environment of deposition was proposed for this site, establishing it as a distinctly different sedimentary cycle from that of the underlying Ettrick Formation (Lindsay & Williams 1977; Lablack 1991).

Deposition of the Mannum Formation ended in the early Middle Miocene accompanying a fall in relative sea level and exposure of the top of the formation to subaerial processes. This resulted in the uppermost beds being recrystallised and well cemented (Williams 1978). An eroded surface occurs on the Mannum Limestone characterised by a north-south-oriented, irregular valley broadly coinciding with the position of the modern Angas River, as well as by enclosed karstic depressions and solution cavities (Williams 1978; Waterhouse & Gerges 1979). Elevated outcrops of calcreted Mannum Formation limestone occur near Strathalbyn.

Morgan Group

The Morgan Group has been subdivided into the Glenforslan, Cadell, Bryant Creek and Pata Formations (Bone 2009). The Middle Miocene Glenforslan Formation contains the distinctive and restricted foram *Lepidocyclina howchini*, which has proved to be useful in demonstrating tectonic offsets (Lindsay & Giles 1973).

LATE MIOCENE THROUGH PLIOCENE, 11-2.58 MA

Another major transgressive marine cycle into the greater Murray Basin occurred from the Late Miocene and through the Pliocene. High-frequency glacial-interglacial cycles were now a dominant global forcing in addition to local basin tectonic influences.

Bookpurnong Formation

The Bookpurnong Formation marks the start of a new marine inundation cycle into the Murray Basin in the Late Miocene, extending into the Pliocene when it is conformably superseded by Loxton Sands. The marl, silty clay and minor fine sand of the Bookpurnong Formation are all variably shelly, glauconitic and micaceous, and indicative of a shallow-water, low-energy marine succession (Ludbrook 1961; Carter 1985). The marine flooding would have extended over the Padthaway Ridge, but was flanked to the west, roughly in the location of the present-day River Murray, by a zone of fluvial and estuarine environments connected to the Southern Ocean (Brown 1985).

The Bookpurnong Formation is present in the central western region of the basin but is absent over the Pinnaroo Block, suggesting that the block uplifted since the last marine transgression and was a submarine platform during the late Miocene transgression (Stephenson & Brown 1989).

Loxton-Parilla Sands

A remarkable sequence of more than 600 stranded arcuate coastal quartzose sand ridges, the Loxton-Parilla Sands occupies and subcrops over a large part of the Murray Basin, stretching up to 500 km inland. With numerous individual ridges, some continuous for up to 300 km in length (Fig. 2.1.7), this forms one of the largest strand-plains in the world (Brown & Stephenson 1991; Kotsonis 1999; Miranda et al. 2009). These strand-lines are also significant as they host economic concentrations of heavy mineral sands in their littoral and sub-littoral facies (Belperio & Bluck 1990). The individual Loxton and Parilla Sands are often jointly referred to as the Loxton-Parilla Sands, because of their close associations and because they are difficult to identify individually (Brown & Stephenson 1991).

The shallow to marginal marine Loxton Sands conformably overlie the Bookpurnong Formation; shell beds at the base of the Loxton Sands indicate a shallow-water or estuarine environment of deposition. The Loxton Sands transition into the Parilla Sands, which are non-fossiliferous, non-marine, fine- to medium-grained clayey quartz sand with thin clay beds (Rogers et al. 1995). The Late Miocene-Early Pliocene high-stand peaked at ~60 m above present sea level, but with repeated high-frequency transgressive-regressive cyclicity, leaving a sequence of partially preserved coastal ridges with fluvial and lacustrine sediments accumulating in interdunal areas (Belperio & Bluck 1990).

The quartz-rich coastal barriers of the Loxton-Parilla Sands are a regressive sequence heralding the onset of the final phase of Neogene sedimentation in the Murray Basin; they were deposited before the Early-Middle Pleistocene Transition, 1.2 Ma to 700 ka ago (Head & Gibbard 2015).

Figure 2.1.7 Strand-lines of the Loxton-Parilla Sands across the Murray Basin. (Modified after Kotsonis 1999)

Obliquity-driven glacial cycles of 41 ka duration resulted in short-term sea-level high-stands followed by short-term forced regressions (Fig. 2.1.8). These fluctuations were superimposed on the progressive draw down of sea level in the late Neogene and simultaneous uplift of the inland Murray Basin. The Early-Middle Pleistocene Transition marks the change from quartz-rich coastal barrier ridge deposition of the Loxton-Parilla Sands to the formation of coastal barriers primarily of bioclastic aeolian sediment lithified to aeolianite (the Bridgewater Formation) on the Coorong Coastal Plain.

The strand-lines fade out on the Padthaway High and terminate at the Marmon Jabuk and Kanawinka Escarpments, which have been interpreted as fault scarps (Sprigg 1952; Bowler et al. 2006), a Pliocene coastal erosional feature (Hossfeld 1950; Belperio & Bluck 1990; Wallace et al. 2005) or a combination of both (McLaren et al. 2011). The escarpment is a laterally persistent geomorphic feature extending more than 600 km from the Mount Lofty Ranges in South Australia to the Portland area of Victoria (McLaren et al. 2011). The Loxton-Parilla Sands record a transgressive-regressive cyclicity and progressive regression of the Late Miocene-Early Pliocene seas from the Murray Basin. According to Miranda et al. (2009), deposition of the strand-lines began by 7.2 Ma and was largely completed by ~5 Ma. The strand-lines of the

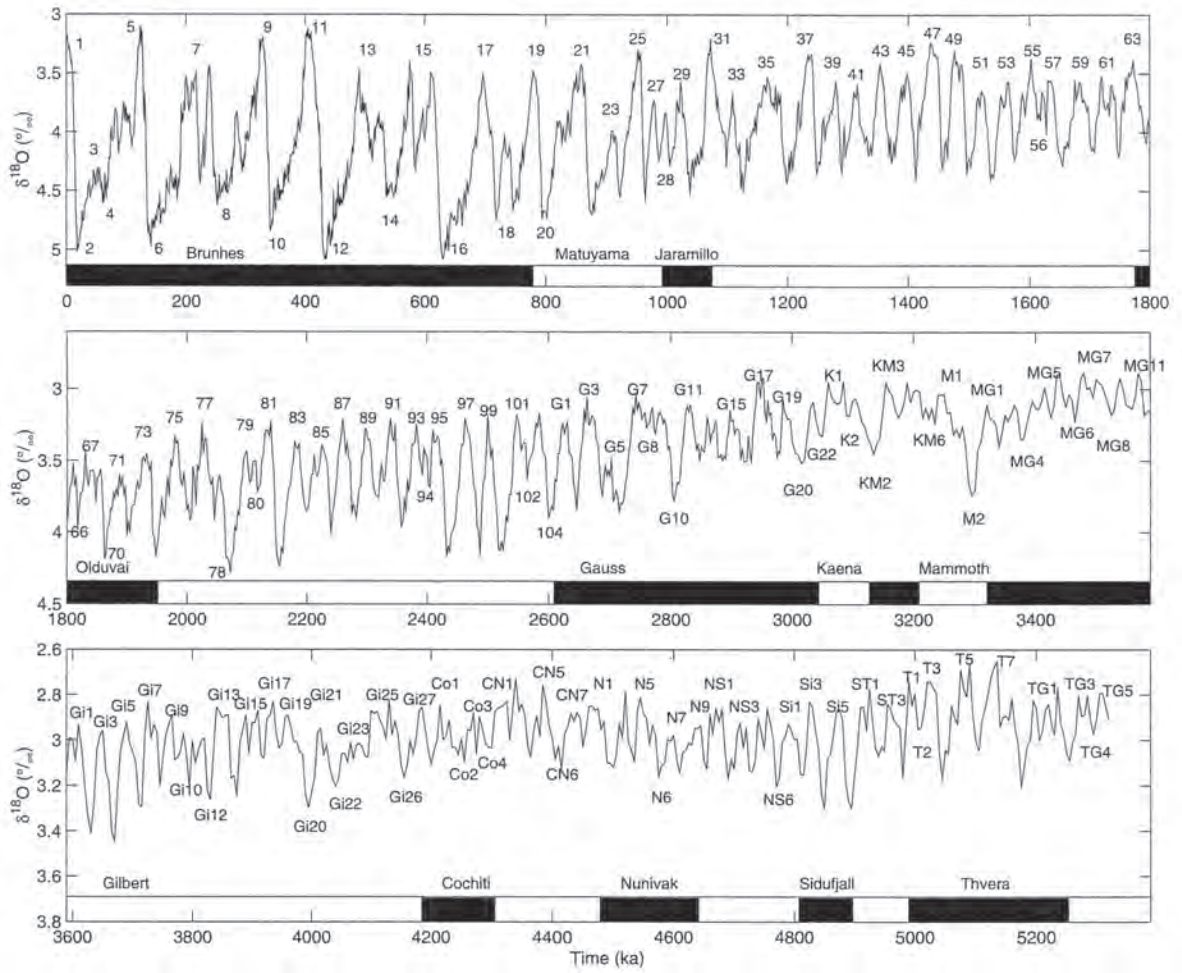

Figure 2.1.8 Oxygen isotope records from deep-sea sediment cores, proxies of sea-level changes and global ice volumes, over the past 5.33 Ma (from Lisiecki & Raymo 2005). Interglacials are indicated by odd numbers and glacials by even numbers. Normal magnetic polarity marked by black shading and reversed magnetisation by white.

Loxton-Parilla Sands are capped by a ferruginous and/or siliceous weathering surface known as the Karoonda Surface, which was probably produced by subaerial exposure in a climate warmer and wetter than present as early as 4.6 Ma ago (Firman 1966, 1972; Kotsonis 1999).

Despite the Loxton-Parilla strand-lines apparently terminating at the Marmon Jabuck Scarp, Parilla Sand or Parilla Sand Equivalents have been reported from boreholes on the Milang and Langhorne Creek Plains on the western side of the Murray Estuary (Williams 1978; Waterhouse & Gerges 1979; Lablack 1991).

Northwest Bend Formation

A rising sea level in the Pliocene led to the estuarine deposition of the Northwest Bend Formation dominated by the oyster *Ostrea angasi*, which suggests a water depth of <20 m (Ludbrook 1984). It overlies the Bookpurnong Formation conformably and is exposed at localities between Tailem Bend and Overland Corner (Bone 2009) on the western side of the Murray Basin, where it also occurs subsurface. Though it was originally thought to only occupy a narrow estuary marking a palaeochannel of the River Murray (Ludbrook 1957), McLaren et al. (2011) have demonstrated that the Northwest Bend Formation is very extensive, with the estuary being up to 60 km wide. Miranda et al. (2008) have suggested that the Northwest Bend Formation is a lateral equivalent of the Loxton-Parilla Sands, with an age of ~5 Ma, but restricted to the far west of the Murray Basin. The formation is usually <15 m thick and thin intervals were intersected in bores at depths between 12-16 m and 22-27 m in the lower reaches of the Angas and Bremer Rivers on the margins of the Murray Estuary.

Lake Bungunnia — Late Pliocene to Middle Pleistocene lacustrine sediments

Lake Bungunnia formerly occupied an extensive area of the Murray Basin, overlying portions of both the Norwest Bend Formation and the laterally equivalent Karoonda Surface (Fig. 2.1.9). At its maximum the Lake covered an area of over 50 000 km^2 and was at least 60 m deep, forming one of the largest Pliocene lakes in the world (Bowler et al. 2006; McLaren & Wallace 2010). Reactivation of faults underlying the Murray Basin, most likely the uplift of the Pinnaroo Block, led to the formation of the mega-lake (Stephenson 1986), but a coastal barrier system may have also been involved (Belperio & Bluck 1990). Although Lake Bungunnia extends

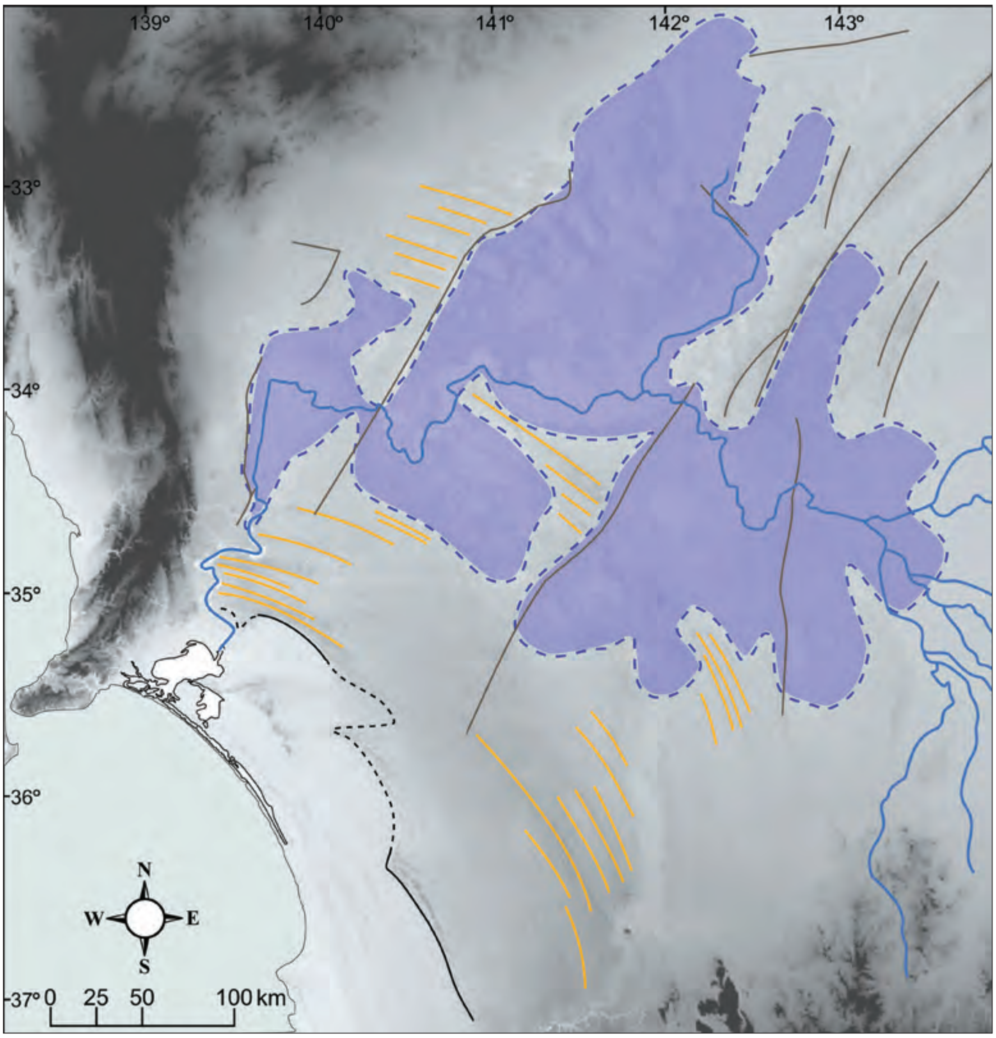

Figure 2.1.9 Map illustrating the location and extent of the former freshwater Lake Bungunnia in relationship to former shorelines and faults. (Modified after Bowler et al. 2006)

well beyond the modern Murray Estuary, it has played an important role in the evolution of the Estuary, as it has influenced the antiquity of the River Murray discharging to the sea in its present location.

The Lake sediments consist of Blanchetown Clay (<40 m) and Bungunnia Limestone (1-3 m) (McLaren et al. 2011; McLaren & Wallace 2010). There are two distinct members in the Blanchetown Clay, the basal Chowilla Sand (Firman 1966), developed by fluvial reworking of the Loxton-Parilla Sands (Firman 1973), and the upper Nampoo Member. The Nampoo Member is a basin-wide aeolian-lacustrine silt unit located approximately 46 m above sea level (McLaren et al. 2009). The Bungunnia Limestone is a patchy lacustrine carbonate deposited in small clastic starved basins (Rogers 1995b).

There has been some controversy about the age of the Lake, but the most recent work suggests that the Lake formed about 2.4 Ma ago (McLaren et al. 2009). Lake demise, however, is not well defined. This is further considered in Chapter 2.2, while Bone (2009) discusses it in detail.

QUATERNARY UNITS

It is within the Quaternary period encompassing the past 2.6 Ma that the River Murray Estuary, as we recognise it, developed.

Coomandook Formation

The Coomandook Formation is a fossiliferous shallow marine limestone of early Pleistocene age characterised by the presence of the marine pelagic gastropod *Hartungia dennanti chavani* (Ludbrook 1978, 1983; Rogers 1980), which may straddle the Pliocene/Pleistocene boundary (Pillans & Bourman 1996; Bourman & Pillans 1997). Equivalent units include the Roe Calcarenite of the Roe Plain on the Nullarbor (James et al. 2006), the Burnham Limestone from the Gulf of St Vincent (Firman 1976), the Point Ellen Formation at Cape Jervis and on Kangaroo I. (Ludbrook 1983), and the Werrikoo Limestone (Belperio 1995) and Nelson Bay Formation of Western Victoria (McLaren et al. 2011).

During the marine transgression responsible for deposition of the Coomandook Formation, an archipelago of granite islands, similar to that of the Oligocene Padthaway archipelago, formed, and perhaps shaped some of the present-day features on the granite outcrops (Rogers 1980). The transgression reached the Marmon Jabuk and Kanawinka Escarpments and extended beyond the Kanawinka Escarpment near its southern extremity (McLaren et al. 2011).

Bridgewater Formation

The Marmon Jabuk and Kanawinka Escarpments generally separate the strand-lines of the calcareous Bridgewater Formation from the ferruginous Loxton-Parilla Sands. However, Miranda et al. (2009) demonstrated that there might be a 4 Ma gap in the sedimentary record between the final deposition of the Loxton-Parilla Sands and initiation of the oldest Bridgewater Formation.

The Bridgewater Formation (Boutakoff 1963) consists of Pleistocene sequences of lithified, calcareous beach/dune coastal barriers (aeolianite), which overlie both the sediments of the Coomandook Formation and other units. The dune ranges extend from the Early Pleistocene up to ~60 ka ago and represent former shorelines equivalent to the modern Coorong Lagoon and Younghusband Peninsula, lithified and preserved by calcrete cappings (Fig. 2.1.10). Each range corresponds to former interglacial high sea levels, which were approximately of the same elevation (±6 m) as modern sea level. Ongoing uplift at an average rate of 0.07 mm yr^{-1} in the south-east of the Coorong Coastal Plain effectively separated each successive shoreline, producing one of the longest eustatic sea-level records of Pleistocene interglacial high-stands in the world. The veracity of this land-based record has been validated by correlation with the oxygen-isotope record and the product of eccentricity band Milankovitch changes in insolation and corresponding glacio-eustatic cycles (Murray-Wallace et al. 2001). Some dunes have been shown to be composite dunes formed over multiple sea-level high-stands (Cook et al. 1977; Schwebel 1984; Huntley et al. 1993; Murray-Wallace et al. 1999). Towards the north-west, the dune ranges progressively converge and overlap in response to decreasing uplift and eventual tectonic down faulting of the Murray Estuary region.

The early Pleistocene Coomandook Formation underlies the middle Pleistocene deposits in the Southeast (Rogers 1979) and the older Bridgewater Formation ranges east of Reedy

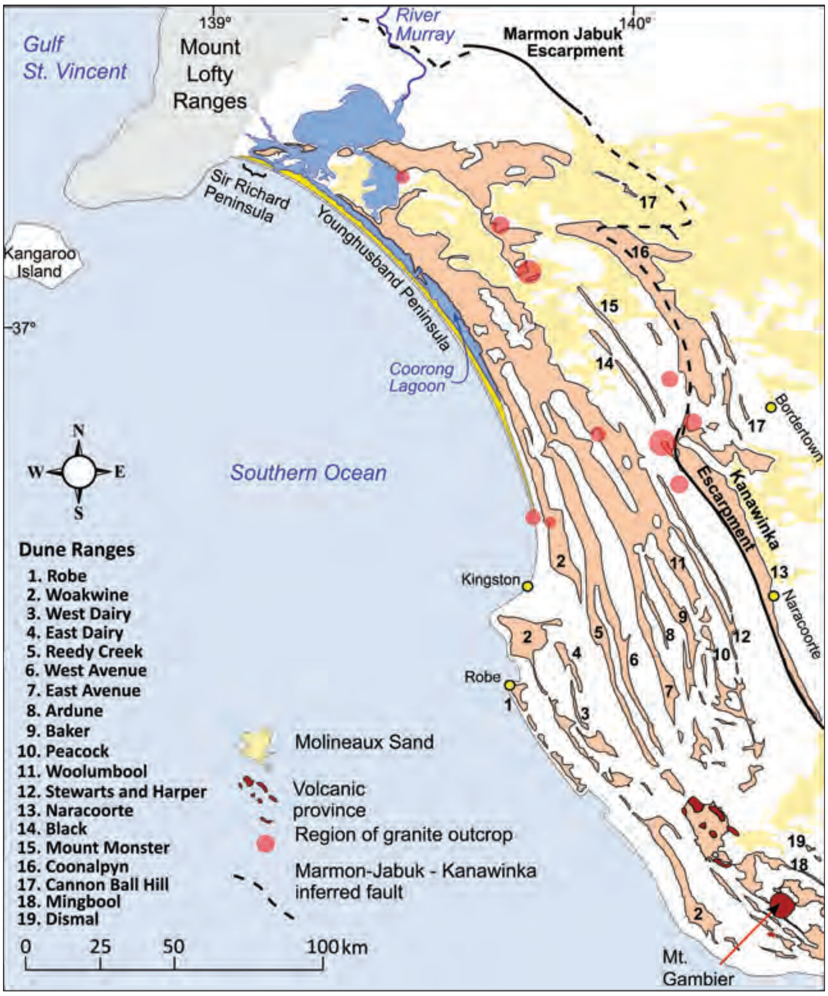

Figure 2.1.10 Pleistocene calcreted dune ranges on the Coorong Coastal Plain, former barrier shorelines similar to the modern Younghusband Peninsula and Coorong Lagoon (modified from Ryan 2015). Note how the ranges converge towards the Murray Lakes. Note also the influence of granite outcrops on the former shorelines and the Marmon Jabuk and Kanawinka Escarpments.

Creek Range (Cook et al. 1977). Towards the north, Quaternary sediments unconformably overlie Lower Palaeozoic granites, Eocene (Buccleuch Beds) or Oligo-Miocene (Ettrick Formation, Gambier Limestone) marine deposits, as well as Coomandook Formation (Rogers 1979). Nearer to the Murray Lakes region, the Bridgewater Formation and associated back-barrier facies variably overlie Oligo-Miocene limestones, Late Eocene Buccleuch Beds and the Permian Cape Jervis Formation (Barnett 1991).

Last Interglacial shoreline

The best and most completely preserved of the Pleistocene shorelines has been confidently dated at 125 ka (Bourman et al. 2016; Murray-Wallace 2018); coastal marine, back-barrier lagoon (Glanville Formation) and dune barrier facies (Bridgewater Formation) have been identified, forming the landward shore of the Coorong Lagoon and the substrate, on which all of the barrages at the Murray Mouth have been built, except for the Goolwa Barrage. This Last Interglacial coastal barrier is referred to as the Woakwine and MacDonnell Ranges in the Southeast (Sprigg 1952) and the Bonney Coastline in the north (de Mooy 1959).

The Last Interglacial Maximum, correlating with Marine Isotope Substage 5e in deep-sea (Shackleton et al. 2002) sediment and ice cores (Masson-Delmotte et al. 2010), occurred between 132 and 115 ka ago. The warmest part of the Last Interglacial Maximum occurred between 128 and 116 ka, with the Last Interglacial Maximum representing the warmest climatic interval during the past 800 000 years. In a global context, an enduring legacy of that warm climatic episode has been the higher-level relict shoreline successions deposited at times of a higher sea level, as well as the preservation of some elements of warmer water marine faunas (Muhs et al. 2002; Murray-Wallace & Woodroffe 2014). In the coastal landscapes of SA, the Last Interglacial Maximum is represented by the Glanville Formation, comprising beach, back-barrier estuarine-lagoon and peritidal facies, which occur landward of their Holocene counterparts on depositional coastlines (Belperio et al. 1995). In the Murray Estuary area, this is the only shoreline where the shelly beach or back-barrier facies is observable. Not only were the older shorelines deposited at elevations below present sea level, but they have also been tectonically depressed.

Sea level around the SA coastline was at least 2 m higher than at present during the Last Interglacial, with this shoreline datum proving useful in quantifying tectonic movements over the past 125 ka (Bourman et al. 2016). Figure 2.1.11 illustrates the relative elevation of the Last Interglacial shoreline in SA, highlighting the tectonic stability of the Gawler Craton, down faulting of the Gulfs, uplift of the Mount Lofty Ranges, tectonic subsidence of the Murray Estuary and progressive uplift of the Coorong Coastal Plain (Murray-Wallace 2002).

Dolomite

An unnamed geological unit, designated Qpu dolomite on the Pinnaroo 1:250 000 Geological Sheet (Rogers 1979, 1980; Brown & Stephenson 1991), occupies the flat plain between the Marmon Jabuk Scarp and the Cooke Plains Embayment. This is an early Pleistocene marginal-marine and lagoonal unit formed in a partially protected, low-energy environment. Deposition of the dolomite postdates initial deposition of the Bridgewater Formation, as it is separated from the southern margin of the Marmon Jabuk Scarp by a wedge of lower Bridgewater

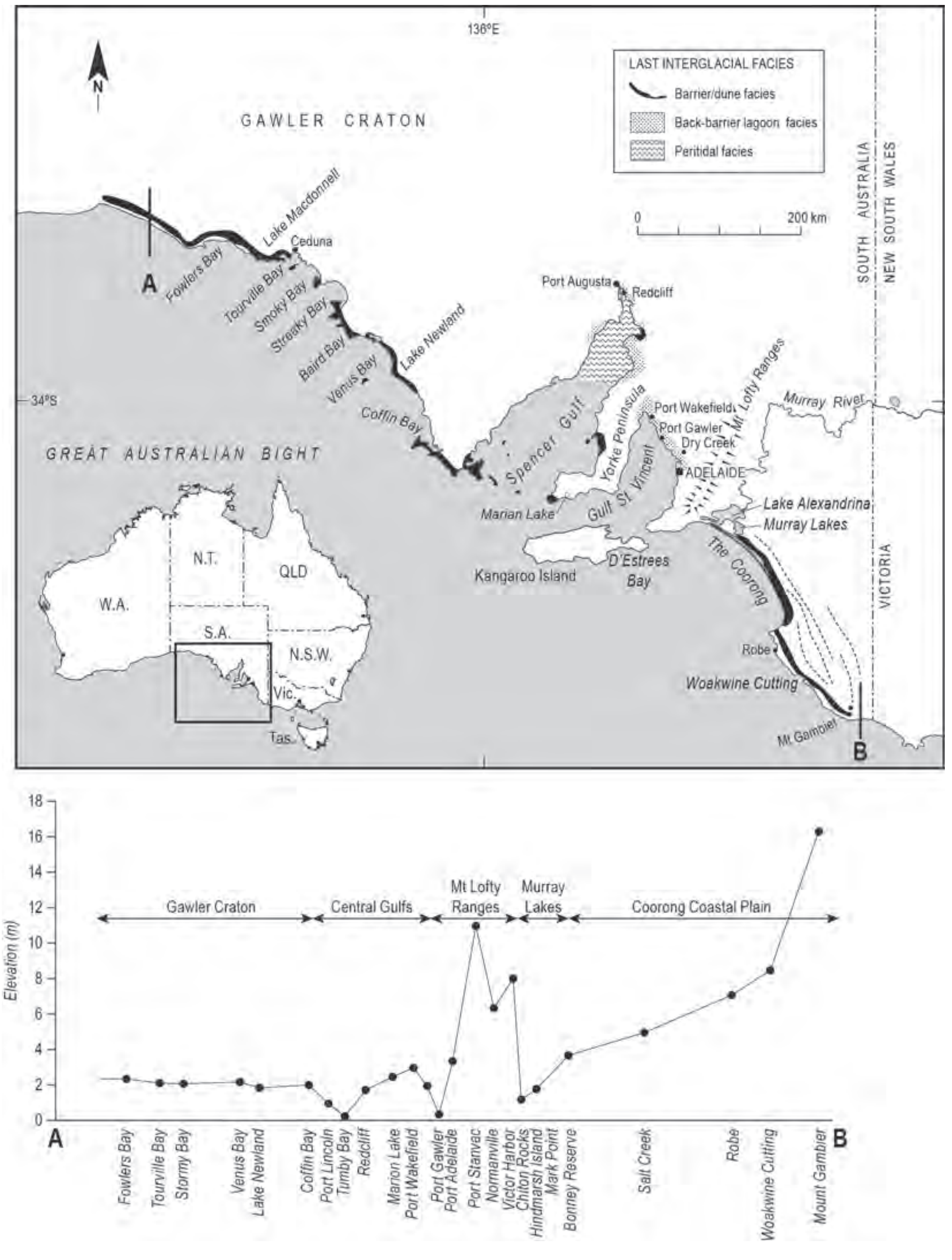

Figure 2.1.11 Positions and relative elevations of Last Interglacial shoreline facies around the South Australian coastline, demonstrating the ongoing tectonic subsidence of the Murray Estuary. (Adapted from Murray-Wallace 2002)

Formation (Rogers 1980). Brown and Stephenson (1991) tentatively placed deposition of the coastal lagoonal carbonate to at least the age of the East Naracoorte Range (>800 ka) based on its stratigraphic relationships. The Qpu dolomite is pale grey, fine-grained and well cemented, containing intraclasts of sandstone, calcarenite and dolomite, and it is locally capped by calcrete (Brown & Stephenson 1991). It disconformably overlies the Coomandook Formation and is disconformably overlain by the aeolian Molineaux Sand and lacustrine deposits of the Cooke Plains Embayment.

Fluvial units

Various alluvial sequences occur on the western margin of the Murray Lakes. These are considered in more detail in Chapter 2.2 but the major units include

a. the Pooraka Formation, a red/brown alluvium of Last Interglacial age (MIS 5e, ~125 ka) sourced from the Eastern Mount Lofty Ranges by streams, such as the Finniss River, Currency Creek, the Angas River and the Bremer River (Bourman et al. 1997; Bourman 2006)
b. an older interglacial deposit (MIS 7e) of the Penultimate Interglacial, which occurs on the left bank of the Finniss River and is the first recognition of this unit in the Lakes area (Ryan 2015; Ryan et al. 2018)
c. a grey/black-coloured alluvium of mid-Holocene age (the Waldeila Formation of Ward 1966), which overlies and occupies valleys cut into the Pooraka Formation, and which occurs in all of the stream valleys (Bourman 2006).

Alluvial units also occur in the main valley of the River Murray, forming floodplains and terraces (Thomson 1975; Rogers 1995b) with sediments largely sourced from Pliocene sands. The top section of a weathered upper terrace formed on alluvium at Roonka returned a thermoluminescence (TL) age of 65 000±12 000 years before present (1950; BP) (Prescott 1983). It was correlated with a period of rising sea level at about that time (Rogers 1995b), but at depth it may be the equivalent of the Last Interglacial Pooraka Formation. The Monoman Formation, which contains fossil marsupial bones, is a Late Pleistocene deposit, which may be the equivalent of the cold interstadial Marine Isotope Stage 3 alluvial unit containing bones of the extinct marsupial megafauna *Diprotodon*, described from other localities in SA (Bourman et al. 2010). Radiocarbon dates suggest that deposition of the overlying Coonambidgal Formation commenced at ~7 000 years BP, as the sea reached up to its present level, and continues through to the present day (Rogers 1995b).

Aeolian desert dunes

Whereas interglacial times were characterised by high sea levels and wet and warm conditions, during ice ages sea levels were lowered and the climates were cold and dry, supporting little vegetation, so that the strong winds developed extensive dune fields, predominantly during the period from 30 ka to 15 ka (Rogers 1995b). In the Murray Basin the Woorinen Formation consisted of east-west linear dunes, especially in the northern part of the basin (Rogers 1995b). Tongues of sand also extend from the valley of the River Murray between Morgan and Swan Reach as source-bordering sands of the Bunyip Sand.

However, it is the east-west-trending, sub-parallel, yellow- to red-coloured parabolic and linear dunes of the Molineaux Sand that make up the majority of the dune fields near the Murray Estuary. They occur on Hindmarsh I., surround Lakes Albert and Alexandrina, and obscure the calcareous dunes of the Bridgewater Formation in many places. Luminescence dating of these dunes reveals that they relate to the late stage of the Last Glacial Maximum (LGM) ~16 ka to 18 ka ago (Bourman et al. 2000).

St Kilda Formation

The St Kilda Formation encompasses all Holocene sediments deposited under the influence of marine processes, including beach-barrier, back-barrier lagoonal, intertidal, lacustrine, lagoonal and estuarine deposits, coastal dunes and storm ridges (Cann & Gostin 1985). Lagoonal sediments within the Coorong are composed of a black, sticky aragonite and magnesium (Mg) calcite mud, and generally consist of two distinct phases of deposition (Harvey 1981; Gostin et al. 1988). The first phase is characterised by bivalve mollusc shells typical of sheltered marine environments. As the lagoon becomes more restricted and increasingly saline, the fauna shifts to those more adapted to hypersaline conditions. The southern half of the lagoon is now considered to be hypersaline (Belperio & Cann 1990). Groundwater mixing may also result in precipitates of aragonite, dolomite and hydromagnesite muds (Gostin et al. 1988).

Lacustrine sediments

During the mid-Holocene, the expanded Lakes Alexandrina and Albert witnessed the deposition of estuarine and lacustrine sediments in surrounding low-lying areas, and this deposition largely coincides with the Malcolm Formation of de Mooy (1959), the largest extension of which is the Cooke Plains Embayment (Fig. 2.1.12) (Brown & Stephenson 1991). Lake expansion has been attributed to a ~1 m higher than present sea level ~6 500 years ago and possibly to increased freshwater flow from the River Murray (von der Borch & Altmann 1979; Belperio 1995). The estuarine and lacustrine deposits associated with Lake expansion are

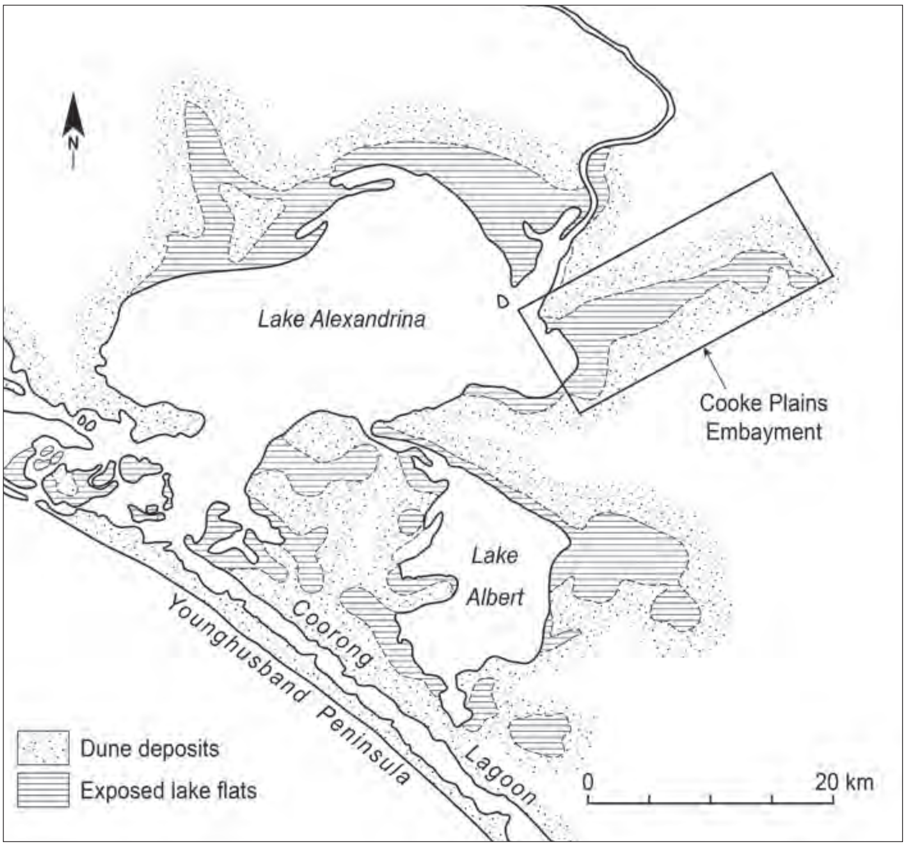

Figure 2.1.12 Map showing exposed lake flats around Lakes Alexandrina and Albert, illustrating their extents during the mid-Holocene. (Modified from von der Borch & Altmann 1979)

composed of unconsolidated lacustrine mud, silt, sand and organic detritus, both calcareous and carbonaceous (Brown & Stephenson 1991).

TECTONICS IMPACTING ON THE MURRAY ESTUARY

Tectonic movements have played major roles in the geological evolution of the Murray Estuary. Initially the Delamerian Orogeny metamorphosed and folded Archaean, Proterozoic and Cambrian rocks and sediments, as well as causing the intrusion of granitic masses. These rocks form the foundation of the Murray Estuary, while the exposure of the formerly deeply buried granitic intrusives has impacted on the morphology of former and present shorelines.

The sea inundated parts of the southern Australian coastline multiple times over the past ~40 Ma since the Eocene. The separation of Antarctica and Australia, the relaxation of the Australian platform and the formation of an extensional continental margin basin allowed the episodic ingress of ocean waters into the Murray Basin. Offsets of the resulting limestones have proved to be extremely useful in elucidating the tectonic behaviour of the subsiding Murray Estuary with respect to the uplifting Mount Lofty Ranges and the Coorong Coastal Plain.

Encounter Fault Zone

The Encounter Fault Zone (Fig. 2.1.13) forms the major boundary between the South Mount Lofty Ranges and the western side of the estuary. It trends in a north-westerly direction from near Port Elliot and cuts across the Bremer and Palmer Faults in a linear fashion, intersecting the River Murray within the Murray Basin, south of Swan Reach, where it offsets the *Lepidocyclina* Zone by up to 20 m (Lindsay & Giles 1973), near the location of the tectonic dam proposed for the formation of Lake Bungunnia. The fault has also dislocated Miocene limestone beneath the Angas-Bremer Plain, where it forms a buried, 100 m high fault escarpment, identified through drilling and geophysics (Williams 1978; Waterhouse & Gerges 1979).

The Encounter Fault, where it crosses the Encounter Bay coastline between Victor Harbor and Port Elliot near Watson Gap, dislocates the Last Interglacial shoreline (125 ka). At Watson Gap the Last Interglacial shoreline stands at ~10 m above present sea level (APSL), but a few kilometres to the east, at the Traeger Sand Quarry, the shoreline is at present sea level (Bourman et al. 2000; Murray-Wallace et al. 2010), while further east, within the Goolwa Channel, Last Interglacial shells were exposed at 0.8 m below present sea level during the Millennium Drought, illustrating tectonic offset between the Estuary and the nearby ranges in excess of 8 m in the past 125 ka.

Although there are no published reports of fault exposures in the immediate estuary region, there is a spectacular exposure of the Palmer Fault on the eastern side of the ranges to the north near Cambrai (Bourman & Lindsay 1989), revealing a reverse fault, with Kanmantoo bedrock being thrust over folded Pleistocene fanglomerates (Fig. 2.1.14). This supports the view that the character of the faulting was east-west compressional in nature. Using geophysics, Stackler (1963) identified a large, buried glacial valley east of the Mount Lofty Ranges, beneath the course of the Finniss River. He noted that this valley was not continuous with the glacial valley in the ranges; he called on very extensive post-Permian sinistral transcurrent faulting to account for this dislocation. Subsequent investigations support the view of transpressional

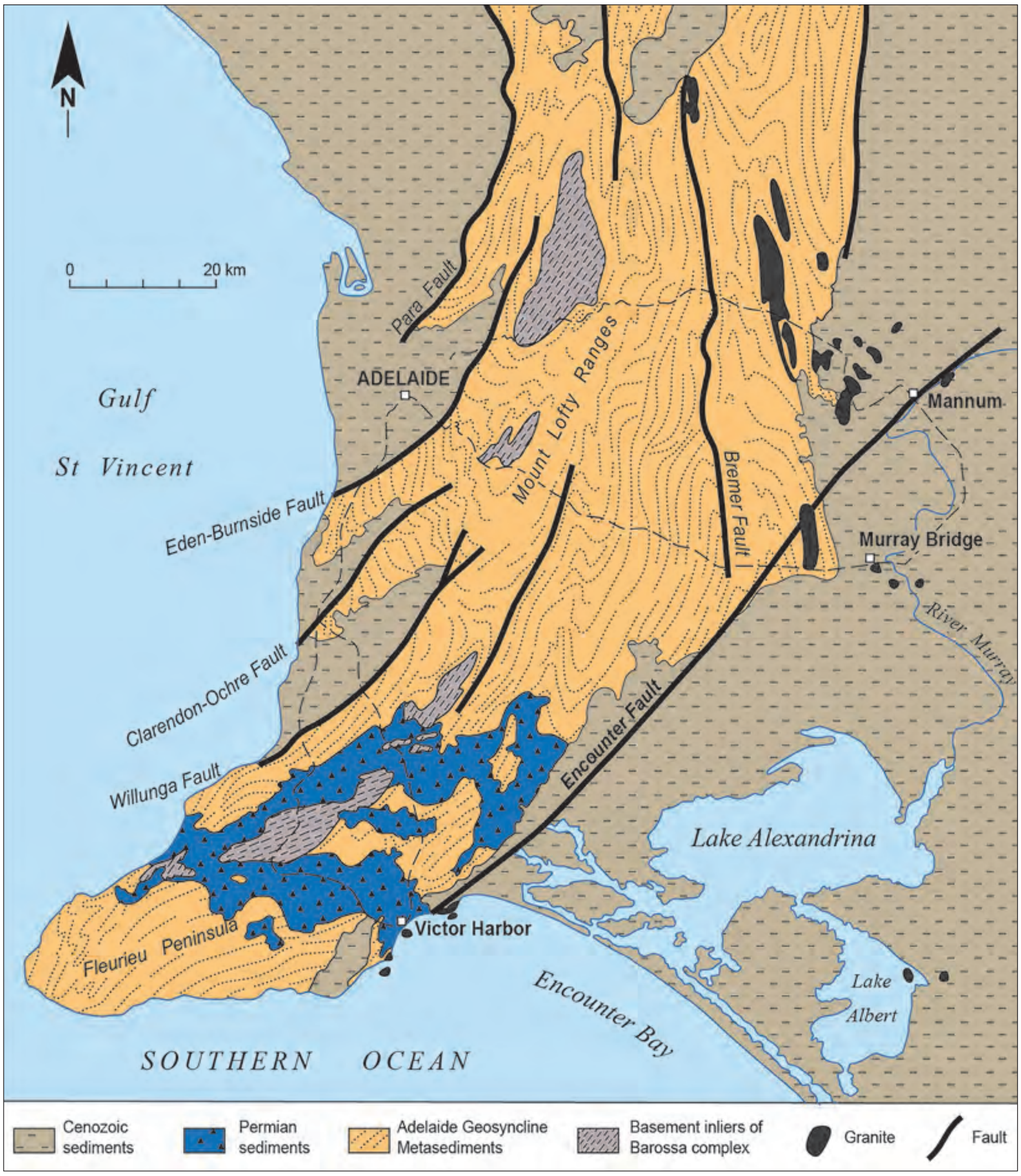

Figure 2.1.13 Location of the Encounter Fault Zone separating the Murray Estuary from the Mount Lofty Ranges. (Bourman et al. 2016)

faulting, involving both compressional and transcurrent movements on the faults on the range margins (Bourman et al. 2010; Jayawardena 2013).

Offsets of Cenozoic limestones

Late Eocene Buccleuch Formation marine sediments have been encountered in bores on Hindmarsh I. and on the Angas-Bremer Plains at depths of 100-147 m below present sea level (Williams 1978; Lablack 1991; Armond et al. 1999), whereas the same unit occurs at 70 m above sea level in the Waitpinga area of the Mount Lofty Ranges, about 40 km to the west (Bourman & Lindsay 1973), demonstrating a potential offset of perhaps 150 m.

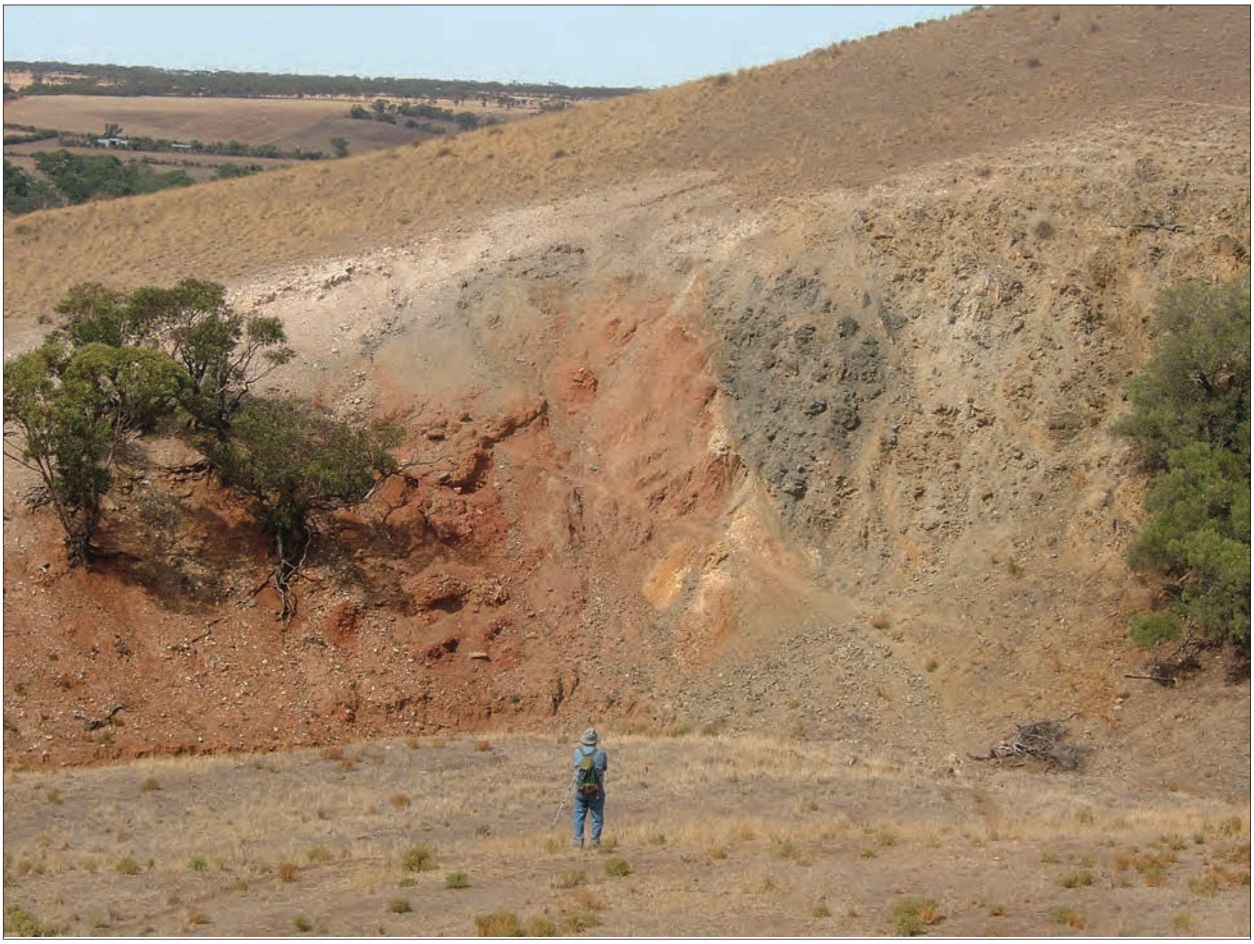

Figure 2.1.14 Exposure of reverse fault, dipping at 45° to the west, on the eastern margin of the Mount Lofty Ranges near Cambrai, showing pods of light-coloured Miocene limestone dragged up from depth along the fault line. Cambrian rocks of the Kanmantoo Group have been thrust over Middle Pleistocene fanglomerates. Palaeomagnetic dating has demonstrated that these sediments have been disturbed since the palaeomagnetic signature was acquired 780 000 years ago. (Bourman & Pillans 1997, Photograph by Sol Buckman)

In a similar fashion, limestones of Oligo-Miocene age have also been offset between the Mount Lofty Ranges and the Murray Basin. Limestones in the Myponga Basin (within the Mount Lofty Ranges) are of Middle Miocene age (Lindsay & Alley 1995), while those in the Hindmarsh Tiers (also within the Mount Lofty Ranges) range from the Late Oligocene to the Early Miocene. Foraminiferal evidence reveals the presence of four transgressive-regressive episodes in these beds, and indicates that there was most likely a marine connection between the Murray Basin and Gulf St Vincent during their deposition (Pledge et al. 2015). In the ranges these limestones extend up to 240 m asl (above sea level) but occur ~40 m below sea level on the western margin of Lake Alexandrina (Lablack 1991).

Other informative localities involving tectonic offsets include *Lepidocyclina*-bearing Miocene limestone about 16 Ma old. The distinctive foraminifer *Lepidocyclina howchini* occupies a thin (1-5 m), precise, marker bed close to water level in the River Murray cliffs between Caloote and Overland Corner (Lindsay & Giles 1973). This zone is also present in the Bremer Valley in the eastern Mount Lofty Ranges, at an elevation of 170 m, which is 160 m above the equivalent unit in the Murray Basin. Conservatively, this suggests a relative uplift of the Mount Lofty Ranges at this locality of at least 100 m in the past 16 Ma (Lindsay 1986).

Further north, near Cambrai, Mills (1965) suggested that the Mount Lofty Ranges had been uplifted along the Palmer Fault 335-366 m since 'pre-Tertiary peneplanation', attributing 60-90 m of this to post-Miocene faulting. In contrast, Twidale & Bourne (1975) preferred to explain the presence of perched limestone on the scarp primarily to a high eustatic sea level. Waterhouse and Gerges (1979) pointed out that there was an insufficient thickness of limestone available to explain the vertical separation of the highest outcrop and the known base of the Miocene limestone, highlighting the role of faulting on the scarp. Bourman and Lindsay (1989) subsequently demonstrated that the limestone dragged up along the fault zone was from the basal part of the Miocene limestone, thereby supporting the interpretation of Mills (1965) (see Fig. 2.1.14).

Tectonic tilting of the Coorong Coastal Plain

On the eastern side of the Murray Estuary ongoing tectonic subsidence has resulted in the merging of progressively younger shorelines and their coastal barriers in a northerly direction. Sprigg (1952) demonstrated that the frontal toes of the barriers also decrease in elevation in a north-westerly direction, with the older barriers showing greater amounts of tilting. This tilting is also reflected in the northerly flow of surface waters draining between the coastal barriers. Near the Murray Lakes, subsidence has caused these barriers to overlap and bury older barriers. The Coomandook Formation, the earliest Pleistocene unit, also tilts down in a north-westerly direction.

In contrast, the progressive uplift of the south-east section of the Coorong Coastal Plain is responsible for the increased spacings between successive barrier shorelines, and indeed their preservation as one of the world's great records of Pleistocene sea-level fluctuations. Crustal doming associated with the emplacement of igneous intrusions and Holocene volcanics is responsible for the upward regional warping and uplift of the coastal barriers across the Southern Coorong Coastal Plain at an average rate of 0.07 mm yr^{-1} near Robe and 0.13 mm yr^{-1} at Mount Gambier during the Quaternary (Murray-Wallace et al. 1998).

The tectonic controls on the Murray Estuary are further illustrated by the Last Interglacial shoreline, which varies in elevation from 6-10 m in the Mount Lofty Ranges to between -0.8 m and 0.9 m in the Lakes area, demonstrating a rate of subsidence of ~0.02 mm yr^{-1}. Along the landward side of the Coorong Lagoon it gradually increases in elevation. Uplift in the South Lagoon has brought coastal barriers, formed when sea level was lower than present, to above sea level where they form the foundations for parts of the Younghusband Peninsula.

SUMMARY

The region now occupied by the Estuary of the River Murray has experienced a rich and fascinating geological history. It included dramatic mountain building, involving the formation of igneous rocks; the passage of thick glacial ice of continental proportions; prolonged denudation and weathering, reducing the topography to an extensive plain; and the separation from Antarctica 43 Ma ago, after which Australia moved rapidly 3 000 km to the north. The formation of an extensional continental margin basin allowed multiple marine transgressions and regressions into a tectonically active region, thereby preserving limestones and barrier shorelines as spectacular records of sea-level and climatic fluctuations throughout the Cenozoic. In more recent times, within this framework of a low-lying marginal basin with preserved barrier shorelines, the site became the outfall of the largest exoreic river in Australia, producing an estuary with regions of large freshwater lakes, a mixing zone of fresh and marine water, and a saline to hypersaline Coorong Lagoon in the interdune corridor between the Last Interglacial shoreline and the modern coastal barriers of Sir Richard and Younghusband Peninsulas. Desert dunes extended over much of the area during the dry, cold and windy times of the Last Glacial Maximum, while terrestrial processes deposited alluvial and lacustrine sediments around parts of the estuary margins during the Pleistocene and Holocene.

ACKNOWLEDGEMENTS

We gratefully appreciate the assistance of the Ngarrindjeri Nation in facilitating our research in the Murray Lakes and Coorong region, and we acknowledge the cooperation of local landowners in the region. Ms Annie Lucas of Hindmarsh I., in particular, has been a constant source of information and assistance. We thank Dr Neville Alley for casting a critical eye over the manuscript of this chapter and making significant improvements.

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CHAPTER 2.2

GEOMORPHOLOGICAL EVOLUTION OF THE RIVER MURRAY ESTUARY, SOUTH AUSTRALIA

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INTRODUCTION

The River Murray Estuary lies at the terminus of the Murray-Darling drainage basin, which drains an area of 1.073 million km^2 or about one-seventh of the Australian continent; it is the largest river system in Australia reaching the sea. The Estuary is a complex area being impacted not only by variations in freshwater and marine influences, but also by longer-term tectonics and more recent human changes.

Prior to human engineering works, the original Estuary comprised the predominantly freshwater Lakes Alexandrina and Albert (Close 1990), while the elongate Coorong, which parallels the shoreline from the Murray Mouth for ~160 km towards Kingston Southeast, (Fig. 2.2.1) was of variable salinity depending on inputs of fresh water from the River Murray and from the south-east. A brackish, migrating mixing zone separated the freshwater Lakes from marine conditions in the Goolwa and Coorong Channels. As increasing amounts of fresh water were abstracted upstream the Lakes became saltier, leading to construction of barrages in the 1930s to retain fresh water and to prevent ingress of sea water during times of low river flow. The barrages have also had the unintended consequence of increasing salinity in the upper reaches of the Coorong Lagoon through limiting freshwater egress from the Lakes into the lagoon during times of low flow. Drainage works in the SE of the state also increased salinity in the Coorong, but some freshwater flow has now been reinstated to the Southern Coorong Lagoon.

The Estuary is a Cenozoic feature occupying an area of progressive tectonic subsidence, impacted by repeated and regular fluctuations in sea level throughout the Pleistocene, with

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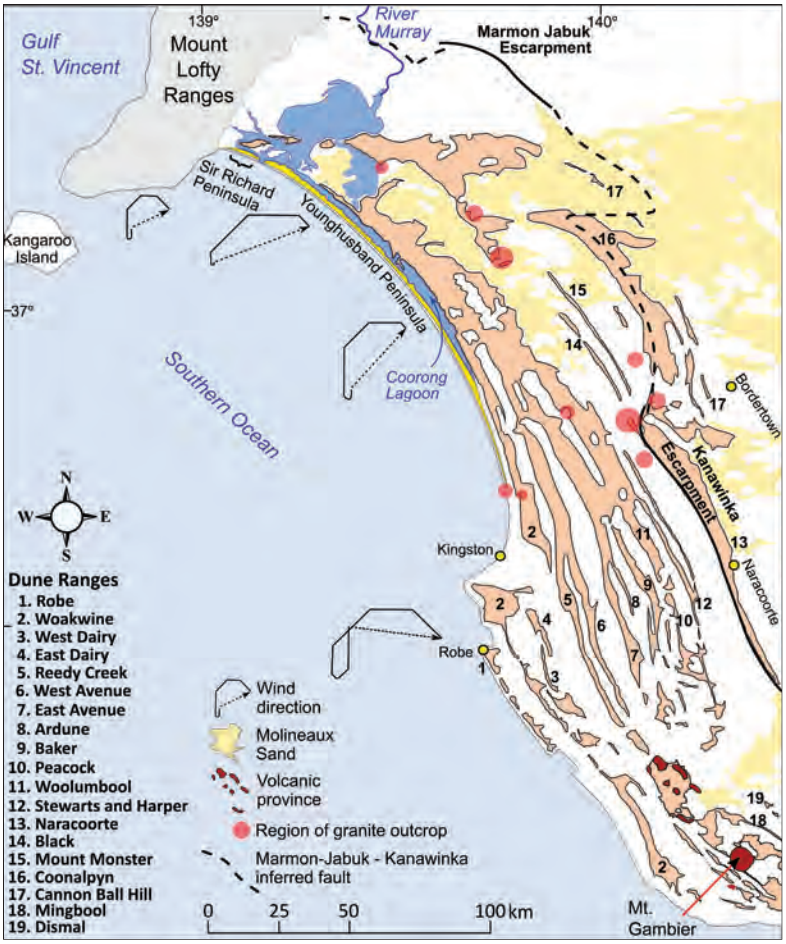

Figure 2.2.1 Location map showing the Murray Lakes and Coorong Lagoon in relationship to Pleistocene coastal barriers and the Mount Lofty Ranges. Weighted wind resultant diagrams (Landsberg 1956) indicate the aeolian sand-shifting capabilities for coastal sites near Victor Harbor, Meningie, Policeman Point and Robe. Vectors are continuous lines and resultants dotted lines (Bourman & Murray-Wallace 1991). Jennings (1967) demonstrated that the resultant of onshore winds only provides the best-observed fit with transgressing dunes.

successive high-stands approximating that of present sea level (Murray-Wallace & Woodroofe 2014). The cycles of interglacials (odd numbers) and glacials (even numbers) are shown in Figure 2.2.2. During low sea levels of glacial times the River breached coastal barrier complexes excavating the broad shallow depressions now occupied by the Lakes, while entrenching its bed across the exposed continental shelf (Hill et al. 2009). The present (Holocene) Estuary formed from 7 000 years ago after the culmination of the last post-glacial rise in sea level, resulting in the formation of the modern coastal barrier systems of Sir Richard Peninsula and Younghusband Peninsula, largely separating the Estuary from the open ocean.

REGIONAL AND GEOTECTONIC SETTING

The River Murray Estuary is located in the south-western portion of the Murray Basin in a zone of subsidence, separated from the uplifting Mount Lofty Ranges by the Encounter Fault (See Chapter 2.1). The zone of subsidence is constrained by the Mount Lofty Ranges to the west and to the south-east by the Padthaway Ridge, a basement high, separating the Murray

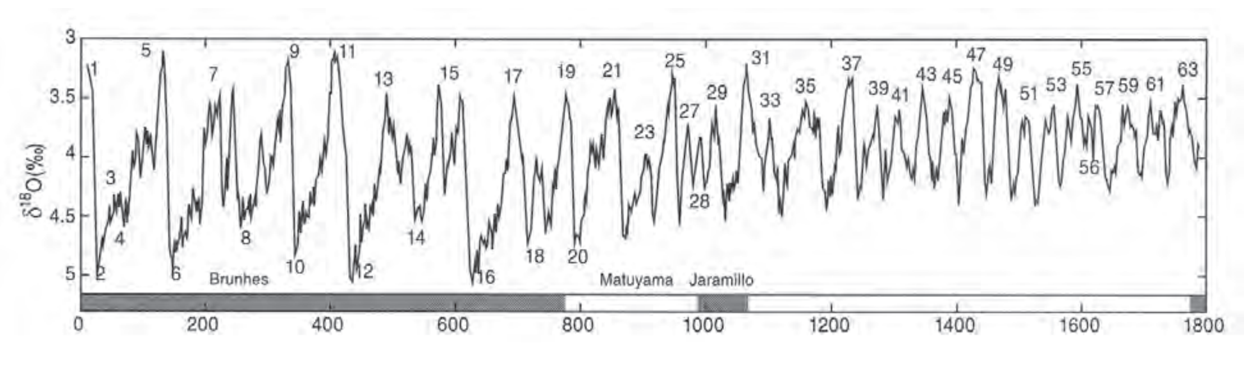

Figure 2.2.2 Cycles of interglacial and glacial periods over the past 1.8 million years based on marine oxygen-isotope records. Low-amplitude, high-frequency 41 ka cycles were replaced by higher-amplitude, lower-frequency 100 ka cycles at the Middle Pleistocene Transition about 1 250 ka ago (Marine Isotope Stage 37). Odd numbers represent high sea levels during interglacials; even numbers represent low sea levels associated with glacials. The palaeomagnetic timescale is also shown, with the Brunhes/Matuyama reversal occurring at 780 ka. (Modified from Lisiecki & Raymo 2005)

and Otway Basins. The Mount Lofty Ranges are a series of block-faulted uplands comprising folded and faulted Mesoproterozoic basement rocks, and Neoproterozoic and Cambrian metamorphosed sediments with associated granites.

The Murray Basin is a large Cenozoic epicratonic sedimentary basin >300 000 km^2 in area (Brown & Stephenson 1991), which developed following the separation of Australia and Antarctica some 43 Ma ago (Veevers et al. 1991). Although much of the basin has been epeirogenically uplifted throughout the Neogene and Quaternary (Brown & Stephenson 1991; Murray-Wallace et al. 1998; Bowler et al. 2006), the River Murray Estuary, which lies within the south-western portion of the basin, has a long history of tectonic subsidence, which continues today. Predominantly Quaternary coastal sediments and landforms define the boundaries of the Estuary, but on its western side Late Pleistocene and Holocene alluvial and lacustrine successions, derived from the Mount Lofty Ranges, fringe the margins of Lake Alexandrina.

The crystalline basement rocks, metasediments and granites underlying the Murray Estuary are overlain by Permian glacigene sediments resting on bedrock topography of considerable relief including deep glacial valleys (Hossfeld 1950; Armond et al. 1999). The Permian deposits are overlain by a Cenozoic sequence of Late Palaeocene to Early Oligocene non-marine and marginal marine sediments, which include the Renmark Group, transgressive Late Eocene to Middle Miocene marine sediments of the Murray Group, and latest Miocene to Late Pliocene marine, coastal and non-marine units (Rogers et al. 1995).

FOR HOW LONG HAS THE RIVER MURRAY FLOWED TO SEA AT ITS PRESENT LOCATION?

There is no doubt that the River Murray has been deflected to its southerly course at Morgan due to the tectonic uplift of the Mount Lofty Ranges. It has been suggested that the River Murray once flowed into Spencer Gulf near Port Pirie before uplift of the ranges (Williams & Goode 1978), but the general consensus is that the Mount Lofty Ranges were in existence before the establishment of the course of the lower River Murray (Gostin & Jenkins 1980;

Harris et al. 1980), and that there had been a pre-Pliocene channel which broadly followed the present course of the river.

The River Murray in South Australia cuts through ~2.4 Ma old Neogene limestone deposits and lake sediments of the former Lake Bungunnia (McLaren et al. 2011). Most recently, McLaren et al. (2011) concluded that during the Early Pliocene the ancestral River Murray flowed to the sea in western Victoria via the Douglas Depression and the Glenelg River, and that tectonic uplift and the formation of a series of tectonic dams, including one near Swan Reach, led to the formation of Lake Bungunnia. The timing of lake demise is uncertain but spans the Brunhes-Matuyama Chron transitions at ~781 ka (An et al. 1986; McLaren et al. 2009). This suggests that the current River Murray in South Australia came into existence following the earth movements, which led to the draining of Lake Bungunnia, a view coincident with the findings of Bowler et al. (2006) and Bourman and Murray-Wallace (1991). McLaren et al. (2011) proposed that the river was tectonically dammed near Swan Reach, leading to the formation of Lake Bungunnia. However, sediments resembling the Blanchetown Clay of Lake Bungunnia occur along parts of the river between Murray Bridge and Tailem Bend (Bourman et al. 2010a) and are worthy of further investigation. Belperio and Bluck (1990) had earlier suggested that coastal barriers might have impounded Lake Bungunnia. The preservation of early Pleistocene coastal features east and south-east of Murray Bridge implies that river discharge has been to the west of these features since their deposition (Ryan 2015), and palaeo-channels on the Lacepede Shelf demonstrate that the river has flowed south from the region of Lakes Alexandrina and Albert since at least the middle Pleistocene (Hill et al. 2009) (Fig. 2.2.3).

MODERN COASTAL BARRIER COMPLEXES

The modern coastal barrier system evolved during the Holocene immediately following the abrupt sea-level rise at the end of the Last Glacial Maximum. The marine transgression was a major forcing mechanism, entraining the landward movement of vast reserves of sand from the then exposed continental shelf as sea level rose between 17 and 7 ka (Lewis et al. 2013). Evolution continued after sea level stabilised, and isolated barrier islands were linked together to form a continuous barrier (Harvey 2006; Harvey et al. 2006), except where the two spits of Sir Richard Peninsula and Younghusband Peninsula, fed by opposed longshore drift, constrained the outlet of the River. Breaching of the barrier by the River Murray has maintained the double reversed barrier spits of Sir Richard Peninsula and Younghusband Peninsula. The present shoreline fronting the Estuary consists primarily of unconsolidated sand and some lithified dune sediments (aeolianite), so that the shape of the arcuate sweeping beach from Middleton to Kingston Southeast, the longest beach in Australia (194 km), is closely related to the effects of wave refraction of open ocean swell waves, with a periodicity of about 16 seconds (Davies 1958), as they 'bottom' on the submarine topography of Encounter Bay.

Tides are microtidal (<2 m) along the Encounter Bay coastline, with mean spring high tides of 0.8 m at Victor Harbor and 1.2 m at Kingston Southeast (Short & Hesp 1982). However, storm surges can increase tides by up to 1.5 m above the level of astronomically predicted tide (Bourman & Harvey 1983). There is a persistent moderate to high-energy wave climate along the coast. Deep water waves are generally >2.5 m with a periodicity >12 seconds, but the low-gradient

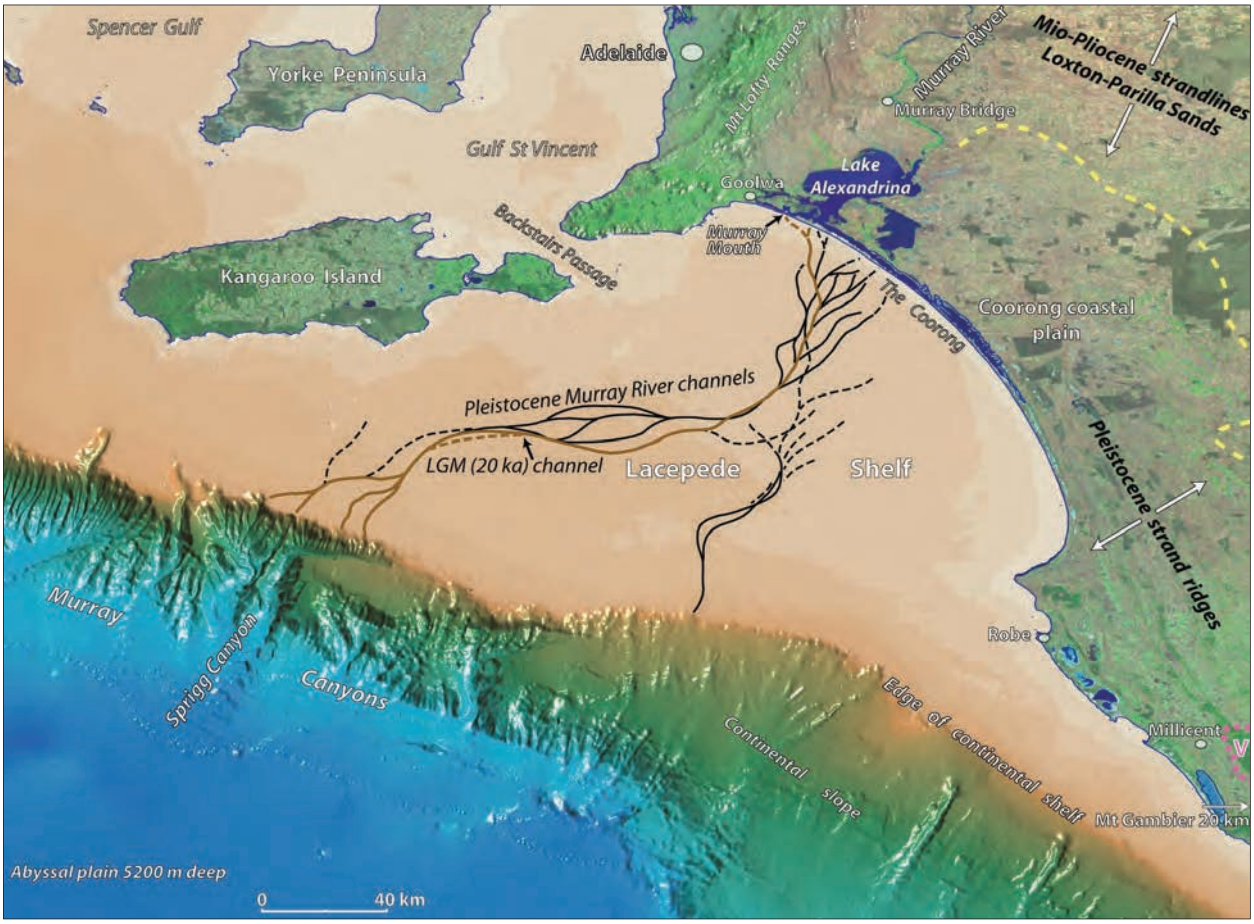

Figure 2.2.3 The Murray Group of submarine canyons and the Pleistocene courses of the River Murray across the continental shelf. (From Hill et al. 2009, reproduced with permission from the Geological Society of Australia)

sea floor causes waves to break up to 500 m offshore, producing dissipative beaches (Short & Hesp 1982). Johnston (1917) recorded waves 6 to 7 m high, breaking in water depths of 10 m during heavy seas that occur five to six times a year at the Murray Mouth; a steep offshore gradient at the Mouth produces only a 20% loss in wave power (Short & Hesp 1982).

Sir Richard Peninsula

Sir Richard Peninsula, a sand spit about 10 km long, terminates at the Murray Mouth; it was named after Sir Richard Graves MacDonnell, Governor of South Australia 1855-1862 (Cockburn 1990). The spit is up to 1 km wide in its central section, narrowing to near 0.5 km at its proximal and distal ends (Fig. 2.2.4). Dunes range up to 25 m high near Goolwa and 10 m high towards the Murray Mouth. Apart from a small outcrop of aeolianite at its proximal end, unconsolidated sediments underlie the spit, with its morphology a direct reflection of aeolian, wave and tidal influences. The Peninsula is migrating landwards (Bourman & Murray-Wallace 1991), as back-barrier and interdunal sediments are sporadically exposed on the ocean beach. Back-barrier, dark organic rich sediments containing plant and shell fragments and the jaw-bone of a rodent recovered from beneath the modern beach in 1986 have been dated at approximately 8 000 years before present (1950; BP) (Bourman & Murray-Wallace 1991), while

Figure 2.2.4 Oblique aerial view along Sir Richard Peninsula towards Goolwa. The spit narrows towards its proximal end where evidence of shoreline erosion is demonstrated by lagoonal muds and interdunal corridor soils sporadically exposed by coastal erosion. (Photograph by R.P. Bourman)

an *Allocasuarina* (sheoak) tree stump and attached shells located on the open ocean beach have been dated at 4630±210 cal yr BP and 5190±380 cal yr BP respectively (Bourman et al. 2000). The coastal erosion of Aboriginal middens and European artifacts, such as surveyed roads and beach shelters (Bourman 1979), provides further evidence of landward migration of the spit.

Coastal erosion and sand migration from the beach and foredunes across the Peninsula, allowing the sea to encroach, partly explain the landward movement of the spit, but another factor, episodic tectonic subsidence, also contributes. At Middleton, rapid coastal erosion occurred in the early part of the 20th century, causing coastal retreat of more than 200 m; this was attributed to subsidence accompanying earthquake activity in 1897 and 1902 (Sprigg 1952), with the latter event being reported as a severe tremor in Goolwa, where it cracked some of the buildings (Bourman 1973). Dislocation of the Last Interglacial shoreline reveals subsidence in the Goolwa area of 2.8 m in the past 125 ka. Last Interglacial shells at the Goolwa Boardwalk occur at 0.8 m below present sea level (BPSL), while the regional level of the last Last Interglacial sea stood at least 2 m above present sea level (APSL) (Murray-Wallace et al. 2010). Future tectonic subsidence could set off renewed rapid erosion of this coastal section.

Back-barrier estuarine lagoonal sediments, weakly cemented interdunal calcareous sands, former beach berms and wash-over fans form the substrate for the Peninsula on which transverse and parabolic dunes have accumulated. The former beaches and wash-over fans, which are marked by shell lags, calcareous sandstone, beachrock and rare rounded clasts of various lithologies including granite and Kanmantoo bedrock, all lie at the same elevation as the modern beach, even though they are separated by dunes up to 10 m high. The mollusc assemblages are Holocene species, apart from reworked valves of the late Pleistocene Sydney cockle *Anadara trapezia*, an indicator of the Last Interglacial Maximum in southern Australia (Murray-Wallace et al. 2001).

In detail the age of the spit varies, being younger towards its distal extremity and on its coastal margin as it migrates landward. At the Thermoluminescence Laboratory of the University of Wollongong, thermoluminescence dating of sediments from the basal, central section of the Peninsula, from the proximal end of the spit, progressively towards the distal end, returned ages of 4.0±0.8 ka (W2314), 4.5±1.2 ka (W2315) and 3.6±0.9 ka (W2316). These ages support the notion of landward migration of the spit, producing basal sediment ages younger than the 7 000 years since sea level broadly stabilised at its present elevation.

Aboriginal middens are widespread throughout the proximal half of the spit, and provide constraints on the geomorphological development of the spit, as Aboriginal occupancy and dune development were intimately related. The beach and wash-over fan deposits are readily distinguishable from the middens (Bourman & Murray-Wallace 1991): the wash-over deposits occur close to modern sea level; they contain shells of variable sizes and species diversities (including extinct molluscs); and the shells are abraded, while many were dead when deposited, as indicated by holes produced by boring organisms. In contrast, the shells in the middens are dominantly mature specimens of the Goolwa cockle (*Donax deltoides*) with rare edible gastropods (*Turbo* sp.); they occur at a range of elevations within the dunes, where they are commonly preserved beneath younger dune deposits; and they are commonly associated with charcoal and burnt hearthstones.

Radiocarbon and amino acid racemisation dating of midden and wash-over fan molluscs demonstrate the dynamic nature of the Peninsula and indicate its continual occupancy by Aboriginal people since at least 3 000 years ago (Bourman & Murray-Wallace 1991). Middens only occur along the proximal half of the spit, suggesting that migration of the Murray Mouth to the west had destroyed the distal half of the spit, which reformed as the mouth moved back to the east (see Fig. 2.3.4 in Chapter 2.3). Abandoned flood tidal deltaic deposits indicate the presence of a former mouth opposite Rushy Island and Swan Point on Hindmarsh Island, coinciding with the distribution of middens on the Peninsula.

The eastward prolongation of Sir Richard Peninsula suggests longshore transport in that direction. Bourman and Murray-Wallace (1991) were in general agreement with this suggestion, but found that the sand coarsens along the spit towards the Mouth, which is the opposite to what would be expected. They concluded that waves generated by south-westerly storms could move all beach sediment, including occasional pebble-sized clasts, towards the Mouth, while persistent swell waves, which generally approach roughly parallel to the shoreline, may only be capable of transporting fine sand away from the Mouth.

In addition to waves transporting sand towards the Mouth, aeolian sand transport along the Peninsula has been observed during strong westerly winds, with speeds of up to 45 km hr^{-1} generating ephemeral transverse sand ridges with wavelengths of 20 m and heights of 30 cm. Under these conditions, 5 000 m^3 of beach sediments were in transit along the 10 km long sand spit (Bourman 1986) (see Fig. 2.3.3).

Younghusband Peninsula and the Coorong Lagoon

Younghusband Peninsula, which was named after William Younghusband, an early Legislative Councillor and Chief Secretary in the Cabinet (Cockburn 1990), separates the waters of the Coorong Lagoon from the open ocean, while the landward side of the Coorong is formed by the Last Interglacial shoreline. The 'Coorong' was probably derived from the Aboriginal word 'Kurangh', meaning a narrow lagoon or neck (Cockburn 1990). As a major coastal barrier shoreline, Younghusband Peninsula extends uninterrupted from the River Murray Mouth for some 190 km to the south-east; the Peninsula is a modern analogue of earlier Pleistocene barrier systems preserved best in the uplifting south-east of the state (Murray-Wallace 2018).

The northern part of Younghusband Peninsula is similar to Sir Richard Peninsula in that it rests on a substrate of back-barrier lagoonal sediments, palaeo-beaches and wash-over fans (Harvey et al. 2006). However, due to tectonic uplift in the south and tilting down to the north, dune aeolianites of the Interstadial Marine Isotope Substages 5c (~100 ka, Robe III) and 5a (~80 ka, Robe II) (Murray-Wallace et al. 2001) have been progressively uplifted to form islands and peninsulas in the southern Coorong such as Cow, Long and Round Islands and Hack Peninsula (~100 ka Substage 5c), while primarily Substage 5a (~80 ka) forms a foundation for Younghusband Peninsula (von der Borch 1975; Harvey et al. 2006; Bourman et al. 2016), particularly from south of the Parnka Point area.

Uplift in the south and subsidence in the north are demonstrated by the elevations of back-barrier lagoonal molluscs associated with earlier barrier complexes, and shelly Last Interglacial beaches, which occur along the landward side of the Coorong, as well as by the natural north-westerly flow of drainage (Sprigg 1952; Murray-Wallace et al. 1998; Murray-Wallace 2002; Harvey et al. 2006; Murray-Wallace 2018). Continuing uplift is also demonstrated by the occurrence of elevated shells (*Sanguinolaria Psammotellina biradiata*) on the landward side of the Coorong near Hack Peninsula on a former tidal flat. These Holocene shells, which were dated at 2 220±50 yr BP (Wk-8172), occur at 0.651 m Australian Height Datum (AHD), while the nearby lagoon surface lies at 0.15 m AHD. Uplift in the south is also responsible for the formation of the ephemeral Coorong Lagoon and the Holocene carbonate lakes occupying low points in the Pleistocene dunes south of Salt Creek (von der Borch 1965; von der Borch & Lock 1979; Cann et al. 1999).

Last Interglacial coastal sediments (125 000 years; MIS 5e) on the landward side of the Coorong were formed when sea level was approximately 2 m higher than present. Today, at the Goolwa Channel the Last Interglacial shoreline lies at -0.8 m, on Hindmarsh Island +0.9 m, +2.0 m at Pelican Point, Salt Creek +4.0 m and at the Woakwine Cutting +8.0 m (Fig. 2.2.5). Even though sea level was up to 9 m lower than present during Substage 5c and 17 m lower in 5a (Murray-Wallace et al. 2010), the associated dunes were considerably higher and they were subsequently elevated by tectonic uplift, resulting in remnants of them protruding above present sea level. The modern unconsolidated dunes of Younghusband Peninsula, which extend well above sea level, began to form from about 7 000 years ago when present sea level stabilised.

Many Aboriginal middens on the Peninsula range in age between 1 and 2.9 ka, but there are older estuarine shells that returned radiocarbon ages between 4.5 and 5.5 ka at Cantara (Luebbers 1981, 1982; Bourman et al. 2000), while on Hack Peninsula an oyster midden dated at approximately 6 000 years reveals that at that time there was a connection to the

Figure 2.2.5 View along the McCourt Cutting through the Last Interglacial Woakwine Range with Lake George and Younghusband Peninsula in the distance. Note the internal bedding structures of the former dune barrier. Beach sands, marine shells and back-barrier lagoonal shells and sediments up to 8 m above present sea level underlie the lithified dune (aeolianite). (Photograph by R.P. Bourman)

open ocean (Harvey et al. 2006), adding support to the view that the Peninsula was not a continuous barrier at this time. A radiocarbon age of 5 020±50 years on *Donax deltoides* near the northern end of the Peninsula demonstrates that there was simultaneous initiation of barrier development in the southern, central and northern sections (Harvey et al. 2006). Although longshore transport may have linked separate barrier islands, these observations challenge the view of Howchin (1929) that the Peninsula progressively grew from the south and instead reveal that the area south-east of Barkers Knoll has been relatively stable for the past 5 000 years.

This interpretation accords with Harvey (2006), who had proposed a four-stage model for the development of Younghusband Peninsula. This involved barrier island development on offshore bars or older calcreted barriers, beach ridge progradation, dune development and island expansion, closure of the tidal entrances and development of a continuous barrier with dunes. This was followed by barrier migration involving dune transgression and foreshore erosion.

As with Sir Richard Peninsula, Younghusband Peninsula is also advancing landward, as evidenced by occasional exposures of palaeosols and back-barrier sediments on the ocean beach, and mud folds in back-barrier sediments as they are differentially loaded by advancing sand dunes (Figs. 2.2.6 & 2.2.7), such as near 42 Mile Crossing (Brown 1969; Townsend 1974). At Cattle Point, back-barrier shells of *Tellina (Macomana) deltoidalis* dated at 899±105 yr BP (Wk-9567) have been uplifted at least 5 m above the local water level in the lagoon due to differential loading imposed by the landward migration of dunes onto the lagoonal muds.

Figure 2.2.6 Transgressive dunes advancing across Younghusband Peninsula and over back-barrier lagoonal sediments on the Coorong. (Photograph by R.P. Bourman)

Figure 2.2.7 Folding deformation of back-barrier lagoonal muds, the result of differential loading by advancing sand dunes. (Photograph by R.P. Bourman)

In 1802 Matthew Flinders mapped sand drifts on Younghusband Peninsula (Flinders 1814), suggesting that drift is a natural phenomenon in dune systems, now known to engender renewal of a healthy dune ecosystem (Hilton et al. 2007). Sand drift was accelerated with the arrival of Europeans, who introduced rabbits and grazed domesticated animals on the Peninsula, causing sand to drift across the barriers into the back-barrier lagoons and across roadways in places (Bourman & Harvey 1986). The activities of off-road recreational vehicles further disturbed dune vegetation (Gilbertson 1977, 1981). With better vehicle management, removal of exotic herbivores and the introduction of exotic grass species, such as Marram grass (*Ammophila arenaria*), Pyp grass (*Ehrharta villosa* var. *maxima*) and Sea wheat-grass (*Thinopyrum junceiforme*), sand drift has been restrained. However, these grasses out-compete the native species and impact on dune morphology and beach width (Heyligers 1985; James 2012).

Longshore transport

Longshore transport of sand along the Encounter Bay shoreline is variable, predominantly with westerly movement on Sir Richard Peninsula, and drift from the south-east along Younghusband Peninsula (Johnston 1917; Bourman 1979). The opposed drift directions converge near, and explain the general location of, the Murray Mouth. Open ocean swell waves approaching from the south-west strike the margins of the curved Encounter Bay coast at opposed angles, causing the reverse drift directions. The general broadening of Younghusband Peninsula in a north-westerly direction, where the greatest sand accumulation occurs, supports this interpretation, although the River Murray outfall acting as a hydraulic groyne might also contribute to this accretion.

Sprigg (1952) dismissed longshore transport as an important process along the Coorong Coast, suggesting that seagrass meadows inhibited north-west longshore transport, but later noted plumes of fine sediment in suspension moving northward along the coast (Sprigg 1959). He also noted that beach and dune sands were comprised predominantly of carbonate at Kingston (65-95%), but increased in silica content towards the Murray Mouth, which he attributed to greater inputs of terrestrial quartz from the River Murray. de Mooy (1959b) noted that aeolianites of the Estuary are comparatively siliceous, also attributing this to fluvial inputs. Bourman and Murray-Wallace (1991) reported SiO_2 contents in beach sediments along Sir Richard Peninsula varying between 72.7% and 64.0% with $CaCO_3$ contents ranging between 20.7% and 27.0%. These high quartz contents might also suggest possible derivation from the former desert dunes which occupied the exposed continental shelf during the Last Glacial Maximum, and which were incorporated into coastal sediments during the post-glacial transgression.

Chappell (1991) used meteorological records to calculate, through wave energy hind-casting methods, a potential net average littoral drift of sediment of up to 260 000 m^3 yr^{-1} from 1940 to 1990, with a potential westerly movement of >1 000 000 m^3 between 1941 and 1942. These volumes of sand movement are compatible with the dredging rates required to clear the Murray Mouth during the Millennium Drought (James et al. 2015). Major directions of drift varied from westerly between 1940 and 1950, to mainly easterly between 1951 and 1968, returning to a predominantly westerly drift between 1969 and 1989.

LAST INTERGLACIAL SHORELINE

Well-preserved and near continuous Last Interglacial shoreline successions can be traced from Victor Harbor to south of Mount Gambier (Murray-Wallace et al. 1996; Bourman et al. 2000; Murray-Wallace et al. 2010). The shelly beach facies of the Last Interglacial shoreline, which parallels the modern shoreline several kilometres inland, provided the foundation for all of the barrages built across the Lower Lake system, apart from the Goolwa Barrage. Surveys by Oliver and Anderson (1940) revealed that the channels cut through the former shoreline are only 1-3.5 m deep, whereas the site of the Goolwa Barrage is underlain by a considerable thickness of unconsolidated sediments; piles 19 m long were driven into the sediments to form sound footings for the barrage, demonstrating that the Goolwa Channel, which cuts deeply through the Last Interglacial deposits, was the main discharge point of the River Murray during and since the Last Interglacial.

Longshore sediment transport during the Last Interglacial was predominantly from the south-east, and de Mooy (1959a) suggested that the Last Interglacial coastal barrier, which he identified as the Bonney Range, had formed in three stages. During Stage 1, the barrier progressively built towards the north-west; at Stage 2 it formed a recurved spit on the south-western side of Lake Albert (see also Blackburn et al. 1965); and at Stage 3 the barrier blocked off a possible former outlet of the River Murray into the Coorong as it grew towards Pelican Point, which de Mooy (1959a) believed was the terminus of the Last Interglacial deposits. At Mark Point, 6.5 km south-east of Pelican Point, MIS 5e successions comprise an open ocean seaward-dipping foreshore facies, dominated by the fossil mollusc *Donax deltoides* (Fig. 2.2.8). Subsequently we have established that these Last Interglacial sediments extend across and beyond Hindmarsh Island (Bourman et al. 2000; Murray-Wallace et al. 2010; Ryan 2015).

Figure 2.2.8 Platform at Mark Point cut across a sequence of Last Interglacial, seaward-dipping, open ocean beach sediments comprising dominantly the Goolwa cockle (*Donax deltoides*). Note the mobile dunes on Younghusband Peninsula. (Photograph by R.P. Bourman)

Remnants of the shoreline stretch over a width of >2 km, largely as a sandflat up to 2 m AHD, with occasional higher calcreted beach ridges and interdunal back-barrier lagoonal sediments preserving a palaeo-sea level at 0.9 m AHD. Many of the calcreted beach ridge mounds have now been removed for road metal. The Last Interglacial shoreline features continue on the western side of the river, with low-lying areas in the Goolwa Township comprising former back-barrier lagoonal environments, while the higher calcreted areas represent lithified dunes.

During Last Interglacial times (125 ka) longshore transport was suppressed where it encountered the main channel of the River Murray, resulting in the accumulation of a large sand spit and dune system, which forms the bulk of the northern half of Hindmarsh Island. De Mooy (1959b) had earlier mapped this feature as part of the Alexandrina Range, which he correlated with the West Naracoorte Range (800±100 ka) in the SE (Murray-Wallace et al. 2010). The Alexandrina Range on Hindmarsh Island has now been shown to be dominantly of Last Interglacial age on the basis of luminescence and amino acid racemisation dating techniques (Murray-Wallace et al. 2010). Although the vast majority of the dune range on Hindmarsh Island is of Last Interglacial age it also contains older stacked interglacial sediments, reflecting ongoing tectonic subsidence; MIS 5e dunes overlie truncated MIS 7 dunes (Ryan 2015) and remnants of an older dune system dated at >329 ka (Murray-Wallace et al. 2010), which may be related to the older Alexandrina Range.

The progradation of the Last Interglacial barrier towards the north-west slowly pushed the River Murray in that direction and explains the somewhat anomalous and circuitous present course of the River to the sea, with the Holocene barrier of Sir Richard Peninsula

Figure 2.2.9 View across the Goolwa Channel, Hindmarsh Island, the Lower Murray Channel and Currency Creek. Calcreted Last Interglacial prograded beach ridges are prominent in the central part of the Island. Inter-ridge depressions, which were occupied by the sea during the Holocene, have been excavated for the marina on Hindmarsh Island. (Photograph by R.P. Bourman)

completing the distinctive elbow in the River's course. The accumulation of sediments against the hydraulic groyne of the River also led to the seaward progradation of the coastal barrier, forming a succession of now calcreted recurved spits and beach ridges (Fig. 2.2.9), which become younger towards the south. The north-west section of Younghusband Peninsula, where there is the greatest accumulation of sand on the Peninsula, bears similarities to the lithified Last Interglacial features on the western end of Hindmarsh Island.

EARLIER PLEISTOCENE COASTAL BARRIERS

Interglacial coastal barrier systems provide the physical landscape framework for the River Murray Estuary. The coastal barrier landforms predominantly comprise calcarenites or aeolianites deposited as shore-parallel aeolian dune complexes defining the positions of former coastlines.

Unlike the barriers of the Coorong Coastal Plain, which have been continually uplifted and consequently separated, those near the Murray Lakes, due to tectonic subsidence, converge, merge and overlap (Bourman et al. 2000; Murray-Wallace et al. 2010). Dating of the barrier complexes in the estuary region reveals generally increasing ages inland from the modern coastline, but due to continuing subsidence the barriers are commonly composite structures with former shoreline positions being reoccupied by successive interglacial high-stands, all of which achieved similar elevations (Murray-Wallace et al. 2001, 2010; Murray-Wallace 2018).

Apart from the Last Interglacial shoreline, no shelly facies associated with the barriers is available for dating due to tectonic subsidence or formation during an interstadial when sea levels were comparably lower; dating was thus reliant upon whole-rock amino acid racemisation and luminescence dating techniques (Bourman et al. 2000; Murray-Wallace et al. 2010). The most seaward range is the barrier exposed at Surfers Beach (105±5 ka), which correlates with the Robe Range (MIS 5c) in the Southeast. The Last Interglacial barrier (130±15 ka; MIS 5e) is the best preserved in the region and is the only one with accessible open-ocean, back-barrier and lagoonal shell beds, which provide reliable palaeo-sea-level indicators.

Without numerical dating of the barriers it is impossible to distinguish between them in the Estuary area based on their sediment and soil characteristics. Physically tracing barriers from the Southeast is hindered by the coalescing of the barriers northwards, their impingement on palaeo-headlands and islands of granite and a widespread cover of Late Pleistocene desert dunes. The coastal barriers of the Middle to Late Pleistocene record, from MIS 17 (688-647 ka) and later, which have minimal contact with granite, appear to coalesce and lose topographic expression as they approach the Murray Lakes region. In contrast, coastal barriers of the early Pleistocene form distinct arcuate shapes in the landscape with headlands developed on granite outcrops; these are recognised as the Coonalpyn Range and the easternmost extent of the Alexandrina Range (Ryan 2015).

Using geographic, morphostratigraphic and chronostratigraphic correlation, Ryan (2015) equated the Coonalpyn Range (See Fig. 2.2.1) with deposition during MIS (Marine Isotope Stage) 31 (1.1 Ma), MIS 35 (1.18 Ma), MIS 37 (1.25 Ma) and MIS 39 (1.3 Ma), and the arcuate Alexandrina coast east of Lake Albert with deposition of MIS 19 (790 ka), MIS 21 (840 ka), MIS 25 (~950 ka) and MIS 31. An outcrop of the potentially oldest coastal barrier, which Bowler et al. (2006) identified as the Cannonball Hill Range near Bordertown, correlating it with MIS 43 or MIS 47 (1.35 to 1.43 Ma), was also recognised on the northern coastal plain near Tauragut Well (S 35°34'26.2" E 140°03'50.6") by Ryan (2015). In the south, the Cannonball Hill Range near Bordertown is at least 80 m APSL, based on the elevation of lagoonal sediments landward of the East Naracoorte Range (Murray-Wallace et al. 2001), a site much higher than the Tauragut Well location in the north, the dune sediments of which occur at an elevation of ~40 m APSL. Assuming that the Tauragut Well site and the Cannonball Hill Range are equivalents, a subsidence of the coastal plain at Tauragut Well in excess of 40 m has occurred since ~1.3 Ma at a rate of >0.03 mm yr^{-1}.

De Mooy (1959a) equated the Alexandrina Range at the Estuary with the West Naracoorte Range of the Southeast, which is now known to be c.790-780 ka old (MIS 19) (Cook et al. 1977). The Alexandrina Range, as mapped along the north shore of Lake Albert through Point McLeay across Point Sturt Peninsula and the northern half of Hindmarsh Island to Goolwa (de Mooy 1959a), has since been established as a composite barrier with a combination of Marine Isotope Stages 5e (125 ka), 7 (223 ka), 9/11 (322-404 ka) and 5e/13 (125-487 ka) (Murray-Wallace et al. 2010). Sprigg (1959) had also equated the Lake Albert Beach with the Naracoorte Range. However, it is unlikely that the MIS 19 (790-780 ka) barrier extends into the estuary region at the surface, given that downwarping in the Murray Mouth region and uplift of the Coorong Coastal Plain began before the initiation of MIS 19 (Ryan 2015).

The merging of the coastal barriers in the estuary area is well illustrated by the observation that since the formation of the Baker Range about 456±37 ka ago (Huntley et al. 1993) on the Southeast Coastal Plain, the coastline has prograded some 65 km, whereas in the estuary area the coastline has only prograded 15 km since the deposition of the equivalent barrier at Point

McLeay II (470±70 ka) on the north-west Narrung Peninsula (Murray-Wallace et al. 2010). Calcreted fossil calcareous dunes, which spread inland from the Last Interglacial shoreline, drape many of the earlier barriers; they cover virtually all of the Narrung Peninsula, including the Point McLeay site and the region immediately south-east of Lake Albert.

The former coastal barrier systems are illustrated in Figure 2.2.10. Sprigg (1959) initially correlated Loveday Bay Beach with the Avenue Ranges (MIS 9/11), but it is now known to

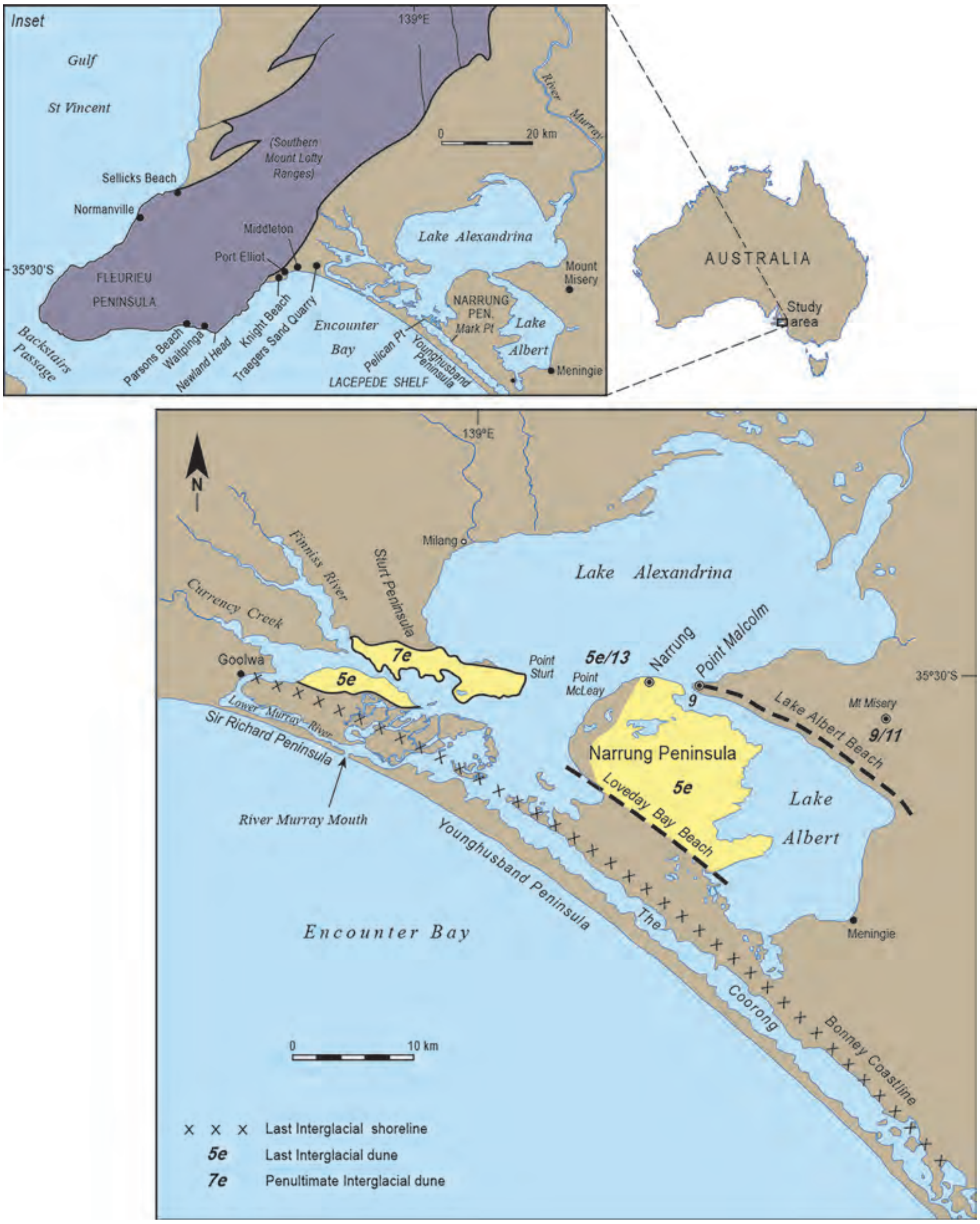

Figure 2.2.10 Former shorelines and dunes of the Murray Lakes area. The Last Interglacial shoreline (MIS 5e) follows the landward side of the Coorong Lagoon as the Bonney Coastline of de Mooy (1959b) and extends across Hindmarsh Island to Victor Harbor. MIS 5e dunes occur on Hindmarsh Island and at Goolwa. The Alexandrina Range of de Mooy (1959b) (outlined in bold), which he equated with the West Naracoorte Range of the Southeast, is actually a composite of Marine Isotope Stages 5e (Last Interglacial) and 7e. (From Bourman et al, 2016)

be of Last Interglacial age (Murray-Wallace et al. 2010). A thermoluminescence (TL) age of 215±35 ka (MIS 7) identifies the penultimate interglacial barrier on Sturt Peninsula (Murray-Wallace et al. 2010). Deposition along the northern shoreline of Lake Albert was correlated with MIS 9 or 11, based upon a TL age of 350±65 ka (Murray-Wallace et al. 2010), but a more recent TL analysis resulted in a minimum age of ≥366±47, indicating that deposition occurred within or before MIS 11 (Ryan 2015). Similarly, a barrier identified within a sedimentary succession at Point McLeay had previously provided a TL age of MIS 11 or MIS 13 (470±70 ka) (Murray-Wallace et al. 2010), but additional analysis using optically stimulated luminescence provided an age of 421±48 ka, suggesting that deposition during MIS 11 is more likely (Ryan 2015). The identification of terra rossa soils beneath and above the MIS 11 unit and the capping of the cliff by consolidated Last Interglacial sand with overlying modern sands indicate long-term deposition at this location (Ryan 2015). The 5 km wide opening between Point Sturt and Point McLeay, which forms the southern boundary of Lake Alexandrina, was probably the general location of the sea mouth during the penultimate interglacial (MIS 7), which was widened by river erosion during subsequent lower sea levels.

PLEISTOCENE ALLUVIAL SEQUENCES

Colluvial and alluvial sediments derived from the Mount Lofty Ranges form gently sloping surfaces down to the western margins of Lake Alexandrina. Along the main streams of Currency Creek, Finniss River, Angas River and the Bremer River, sets of river terraces record tectonic and sea-level changes. These streams grade towards the base level of the Lakes, and the behaviour of the terraces is partly determined by the distances and gradients from the sediment sources in the Mount Lofty Ranges to the Lake.

The vast majority of the alluvial sediments are those of the Pooraka Formation (Bourman et al. 1997), also named the Currency Creek Formation by Maud (1972). These sediments are red/brown alluvial deposits of Last Interglacial age (132-118 ka), deposited in former valleys eroded during earlier low sea-level stands. Rare remnants of older interglacial alluvial sediments may occur in the area, but they have largely been destroyed during the erosional phases of glacial cycles before the Last Interglacial (Bourman 2006). However, one such remnant has been identified on the margin of the alluvial plain between Currency Creek and the Finniss River (35°27’53.8” S 138°49’10.8” E). The alluvial sediment is reddish-brown in colour and thermoluminescence analysis provided an age of 227±24 ka, demonstrating the existence of a penultimate interglacial alluvial event (Ryan 2015; Ryan et al. 2018), older than the Last lnterglacial Pooraka Formation. The penultimate interglacial alluvium was inundated by the Last Interglacial estuary, reflecting a change in base level between the two interglacials as a consequence of either the higher sea level reported for the Last Interglacial in the region, the lower known sea level for the Penultimate Interglacial (Murray-Wallace et al. 2001), the ongoing tectonic subsidence of the estuary or a combination of all factors.

Along Currency Creek and the Finniss River, Last Interglacial Pooraka Formation sediments form high-level, fill-top, paired river terraces, former flood plains stranded by stream incision. These terraces grade to the Last Interglacial shoreline, and they are represented within the Milang Soil Combination of de Mooy (1959b), who also recognised lower terraces carved into the Pooraka Formation during stream incision; this developed unpaired fillstrath terraces during a falling sea level. It is also possible that an alluvial deposit younger than the Pooraka Formation could form some of the lower terraces. For example, Bourman et al. (2010a) reported a Late Pleistocene Marine Isotope Stage 3 interstadial, sub-pluvial deposit (43±3 ka), with superficial similarities to the Pooraka Formation, from other alluvial sediments flanking the Mount Lofty Ranges.

During the Last Glacial Maximum about 23-21 ka ago when sea level fell to about -125 m, valleys eroded into the Pooraka Formation were subsequently infilled with grey/black alluvium of the Waldeila Formation (Ward 1966) of mid-Holocene age (7-4 ka) (Bourman 2006), as sea level rose to near its present level. In places these sediments have been incised to form paired inset terraces. Due to a combination of sea-level changes and tectonic subsidence, the sets of terraces along the Finniss River and Currency Creek, which originally graded to different base levels, converge downstream but do not overlap.

However, the terraces of the Angas and Bremer Rivers behave in a different way. Because of the very low gradients across the Bremer Soil Combination (Fig. 2.2.11), which these streams have developed, and the greater distances between the ranges and the Lake, the two terrace deposits merge, cross over and overlap. Consequently, the grey/black Waldeila Formation, which begins as paired terraces set within a valley carved into the Pooraka Formation, is eventually deposited as levees on top of the Pooraka Formation. It is typical that terraces along streams with long courses, which extend over gentle alluvial plains, eventually merge and cross over, with the younger grey alluvium spilling from the main channel to submerge the older red alluvium (Bourman 2006). It is of interest that the cross-over points on the Bremer and Angas rivers coincide with the location of a sub-surface fault scarp of the Encounter Fault, as determined by drilling and geophysics (Williams 1978). This suggests that down faulting has favoured the spilling of grey alluvium out of its constraining valley over the down-faulted red alluvium, a characteristic also noted on the River Torrens (Bourman et al. 2010b).

Flooding still occurs on the lower reaches of the Angus and Bremer Rivers, occasionally inundating the area between the two streams, so that levee formation is probably still occurring; consequently the deposits here may be somewhat younger than the mid-Holocene Waldeila Formation, where flooding is restricted to the former stream channel. Dury (1964), for example, reported a date of 3540±230 years BP on wood recovered from the fine grey/brown silt of the levees on the lower reaches of the Angas River.

Causative links have been established between valley incision, the formation of filltop terraces and cyclic variations in the global climatic and sea-level changes associated with the marine oxygen isotope record (Shackleton & Opdyke 1973), with the terraces reflecting terrestrial changes that include neotectonic influences (Bridgland 2000). These links are apparent in the alluvial sequences described here; erosion of large valleys occurred during times of low sea level associated with drier glacial episodes, whereas infilling can be coupled with warmer, wetter interglacial times and higher sea levels.

LAST GLACIAL MAXIMUM DUNES

Sub-parallel, east-west-oriented, quartzose, unconsolidated sand dunes, indicating an arid phase, are widespread around the Murray Estuary (Sprigg 1979), including occurrences on Hindmarsh and Mundoo Islands. These dune sands with patinas of iron oxides are characteristically red, orange or yellow in colour and are easily distinguishable from the calcareous coastal dunes. The dunes have been dated by thermoluminescence on Hindmarsh Island at 18.8±1.8 ka, W2254 (Bourman et al. 2000) and at approximately 16 ka on the north shore of Lake Albert (Gloster 1998), indicating a late stage of the Last Glacial Maximum. At this time sea level was about 125 m lower than present and about 180 km seaward of the present coast, with the River Murray extending across the continental shelf (Sprigg 1979; Hill et al. 2009) (Fig. 2.2.3). The climate was dry, cold and windy (Belperio 1995), with dune development being encouraged by poor vegetation cover (Hesse et al. 2004; Hesse 2010). The dunes would have extended across the exposed Murray Estuary and the continental shelf, later to be incorporated into marine estuarine and lacustrine environments during the post-glacial rise in sea level.

Some of these former desert dunes have been episodically reactivated (Ryan 2015). Dark brown-coloured sands and soils form low dunes and sandy rises 1-2 m high over large areas of Hindmarsh Island. Stratigraphically, they represent the youngest of the pre-European dunes with a TL age of 3.9±0.8 ka (Bourman et al. 2000). There are recent wind-blown deposits related to bad land management, attested to by sand accumulation around and along fence lines. Many of the sands of the Island are water-repellent, drying out rapidly in summer and being readily prone to sand drift.

THE TERMINAL LAKES ALEXANDRINA AND ALBERT

Lakes Alexandrina and Albert are two broad and shallow freshwater lakes at the terminus of the River Murray. Lake Alexandrina, the larger of the two, is 38 km (E-W) and 21 km (N-S), covering an area of 580 km^2. It has an average depth of about 3 m and a maximum depth of only 4.5 m, while along much of the shoreline water depths are <1 m for several hundred metres offshore. Lake Albert (180 km^2), which is linked to Lake Alexandrina through a constricted channel, 'The Narrows', is 13 km (E-W) and 18 km (N-S) with a maximum depth of 2.5 m and an average depth of about 2 m. Lake Albert has no direct outlet to the sea, but a former outlet to the Coorong at the south-eastern corner of the Lake may have existed in the past (Taylor & Poole 1931). However, Murdoch (2009) suggested that the occurrence of freshwater pollen and algae, together with the absence of dinoflagellates in the pollen assemblages recovered from cores, demonstrates that Lake Albert has never been directly connected to the Coorong Lagoon since sea level stabilised ~7 000 years ago.

There is little doubt that under natural conditions the Lakes were dominantly freshwater bodies, as indicated by the presence of freshwater microfossils, fish, mussels and other molluscs over thousands of years; freshwater vegetation fringing the Lakes; the absence of mangroves; and modelling of the freshwater flows, which would have kept the sea at bay.

Seven distinct geomorphic units equivalent to soil combinations were recognised surrounding the Lakes by de Mooy (1959a) (Fig. 2.2.11):

1. The Milang Combination primarily comprises clay-rich colluvial and alluvial deposits, which grade smoothly towards Lake Alexandrina from the Mount Lofty Ranges. Currency Creek and the Finniss River dissect it, producing sets of river terraces.
2. The Seymour Combination comprises gently undulating plains of Pleistocene age, which grade seawards. The sediments are coarse-textured, calcreted at the surface and reworked by aeolian processes to produce dune ridges.

3. The Alexandrina Combination comprises former coastal barriers of aeolianite, now calcreted.
4. The Bonney Combination is occupied by a former Last Interglacial coastal barrier system with a core of aeolianite on the eastern, southern and western shore of Lake Albert.
5. The Bremer Combination was produced by alluvial deposition by the Angas and Bremer Rivers, deposited in valleys carved into the Seymour and Milang Combinations.
6. The Malcolm Combination comprises fine-textured lacustrine and estuarine sediments in swamp environments on the Lake margins.
7. The Younghusband Combination consists of the modern calcareous coastal barriers.

Lacustrine sediments of the Lakes

Much of the country immediately surrounding the Lakes is low-lying and is occupied by sediments of the Malcolm Combination deposited during the Holocene when Lake levels were higher than at present (de Mooy 1959b; von der Borch & Altmann 1979). Stranded cliffs, sedimentary deposits, black soils and abandoned embayments, which are characteristically flat and vegetated by halophytic samphires, mark former Lake shores developed when the Lake level was at least 2.7 m higher than at present (von der Borch & Altmann 1979). In particular,

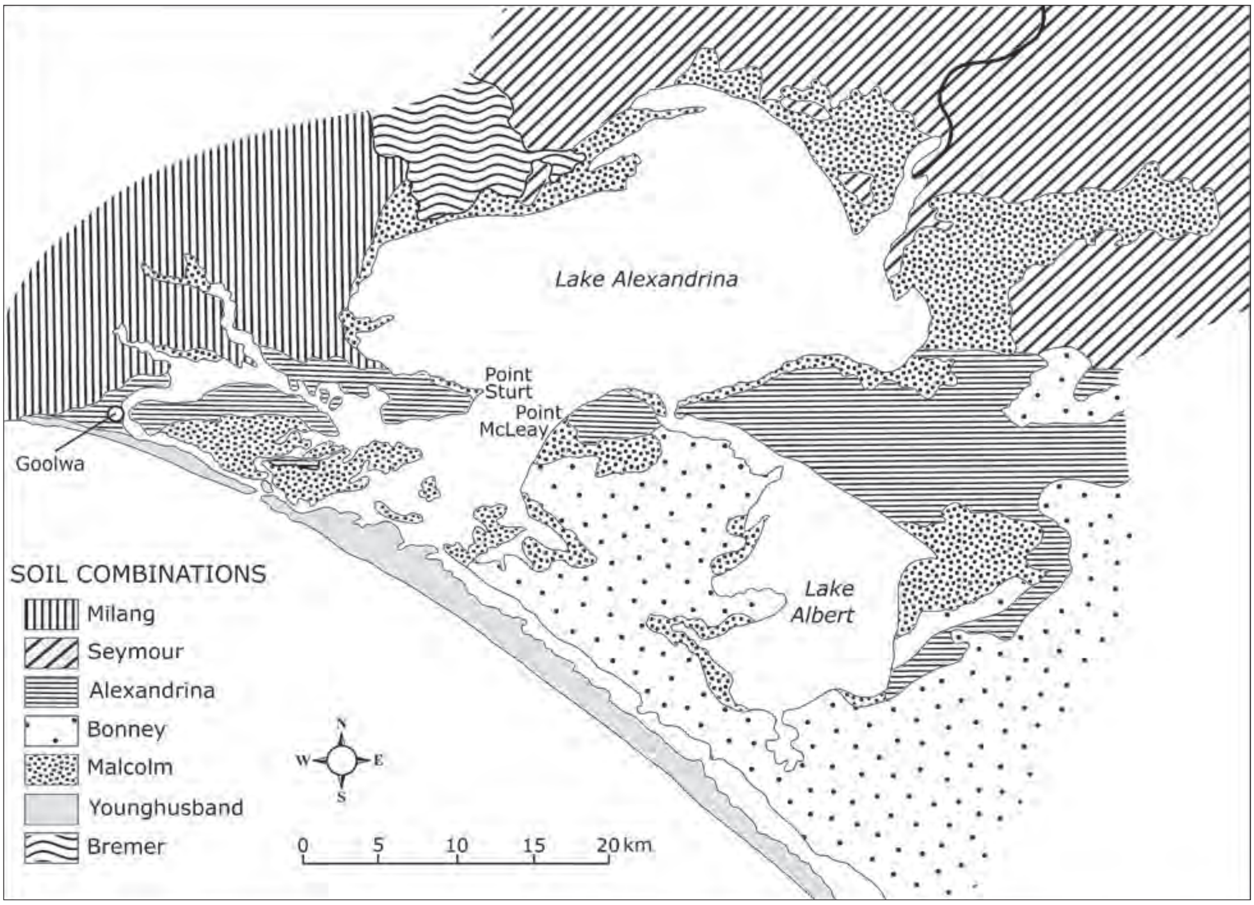

Figure 2.2.11 Map showing the seven geomorphic units, equivalent to the soil combinations of de Mooy (1959a), which surround Lakes Alexandrina and Albert. (Modified from de Mooy 1959a)

de Mooy (1959b) regarded the Malcolm deposits, which are predominantly freshwater, fine black clays, to be the result of extensive sedimentation in the low-lying Lake margins during higher Lake levels. He also noted that the Malcolm deposits, which mask the pre-existing landscape, were not submerged during the 1956 flood, and that, for their deposition, water levels 3 m higher than at present would have been required.

Von der Borch and Altmann (1979) undertook a detailed investigation of the stratigraphy of the Cooke Plains Embayment (See Chapter 2.1; Fig. 2.1.12), a former extension of Lake Alexandrina (Fig. 2.2.12), which revealed a succession of Holocene lacustrine and estuarine sediments representing expansion of the Lake, a still stand and regression of the Lake shore. The high Lake level was attributed to the coincidence of the peak of the Holocene transgression at about 6 500 radiocarbon years, with a mid-Holocene humid period 8 000-5 000 years ago.

Organic rich sapropel, which developed under eutrophic conditions, recovered from the basal section of cores into the bed of Lake Albert, returned radiocarbon ages between about 6 800 and 5 350 years BP, illustrating the variable time of formation of the sapropel in different parts of the Lake (Gloster 1998). Deposition of the sapropels corresponds with the mid-Holocene humid period when Lake levels were most likely at their highest. These ages are comparable with those obtained by von der Borch and Altmann (1979) from the Cooke Plains Embayment and radiocarbon ages obtained by Murdoch (2009) from the base of the sediments underlying Lake Albert.

Murdoch (2009) carried out a palaeo-environmental reconstruction of Lake Albert, based on stable isotope and palynological analysis of two cores, which captured a complete record of sedimentation in Lake Albert since sea level stabilised following the post-glacial rise in sea level. Radiocarbon dates on macrofossils from the core bottoms returned ages of 7195±35 yr BP and 7305±35 yr BP. There was a decreasing trend in total organic carbon values and increasing carbonate content upwards from the base, suggesting diminishing water depths and productivity along with increasing isolation in predominantly freshwater eutrophic conditions.

Figure 2.2.12 The Cooke Plains Embayment, showing the former Holocene extension on the eastern extremity of Lake Alexandrina. (Modified from von der Borch & Altmann 1979)

Further evidence of elevated Lake levels is provided by a sequence of quartzose Lake shore ridges up to 2-3 m high and 500 m wide, which parallel the lake shore on the Nalpa Station for about 9 km on the north-eastern shore of Lake Alexandrina (Fig. 2.2.13). The toe of the highest ridge is at 1.75 m AHD and up to 10 smaller regressive lake shore/dune ridges occur between it and the modern lake shore at 0.75 m AHD. The quartzose character of the sediments, which are of refractory quality, suggests derivation from a terrestrial freshwater environment rather than a marine one, which is more likely to have produced calcareous sediments. Thermoluminescence dating of a sample collected from near the base of the largest ridge (35°19'46" S, 139°16'03" E) returned an age of 8.0±1.2 ka (W2696), an age commensurate with the maximum level reached by the Lake during the Holocene.

Supporting evidence for Lake levels at least 3 m higher than the natural present level occurs on the west-facing shore at 'The Willows'. Here freshwater shells (*Corbina australis*), which currently occur at about 2 m above Lake level in the Cooke Plains Embayment (35° 19' 33" S 139 ° 16' 03.11" E), have been radiocarbon dated at 2650±90 yr BP (Wk-5409).

Holocene marine/coastal sediments

Holocene marine and coastal sediments fringe the southern shores of the festoon of islands that occur on the southern side of the Estuary. The inter-ridge depressions between the calcreted

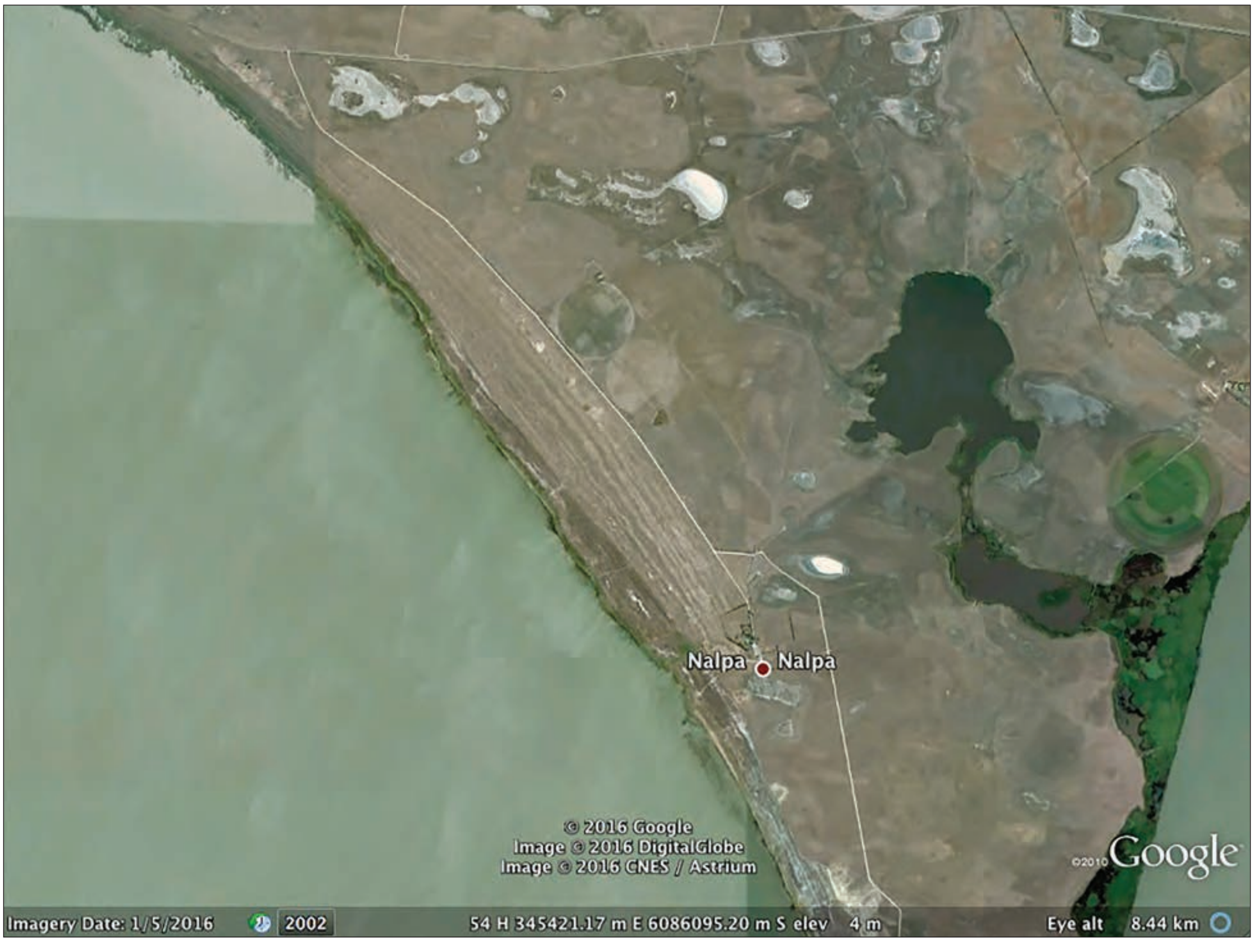

Figure 2.2.13 Google Earth Image showing the stranded lake shore sand ridges on the Nalpa property on the north-eastern shore of Lake Alexandrina.

beach ridges near the south-west shore of Hindmarsh Island, which may have been eroded deeper during the low sea level of the Last Glacial Maximum, were subsequently invaded by the sea as demonstrated by the recovery of Holocene molluscs from these depressions (Murray-Wallace et al. 2010), which were excavated to form the marina on Hindmarsh Island. Shells (*Donax deltoides*) recovered during dredging for a mooring near the eastern end of the Hindmarsh Island Bridge from a depth of several metres below water level were radiocarbon dated at 10 639±100 yr BP (Wk-5408), reflecting the post-glacial rise in sea level.

Much of the southern halves of Hindmarsh Island and Mundoo Island consist of mid-Holocene sandflats up to 2 m AHD, which broadly coincide with the sandflat of the Last Interglacial. In a few places the Holocene shoreline abuts cliffed Last Interglacial calcreted beach ridges. The majority of the sandflat sediment is calcareous and contains shells and shell hash demonstrating its source from the coast, delivered by waves and flood tides through a Murray Mouth, much wider and prone to greater migration than at present. Radiocarbon ages on marine molluscs suggest that the sandflat evolved 6 000-3 500 years BP (Bourman et al. 2000).

A jumble of seemingly anomalous dune fringes the south coast of Hindmarsh Island for several kilometres west of the Murray Mouth, where they have no obvious sand source for their development. They are younger than the mid-Holocene sandflat on which they have formed; at Swan Point they are underlain by a former beach deposit at present sea level containing *Katelysia* shells dated at 2381±64 yr BP (Wk-13080). Moreover, they are also younger than the coastal barriers of Sir Richard and Younghusband Peninsulas. This suggests that the dunes were formed during the migration of the Murray Mouth, with sand being delivered through the Mouth to sandflats, from where it was blown to form dunes. Bourman et al. (2000) reported that during Mouth migration modern analogues of these dunes developed between 1981 and 2000, with some dunes up to 2 m high being formed and vegetated in 12 months directly inland from the Mouth. Dune systems have also been formed landward of the coastal barriers on Bird Island since 1945 (James et al. 2015).

Human impacts and lake shore erosion

Four major soil types and deposits, listed below, form the Lake borders (Fig. 2.2.14) and influence lake shore erosion that has been accelerated by the artificial elevation of water levels following barrage construction. The Lakes are generally held at 0.75 m AHD with surcharging to 0.85 m prior to summer, thereby bringing Lake waters into contact with vulnerable sites (McCord 1979).

a. Limestone Soil on calcreted aeolianite of former coastal barrier systems is relatively resistant to erosion.

b. The Black Swamp Soils Association, which consists of low-lying heavy black clays in swamps on the Lake fringe, has a moderate to high erosion susceptibility.

c. The Poltallach Association comprises a heavy clay topsoil 40-90 cm thick, underlain by bleached, siliceous, white sand. This unit is highly susceptible to erosion when water levels are below the clay horizon.

d. The Border Association on the eastern side of Lake Alexandrina consists of dune sand or sandy Lakeshore sediment overlying the three previous soil types; it is also susceptible to erosion.

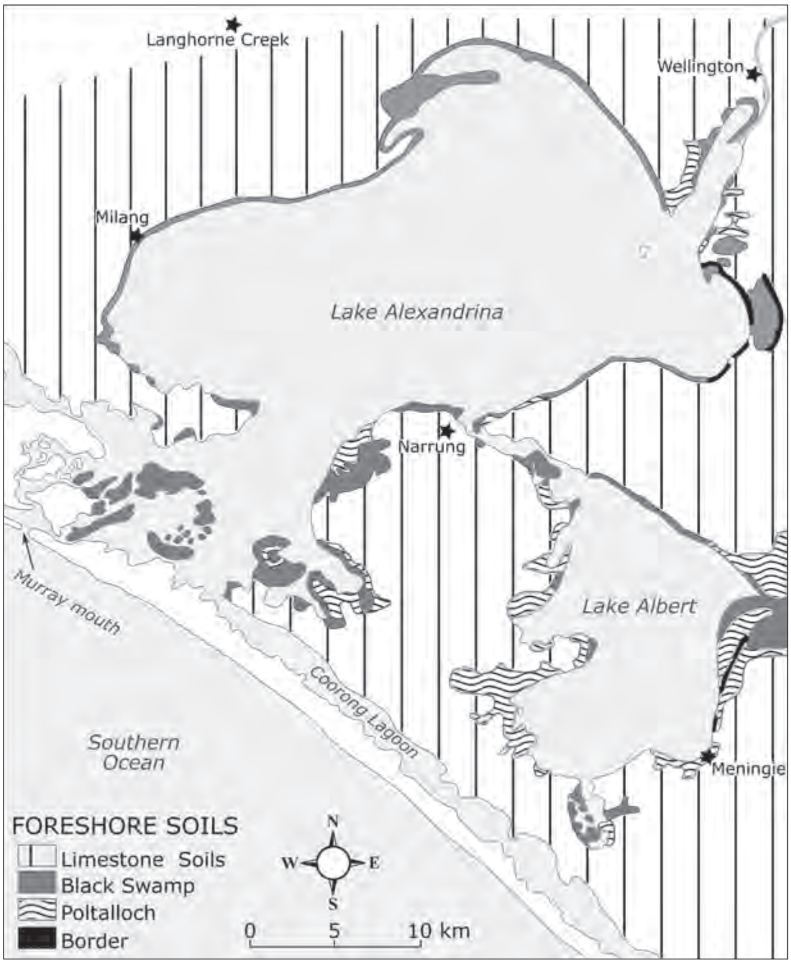

Figure 2.2.14 Foreshore soils of Lakes Alexandrina and Albert and their susceptibility to erosion. (Adapted from McCord 1979 and Coulter 1992)

The average rate of accelerated lake shore erosion has been calculated at 1 m yr^{-1}, but in exposed and vulnerable sites rates of erosion of up to 12 m yr^{-1} have been recorded, increasing salinity, turbidity and nutrient levels (Coulter 1992). The replacement of shoreline-fixing plants such as saltmarsh vegetation, lignum and paper barks with pasture grasses along with uncontrolled grazing by livestock has accelerated shoreline erosion (Fig. 2.2.15). Stock exclusion and revegetation have proved to be successful in sheltered areas, but exposed areas require engineering responses.

In some cases of geomorphic change, such as in eroding coasts and gullies, landscape modification after initial disturbance briefly remains stable, but is followed by rapid and dramatic erosion. However, the rate of erosion gradually slows down and develops new quasi-equilibrium conditions, which may lead to stabilisation. This has been the case with gullying in Sellicks Creek and erosion of the Middleton coastline, and there may be some parts of the Lake shorelines which will behave in a similar manner. However, there are situations around the Lake shores where there is extensive sandy low-lying land that will not naturally stabilise without the loss of considerable tracts of land, so that physical protection will be required.

A very vulnerable section of shoreline lies at the western extremity of the Cooke Plains Embayment, where the shore is composed of a quartz sand ridge, which von der Borch and Altmann (1979) described as a chenier, but which is more likely to be a sand spit and dune

Figure 2.2.15 Eroding low sandy shoreline on the west shore of Lake Albert. Freshwater shells (*Corbina australis*) occur in the sandy sediments. (Photograph by R.P. Bourman)

(see Fig. 2.2.12). It protects a swamp which is close to lake level, and if it were breached, the lake shore would advance landwards more than a kilometre to a similar sand barrier. A wall of tyres has been used to protect part of this eroding shoreline (Fig. 2.2.16).

Under pre-barrage conditions, lake shore erosion would probably have occurred during floods and storm conditions when strong winds caused Lake setups. In contrast, on protected shores with little Lake setup the lake shore has actually prograded; digitate deltas occur, such as at the outlet of Currency Creek, while sand spits have developed on the sheltered shores at Tolderol Point and Mosquito Point in Lake Alexandrina fed with sediments from the Angas and Bremer Rivers. In Lake Albert sand spits have also formed at Murrangong, Rumply Point, Reedy Point, south of the entrance to Waltowa Swamp and at the entrance to the Warringee Embayment (Gloster 1998). The prominent, calcreted headland of Campbell Park, which terminates at Rumply Point, may well have formed as a dune on a spit during the Last Interglacial.

Lake sedimentation

Lakeshore erosion and land clearance have contributed to accelerated sedimentation in Lake Alexandrina, during the 100 years before 1990 (Bourman & Barnett 1995). Barnett (1993, 1994, 1995) established a long-term, millennial-scale sedimentation rate of 0.5 mm yr^{-1} in the central channel of the Lake, but an enhanced, shorter-term, decadal rate of 1.7 mm yr^{-1}. Upstream of the Goolwa Barrage there is an even greater rate of sedimentation of 4.5 mm yr^{-1} over a 50-year period, with a change in sediments from marine-derived bioclastic sands to

Figure 2.2.16 A tyre wall protecting the sand barrier on the western extremity of the Cooke Plains Embayment. (Photograph by R.P. Bourman)

fluvial muds. Murdoch (2009) also recorded an increase in sedimentation rates in Lake Albert since European settlement, as well as changes in the geochemistry of the Lake sediments.

It is of significance, given the size of the Murray-Darling drainage basin, that there is no classic delta offshore from the River Murray; most sediment is deposited in the settling basins of the terminal Lakes. Thus the River Murray Mouth region represents a failed delta; any terrestrial sediment delivered to the coast was rapidly dispersed alongshore, incorporated into coastal barriers or spread across the Lacepede Shelf (Murray-Wallace et al. 2010), with only a small digitate delta developing where the River enters Lake Alexandrina.

However, terrestrially derived quartzose sands are present in the Lakes. Sandy sediments occur in the Narrung Narrows and rim the entire shore of Lake Albert in shallow water for distances of up to 180 m offshore, while muds occur in the central part of the Lake at depths greater than 1.8 m (Gloster 1998). There are transitional zones of sandy mud and muddy sand between these two units. There may have been bigger fluvial inputs of sand in the past as the quartz contents of beach sediments near the Murray Mouth are far greater than along the Coorong shore (Sprigg 1952). It is also possible that the siliceous sands were derived from the reworking of last glacial maximum desert dunes. The construction of dams and weirs has restricted the movement of coarse bedload sediments downstream so that suspended sediments make up the majority of the current stream load. Johnston (1917) reported mainly clay-sized suspended sediments in Goolwa Channel before completion of all the regulatory structures along the river. During high discharge phases the sea offshore from the Mouth is commonly stained brown with suspended clays and phytoplankton (Fig. 2.2.17), highlighting the need

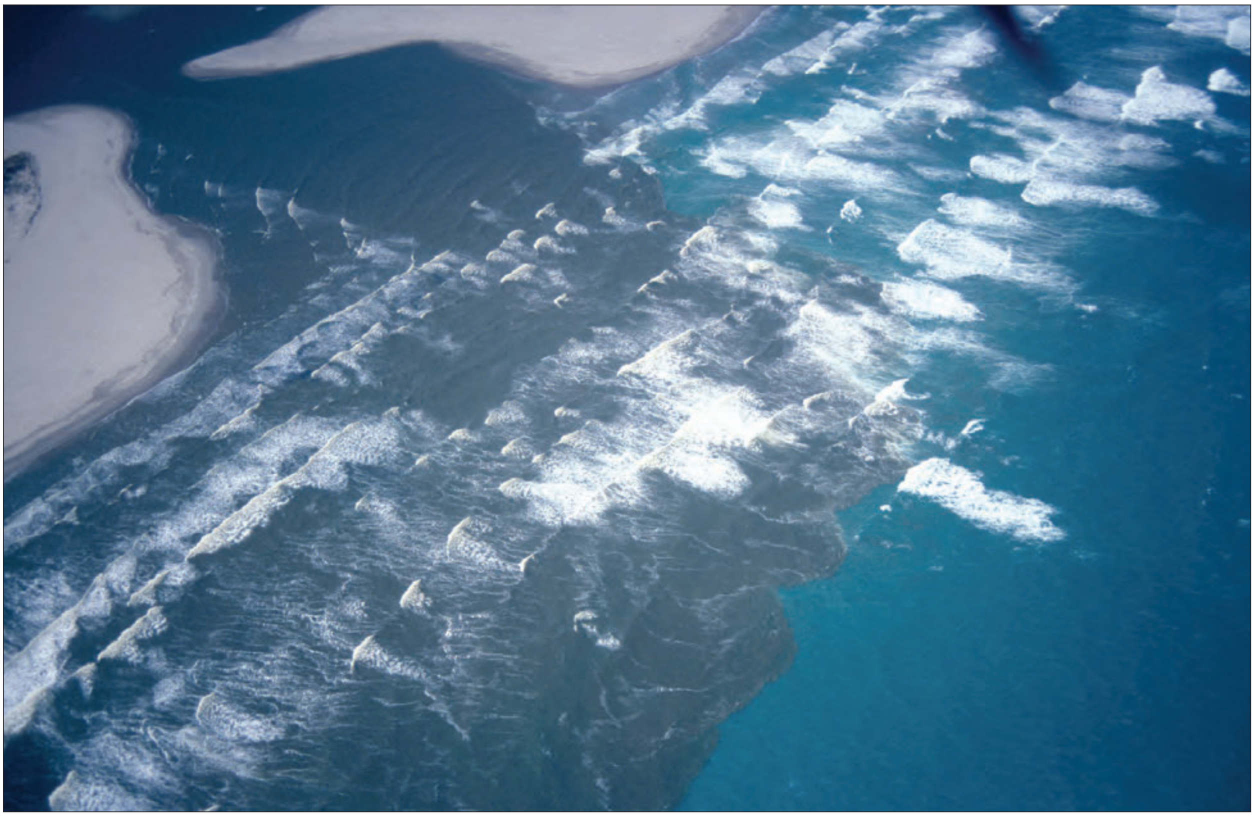

Figure 2.2.17 Suspended sediment and organic phytoplankton being washed out of the Murray Mouth during a high river flow in the 1990s. Note the movement along the coast towards Middleton where it disrupted a surfing carnival. Currents occasionally carry fine-grained sediments and organic materials across Encounter Bay towards Backstairs Passage. (Photograph by R.P. Bourman)

for regular flushing of the river system to avoid the build-up of noxious sediments, chemicals and minerals in the Estuary.

SUMMARY AND CONCLUSIONS

The present Lakes and the Coorong Lagoon are Holocene estuarine features formed over the past 7 000 years following the post-glacial marine transgression and the development of the modern coastal barriers of Sir Richard Peninsula and Younghusband Peninsula, which separate the estuary from the sea. The spatial extent of the estuary has subsequently been constrained by the construction of artificial barrages separating the Lakes and lower river from the estuarine system. Geomorphologically, the Murray Estuary is a complex and dynamic area of interaction between large inputs of fresh water with the coastal and marine influences of tides, waves, currents and winds together influencing development of beaches, dunes, coastal barriers and back-barrier lagoons and lakes. These processes are superimposed upon a tectonically subsiding landscape in the Lakes area with gentle uplift in the southern Coorong Lagoon.

Equivalent processes and morphological developments occurred during earlier sea-level high-stands. The fluctuations in sea level, roughly on a 100 000-year cycle, saw sea levels ranging from near the present level down to 125 m below sea level. During low sea levels the River Murray incised its channel and extended across the exposed continental shelf. Accompanying these sea-level fluctuations were climatic changes, with high sea levels being associated with warmer, wetter interglacials favouring stream aggradation, and low sea levels with cold, dry and windy conditions that instigated desert dune development and stream incision. These climatic and sea-level fluctuations are recorded in river terraces along streams flowing from the Mount Lofty Ranges to the Murray Lakes as well as in the stranded former coastal barrier complexes around the Lakes and the Coorong Lagoon, now well preserved with calcrete cappings. Because of tectonic subsidence during the formation of the coastal barriers in the Lakes area, they merge and overlap, complicating their interpretation. They stand in stark contrast to the equivalent but widely separated and distinct barriers in the uplifting south-east of the state. The dominance of calcareous sediments in the Estuary region illustrates that despite the close proximity to the Mouth of Australia's largest exoreic river system, aeolianites continued to form during interglacial sea-level high-stands of the past 500 ka. Due to its dynamic nature, the landforms of the Estuary are very vulnerable to human impacts.

ACKNOWLEDGEMENTS

We gratefully acknowledge the cooperation and assistance of the Ngarrindjeri Nation in facilitating our research in the Murray Lakes and Coorong region. Local residents are thanked for allowing access to their properties. Annie Lucas, in particular, must be acknowledged for drawing our attention to the first confirmed Last Interglacial shell beds on Hindmarsh Island, and later, many others, along the landward Coorong shore.

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CHAPTER 2.3

THE MOUTH OF THE RIVER MURRAY, SOUTH AUSTRALIA

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INTRODUCTION

The Murray Mouth is dependent on river flows for its existence. If there were no river there would be no mouth: coastal sediments transported by waves and tides would rapidly heal up the opening and permanently separate the current estuary from the sea. In the natural state of the estuary, Lakes Alexandrina and Albert were predominantly freshwater bodies (Close 1990). Sturt (1833) reported that there were freshwater reeds and rushes along the shore of Lake Alexandrina as far as the eye could see; freshwater mussels and other freshwater molluscs occupied the Lakes over thousands of years; and no mangroves were present in the Lakes.

The Mouth of the River Murray is flanked by the double reversed spits of Sir Richard and Younghusband Peninsulas (Fig. 2.3.1). These are Holocene coastal barriers, which, apart from the narrow Mouth opening, separate the Murray Estuary from the sea (see Chapter 2.2). The general location of the Mouth is an equilibrium response to opposing directions of sediment drift along Sir Richard and Younghusband Peninsulas. The arc-shaped character of the Encounter Bay coastline causes south-westerly open ocean swell waves to strike the coastline at opposed angles, causing drift to the east along Sir Richard Peninsula and to the north-west on Younghusband Peninsula, merging near the Murray Mouth (Johnston 1917; Bourman & Murray-Wallace 1991). The Murray Mouth is extremely dynamic, responding to episodic changes in river flow and wave, tide and storm conditions, which cause variations in Mouth location and size over time. The complete blockage of the Murray Mouth in 1981 (Bourman & Harvey 1983) triggered a management response, which was complicated by a confusing array of overlapping State Government management jurisdictions (Harvey 1988). Since then there has been a recognition of a broader responsibility by the Murray-Darling Basin Authority,

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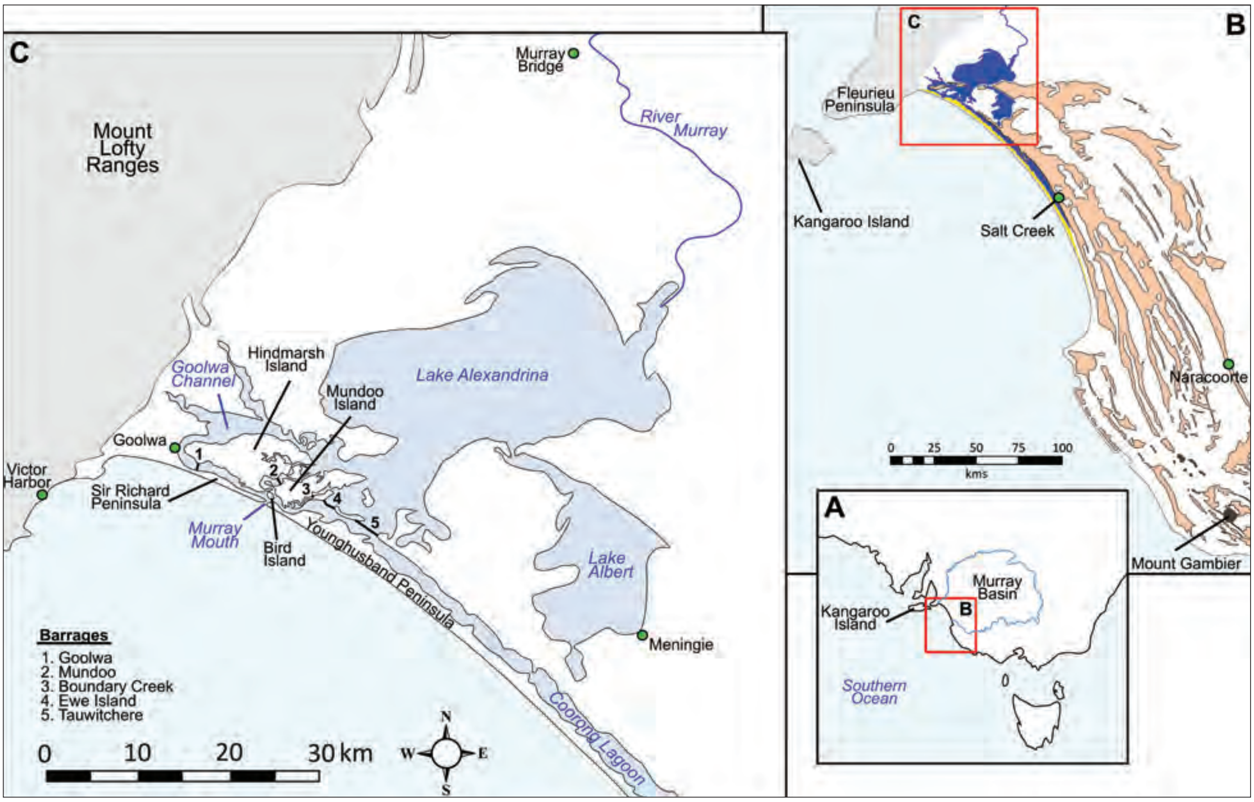

Figure 2.3.1 Location of the Murray Mouth.

which has contributed funding for two major dredging operations at the Mouth, the latest being active in 2018 at the time of writing. It is widely recognised that dredging is not a long-term solution. The problems at the Mouth have been likened to a canary in the cage, indicating a need for a 'whole of basin' approach (James et al. 2015).

WHY IS THERE NO FLUVIAL DELTA AT THE MOUTH OF THE RIVER MURRAY?

Despite the fact that the Murray-Darling river system is the largest Australian river discharging into the sea, there is no classic river delta at its outlet (Murray-Wallace et al. 2010). Many factors have played roles in limiting the amount of terrigenous-clastic (terrestrial) sediment reaching the settling basins of the terminal Lakes Alexandrina and Albert, where the River has produced only a small digitate delta downstream of Wellington. For example:

1. Regional aridity yields a relatively low discharge. Furthermore, the basin was subjected to an increasing intensity of aridity during successive glacial cycles associated with the northward movement of the Australian continent (Fujioka & Chappell 2010). The discharge of the River Murray is only 16% of that of the River Nile, 3.5% of the Mississippi and 0.24% of the Amazon, with one day's flow of the Amazon equalling the annual discharge of the Murray (Eastburn 1990).
2. The low topographic relief of the basin has resulted in very slow rates of continental denudation, a very low-gradient stream system and reduced sediment supply to the lower basin. For example, the river only falls about 3 m between Blanchetown and the sea in a river distance of 274 km.

3. River loads are mainly carried in suspension and solution. Coarse sediment is primarily deposited within the River valley as point bars and in abandoned channels, while sediments reaching the Lakes are predominantly fine-grained muds (Johnston 1917; Thoms & Walker 1992, 1993). Today, with numerous dams and weirs, even less coarse sediment reaches the Lakes.
4. Finally, any sediment reaching the coast is rapidly dispersed in a high-energy beach setting, which promotes longshore and offshore sediment transport.

Neither Matthew Flinders nor Nicholas Baudin mapped the Mouth of the River Murray during their meeting in Encounter Bay in 1802, a fact that is sometimes cited as evidence for there not being a marine opening for the River under natural conditions. However, it is not remarkable that the Mouth was not identified, as Flinders and Baudin were many kilometres away from a low-lying shoreline backed by higher country, and there was no large discharge of freshwater and sediment from the River, and no sign of a delta. Fornasiero et al. (2010) noted Flinders's earlier failures to chart the outlets of the Brisbane River in Queensland and the Clarence River in New South Wales, emphasising the difficulties of recognising river mouths from the sea.

The fact that Sturt was unable to sail out of the Murray Mouth in 1830 has also been cited as evidence for mouth closure. However, it was sand shoals in the Goolwa Channel that thwarted Sturt, not mouth closure, as indicated by this extract from Grenfell Price (1928, p. 48):

> The next day, 12th February, Sturt, McLeay and Fraser again crossed the sand-hills and followed the ocean beach for some seven miles until they were stopped by the entrance of the river to the sea.

They reported that the water was deep and the current strong under what became known as Barkers Knoll on the eastern side of the Mouth, indicating that the Mouth was open. When Sturt revisited the site in 1836, the River had created a wide mouth. Barkers Knoll is the highest and widest part of the Younghusband Peninsula barrier, a dune area that has been in place for the past 5 000 years (Harvey et al. 2006).

PROCESSES OPERATING AT THE MOUTH

Processes impacting the detailed position and character of the Mouth include river flows, tides, swell and storm waves, storm surges and aeolian sand drift. The most important processes operating at the Mouth relate to river flow. Tidal flux alone can maintain the Mouth for some periods of time (Johnston 1917), but without river flows the Mouth would eventually become clogged with coastal sediments delivered by flood tides and waves to form a continuous coastal barrier. River flows during the mid-Holocene (6 000 to 4 000 years ago) were greater than today, and relative sea level was probably 1 m higher than now. Consequently, at that time, the Mouth was much larger and migrated over a range of up to 6 km, compared with the 2 km of modern times.

Under pre-European conditions the Mouth was river-dominated (Walker 2002; Shuttleworth et al. 2005), an outcome of fluvial breaching. The largest recorded flood in the River Murray in South Australia is that of 1956, a flood of 341 000 megalitres a day (ML day^{-1}), with a return interval of 170 years and a stage height of 1.43 m at the Mouth. The next-largest event was that in 1870, estimated at 319 000 ML day^{-1}. However, there is evidence of larger palaeo-floods occurring in the River Murray (Snowball et al. 2006). For example, a flood peak at ~3 000 yr BP, established from fluvial sediments interfingering with Aboriginal occupation layers, probably exceeded the discharge of the 1956 flood (Mulvaney et al. 1964). In addition, Snowball et al. (2006) identified several other palaeo-floods over the past 2 500 years of similar dimensions to the 1956 flood, a finding based on stranded logs of red gum (*Eucalyptus camaldulensis*). Furthermore, they recognised a megaflood with twice the discharge of the 1956 flood (possibly the flood of 1 000 years), using the flood peak germination line of black box (*Eucalyptus largiflorens*), for which they established a date of c.1760 AD. During these events the Mouth would have been substantially cleared. However, today, due to human interference, the Mouth has become a micro-tidal, high-wave-energy environment producing a wave- and tidally dominated inlet with a large flood tidal delta but no associated ebb tidal delta.

Sprigg (1952) acknowledged the operation of northerly longshore transport along the coastline of Southeast Australia but considered that the volumes of material involved are not great. He concluded that most beach sand on this section of coast has a local origin derived from recent shell banks and erosion of pre-existing aeolianite (dune limestone), with increases in silica content near the Murray Mouth reflecting inputs of terrestrial sand from the River. Swell waves with a periodicity of 14 to 16 seconds, but predominantly storm waves (periodicity of 6-8 seconds), transport sediment along Sir Richard Peninsula towards the mouth (Bourman et al. 2000), a drift direction supported by the analysis of onshore winds >28.8 km hr^{-1}, which are effective in generating longshore transport; the resultant of these winds is from 227° (see Fig. 2.3.5) (Bourman & Murray-Wallace 1991). If it were not for this easterly drift along Sir Richard Peninsula, the River Murray would flow out to sea just upstream of the Goolwa Barrage.

Tides along the Encounter Bay coastline are micro-tidal; mean spring high tides vary from 0.8 m at Victor Harbor to 1.2 m at Kingston (Short & Hesp 1982). Storm surges associated with strong onshore winds and low atmospheric pressure may raise tides by up to 1.5 m above predicted levels (Bourman & Harvey 1983; Haslett 2009) and help to clear the Mouth. During the 1981 closure of the Mouth, a storm surge cut a channel across the extremity of Younghusband Peninsula (Fig. 2.3.2), but it rapidly in-filled. The tidal range inside the Murray Mouth is attenuated: a difference of 0.55 m was recorded between the spring tidal range at Victor Harbor and in the estuary (Johnston 1917), with extreme storm-enhanced tidal ranges of 2.18 m for Victor Harbor and 1.30 m for the estuary (Radok & Stefanson 1975). Generally, ebb tidal flows are insufficient to clear the marine-derived sands from the back-barrier lagoon; river flows are essential for this purpose.

There is a persistent moderate- to high-energy wave climate at the Mouth, resulting in considerable deposition of flood tidal delta sediments inside the Mouth (Short & Hesp 1982). Waves 5 to 6 m high, breaking in water 10 m deep, were occasionally observed at the Mouth by Johnston (1917, p. 17), while Short and Hesp (1982) noted that the steep offshore gradient results in only a 20% loss in wave power. These high-energy wave conditions result in the rapid dispersal of any fluvial or ebb tidal sediments, partly explaining the absence of a delta and the formation of offshore bars, which cause lines of breakers offshore from the Mouth and which have proved hazardous for vessels negotiating the Mouth.

Aeolian processes are also important on this exposed coast, with the resultants of winds capable of moving sand trending from the south-west and near normal to the coastline (Bourman 1986). At times strong westerly winds drive sand along the beach towards the Mouth. On 25 March 1984, strong westerly winds with speeds of up to 45 km hr^{-1}, coinciding with low

Figure 2.3.2 A temporary channel cut through the northern end of Younghusband Peninsula by a storm surge during mouth closure in 1981. (Photograph by R.P. Bourman)

tide, generated ephemeral transverse sand ridges with wavelengths of 20 m and heights of 30 cm (Fig. 2.3.3). Some 5 000 m^3 of beach sediments were in transit along the 10 km long sand spit towards the Mouth into which the sand was blowing (Bourman 1986). The dynamic character of the Murray Mouth area is illustrated by the fact that on the day after the ephemeral sand ridges were forming, high water, strong winds and storm waves strongly eroded the beach and the distal end of the spit near the Murray Mouth (Bourman 1986) (Fig. 2.3.4), cutting back the shoreline by 14 m. Paradoxically, the landward side of Sir Richard Peninsula may also be eroded by high-energy waves passing through the Murray Mouth as they reflect back from the southern shore of Hindmarsh Island (Bourman & Barnett 1995). The River also eroded the landward side of the spit following the artificial opening of the Mouth in 1981 (Bourman & Harvey 1983), after which the Mouth migrated to the west (Harvey 1996).

FORMER MOUTH POSITIONS

Pre-European changes

Various former Mouth positions have been postulated. During the Last Interglacial there was a major outlet to the sea near the Goolwa Barrage, with another possible former outlet at the south-eastern extremity of Lake Albert. Other former possible positions within the Holocene include Goolwa Beach, opposite Swan Point and opposite the south shore of Mundoo Island. These interpretations are based on the distribution of Aboriginal middens on Sir Richard Peninsula, dunes along the south shore of Hindmarsh Island, which formed as the

Figure 2.3.3 Ephemeral transverse sand ridges on Sir Richard Peninsula during sand transport towards the Murray Mouth on 25 March 1984. (Photograph by R.P. Bourman)

Figure 2.3.4 The dunes near the mouth on Sir Richard Peninsula were steeply cliffed and eroded landward 14 m in 24 hours on the following day, 26 March 1984. (Photograph by R.P. Bourman)

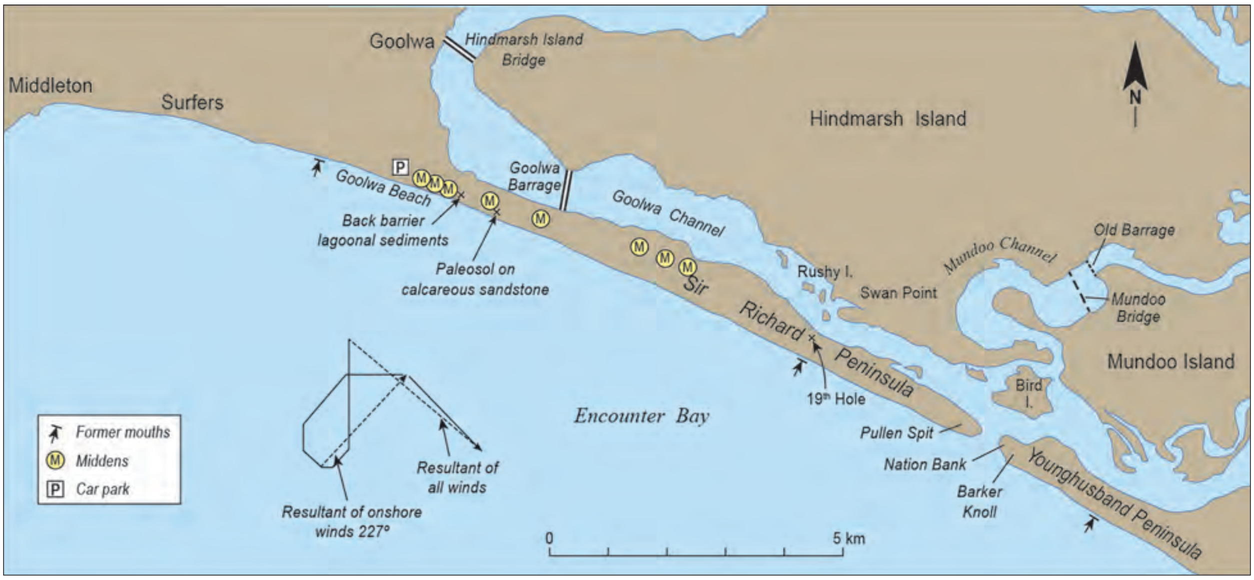

Figure 2.3.5 Murray Mouth area showing postulated former mouth positions indicated by arrows opposite Swan Point and the southern shore of Mundoo Island. Extreme points of Holocene migration indicated by abandoned flood tidal deltas opposite the south shore of Mundoo Island (Mulloway Point) and Swan Point on Hindmarsh Island. The absence of Aboriginal middens (M) on the eastern half of Sir Richard Peninsula suggests reformation of the eastern end of the peninsula after earlier mouth migration to the west. The resultant of onshore winds >28.8 km hr^{1} supports the notion of longshore drift along Sir Richard Peninsula towards the Mouth. (From Bourman et al. 2016)

Mouth migrated, and the presence of abandoned flood tidal deltas in the back-barrier lagoons (Fig. 2.3.5). These lines of evidence indicate migration of the Mouth over 6 km during the past 3 000 years (Bourman & Murray-Wallace 1991). Subsequent work has shown that the outlet opposite Mundoo Island most likely existed more than 5 000 years ago (Harvey et al. 2006).

Post-European changes

The position of the Murray Mouth is constantly changing and has migrated over about 2 km since it was first surveyed in 1837, with some very rapid migrations occurring (James 2004b). For example, Harvey (1996) calculated retreat of the distal end of Sir Richard Peninsula at an average rate of 80 m a year between 1981 and 1995.

James (2004b) examined eight historical surveys of the Murray Mouth for the period 1839 to 1938, revealing great variability in the positions and conditions of the Mouth prior to the installation of the barrage system across the lower River Murray channels. Over this time it was demonstrated that the Mouth had migrated about 1 km to the south-east, followed by a migration back to the west, to almost the same position it had been in at the time of the original survey. Thomson (1975) mapped the migrations of the Murray Mouth between 1839 and 1967 (Figs. 2.3.6a, 2.3.6b). Although there may be some cartographic issues of lack of precision, it is of note that the size of the Murray Mouth has reduced over this time, reflecting a diminution in river flows.

Chappell (1991) used meteorological data and wave-energy hind-casting to demonstrate an average net potential littoral drift of sediment of 260 000 m^3 yr^{-1} at the Mouth between 1940

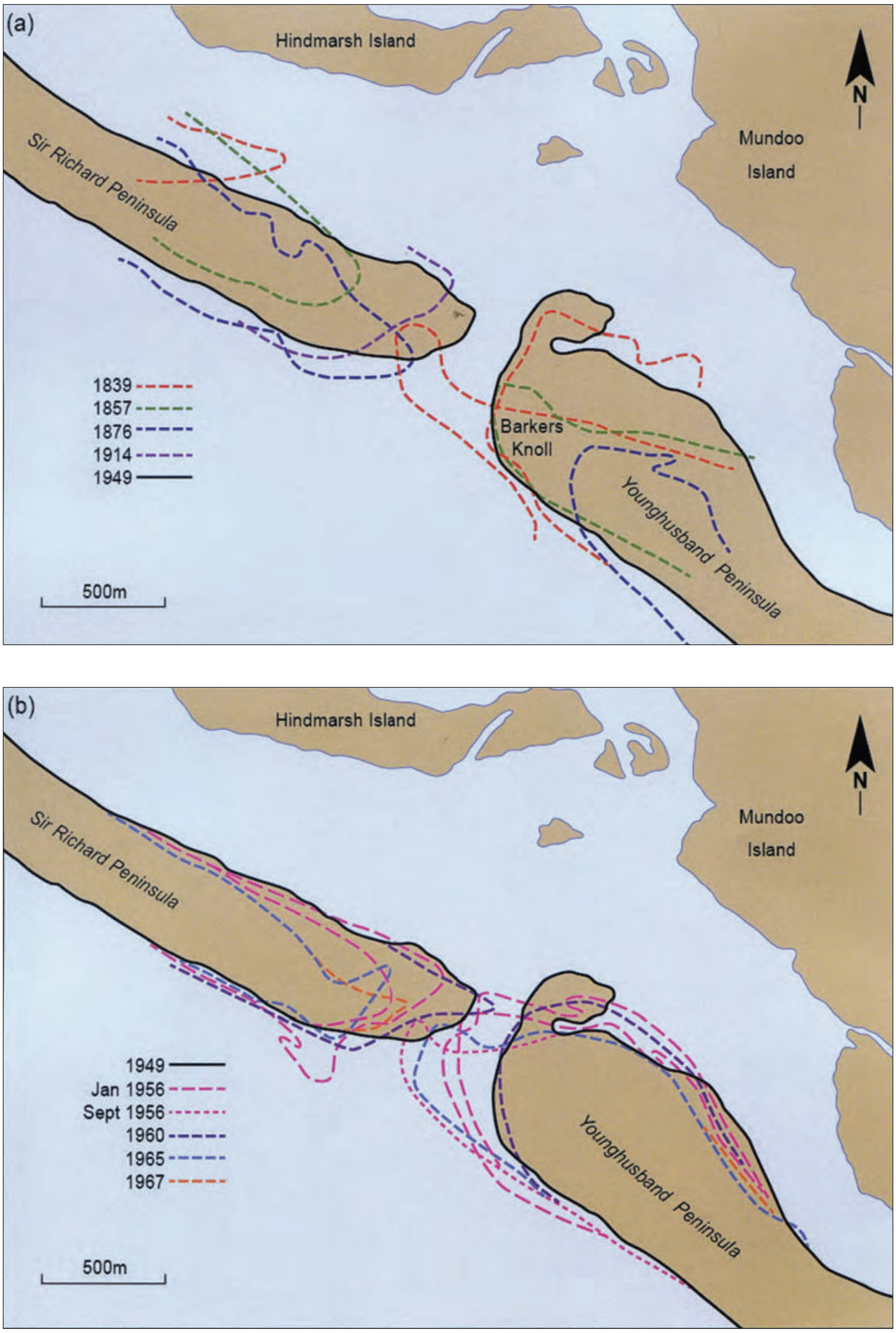

Figure 2.3.6 (a) Former Mouth positions over the period 1839 to 1949; (b) former Mouth positions over the period 1949 to 1967. (Reproduced with permission from Thomson 1975)

and 1990. Major directional shifts in potential sand movement were reported, which broadly coincide with the directions of Mouth migration (Harvey & Chappell 1994). For example, between 1940 and 1950 the movement was predominantly to the west, between 1951 and 1968 predominantly to the east, and between 1969 and 1989 predominantly to the west. Although Mouth migration may be influenced in the short term by high river flows, it is mainly related to wave-generated littoral drift (Botting & Associates 1990). Longshore sand transport provided the beach sediments responsible for the development of Bird Island and blockages of the Mouth. For 1941 and 1942, a potential westerly movement of over 1 000 000 m^3 was calculated. This annual volume of sand movement matches the dredging rates undertaken to clear the Murray Mouth during the Millennium Drought (James et al. 2015).

MOUTH CLOSURES AND THE GROWTH OF BIRD ISLAND

In its original condition there is evidence for only one prolonged closure of the Mouth over the 5 000 years before the arrival of Europeans. The absence of marine microfossils in cores in the lower Goolwa Channel immediately upstream of the Goolwa barrage ~3 500 years ago suggests that the Mouth was restricted or closed at this time, not allowing movement of sediment from the continental shelf into the Estuary (Cann et al. 2000). The closure of the Mouth was attributed to the onset of arid climatic conditions and reduced river flows.

There have been anecdotal accounts of Mouth closure or near-closure in 1914, 1930 and 1938 (James 2004b), when fishermen cut a channel to allow fish migration. However, James (2004b) concluded that over the 100-year period of Mouth surveys between 1839 and 1938, the Mouth had never permanently closed. A condition of partial closure occurred in 1974 when it was possible to drive onto the broad sandflat of Bird Island from Sir Richard Peninsula, but an open channel to the Coorong remained (Fig. 2.3.7). One of the early indicators of potential closure is the formation of recurved spits or sand hooks extending into the back-barrier lagoons from the extremities of the Peninsulas as shown in Fig. 2.3.8, which illustrates the complete blockage of the Mouth in 1981. These hooks develop because of the dominance of marine over fluvial processes, but are truncated when there is strong river flow.

Figure 2.3.7 Oblique aerial photo of the Murray Mouth in April 1974 showing the link between Sir Richard Peninsula and Bird Island. Note the dune extending across the Island backing the frontal sandflat. Note that the narrow Peninsula on Hindmarsh Island immediately inland from Bird Island with dunes and samphire had previously formed as a flood tidal delta under natural conditions. (Photograph by R.P. Bourman)

Figure 2.3.8 The Murray Mouth at the time of the blockage of the Mouth in 1981. (Reproduced with permission from Mapland, Department of Environment, Water and Natural Resources, Adelaide)

Restricted river flows resulted in less dynamism inside the Mouth, which fostered dune development on the flood tidal delta, and by 1945 a dune trapped by a small patch of vegetation had established, becoming the core of an incipient island, which survived the passage of the highest recorded River Murray flood of 1956, with a stage height of 1.43 m at the Mouth. The circular central dune formed because it was surrounded by sandflat, so that, whatever the wind direction, there was a sand source. Its base was also trimmed by high water. The evolution of Bird Island was established using aerial photography from 1945 onwards (Fig. 2.3.9) (James 2004a; James et al. 2015), revealing an intimate association between landforms, vegetation and increasing permanence of the Island. Samphire marsh colonised the area landward of the central dune, depriving the central dune of a sand source from the north, and two wing dunes (2M) grew from the central dune. The southern limit of the marsh provided a template for the development of the next dune (3D), which extended across the Island by trapping sand driven from the south (See Fig. 2.3.7). Initially this dune linked to the central dune, but it was breached by high water, isolating the eastern extremity of the 3D dune, in front of which marsh established (4 M). Following this, the truncated 3D dune extended eastward to form dune 4D.

Saltmarsh 5M is higher than the other saltmarshes. The sandflat it occupies was initially colonised by small patches of sea rocket and samphire, which trapped sand as shadow dunes; these sand accumulations were flattened and the trapping vegetation destroyed by high tides, but the outcome was an increased elevation of the sandflat. This process happened several times, increasing the height of the sandflat, which became covered by stabilising samphire vegetation, the south-western limit of which determined the location of the next dune.

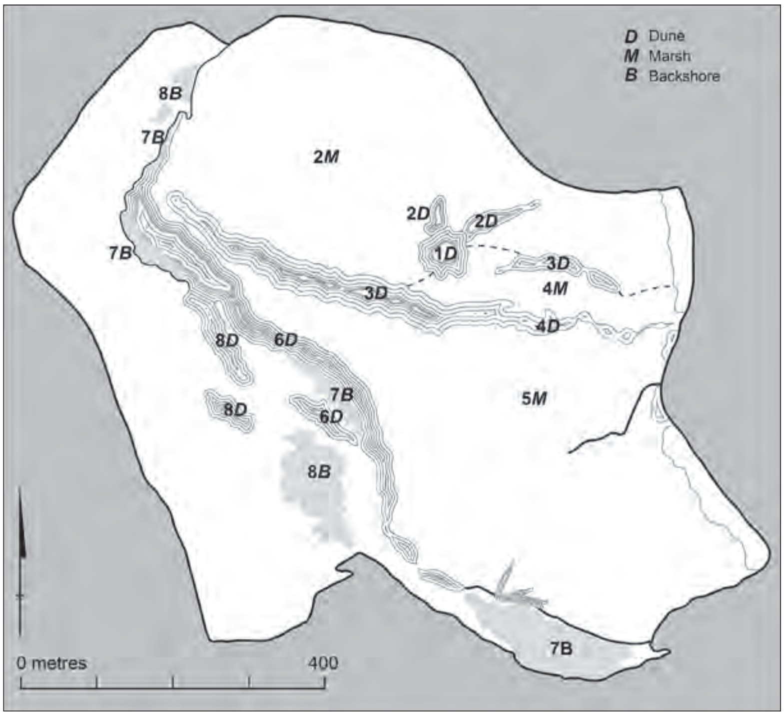

Figure 2.3.9 Map of Bird Island showing dunes (contours), sandflats and saltmarsh (blank), recent samphire colonisation (hashed areas) and tidal channels. The numbers refer to evolutionary stages in the Island's formation (1 to 8) from 1945 to present, with the central dune (1D) marking the initiation of the island. Contour interval 0.2 m. (Map by K.F. James, R.P. Bourman and N. Harvey)

As the Island was developing, the Murray Mouth was migrating to the west, changing the location of the sand source that was derived from the coast via the Mouth. This resulted in the clockwise establishment of dunes on the expanding Island. As each dune was isolated from its sand source and was vegetated, it became frozen in time, archiving the evolution of the Island. The southern side of the central dune is 5 m high and the other dunes extend up to about 3 m, but all of the dunes decrease in elevation toward the east as they were further removed from the sand source during mouth migration.

Today Bird Island, which has been colonised by some 80 species of plants (James et al. 2015), is very stable; it restricts water flow and is protected from the sea by Younghusband Peninsula and from the River by Mundoo Barrage. The migration of the Mouth to the west limited the impact of waves passing through the Mouth on the Island. Furthermore, flow through the Mundoo Barrage over the past 70 years has been minimal. Originally the Mundoo Channel delivered about 10% of the River's flow through the most direct path to the sea, but the Mundoo Barrage was rarely opened because it also acted as a bridge and was cumbersome to operate (Bourman & Barnett 1995). More recently a few gates on the barrage have been automated, but this will do little to remove the sediments accumulated over decades of restricted flows through the barrage. A Senate Committee recommended removal of Bird I. to improve flow through the Mouth, but unless there is an allocated freshwater flow sufficient to clear the Mouth regularly, the flood tidal delta will reform and the ocean coast will erode as waves and tides push coastal sand through the Mouth, potentially causing more problems.

MANAGEMENT OF THE MURRAY MOUTH

The management response to the complete blockage of the Mouth in 1981 was complex for a number of reasons. As noted by Harvey (1988) the closure of the Mouth primarily affected the activities of five State Government departments and also had the potential to involve the then River Murray Commission, which included the Commonwealth government plus three State Governments (NSW, Victoria and SA). Initially there was confusion over what the management response should be, because jurisdictions of the State Government departments overlapped and uncertainty existed whether the main issue related to blockage of river flow, navigation, impact on the Coorong fishery or potential flooding (Harvey 1988).

The then River Murray Commission (now the Murray-Darling Basin Authority) was responsible for the quantity and quality of river flow under the River Murray Waters Agreement 1982, but needed to be convinced that the blockage of the Mouth was attributable to construction, maintenance, operation or control of any works under Clause 34 of that agreement (Harvey 1988). In any event the Commission at that time considered that its responsibility stopped at the artificial barrages, thus essentially ignoring responsibility for the current (post-barrage construction) Estuary and River Mouth.

Although the *Water Resources Act 1976* (SA) (amended 1983) was largely aimed at conserving water, rather than unblocking the Mouth and releasing water, it was finally decided that the water authority, the then Engineering and Water Supply Department (E&WS), should assume responsibility for the Mouth (Harvey 1988). Subsequently, the Mouth was artificially opened in July 1981 and strong flows maintained the opening, which increased to a width of 150 m and a depth of 7 m with a total of over 7 ML flowing out to sea up to December of the same year (Harvey 1988).

Following the opening of the Mouth in 1981 it migrated in a north-westerly direction. In 1995 it was calculated that Sir Richard Peninsula had eroded 'at an average rate of 80 m yr^{-1} with an estimated loss of 45 ha of vegetated dunes and ~3 million m^3 of sediment since the Mouth was artificially opened in 1981' (Harvey 1996, p. 55). Initially, water flow along the Goolwa Channel rapidly eroded the landward, distal end of the Peninsula, but then marine processes took over, with strong wave action operating from the south-east. In about 1992 part of Scab Channel, which flows around the western side of Bird Island and at times is an important flow route for the River, filled in (Bourman & Barnett 1995). This north-westward migration of the Mouth was the continuation of a trend starting in 1972 (Harvey 1996). For the previous 27 years the position of the Mouth was east of its relative 1945 position (Figs. 2.3.10a, 2.3.10b). More recently, readily accessible Google satellite imagery depicts an easterly movement of the Mouth from 6 December 2003 to the present.

It is desirable to maintain an opening to the sea for flood control purposes as well as for the evacuation of accumulated salts, nutrients and heavy metals and the dispersal of algal blooms. Harvey (1988) considered various management options if the Mouth should close again. These included using fresh water stored in the Lakes to clear the Mouth when necessary; dredging the Mouth to improve tidal flow; providing temporary groynes to restrict sand carried into the Mouth by tides; installing drift fencing on Younghusband Peninsula; and controlling off-road recreational vehicles. It was noted that an outflow of 20 000 ML per day for one month

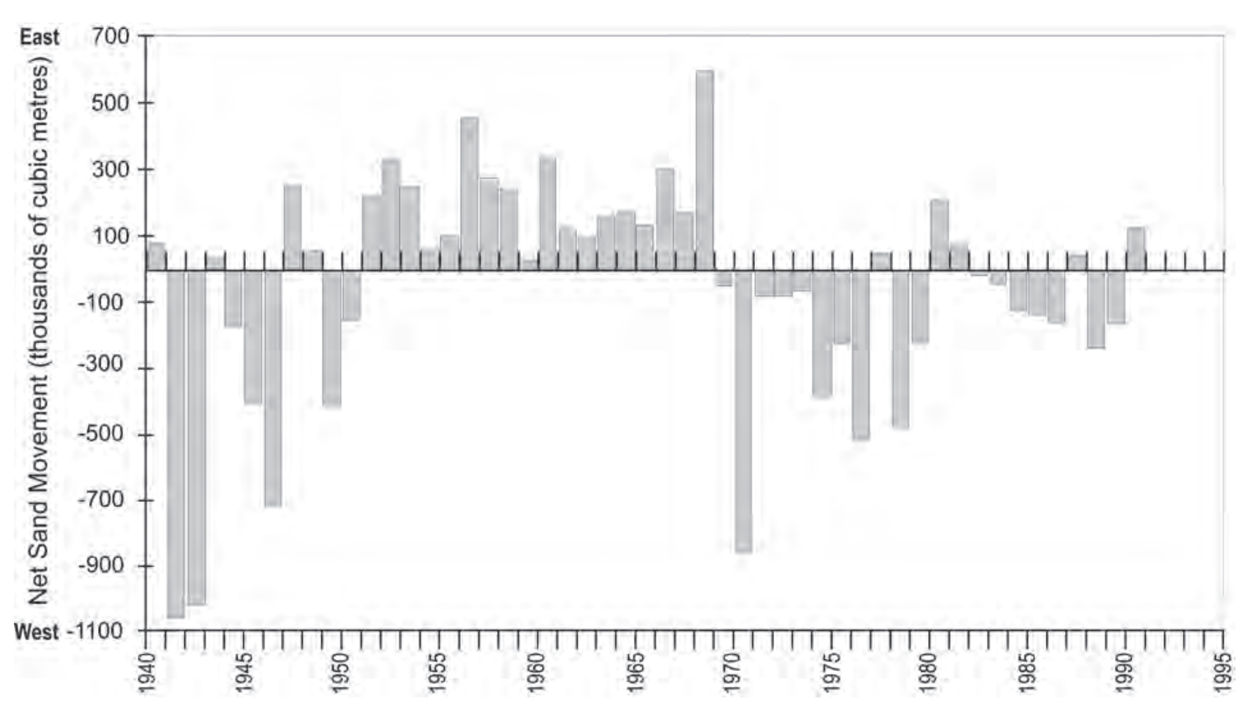

Figure 2.3.10a Net potential sand movement in easterly or westerly direction in vicinity of Murray Mouth. Positive values indicate drift to the east, negative values to the west. (Modified from Chappell 1991)

Figure 2.3.10b Cumulative movement of the Murray Mouth in a westerly or easterly direction relative to its 1945 position. (Modified from Harvey 1996)

or more clears a severely restricted Mouth. Ideally, the timing of these strategies should be adjusted to facilitate fish recruitment and water quality issues.

Dredging of the Mouth

After initial failure, the first substantial historical closure of the Mouth in 1981 naturally cleared after a channel was dug, but the Mouth threatened to close several times in the ensuing two decades, such as in March and June 1983. In December 1998 mechanical diggers were used to excavate a channel to allow access of fresh oxygenated sea water to the Coorong. At the beginning of the Millennium Drought in March 2002 the Mouth was threatening to close, and in October 2002 conditions were so bad that dredging was undertaken to clear the Mouth and improve lagoon water quality. Shuttleworth et al. (2005) estimated the rate of lagoon infilling to be of the order of 100 000 m^3 y^{-1} between June 2000 and May 2003, a rate compatible with estimated rates of longshore transport (James et al. 2015). Spoil from dredging was dumped on the ocean beach either side of the Murray Mouth (Fig. 2.3.11), to be later reincorporated into the coastal sediments.

Dredging ceased in December 2010 when substantial river flows cleared the Mouth, highlighting the necessity of river flows for Mouth maintenance. During the eight-year dredging program, >6 million m^3 of sand were pumped, at a cost exceeding A$30 million (James et al. 2015). Under the Murray-Darling Basin Plan a key objective is to maintain an open River Mouth. This plan aims to keep the Mouth open without the need for dredging 95% of the time under the 3 200 GL water resource recovery scenario, which is expected to be achieved by 2019.

Figure 2.3.11 Murray Mouth in December 2004 (from Google Earth image, 18 December 2004). Dark spoil heaps of dredged sediments are visible on the ocean beach either side of the Murray Mouth. (From Google Earth image. Image copyright 2018 Digital globe, copyright 2018 Google)

Reduced river flows resulted in the reinstatement of dredging after there was a risk of Mouth closure during the summer of 2014/15. In response, the Murray-Darling Basin Ministerial Council agreed in 2014 to provide A$4 million for another dredging program. Dredging operations at the Murray Mouth began on 9 January 2015 to maintain connectivity (exchange of water) between the Coorong and the Southern Ocean, with dredges operating in the Tauwitchere and Goolwa Channels. A flow report issued on 2 March 2018 noted that two dredges were operating continually in the Goolwa and Tauwitchere channels and that as at 25 February 2018 a total of 2 700 925 m^3 of sand had been removed (Department for Environment and Water 2018).[7]

Some of the outcomes of mathematical modelling of the Mouth (Walker 1990; Elford et al. 1999; Frick et al. 1996a, b) show that the Mouth size is strongly dependent on monthly river flows, that the effects of river flow on Mouth size reflect the barrage being used in any month, that the impacts of river flow on the Mouth are delayed by one or two months, and that it is possible to control the Mouth size by flow controls under a variety of wind and tide conditions. Some of the barrage openings have now been automated and the automation of all would allow a more finely tuned system of operation that would benefit the environment and the Mouth. For example, suitable barrages could be opened at appropriate times and at appropriate water levels, in order to allow fish migration and to have maximum impacts on the Mouth.

The management of barrage openings is critical in terms of the frequency of openings, the timing and volume of water released as well as the interaction between tides relative to Lake pool level and episodes of openings or extended closures. This was illustrated by Harvey (1996), who noted an association between an extensive period of barrage closure during 1982-1983, low maximum monthly sea tides (Fig. 2.3.12a) and increased sedimentation within the Mouth. Another period of barrage closure in 1994-1995 (Fig. 2.3.12b) was associated with increased sedimentation, which prompted the SA Minister for Environment and Natural Resources to examine the possibility for artificially opening the Mouth in 1995 (Harvey 1996).

Many calls have been made to remove the barrage system, with arguments that the Lakes were originally occupied by sea water (Marohasy 2010). However, in pre-European times there is ample evidence that Lakes Alexandrina and Albert were predominantly fresh; conditions were marine in the Coorong and Goolwa Channels; and there was a brackish mixing zone between them, forming a classic estuary (Bourman 2010). Close (1990) considered that for the vast majority of time, under natural conditions, Lakes Alexandrina and Albert were fresher than they are at present. The River Murray is a highly controlled and regulated system, and the best way to manage the Lower Lakes and Murray Mouth is by simulating the natural system as closely as possible. Even though there have been unexpected consequences of barrage construction, the present situation more closely resembles the natural ecosystem in contrast with filling the Lakes with sea water.

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[7] As this publication goes to press, these figures have changed, and over 3 million m^3 of sand have been removed by dredging. For the most up-to-date figures, see https://www.waterconnect.sa.gov.au/Content/Flow%20Reports/DEW/RM-Flow-Report-20180629.pdf.

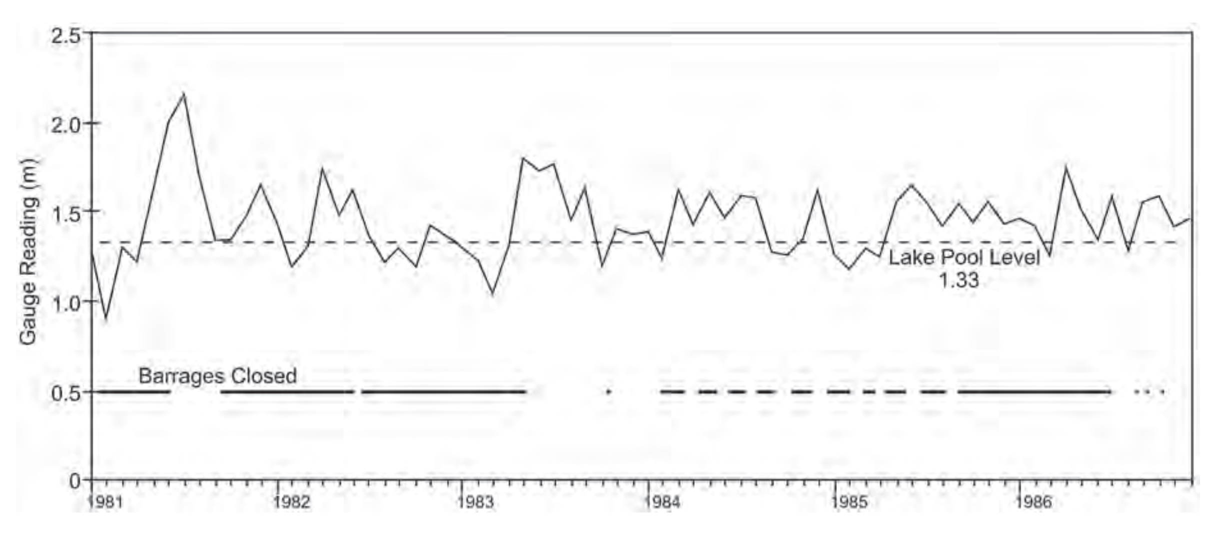

Figure 2.3.12a Maximum monthly sea-tides for Victor Harbor for 1981-1986 showing lake pool level and associated periods of barrage closure. To convert gauge reading to AHD, subtract 0.581. (Adapted from Harvey 1996, based on tidal data from Bill Mitchell, National Tidal Facility, and barrage data from SA Water)

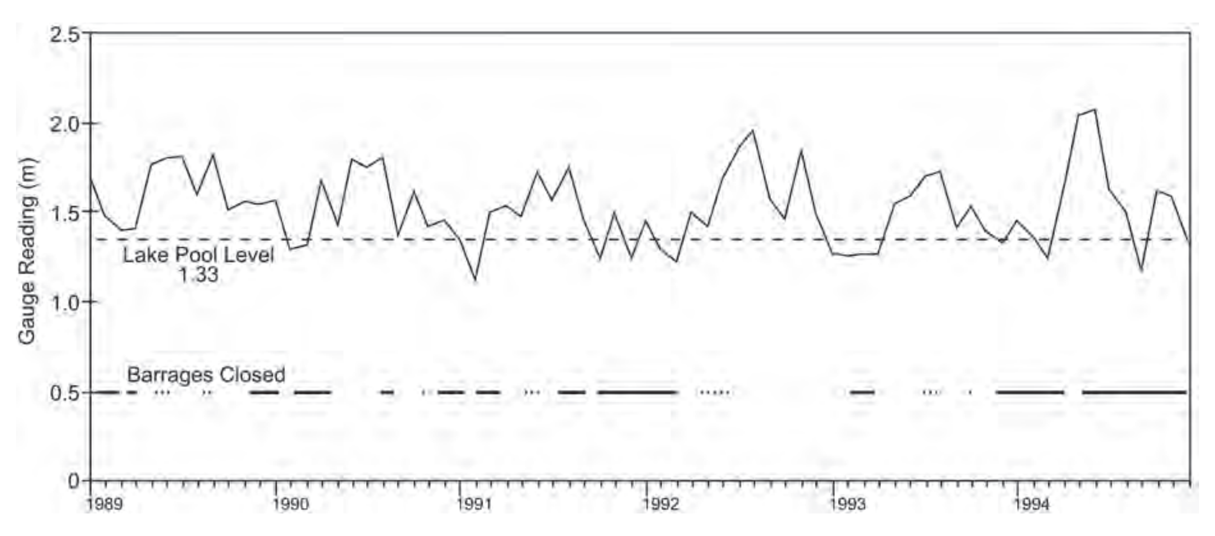

Figure 2.3.12b Maximum monthly sea-tides for Victor Harbor for 1989-1994 showing lake pool level and associated periods of barrage closure. To convert gauge reading to AHD, subtract 0.581. (Adapted from Harvey 1996, based on tidal data from Bill Mitchell, National Tidal Facility, and barrage data from SA Water)

CONCLUSIONS

The Murray Mouth is a very dynamic environment and is in a state of delicate balance between tides, winds, waves, river flows and human impacts. The position of the Mouth between the two Holocene sand barriers of Younghusband Peninsula and Sir Richard Peninsula is predominantly related to the dominant direction of littoral sediment transport, which has been demonstrated to change direction for periods of many decades at a time. Thus the Mouth migrates within a broad envelope of ~2 km. Major River floods can have a short-term influence on the position of the Mouth, such as occurred following the opening of the Mouth in 1981, but generally there is little correlation between river flow and Mouth migration.

Human interference with river flow, however, has had a major impact on the Murray Mouth. Within the broader Murray-Darling basin there have been extensive river regulation, construction of artificial storages, changing patterns of water extraction and use, and an overall reduction in the amount of water reaching the River Mouth. In addition, the Estuary has been modified with the construction of the barrages to store fresh water and prevent sea water from entering the lower Murray and distal lakes. There have been numerous times when these barrages have been completely closed for periods in excess of 100 consecutive days, thereby removing any influence of the River on the Mouth and making it more susceptible to blockage during appropriate tide and wind conditions.

The complete blockage of the Mouth in 1981 provided a symptom of upstream problems in River management and triggered a management response. Initially, the SA Government took the initiative to artificially open the Mouth, but subsequently there has been recognition that the cause of the problem is in part a responsibility of the broader River basin management authority. Consequently, the Murray-Darling Basin Authority funded a major eight-year River Mouth dredging project during the Millennium Drought between 2002 and 2010 and more recently a second dredging project, which started in 2015 and is ongoing at the time of writing. Thus dredging of the Mouth has occurred for ~70% of the past 14 years (2004-2018) in contrast to the stated aim of only 5% in the Murray Basin Plan, contingent on increased flows by 2019.

ACKNOWLEDGEMENTS

We gratefully acknowledge the cooperation and assistance of the Ngarrindjeri Nation in facilitating our research in the Murray Lakes and Coorong areas. Ms Annie Lucas of Hindmarsh Island is thanked for her updates of changes in, and new information about, the Murray Mouth.

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CHAPTER 2.4

PALAEOLIMNOLOGY OF THE LOWER LAKES AND COORONG LAGOON

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INTRODUCTION

Lakes Alexandrina and Albert (known colloquially as the Lower Lakes), the Murray Mouth estuary and the Coorong Lagoon are important cultural and environmental assets that are recognised under the Ramsar Convention on Wetlands of International Importance (Phillips & Muller 2006). Knowledge of the natural hydrological state and behaviour of the Lower Lakes and Coorong prior to colonisation by Europeans is limited.

We present a history of the wetlands using diatoms archived in dated bottom sediments. Diatoms are microscopic algae ubiquitous in aquatic environments; they form siliceous valves that are easily recovered from the sediments of water bodies. The often intricate and complex ornamentation found on their silica valves is easily identified to genus level or lower. The ecology of many taxa is well documented and some species occupy narrow ecological niches and hence they can be useful indicators to infer past water conditions.

NATURAL HYDROLOGY

The main water source for the Lower Lakes is the River Murray. Lake Alexandrina also receives inflows from the eastern Mount Lofty Ranges via the Bremer and Angas Rivers, while the Finniss River and Tookayerta and Currency Creeks flow into the Goolwa Channel (Green & Stewart 2008). Water in Lake Alexandrina transits through six channels; through the Narrung Narrows Channel to Lake Albert, or via Boundary Creek and the Goolwa, Mundoo, Ewe Island and Tauwitcherie Channels through to the Murray Mouth, exiting to the eastern Indian Ocean, or to the south-east into the North Lagoon of the Coorong (Fig. 2.4.1). Maximum water depths are 5 m in the Goolwa Channel, 4.5 m in Lake Alexandrina and 4 m in Lake Albert, although the Lakes have average depths of <3 m and <2 m respectively.

At the northern end of the Coorong, water levels are controlled by tidal inputs to the lagoon through the Murray Mouth, discharges from Lake Alexandrina and wind seiching (DEH 2010). Occasional water discharges from the catchment in the south-east of South

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Australia can reduce salinity levels and raise water levels in the South Lagoon. At peak water volume, average depths in both lagoons are <3 m, while maximum depth is >5 m in the main channel near Salt Creek in the South Lagoon (Fig. 2.4.1).

SALINITY AND GROUNDWATER

Lake Albert is a terminal lake with no throughput to the ocean, and its principal water source is Lake Alexandrina (Phillips & Muller 2006). Salinity is higher in Lake Albert than in Lake Alexandrina (Lamontagne et al. 2004), a condition largely driven by a lack of flushing, evaporation and groundwater influx. During non-drought years, average salinity since 1975 to the present day in Lake Alexandrina was <1 gram per litre (g L^{-1}) and ~1.5 g L^{-1} in Lake Albert (Heneker 2010). Average salinity in the North Lagoon of the Coorong during non-drought years for the same period was between ~20 and 35 g L^{-1} and between ~40 and 100 g L^{-1} in the South Lagoon (DEWNR 2011).

The Lower Lakes and Coorong are discharge zones for local and regional aquifers, although the volume of groundwater inflow is not known. Salinity in the groundwater varies from ~<1 g L^{-1} in the Mount Lofty Ranges aquifers on the western margin of Lake Alexandrina (Green & Stewart 2008) and from ~6 to 35 g L^{-1} in the Murray Limestone, Renmark and surface aquifers to the north and east of both Lakes and the Coorong (MDBC 2000; Haese et al. 2009).

COLONIAL HISTORY

Subsequent to the arrival of Europeans in Australia, water resources in the Murray-Darling basin (MDB) (see Fig. 2.4.1) were harnessed and used ever more intensively for food production, industry, waste disposal and transportation. The seasonality of river flows throughout the basin proved an impediment to agricultural, industrial and population development, and locks and weirs were constructed to ensure reliable passage along the river, as well as to secure water supply to towns and industry (Connell 2007; Quiggin 2001). Marine water incursions to Lake Alexandrina occurred during the Federation Drought (1896-1902) and during a series of drought years a decade later (1911-1916) (Phillips & Muller 2006).

Modifications to the Murray-Darling Basin and south-east catchments of South Australia

These droughts were the impetus to construct a series of barrages across Boundary Creek and Goolwa, Mundoo, Ewe Island and Tauwitcherie Channels inside the Murray Mouth (Fig. 2.4.1) between 1931 and 1940. The barrages prevent marine incursions and maintain water levels in the Lower Lakes at an average of ~0.85 m above sea level when there is sufficient flow from the River Murray, ensuring potable, irrigation and stock water for the enterprises around the Lower Lakes. Upstream development since 1870 has reduced flow into the Lower Lakes, and median annual flow is now 25% of median natural flow (Cann et al. 2000), while the barrages have reduced the area of the tidal prism at the Murray Mouth (Bourman & Barnett 1995; Harvey 1996).

Although groundwater discharge into the River Murray occurred naturally, greater volumes of saline groundwater now enter the River following upstream vegetation clearance and the development and rapid expansion of irrigated agriculture throughout the MDB (MDBC 2000, 2006). Upstream groundwater discharge therefore accounts for some of the increased salinity levels in the Lower Lakes (Allison et al. 1990; Cook et al. 2008).

The south-east catchment of South Australia is an area of dune ridges and swales that developed as a result of sea-level fluctuation over the last ~800 000 years. The suite of wetlands that established in the low-lying swales had few natural outlets to the sea. Coupled with higher elevation to the north-east emanating from uplift around the Mount Gambier volcanic province (Tyler et al. 1983), the dune ridges operated as an effective funnel, directing surface water into the southern Coorong Lagoon, through Salt Creek (DWLBC 2006) (Fig. 2.4.1). The region was extensively modified by drain construction from as early as the 1860s (SEDB 1986). Successive drains were constructed to facilitate transport through the region and maximise agricultural land by diverting surface water to the ocean, effectively severing the northward flow of water into the Coorong.

Increasing consumptive use of water resources in the MDB coupled with drought periodically diminished water discharges at the Murray Mouth and, along with longshore processes, promoted sand accretion inside the Murray Mouth. These processes resulted in complete Mouth closure in the early 1980s, which threatened to occur again as a result of the Millennium Drought (1996-2010, BoM 2015). A series of water releases over the barrages cleared the blockage in 1982, but reduced outflows in the years following the Millennium Drought necessitated the implementation of sand dredging to clear the Mouth channel.

Mouth closure impacts the Coorong by preventing tidal inflows to the lagoon; this was a short-lived consequence in the 1980s, but during the Millennium Drought, closure of the barrages in response to lack of river flows and a reduction in tidal flushing caused salinity levels to increase throughout the lagoon, but particularly in the South Lagoon, where salinity rose to >200 g L^{-1} during summer (Haynes et al. 2011), compared with average seawater salinity of ~35 g^{-1}.

REVEALING THE HISTORY OF THE LOWER LAKES AND COORONG FROM SEDIMENT CORES

Methodology

Core collection

Nine sediment cores were collected in total — three from Lake Alexandrina, two from Lake Albert and four from the Coorong. The core prefixes indicate which water body they were collected from, viz. 'Ax' for Lake Alexandrina, 'Ab' for Lake Albert and 'C' for the Coorong.

Of the three piston cores from Lake Alexandrina (Ax1, Ax3 and Ax9), aspects of two have previously been reported: Ax3 (494 cm long, collected in 1986 from water 3.5 m deep) was used in Barnett (1994) as core 'number 22', and as 'LA2 core' in Fluin et al. 2007, while Ax1 (84 cm long, collected in 1996) is reported in Fluin et al. (2007) as 'LA1 core'. The third Lake Alexandrina core, Ax9 (296 cm long), was extracted in 2002 from water 3.5 m deep (Fig. 2.4.1). Sediment cores were collected from two sites in Lake Albert in 2009 using a Livingstone corer (Ab2 core — 667 cm long and Ab1 — 298 cm long) in water ~40 cm deep (Fig. 2.4.1). The Coorong cores were collected in 2005 with a piston corer — two from the North Lagoon (C3 — 145 cm long in water 1.8 m deep and C7 — 154 cm long in water 1.6 m deep, both

Figure 2.4.1 Location map of the core sites in the Coorong, Lakes Alexandrina and Albert. Also shown are the main towns and places of interest in the region and those mentioned in the text. Inset map: the shaded outline indicates the extent of the Murray-Darling Basin (MDB) with the study site indicated by the square. (Map by D. Haynes)

of which were reported in Fluin et al. 2007), and two from the South Lagoon (C23 — 76 cm long in 1.2 m deep water and C27 — 105 cm long in water 1.7 m deep) (Fig. 2.4.1). Aspects of all four Coorong cores are also reported in Reeves et al. (2015).

Core sampling

The cores were split lengthwise and the sediment properties recorded. Samples for diatom analyses were taken at intervals ranging from fine (0.5-1 cm) at the top of the cores and across sections of special interest (i.e. highly organic sections) to medium (3-5 cm) and coarse (10-40 cm) resolution in the mid- and basal sediments. Sample treatment and slide preparation followed Battarbee et al. (2001). Sub-samples of the digested material were deposited on coverslips, allowed to dry, and mounted on slides using Naphrax mountant. The samples were enumerated to a minimum of 300 diatom valves per sample; diatoms were identified with reference to Krammer and Lange-Bertalot (1986, 1988, 1991a, 1991b) and Witkowski et al. (2001).

Chronologies for the cores were developed using radiocarbon (^{14}C) dating and optically stimulated luminescence (OSL) dating for older sediments and radionuclide, i.e. Lead-210 (^{210}Pb) and/or Caesium-137 (^{137}Cs) dating for younger sediments. The latter method was supplemented by the detection of *Pinus* pollen, an exotic tree species introduced to the Australian landscape following European colonisation. When this marker was detected, it was particularly useful in sediments with low inventories of radionuclides in determining a post-colonisation depositional horizon and sedimentation rates. The ^{14}C in bulk sediment, mollusc shells, macrofossils or pollen contained within a total of 41 samples was measured, while eight samples from cores C3, C7 and C23 were subjected to OSL dating. ^{14}C ages were calibrated to the SHCal04 calibration curve (McCormac et al. 2004) or the Marine04 calibration curve (Hughen et al. 2004) using OxCal v.4.0.5 (Bronk-Ramsey 2010). Sediments <250 years old are expressed in calendar years, e.g. 1860 AD, while older ages are expressed either as an absolute age, e.g. 7 300 years old, or as years before present, 7 300 years BP.

Diatom categories

The diatom species are presented in groups according to their known environmental preferences; the three first-order categories (continental, brackish/euryhaline, estuarine/marine) indicate the dominant waters in which the species reproduce. The facility to reproduce in a particular environment is an important consideration in palaeo-environmental reconstructions. Whether diatom representation in sediments is the result of transportation to the site (i.e. allochthonous components of the assemblage), or whether they indicate in situ growth (i.e. authochthonous), is a critical distinction, particularly in riverine and estuarine environments (Vos & de Wolf 1993).

Continental diatoms in the current context refer to those that live and reproduce in water with salt concentrations of <3 g L^{-1}. The most abundant diatoms in this category are *Aulacoseira* spp. and members of the *Fragilariaceae* family, with the dominant genera in the latter group being *Fragilaria*, *Pseudostaurosira*, *Staurosira* and *Staurosirella*. *Aulacoseira granulata* is the dominant planktonic diatom in the modern River Murray (Bormans & Webster 1999). The estuarine/marine group is made up of those that only reproduce in the marine littoral environment or in estuaries, but not in continental saline settings. The salinity tolerance of diatoms in this group ranges from c.5-35 g L^{-1}; the most abundant genera in this category are *Paralia*, *Grammatophora*, *Cocconeis* and *Campylodiscus*. The diatom species grouped as brackish/euryhaline are perhaps the most difficult to classify and least useful in reconstructing salinity. Some of these species occur in weakly to highly brackish settings as well as in estuaries (e.g. *Campylodiscus echeneis* and *C. clypeus*, *Cocconeis placentula* and *Staurosirella pinnata*); this means that their value, as salinity indicators, is limited unless considered as part of the whole diatom assemblage.

The three second-order categories (planktonic/tychoplanktonic, epiphytic and epipelic) refer to the habitats in which the diatom groups are most commonly found. Planktonic diatoms live in the water column and are held in suspension through the agency of water currents, while the tychoplankton are normally benthic species that are carried in the water column following disturbance of the benthos by mechanisms like tide, wind or waves, particularly in shallow water bodies. Most planktonic/tychoplanktonic diatoms are chain-forming, a structural characteristic that enhances their entrainment in the water column.

Epiphytic diatoms live attached to aquatic plants; they are pennate in shape and have one or two raphes, a structure that allows the cells to move over surfaces. Epipelic diatoms live on or in the bottom sediments of water bodies; these bi-raphid pennates are often motile in response to diurnal and tidal cycles.

PALAEO-ENVIRONMENTAL INTERPRETATION FROM THE SEDIMENTS

Age of the sediments in the Lower Lakes and Coorong

Radiocarbon dating shows that the basal sediments of the cores collected in Lake Alexandrina are 7 600-7 900 years old, while those in Lake Albert are 8 100-c.8 350 years old (Figs. 2.4.3-2.4.6). OSL and radiocarbon dating show that site C3 in the Coorong North Lagoon has basal sediments ~7 200 years old (Fig. 2.4.7), 1 400 years older than those at the base of core C7 (Fig. 2.4.8), while basal sediments of the two cores from the South Lagoon are <1 000 years old (Figs. 2.4.9, 2.4.10).

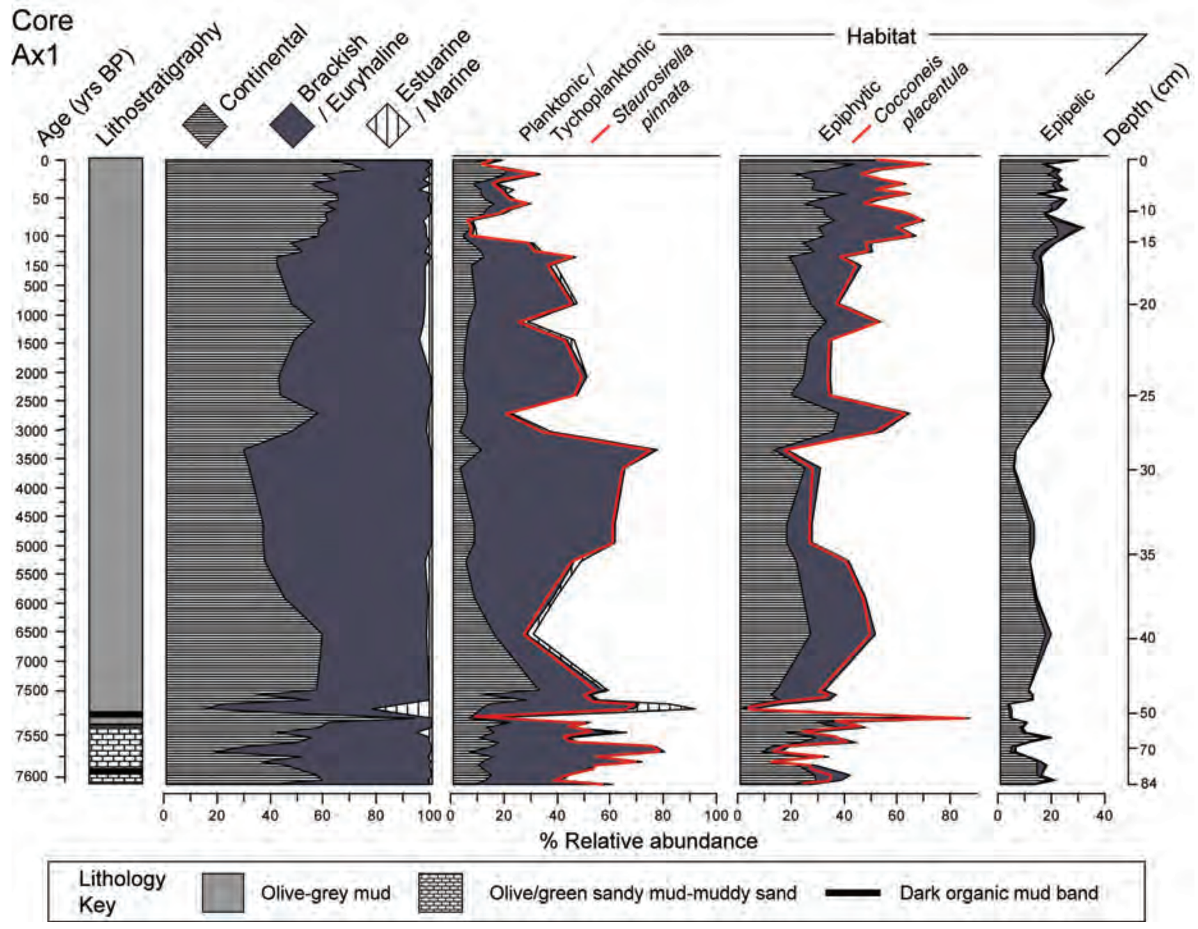

Figure 2.4.2 Lake Alexandrina core Ax1: summary diatom stratigraphy and lithostratigraphy. Shown: the age and depth scales on the y-axes; lithological units of the core; the relative abundances of continental, brackish/euryhaline and estuarine/marine diatoms and their habitat proportions. Maximum abundances of *Staurosirella pinnata* and *Cocconeis placentula* are shown to demonstrate that these species comprise the bulk of the respective habitats. Note the variable age scale. (Data used with permission from J. Fluin)

Taken together with the sediment stratigraphies, the dating results indicate that sediments are missing in several cores. In core Ax9 from central Lake Alexandrina almost 6 800 years' worth of sediments are missing prior to c.1950; in Lake Albert prior to c.1875 almost 4 000 years of sediments are missing at site Ab2 in the northern part of the Lake, and in the centre of the Lake, ~2 000 years of sediments are missing at site Ab1. Prior to 650 years BP, 6 000 years of sedimentation are also absent at site C3 at the northern end of the Coorong.

Sedimentation rates during the Holocene

Annual sedimentation rates during the Holocene ranged from <1 to >3 mm in Lake Alexandrina, <1 to 1.5 mm in Lake Albert, and from 1.6 mm at site C3 to <1 mm at the other sites in the Coorong (Table 2.4.1).

Before colonial manipulation of the Murray-Darling River system and of the catchment in the south-east of the state, sediment delivery to the Lower Lakes and Coorong would have been driven by climate. Sea level reached its present position along the South Australian coastline

Table 2.4.1 Sedimentation rates for cores from Lake Alexandrina, Lake Albert and the Coorong based on the ages returned from ^{14}C, OSL and radionuclide dating.

Location	Core site	Year of Collection (AD)	Basal age (c. years BP)	Sedimentation		
				Depositional Ages	Depositional Period (years)	Sedimentation Rate (mm/year)
Lake Alexandrina	**Ax1**	1996	7 600	7 600-7 500 years BP 7 500 years BP-c.1860 AD c.1860-1996 AD	110 7 362 138	3.6 <0.1 1.3
	Ax9	2002	7 840	7 840-6 880 years BP * sediments missing c.1930-2002 AD	960 -- 72	2.9 -- 2.2
	Ax3	1986	7 900	7 900 years BP-c.1900 AD c.1900-1986 AD	7 814 86	0.6 2.2
Lake Albert	**Ab2**	2009	8 360	8 360-4 200 years BP * sediments missing c.1890-2009 AD	4 160 -- 119	1.5 -- 2.5
	Ab1	2009	8 180	8 180-2 150 years BP * sediments missing c.1800-2009 AD	6 030 -- 209	<0.5 -- 0.8
Coorong North Lagoon	**C3**	2005	7 220	7 220-6 600 years BP * sediments missing c.650 years BP-c.1955 AD c.1955-2005 AD	620 -- 600 50	1.6 -- <0.2 6.0
	C7	2005	5 820	5 820 years BP-c.1955 AD c.1955-2005 AD	5 770 50	0.2 6.8
Coorong South Lagoon	**C23**	2005	860	860 years BP-c.1955 AD c.1955-2005 AD	810 50	0.8 2.8
	C27	2005	600	600 years BP-c.1955 AD c.1955-2005 AD	550 50	0.9 10.8

between 8 000 and 7 500 years ago (Belperio et al. 2002) and continued to rise to maxima of c.0.5-2 m above present levels over the next ~1 000 years, before declining gradually until reaching present-day levels again ~1 000 years BP (Lewis et al. 2013).

Effective precipitation (precipitation/evaporation) was substantially higher between 8 900 and 5 200 years BP than at present in southern Australia (Wilkins et al. 2013). High outflows from the River Murray in association with the development of the Younghusband and Sir Richard Peninsula coastal barriers (Fig. 2.4.1) ~7 000 years ago (Bourman & Murray-Wallace 1991) are likely to have prevented major marine incursions into the Lower Lakes. These processes may account for the comparatively high sedimentation rates at northerly sites in Lake Alexandrina during the mid-Holocene (Table 2.4.1).

The sediment loss from some of the cores (Ax9, Ab2, Ab1 and C3) may be a function of lower water levels, a product of gradually declining sea levels, coupled with the onset of aridity in southern Australia following reductions in effective precipitation after 5 200 years BP (Wilkins et al. 2013). Shallow water bodies are more susceptible to river scouring and wind-induced disturbance of bottom sediments, a process that has been observed in present-day Lake Alexandrina (Skinner et al. 2014). Similarly, in the northern Coorong a shallower system would make the sediments prey to tidal and wind-driven resuspension as well as scouring by outflows from Lake Alexandrina, a scenario that may explain the loss of sediment from site C3.

Post-colonial sedimentation

The accelerated sedimentation rates post-colonisation (see Table 2.4.1, Figs. 2.4.2-2.4.6) can be attributed to land erosion following vegetation clearance throughout the lower catchment, as well as bank erosion in the Lower Lakes due to elevated water levels and more effective sediment trapping following the construction of the barrages (Bourman & Barnett 1995). This increase in inorganic sedimentation may have been accentuated by increases in organic sediment delivery as a result of nutrient enrichment. Using C and N isotopes in short sediment cores representing the last ~120 years in Lake Alexandrina, Herczeg et al. (2001) demonstrated how eutrophication of the water stimulated increased productivity of some algae, bacteria and aquatic macrophytes. The increased biomass subsequently increased the quantity and changed the type of material deposited post-1950.

In the Coorong, the type of sediment and quantities being deposited in the lagoons changed in the mid-20th century. These changes are reflected in the deposition, at exponentially increased rates, of organic rich black muds at the top of all the cores taken from the Coorong after c.1950, material not found in the older sediments (Figs. 2.4.7-2.4.10). Increased anoxic preservation of degraded phytoplankton, i.e. diatoms in the organic matter

BOX 2.4.1 DIATOM ASSEMBLAGES

The complexity of the diatom assemblages found in the wetlands is highlighted by the number of species found in the respective environments: cores from Lakes Alexandrina and Albert contain >340 species, of which 60% are continental (fresh) species, whereas Coorong cores contain >400 species, of which 25% derive from continental water sources and the majority (65%) are from estuarine and marine waters.

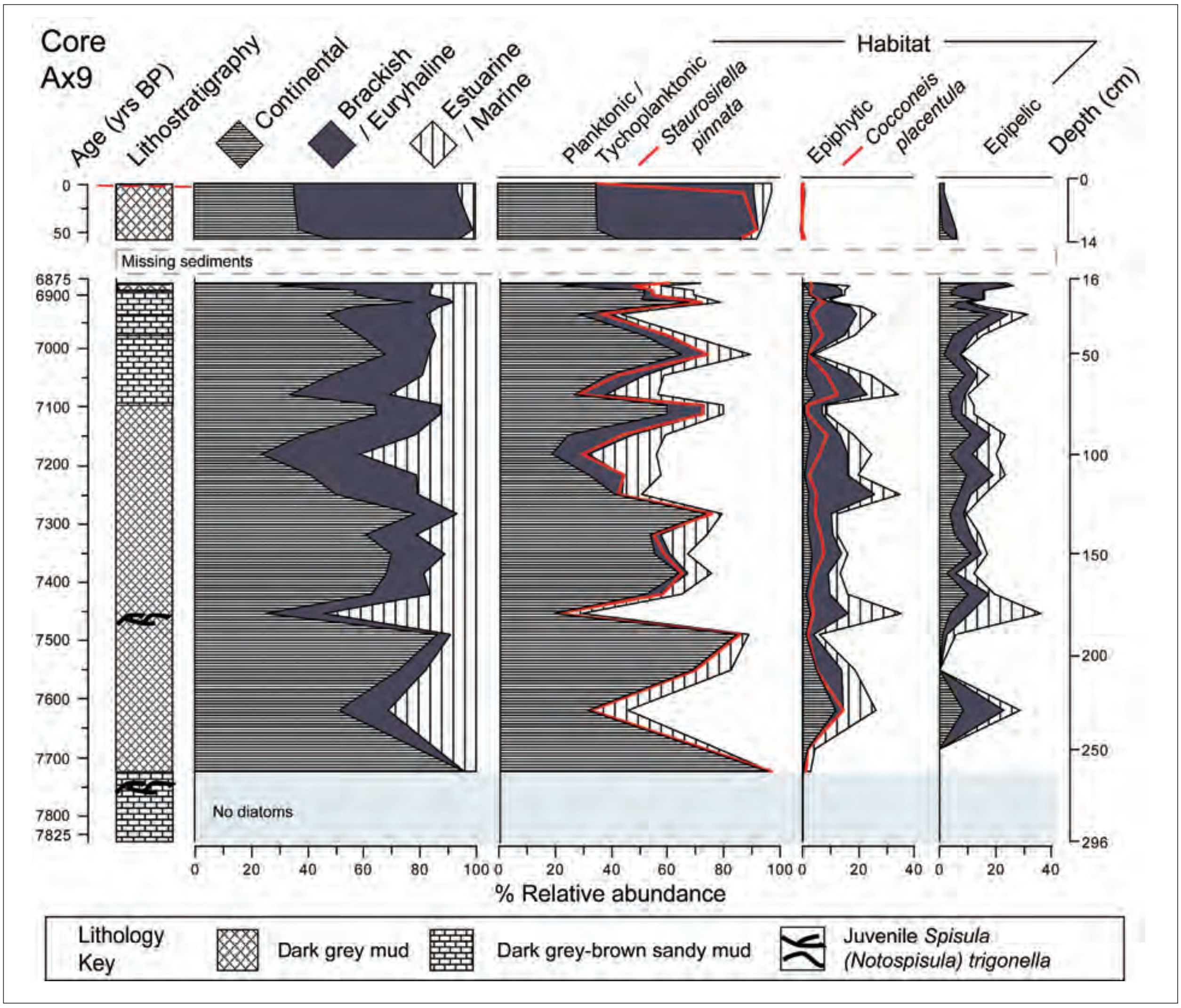

Figure 2.4.3 Lake Alexandrina core Ax9: summary diatom stratigraphy and lithostratigraphy. Shown: the age and depth scales on the y-axes; lithological units of the core including carbonate fauna and a red dotted line indicating the lowest depth at which *Pinus* pollen was detected; the relative abundances of continental, brackish/euryhaline and estuarine/marine diatoms and their habitat proportions. Maximum abundances of *Staurosirella pinnata* and *Cocconeis placentula* are shown as red lines to demonstrate that these species comprise the bulk of the respective habitats. Note the variable age scale and gap that indicates missing sediments. (From data by D. Haynes)

(OM) of the upper sediments, replaced lignin-rich OM sourced from aquatic plants like *Ruppia* in the older sediments (Krull et al. 2009; Revill et al. 2009; McKirdy et al. 2010; Tulipani et al. 2014).

Palaeolimnology of the Lower Lakes

The presence, and occasional dominance, of brackish/euryhaline diatom species in the Lower Lakes might, at first glance, indicate that water conditions were brackish, rather than fresh. As already mentioned, most of the species in this group have a tolerance for a wide range of water conditions. Abundances of the species that dominate this group, tychoplanktonic *Staurosirella pinnata* and epiphytic *Cocconeis placent*ula (shown as red lines in the respective figures) occur

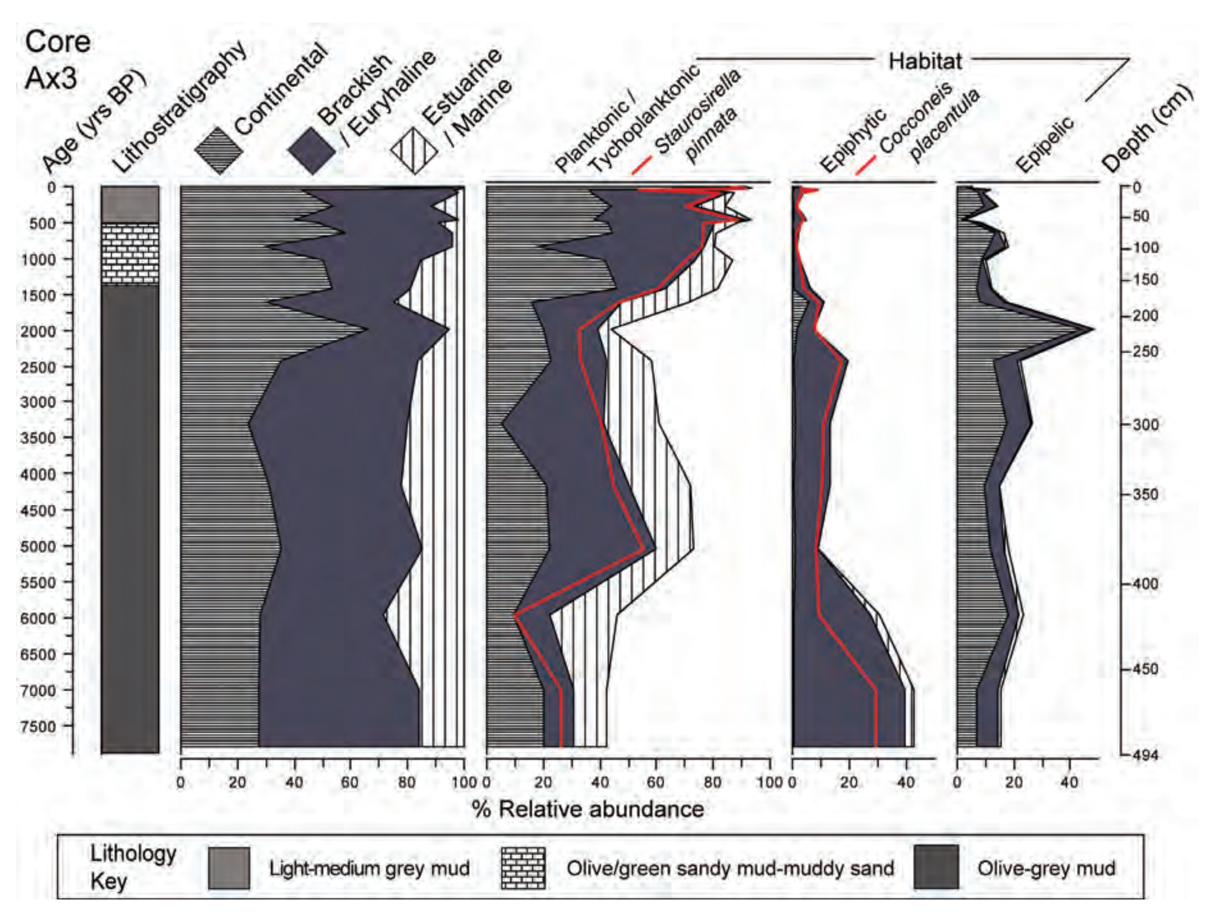

Figure 2.4.4 Lake Alexandrina core Ax3: summary diatom stratigraphy and lithostratigraphy. Shown: the age and depth scales on the y-axes; lithological units of the core; the relative abundances of continental, brackish/euryhaline and estuarine/marine diatoms and their habitat proportions. Maximum abundances of *Staurosirella pinnata* and *Cocconeis placentula* are shown as red lines to demonstrate that these species comprise the bulk of the respective habitats. (Data used with permission from J. Fluin)

in association with freshwater species for the most part and are therefore taken to indicate predominantly fresh/weakly brackish water conditions.

Carbonate faunal remains

No estuarine, marine or freshwater shells were found in the cores from the Lower Lakes except for bands of juvenile *Spisula* (*Notospisula*) *trigonella* bivalves shells in Ax9 at 7 750 and 7 450 years BP (Fig. 2.4.3). *S.*(*N.*) *trigonella* is a shallow-water bivalve that lives in unvegetated and/or sandy mud in the marine littoral, estuaries, river mouths and coastal lagoons along the entire coast of Australia. Shell physiology means that juveniles are more tolerant of lower estuarine salinities (i.e. <15 g L^{-1}) and deeper water than adults (Ludbrook 1984; Semeniuk & Wurm 2000). The presence of juvenile *S.*(*N.*) *trigonella* for the period c.7 750-7 450 years BP therefore suggests estuarine episodes in the centre of Lake Alexandrina; a peak in estuarine/marine diatoms at ~7 500 BP in Ax1 core indicates that these episodes may have extended into the northern part of the Lake periodically over that 300-year period (Fig. 2.4.2).

The lack of adult populations indicates only sporadic spikes in salinity, rather than persistently estuarine conditions, given that the species requires several years of optimal conditions (salinity >15 g L^{-1}) to achieve maturity (Semeniuk & Wurm 2000).

Diatom-inferred water conditions in the Lower Lakes

Diatoms in the Lake Alexandrina cores show that conditions were persistently fresh/brackish for at least the last 7 000 years; indeed, a trajectory of freshening is evident in Ax9 and Ax3 cores (Figs. 2.4.3 and 2.4.4). This is demonstrated as the proportions of estuarine/marine diatoms diminish upcore, a trend that was occurring well before barrage emplacement and may have been in response to gradually declining sea levels (Lewis et al. 2013). Site Ax1 in northern Lake Alexandrina (Fig. 2.4.2) shows only minor representations of estuarine/marine diatoms, so it is reasonable to assume that fluvial pressure restricted marine incursions, if they occurred at all, to the southern portion of the Lake for the last ~7 000 years. The absence of any major marine incursions being evident in core Ax3 from the southern portion of Lake Alexandrina (Fig. 2.4.4) may be an artifact of coarse sampling resolution, as sections of the core not sampled for diatoms may have contained evidence to the contrary.

Given that the largest source of fresh water for Lake Albert then, as now, was Lake Alexandrina, we use the diatom flora in the Lake Albert cores to aid reconstruction of conditions in the centre of Lake Alexandrina for the period of time unrepresented by sediments. Proportions of continental and brackish diatoms exceed 40% and 25% respectively between 6 000 and 4 000 years BP in cores Ab2 and Ab1 in Lake Albert (Figs. 2.4.5, 2.4.6). Except for one major estuarine/marine incursion ~3 750 years BP in core Ab1 (Fig. 2.4.6), continental planktonic/tychoplanktonic species dominate in the centre of Lake Albert until ~2 200 years BP. For the environment in Lake Albert to be predominantly fresh, then the ambient environment in Lake Alexandrina must also have been predominantly fresh during the period of time for which sediments are missing in core Ax9 (Fig. 2.4.3). Both Lake Albert cores also exhibit the same freshening upcore trend found in Lake Alexandrina cores. What evidence there is for more saline episodes, particularly in Lake Albert, may also have been driven by periodically increased groundwater discharge along the Lake margins or evapo-concentration of any solutes in response to a drier climate.

In Lake Albert, core Ab2 (Fig. 2.4.5) has older sediments (containing diatoms) than those in Ab1 (Fig. 2.4.6); the diatoms in this basal section of core (shown in the epipelic group) are exclusively freshwater aerophilic species. These diatoms often live on wet sediments and plants, indicating that the northern portion of the Lake may have been a freshwater swamp, rather than fully lacustrine for the 100 years before 8 000 years BP. These diatoms are not in the basal sediments of core Ab1 in the centre of the Lake (Fig. 2.4.6), which implies the onset of brackish-estuarine conditions over the next 100 years at both sites as sea levels rose. This conclusion is supported by abundances of brackish epiphytic *Campylodiscus echeneis* and *C. clypeus*, which occur with abundances of estuarine/marine taxa at the base of Ab1 core, but decline upcore as freshwater taxa in association with *S. pinnata* increase (Fig. 2.4.6). The most likely scenario here is the onset of sea-level transgression with clear, brackish to salty conditions between ~7 900 and 6 000 years BP, followed by the gradual freshening of the Lake Albert basin, perhaps with increasing proportions of suspended particulates in the water column as the Lake infilled and shallowed.

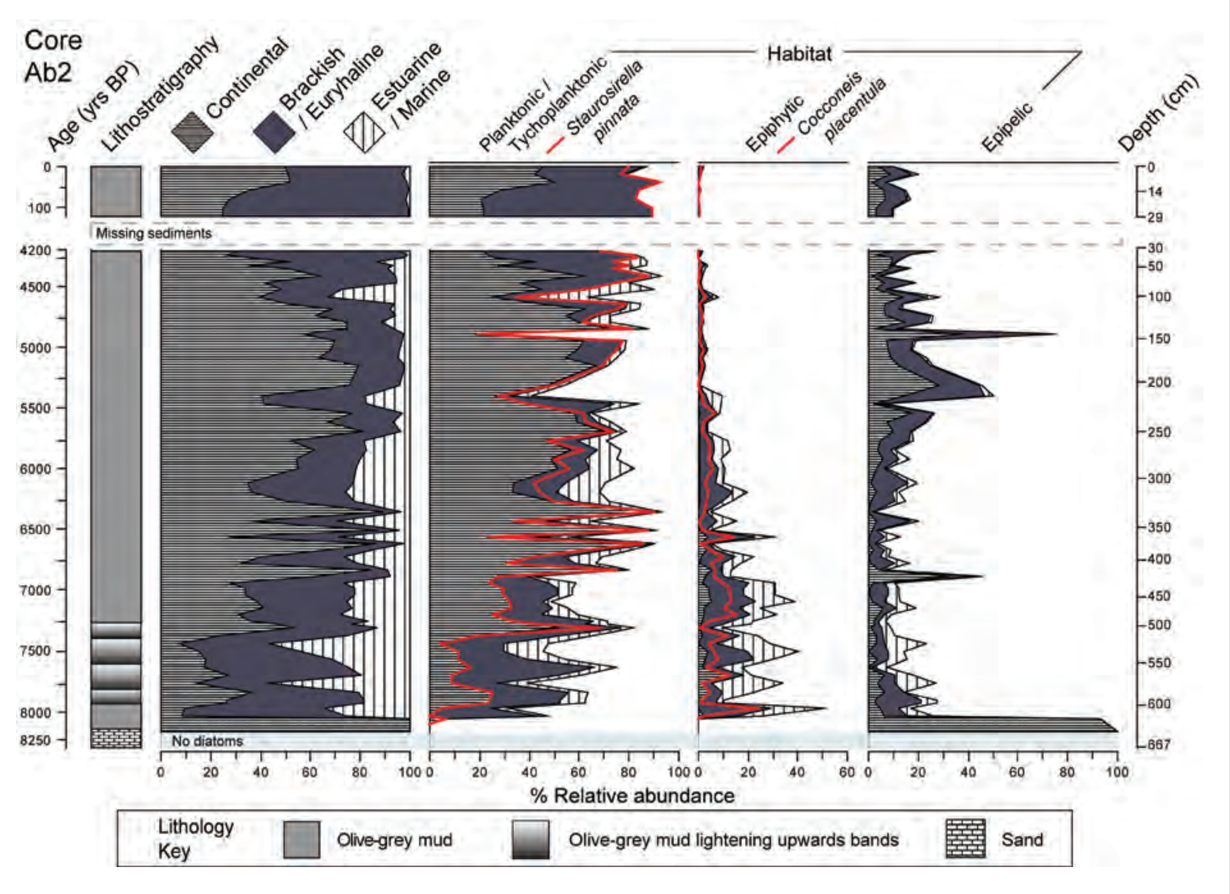

Figure 2.4.5 Lake Albert core Ab2: summary diatom stratigraphy and lithostratigraphy. Shown: the age and depth scales on the y-axes; lithological units of the core; the relative abundances of continental, brackish/euryhaline and estuarine/marine diatoms and their habitat proportions. Maximum abundances of *Staurosirella pinnata* and *Cocconeis placentula* are shown as red lines to demonstrate that these species comprise the bulk of the respective habitats. Note the variable age scale and gap that indicate sediments are missing. (From data by D. Haynes)

Post-colonial water conditions

Conditions in the Lower Lakes for the last 100 years are notably different from those evident in previous millennia. Abundances of *S. pinnata* are significantly higher at all sites except Ax1 at the confluence of the River Murray (Fig. 2.4.2). Diminishing abundances of epiphytic and epipelic taxa upcore are a signal that light penetration became insufficient to promote growth and reproduction in bottom sediment-dwelling diatoms. As is clear from Figs. 2.4.2-2.4.5, *S. pinnata* and *C. placentula* comprise the major portion of their respective habitats in the Lower Lakes cores, and the two species have an inverse relationship, i.e. when *S. pinnata* abundances are high, *C. placentula* abundances are low. Given that *S. pinnata* is an opportunistic weedy species that often thrives in turbid water, whereas *C. placentula* requires aquatic plant substrates on which to attach, these two species may well provide a simple means to infer fluctuations in water clarity in the Lower Lakes.

Alternatively, although the presence of aquatic plants can mean that the water is clear, some aquatic plants float on top of turbid water in sheltered calm water environments (e.g. *Azolla* and *Lemna*, or duckweed). In northern Lake Alexandrina, at site Ax1 (Fig. 2.4.2), proportions of *S. pinnata* diminish towards the top of the core, whereas abundances of *C. placentula* and

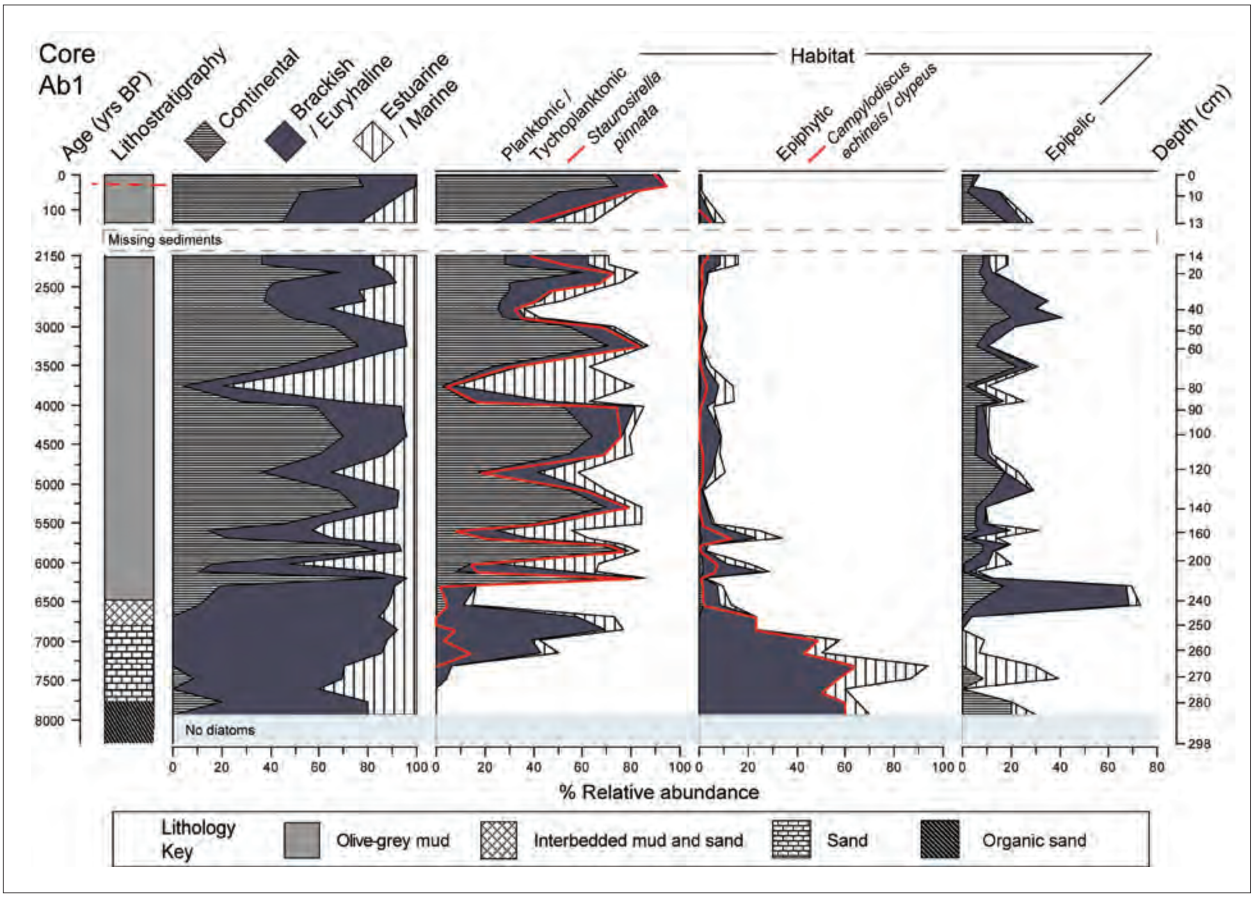

Figure 2.4.6 Lake Albert core Ab1: summary diatom stratigraphy and lithostratigraphy. Shown: the age and depth scales on the y-axes; lithological units of the core including a red dotted line indicating the lowest depth at which *Pinus* pollen was detected; the relative abundances of continental, brackish/euryhaline and estuarine/marine diatoms and their habitat proportions. Maximum abundances of *Staurosirella pinnata* and *Campylodiscus* species (*C. echeneis*/*C. clypeus*) are shown as red lines to demonstrate that these species comprise the bulk of the respective habitats. Note the variable age scale and gap that indicates sediments are missing. (From data by D. Haynes)

the suite of epipelic diatoms increase. This process started ~100 years ago, so it is likely that a combination of factors is at play. Given that the core site is located away from the main river channel, this trend might be in response to aforementioned increased nutrient levels from agricultural enterprises located upstream, to the benefit of fringing or floating aquatic plant growth and their symbionts. Alternatively, the site displays no sign of sediment scouring, and water shallowing may explain the change in diatom composition; as sediments infill, plants are likely to vegetate more in the littoral environment. This process may also enhance the advantage that diatoms like *Cocconeis placentula* have when the epiphytic diatom community is grazed by shallow water fauna, e.g. by freshwater molluscs (Jones et al. 2000).

Palaeolimnology of the Coorong

The importance of an open Murray Mouth

The most notable feature of the Coorong diatom records is that estuarine/marine diatoms comprise the bulk of the assemblages prior to c.1950 at sites C3 and C7 in the North

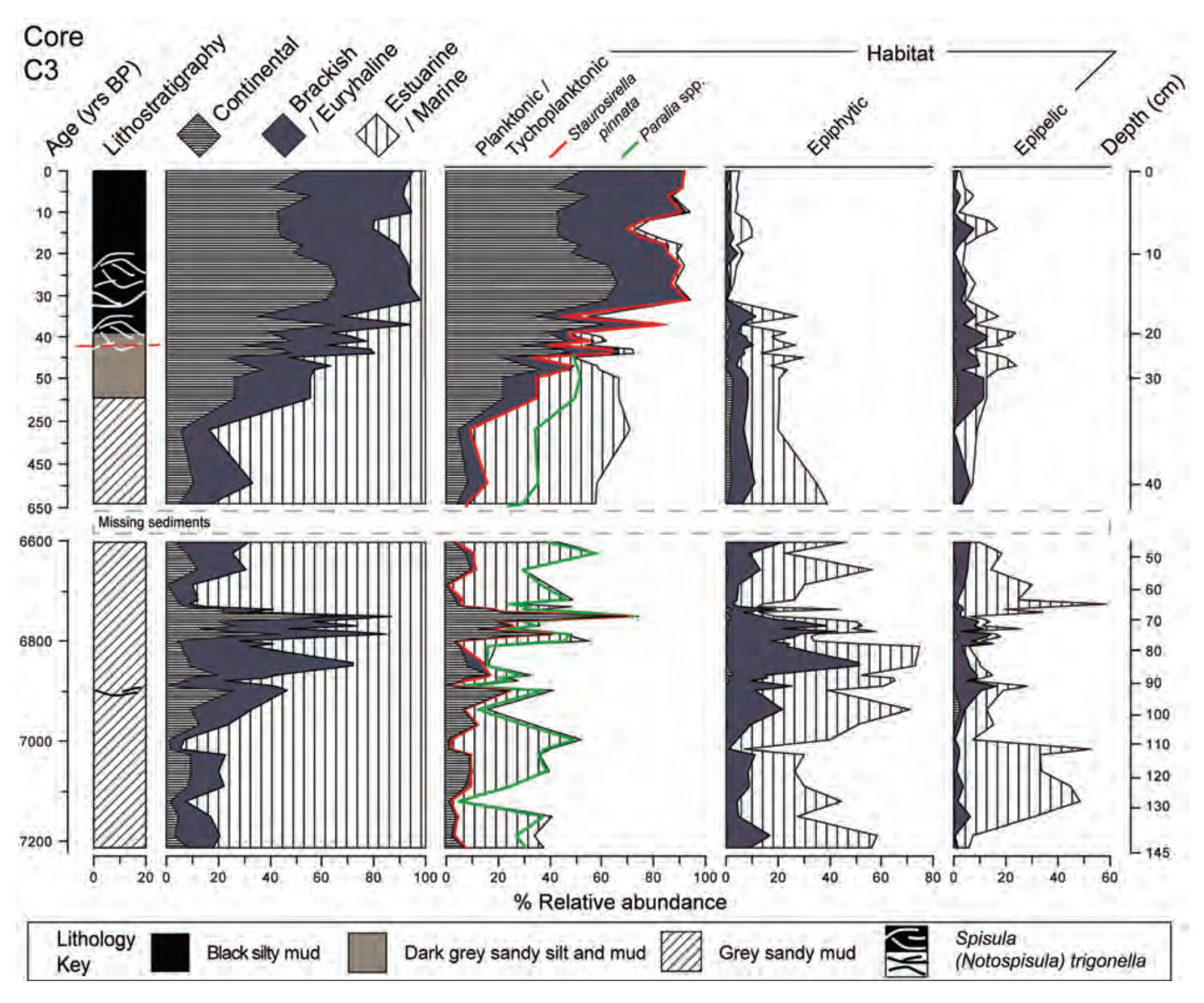

Figure 2.4.7 Coorong core C3: summary diatom stratigraphy and lithostratigraphy. Shown: the age and depth scales on the y-axes; lithological units of the core including carbonate fauna and a red dotted line indicating the lowest depth at which *Pinus* pollen was detected; the relative abundances of continental, brackish/euryhaline and estuarine/marine diatoms and their habitat proportions. Maximum abundances of *Staurosirella pinnata* and *Paralia* spp. are shown as red and green lines respectively, to demonstrate that these species comprise the bulk of the respective habitats. Note the variable age scale and gap that indicate sediments are missing. (From data by D. Haynes)

Lagoon (Figs. 2.4.7 & 2.4.8), but are only periodically dominant in the South Lagoon cores (Figs. 2.4.9 & 2.4.10). The dominant species during the Holocene in the North Lagoon are tychoplanktonic *Paralia sulcata* and *P. fenestrata*, grouped together as *Paralia* spp. and shown in Figures 2.4.7-2.4.9. Both species are chain-forming, centric diatoms that are typically major components of benthic communities in coastal, estuarine or lagoonal environments. They have no way of attaching to a substrate, which makes them susceptible to tidal or wind disturbance, and they are thus easily entrained in the water column, particularly in shallow coastal waters and lagoons (McQuoid & Nordberg 2003).

High abundances of *Paralia* are therefore likely to indicate an open Murray Mouth and estuarine-marine conditions, while low abundances or absence may indicate a closed or restricted mouth and more lagoonal periods when brackish/euryhaline taxa flourished.

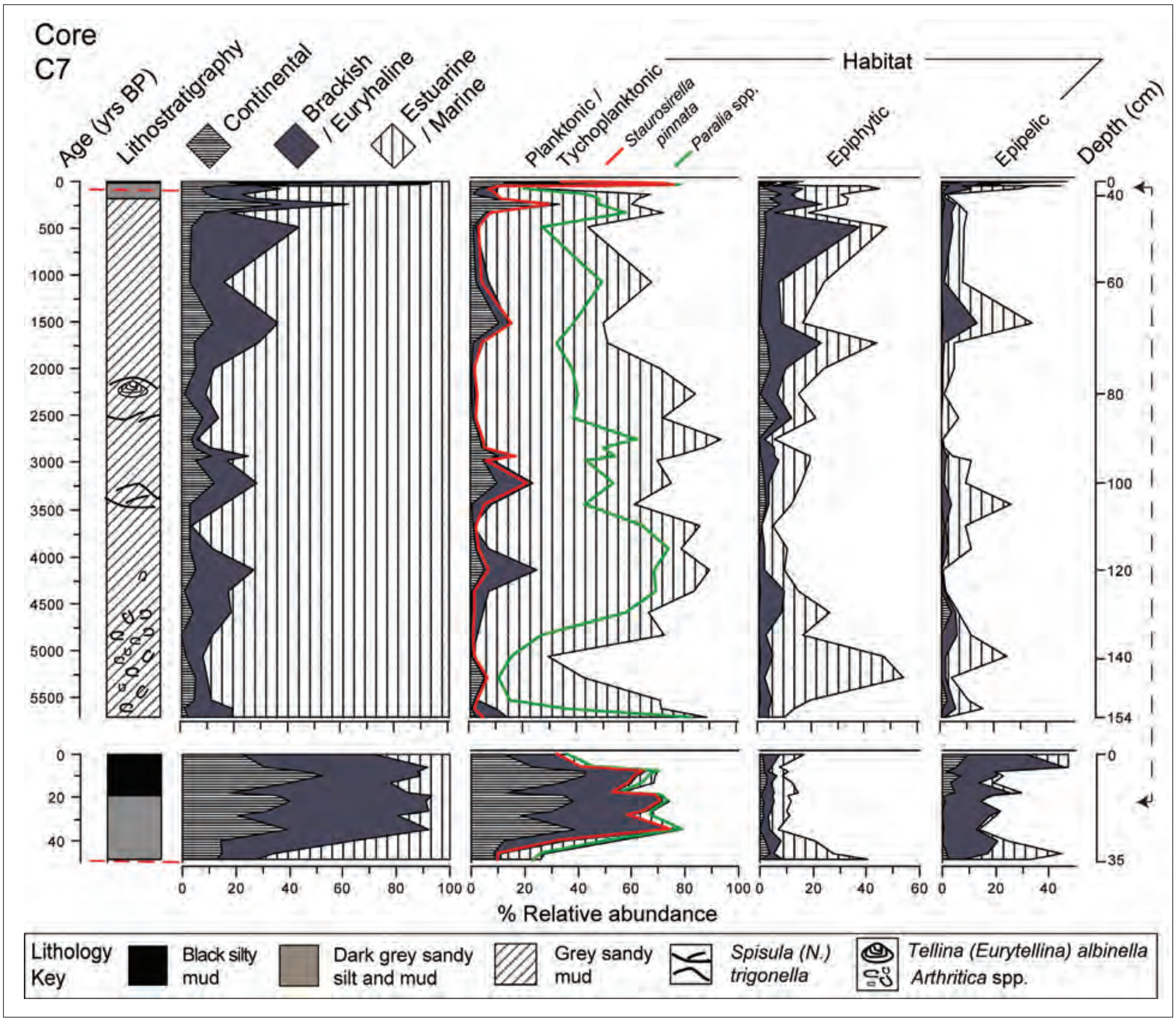

Figure 2.4.8 Coorong core C7: summary diatom stratigraphy and lithostratigraphy. Shown: the age and depth scales on the y-axes; lithological units of the core including carbonate fauna and a red dotted line indicating the lowest depth at which *Pinus* pollen was detected; the relative abundances of continental, brackish/euryhaline and estuarine/marine diatoms and their habitat proportions. Maximum abundances of Staurosirella *pinnata* and *Paralia* spp. are shown as red and green lines respectively, to indicate that these species/groups comprise the bulk of the respective habitats. Note the variable age scale and the enlargement of the top 35 cm of the core representing ~50 years of sedimentation before 2005. (From data by D. Haynes)

For marine water to enter the Coorong Lagoon, the Murray Mouth must be open and river outflows must work in concert with marine inflows as in the classic estuary model, where the water column is stratified across a halocline. This describes the way the denser and heavier marine water flows below, and in the opposite direction under tidal pressure, to the outgoing freshwater layer (Kjerfve et al. 1978). Hence, abundances of *Paralia* species demonstrate the role of an open mouth in the functional relationship between the Coorong and the marine environment as one of the dominant water sources in the northern lagoon.

Evidence for a period when the Murray Mouth was more restricted and salinity levels were at or above 35 g L^{-1} in the North Lagoon can be found in core C7 in sediments dated

5 500-5 000 years BP (Fig. 2.4.8). At that time, small bivalve *Arthritica* species are found coincident with the lowest abundances of *Paralia* species at that site. These bivalves are typical of low-energy coastal and lagoon environments along the southern Australian coast and are particularly well adapted to less dynamic areas in estuaries (Kanandjembo et al. 2001; Jespersen & Lützen 2009). This period is marked by increased abundances of estuarine/marine epiphytic diatoms, indicating that conditions at the site were most likely characterised by clear water with abundant coverage of aquatic plants, in keeping with the preferred habitat for these fauna of vegetated, sandy muds (Semeniuk & Wurm 2000). Diatom sampling during 2007, at the height of the Millennium Drought when connection with the marine environment was only possible through continued dredging at the Murray Mouth, failed to detect *Paralia* species at most sites in the Coorong in any but minor abundances (Haynes et al. 2011).

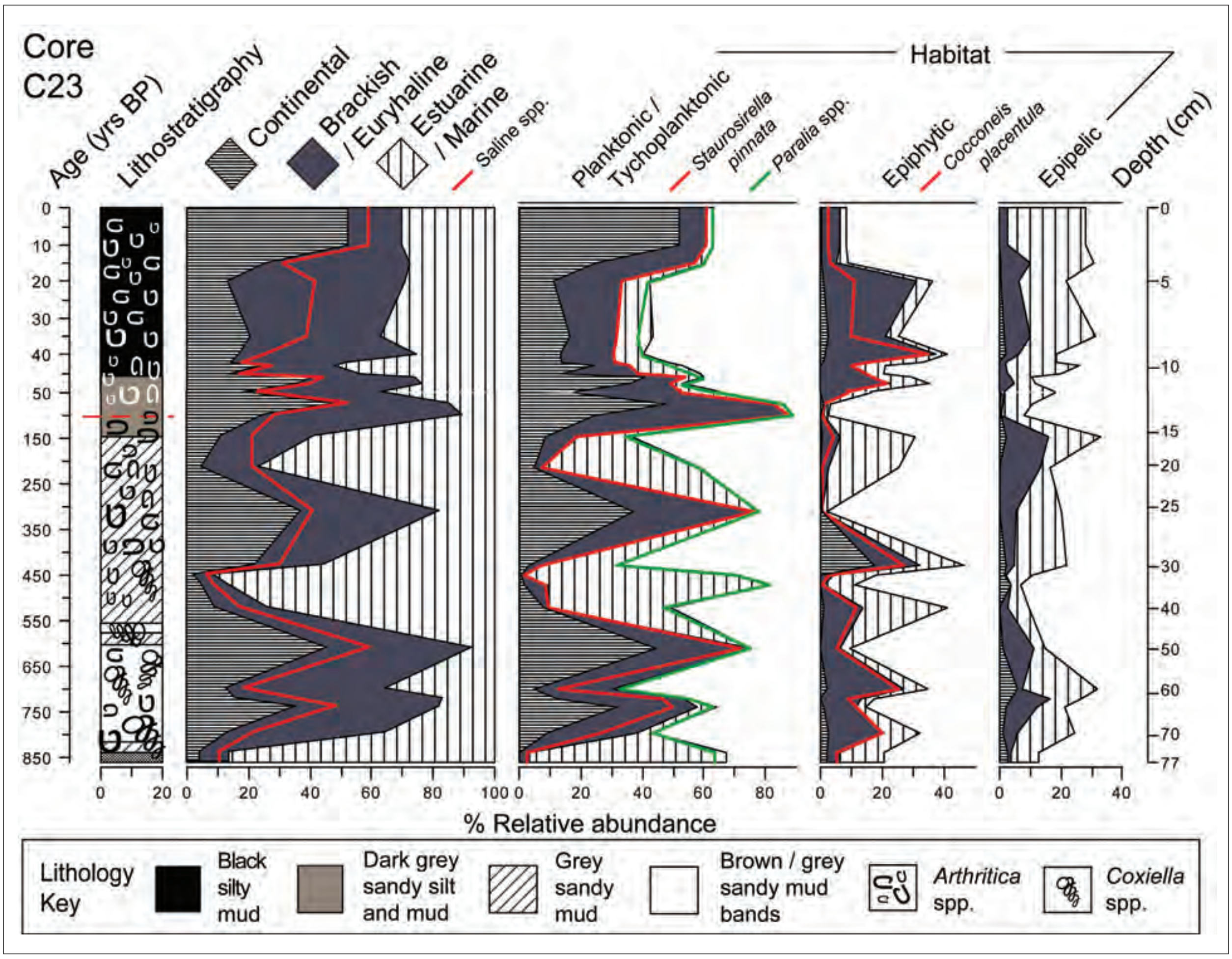

Figure 2.4.9 Coorong core C23: summary diatom stratigraphy and lithostratigraphy. Shown: the age and depth scales on the y-axes; lithological units of the core including carbonate fauna and a red dotted line indicating the lowest depth at which *Pinus* pollen was detected; the relative abundances of continental, brackish/euryhaline and estuarine/marine diatoms and their habitat proportions. Maximum abundances of *Staurosirella pinnata* (red line), *Paralia* spp. (green line) and *Cocconeis placentula* (red line) are shown to indicate that these species/groups comprise the bulk of the respective habitats. The maximum abundances of Saline spp. are also shown. Note the variable age scale. (From data by D. Haynes)

Evidence for variable water sources

Continental diatoms are allochthonous components in Coorong assemblages. Despite their modest averaged abundances of 14% and 17% respectively in the North and South Lagoons, before 1950, their presence alone indicates that fresh water has reached the core sites. Continental diatoms are present in core C7 for most of the last 5 500 years, and, taken together with the diatom evidence from site C3 (Figs. 2.4.7, 2.4.8) and evidence from archived ostracod and foraminifera remains from site C5 (Lower et al. 2013), it is likely that outflows from Lake Alexandrina were persistent and influential in creating estuarine conditions for >7 000 years to a distance of at least 30 km into the North Lagoon. The incidence of mature *S.*(*N.*) *trigonella* shells in C3 core ~6 900 years BP and sporadically between 3 500 and 2 000 years BP in core C7 indicates that salinity was between 15 and 35 g L^{-1} for sustained periods (Semeniuk & Wurm 2000).

The dominant taxa from the River Murray (planktonic *Aulacoseira* species) are absent from the South Lagoon cores, but continental diatoms were nevertheless present in the South Lagoon for the last 850 years. The closest source of fresh water in the South Lagoon is from the south-eastern catchment through Salt Creek. Site C23 (Fig. 2.4.9) is about 25 km from Salt Creek (see Fig. 2.4.1), so palaeo-outflows would have been episodically substantial. The existence of a 5 m deep channel emanating from Salt Creek that parallels the western shore for about 10 km is evidence of a flow pathway and of the magnitude of the flows and their capacity to scour to that depth. Ostracods preserved in a number of sediment cores from around the Salt Creek area were used to reconstruct past water conditions in the South Lagoon (Thomlinson 1996). This study provided strong evidence that hypersalinity in the South Lagoon occurred post-colonial settlement as 'a result of changes to the land' (Thomlinson 1996, p. 2), and that regular and substantial (although unquantified) freshwater inflows would have occurred prior to that time. In addition, ethnological evidence of quasi-annual outflows from the south-east prior to modification of the south-eastern catchment has been documented in Bell (1998) and Phillips and Muller (2006), lending support to the proposition of greater freshwater contributions to the South Lagoon in the past and their capacity to flush salts northwards out of the lagoon.

Estuarine/marine diatom species are only periodically dominant in the South Lagoon assemblages; abundances of *Paralia* spp. in core C23 (Fig. 2.4.9) indicate episodes of tidal water inflows from the North Lagoon, the result of an open Murray Mouth. Given that marine water reached the South Lagoon from the Murray Mouth, continental abundances that are periodically higher at site C23 than at site C27 (Fig. 2.4.10) may also be the result of fresh water from the North Lagoon penetrating into the northern South Lagoon. The low abundances of *Paralia* species at site C27 lend support to the suggestion that the inflows from the North Lagoon, whether marine, fresh or estuarine, were confined to the northern part of the South Lagoon for the last 850 years, and that the majority of continental diatoms in that core originated from the south-eastern catchment.

Carbonate faunal remains in the South Lagoon

Shells found in both South Lagoon cores are *Arthritica* species as well as some small, salt-tolerant gastropod *Coxiella* species, which are common to estuaries, coastal lagoons and salt

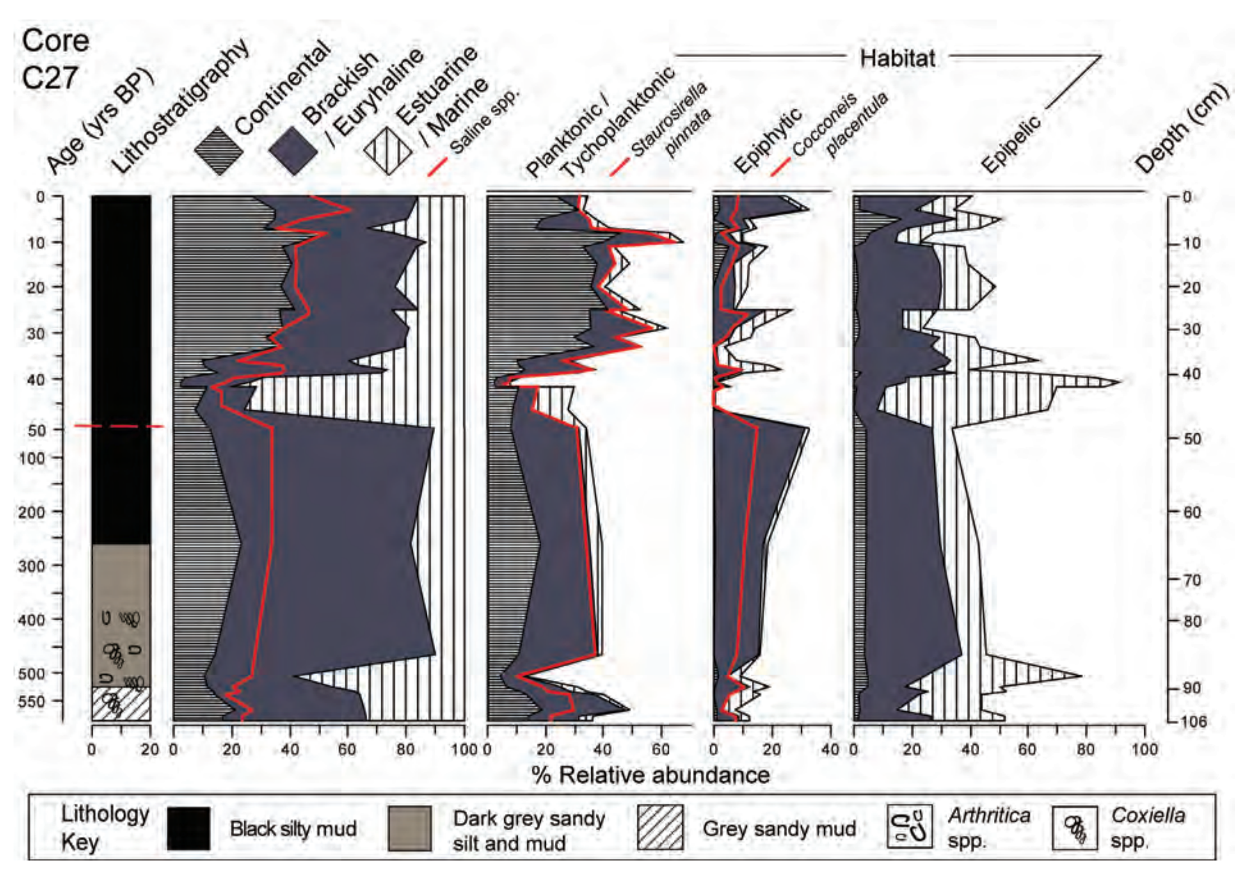

Figure 2.4.10 Coorong core C27: summary diatom stratigraphy and lithostratigraphy. Shown: the age and depth scales on the y-axes; lithological units of the core including carbonate fauna and a red dotted line indicating the lowest depth at which *Pinus* pollen was detected; the relative abundances of continental, brackish/euryhaline and estuarine/marine diatoms and their habitat proportions. Maximum abundances of *Staurosirella pinnata*, *Paralia* spp. and *Cocconeis placentula* are shown as red lines to indicate that these species/groups comprise the bulk of the respective habitats. The maximum abundances of Saline spp. are also shown. Note the variable age scale. (From data by D. Haynes)

lakes in southern Australia (Williams & Mellor 1991). *Arthritica* shells are densely aggregated throughout core C23, with scattered *Coxiella* shells in sediments older than ~400 years BP, while *Coxiella* shells are dominant between 600 and 400 years BP in C27 core, but shells of any sort are absent otherwise in that core (Figs. 2.4.9 & 2.4.10). *Arthritica* can tolerate elevated salinity, while *Coxiella* has been found living in brine (e.g. salinity 124 g L^{-1}; Williams & Mellor 1991). This possibly indicates that salinity levels were above those of sea water prior to 400 years BP at both sites.

The absence of shell fauna at site C27 for the last 400 years may have been in response to low dissolved oxygen levels and high turbidity, a by-product of increased phytoplankton productivity. Reeves et al. (2015) used ostracods to infer water conditions from these two cores and concluded that the South Lagoon was periodically more saline than sea water even before colonisation. The diatom evidence is more ambivalent; halo-tolerant species like *Halamphora coffeaeformis*, *Navicula duerrenbergiana*, *N. incertata* and *Synedra acus* var. *varipunctata* (grouped, and shown as Saline spp. in Figs. 2.4.9 & 2.4.10) have their highest abundances after the 1950s during the period when salinity is known to have been high, but average only 5% in core C23 and 11% in core C27 in the older sediments of the South Lagoon.

Biogeochemical evidence from the Coorong

Biogeochemical data from Coorong sediments have highlighted the functional differences between the North and South Lagoons. Salinity, net deposition of OM and nutrients have been higher in the South Lagoon over the last ~5 000 years, reflecting ecological impoverishment, nutrification and pore-water anoxia compared with the North Lagoon over the same period (McKirdy et al. 2010). Krull et al. (2009) identified the dominant role that macrophytes, particularly *Ruppia* species, played in the food web of both lagoons prior to the 1950s. Dick et al. (2011) documented the history of aquatic plants in the South Lagoon for the last ~3 600 years. They found that salt-tolerant annual *Ruppia tuberosa* is only present in post-European settlement sediments. Prior to that time, perennial *Ruppia megacarpa*, which has a limited tolerance for elevated salinity, had persisted for several millennia in the South Lagoon and was noted as a significant contributor to OM in Holocene-age sediments in the North Lagoon (Tulipani et al. 2014). Discharges of 40 500 megalitres of brackish-saline (7.5-30 g L^{-1}) water through Salt Creek over the period 2000-2005 had little effect on lowering the salinity levels in the South Lagoon (Everingham et al. 2007). This demonstrates that in order for *Ruppia megacarpa* to have persisted for several millennia in the South Lagoon before colonisation (*sensu* Dick et al. 2011), salinity levels must have been much lower than those observed in the early 21st century (Haynes et al. 2011; Phillips & Muller 2006).

Post-colonial conditions in the Coorong

Conditions in the Coorong since colonisation have been markedly different from those that prevailed in the previous millennia. After 1950, continental diatom abundances increase exponentially to 38% and 26% in the North and South Lagoons respectively, indicating that the switch to a *Fragilariaceae*-dominated system observed in the Lower Lakes also occurred in the Coorong, albeit in more modest representations in the South Lagoon. This dramatic change most likely reflects the transport of those diatoms to the North Lagoon in discharges over the barrages. Their high proportions are a direct result of the Murray Mouth functioning less efficiently. The reduction of water exchanges through the Murray Mouth has reduced the ingress of marine water and reduced water circulation throughout the lagoons. Coupled with reduced discharges through Salt Creek, the flushing capacity today fails to rid the system of excess salts, and phytoplankton productivity and turbidity have increased to the detriment of all but the most halo-tolerant aquatic plants, particularly in the South Lagoon.

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CHAPTER 2.5

FOSSIL MOLLUSCS, FORAMINIFERA, OSTRACODS AND OOGONIA RECORD A COORONG HISTORY

JOHN CANN[1,2] AND CHANTELLE LOWER[1]

GLOBAL CLIMATE AND SEA LEVEL

This chapter considers first the effects of ice ages, global warming and sea-level changes in the formation of the Coorong Lagoon and regional areas of south-east South Australia. From about 30 000 to 18 000 years ago, global climate favoured expansion and maintenance of glaciers. Ice sheets covered much of North America and Europe, the Antarctic ice sheet was at its maximum thickness and extent, while glaciers formed in Tasmania and on the southern highlands of eastern Australia (Barrows et al. 2002 and references therein). The most extreme parts of this climatic event and the time of its occurrence are commonly referred to as 'The Last Glacial Maximum' (Fig. 2.5.1) which spanned the period 23 000 to 19 000 years ago (Yokoyama et al. 2000). With so much of Earth's water frozen in place on the continents, sea levels were 120-130 m lower than they are today (e.g. Ferland et al. 1995; Murray-Wallace 2007). The local shoreline was south of what is now Kangaroo Island, at the outer edge of the continental shelf. At that time, and during similar earlier episodes of global glacial climates and lowered sea level, the ancient River Murray flowed across the exposed continental shelf (Lacepede Shelf) to canyons deeply incised into the continental slope (Hill et al. 2009).

With the passing of the Last Glacial Maximum and transition to global warming, the ice sheets and glaciers began to melt and sea levels rose, transgressing over the formerly exposed parts of the continental shelf and flooding into Spencer and St Vincent Gulfs. This event is known as the 'Postglacial Marine Transgression'. Backstairs Passage became a seaway, isolating Kangaroo Island only about 10 000 years ago.

There is every reason to suppose that these conditions were witnessed by local populations of coastal-dwelling humans, who retreated landwards as sea levels rose. Earliest evidence of a human presence on South Australian coasts is dated at about 8 000 years ago (e.g. near Robe; Cann et al. 1991), the rising sea having covered any older artifacts or midden materials. Sea-level rise due to deglaciation culminated about 7 000 years ago. Subsequent changes in relative sea level have been minor and are due, at least in part, to physical adjustment of the continental margins to the loading of additional water following deglaciation (Belperio 1995).

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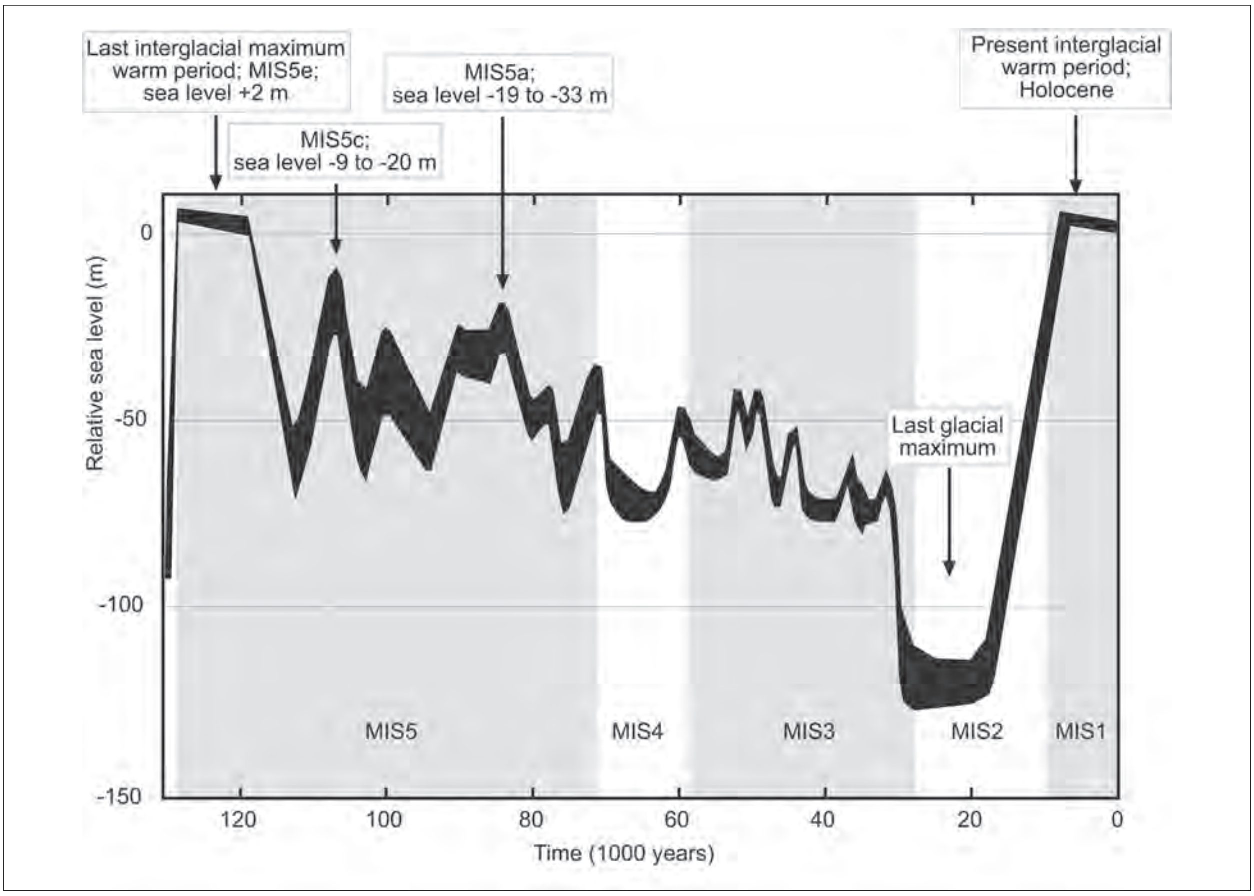

Figure 2.5.1 Sea-level curve for the past 130 000 years, in relation to Marine Isotope Stages (MIS) 1 to 5, derived from observations of flights of coral terraces on the uplifting Huon Peninsula, Papua New Guinea (adapted from Lambeck & Chappell 2001). The thickness of the line of the curve is an expression of the degree of uncertainty of the calculated sea levels. Numbers 1 to 5 refer to episodes of time (stages) defined by marine oxygen isotopes. The Last Glacial Maximum, when sea level was about 120 m lower than at present, is shown within Stage 2. The Last Interglacial warm period (within Stage 5) occurred about 130 000 to 120 000 years ago, when sea level was at least 2 m higher than at present. The present interglacial warm period (Stage 1) has existed for little more than the past 10 000 years. The rapid rise in sea level during the transition from Stage 2 to Stage 1 is known as the Postglacial Marine Transgression. The last 12 000 years (approximately) constitutes the Holocene Epoch.

THE YOUNGHUSBAND PENINSULA

Younghusband Peninsula (Fig. 2.5.2) is a Holocene beach-dune barrier complex which originated as the rising postglacial sea transported sandy sediment shoreward from the exposed Lacepede Shelf. It stabilised at the culmination of the postglacial marine transgression, at the same time isolating a narrow back-barrier lagoon (the Coorong) from the direct impact of the Southern Ocean. The Peninsula extends from the mouth of the River Murray some 180 km towards the south-east town of Kingston. Transgressive dune systems are characterised by unvegetated active dune sheets, large-scale parabolic and transgressive dunes up to ~40 m in altitude, and deflation hollows (coastal blow-out dunes) that extend down to sea level. However, large parts of the dune complex are now fixed by vegetation, principally species of *Acacia* (coastal wattle), *Leptospermum* (tea tree) and *Melaleuca* (paper bark).

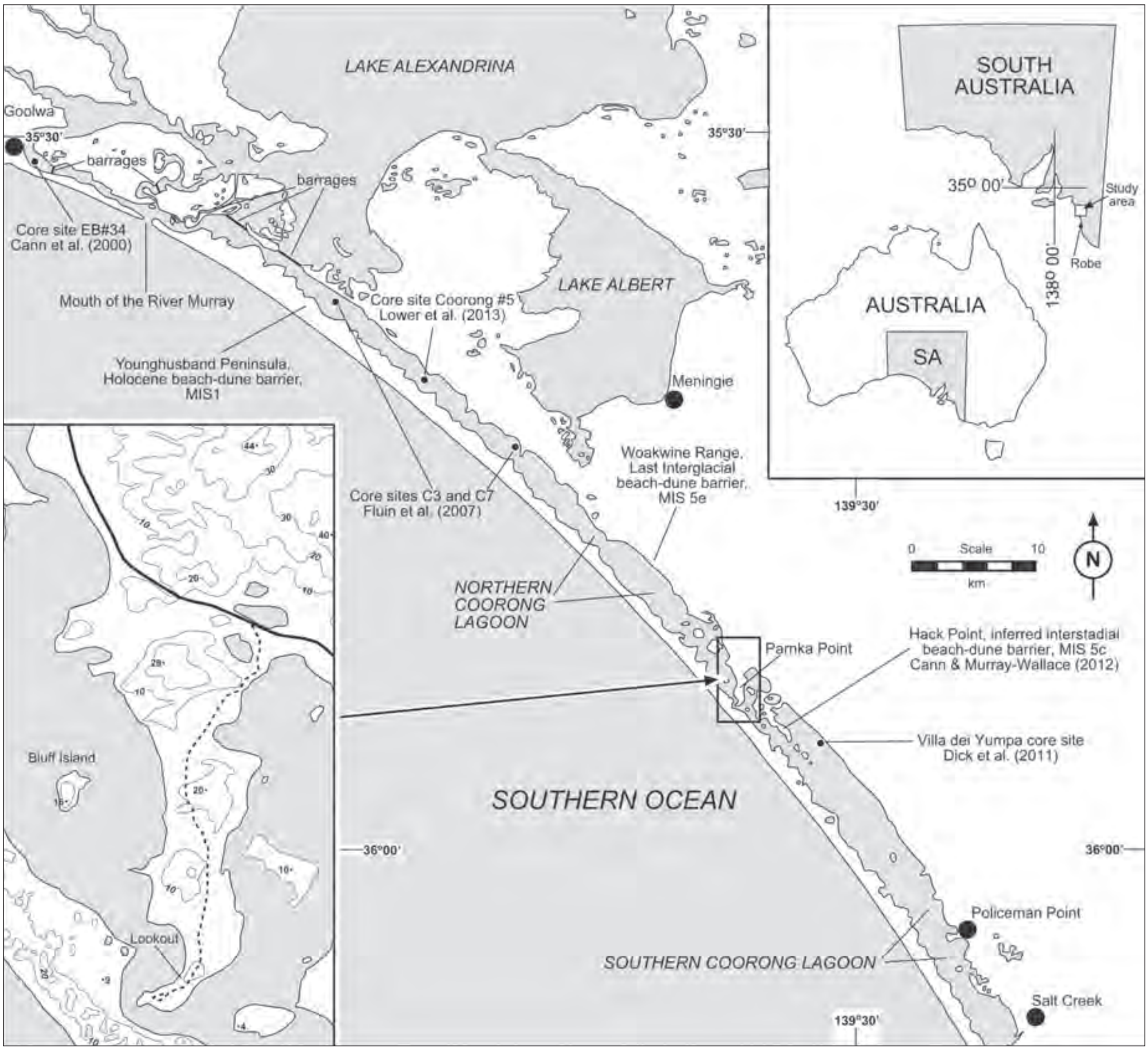

Figure 2.5.2 Location map of the Coorong Lagoon and Lakes Alexandrina and Albert showing the sites of the core Coorong #5 and of other cores discussed in the chapter (adapted from Lower et al. 2013). Parnka Point, inferred to be of interstadial MIS 5c age, divides the Coorong into northern and southern components, separated by a narrow channel. The inset map of the Parnka Point area shows spot heights in metres and topographic contours at 10 m intervals.

THE COORONG

The Coorong (Fig. 2.5.2) is a back-barrier lagoon that is confined by the Younghusband Peninsula on the seaward side, and on the landward side by the Last Interglacial (MIS 5e; Fig. 2.5.1) shoreline of 125 000 years ago (Murray-Wallace et al. 2001 and references therein). It is a narrow, shallow, coastal lagoon, never more than a few kilometres wide, and water depth is generally less than 2 m. In association with Lakes Alexandrina and Albert, the Coorong Lagoon forms part of the complex estuarine system that comprises the lower reaches of the River Murray. The lagoon extends about 150 km in a south-eastern direction from the Murray mouth; it consists of a number of interconnected basins that become increasingly restricted, hypersaline and ephemeral towards the south-eastern end. At times of substantial river flow, when freshwater outflow exceeds the seawater inflow via the Murray Mouth, the more northern waters of the Coorong are less saline than those of the Southern Ocean. At such times, high river levels preclude flood-tide sedimentation and the mouth of the river remains open. Conversely, during extended episodes of drought within the river catchment, incoming sea water, undiluted by freshwater river flows, together with prevailing high rates of evaporation, causes salinity to rise. At those times the Murray Mouth may close, thus preventing transport of holomarine organisms (e.g. foraminifera) into the lower estuary, and favouring expansion of populations of euryhaline organisms that are more characteristic of the lagoon environment (Cann et al. 2000). Between 1935 and 1940 barrages (Fig. 2.5.2) were constructed to stabilise a freshwater environment in Lakes Alexandrina and Albert, effectively isolating those lakes from the saline waters of the Coorong. During the severe drought that prevailed for much of the first decade of this century, freshwater flows were not sufficient to sustain the Lower Lakes, and salinity in the waters of the southern lagoon near Salt Creek reached more than four times that of sea water. Sedimentation caused closure of the Murray Mouth.

About 60 km south-east of the Murray mouth, Hack Point (Fig. 2.5.3) is a narrow body of aeolianite within the Coorong Lagoon, tenuously connected to the inland shore via low-lying

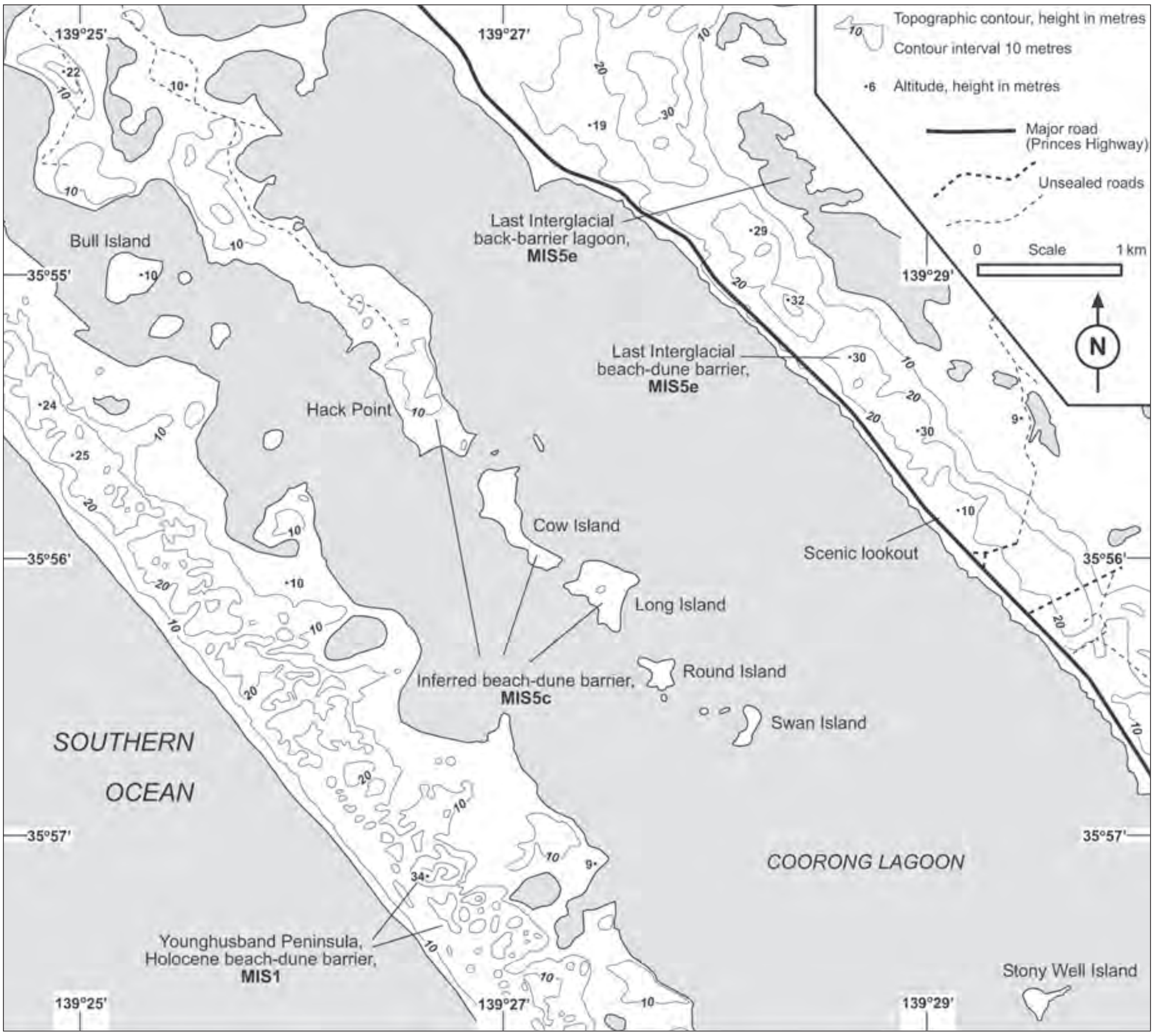

Figure 2.5.3 Map showing the location of Hack Point and islands to the south-east in the southern Coorong Lagoon (adapted from Cann & Murray-Wallace 2012). The linear distribution of these features, located between the Holocene Younghusband Peninsula and the Last Interglacial barrier, is evidence for an interstadial MIS5c coastal barrier.

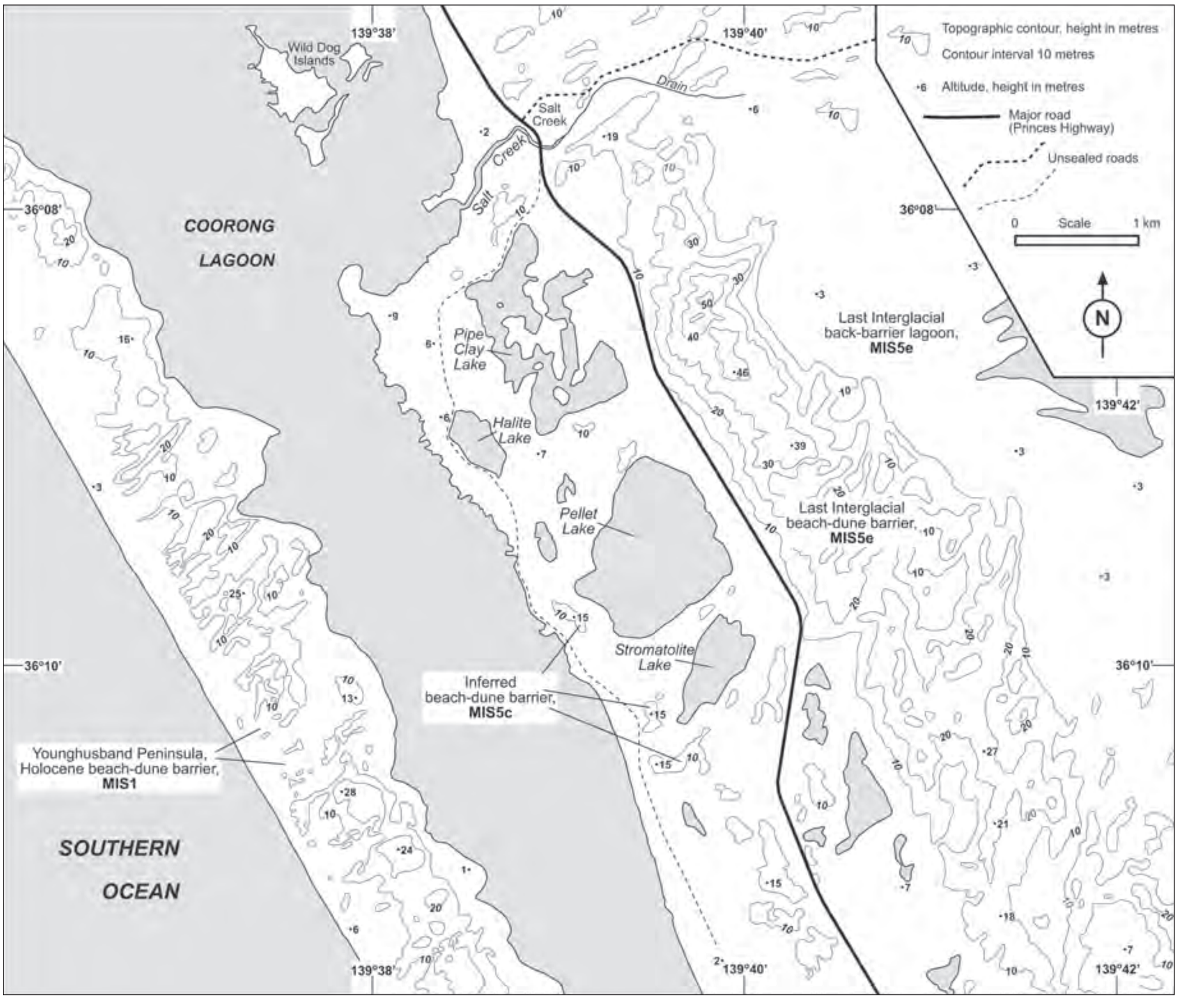

Figure 2.5.4 Map showing the major features of the landscape in the vicinity of Salt Creek in the southern lagoon (adapted from Cann & Murray-Wallace 2012). The Coorong persists as a narrow coastal lagoon on the western side of the inferred MIS5c barrier, but on the eastern side it is now reduced to a series of lakes. Immediately south-east of Salt Creek, the 10 m contour defines the eastern boundary of the Last Interglacial coastal barrier; the western margin is similarly defined. The Last Interglacial back-barrier lagoon is signified by the adjacent area of altitude ~3 m.

swampland. It is slightly longer than 3 km, about 500 m wide, and is situated midway between, and parallel to, the Holocene Younghusband Peninsula (seaward) and the Last Interglacial beach-dune barrier (landward). Maximum elevation is 22 m and calcrete capping is extensive. A linear array of islands, Cow Island to Stony Well Island, extends about 5 km from Hack Point, and trends in the same sense in the middle of the lagoon (Fig. 2.5.3). These islands also comprise calcrete-capped aeolianite, and at least one, Long Island, has an elevation of more than 10 m. These features provide evidence of an earlier coastal barrier that formed during MIS5c, about 105 000 years ago (Cann & Murray-Wallace 2012). In the same area and also a residual component of the 5c barrier, Parnka Point extends southward across much of the Coorong corridor, leaving only a narrow channel connecting the northern and southern lagoons. Immediately south-east of Salt Creek, the inferred MIS5c barrier separates a series of ephemeral saline-carbonate lakes, residual features of the eastern lagoon, from the remaining waters of the western Coorong.

Elevated aeolianite adjacent lakes south of Salt Creek

The linear trend of islands within the southern Coorong Lagoon, noted above, continues to Wild Dog Islands (Fig. 2.5.4), beyond which, south of Salt Creek, the more landward component of the lagoon is expressed as a series of lakes. Sediments exhumed from beneath the floors of these lakes preserve assemblages of molluscan and microfossils that record an earlier marine connection. Between these lakes and the now much narrower, seaward component of the Coorong Lagoon, the unsealed road lies close to the landward shore of the lagoon, particularly west of Pellet and Stromatolite Lakes (Fig. 2.5.4). Elevated aeolianite representing the interstadial MIS5c coastal barrier, exposed in the road cutting at this location, is extensively calcreted. Solution pipes, rhizomorphs and a soft calcareous earthy profile associated with the carbonate paleosol extend down several metres into the strata beneath the surficial carbonate hardpan. The maximum elevation of the remnants of this MIS5c coastal beach-dune barrier is about 15 m.

Throughout the Coorong and adjacent lakes, shelly invertebrate remains are major contributors to bioclastic sediments. Of the molluscs (Ludbrook 1984), the small cockle *Spisula* (*Notospisula*) *trigonella* and an even smaller snail, *Coxiella striata*, are particularly evident. At a microscopic scale there are distinctive species of foraminifera, principally species of *Ammonia* and *Elphidium* (Cann & De Deckker 1981; Cann et al. 2000; Lower et al. 2013) and ostracods, notably *Osticythere baragwanathi* and *Leptocythere lacustris* (De Deckker & Geddes 1980; De Deckker 1981; Lower et al. 2013).

THE YOUNGHUSBAND PENINSULA AND COORONG: A MODEL FOR EARLIER COASTAL BARRIERS AND LAGOONS

From the town of Meningie to south of Salt Creek, the Princes Highway mostly follows the Last Interglacial shoreline, with the MIS5e coastal barrier elevated up to 40 m on the landward side. Immediately inland of this barrier, wetlands and ephemeral lakes mark the remnants of the Last Interglacial back-barrier lagoon (Figs. 2.5.3 & 2.5.4). Some exposed sediments of this Last Interglacial lagoon have revealed fossil remains of *Anadara trapezia*, a distinctive species of bivalve that has served as an indicator species for the Last Interglacial Glanville Formation in South Australia (Ludbrook 1984 and references therein).

Further south-east, near the town of Robe, drainage excavations through the Last Interglacial Woakwine Range revealed a physical stratigraphy, dominated by sand dune structures, which is in accord with the seaward side having formed under the influence of the Southern Ocean, and the landward sediments having prograded over the more muddy sediments of a back-barrier lagoon. These inferences are supported by the occurrence of fossil coastal shelf foraminifera (e.g. *Elphidium crispum*) in the seaward sediments and fossil lagoonal foraminifera (e.g. *Ammonia* sp.) in the back-barrier sediments (Murray-Wallace et al. 1999). Early accounts of the internal stratigraphy of the ‘Drain L Cutting’ (Sprigg 1952) noted the presence of several calcrete paleosols, signifying episodes of subaerial exposure. At least one of these calcrete bodies was exposed to the open ocean for a time; Cann et al. (1991) reported the presence of *Haliotis* sp. (abalone) and *Turbo* (large edible marine gastropod), molluscs that typically live on rocky coasts, as supporting evidence. These observations confirm that the Last Interglacial Woakwine Range was constructed during several episodes of high sea level.

Across the gently uplifting, otherwise featureless Coorong Coastal Plain, between Robe and Naracoorte, there are many 'ranges' that are morphologically similar to Woakwine Range and essentially parallel with each other and the modern coast. Each is associated with back-barrier lagoon deposits. Numerical dating of these couplets reveals increasing age inland towards Naracoorte (Murray-Wallace et al. 2001 and references therein). Thus there has emerged a consistent geomorphic pattern of coastal evolution. When sea levels are high during times of warm global climate, transgressive waves construct coastal beach-dune barriers, behind which are formed shallow back-barrier lagoons. The modern Younghusband Peninsula and associated Coorong Lagoon are the most recent manifestation of this pattern and provide a robust model for interpretation of these older coastal barriers.

SEDIMENT CORES FROM THE COORONG

Sediment cores were obtained from 30 sites over the length of both the northern and southern lagoons to investigate the history of Holocene sedimentation in the Coorong (Gell & Haynes 2005). One of these cores, Coorong #5, was subjected to detailed analysis of its preserved fossils, principally the micro-organisms foraminifera and ostracods (Lower et al. 2013). Molluscs (e.g. Peacock 1993), foraminifera (e.g. Murray 1991), ostracods (e.g. Frenzel & Boomer 2005) and oogonia, the calcified reproductive organ of the subaqueous charophyte plant (e.g. Burne et al. 1980), both individually and collectively, have provided useful proxies in palaeoecological reconstructions, in a variety of aquatic environments.

Core Coorong #5

The core Coorong #5, which recovered 594 cm of Holocene sediment, was taken in the northern Coorong Lagoon, about 25 km south-east of the Murray Mouth, and 15 km from the southernmost (Tauwitcherie) barrage (Fig. 2.5.2). Water depth there was 1.6 m. The following observations were reported by Lower et al. (2013).

The core sediments were essentially monotonous, fine sandy to silty grey mud, grading to fine sand at depth, with shells and shell fragments scattered throughout, commonly in discrete bands (Fig. 2.5.5). Bivalve shells were mostly representative of *Spisula* (*Notospisula*) *trigonella* (Figs. 45m, n, o in Ludbrook 1984), but there were also several well-preserved valves of *Tellina* (*Eurytellina*) *albinella* (Figs. 48a, b in Ludbrook 1984). Rare shells of the small gastropod *Coxiella* sp. were present at several intervals.

Sediment samples were taken as 2 cm sections from the top of the core and at 10 cm intervals downcore (e.g. 20-22 cm, 30-32 cm) and prepared for microscopic analysis of their components of foraminifera, ostracods and oogonia. Most samples yielded microfossils, all of which were identified (Yassini & Jones 1995; Hayward et al. 1999) and transferred to standard microfossil slides. Selected specimens were further examined using a scanning electron microscope, providing the images included in this chapter (Fig. 2.5.6).

Four bivalve shell specimens were selected from the core for radiocarbon dating at the Waikato Radiocarbon Dating Laboratory in New Zealand (Table 2.5.1). Organic matter in the bottom sediment of the core was also dated (McKirdy et al. 2010). The first appearance of preserved *Pinus* pollen was used as a proxy record for the commencement of European influence.

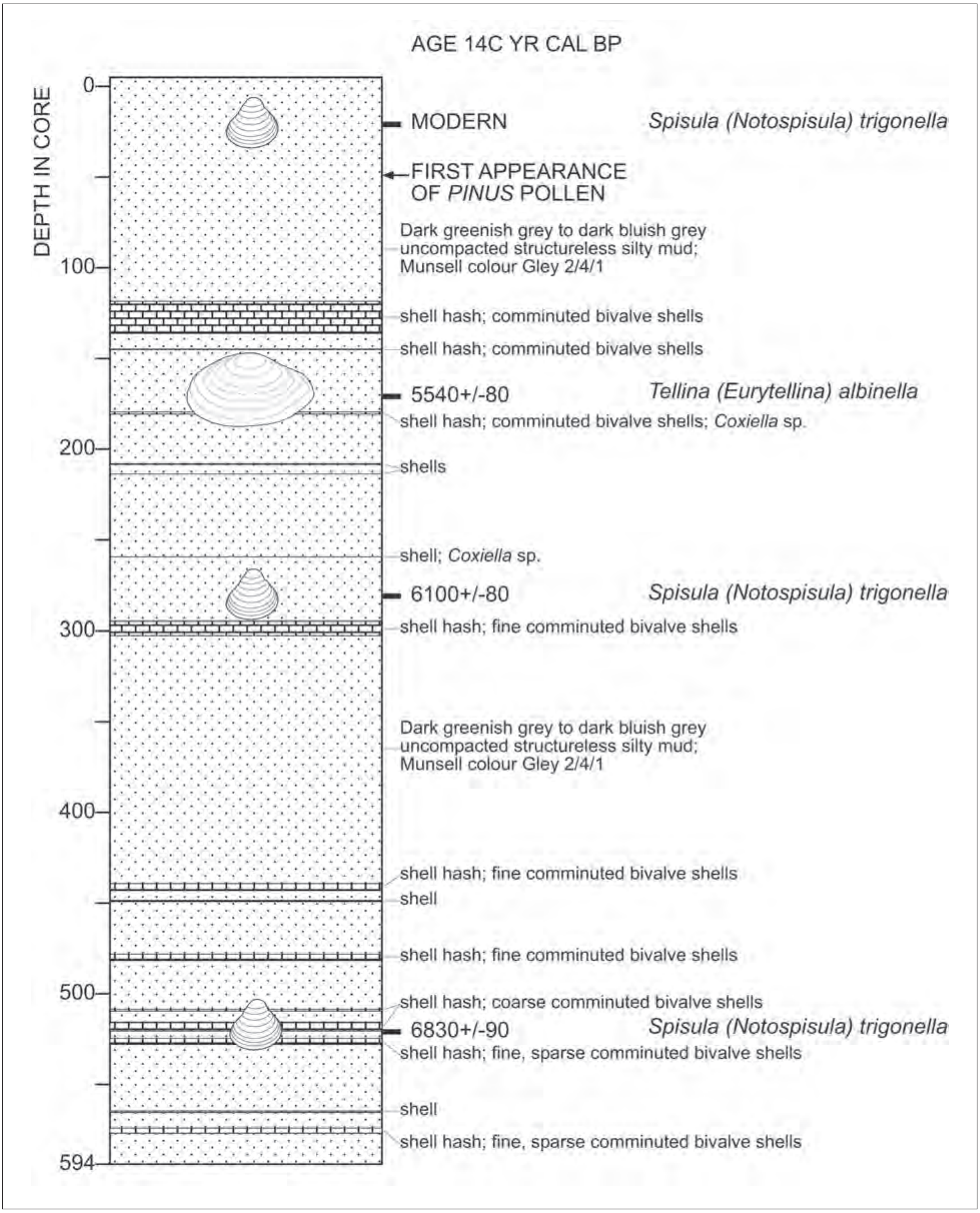

Figure 2.5.5 Lithological log of core Coorong #5 (adapted from Lower et al. 2013). The recovered sediments comprise uncompacted, structureless, silty mud, with scattered sparse shell fragments and intervals of shell hash. Also shown are the core intervals from which bivalve shells were taken for radiocarbon analysis, together with their calibrated ages. The first appearance of *Pinus* pollen signifies the onset of European settlement in the catchment of the River Murray. The images of the bivalve shells are symbolic only and are not drawn to scale.

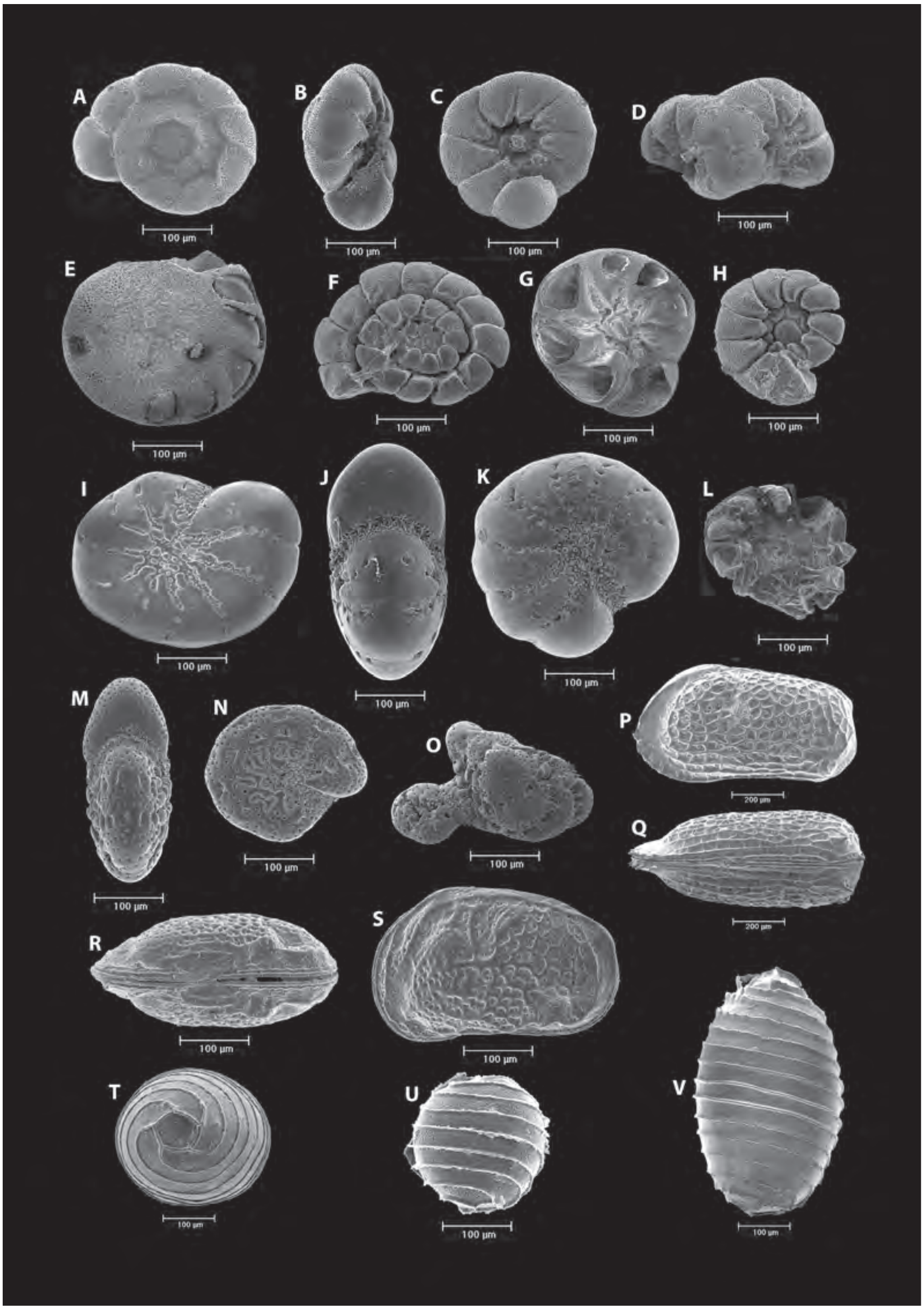

Figure 2.5.6 Scanning electron photomicrographs of microfossils from core Coorong #5 (adapted from Lower et al. 2013).
A-D: *Ammonia* sp. [= *Ammonia beccarii* of Cann & De Deckker (1981) and Cann et al. (2000)] A, dorsal view; B, apertural view; C, ventral umbilical view; D, aberrant twin.
E-H: examples of dissolution of tests of *Ammonia* sp.; E-F, dorsal views; G-H, ventral umbilical views.
I-L: *Elphidium excavatum*; I, general view; J, edge apertural view; K, general view of test showing minor dissolution; L, general view of test that has undergone dissolution exposing the inner organic layer.
M-O: *Elphidium gunteri*; M, edge apertural view; N, general view; O, aberrant twin.
P-Q: *Osticythere baragwanathi*.
R-S: *Leptocythere lacustris*.
T-V: Oogonia.

Table 2.5.1

Sample depth in core (cm)	Laboratory code	Material dated	Reported radiocarbon age (yr BP)	Calibrated age (yr cal BP)
20-22	Wk-19373	*Spisula (Notospisula) trigonella*	118.5±0.41%M	modern
170-172	Wk-19374	*Tellina (Eurytellina) albinella*	5271±36	5540±80
280-282	Wk-19375	*Spisula (Notospisula) trigonella*	5779±34	6100±80
520-522	Wk-19376	*Spisula (Notospisula) trigonella*	6448±38	6830±90
592-593	Wk-17296	Dried mud	5334±37	6110±70

Pinus radiata is an exotic species, first introduced to south-eastern Australia by Europeans, largely as a plantation timber, and its detection in sediments has become an accepted method to recognise the post-European phase of a sedimentary succession (Tibby 2003). The depth at which *Pinus* pollen first appears upcore potentially provides a maximum age of 1840 CE. The first appearance of *Pinus* pollen in this core was recognised at 49 cm.

Radiocarbon ages

The four calibrated AMS ^{14}C ages derived for shell samples are in accord with the stratigraphic positions from which they were taken, ranging from 6830±90 yr cal BP at a core depth of 520 cm to essentially modern at 20 cm (Table 2.5.1). The sample of organic sediment from close to the base of the core yielded a calibrated age of 6110±70 yr cal BP (McKirdy et al. 2010), some 700 years younger than the calibrated age recorded for the oldest shell, 70 cm higher in the core.

Foraminifera

Ammonia sp. (Fig. 2.5.6A-D) is the most common foraminifer present in the core sediment samples (*Ammonia beccarii*, in the sense of Cann & De Deckker 1981 and Cann et al. 2000). Tests of this species first appear within the shelly interval at 520-522 cm (300 individuals). Upcore, it is absent or rare until 260-262 cm (204 individuals); from 190-192 cm several intervals yielded numbers >100; intervals 130-132, 30-32 and 20-22 cm each yielded >1 000 (Fig. 2.5.7). The state of preservation of *Ammonia* sp. is variable, ranging from pristine, with glass-like, calcite walls, to individuals that have suffered total dissolution of carbonate and are represented by the organic membrane only (Fig. 2.5.6E-H). This latter form of preservation, which effectively represents an internal mould of the test, is most common in samples from 40-42 cm to 80-82 cm inclusive. These organic moulds record the structural features of the test in exquisite detail, including the trochospiral form, the umbilical plug and perforations of the outer wall.

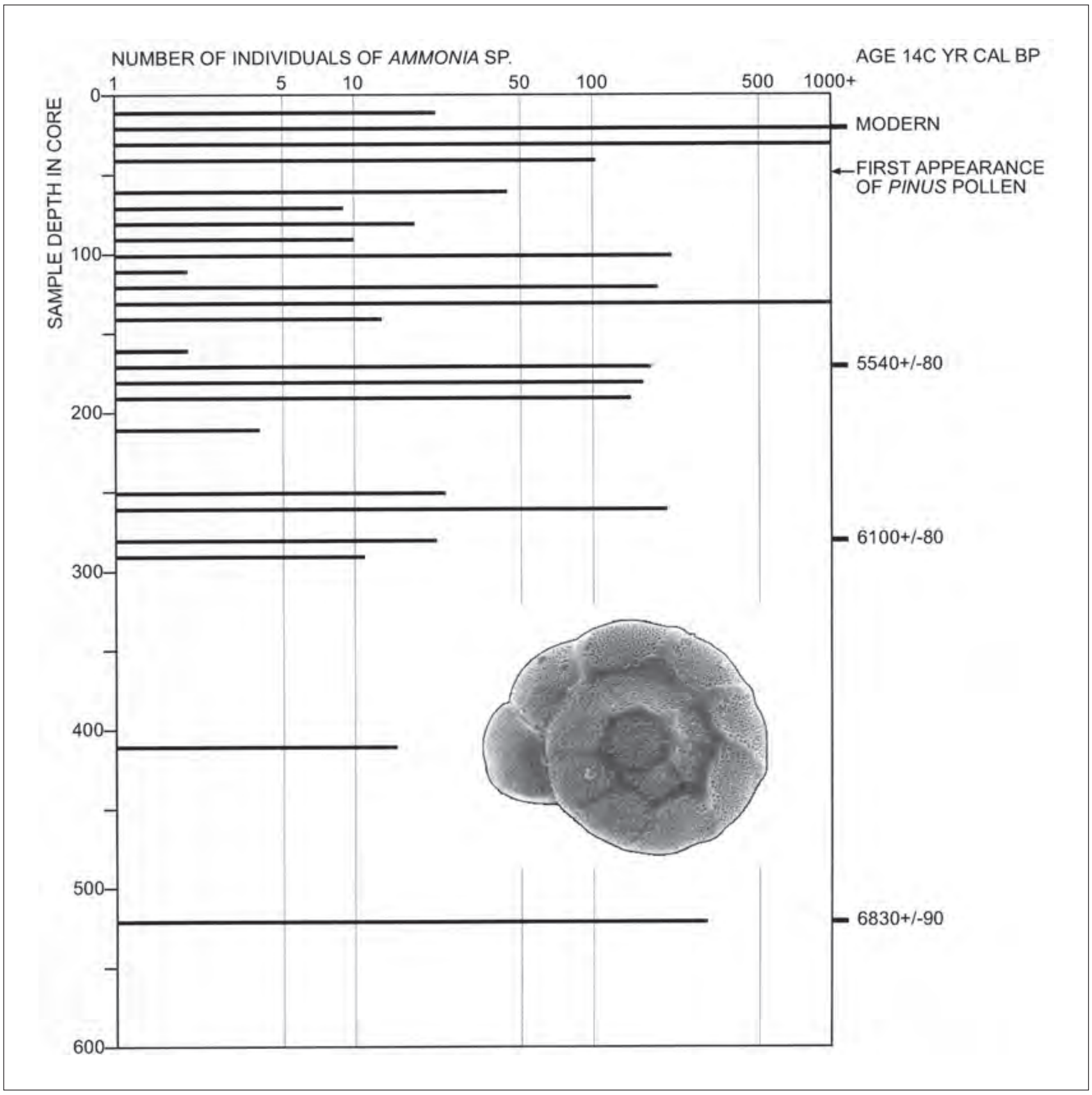

Figure 2.5.7 Numerical distribution of tests of the foraminifer *Ammonia* sp. in Coorong #5 (adapted from Lower et al. 2013). Note that the horizontal scale is logarithmic. Also shown are the calibrated radiocarbon ages determined from mollusc shell analyses. The first appearance of *Pinus* pollen indicates evidence of early European settlement.

Elphidium excavatum excavatum (Fig. 2.5.6I-K), in the sense of Hayward et al. (1997), is less common. This species is present in fewer intervals, and is also less abundant (Fig. 2.5.8), represented by >10 individuals at only four sampled intervals: 260-262 (43), 130-132 (58), 30-32 (84) and 20-22 cm (81), intervals where *Ammonia* sp. is also abundant. Individuals of pristine appearance are rare; the majority of specimens have slightly etched, opaque walls and a few are represented by only the inner organic layer (Fig. 2.5.6L). However, preservation of the tests of *E. e. excavatum* is generally better than that observed for those of *Ammonia* sp.; the better-preserved specimens occur towards the top of the core.

A second species of *Elphidium, E. gunteri* (Fig. 2.5.6M, N), in the sense of Hayward et al. (1997), is confined to the upper part of the core (Fig. 2.5.9) where it is abundant in the intervals 30-32 and 20-22 cm (875 and 1 520 individuals, respectively). Tests of this species are generally better preserved than those of *Ammonia* species. However, there are many specimens that lack the calcitic chamber walls on the outer whorl, exposing the inner organic membrane,

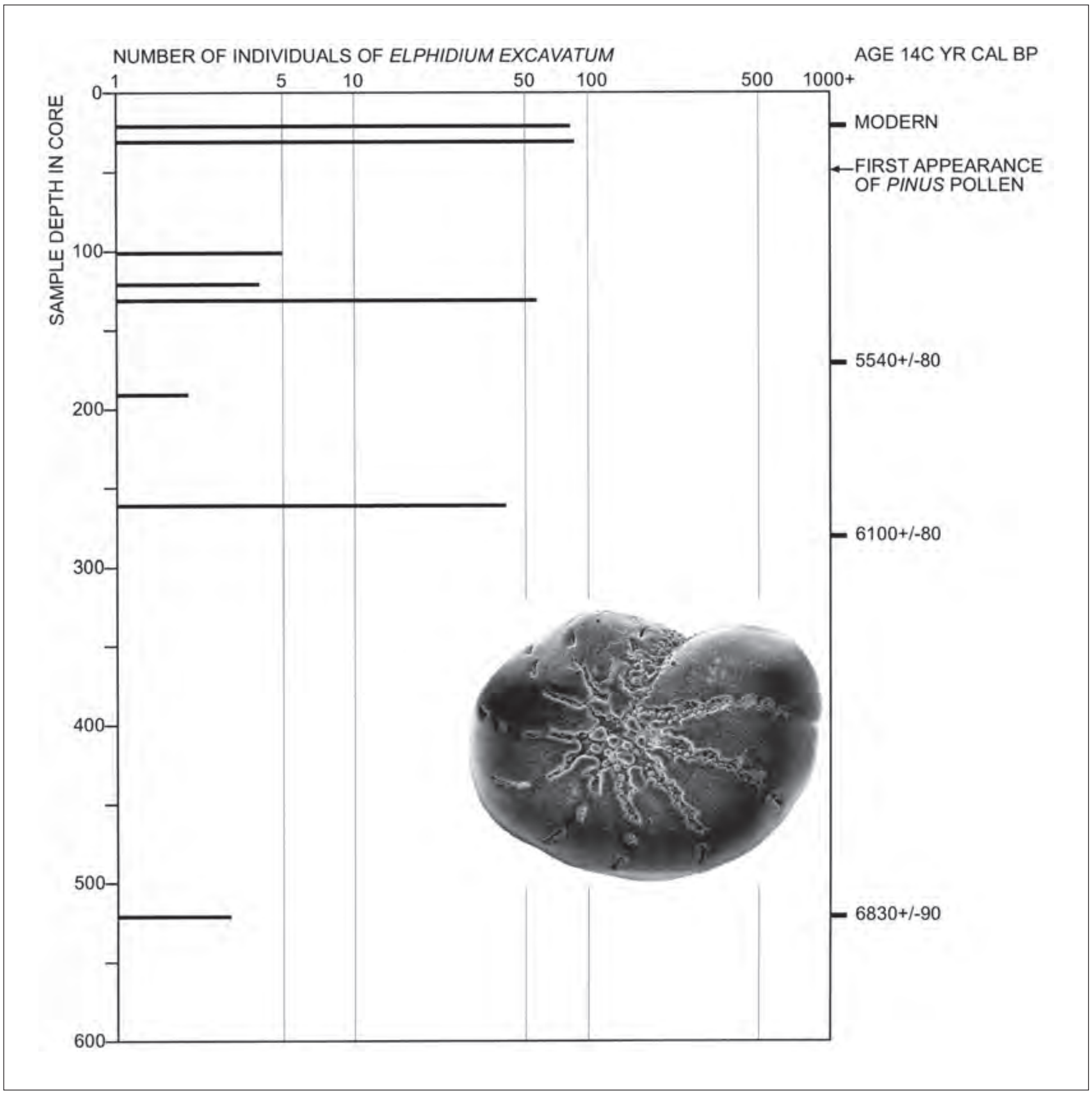

Figure 2.5.8 Numerical distribution of tests of the foraminifer *Elphidium excavatum* in Coorong #5 (adapted from Lower et al. 2013). Other details are as for Figure 2.5.7.

and there are rare, completely decalcified tests. Aberrant specimens of *E. gunteri* are common in the preserved assemblages. Features such as the perforate test wall, sutures, septal bridges, tubercles and aperture all show aberrant variation, and in extreme cases additional chambers distort the shape of the involute whorl and associated sutures (Fig. 2.5.6O).

Ostracods

Osticythere baragwanathi (Fig. 2.5.6P, Q), in the sense of Yassini and Jones (1995), is the dominant ostracod species observed in the core sediments, represented by both adult and juvenile carapaces. Below 130 cm, specimens of *O. baragwanathi* are rare, but substantially larger numbers occur at 130-132 and 120-122 cm (80 and 27 individuals respectively). The acme of *O. baragwanathi* occurs at 30-32 and 20-22 cm, where there are 419 and 515 individuals respectively (Fig. 2.5.10). Both articulated and disarticulated valves are preserved and many are etched and of opaque appearance; pristine valves were observed only in the intervals 30-32 cm and higher.

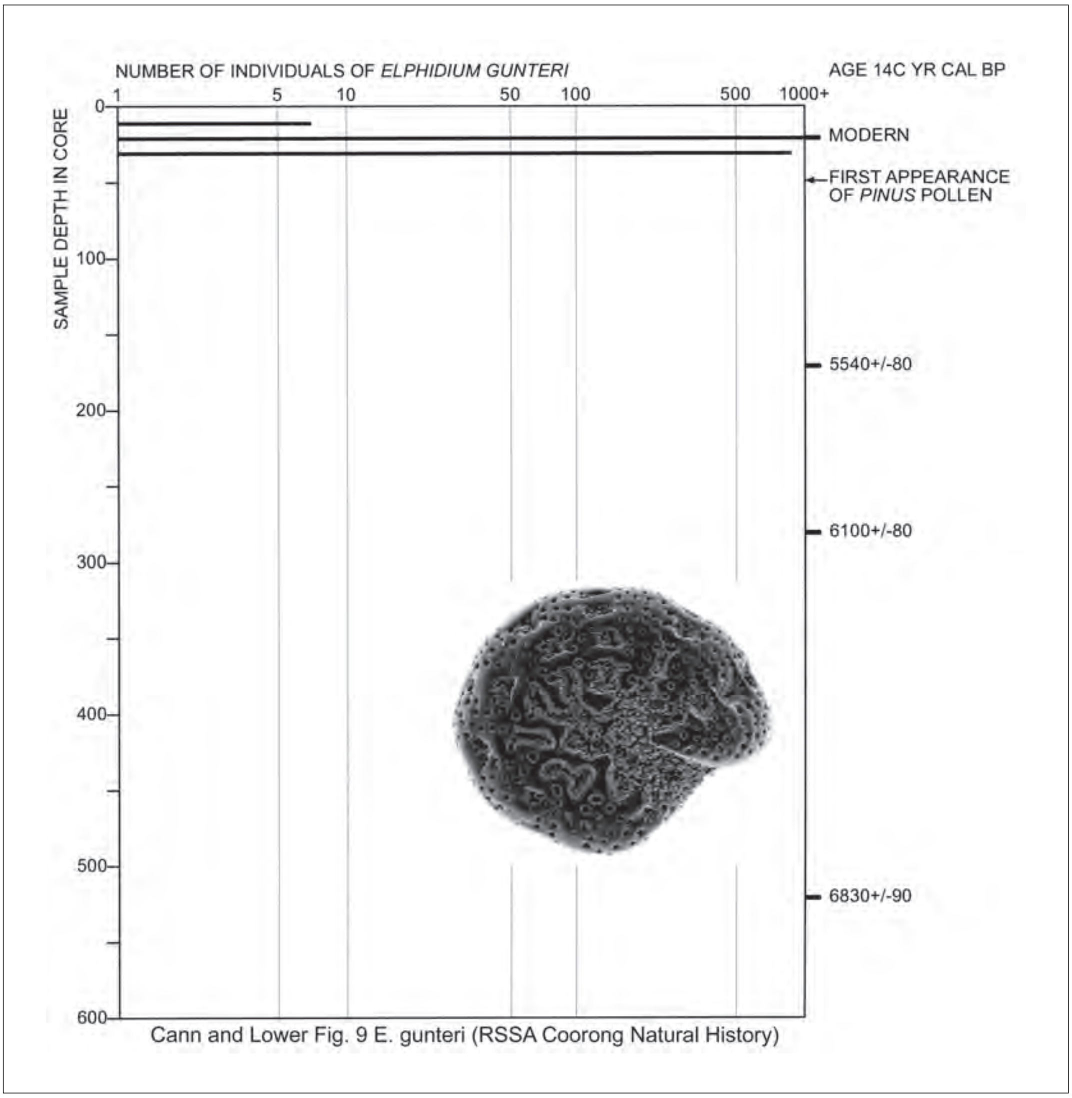

Figure 2.5.9 Numerical distribution of tests of the foraminifer *Elphidium gunteri* in Coorong #5 (adapted from Lower et al. 2013). Other details as for Figure 2.5.7. Tests of *E. gunteri* do not occur below the *Pinus* horizon. Adapted from Lower et al. (2013).

Leptocythere lacustris (Fig. 2.5.6R, S), in the sense of Yassini and Jones (1995), is the only other species of ostracod observed in the core sediments. It is abundant in the interval 20-22 cm (90 individuals), where articulated valves are common, well preserved and of similar size. Elsewhere the species is represented by just a few scattered valves (Fig. 2.5.11).

Charophyte oogonia

Black, elongate and spirally ornamented specimens, ~250 µm in size, were identified as the female reproductive organs of aquatic plants known as charophytes (Fig. 2.5.6T-V). They are known to grow as water plants in a variety of non-marine environments (Burne et al. 1980; Garcia et al. 2002) and their calcified reproductive organs, oogonia, have proved useful as microfossils (e.g. Cann et al. 2006). Oogonia are present in the basal sediments of the core, but their occurrence upcore is sporadic and they are few in numbers until the interval 170-172 cm (22 individuals). Higher in the core, substantially larger numbers occur at 130-132 cm (155) and >100 individuals were counted for each of the four intervals 50-52 to 20-22 cm, inclusive (Fig. 2.5.12).

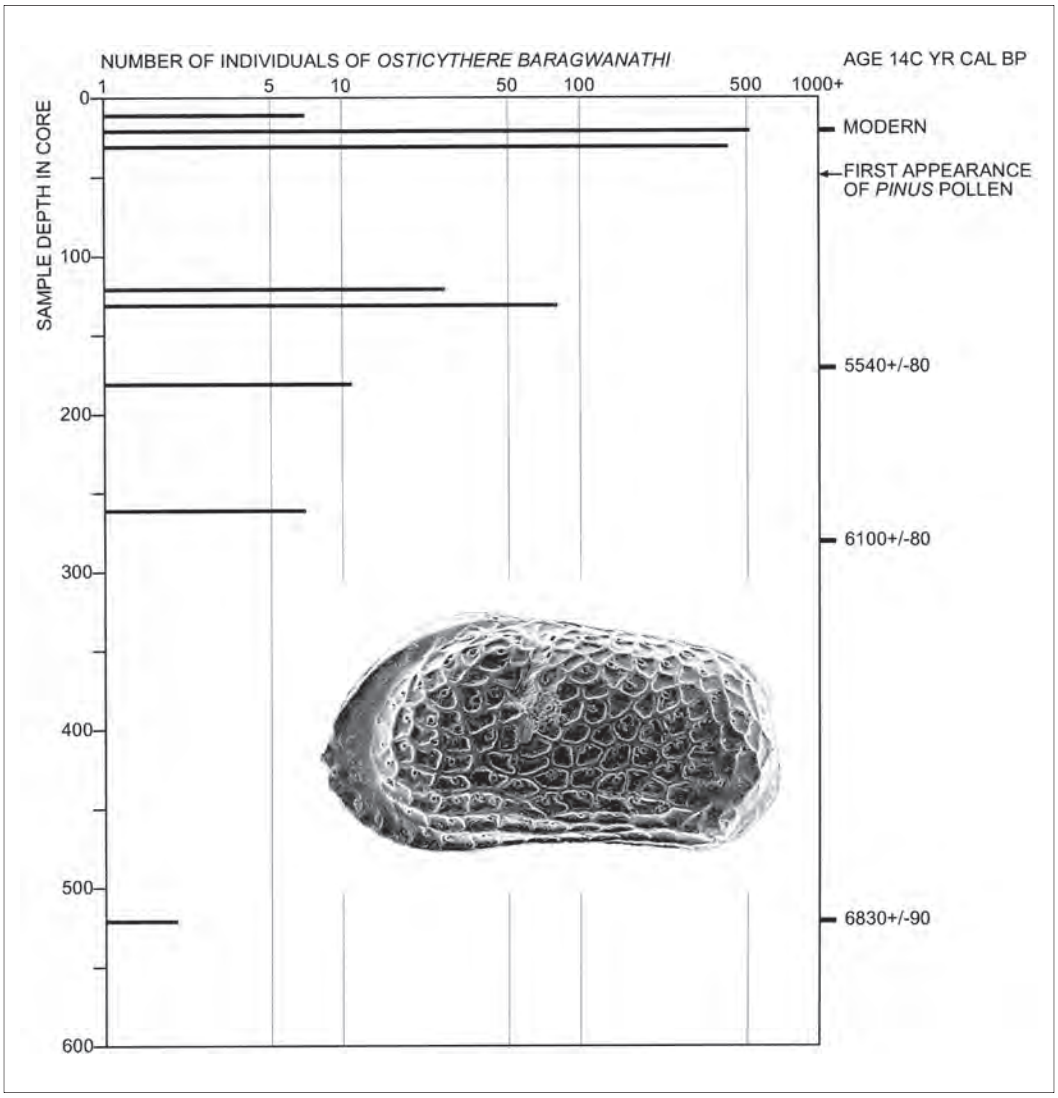

Figure 2.5.10 Numerical distribution of carapaces of the ostracod *Osticythere baragwanathi* in Coorong #5 (adapted from Lower et al. 2013). Other details are as for Figure 2.5.7.

ENVIRONMENTAL PROXIES

We now consider the potential of these organisms, preserved as fossils in the core Coorong #5, to provide evidence of the successive environmental conditions that prevailed at the core site in the northern Coorong Lagoon, following culmination of the postglacial marine transgression. We note the known present-day life requirements of the identified examples of molluscs, foraminifera, ostracods and charophyte oogonia and evaluate their potential significance as environmental proxies. Thus, within a timeframe of calibrated radiocarbon ages, we seek to construct a geological history.

Molluscs

Spisula (*Notospisula*) *trigonella* is the dominant bivalve species preserved in the core sediments. This infaunal species is common in estuarine settings throughout southern Australia, living in muddy sediments. Populations are known to rapidly decline and later re-establish in large

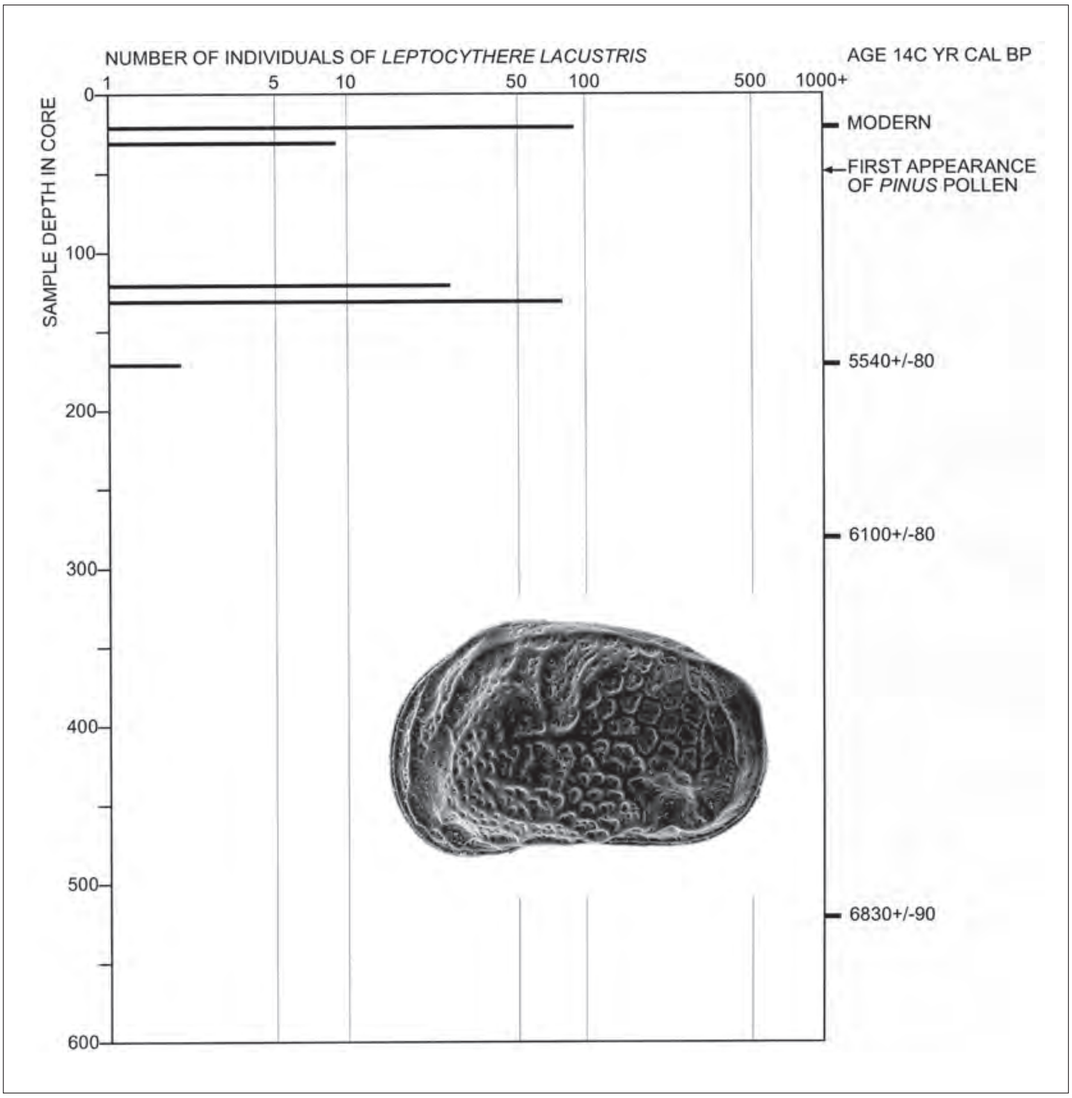

Figure 2.5.11 Numerical distribution of carapaces of the ostracod *Leptocythere lacustris* in Coorong #5 (adapted from Lower et al. 2013). Other details as for Figure 2.5.7.

numbers equally suddenly (Ludbrook 1984). In a study of molluscs in a Western Australian estuary, Cresswell et al. (2000) noted that the abundance of this species decreased markedly with increased salinity and that it was intolerant of hypersaline conditions. Thus the sporadic and concentrated occurrence of the species as shell bands in the core (Fig. 2.5.5) is probably an expression of such population dynamics and signifies hyposalinity.

Foraminifera

While there are core intervals in which *Ammonia* sp. is the only foraminiferal species present, there are no intervals in which either of the species of *Elphidium* appears without an accompanying presence of *Ammonia* species. Thus, in the first instance, we consider the environmental requirements of *Ammonia* species. Laboratory studies have shown that, while *Ammonia beccarii* can briefly tolerate fresh water, growth and reproduction are possible only within a salinity range of 15-40‰, and they are most effective at values commonly recorded for normal sea water, about 34‰. High temperatures of ~35 °C are fatal and most successful reproduction is constrained

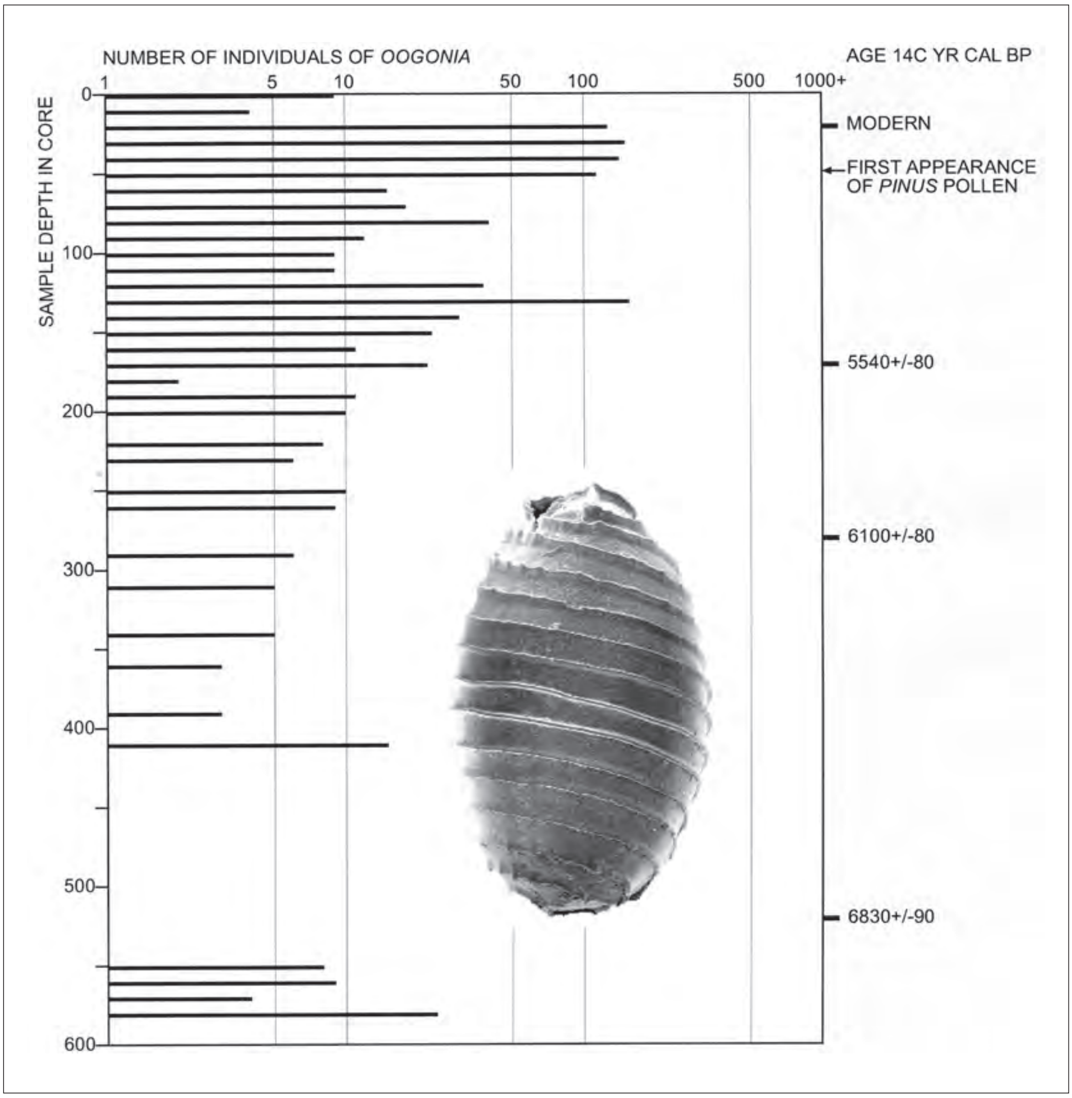

Figure 2.5.12 Numerical distribution of charophyte oogonia in Coorong #5. Calcified oogonia are rare throughout the core; most of the fruiting bodies of these aquatic plants are non-calcified, black and elongate. Other details as for Figure 2.5.7. Adapted from Lower et al. (2013).

to 20-30 °C (Bradshaw 1957, 1961). In field studies this species is widely reported from coastal lagoons, inlet channels of coastal lagoons and estuaries (e.g. Yassini & Jones 1995; Nash et al. 2010) where it thrives in brackish waters. Lacking competition from other species that require normal seawater salinity, *A. beccarii* occurs in large numbers in assemblages of low diversity. Thus it would seem that where ≥ 1 000 individuals of *Ammonia* sp. were observed for a core interval, those sediments were deposited under conditions that were favourable for growth and reproduction of the species, water temperatures 20-30 °C and salinity >15‰ but <34‰.

Subspecies of *Elphidium excavatum* commonly occur with *Ammonia* sp. in euryhaline environments. *E. e. clavatum* (species B of Cann & De Deckker 1981) and *E. e. excavatum* (species A of Cann & De Deckker 1981) are restricted to brackish or marginal marine environments, such as shallow-water coastal lagoons and estuaries (Hayward et al. 1997). The assemblages reported by Cann and De Deckker (1981) were mostly from ephemeral saline lakes adjacent to the Coorong Lagoon and from a permanently saline lake further south near the town of Robe. It was shown that *E. excavatum* is able to survive the drying-out phases of the ephemeral lakes, but *Ammonia* sp. (*A. beccarii* of Cann & De Deckker 1981) requires permanent water to sustain a reproductive population. Numbers of *E. excavatum* did not exceed those of *Ammonia* sp. in any of the Coorong #5 core sediment samples, so the relative abundance of these two species of foraminifera provides no evidence of hypersalinity.

In New Zealand *E. gunteri* is restricted to brackish environments, most commonly in muddy substrates, in the middle and seaward parts of estuaries, and in the intertidal, upper reaches of inlets and harbours, always in association with *Ammonia* sp. (Hayward et al. 1997). In Australia, Apthorpe (1980) recorded the species (as *Elphidium oceanensis*), again in association with *Ammonia* sp., from the Gippsland Lakes near Lakes Entrance, Victoria. The spectacular first appearance of *Elphidium gunteri* in the interval 30-32 cm is immediately higher in the core than the first appearance of *Pinus* pollen, which signifies European anthropogenic influence. It seems likely that the sudden and extraordinarily successful development of the population of *E. gunteri* was related in some way to changed water conditions, probably human-induced.

Dissolution of the tests of *Ammonia* sp. (Fig. 2.5.6E-H) observed in intervals from 80-82 to 40-42 cm inclusive, but not elsewhere in the core, also signifies changed environmental conditions. Similar dissolution of tests of *A. beccarii* has been reported from saltmarsh sediments by Murray and Alve (1999). It is possible that dissolution of $CaCO_3$ tests resulted from increased amounts of organic matter and reduced pH. However, it is also likely that dissolution signifies increased influence of fresh water. In contrast to sea water, which is essentially saturated in Ca^{2+} and HCO_3^- in shallow coastal environments, fresh water is generally under-saturated and so has the potential to dissolve shell material. We believe it is likely that an increased influx of fresh water from the River Murray could be signified by these organic internal moulds of *Ammonia* species.

Ostracods

Osticythere baragwanathi is widely recognised as a species characteristic of lagoonal environments in which fluctuations in salinity and dissolved oxygen occur (e.g. Yassini & Jones 1995). The coincidental occurrence of this species with maximum numbers of the foraminifer *Ammonia* sp. supports the interpretations expressed above.

De Deckker (1981) reported the occurrence of *Leptocythere lacustris* from permanent lakes in the vicinity of Robe, South Australia, in which salinity ranged from 19‰ to 28‰. It is known that the species can accommodate much lower salinity values, but probably not hypersaline waters. The only major occurrence of *L. lacustris* in the core is coincident with maximum numbers of *O. baragwanathi*, thus also supporting the above interpretations.

Charophyte oogonia

Calcified oogonia are rare throughout the core; most of the fruiting bodies of these aquatic plants are non-calcified, black and elongate. While there is a general trend of increasing numbers upcore, the significance of this observation is not immediately apparent, given that charophytes are known to tolerate a wide range of salinity in non-marine environments. In the upper part of the core, the intervals that yielded the maximum numbers of foraminifera and ostracods are also those in which >100 oogonia were counted. These data are thus in accord with those derived for the other microfossils.

CHRONOLOGY

The core Coorong #5 recovered 594 cm of uncompacted sediment. Organic sediment from close to the base of the core yielded a radiocarbon age of 6110±70 yr cal BP (McKirdy et al. 2010). The four radiocarbon ages derived for molluscan shell samples are in accord with the stratigraphic positions from which the shells were taken, ranging from 6830±90 yr cal BP at a core depth of 520 cm. This age approximates to the estimated time of culmination of the postglacial marine transgression. Given that the analysed shell from 520 cm was ~70 cm higher in the core than the organic sediment that yielded an age some 700 yr younger, and given the stratigraphic coherence of the ages determined from the shell analyses, the balance of credibility does not favour acceptance of the age determined for the lowermost sediment in the core. The radiocarbon analysis of the shell from a core depth of 20 cm, which indicated that it is essentially modern, is in accord with the first appearance of *Pinus* pollen at a core depth of 50 cm, as a proxy for the onset of European activity.

The radiocarbon ages determined from shell analyses signify that the lower two-thirds of the core were deposited from approximately 7 000 to 5 500 yr before present (BP). This relatively rapid rate of sedimentation can be related to high rates of freshwater flow from the River Murray at this time. Studies of Holocene sediments taken from the maar Lake Keilambete in central western Victoria reveal that this was a time of prolonged high rainfall (Bowler & Hamada 1971; Dodson 1974; Bowler 1981; Chivas et al. 1985, 1986). The younger pre-modern sediments were deposited at a much-reduced rate, corresponding to a more arid climate that has also been inferred from the Lake Keilambete studies.

SALINITY EVENTS IN THE COORONG BEFORE EUROPEAN SETTLEMENT

Scattered shell fragments in the lowermost 70 cm of Coorong #5 are evidence that these sediments were subject to some marine influence, but the absence of foraminifera (including absence of organic membrane moulds (e.g. Fig. 2.5.6E-H) that might otherwise have survived dissolution) and ostracods from these same sediments indicates that at the core site salinity was not sufficient to support populations of these organisms. Thus it may be assumed that prior to 6830±90 yr cal BP the Younghusband Peninsula was in place, effectively isolating at least the northern reaches of the northern lagoon from the Southern Ocean, and that freshwater inflow from the River Murray was the dominant factor influencing salinity at the core site.

An initial salinity event is signified by 300 tests of *Ammonia* sp. for the core interval 520-522 cm (6830±90 yr cal BP), signifying reduced inflow of fresh water and salinity at a level adequate for the establishment of this foraminifer. *Ammonia* sp. is a minor component of the modern coastal shelf fauna, where it competes with many more successful species, but it thrives in the hyposaline lagoon environment, where there is little or no competition. However, successful occupation at the core site was apparently brief.

Similar substantial numbers of *Ammonia* sp. do not reappear for about another 700 years, when the lagoon was again sufficiently saline to support a viable population; the core interval 260-262 cm yielded 204 individuals of this species, accompanied by 43 tests of *E. excavatum*. What is the explanation for this absence of foraminifera? Studies of sediment cores taken from the maar Lake Keilambete in central western Victoria identified maximum water levels to overflow about 6 000 years ago (Bowler & Hamada 1971; Dodson 1974; Bowler 1981; Chivas et al. 1985, 1986). Regional high rainfall for this time can be inferred from the Lake Keilambete data, which in turn indicates high levels of freshwater flow in the River Murray. The large volumes of fresh water that were delivered to the Coorong Lagoon at that time were sufficient to dilute salinity to unviable levels.

Evidence from other cores

These observations and inferences are in accord with those of Fluin et al. (2007) who reported specifically on Coorong cores #3 and #7 (Fig. 2.5.2). On the evidence of the preserved diatoms, they noted that for the mid-Holocene interval of core Coorong #3 (C3 in Fig. 2.5.2) 'river flora made a notable contribution to the fossil assemblage' (p. 132). However, they further concluded that, for the last 5 000 to 4 000 years, there had been reduced riverine influence, giving way to 'a prevailing marine influence with salinity levels varying within the subsaline range' (p. 132). Not surprisingly, Fluin et al. (2007) noted that the greatest changes in the diatom flora were associated in time with European settlement.

An age of 14C 6327±40 yr BP is shown for the basal sediments of this core, but on the evidence of the spurious age derived from radiocarbon analysis of organic sediment in Coorong #5, they are probably older. Thalassic diatoms reported from these basal sediments probably signify marine influence at the site of sedimentation, at about the time of the culmination of the transgression and in the early stages of formation of the coastal barrier. Subsequently, emplacement of the Younghusband Peninsula established at least the northern back-barrier Coorong Lagoon, effectively isolating the core site from the Southern Ocean, and thus ensuring substantial containment of freshwater flows from the River Murray.

Dick et al. (2011) analysed fossils extracted from a short core, representing about the past 4 000 years, taken at Villa del Yumpa, on the landward coast of the southern lagoon (Fig. 2.5.2). They noted that tests of the foraminifera *Ammonia* aff. *aoteana* and *Elphidium excavatum* were preserved throughout the core and that the ostracod *Osticythere baragwanathi* was present in the near-basal sediment. They concluded that prior to European settlement, water in the southern lagoon, in the vicinity of the core site, had been predominantly, or frequently, below the salinity of sea water. Towards the top of the Villa del Yumpa core, three additional ostracod genera were identified — *Australocypris*, *Cyprideis* and *Leptocythere*. For the uppermost, post-European interval of the core, Dick et al. (2011) interpreted the range of environmental proxies to signify substantial changes in the study area, including elevated water salinity.

Cann et al. (2000) investigated assemblages of foraminifera in a core of Holocene sediment taken from the channel of the River Murray in the vicinity of Goolwa (core EB#34; Fig. 2.5.2). Relative abundances of species favouring holomarine coastal environments (e.g. *Discorbis dimidiatus*, *Elphidium crispum*) were compared with those more characteristic of lagoonal environments (principally *A. beccarii* and *E. articulatum*, the latter now recognised as *E. excavatum*). They reasoned that an abundance of coastal shelf species indicated that the mouth of the River Murray was open, while in contrast, dominance of lagoonal species was evidence that there was little or no inflow from the Southern Ocean into the estuary. Core sediments with radiocarbon ages of 3605±72 to 3535±58 yr BP preserved an assemblage dominated by lagoonal species and it was concluded that sedimentation had occurred during drought conditions. Plausible correlation with data from Lake Keilambete, which provided evidence of aridity for the same time interval, showed that drought conditions had prevailed on a regional scale. Where is the evidence for this event in Coorong #5?

Sediment of equivalent age in Coorong #5 is above 120 cm, where an age of 5540±80 14C yr cal BP was determined for mollusc shell, and below 50 cm where *Pinus* pollen first appears. The core sample 130-132 cm provided maximum numbers of *Ammonia* sp. (2 110 individuals) and that species is accompanied by the pre-European settlement maximum numbers of *Elphidium excavatum* (58), *Osticythere baragwanathi* (80) and oogonia (155). The proxy micro-organisms preserved at this horizon signify a salinity event that probably corresponds in time to the regional drought conditions identified by Cann et al. (2000).

CONCLUSIONS

In Holocene sediments of the northern Coorong Lagoon, fossil molluscs, foraminifera, ostracods and Charophyte oogonia provide a credible multiproxy record of salinity from the time of the culmination of the postglacial marine transgression through to the impact of modern anthropogenic activity. In particular, assemblages dominated by *Ammonia* sp., which tolerate a range of brackish water conditions, but which require salinity of at least 15‰, first appeared in association with the brackish water bivalve *Spisula* (*Notospisula*) *trigonella* about 6 800 years ago. These fauna signify the first salinity event following the partial isolation of the lagoon from the Southern Ocean. That event, which is attributed to reduced inflow of fresh water, was of relatively short duration. For about the following 700 years, salinity in the northern lagoon was too low to support a reproductive population of *Ammonia* sp., and this may be attributed to substantial inflow of fresh water from the River Murray. After about 5 500 years ago, populations of *Ammonia* sp. waxed and waned, signifying variable salinity. While *Ammonia* sp. was often accompanied by *Elphidium excavatum*, this latter species was never present without *Ammonia* sp. and was never dominant, thus signifying that prior to European settlement the lagoon waters were never hypersaline. A significant salinity event in the Coorong Lagoon is signified by the combined presence of maximum numbers of *Ammonia* sp., *E. excavatum*, *Osticythere baragwanathi* and oogonia, probably corresponding to regional drought about 3 500 yr BP. Since European settlement, the character of the water in the northern Coorong lagoon has changed in ways that have favoured the introduction and rapid expansion of populations of *Elphidium gunteri*. Many individuals of this species exhibit aberrant tests; aberrance is usually taken to signify some form of adverse environmental condition, such as anoxia.

ACKNOWLEDGEMENTS

The analyses of fossil micro-organisms in core Coorong #5 were data acquired by Chantelle Lower as part of her B.App.Sc. Honours research. The core was one of a suite funded by an Australian Research Council Linkage Grant to Peter Gell, David McKirdy and John Tibby, in which the industry partners were the Department of Water, Land and Biodiversity Conservation and the Department of Environment and Heritage, South Australia. Funding for the radiocarbon analyses of mollusc shells was provided by the University of South Australia.

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CHAPTER 2.6

THE ROLE OF CLIMATE IN SHAPING THE COORONG, LOWER LAKES AND MURRAY MOUTH

DEIRDRE D. RYAN[1]

INTRODUCTION

Climate is generally recognised as the average weather for a region, derived from the means of surface variables such as temperature, precipitation and wind on timescales ranging from months to millions of years (Baede et al. 2001). Statistically significant deviations from those means, persisting for decades or longer, are recognised as climate change. Past climatic changes and associated fluctuations in sea level have greatly influenced the development of the Murray Estuary, which encompasses the Coorong, Lower Lakes and Murray Mouth (CLLMM). The Quaternary Period (2.588 Ma to present) is characterised by marked global climate oscillations and the repeated growth and decay of continental ice sheets, associated with substantial fluctuations of global (eustatic) sea level (Woodroffe 2002; Miall 2010; Murray-Wallace & Woodroffe 2014). It is important to fully understand how climatic and associated sea-level changes have impacted landscape development so that we can be better prepared for the consequences of future changes.

This chapter provides an understanding of how climate change through the Quaternary has shaped the regional landscape, and how the variability of the modern climate and River Murray regulation has impacted on the ecology of the Murray Estuary. The chapter begins with a short review of the impetus behind Quaternary global climate change, as explained by the Milankovitch Hypothesis. This is followed by a brief discussion of what the sedimentary record of the Murray Estuary landscape tells us about palaeoclimates, before a more comprehensive discussion of Holocene and modern climates. The chapter concludes with comments on possible future climatic changes.

QUATERNARY CLIMATE CHANGE

The extremes of Quaternary climate are recognised as interglacial and glacial periods. Glacial periods with expansive continental ice sheets and lowered global sea level are generally referred to as ice ages. The most recent glacial period is known as the Last Glacial Maximum (LGM), which peaked around 26 ka to 21 ka when global sea level was ~120 m lower than present (Peltier & Fairbanks 2006). Interglacials refer to warmer climatic periods with higher global sea levels separating consecutive glacial periods. We are currently living within an interglacial period, the Holocene. The transitional period between extreme glacial and interglacial periods is characterised by interstadials (mild climates) and stadials (cool climates) and intermediate

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sea levels. The Milankovitch Hypothesis explains the global climatic oscillations and sea-level fluctuation of the Quaternary.

The Milankovitch Hypothesis

The Milankovitch Hypothesis recognises the orbital geometry of the Earth around the sun as a major force behind the fluctuation of long-term global ice volume, global climate and the cyclicity (10^4-10^5 years) of change recognised in the sedimentary record (Broecker et al. 1968; Hays et al. 1976; Chappell & Shackleton 1986; Petit et al. 1999; Zachos et al. 2001). 'Milankovitch cycles' are the result of three orbital rhythms (Box 2.6.1), which control the latitudinal seasonal distribution of incoming solar radiation, also known as insolation, and subsequently global climate (Hays et al. 1976; Plint et al. 1992; Zachos et al. 2001). These orbital rhythms produce the climatic variance of the Quaternary record through cyclical variation in the intensity and seasonal distribution of incoming solar radiation, resulting in the succession of Quaternary ice ages by affecting the summer melt period and ice sheet development.

The influence of Milankovitch cycles on the growth and decay of large continental ice sheets, and therefore on Quaternary sea level, is reflected in the records provided by deep-sea cores and polar ice sheets. The development of the sea level and climatic history of the Earth has been made possible by proxy analysis of marine sediment, oceanic oxygen isotopes and ice cores (Shackleton & Opdyke 1973; Chappell & Shackleton 1986; Zachos et al. 2001; Siddall et al. 2007). Changes within these records have been directly correlated with Milankovitch cycles and calibrated to orbital parameters to provide a timescale (Shackleton 1967, 2006). Variations in the isotopic composition of the ocean as detected in deep-sea sediment cores are used to provide a global stratigraphic record. Peaks in the record correspond with warmer intervals (interglacial or interstadial) and are assigned an odd Marine Isotope Stage (MIS) number. The strength and length of warm periods are driven by incoming solar radiation, and because radiation cycles are relatively short, interglacial peaks generally do not exceed 10 000 to 13 000 years in length (Forsström 2001; Jouzel et al. 2007). Troughs corresponding to glacials or stadials are assigned an even number. The record provides a framework of standard stages allowing correlation of Quaternary records not only from deep-sea sediments but from other proxies as well. The Holocene is assigned MIS 1, the Last Interglacial MIS 5e (~125 ka) and the intervening Last Glacial Maximum MIS 2. MIS 3 corresponds to an interstadial and MIS 4 to a stadial.

The record presented in deep-sea sediments has provided a timeframe in which the development of the Murray Estuary region has been placed. The Coorong Coastal Plain, which extends from the Lower Lakes and Murray Mouth south-east beyond Mount Gambier and into Victoria, retains a terrestrial record of Quaternary climate and sea-level change for the region. This record provides insights into the development of the region throughout fluctuations of global climate and sea level and is therefore briefly discussed before the Holocene and modern climates.

THE COORONG COASTAL PLAIN RECORD

The Quaternary Period is subdivided into the Pleistocene and Holocene Epochs, with the boundary defined by a clear climatic signal, the end of the Younger Dryas (11 700 cal yr BP),

BOX 2.6.1 THE THREE PRINCIPAL ORBITAL RHYTHMS DRIVING THE CYCLICITY OF GLOBAL CLIMATE CHANGE ARE

1. eccentricity, the shape of the orbit of the Earth around the sun from near circular to elliptical (400 ka and 100 ka oscillation)
2. obliquity, the tilt of the axis of the Earth relative to the plane in which it orbits the sun, varying between 21.8° and 24.4° (41 ka oscillation)
3. precession, the wobble of the Earth around its axis of rotation (23 ka oscillation).

The combined effect of these rhythms determines the insolation (solar radiation) that reaches the surface of the Earth.

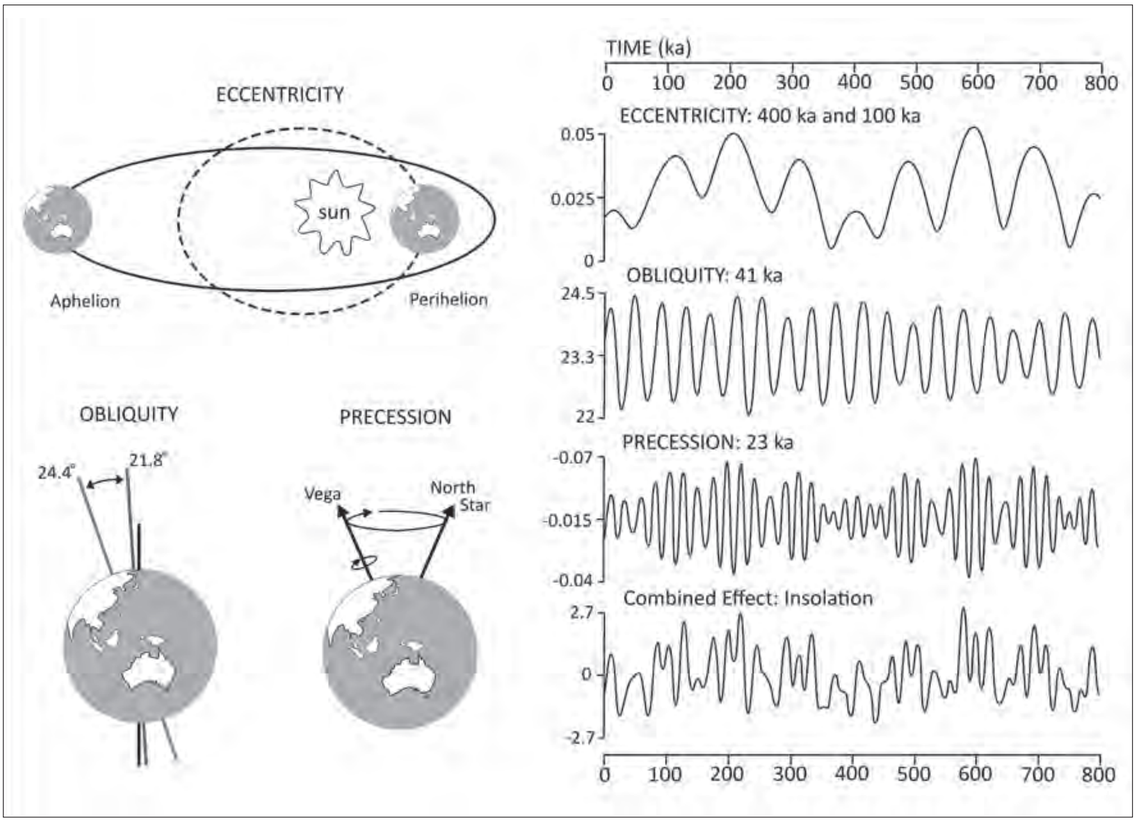


Figure 2.6.1 Variation in eccentricity, obliquity and precession over the past 800 ka and their combined effect on insolation (from Imbrie 1985). The obliquity scale is in degrees. The insolation scale is in standard deviation units.

expressed in the Northern Hemisphere as the most recent cold episode of the Pleistocene (Walker et al. 2009). Two Pleistocene-aged sedimentary successions provide a record of the Quaternary climate and sea-level fluctuation that have occurred in Southeast Australia: the interglacial Bridgewater Formation and the glacial Molineaux Sand.

The Bridgewater Formation

The Bridgewater Formation (reviewed more extensively in Chapter 2.1) is composed of coastal beach-barrier dunes, which are the Pleistocene equivalents of the modern Sir Richard and Younghusband Peninsulas. These dunes are found sub-parallel to the modern coastline and are regionally recognised as 'ranges'. For example, the Last Interglacial beach-barrier succession is known as the Woakwine Range. Each range represents a Pleistocene sea-level high-stand over the past 800 000 years (Sprigg 1952; Belperio & Cann 1990; Huntley et al. 1993; Murray-Wallace et al. 2001). Their orientation and preservation across the Coorong Coastal Plain have been a result of variable tectonics across the coastal plain, the height of successive sea-level high-stands and the development of protective calcrete surfaces.

The dunes of the Bridgewater Formation beach-barriers are similar in sediment composition (Cook et al. 1977) and orientation. The north-west to south-east trend of the barriers is transverse to the prevailing winds at the time of deposition (Sprigg 1952). The consistency in the orientation and composition of the Pleistocene beach barriers and their similarity to their modern counterparts indicate similar wind and wave regimes as well as offshore shelf environments for each interglacial represented within the record.

Preservation of the Bridgewater Formation is in part due to the formation of calcrete within the soil profile of the dunes. Calcrete is a near-surface accumulation of predominantly calcium carbonate of variable thickness, the development of which is made possible by a semi-arid climatic regime and a sufficient carbonate content within the dunes (Semeniuk & Meagher 1981; James & Choquette 1983; Milnes & Hutton 1983). The continued development of calcrete within the Bridgewater Formation throughout the Pleistocene is another indicator of a similar climatic regime during each interglacial period.

Back-barrier lagoon deposits associated with the Last Interglacial (MIS 5e) Woakwine Range are populated by fossil fauna of tropical association including the Sydney blood cockle, *Anadara trapezia*, the Shark Bay pearl oyster, *Pinctada carchariarum*, and the foraminifer *Marginopora vertebralis* (Belperio et al. 1995). The extensive distribution of the Sydney blood cockle during the Last Interglacial indicates that climate at the time was more humid than at present with more regularly sustained and less seasonally contrasting precipitation patterns. The contraction of the previous geographic range is a reflection of increasing aridity in Australia over the last glacial cycle and into the present (Murray-Wallace et al. 2000).

The Molineaux Sand

The activation and deposition of dunefields consisting predominantly of quartz sand within the Murray Basin are associated with glacial period aridity. Intensified glacial aridity is attributed to increased atmospheric circulation, reduced atmospheric moisture, possibly increased evaporation and the increased size of the continent due to lowered sea levels (King 1960; Beard 1982; Bowler 1982; Fujioka & Chappell 2010). The formation of desert dunes was promoted by aeolian processes, such as deflation acting upon a landscape with sparse protective vegetation and a supply of unbound surface materials. The predominant eastward trend of the dunefields reflects a 5° northward latitude shift of the dominating westerly 'frontal' air stream (Fig. 2.6.2); during glacial intervals the 'Roaring Forties' became the 'Roaring Thirties' (Sprigg 1982).

The Molineaux Sand dunefield is present within the Murray Estuary region as the westernmost extension of the Big Desert, which extends eastward into Victoria. The continental shelf offshore from the modern Murray Mouth, exposed during glacial periods when sea level was 125 m below present and near the continental margin, ~180 km to the south, served as

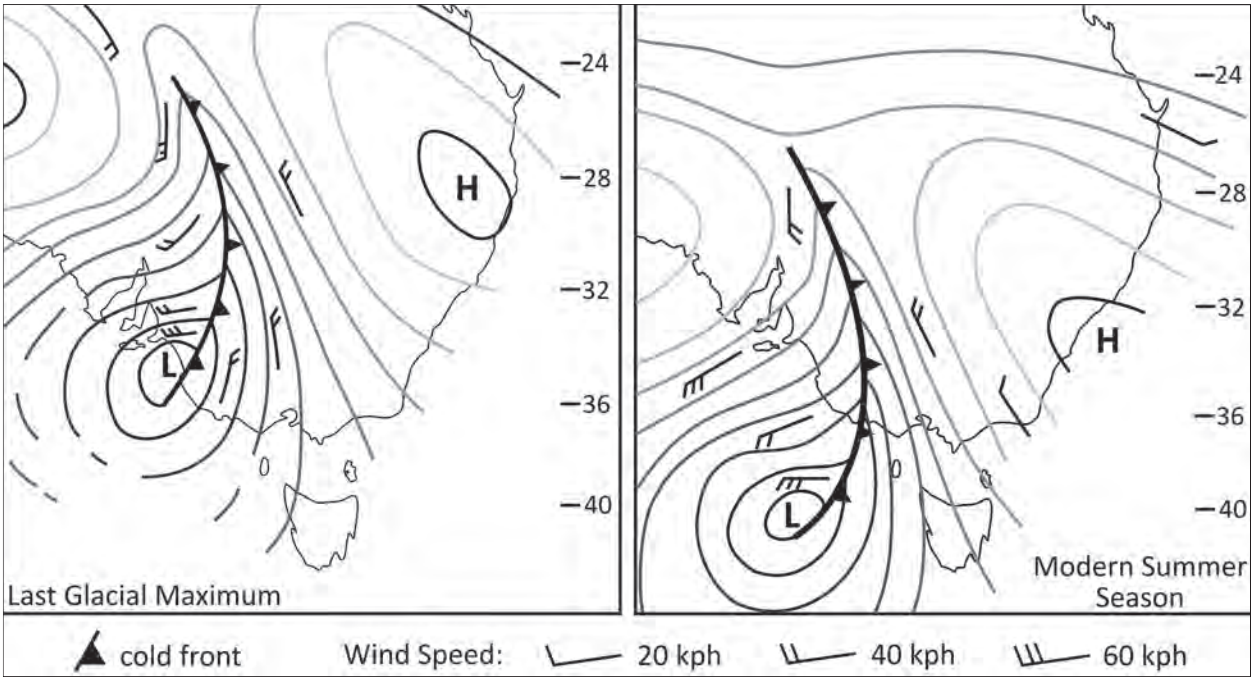


Figure 2.6.2 Isobaric charts illustrating the approximate 5° latitude shift of westerly winds between the Last Glacial Maximum and current Holocene interglacial. (Modified from Sprigg 1982)

a setting for extensive dunefield development made possible by the delivery of terrigenous sediment via the River Murray (Sprigg 1979; Harvey et al. 2001; Hesse 2010).

Deposition of the glacial period dunefields within the Murray Basin was initiated by 380 ka (Lomax et al. 2007, 2011), with Molineaux Sand deposition initiated by 200 ka (Fitzsimmons & Barrows 2012); ages of earlier deposits have not yet been successfully determined. Deposition within the dunefields occurred during phases broadly associated with more arid conditions versus periods of non-deposition coinciding with more humid phases. Although the dunes of the Molineaux Sand trend eastward, they are slightly asymmetric with a steeper northern slope, consistent with the existing wind regime (Lawrence 1980). Active deposition of the Molineaux Sand within the Holocene has been identified near Naracoorte to the south-east of the Murray Estuary (Fitzsimmons & Barrows 2012) and within the Murray Estuary on Hindmarsh I. and areas surrounding Lakes Alexandrina and Albert (Bourman et al. 2000; Ryan 2015). The continued movement of the Molineaux Sand is attributed to a lack of dune stability due to the unconsolidated nature of the sands and anthropogenic disturbance.

The initiation of arid dunefield development within the Pleistocene reflects a trend of increasing aridity within Australia through the Quaternary (Bowler et al. 2006; Hesse 2010). This trend is mirrored in the desiccation of once-large inland lakes (Stephenson 1986; Nanson et al. 1998; McLaren & Wallace 2010; Cohen et al. 2011, 2012). Evidence of more pluvial conditions during the Last Interglacial and the penultimate interglacial is provided by the widespread deposition of alluvial sediments, identified as the Pooraka Formation, on the margins of the Mount Lofty Ranges (Bourman et al. 2010; Ryan 2015). As Australia moves towards a future of predicted lowered precipitation and increased temperatures, the legacy of increasing aridity continues.

THE HOLOCENE AND HISTORICAL CLIMATE

Climate is determined by the interaction of five major components: the atmosphere, the hydrosphere (all fresh and saline water), the cryosphere (ice, snow and permafrost), the land-surface and the biosphere (Baede et al. 2001). Together these components form a climate system, and they are linked by fluxes of mass, heat and momentum. The atmosphere and the oceans are strongly coupled by the hydrological cycle and through the exchange of gases (Baede et al. 2001). The exchange of water vapour and heat between the atmosphere and oceans supplies energy to weather systems, leading to condensation, cloud formation, and precipitation and run-off, the latter influencing ocean circulation.

The climate of southern Australia is governed by the interaction and variation of three dominant climate systems: 1) the Southern Annular Mode (SAM) and associated Southern Hemisphere Westerly Wind system 2) the El Niño Southern Oscillation (ENSO) phenomenon 3) the Indian Ocean Dipole (IOD) (CSIRO 2012; Gouramanis et al. 2013). The dominant climate systems in turn affect lesser climate systems such as the subtropical ridge (STR) (Cai et al. 2011) and the Australian summer monsoon (ASM) (Quigley et al. 2010) (Fig. 2.6.3). Variations in

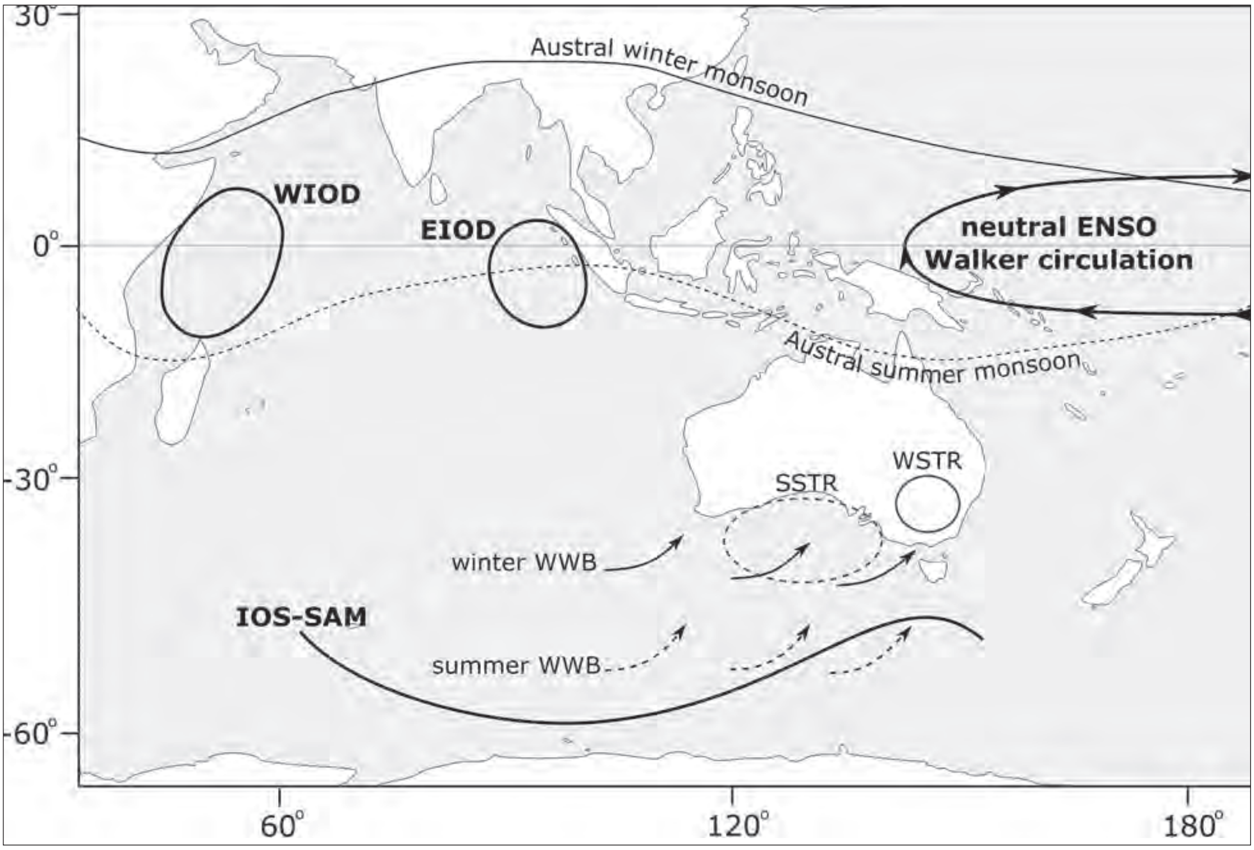
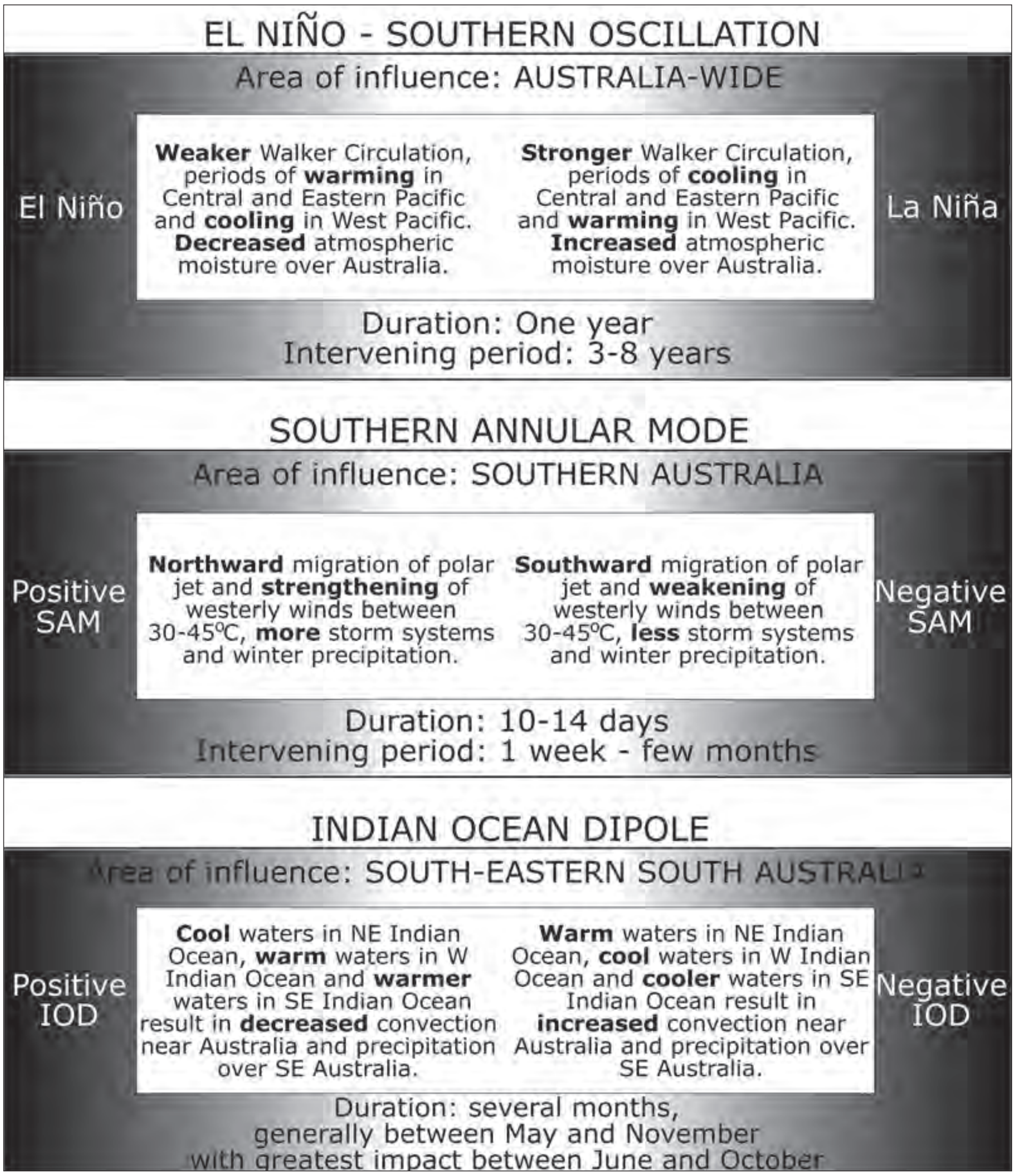


Figure 2.6.3 The position of the three dominant climate systems affecting the temperature, wind and precipitation patterns across southern Australia: the Indian Ocean Sector of the Southern Annular Mode (IOS-SAM), the El Niño Southern Oscillation (ENSO), and the mean position of the western and eastern poles of the Indian Ocean Dipole (IOD). The dominant climate systems determine the positions of the lesser westerly wind belt (WWB) and subtropical ridge (STR) climate systems, shown here in their mean winter and summer positions. (Figure redrawn from Gouramanis et al. 2013; neutral position of the ENSO from BOM 2016a)



EL NIÑO - SOUTHERN OSCILLATION

Area of influence: AUSTRALIA-WIDE

El Niño

Weaker Walker Circulation, periods of **warming** in Central and Eastern Pacific and **cooling** in West Pacific. **Decreased** atmospheric moisture over Australia.

La Niña

Stronger Walker Circulation, periods of **cooling** in Central and Eastern Pacific and **warming** in West Pacific. **Increased** atmospheric moisture over Australia.

Duration: One year
Intervening period: 3-8 years

SOUTHERN ANNULAR MODE

Area of influence: SOUTHERN AUSTRALIA

Positive SAM

Northward migration of polar jet and **strengthening** of westerly winds between 30-45°C, **more** storm systems and winter precipitation.

Negative SAM

Southward migration of polar jet and **weakening** of westerly winds between 30-45°C, **less** storm systems and winter precipitation.

Duration: 10-14 days
Intervening period: 1 week - few months

INDIAN OCEAN DIPOLE

Area of influence: SOUTH-EASTERN SOUTH AUSTRALIA

Positive IOD

Cool waters in NE Indian Ocean, **warm** waters in W Indian Ocean and **warmer** waters in SE Indian Ocean result in **decreased** convection near Australia and precipitation over SE Australia.

Negative IOD

Warm waters in NE Indian Ocean, **cool** waters in W Indian Ocean and **cooler** waters in SE Indian Ocean result in **increased** convection near Australia and precipitation over SE Australia.

Duration: several months,
generally between May and November
with greatest impact between June and October

Figure 2.6.4 Opposing modes of the three dominant climate systems affect temperature, wind and precipitation patterns across the south of the Australian continent (Hendon et al. 2007; Evans et al. 2009; Quigley et al. 2010; BOM 2016a). Modes are shown here by their general impact on rainfall patterns; however, exceptions occur due to interactions between the systems that are not yet fully understood and with lower-frequency climatic processes. Lower rainfall is generally associated with higher temperatures and vice versa.

these systems have determined Holocene temperature, wind and precipitation patterns across the south of the Australian continent (Fig. 2.6.4). This section reviews the record of Holocene climate as determined from proxy indicators and the recorded historical climatic regime since European records began, including the record of droughts and floods, which are extreme climate events.

Holocene climate and sea-level change

Global sea-level rise following the Last Glacial Maximum was rapid until it neared present levels at the start of the Holocene (11.7 ka), after which the height of sea level and the rate of change became spatially variable as affected by proximity to former ice sheets and regional and localised physical response to changed ocean volume (Murray-Wallace & Woodroffe 2014). The southern Australian coastline records a peak in the Holocene sea-level transgression between ~7 to 6 ka followed by a concomitant fall in relative sea level (Cann et al. 2000; Belperio et al. 2002; Harvey 2006). The shoreline at the culmination of the transgression was located along the present eastern shore of the Coorong Lagoon, which has formed at the calcrete-capped Last Interglacial beach-barrier complex ~2 km inland (Bourman et al. 2000). An incremental drop in sea level from the Holocene maximum is reflected by distinct soil profiles around Lake Alexandrina (de Mooy 1959) and abandoned cliff lines and fields of recessional beach/dune ridges around Lake Albert (Bourman et al. 2000).

The high sea level at 7 to 6 ka corresponds with a record of peak effective precipitation and falls within the middle Holocene 'climatic optimum', ~8 to 5 ka, when many of the globally dominant climatic systems operated differently to the present (Quigley et al. 2010). As summarised by Quigley et al. (2010), during this time El Niño Southern Oscillation variability was suppressed and the Asian and Australian summer monsoons were stronger than the present, with increased effective precipitation across the Australian continent. Increased strength of the monsoon between 11 and 7 ka has also been linked to the sea-level rise following deglaciation and an increased supply of moisture to the Indonesian archipelago, the source of monsoon precipitation (Griffiths et al. 2009).

The increased effective precipitation of the early to middle Holocene is reflected in proxy records within and surrounding the Murray Estuary region. Alluvial sediments of the Waldeila Formation found in the streambeds of Fleurieu Peninsula have been associated with more pluvial (wetter) conditions during the mid-Holocene (Bourman 2006; Bourman et al. 2010). Clay/silt-ratios in the Murray Canyons located offshore on the continental margin suggest strong discharge by the River Murray between 11 and 9 ka and 7 to 6 ka ago, and imply more humid conditions in the Murray catchment (Gingele et al. 2004). Radiocarbon analysis of microfossils retrieved from Coorong Lagoon core sediment ~15 km south-east of the Murray Mouth indicates high rates of freshwater flow between 7 000 and 5 500 yr BP (Lower et al. 2013). The palaeoclimatic record provided by Lake Keilambete in Victoria supports a regional increase in fluvial discharge during the early and middle Holocene (Bowler & Hamada 1971), and von der Borch & Altmann (1979) suggested that the increased size of Lake Alexandrina and flooding of the Cooke Plains Embayment at this time were partially due to increased freshwater discharge from the River Murray.

A number of proxy records indicate that the 'modern', more arid, climatic regime was established between 5 and 4 ka. Marine sediment cores linking higher precipitation at 8 to 6 ka to warmer sea surface temperatures (SSTs) in the southern hemisphere mid-latitudes show SSTs to cool at 4 ka, coinciding with records of increased aridity (Calvo et al. 2007). Modern Holocene sedimentation rates and grain size distribution in the offshore Murray Canyons with a switch to aeolian dust as the main terrigenous source were established by 4 ka, with only minor fluctuations since (Gingele et al. 2004). Cave speleothem growth in the northern Flinders Ranges, continuous during the Holocene climatic optimum, ceased about 5 ka (Quigley et al. 2010). Falling water levels at Lake Keilambete between 5 500 and 3 100 yrs BP as indicated by organics in lake sediments (Bowler & Hamada 1971) correspond with a record of falling lake level at Lake Alexandrina initiated at about 5 000 years ago (von der Borch & Altmann 1979) and falling relative sea level and more restricted, estuarine-lagoonal sedimentation near the Murray mouth, which has been constrained by ^{14}C dates between 5 255±60 and 3 605±70 yrs BP (Cann et al. 2000).

The transition of Holocene climate in southern Australia from high effective precipitation to increased aridity ~5.5 ka is attributed to an enhanced positive Indian Ocean Dipole, concurrent with a weakened Australian monsoon and intensification of austral summer solar insolation (Berger & Loutre 1991; Gouramanis et al. 2013). This phase lasted for a period of ~1 ka. It was followed by a strengthening of the Australian monsoon, a more southerly mean position of the Indian Ocean Sector Southern Annular Mode during austral winter and drier conditions across southern Australia. An increased incidence and strength of El Niño/La Niña events, coupled with positive/negative modes of the Indian Ocean Dipole, resulted in the increased climate variability experienced today (Gouramanis et al. 2013).

Modern and historical climate

Instrumental weather observations in Australia began shortly after the arrival of the First Fleet. The use of standardised and calibrated equipment by the Bureau of Meteorology began in 1908 (BOM 2016b). The recorded weather of Murray Estuary region is considered Mediterranean in style with generally hot dry summers and cool wet winters (Fig. 2.6.5).

The Murray Estuary and south-eastern coastal plain are subject to the progression of high-pressure anticyclonic (the subtropical ridge, STR) and mid-latitude depressional flows, including the prominence of a 5-6 day anticyclonic periodicity of westerlies, southerlies and southeasterlies (Short & Hesp 1984). Wind directions with aeolian sand-shifting capabilities are dominant from the south-west, resulting in the orientation of parabolic dunes and the migration of transverse dunes across Sir Richard and Younghusband Peninsulas into the back-barrier lagoon (Bourman & Murray-Wallace 1991). Northwesterlies are more prominent in winter and southwesterlies in the summer. In winter the subtropical ridge extends equatorward and the westerly wind belt associated with the Southern Annular Mode is positioned over the southern margin of the continent, providing precipitation from frontal systems (Fig. 2.6.3) (Hendon et al. 2007; Evans et al. 2009; Gouramanis et al. 2013). During summer months the system shifts poleward, resulting in decreased precipitation as the westerly wind belt is positioned south of the continental landmass. The variation in wind regime and coastal orientation indicates that the significance of processes such as open ocean swell waves and locally generated storm waves and the effects on onshore winds will vary spatially and temporally (Bourman 1986).

The shoreline along the length of the Coorong Coastal Plain is a high-energy microtidal (0.8 m) environment dominated by persistent year-round open ocean swell and strong onshore winds. The coast is exposed to waves from the west, south-west, south and south-east, and is subject to the full force of the dominant south-west waves, swell and accompanying winds, although Kangaroo I. provides some protection from westerlies (Harvey & Chappell 1992). The impacts of swell waves can be further enhanced by locally generated wind waves.

A low beach gradient (0.03 m) accounts for the dissipative nature of the shoreline; however, due to high wave energy there is only a 20% loss in wave power, meaning that more sediment

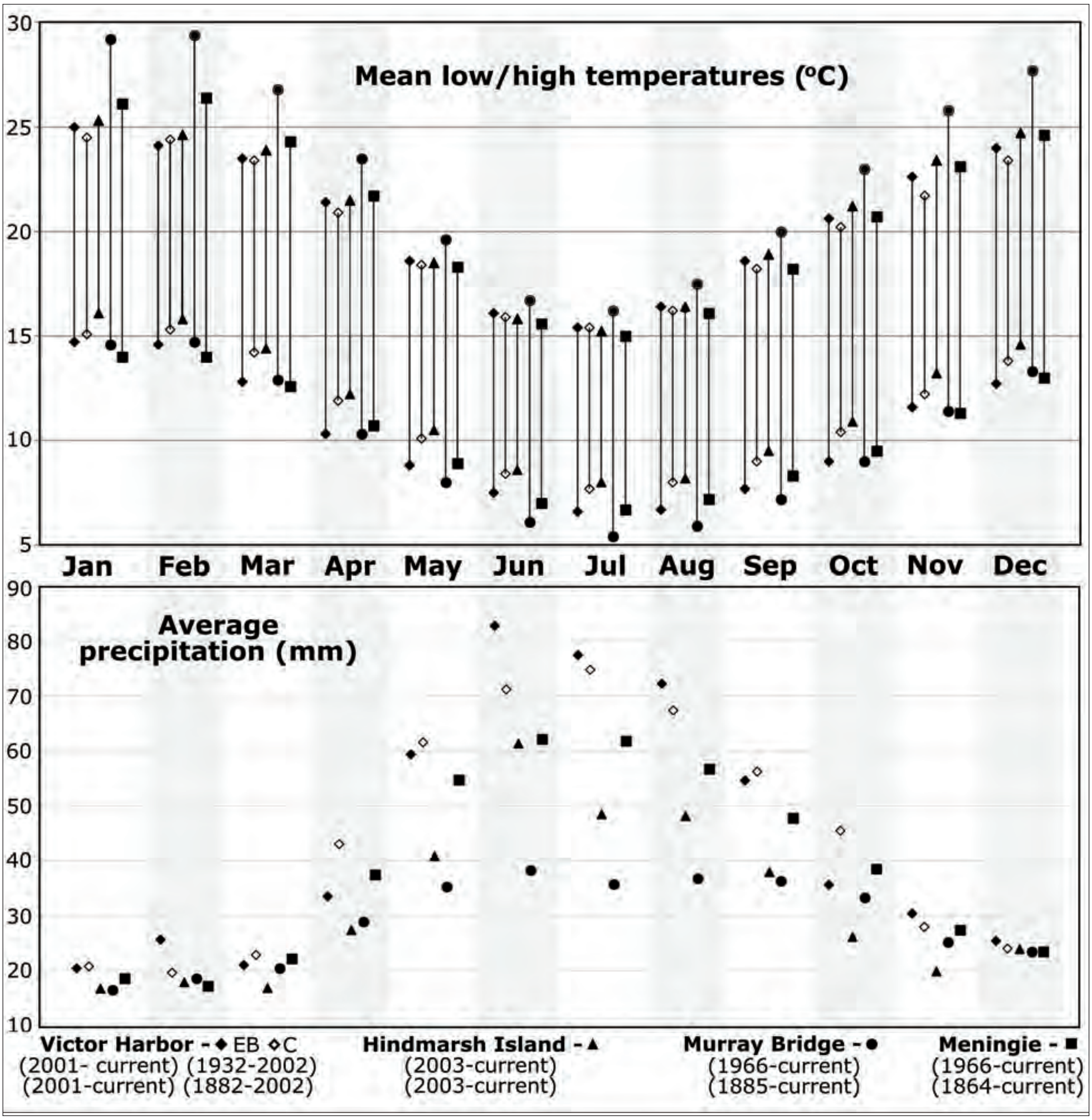


Figure 2.6.5 Bureau of Meteorology (BOM) weather station records from localities in the Murray Estuary region showing mean high and low temperatures and average precipitation by month, illustrating the Mediterranean-style climate of the region. The length of record is listed beneath locality with temperature given above rainfall. The location of the Victor Harbor weather station was moved in 2001; records for both locations are provided: Victor Harbor — Encounter Bay (EB), Victor Harbor — Comparison (C). (Data compiled from BOM 2016c)

is capable of being moved onshore (Short & Hesp 1984). Spring high tide at Victor Harbor near the Murray Mouth reaches 0.8 m, although a maximum amplitude of 1 m may be reached during a storm surge (Short & Hesp 1984), with extremes of 2.18 m and 1.40 m measured at Victor Harbor and inside the Murray Mouth respectively (Radok & Stefanson 1975). Storm surges may form wash-over fans and flood tidal plumes and may help to clear sediment from the mouth (James et al. 2015).

The position and morphology of the Murray Mouth are a result of the interplay between littoral drift, wind drift, waves, ocean currents, tidal prisms, freshwater flow and supply of sediment (Reissen & Chappell 1991). Mouth migration is consistent with the direction of sand movement, which, in turn, is determined by wind direction. The direction of movement between years can be highly variable due to a high rate of sand movement and major directional shifts in potential sand movement (Harvey 1996). Maintenance of the Mouth is related directly to river discharge, wave action and tidal flushing (Bourman & Harvey 1983).

Between 1936 and 1940 barrages were built across the tidal channels at the Murray Mouth in order to create and maintain a freshwater source. As a result, river flow was reduced by 75%; the tidal prism contracted by 90%; the width of the Mouth was greatly reduced; and it was transformed from a river-dominated to a wave- and tidally dominated outlet (Bourman & Harvey 1983; Reissen & Chappell 1991; James et al. 2015). This had significant consequences for the River Mouth. Prior to barrage completion, shoals were present most years in the vicinity of the Murray Mouth as exposed flood tide delta plumes, lobes or associated features that were constantly changing and never vegetated (James 2004). The barrages allowed stabilisation of flood tidal delta sediments and the creation and growth of a more permanent shoal directly inland from the mouth within five years of barrage completion (e.g. Bird I.) (Bourman & Harvey 1983; Reissen & Chappell 1991; James et al. 2015). In 1981, following

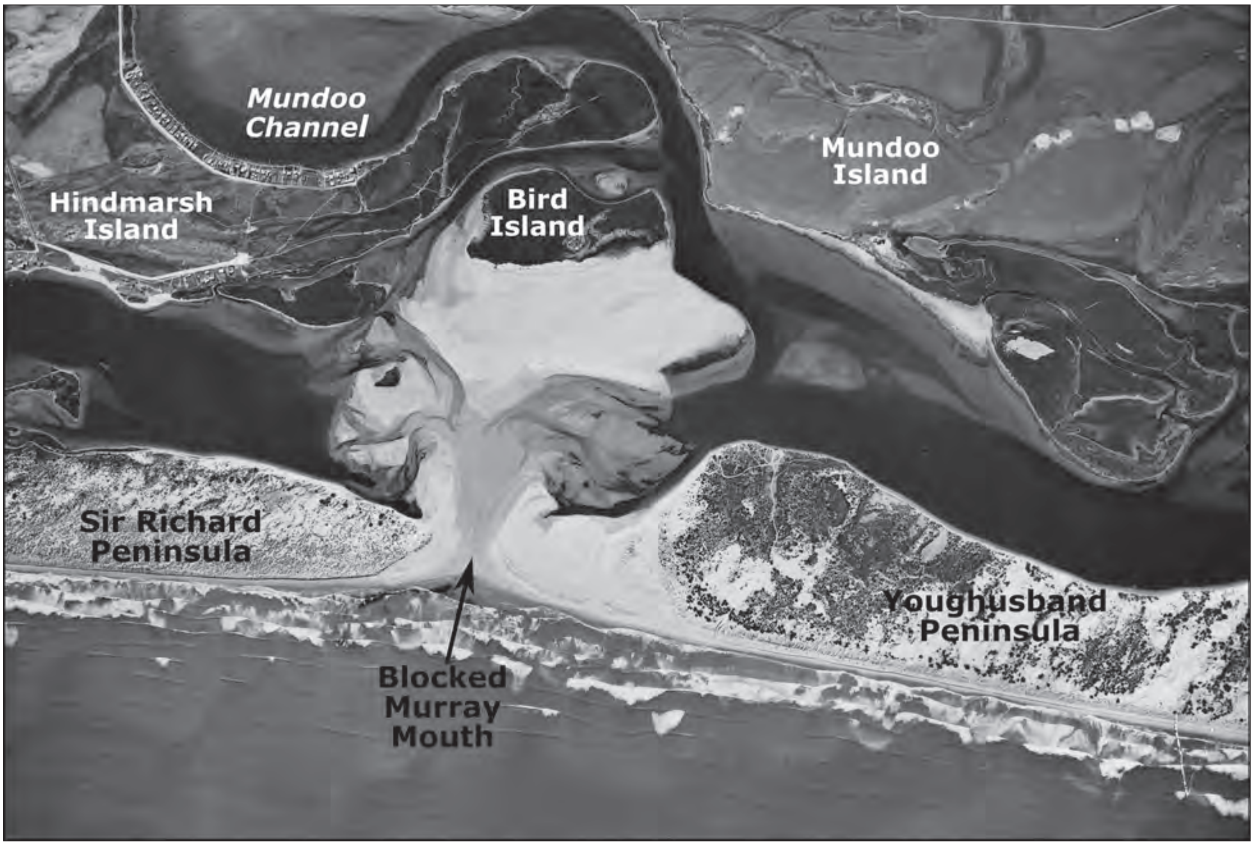


Figure 2.6.6 The closed Murray Mouth in 1981 (reproduced with permission from Mapland, Department for Environment and Heritage, South Australia). Aeolian sand drift and wave action facilitated the development of a sand barrier approximately 2 m above sea level between the ocean and back-barrier lagoon (Bourman 1986; James et al. 2015).

a sustained period of low maximum monthly sea tides and no river flow through the barrages, sedimentation caused the Murray Mouth to close (Fig. 2.6.6), requiring artificial clearance and continued maintenance (Harvey 1996). In 2002, over-extraction and drought again kept the River Murray from flowing to the sea (Hebeger 2012).

Highly variable weather conditions, such as drought, are possible because of the highly complex nature and interaction of the dynamic and thermodynamic processes of the climate systems determining weather (Lavell et al. 2012). Extreme climatic events often have adverse impacts on health, survival, property, infrastructure and ecosystems (Climate Commission 2013). These events and their impact on the Murray Estuary are reviewed here.

Extreme climatic events

An extreme climate or weather event is defined by the Intergovernmental Panel on Climate Change (IPCC) (Seneviratne et al. 2012, p. 111) as 'the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends ('tails') of the range of observed values of the variable'. More explicitly, extreme climatic events are statistically rare or unusual weather or climatic occurrences, such as extremes of precipitation or temperature, which can have severe natural impacts on the environment (Leigh et al. 2015). The ability to identify an extreme climatic event is dependent upon the availability of observational data with which climatic thresholds are defined (Lavell et al. 2012) — that is, the extremity of an event can only be assessed in the context of the availability and quality of records. It is also important to recognise that extreme climatic events are defined not only by severity, but also by their ability to surpass critical thresholds and by their geographic locations, and in some instances they are the result of the accumulation or coincidence of climate events that alone would not be considered extreme (Seneviratne et al. 2012).

The Australian Climate Commission recognises the following types of extreme events as threats to the Australian ecosystem: droughts; floods; storm surges and coastal flooding; heat waves and hot days; fires; and tropical cyclones (Climate Commission 2013). Tropical cyclones, which occur in northern Australia, are not discussed here.

Fire has not been a significant issue in the Murray Estuary region, although in December 1979, near Meningie, east of Lake Albert, 480 hectares burned (South Australian Country Fire Service 2016). However, bushfire risk is partially dependent upon temperature (Clarke et al. 2011). Since the 1970s the duration and frequency of heat waves across Australia have increased; the hottest days of heat waves have become hotter (Perkins & Alexander 2013) and extreme fire weather has increased (Lucas et al. 2007; Clarke et al. 2011; CSIRO & BOM 2014), implying an increasing likelihood for a major fire event in the region. Heat waves and hot days can also result in raised air and water temperatures exceeding the upper thermal limits of aquatic biota with detrimental effects (Leigh et al. 2015). Numerous heat records were broken in December 2015, not only in South Australia but also in Victoria and Tasmania. In parts of southern South Australia, maximum temperatures were more than 5 °C above average (BOM 2016d). New state records for average minimum temperature and daily mean temperature were set. Since December 2015, Australia has experienced its warmest March on record (in 2016), exceptional heat in the months of January, February and September (in 2017), and the warmest April (in 2018) on record (BOM 2016e, 2017b, 2017d, 2018). Each event set new national and state records.

Droughts and floods are easily recognisable climatic extremes that have impacted the

South Australian industry and population and the Murray Estuary. Storm surges and coastal flooding have and will continue to impact the coastline of the Murray Estuary region. The records of these extreme climatic events are reviewed here.

Droughts and floods

Droughts have been formally recognised as a natural characteristic of the variable and changing climate of Australia since the 1990s (Hennessey et al. 2008). The cause of drought is unlikely to be attributed to a single climatic phenomenon, e.g. El Niño Southern Oscillation, the Indian Ocean Dipole or the Southern Annular Mode (Vernon-Kidd & Kiem 2009). Although it is recognised that the El Niño Southern Oscillation, the Indian Ocean Dipole and the Southern Annular Mode are the dominant climatic systems affecting climate and observed rainfall patterns over southern Australia, how they interact and their influences on climatic variability are still not fully understood (Cai & Cowan 2008; Evans et al. 2009; Risbey et al. 2009; CSIRO 2012; Palmer et al. 2015). Risby et al. (2009) showed that each individual climatic phenomenon, treated as a single driver, accounts for less than 20% of monthly rainfall variability for most Australian regions. As an example, El Niño events, which generally result

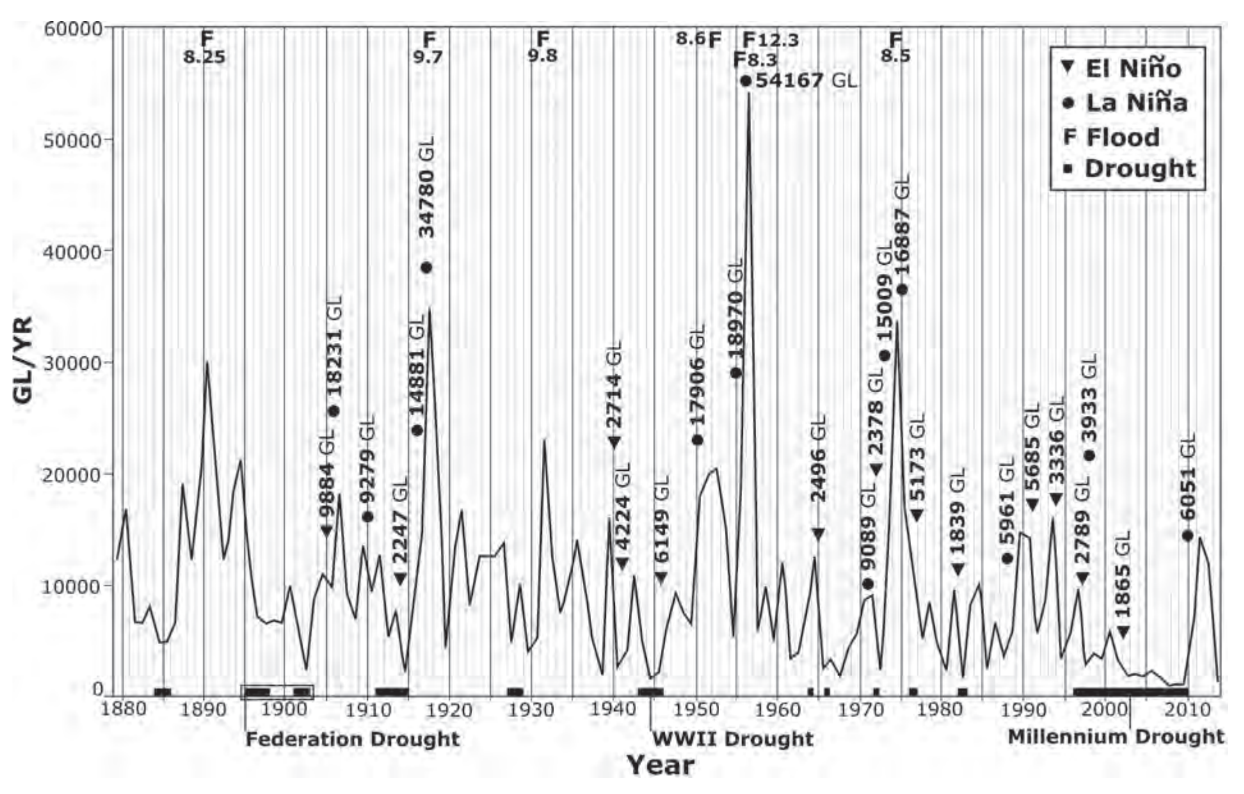


Figure 2.6.7 The record of annual flow into South Australia (in gigalitres/year) with the strongest El Niño Southern Oscillation (El Niño and La Niña) events and their corresponding flow (from James et al. 2015, reproduced with permission from the Coastal Education and Research Foundation, Inc.). Also shown is the record of severe droughts affecting the River Murray and River Murray Floods with corresponding flood peak heights at Morgan, SA in metres, as recognised by the Government of South Australia (SA Memory 2009) over the same time span. Earlier River Murray floods are recorded in 1867 and 1870, the latter with a peak flood height of 11 m. This figure demonstrates that El Niño Southern Oscillation events are not solely responsible for Australian precipitation and subsequent river flow or the climatic extremes of drought and flood.

in below-average winter and spring rainfall, and which in extreme instances can result in widespread drought, can also be weak with limited effects (Evans et al. 2009) (Fig. 2.6.7). The recent Millennium Drought is unlikely to have been the result of either an El Niño Southern Oscillation or Indian Ocean Dipole event (CSIRO 2012). This implies that establishing a singular cause for drought events or any other climatic extreme is also unlikely.

Drought is most simply defined as rainfall deficiency, although it can be defined in meteorological, agricultural, hydrological and socioeconomic contexts (Hennessey et al. 2008). Meteorological drought refers to a period of insufficient rainfall compared to the long-term average; agricultural drought refers to insufficient soil moisture negatively affecting crop production; hydrological drought occurs when stream flow, lake levels or groundwater levels drop to a sufficiently low level; and socioeconomic drought is the effect of the above droughts on the supply and demand of economic goods and human wellbeing. Drought is also linked to wind speed and humidity, and temperature and rainfall, and is therefore an example of an extreme climate event that is actually an accumulation of events that may not be considered 'extreme' individually (IPCC 2012; Climate Commission 2013). The link between drought, bushfire, wind and temperature is made apparent with the recognition that Australian droughts have been associated with massive dust storms in 1902, 1983 and 2009 and with destructive fires in 1939 and 1982, with numerous fires occurring during the Millennium Drought, most notably the Black Saturday Bushfires in Victoria (Lake 2008; Heberger 2012). Regional droughts in south-eastern Australia have had dramatic impacts on the functioning of the Murray Estuary.

The most protracted droughts since European settlement and during the instrumental history of south-eastern Australia are the 'Federation Drought' (c.1895-1902), the 'World War II Drought' (c.1937-1945), and the 'Big Dry' also known as 'Millennium Drought' (c.1997-2009) (Vernon-Kidd & Kiem 2009; Climate Commission 2013) (Fig. 2.6.7). During the Millennium Drought, annual rainfall in southern Australia was 12% below the long-term average (1900 to 2010) and represented the most severe hydrological drought since accurate records began in 1865 (CSIRO 2012). By the end of the Millennium Drought, south-eastern Australia had recorded the driest 11-year, 10-year, 9-year, 8-year and 7-year periods on record (NCC-BOM 2012).

Water resource development of the Murray-Darling Basin between the 1950s and mid-1990s did not allow for drought and the cumulative impacts (Kingsford et al. 2011). Severe flow constrictions, near-closure and closure events of the Murray Mouth coincide with periods of drought and prolonged periods of no-flow through the barrages due to low River Murray flow conditions (Yu 2014). During the Millennium Drought, river flow regimes, and therefore discharge through the barrages, varied with drought conditions (Leterme et al. 2015). Flows during the early stages of the drought (1997 to 2001) were 180 GL, compared with 581 GL after the drought (2010 to 2013). Freshwater release through the barrages, typically occurring in late winter and decreasing into the summer months, averaged only 15 gigalitres (GL) during the drought (2002 to 2009). No water was released during 2002 and 2007 to 2009. A near-closure of the Mouth in the spring of 2002 prompted the initiation of a dredging and sand-pumping project, which continued until late 2010 (Yu 2014) and cost in excess of A$32 million (Kingsford et al. 2011). The near-closure, created by very low to absent barrage releases, has been attributed to a combination of drought conditions, the growth of the flood tidal delta and the over-allocation of water resources upstream.

The reduced river flows during the Millennium Drought not only increased the likelihood of Murray Mouth closure but also had detrimental ecological impacts in the Lakes and Lagoon, as higher salinities, higher water temperatures and altered water levels exposed acid sulfate soils and deteriorated the environment for plant and wildlife (Kingsford et al. 2011; Lower et al. 2013; Dittmann et al. 2015; Leigh et al. 2015; Leterme et al. 2015). The barrages, although isolating the Lakes from the saline lagoon waters, allowed the level of Lake Alexandrina to fall below sea level. Lake Albert evaporated, aerially exposing large areas of the Lake floor. Lowered lake levels allowed the development of acid sulfate soils with potential environmental, human and animal, and economic impacts (DEH 2009). The management responses to the symptoms of the Millennium Drought were short-term, and involved costly engineering solutions, which led to the compartmentalisation of ecosystems through the construction of weirs, further reducing the connectivity of flow in the Lower Lakes and affecting the migration of aquatic organisms and nutrients (Kingsford et al. 2009, 2011). Intervention and impact expenditures have been estimated to have been >A$2 billion.

Water quality assessment of the lower reaches of the River Murray, north of the Lakes at Murray Bridge and Tailem Bend, and also within the Lakes near Milang (Lake Alexandrina) and Meningie (Lake Albert) and from the Goolwa Channel, was undertaken during an extreme low-flow period (March 2007 to November 2009) and compared with a preceding reference period (March 2003 to November 2005) (Mosley et al. 2012). Increased river salinity levels coupled with decreased nutrient and turbidity concentrations were attributed to decreased catchment inputs and increased influence of saline groundwater inputs. Within the Lakes, significant increases in salinity, total nitrogen, total phosphorus, chlorophyll and turbidity were observed; and consequently, water quality guidelines for the protection of aquatic ecosystems were greatly exceeded. It should be noted that the reference period (March 2003 to November 2005) is one in which the system was already in ecological decline, implying that the degradation seen by November 2009 was much further from healthy conditions than indicated. The increased salinity levels in the Lower Lakes allowed salt-tolerant biota, particularly estuarine and marine species, to dominate (Kingsford et al. 2009, 2011). The marine serpulid tubeworm (*Ficopotamus enigmatius*) invaded previously freshwater habitats and formed dense masses of calcareous tubes on hard surfaces, including shells, leading to the death of freshwater mussels, turtles and other organisms.

Coorong water levels are determined by the sea, especially during the summer when freshwater flow is lowest (Kingsford et al. 2011). In the winter, tides rise and refill the lagoon, and high freshwater flows from the River Murray help to maintain water level and lower salinities throughout the Coorong. The natural salinity variation along the length of the Coorong supports different ecological communities broadly defined as estuarine, marine and hypersaline (Brookes et al. 2009). During the Millennium Drought, due to the lack of freshwater inflow and as a result of evaporation, salinity levels (Practical Salinity Scale) in the Coorong, which typically increase with distance south-east from the Mouth and reach that of sea water >41 (where 0 is fresh water) in the South Lagoon, rose to levels of extreme hypersalinity between 180 and 200, well above hypersaline levels of >85 (Brookes et al. 2009;

Lester et al. 2009; Leterme et al. 2015). These levels exceeded the maximum levels tolerated by the plants, fishes and birds, significantly altering food webs and the distribution and abundance of biota and thereby the distribution of ecosystem states along the length of the Coorong.

An ecosystem evaluation of the Coorong between 2006 and 2008 (Brookes et al. 2009) found the estuarine environment to have been essentially removed from the system. The elevated salinity levels directly influenced fish and benthic invertebrates and indirectly influenced bird species, especially in the South Lagoon. The formerly abundant aquatic grass *Ruppia tuberosa* was absent here, but colonised the North Lagoon, and the fish species smallmouth hardyhead (*Atherinosoma microstoma*) was absent or found only in very low quantities. The decline in abundance of key waterbird species since 1985 had intensified and was most pronounced in the South Lagoon. However, the colonisation of the South Lagoon by the Australian brine shrimp *Parartemia zietziana* saw an increase in the presence of the banded stilt (*Cladorhyncus leucocephalus*).

The Millennium Drought highlighted the ecological change in the Murray-Darling Basin due to river regulation and water allocation policies (Finlayson et al. 2013). Water resources in the Murray-Darling Basin were already stressed before the Millennium Drought, due to land clearance, irrigation, water extraction and use with accompanying water regulation and infrastructure (Leblanc et al. 2012). The maintenance of the Murray-Darling Basin rivers and wetlands was further challenged by increased demands from irrigation and urban areas during the drought and the shared governance of the Murray-Darling Basin by four states (Queensland, New South Wales, Victoria, South Australia) and one territory (Australian Capital Territory). The negative consequences of the lack of freshwater flows to the ecosystem health of the Murray Estuary were already apparent in 1999 and showed that the two strongest determinants of the ecological condition of the future estuary are climate change and upstream extraction and regulation (Brookes et al. 2009; Lester et al. 2009).

The Millennium Drought was broken by back-to-back La Niña events and exceptional rainfall beginning in 2010, resulting in that year being the third wettest calendar year on record for Australia, 2011 being the second wettest year (BOM 2012), and 2010-2011 the wettest two-year period on record (NCC-BOM 2012). The Murray-Darling Basin experienced its wettest calendar year on record in 2010, and due to the La Niña many parts of Australia experienced record rainfall and widespread flooding. Multiple factors contributed to the record rainfall (CSIRO 2012). The La Niña event was the strongest of the past 50 years and was accompanied by unusually high sea surface temperatures in the western equatorial Pacific Ocean and a near record high negative Indian Ocean Dipole. The high springtime rainfall in 2010 is attributed to the largest amplitude of the positive phase of the Southern Annular Mode Index since 1960 (CSIRO 2012).

Another strong positive phase of the Indian Ocean Dipole in 2016 and abnormally warm waters in the eastern tropical Indian Ocean led to above-average rainfall over almost all of Australia and the wettest May-September period on record (BOM 2017c). In December 2016, a low-pressure system brought unusually humid tropical air into southern Australia. Thunderstorms and heavy rainfall led to flash flooding in South Australia and coincided with temperatures well above average. It is the wettest December on record for the state (BOM 2017a), in stark contrast to the below-average rainfall across much of the state the previous year.

Flooding is the impact of very heavy rainfall events (Climate Commission 2013), and although floods occurred elsewhere in 2010, flow conditions into South Australia peaked around 76 000 ML day^{-1} and were not high enough to be considered a flood event (Department for Water 2011). In order to be considered a major flood, water flow of the River Murray must be equivalent to or greater than 200 001 ML day^{-1} at the state border (Water Connect 2015). Moderate flood flow is recognised between 130 001 and 200 000 ML day^{-1}, and minor flood flow between 100 001 and 130 000 ML day^{-1}. Flooding of the River Murray in South Australia is only considered 'exceptional' if the water level is 5 m or more above pool level. This occurred in recorded history during the 1931, 1956, 1973 and 1974 floods (SA Memory 2009; Water Connect 2015). Annual inflow to the Murray-Darling Basin in 1956 was five times as large as the long-term average (Cai & Cowan 2008). Peak flow during the 1956 flood reached 341 000 ML day^{-1}. The flood is considered one of the greatest natural catastrophes of South Australia (SA Memory 2009).

Less research has been completed on the impacts of floods on the Murray Estuary. High flows and the inundation of River Murray floodplains have multiple environmental benefits, including nutrient cycling from the river into the floodplain and salt export from the floodplain into the river (Department for Water 2011). The increased flow to floodplains and wetlands also increases the habitat for native plants and animals, providing an ideal feeding habitat for waterbirds and for some species a habitat for breeding. The high flows from the River Murray during 2010 and 2011 were used to flush salt from Lakes Alexandrina and Albert, which had accumulated during the drought (Department for Water 2011). Dittmann et al. (2015) found that benthic species within the Murray Estuary, which had exhibited an overall pattern of decreased species abundance during the Millennium Drought and low abundances during the 2010 flow peak, increased in abundance in the Murray Mouth and other parts of the Coorong in the following years with flow. In contrast, a negative impact of the extensive flooding within the basin following the Millennium Drought was a 'black water' event, where anoxia caused by organic matter washout led to widespread native fish deaths in the tributaries of the River Murray (Department for Water 2011; Leblanc et al. 2012).

Extending the record of drought and flood events and the relationship between magnitude and frequency (or Average Recurrence Interval, ARI) would allow for better prediction of when these events will occur (Snowball et al. 2006). In order to reveal the relationship between the magnitude and frequency of droughts and floods, and therefore the awareness of greatest extremes of these climatic events, it is imperative to have a very long record. The European records of Australian rainfall reveal regular drought cycles, sometimes exceeding a decade in length, interspersed with years of above-average rain (Ummenhofer et al. 2009); however, this record only began following the arrival of the First Fleet (1788) and was not standardised across the country until 1910 (BOM 2016b). The recently released Australia and New Zealand Drought Atlas (ANZDA) (Palmer et al. 2015) has pushed the record of hydroclimatic variability back to CE 1500, using tree ring and coral proxy records to indicate a 'wetter' period from 1730 to 1760, and drought conditions more extreme than seen in the European record at the start of the 16th century. Sediment cores from within the Coorong Lagoon indicate regional drought conditions at 3 500 yrs BP (Cann et al. 2000; Lower et al. 2013), and terraces within alluvial sediments in the Mount Lofty Ranges indicate five large flood events between ~5.9 ka and 1950 (Quigley et al. 2007, 2010). The identification and interpretation of biological, erosional and depositional features along the River Murray have allowed the identification of several flood events approximating the 1956 flood over the past 2 600 years (recurrence interval of 170 years), a flood at 3 000 yrs BP at least as large and likely larger than the 1956 flood, and a flood event in about 1760 (~150 years ago) with discharge almost double that of the 1956 flood (Snowball et al. 2006). The c.1760 flood reached heights ~2 m higher than the 1956 flood at Overland Corner, and has a probable recurrence interval of 1 000 years. Potentially coincident flooding in the Flinders Ranges and Northern Queensland indicates widespread rainfall across Australia at the time (Snowball et al. 2006) and appears to coincide with the wet period identified by Palmer et al. (2015).

Storm surges and coastal flooding

Coastal flooding events are caused by wind-driven waves or a storm surge during periods of extreme sea level, which can be exacerbated by high tide (IPCC 2012; Climate Commission 2013). Sea-level rise is worsening the effects of such events. The susceptibility of a coastal region to erosion and inundation is dependent upon its physical, geomorphological and ecosystem attributes (IPCC 2012). Erodible shorelines are subject to erosion and retreat and low-lying areas to inundation (Woodroffe & Murray-Wallace 2012). The low relief of coastal ecosystems and wetlands implies that small rises in sea level can result in saltwater intrusion and the expansion of the estuarine wetland system and decrease of freshwater wetlands (Hughes 2003, 2011).

Coastal erosion during the 20th century is apparent at both Surfer Beach and Middleton Beach, the latter having been subject to nearly 200 m of erosion since 1900, largely due to subsidence that has been associated with earthquake activity in 1897 and 1902 (Sprigg 1952; Bourman et al. 2000). Ongoing subsidence at a rate of 0.02 mm yr^{-1} for the past 125 ka (Bourman et al. 2000) at the Murray Mouth and projected sea-level rise (Wong et al. 2014) suggest that the region will continue to be impacted by more frequent large storm events and higher extreme water levels.

Records spanning the past 50 years show a rising average temperature in Australia and New Zealand and, over the Australasian (AUS and NZ) region, a long-term trend towards higher surface air and sea surface temperatures, more hot extremes and fewer cold extremes, and changed and uncertain rainfall patterns (Reisinger et al. 2014). The warming trend is expected to continue through the 21st century. In southern Australia the number of extreme fire-weather days is expected to increase with a longer fire season; rainfall is projected to decrease with a likely increase in drought frequency and severity; and projected sea-level rise will increase the frequency of extreme sea-level events (CSIRO & BOM 2014). Although extreme events are key elements of the natural variability that shapes river ecology, the intensification of disturbance from future extreme events due to gradual climate change could exceed the capacity of ecological communities' abilities to rebound (Leigh et al. 2015). Understanding the response of extreme events to climate change is necessary in order to adequately prepare for the future (Climate Commission 2013). Climate changes affecting the Murray-Darling Basin, from which the Murray Estuary receives its freshwater flow, and government responses are the subject of the final section of this chapter.

CURRENT AND FUTURE CLIMATE CHANGE

The Murray Estuary region is the discharge point of all flow through the Murray-Darling Basin, the largest river basin of Australia, and its health is therefore dependent upon the entire upstream basin. About 1% of precipitation and 17% of river flow over the Murray-Darling Basin reach the Murray Mouth (Leblanc et al. 2012). The rivers within the basin are highly regulated with more dams, storage capacity and water diversions than any other large river basin in Australia (Finlayson et al. 2013), resulting in a hydraulic regime very different from predevelopment conditions in terms of annual flow, seasonality, flooding events and low flows (CSIRO 2008; Leblanc et al. 2012). Water consumption in the basin has greatly reduced natural streamflow conditions at the Murray Mouth (CSIRO 2008). Average annual streamflow has been reduced by 61% (from 12 333 GL yr^{-1} to 4 733 GL yr^{-1}); cessation of flow conditions at the Mouth has increased from 1% of the time to 40% of the time on average; and the average period between flood events large enough to flush the Murray Mouth has increased from two to nearly six years. Future climate change is projected to have a disproportionately large impact on all aspects of biodiversity in freshwater and coastal fringe systems including wetlands (Hughes 2003, 2011), and is critically important to the management of the Murray-Darling Basin.

The Australian State of the Climate Report (CSIRO & BOM 2014) reports the following facts:

- The Australian annual average daily mean temperature has warmed by 0.9 °C since 1910 and is projected to continue to increase, with more extremely hot days and fewer extremely cool days.
- Sea surface temperatures in the Australian region have warmed by 0.9 °C since 1900 and global ocean temperature is warmer than at any time since instrumental recording began.
- Global mean sea level in 2012 was 225 mm (±30 mm) above the level in 1880 (an average increase of 1.7 mm yr^{-1}), higher than any time since instrumental recording began, and it is projected to continue to rise.

Rising temperatures and variable rainfall reductions over the Murray-Darling Basin since 1950 have led to a decrease in annual total rainfall of about 56 mm, and it is projected that a 1 °C rise in temperature will lead to a further 15% reduction in annual inflow to the Murray-Darling Basin, even if the amount of precipitation does not change (Cai & Cowan 2008). Median climate change scenarios for the Murray-Darling Basin have predicted that by 2030 the average volume of surface water will fall by 11%; surface water use will fall by 4%; and flows at the Murray Mouth will fall by 24% (CSIRO 2008). By the end of the 21st century, annual rainfall could decline by up to 11.4%; maximum temperatures could increase by up to 1.9 °C; and minimum temperatures by up to 1.5 °C (Charles & Fu 2014). Water flow at the Murray Mouth barrages is expected to decrease, increasing the maximum number of days without flow, while increased evaporation rates in the Coorong Lagoon will also lead to increased maximum salinity levels (Lester et al. 2009). Under the median climate change scenario, in which the mean total end of system flow would be 3 482 GL yr^{-1}, a) the occurrence of severe drought inflow at the Lower Lakes (i.e. <1 500 GL) would increase to 13% of years b) the maximum period between flood events that flush the Mouth would increase slightly to nearly one in eight years c) the average annual volumes of environmentally beneficial floods would be nearly halved (DEH 2009). Decreased local annual rainfall and freshwater inflow to the Lower Lakes, coupled with high evaporation, have serious implications for the life of the shallow Lakes, as under current conditions they would dry out in about three years without freshwater inflow (Kingsford et al. 2011).

Future sea-level change is unpredictable due to a lack of detailed understanding of how the processes which contribute to relative sea-level change have been impacted by anthropogenic climate change and how they will respond (Murray-Wallace & Woodroffe 2014). The current ~1.7mm yr^{-1} rate of rise is still substantially lower than the ~12.5 mm yr^{-1} rate of rise (125 m in 10 000 yrs) during deglaciation, assuming the peak of the Last Glacial Maximum at ~21 ka. The response of the coastline to future sea-level rise and storm surges will vary regionally; however, it is expected that coastal systems will increasingly experience extreme sea levels and their adverse impacts (Wong et al. 2014). Potential changes to wave climate in the Southern Ocean could have consequences for sediment dynamics and shoreline processes. Any breach of the peninsulas by the Southern Ocean would affect the ecosystem states of the Coorong (Lester et al. 2009). Sea-level rise could potentially result in a further constriction of the Murray Mouth and hypersaline conditions within the lower parts of Lake Alexandrina (DEH 2009). However, it has also been suggested that increased sea level may mitigate some of the climate change effects within the Coorong, as higher water levels increase connectivity, assuming a similar Murray Mouth to the present (Lester et al. 2009). Sustained sea-level rise will also encourage the ongoing landward migration of the Sir Richard and Younghusband Peninsulas (Bourman & Murray-Wallace 1991; Bourman et al. 2000), and without anthropomorphic interference this would result in an adjustment of the position and morphology of the tidal channels and islands within the Murray Estuary.

The Millennium Drought not only highlighted the ecological condition of the Murray-Darling Basin, but also raised the concern of how, in an anticipated drier future, reductions in available water will be shared between consumptive use and the riverine environment (Neave et al. 2015). Drought protection for the Murray Estuary wetlands is achievable through a well-timed relatively small 6% increase in freshwater environmental flow to an annual median flow of 3 800 GL at the barrages during low-flow periods (Brookes et al. 2009; Kingsford et al. 2009; 2011; Lester et al. 2009). This flow represents about one-third of the natural flow volume and is still below the long-term median flow, and considerably below historical levels, but is dependent upon sophisticated water management and stakeholder cooperation.

The Murray Estuary, recognised as one of the most significant wetlands in Australia (DEH 2009), is one of 16 Ramsar-listed wetlands within the Murray-Darling Basin over which the Federal Government has administrative authority. The rivers and water resources of the Murray-Darling Basin are currently under the management of the federal Murray-Darling Basin Authority, established under the *Water Act 2007* (Cth) (Kingsford et al. 2011; Heberger 2012; Alston et al. 2016). Water policy reform has been aimed at improving long-term water resiliency and mitigating the socioeconomic damage from drought through market solutions and economic efficiencies. In 2008, the Murray-Darling Basin Authority prepared 'the Basin Plan' for the sustainable management of the water resources of the Basin with consideration to the risks of climate change (Neave et al. 2015). The plan provides a key framework for an adaptive approach to changing climate, with response measures falling into four broad categories: those that refine existing water management arrangements, those that buffer the system from the additional stress of climate change, those that enhance responses to climate change, and those that facilitate adaptation to climate change at a range of timescales. Since adoption of the plan, 2 750 GL yr^{-1} of water have been recovered from consumptive use for environmental purposes (Neave et al. 2015). However, in an examination of the state of the Basin Plan and water policy reform, Alston et al. (2016) found that, due to changing governments and shifts in water reform policies towards more economic outcomes, uncertainty has risen among stakeholders and concern has grown about social outcomes at a community level.

The South Australian State Government has taken a proactive approach to climate change, identifying it as one of the biggest economic opportunities of the 21st century (DEWNR 2015). The State Government has introduced new initiatives, including building coastal resilience, implementing water-sensitive urban design and managing bushfire risk. It has also implemented a number of restoration programs along the length of the River Murray, including the Coorong and Lower Lakes Recovery Project (DEWNR 2014). The project is a key component of the A$610 million Murray Futures program, funded by the Australian Government through the Water for the Future Initiative. In 2010 the State Government (DEH 2010) released 'Securing the Future, Long-term plan for the Coorong, Lower Lakes and Murray Mouth'. The plan, prepared before the Millennium Drought broke, recognises that due to the drought and over-allocation of water resources across the Murray-Darling Basin, the ecology of the Murray Estuary no longer functions effectively, and that long-term regional social and economic wellbeing depends upon a healthy and functioning environment. The primary objective of the plan is to restore ecological function to the Murray Estuary.

It is worth noting that at the time of writing, dredging operations, which had commenced on 9 January 2015, were ongoing 24 hours a day, 7 days a week within the Goolwa and Tauwitchere Channels (DEWNR 2018).

SUMMARY

Our understanding of climate change and its impacts on depositional environments and ecosystems within the Murray Estuary is dependent upon the records available. The consistency in the orientation and composition of the Pleistocene beach barriers of the past 800 ka and their similarity to Sir Richard and Younghusband Peninsulas, their modern counterparts, indicate a comparable wind regime, wave climate and offshore shelf environment for each interglacial represented within the record. The continued development of calcrete within the Bridgewater Formation throughout the Pleistocene is another indicator of a similar, semi-arid climatic regime during each interglacial period. Increasing aridity throughout the Quaternary is recognised in 1) the decreased humidity of the Holocene in comparison with the Last Interglacial 2) the development of the glacial Molineaux Sand dunefields — providing a record of the altered climatic regime during the more arid glacial periods when the coastline was located at the continental margin ~180 km to south. While the sedimentological records preserved within the Bridgewater Formation, and to a lesser extent the Molineaux Sand, are chronologically extensive, they nevertheless provide only a broad record of climatic variability and the impact of that variability on depositional environments and ecosystems.

Governments and communities are most concerned with the variability of climate within the Holocene interglacial period. Although this sedimentological and climatic record is the most recent within the geological time scale, and is bolstered by the historical data period nested within, it still provides only limited insights into past climatic conditions. If it is accepted that the current climatic regime was established at 4 ka, then the European record of Australian climate over the past 228 years accounts for 5% of the modern climatic regime and only 1% of the Holocene. Proxy records within and surrounding the Murray Estuary region have allowed the identification of the mid-Holocene (8 to 5 ka) climatic optimum and indicate drought and flood events within the past 4 ka more extreme than what has been experienced within historical records. Yet even those records are constrained, not only by our ability to recognise them, but also by their preservation within the sedimentary record.

The climatic variability within the south-eastern Australia record is driven by the interaction of three dominant climate systems: the Southern Annular Mode, the El Niño Southern Oscillation phenomenon and the Indian Ocean Dipole. While these systems are currently not fully understood, thereby complicating future climatic change predictions, a hotter, drier, more arid future within this interglacial period seems certain. It is also prudent to remember that as the climate warms, the Holocene interglacial period, at 11 700 years' duration, is nearing the average maximum interglacial length (13 000 years) as recorded in the sedimentary record. The brevity of the historical record and the paucity of the sedimentary record limit our understanding of how the Murray Estuary region will respond to the predicted changes of higher sea levels and increased occurrence of extreme events, complicating the planning process for change and highlighting the need for continued research into the response of the landscape to past climatic changes. For example, the predicted dry, windy and arid conditions, reminiscent of the Last Glacial Maximum, beg the question of Molineaux Sand dunefield stability and reactivation within this interglacial. Further concern for the future ecological health of the Murray Estuary region arises from the recognition of the intensive water regulation upstream within the Murray-Darling Basin and the socioeconomic interests with which environmental interests must contend. The federal and State Governments are both obliged to maintain the ecological health of the Murray Estuary and have made steps to do so, but the success of these endeavours remains to be seen.

ACKNOWLEDGEMENTS

I thank the editors for giving me the opportunity to contribute a chapter to this publication. Nathan Jankowski deserves mention for his much-appreciated feedback. I also thank my Ph.D. supervisors, Colin V. Murray-Wallace and Robert Bourman, for their generous review of chapter drafts and their ongoing support.

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CHAPTER 2.7

HYDROLOGY AND HYDRODYNAMICS OF THE LOWER LAKES, COORONG AND MURRAY MOUTH

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INTRODUCTION

The water regime of the Lower Lakes and Coorong, which includes the hydrology, climate, hydrodynamics and water quality, is a significant driver of the ecology in the region. Changes in water level and salinity have a strong influence on ecosystem variability and habitat conditions (e.g. Paton et al. 2009; Ye et al. 2016). At a whole-of-site level, the water regime of the region is primarily dependent on inflows from the River Murray, but flow from the eastern Mount Lofty Ranges, upper south-east drainage network and groundwater, as well as evaporation from the water bodies, also contribute. At a habitat scale, the components of the water regime (for example, the duration, timing and frequency of inundation) dictate how available a given habitat is and therefore what patterns of plants, animals and processes will occur (Phillips & Muller 2006). This chapter provides an overview of the hydrology of the region, including key features of the Lower Lakes and Coorong; historic variability in inflows, outflows and climate; and the resulting water levels and salinities that have occurred at the site.

The Lower Lakes

The Lower Lakes comprise the large, freshwater lakes of Lakes Alexandrina and Albert at the downstream end of the Murray-Darling River system. The Lakes are physically separated from the Coorong estuary and Murray Mouth by five barrages, which were constructed between a series of islands from 1935 and 1940. The barrages were constructed to manage the salinity risk due to marine incursion in the lower reaches of the River Murray, Lake Alexandrina and Lake Albert, as well as to stabilise the river levels for irrigation and navigation.

The hydrology of the Lower Lakes is primarily influenced by inflows from the River Murray, but other surface water and groundwater sources, and the Southern Ocean, are also important drivers. The interaction between these factors can be complex, and can vary spatially and temporally depending on conditions. Water levels in the Lower Lakes fluctuate seasonally, and are generally higher in winter and lower in summer following the pattern of River Murray and tributary inflows and climatic factors, such as wind, tides and evaporation (Phillips & Muller 2006).

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Lake Alexandrina is a broad, well-mixed, freshwater, regulated water body. The Lake is relatively shallow, with an average depth of 2.9 m and maximum depth of 4.8 m (AWE 2011). Lake Albert is a terminal lake linked to Lake Alexandrina by a narrow channel ('The Narrung Narrows') between Point Malcolm and the Narrung Peninsula. Lake Albert is also a broad and shallow lake, smaller and shallower than Lake Alexandrina. Given its terminal nature, the water levels of Lake Albert are primarily driven by the water levels in Lake Alexandrina, but also by wind and evaporation.

A profile of the bathymetry (bottom elevation) across the Lower Lakes can be seen in Figure 2.7.1, where this broad and shallow morphology can be seen. Relatively steep banks above ~0.3 m AHD (Australian Height Datum) can also be seen, and because of the steep banks, there is only a relatively small increase in surface area, with increases in water level above this elevation. Figure 2.7.1 shows only one possible transect across the Lake and does not show the relative widths at each location (for example, the very narrow nature of the connection between the Lakes at The Narrung Narrows). These can be seen in Figure 2.3.1 in Chapter 2.3.

The barrages may hold water levels in the Lower Lakes up to around 0.83 m AHD, before water starts to flow over spillways between the barrages. However, a level of 0.75 m AHD is generally referred to as the nominal full supply level. At this level, the surface area and volume of Lake Alexandrina is ~65 300 ha and 1 620 GL respectively. For the same level, Lake Albert has a surface area of 17 270 ha and a volume of ~280 GL. The relationships between area and volume with depth, both for each lake and combined, can be seen in Figure 2.7.2. As noted above, there are only small increases in surface area when water levels are greater than 0.3 m AHD. This also results in a linear increase in combined storage volume in both Lakes of ~82 GL for each 0.1 m increase in water level.

The Coorong

The Coorong is a shallow and narrow saline to hypersaline lagoon, which runs north-west to south-east, parallel to the coast for ~110 km and separated from the sea by a sand barrier. It has a constricted channel connection to the sea towards its western end. The Mouth allows exchange with sea water through the Tauwitchere Channel to the main body of the Coorong to the south-east and to the Goolwa Channel towards the north-west, the latter connected to Lake Alexandrina via the Goolwa barrage.

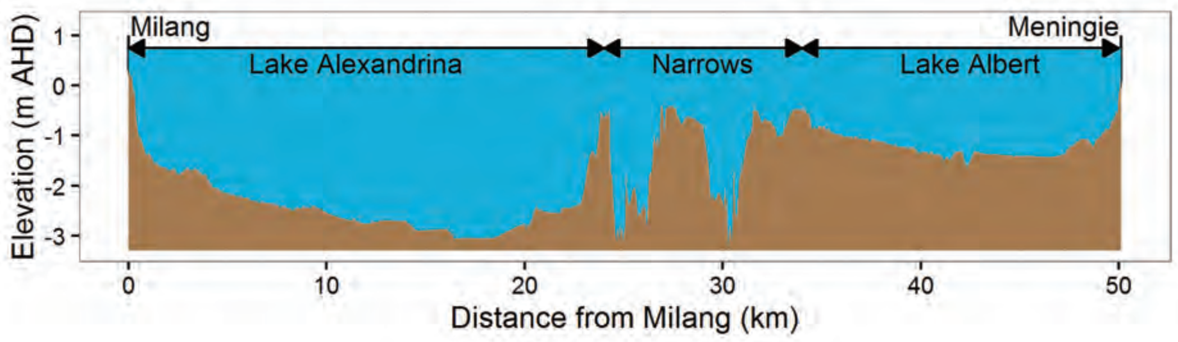

Figure 2.7.1 Bottom profile of the lake bed from Milang to Meningie, across the deepest point in the centre of the Lakes, and The Narrows in between. (Derived from Department for Environment and Water (DEW) bathymetry data)

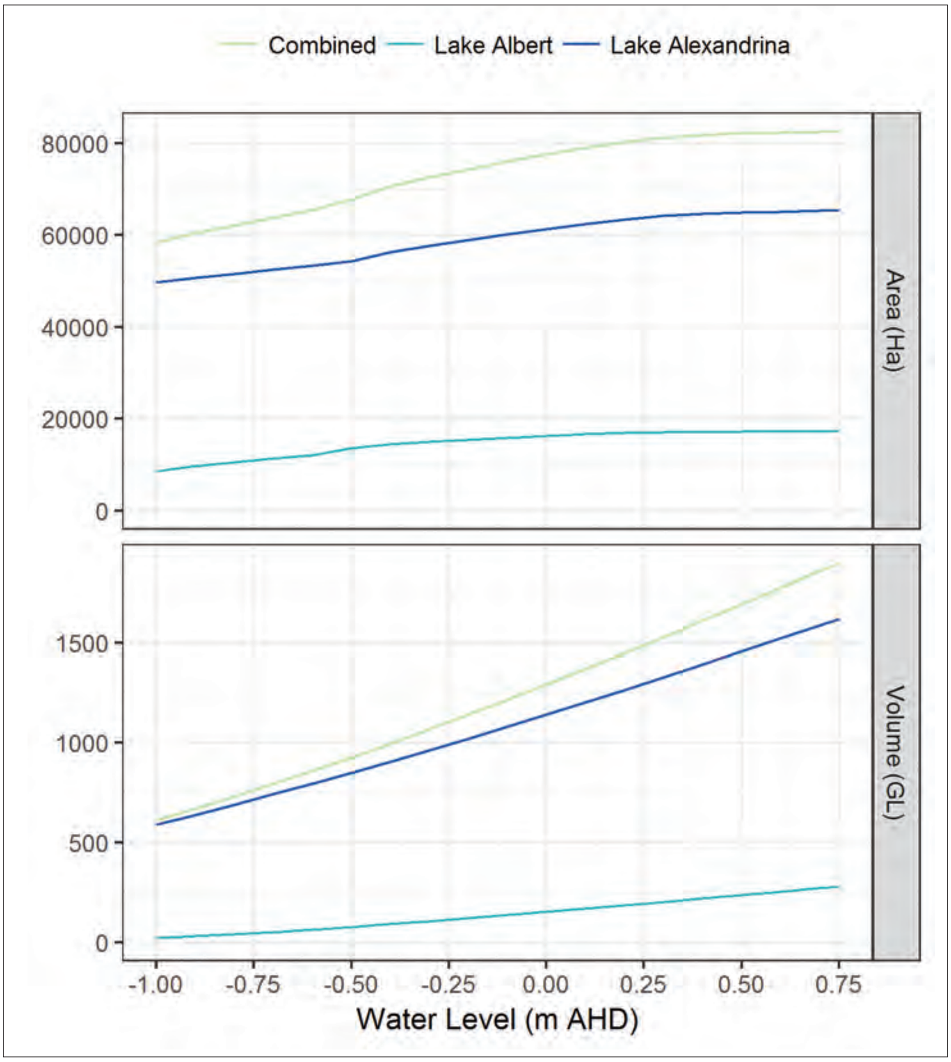

Figure 2.7.2 Area and volume relationships for Lake Alexandrina, Lake Albert and the two Lakes combined. (Derived from Department for Environment and Water (DEW) bathymetry data)

The Coorong naturally splits about halfway into the North and South Lagoons at a narrow constriction ('the Parnka Narrows') with width down to ~100 m. At 0 m AHD the average widths of the North and South Lagoons are 1.5 km and 2.5 km respectively, whereas the average depths are 1.2 m and 1.4 m respectively (Fig. 2.7.3). Because the majority of the freshwater input to the Coorong occurs through the barrages in the North Lagoon, close to the same end as the connection to the sea, the Coorong acts as an inverse estuary, in which salinity generally increases away from the Mouth channel. In addition, the southern end of the South Lagoon receives smaller volumes of fresh to brackish water from a network of drains culminating at Salt Creek.

As the South Lagoon receives less freshwater inflow it has a higher salinity than the North Lagoon. During extended periods of low barrage flows and reduced connection between the two lagoons, the salinity in the South Lagoon well exceeds the salinity of sea water (~35 g L^{-1}), a state that is called hypersaline. During the Millennium Drought there was no flow through the barrages for several years, and in consequence summer-time salinity in the South Lagoon exceeded four times that of sea water.

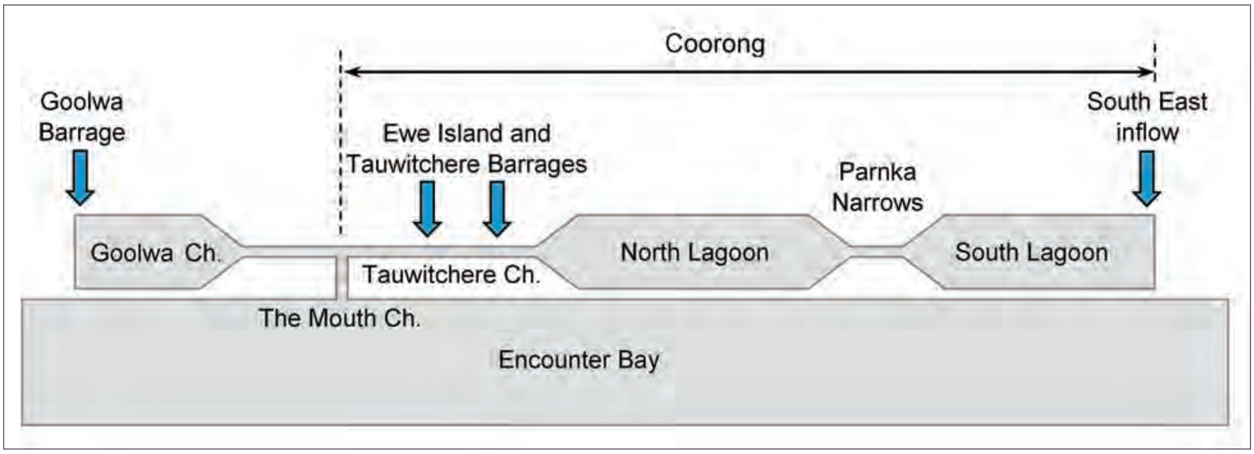

Figure 2.7.3 Schematic view of the Coorong.

INFLOWS AND OUTFLOWS

Most freshwater inflows to the Lower Lakes, Coorong and Murray Mouth are from the River Murray, with relatively minor contributions from other sources. A description of the historical range of inflows and outflows to the site is provided in this section, based on data available.[5]

River Murray

The River Murray enters Lake Alexandrina near Wellington. However, the most downstream location at which river flow is calculated is at Lock 1 at Blanchetown, which is 274 km AMTD (adopted middle thread distance, or distance from the Murray Mouth) upstream of Wellington. The data record from Lock 1 provides an indication of the inflow reaching Lake Alexandrina, noting that it is higher than the flow actually reaching Wellington due to evaporation and other losses (e.g. to groundwater); extraction for consumptive uses, such as water supply for Adelaide; and irrigation. Statistics of the annual flow volumes at Lock 1 can be seen in Table 2.7.1, with an average flow over Lock 1 of 5 783 GL yr^{-1} for the period considered.

The monthly averaged flow over Lock 1 from 1960-2016 is presented in Figure 2.7.4. Typically, there is a regular seasonality to the flow pattern, with higher flows occurring over winter and spring. The highest flows generally occur in September to November and the lowest in February to April, but higher-flow events can occur at almost any time of year. This seasonal pattern is highlighted in Figure 2.7.5, where for each month, the horizontal line inside the box represents the median monthly flow, with the size of the box the interquartile range (between

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[5] Flow into the lakes from the River Murray is calculated at Lock 1, based on upstream and downstream water levels and the weir configuration (number of logs). Flow from the Mount Lofty Ranges was modelled over the period 1 January 1960 to 31 December 2009, based on Alcorn (2011). Flow through the barrages was calculated by the MDBA using a water balance approach from 1 January 1963 to 30 June 2012. From 1 July 2012 to 31 December 2016 barrage flow was calculated based on the upstream and downstream water levels, and the flow through the number of gates and fishways open at each barrage. Flow from the South East drainage system into the Coorong is based on station A2390568, from 11 August 2001 to 30 June 2017. It should be noted that a number of drains have been constructed during this time, and consequently the flow has increased over this period.

Table 2.7.1 Summary statistics of annual volumes (GL yr^1) for water sources to the Lower Lakes and Coorong.

	Lock 1	Eastern Mount Lofty Ranges	Barrages	South East Inflow
Minimum	434	13	0	0
1st Quartile	1770	48	631	5
Median	4077	73	2258	11
Average	5783	85	4335	15
3rd Quartile	7654	115	5693	24
Maximum	27 912	256	19 723	45

the 25th and 75th percentile values, occurring 50% of the time). Events in winter are typically driven by flows from tributaries in the southern River Murray system, such as the Goulburn and Murrumbidgee Rivers, with events in summer primarily the result of tropical storms in the northern Darling River system. Wet periods in the mid-1970s and early 1990s are evident, as well as the Millennium Drought, from 2002 to 2010. More recently, Lock 1 flow has exceeded 70 GL d^{-1} during events in 2010-2011 and 2016.

Eastern Mount Lofty Ranges (EMLR)

There are a number of smaller tributaries that flow from the EMLR directly into Lake Alexandrina. These include Currency Creek, Tookayerta Creek, Finniss River, Angas River and Bremer River. These largely ephemeral creeks generally have a strong winter-spring flow season. There is limited flow from January to May, aside from the wetter catchments of Currency Creek, Tookayerta Creek and the Finniss River.

Statistics of the total annual volume across all creeks flowing into Lake Alexandrina are presented in Table 2.7.1, with an average volume of 85 GL and an interquartile range (between the 25th and 75th percentile values, occurring in 50% of years) of 48 to 115 GL yr^{-1} (based on Alcorn 2011). While these inflows are minor in volume in comparison to the flow over Lock 1, the EMLR creeks are considered ecologically important because they support species listed under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) and species of conservation significance to South Australia (AWE 2011).

Groundwater discharge

Shallow saline aquifers exist on the northern and eastern sides of Lake Alexandrina and on Lake Albert. These low-lying areas contain highly saline groundwater, where salinity is greater than 100 g L^{-1} (Haese et al. 2009). Groundwater inflow volumes from these aquifers are considered negligible compared with river inflows (Lester et al. 2011). Nonetheless, this process does contribute an additional salt load to the Lakes. The mean monthly salt inflow into Lake Alexandria from groundwater and other sources, such as the EMLR, can vary between 300 and 800 tonnes day^{-1} (Heneker 2010). For further information on the groundwater and hydrogeology of the region, see Chapter 2.8.

Barrage outflow

Flow through the barrages (Box 2.7.1) into the Coorong is dependent on the magnitude of inflows to Lake Alexandrina, net evaporative losses, consumptive use and any change in storage volume within the Lakes. In Figure 2.7.4 it can be seen that barrage flow closely follows the flow pattern at Lock 1 but is generally slightly lower, due to losses and extractions. The Millennium Drought period is again pronounced, with very low barrage flows from 2002 culminating in almost four consecutive years with no barrage flow from November 2006 to September 2010.

As far as practicable, barrage outflow is managed to provide an annual cycle in Lake water levels. Some inflows are stored over the higher flow period (winter to late spring-early summer) to a high water level of 0.75 m-0.85 m AHD. This storage may allow some barrage flow to be released as water levels are reduced to a low of 0.5-0.6 m AHD in autumn, continuing over the period with typically lower inflows and higher losses (see *Salinity* below).

South-east inflow

Flow from the south-east of South Australia contributes comparatively small flows directly into the south of the Coorong South Lagoon at Salt Creek. The natural drainage in the region involves flow toward the west until one of a series of low ranges parallel to the coast is encountered, when the water is banked up and eventually deflected towards the north-west on the eastern side of the range. This forms a sluggish and ill-defined water course, which slowly migrates towards the Coorong (Williams 1964). Since the 1860s, a number of drainage networks have been constructed, initially to divert this water off the land and out to sea. More recent programs, such as the Upper South East Dryland Salinity and Flood Management Program, and the South East Flow Restoration Program, have looked to restore some of the north-westerly natural flow paths toward the Coorong. Because of these changes in the catchment, there has been a general increase in the flows reaching the Coorong since records began in 2001. From Table 2.7.1 it can be seen that an average volume of 15 GL yr^{-1} has occurred over the period considered.

BOX 2.7.1 THE BARRAGES

There are five barrages that separate Lake Alexandrina from the estuary, located at Goolwa, Mundoo, Boundary Creek, Ewe Island and Tauwitchere. The barrages were constructed in the 1930s, are 7.6 km long, and have a total of 593 independent operable gates across the structures. With the exception of Goolwa, the barrages are built on a natural sill of lithified calcium sediments (the remnants of the Last Interglacial shoreline), which separates Lakes Alexandrina and Albert from the estuary (Gell & Haynes 2005). It is hypothesised that this sill, in conjunction with flow down the River Murray, historically impeded the ingress of sea water into the Lower Lakes, in addition to the Murray Mouth, which was also a constriction that reduced seawater inflows (Phillips & Muller 2006).

Oceanic inflows

A key driver of the Coorong dynamics is oceanic water-level fluctuations. Sea levels in Encounter Bay are mainly semi-diurnal. Tidal ranges vary between 1.2 m and 0.4 m during spring tides and neap tides respectively. This leads to a water exchange with the North Lagoon through the Murray Mouth and the connecting Mouth channel. The exchange largely depends on the geometry of this restriction and might drop to zero during times of Mouth closure. The tidal signal in water level is mainly visible in the North Lagoon closer to the Mouth, reaching up to 0.2 m in amplitude and fading away with distance to the Mouth.

The Mouth channel is relatively narrow and shows dynamic changes in its width, varying between several hundred metres during flood flows and complete closure. Barrage flows tend to broaden and deepen the Mouth channel during typically higher flows in spring. When barrage flows are low or when they cease, infilling with sediments occurs. The Murray Mouth completely closed in 1981 and 2003. From 2002 and 2010 it was necessary to carry out dredging operations to maintain connectivity and water exchange between the Coorong and the ocean. The high flows in 2010-2011 scoured enough sand at the Murray Mouth to enable dredging to be suspended until 2015.

The geometry of the Mouth channel is continually changing, due to barrage flows that scour the channel and infilling processes associated with such processes as suspension of sands by ocean waves. The rate of channel broadening and deepening through scouring increases almost directly with flow velocity. In general, a large barrage flow delivered over a short period of time results in a deeper channel than the same volume of water delivered more slowly over a longer period of time. However, the smaller discharge may result in channel depth that is similar when averaged over time, since it takes longer before infilling commences on cessation of the flow.

CLIMATE

Rainfall and evaporation

Most inflow to the Lower Lakes comes from the River Murray as opposed to from local rainfall. The main impact on the hydrology of the Lakes and Coorong due to direct rainfall is actually a lack of it — there is typically significantly more evaporation than rainfall over the water body each year.

The region has a Mediterranean climate with mild, wet winters and hot, dry summers. Based on the Meningie rainfall station (24518), the average annual rainfall is ~470 mm and average maximum temperatures range from 26 °C in February to 15 °C in July. The combination of heat and wind leads to significant evaporation from the Lakes and Coorong.

Over a water year (defined from July to June, inclusive), the amount that evaporation exceeds the rainfall is called the net evaporation or net loss. Since construction of the barrages, the total annual net loss from the Lower Lakes has ranged from 600 to 950 GL, with an average of 800 GL (Heneker 2010).

The monthly pattern of rainfall and evaporation can be seen in Figure 2.7.6. The data were derived from the Scientific Information for Land Owners (SILO) database (Jeffrey et al. 2001) and represent a weighted average of six stations around the Lower Lakes. The Morton's Lake method was used to derive evaporation from a shallow lake (McMahon et al. 2013). For each

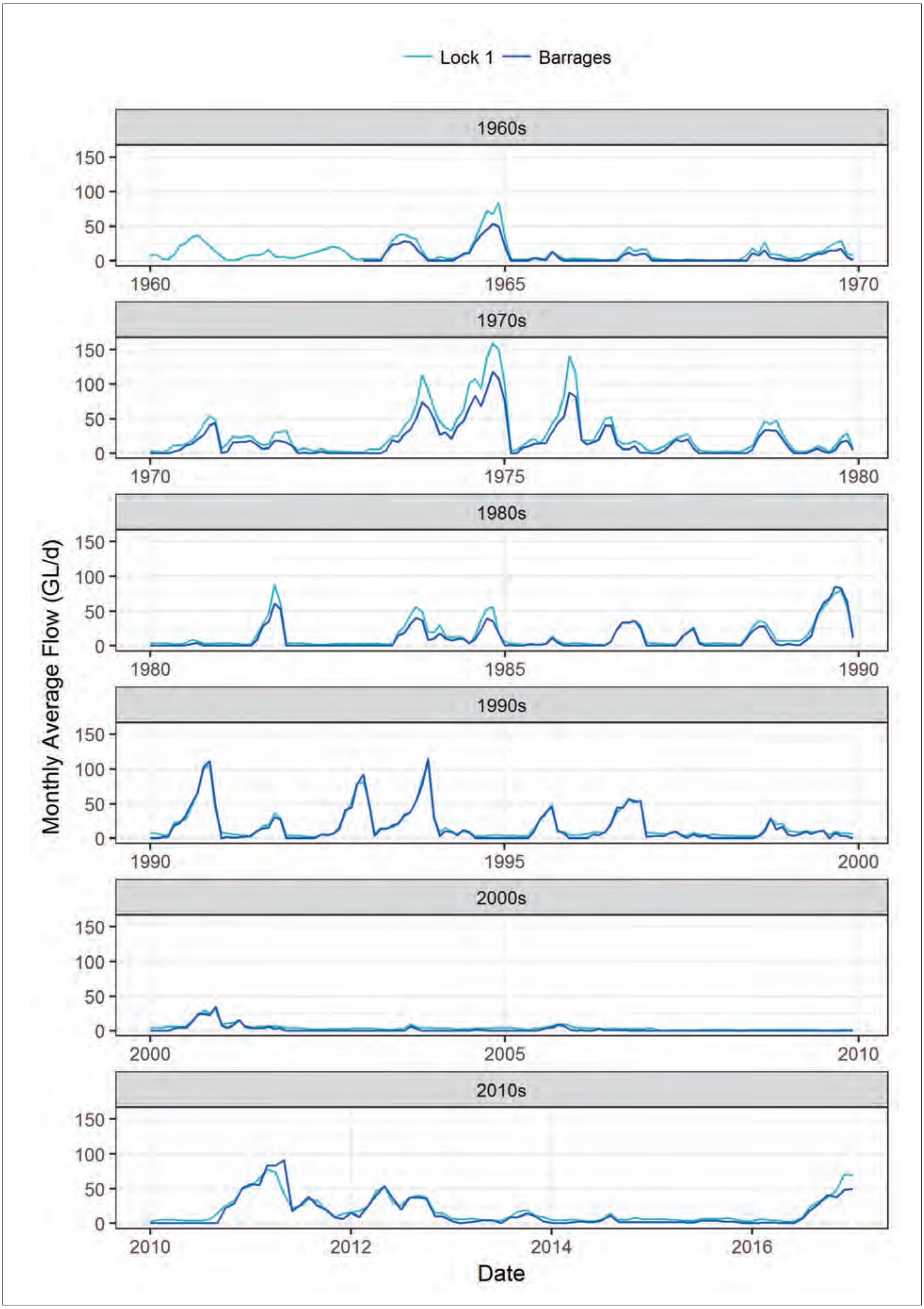

Figure 2.7.4 Monthly average flow at Lock 1 and the barrages January 1960 to December 2016. Estimates of barrage flow commence in January 1963..

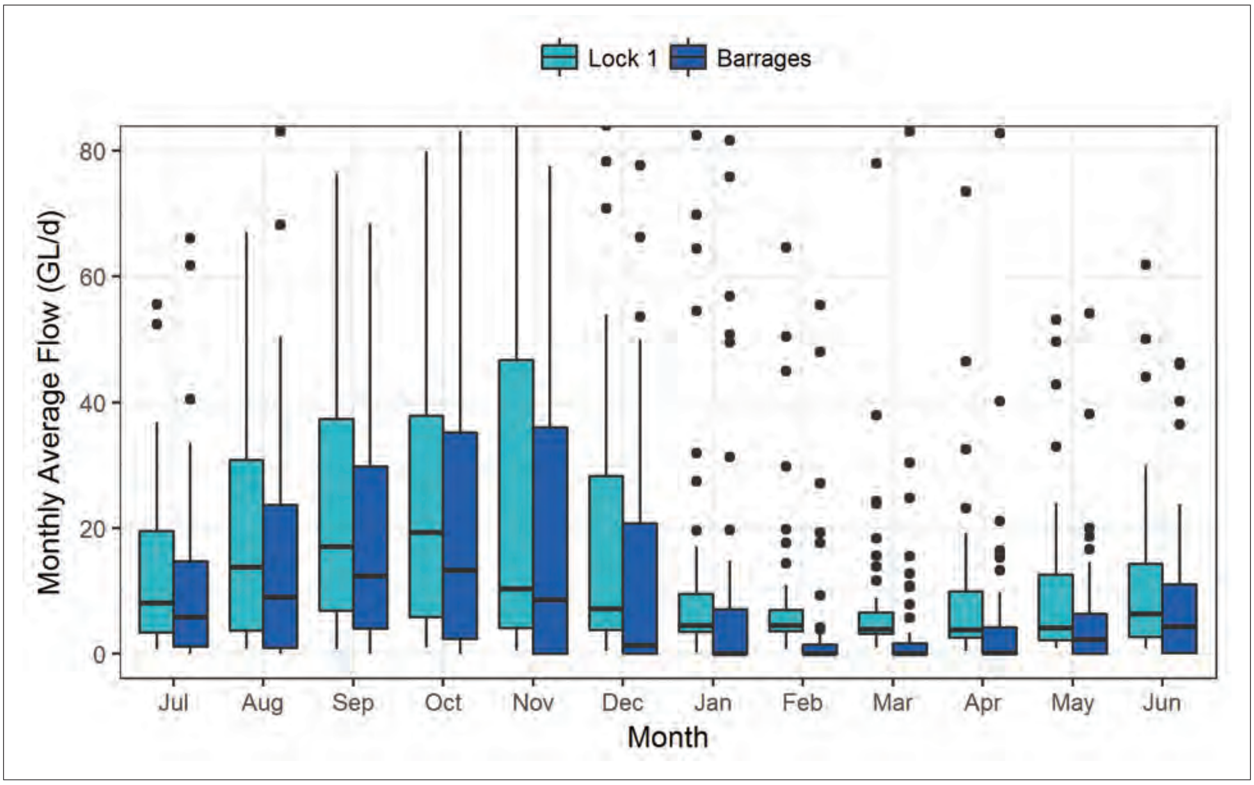

Figure 2.7.5 Range in monthly average flows at Lock 1 and the barrages based on the period January 1960 to December 2016. Note that flows greater than 80 GL d^{-1} are not shown on this figure.

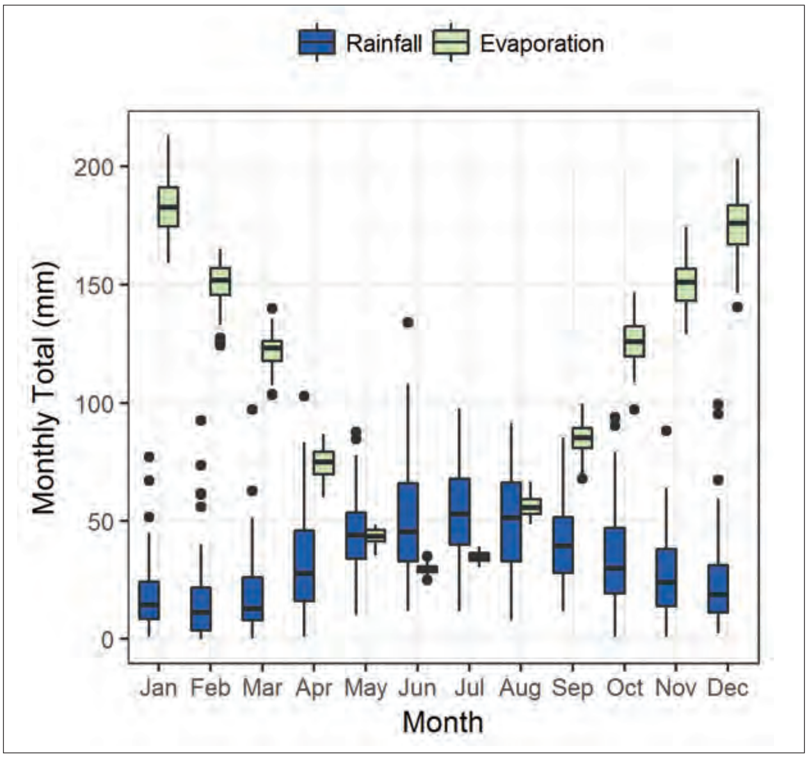

Figure 2.7.6 Monthly rainfall and evaporation (July 1960 to June 2016). Evaporation can be seen to exceed rainfall from September to April most years. (Data derived from the Scientific Information for Land Owners (SILO) database (Jeffrey et al. 2001), representing a weighted average of six stations around the Lower Lakes)

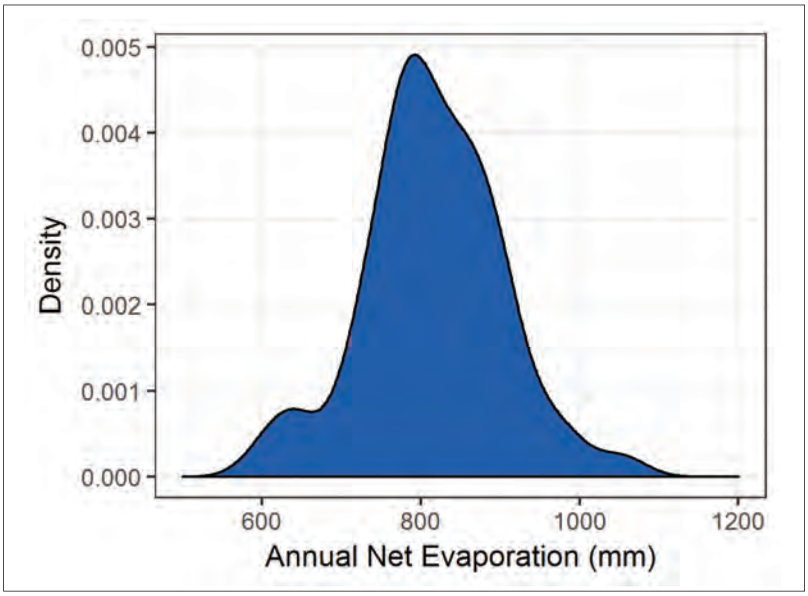

Figure 2.7.7 Range in annual net evaporation from the Lakes (July 1960 to June 2016). (Data derived from the Scientific Information for Land Owners (SILO) database (Jeffrey et al. 2001), representing a weighted average of six stations around the Lower Lakes)

month, the horizontal line inside the box represents the median monthly total, with the size of the box the interquartile range (between the 25th and 75th percentile values, occurring 50% of the time). It can be seen that typically rainfall is more than evaporation for June and July, and for around half the time in the adjacent months of May and August. For the remainder of the year (September to April), evaporation is typically more than rainfall.

The net evaporation from 1960 to 2016 can be seen in Figure 2.7.7, indicating a range between ~600 and 1 000 mm, and a median value of 807 mm. Evaporation is typically fairly consistent each month, as seen by the relatively short boxes in Figure 2.7.6. Hence, it is the variability in rainfall that causes the variation in net evaporation and the volume ultimately lost from the Lakes and Coorong each year. The years with the lowest net evaporation are generally the very wet years, such as 2010-2011, 1986-1987 and 1992-1993, when <640 mm of net evaporation occurred. The highest net evaporation occurred during the Millennium Drought, with >980 mm in 2006-2007 and 2007-2008. In the 56 years of data considered, 6 of the 10 highest net evaporation years have occurred since 2006-2007.

Wind

Wind speed, direction and duration produce waves and seiching across the Lakes. This creates variation in water levels, and directly influences the exchange of water between the two Lakes and between the Lakes and the estuary across the barrages. Wind also causes vertical mixing within the Coorong, as well as oscillatory flow blowing water back and forth.

Wind roses for each month, based on the hourly wind data recorded at Pelican Point, can be seen in Figure 2.7.8. For each compass direction, the length of each branch represents the proportion of time that the wind blows from that direction in that month. Within each branch, each coloured segment shows the proportion of time that the wind was recorded at

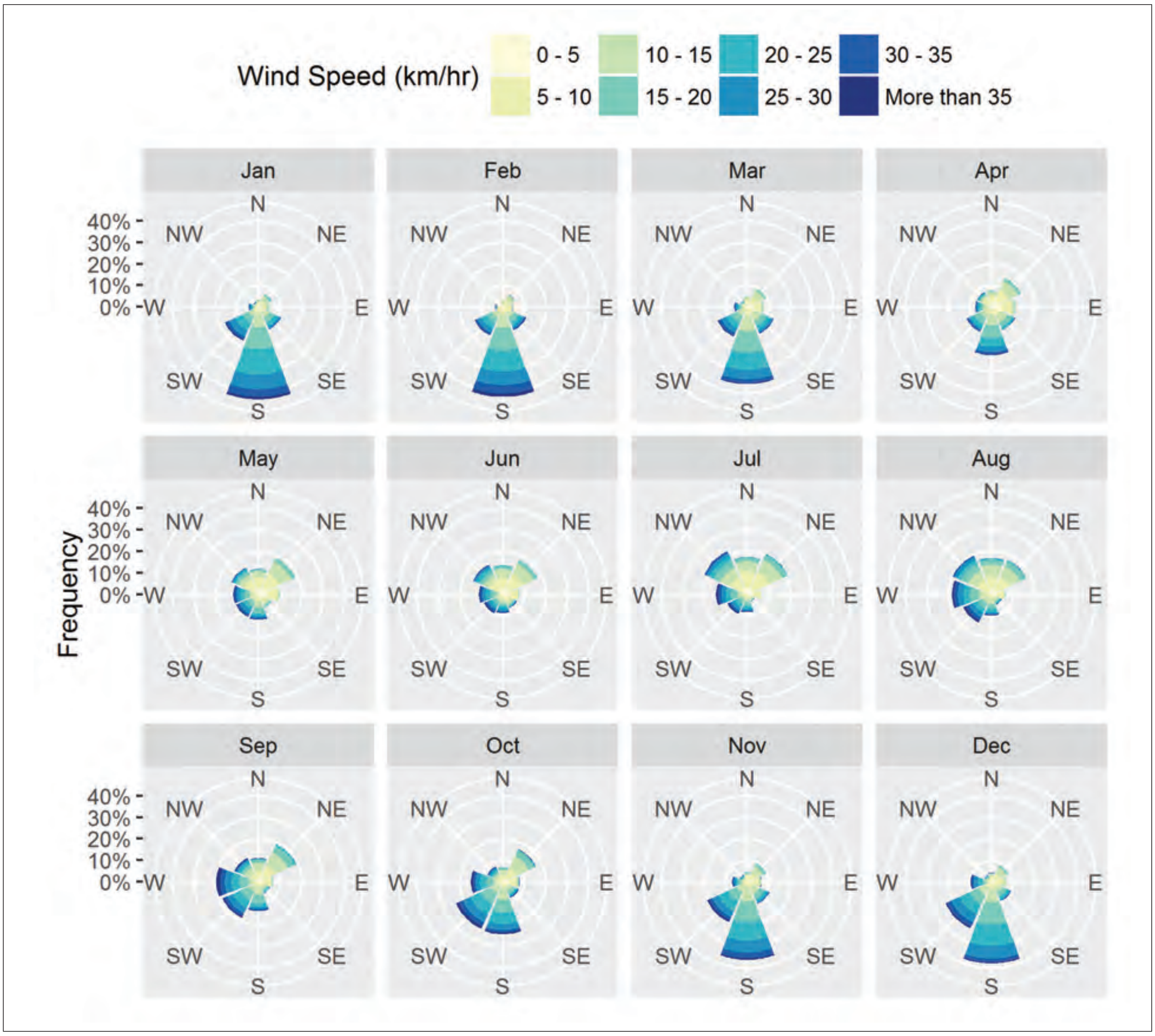

Figure 2.7.8 Hourly average wind speed and direction at Pelican Point (1989-2016). (From Department for Environment and Water, (DEW) SA)

that speed. It can be seen that there is a distinct seasonal pattern in wind speed and direction. Winds from the south dominate from late spring to autumn (November to March) and during much of this time the wind speed exceeds 20 km hr^{-1}. Over July and August, winds tend to prevail from the northern side of the compass, typically at lower speeds.

The differences in wind direction over the year produce consistent differences in water level between the two Lower Lakes. Ranges in water level for each month for each lake can be seen in Figure 2.7.9. Southerly winds will create a seiche effect across each lake, by pushing water in one direction, generating lower water levels on the southern side compared to the northern side. They also tend to move water out of Lake Albert and into Lake Alexandrina. Seiching across Lake Alexandrina may extend all the way to Lock 1.

From Figure 2.7.8, winds from the south were most common over November to March. This corresponds with the median water level being consistently lower in Lake Albert compared to Lake Alexandrina over these months, as shown in Figure 2.7.9. It is also substantially lower

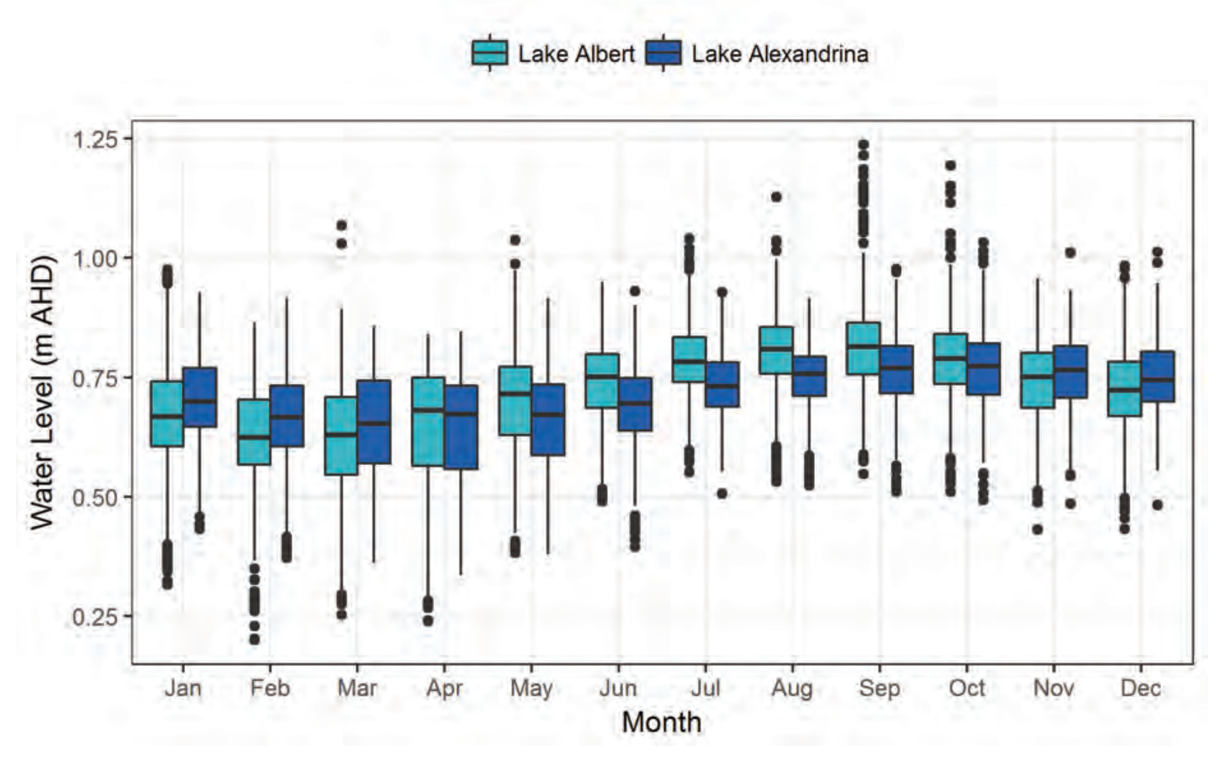

Figure 2.7.9 Variation in daily water levels for Lake Alexandrina and Albert (period of extremely low water levels from July 2006 to September 2010 excluded). The impact of wind on the difference between the Lakes can be seen, with southerly winds resulting in Lake Albert water levels typically lower than Lake Alexandrina from November to March, and higher in July and August with typically northerly winds. (From Department for Environment and Water, SA)

in January and February when the strongest and most predominant southerly winds occur. The opposite effect can be seen in July and August, when there is almost no wind from the south and, in particular, from the south-east along the direction of The Narrows. This results in a higher water level in Lake Albert than in Lake Alexandrina.

Beside the seasonal patterns in wind speed and direction, short-term events also have a pronounced effect on the hydrodynamics of the Lower Lakes and Coorong. One example in the Lower Lakes in July 2016 can be seen in Figure 2.7.10. During this event the wind blew persistently from the west to north-west for over 2 days with an average wind speed of 36 km hr^{-1}. The sustained duration of this event resulted in the average water level across Lake Albert being 0.3 m higher than in Lake Alexandrina. The difference in water level was even greater at the extremes of each lake (recorded at Milang and Meningie), where the difference in water level was 0.6 m, and up to 0.9 m at times.

Wind events like this result in mixing between the Lakes, which is particularly important for the salinity of Lake Albert. Without this wind-driven mixing between the Lakes, Lake Albert would continue to lose fresh water to evaporation, which is replaced by more saline water from Lake Alexandrina. This leads to the continued evapo-concentration of salt (and other water quality parameters) in Lake Albert. The effect of a lack of connection between the Lakes was highlighted during the Millennium Drought when salinity in Lake Albert reached

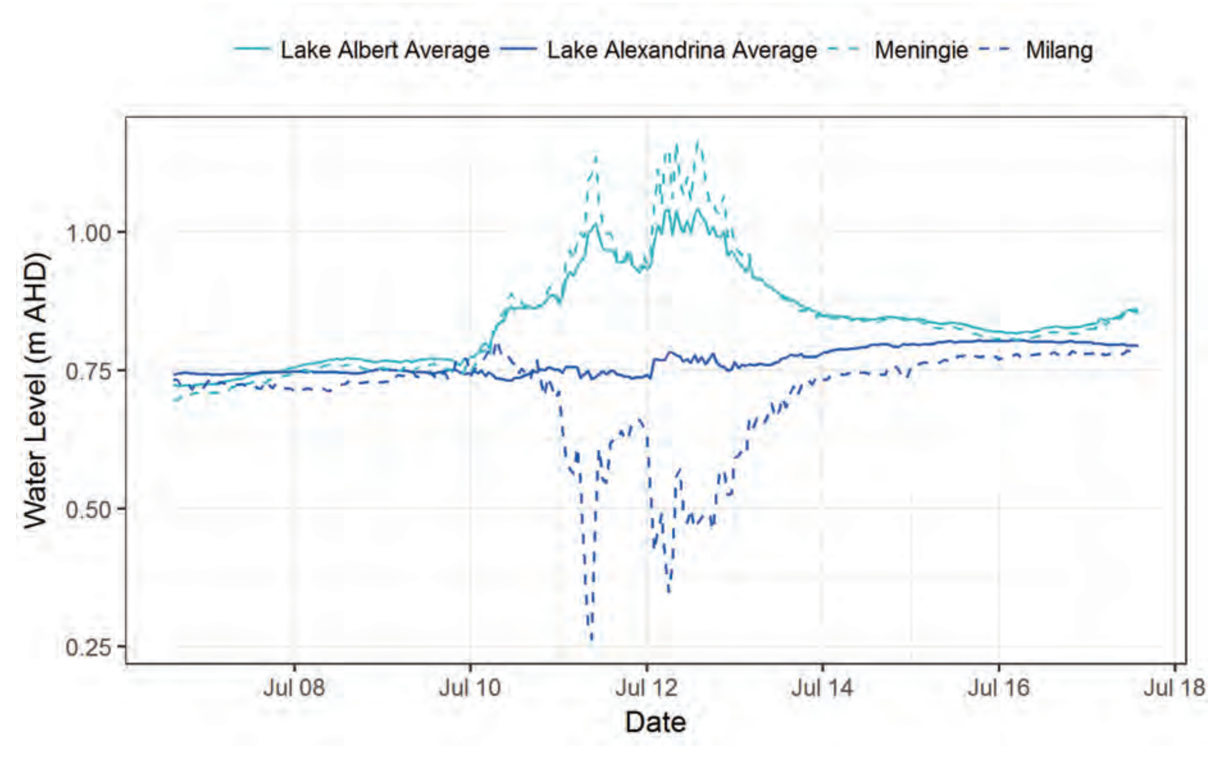

Figure 2.7.10 Hourly water levels during a strong wind event in 2016, where the difference in water level across the Lakes (from Milang to Meningie) reached 0.9 m. (From Department for Environment and Water, SA)

over 20 000 electrical conductivity units (EC) (see *Salinity* below). The same physical processes occur in the Coorong, between the South and North Lagoons.

Rapid changes in water level can also have other impacts, like erosion of the lake shore, overtopping of the barrages, and major changes to the water regime at a habitat scale, such as drying out inland areas like, for example, the mouth of Currency Creek (Phillips & Muller 2006).

Water temperature

The rates of many ecosystem processes vary with water temperature. Water temperature is determined by the way in which incoming solar radiation that is absorbed in the water column balances heat loss from the water surface through evaporative cooling and longwave thermal emission to the sky. Such shallow systems as the Coorong show a seasonal pattern in water temperature similar to air temperature. Usually, water column mixing due to the action of the wind on the water surface is sufficient to maintain a homogenous, vertically mixed water column. However, on calm, sunny days, the lack of wind mixing can allow thermal stratification to occur, where the surface water layer becomes warmer than the water nearer the bottom. Likewise, salinity stratification can occur, with water of denser, higher salinity at the bottom than that at the surface, generated by horizontal, advective flow of fresher water over a water body with higher salinity, or vice versa. Although these stabilising effects can last for several days, in the shallow Coorong wind action and night-time cooling will likely mix the water column again.

HISTORICAL VARIATION IN THE LOWER LAKES IN WATER LEVEL AND SALINITY

The water levels and salinities experienced within the Lower Lakes are a function of the inflows, barrage outflows and climatic factors outlined above, over both short and long (multiple years) timescales.

Water levels

The historical range in water level for each month can be seen in Figure 2.7.9, and over time in Figure 2.7.11. It can be seen that prior to 2002 and the period of the Millennium Drought, when the flow was very low, the water level in Lake Alexandrina was managed within a narrow range. While there is day-to-day variability, primarily due to wind, water levels tended to peak at ~0.8 m AHD in September or October, before reaching a minimum level of around 0.65 m AHD in February and March. With generally lower inflows from 2002 onwards, the lake level can be seen to be even lower over summer, although it was typically able to be refilled until 2006. From the end of 2006 until 2010, water level in Lake Alexandrina plummeted to an average across the Lake of -1.05 m AHD (as low as -1.4 m AHD at Beacon 97), with a corresponding increase in salinity. During these extremely low water levels, management actions were undertaken to support water levels within Lake Albert (Box 2.7.2).

Over the past three to four years it can be seen that the Lakes have been managed to a more variable regime compared to the pre-2002 period, with slightly higher water levels to 0.85 m AHD in late spring, and lower levels approaching 0.5 m AHD in autumn. Increased variability in water level has been identified as a key requirement for developing a target water level envelope for the Lower Lakes and River below Lock 1 (Lester et al. 2011). The pattern of raising and lowering water levels is driven by the seasonal requirements of the ecology in and around the Lower Lakes. Gradual winter-spring filling of the Lake supports the growth of new vegetation shoots while ensuring that fauna have access to vegetation for food, shelter and recruitment. Water levels are kept high during spring to ensure fauna access to habitat (Lester et al. 2011). Generally speaking, gradual drawdown over summer and autumn months aims to expose mudflats and support diverse vegetation. This drawdown also allows fishways and some gates at each barrage to remain open over summer during the general period of low inflow.

BOX 2.7.2 WATER LEVELS DURING THE DROUGHT

In 2008, water levels fell to below -0.5 m AHD, which caused a hydrological disconnection between Lake Alexandrina and Lake Albert as a result of a natural sill within The Narrows. Soon after this disconnection occurred, a temporary bund was constructed and up to 1 GL d^{-1} pumped from Lake Alexandrina to Lake Albert to enable water levels in Lake Albert to be maintained at a higher level. This ensured that the acid sulfate soils within Lake Albert continued to be kept underwater, avoiding exposure to oxygen and the formation of sulphuric acid and release of contaminants (see Chapter 2.10). The bund was in place from 2008 to 2010, during which time Figure 2.7.9 shows a water level difference of approximately 0.5 m between the Lakes. On the return of inflows to the Lakes and higher Lake Alexandrina water levels, this bund was removed in 2011.

Maintaining the Lakes at a minimum water level is designed to promote diverse littoral and riparian vegetation diversity and support biogeochemical cycling (Lester et al. 2011).

Salinity

Salinity changes in recent years, as recorded by salinity-monitoring stations, are considered in this section. Longer-term changes in the salinity of the Lower Lakes are presented in Chapter 2.4. This contemporary record of salinity data can be seen in Figure 2.7.11, presented as the daily average of available data at a number of stations within each lake.

The freshwater system of Lake Alexandrina has a median salinity of 742 EC, and an interquartile range (occurring 50% of the time) of 558 EC to 1 154 EC. Salinity in Lake Alexandrina is primarily controlled by inflows from the River Murray and the Eastern Mount Lofty Ranges, and outflows through the barrages (Heneker 2010). This is most evident during periods such as the Millennium Drought, when significantly reduced inflows led to a peak salinity in Lake Alexandrina of over 6 000 EC in 2010 (Figure 2.7.11).

The nature of Lake Albert as a terminal wetland, with a narrow connection with Lake Alexandrina, means that flow into and out of this lake is controlled by water level, wind and evaporation. Lake Albert acts as a sink for salt and sediment due to inflows from the River Murray and groundwater (Phillips & Muller 2006). This can be seen in Figure 2.7.11, where the salinity in Lake Albert is consistently higher than in Lake Alexandrina, with a median salinity of 1 734 EC and interquartile range of 1 385 EC to 2 507 EC. Given Lake Albert's terminal nature and the fact that it is much shallower than Lake Alexandrina, peak salinities over the Millennium Drought were much higher in Lake Albert, at over 20 000 EC, before inflows returned in 2010. Lake Albert salinity has only returned to the long-term median value six to seven years after this peak value during the Millennium Drought. At the start of the record in Figure 2.7.11 the salinity can be seen to freshen, with the higher flows in the early to mid-1990s. This is before flows decreased from 2002 onwards, and salinity in turn started to increase, before substantially increasing from 2006 to 2010 when lake levels were dramatically lower. As flow and water levels have returned, the salinity in Lake Albert has continued to reduce, with the average salinity over the last year of the record in Figure 2.7.11 the same as that over the first year of the record shown, i.e. 1 755 EC.

HISTORICAL VARIATION IN THE COORONG IN WATER LEVEL AND SALINITY

As with the Lower Lakes, water level and salinity in the Coorong also have a strong influence on ecosystem variability and habitat conditions for macrophytes, fish and birds (e.g. Paton et al. 2009; Ye et al. 2016). Water levels also influence particle resuspension and turbidity generated by wind-wave action in the shallow lagoons and thus play a major part in controlling growth of plankton and macrophyte communities by reducing light conditions necessary for photosynthesis. Further, water level variations play a role in the suitability of shoreline mudflats for invertebrates.

Water level

Coorong water levels vary over timescales of seasons down to hours. Hourly variations are associated with wind events, such as the sea breeze, and with the semi-diurnal tides (12-hour

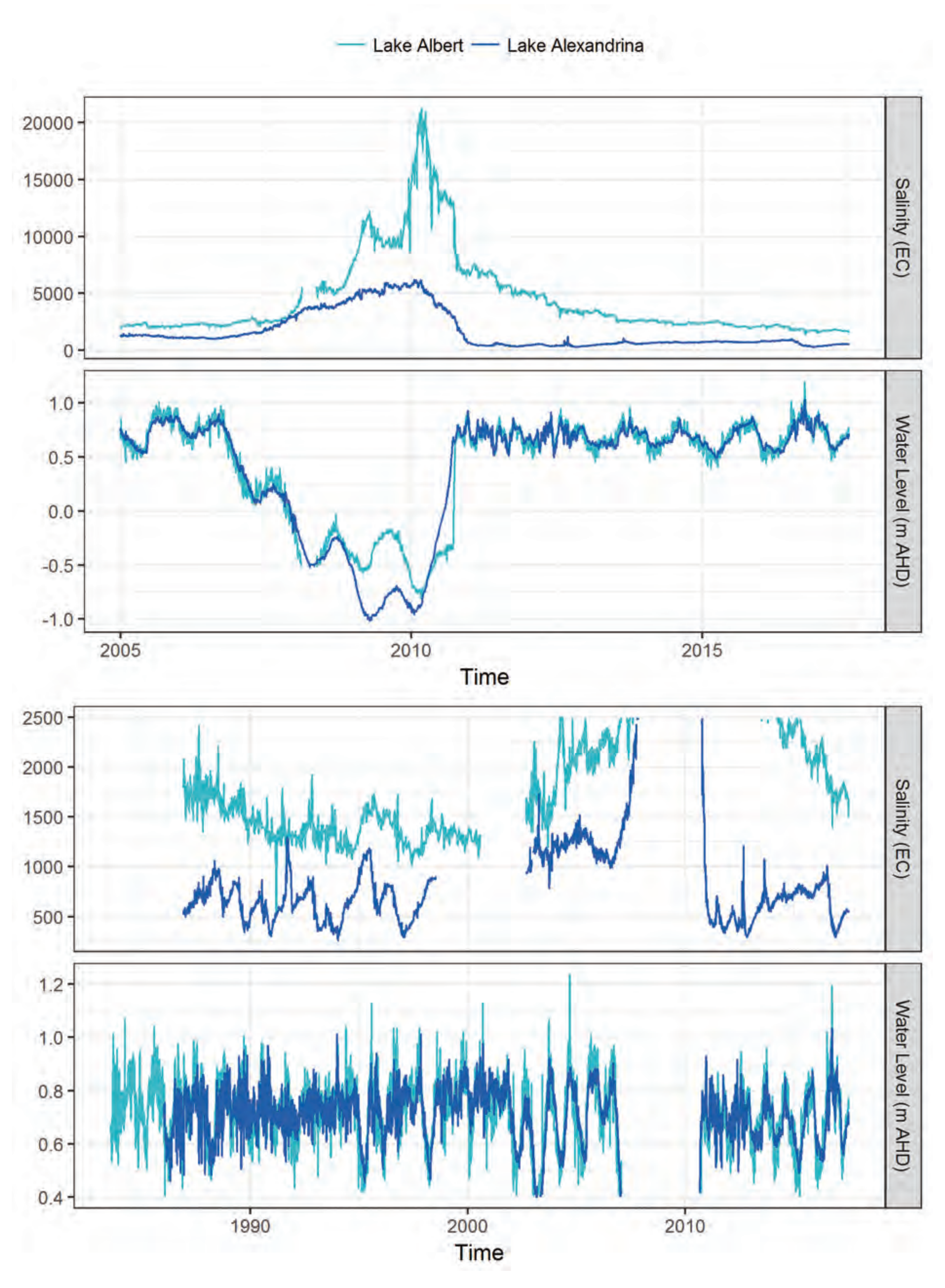

Figure 2.7.11 Historical water levels and salinities in the Lakes.
Above: data since 2005, where the extreme low water levels and high salinities can be seen.
Below: the same data over the whole period of data available, excluding salinities exceeding 2500 EC or levels below 0.4 m AHD. (From Department for Environment and Water, (DEW) SA)

period). Flows across the barrages, evaporation and precipitation change seasonally and on inter-annual timescales due to climate variations. Levels in the North Lagoon at Tauwitcherie follow increasing sea level through autumn. When barrage flows increase in winter, levels rise due to flow blocking through the Mouth channel. Depending on barrage flow timing and strength, peak levels in the North Lagoon of ~0.3 m greater than the seasonal Victor Harbor (Encounter Bay) peak occur in late spring or early summer.

Water levels in the South Lagoon show a strong seasonal cycle due to evaporation-precipitation and variations due to exchange with the North Lagoon. Often in summer, when levels in the North Lagoon reduce, flow through the Parnka Channel between the two lagoons is limited, and the South Lagoon water levels fall further due to evaporation. Figure 2.7.12

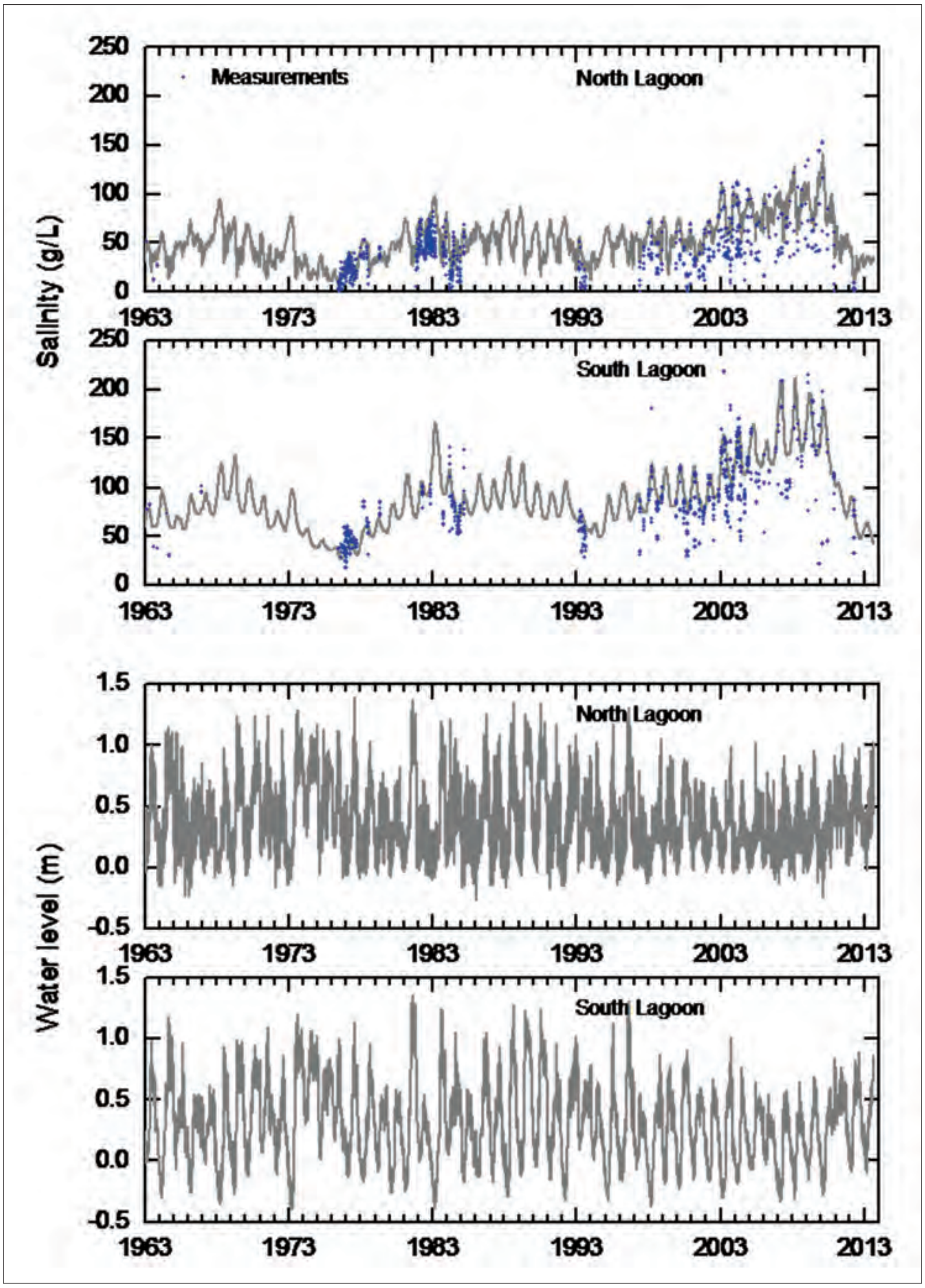

Figure 2.7.12 Simulated salinity and water level in the Coorong. (Based on data from Joehnk & Webster 2014)

shows the simulated water level in the lagoon over the period with barrage flow estimates available (see Joehnk & Webster 2014; Webster 2010), and Figure 2.7.13 shows the monitoring data along the Coorong from when this data commenced in 2008. Both plots illustrate that the North Lagoon has higher variability in water levels than the South Lagoon, and the lower water levels in the South Lagoon over summer can also be seen in Figure 2.7.13.

Salinity

The South Lagoon shows a highly regular cycle of salinity, with peak salinity occurring near the end of March, following the summer of high evaporation rate and reduced connection with the North Lagoon. After this, sea level rises in a seasonal pattern, and the associated flow of water of lower salinity through the Parnka Narrows into the South Lagoon dilutes the salinity. The lowest salinity tends to occur in early spring. Large seasonal variations in salinity can be

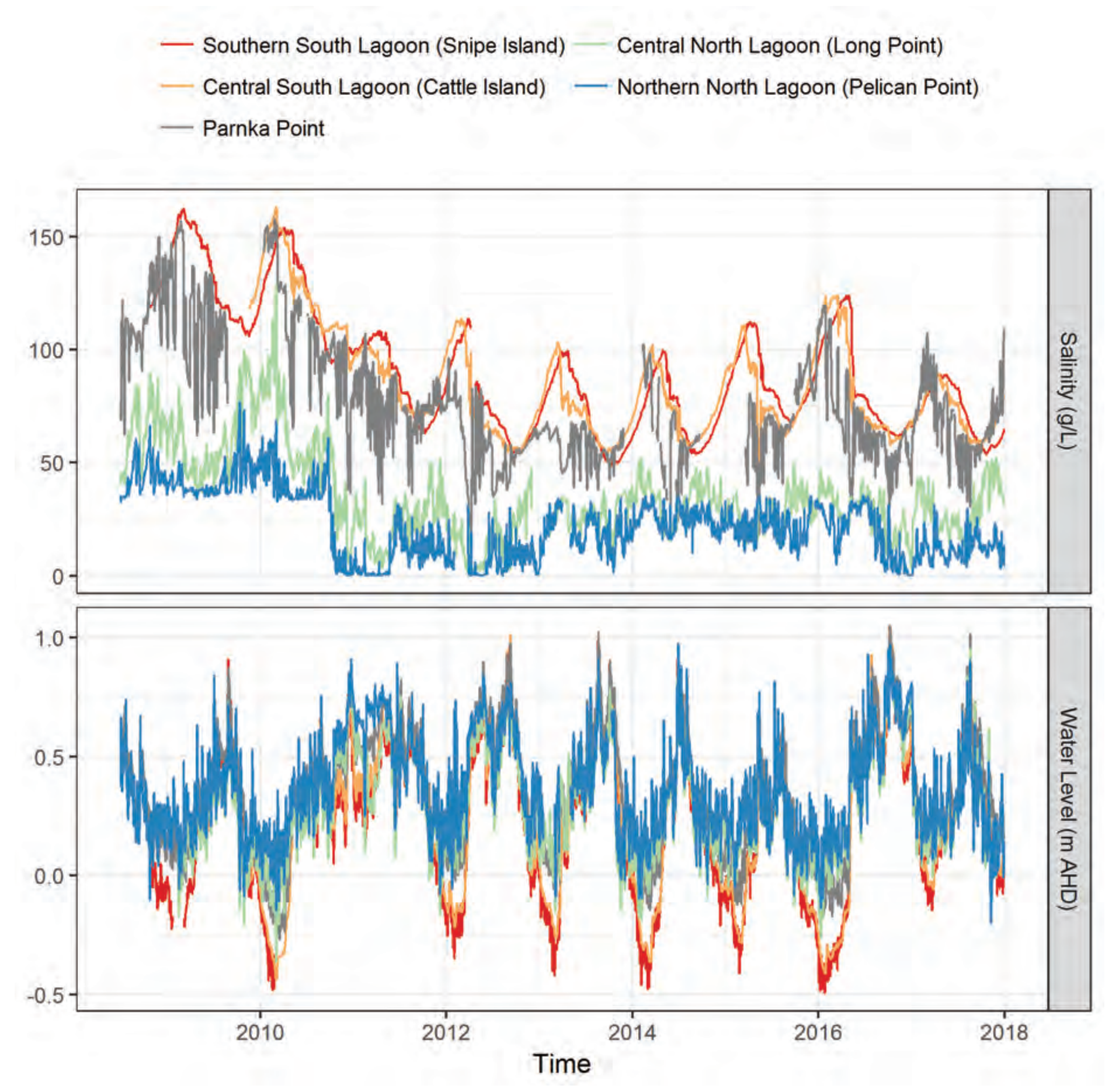

Figure 2.7.13 Coorong water level and salinity data. (From Department for Environment and Water (DEW), SA)

a stressor in their own right, but they also may be of concern if they result in peak salinities exceeding the toxic threshold of organisms living in the lagoon.

Salinity in the North Lagoon also undergoes a significant seasonal cycle (Figs. 2.7.12 and 2.7.13), although it is less regular than the cycle in the South Lagoon. Prior to the virtual cessation of barrage flows after 2001, salinity was generally about half seawater salinity. Maximum salinity in mid-lagoon tended to occur closer to mid-summer, several months earlier than in the South Lagoon. Up to this time, falling sea level would cause more highly saline water from the south end of the North Lagoon to flow towards the Mouth, raising salinity within the lagoon's middle section. It is also apparent that salinity in mid-lagoon is more immediately responsive to barrage flows compared to the salinity in the South Lagoon, with salinity depressions associated with peak flows. This behaviour is due to the proximity of Tauwitcherie barrage. Reduced barrage flows after 2001 were also associated with the onset of higher salinity in the lagoon.

It has been evident for a long time that barrage flows and salinity have been inversely related to one another. High salinity in both lagoons tends to be associated with periods of reduced barrage flows and vice versa. The South Lagoon always has higher salinities than the North Lagoon. During November 1975, salinities in the South Lagoon were measured to be similar to those of sea water, whereas salinities in the North Lagoon were mostly much less than a quarter of those of sea water (Geddes 1987). These followed a time of very large barrage flows. Barrage flows during the drought years (2001-2010) were small, and salinities in both lagoons were much higher than normal, allowing salinity in the South Lagoon to exceed 150 g L^{-1} in summer. These salinities would have been even higher if a dredging program had not been implemented in the Mouth channel in late 2002.

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Chapter 2.8

Hydrogeology of the Lower Lakes and Coorong Region

Steve Barnett[6]

INTRODUCTION

The Coorong, Lower Lakes and Murray Mouth (CLLMM) region lies on the south-western margin of the Murray Basin, and consequently it has a much more complex sedimentary history than elsewhere in the Basin, ranging from Permian glaciations to several marine transgressions, all occurring on an undulating basement surface. Perhaps the most significant geological event in shaping today's landscape and human interaction with it was the Pleistocene marine transgression which occurred about one million years ago. It eroded away much of the older Tertiary sands and limestones and left a broad, flat, low-lying coastal plain.

As a whole, the Murray Basin is a relatively low-lying, saucer-shaped basin containing Cainozoic (Tertiary and Quaternary) sediments deposited in shallow-marine, fluvio-lacustrine and aeolian environments. These sediments form generally thin geological units, which are continuous and flat-lying, and attain a maximum thickness of about 600 m where the River Murray flows across the border into South Australia. In the CLLMM region, the Cainozoic sequence is mostly underlain by the Cambrian rocks of the Kanmantoo Group and unconsolidated Permian sediments.

Figure 2.8.1 presents the simplified geology of the study area and the extent of the Pleistocene marine transgression. The various geological units will be discussed in order of increasing depth below the ground (and increasing geological age).

QUATERNARY

The Quaternary sediments are the youngest and most visible of all the geological units within the study area. They were deposited over a number of different environments, ranging from marine through lacustrine to colluvial. As stated previously, a Pleistocene marine transgression eroded away much of the older Tertiary sands and limestones and left a broad, flat, low-lying coastal plain where shallow marine limestones of the Coomandook Formation were laid down (Rogers 1980). As the sea retreated gradually in response to tectonic uplift, a series of stranded coastal ridges formed, comprising shelly and sandy limestones of the Bridgewater Formation. To the north-west of Lake Alexandrina, outwash deposits from the Mount Lofty Ranges occur, consisting of red-brown clays and interbedded sands of the Pooraka Formation (Fig. 2.8.1).

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Recent aeolian Molineaux Sands form a thin veneer over these Quaternary units. In addition to the alluvium deposited in the River Murray floodplain, alluvial silts and sands have been deposited in the floodplains of streams that flow eastward from the Mount Lofty Ranges toward Lake Alexandrina. These streams include the Angas and Bremer Rivers and the Finniss and Tookayerta Creeks. Black organic clays of the St Kilda Formation were deposited in low-lying areas around the Lakes, when they expanded in response to a higher sea level about 6 000 years before the present (BP).

Chapter 2.2 presents more detail about the complex Quaternary stratigraphy found within the CLLMM region.

TERTIARY

Three major depositional sequences have been identified within the Tertiary succession, each containing distinct sediments separated by disconformities. Each sequence forms a thin but continuous veneer, which has been deposited on a topographically flat, low-lying platform (Brown & Stephenson 1991). In order of increasing depth (and age), the sequences comprise

1. *Late Miocene to Pliocene*, consisting of non-marine fine- to medium-grained clayey quartz sands with thin clay beds which form the Parilla Sands. These sediments lie to the north of the study area (Fig. 2.8.1)
2. *Oligocene to Middle Miocene*, consisting of shallow marine fossiliferous limestone with minor marls, which form the Murray Group Limestone underlying most of the study area and exposed in the low cliffs bordering the River Murray floodplain
3. *Palaeocene-Eocene to Lower Oligocene*, consisting of non-marine dark-brown, fine- to medium-grained sands with interbedded carbonaceous clays and lignites, which form the Renmark Group, lying at depths ranging from 60-140 m below ground level. A short-lived marine trangression during the Eocene deposited bryozoal limestones, carbonaceous clays and fossiliferous sands, forming the Buccleuch Group (Rogers 1980) in an embayment, which coincidentally has a similar extent to the Pleistocene marine transgression (Fig. 2.8.1).

All three sequences are only found in the north-west of the CLLMM region between Lake Alexandrina and the Mount Lofty Ranges, with erosion removing the Parilla Sand and a considerable thickness of the Murray Group Limestone to the south-east of the Lakes.

PERMIAN

During the Permian era, large continental ice sheets moving from the south-east to the north-west carved out several large U-shaped valleys from the older basement rocks in the Mount Lofty Ranges, which were later filled by glacial deposits. These sediments consist of unconsolidated sands, silts and clays with occasional gravel beds, and are known as the Cape Jervis Formation. In outcrop, these sediments form low, rounded hills in the Ranges to the east of Mount Compass. They extend eastwards beneath the Tertiary sediments below Lake Alexandrina, and have also been intersected in an old oil exploration well at Salt Creek.

The Cape Jervis Formation beneath Lake Alexandrina could be up to 500 m thick. Compaction and settlement of this large thickness of unconsolidated sediments over millions of years may have contributed to the low topography that has contributed to the formation of the Lake.

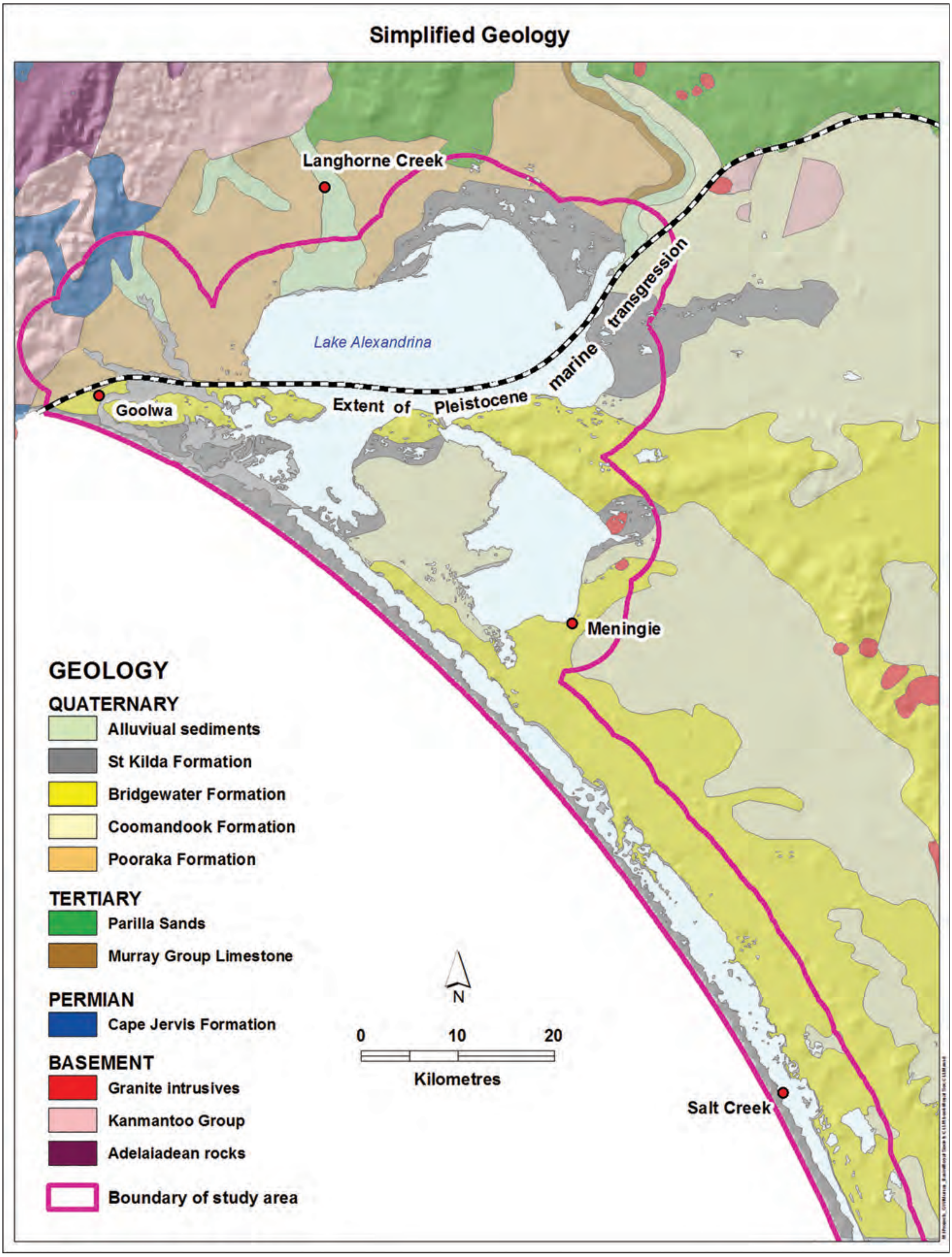

Figure 2.8.1 Simplified geology of the CCLM region. (From Department for Environment and Water)

BASEMENT

Basement rocks of the Cambrian Kanmantoo Group form the Mount Lofty Ranges to the west of the Murray Basin, and extend beneath the basin sediments within the CLLMM region at a depth of about 150 m below ground level. These rocks have been metamorphosed by heat and pressure and consist mainly of greywacke, schist and gneiss. In some areas, Cambro-Ordovician granites have intruded the Kanmantoo Group to create the Padthaway Ridge, which forms local basement 'highs'. Granite outcrops can be seen near the highway at the southern end of the Coorong and also in the north-eastern corner of Lake Albert, where they form small islands.

Tables 2.8.1 and 2.8.2 contain more detailed lithologies and typical thicknesses of these geological units, while Figure 2.8.2 presents composite geological and geophysical logs of an investigation well, which is typical of the geological sequence on the low-lying coastal plain.

GROUNDWATER

In a similar manner to surface water, the low-lying CLLMM region lies at the end of long groundwater flow paths and is the focus of groundwater discharge from the regional aquifer systems occurring in the Murray Basin. Because groundwater salinities are generally brackish to saline, there is little development of groundwater, with the exception of areas north-west of Lake Alexandrina, where extraction for the irrigation of vineyards occurs in the Langhorne Creek and Currency Creek areas. The following discussion will concentrate on the significant aquifers and their interaction with other natural resources. Because of their depth, poor yields and high salinities, there is no extraction from the Renmark Group and Basement aquifers in the CLLMM region.

Quaternary Limestone aquifer

This shallow water table aquifer lies within several Quaternary units, whose extent is defined by the Pleistocene marine transgression (Fig. 2.8.1). The most widespread of these units are the sandy limestones of the Coomandook Formation and the Bridgewater Formation, which are very similar to the underlying Murray Group Limestone, and as there is no evidence of any low permeability unit separating them, they are considered to be strongly hydraulically connected.

Within this aquifer, groundwater movement is from east to west towards the Lakes and Coorong under a very low hydraulic gradient. The groundwater flow-paths are shown in Figure 2.8.3. The salinity distribution (Fig. 2.8.3) shows that values generally range between 3 000 and 7 000 mg L^{-1} over significant areas; however, salinity values may increase with depth in some areas. Due to these high salinities, no irrigation extraction occurs, with the main use being for stock-watering purposes.

Very high salinities of up to 100 000 mg L^{-1} are associated with evapo-concentration in low-lying groundwater discharge areas adjacent to Lakes Alexandrina and Albert, where the Quaternary Limestone aquifer is overlain by the St Kilda Formation (shown as red in Fig. 2.8.3). Water table elevations at these discharge areas, after being corrected for density effects, are often below sea level, and are consequently the focus for regional groundwater discharge in preference to the Lakes, which are held at +0.75 m AHD (Barnett 1992). These low-lying discharge areas

Table 2.8.1 Hydrogeology of the area north-west of the Lakes (Langhorne Creek area).

	Unit	Lithology	Thickness (m)	Hydrogeology
Quaternary	Pooraka Formation	Clays, sands, silts with occasional gravels	30	Salinities range up to 20 000 mg L^{-1}. Low yields (<5 L sec^{-1}) for stock water supply only.
Tertiary	Murray Group	Fossiliferous limestone with sandy and marly interbeds	50	Salinities range from ~1 000 to 10 000 mg L^{-1}, yields 5-40 L sec^{-1}. Main source of groundwater irrigation supplies.
	Ettrick Formation	Glauconitic, fossiliferous marl and calcareous clay	10	Aquitard.
	Renmark Group	Carbonaceous sands and clays	25	Confined aquifer, not used due to low yields and discontinuous nature.
Cambrian	Kanmantoo Group	Metamorphosed sandstone, siltstone, greywacke		Poor aquifer, generally with high salinities and low yields.

Table 2.8.2 Hydrogeology of the area south-east of the Lakes (coastal plain area).

	Unit	Lithology	Thickness (m)	Hydrogeology
Quaternary	Bridgewater Formation Coomandook Formation	Shelly and sandy aeolianite deposited in topographic ridges Interbedded sandy limestones and shelly sandstones	<40	Salinities range up to 20 000 mg L^{-1}. Low yields (<5 L sec^{-1}) for stock water supply only.
Tertiary	Murray Group	Fossiliferous limestone with sandy and marly interbeds	<50	Salinity range ~1 000 to 10 000 mg L^{-1}, yields 5-40 L sec^{-1}. Main source of groundwater irrigation supplies.
	Ettrick Formation	Glauconitic, fossiliferous marl and calcareous clay	10	Aquitard.
	Renmark Group	Carbonaceous sands and clays	<60	Confined aquifer, not used due to low yields and discontinuous nature.
Permian	Cape Jervis Beds	Predominantly fluvio-glacial clays with sandy interbeds	>500	Very poor aquifer.
Cambro-Ordovician	Delamerian acid intrusives	Granites of the Padthaway Ridge		Very poor aquifer.
Cambrian	Kanmantoo Group	Metamorphosed sandstone, siltstone, greywacke		Poor aquifer, generally with high salinities and low yields.

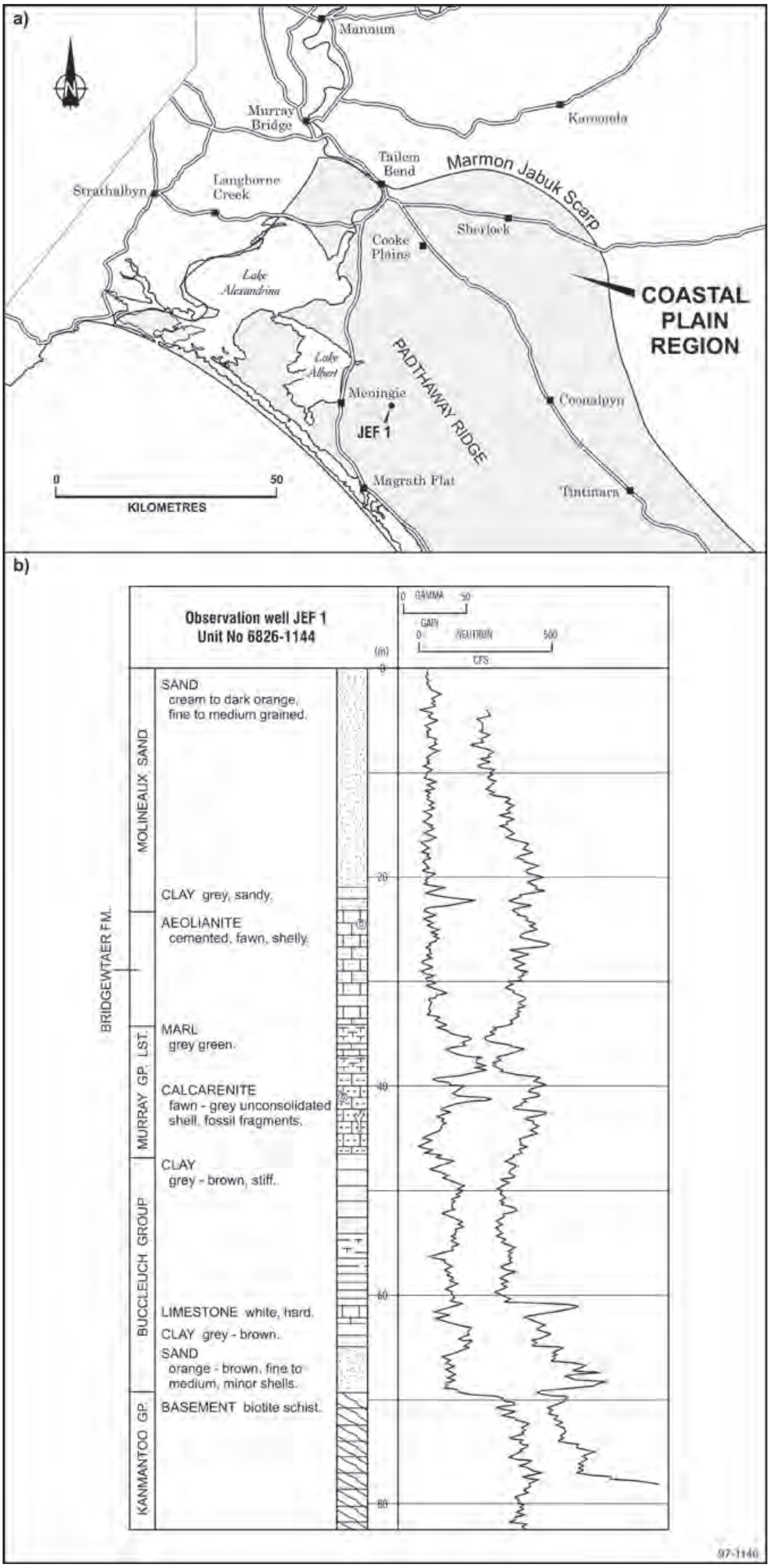

Figure 2.8.2 Representative composite log for investigation well JEF 1. (From Department for Environment and Water)

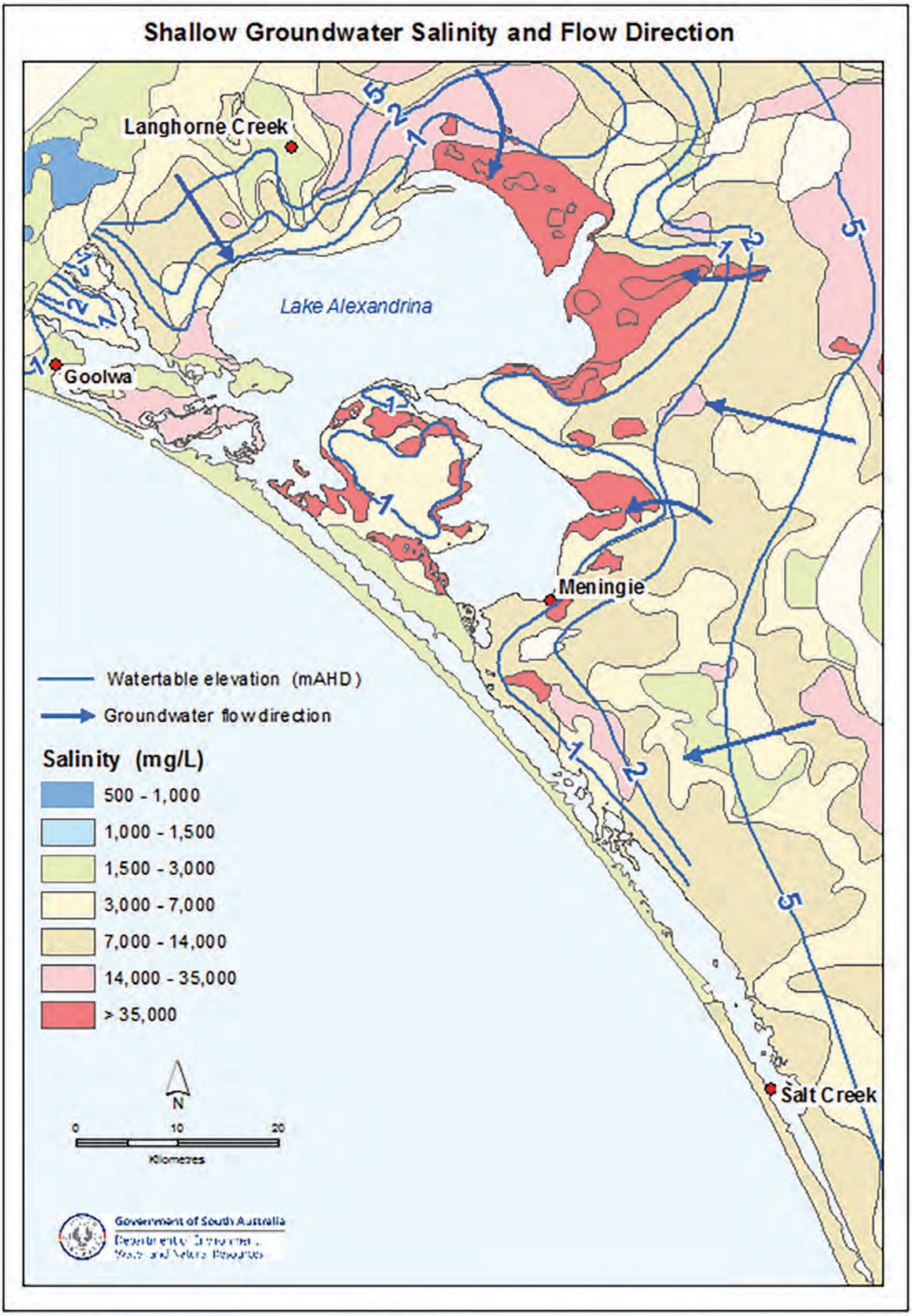

Figure 2.8.3 Shallow groundwater salinity and flow direction. (From Department for Environment and Water)

also occur further south, and would similarly prevent groundwater inflows to the Coorong; however, the consequence of brackish groundwater discharge, where it does occur, is relatively insignificant, due to the Coorong's very high salinity.

In areas where groundwater discharge does occur to the Lakes, the low hydraulic gradients limit the impact of such inflows. Simple calculations using observed gradients and groundwater salinities suggest inflows of about 25 tonnes of salt per day. Assuming a storage volume of 2.3 GL and an average Lake salinity of 500 mg L^{-1}, these inflows would cause an increase in salinity of the Lake water of only 4 mg L^{-1}.

In the late 1980s, landowners noticed that the saline discharge areas were expanding and that new ones were appearing in topographic depressions. Regional groundwater level monitoring, which began in the Upper South East region in 1983, showed a rising trend in response to the increased recharge following the clearing of native vegetation. When the water table rises to within about 2 m of the land surface, the evaporative discharge causes dryland salinisation and increased groundwater salinity.

An extensive network is now monitoring the Quaternary Limestone aquifer throughout the Coastal Plain area, and widespread rising trends were recorded (Barnett 1997). Although below average rainfall from 2000 to the end of the drought in 2009 resulted in declining groundwater levels and a much-reduced risk of dryland salinity, recent wet years have caused an apparent increased in salinised areas. This suggests that climate variation is now a stronger influence on dryland salinity than is past vegetation clearance.

Murray Group Limestone aquifer

The Murray Group Limestone (MGL) aquifer is confined by the clays of the overlying Pooraka Formation, and contains irrigation-quality groundwater on the south-western margin of the Murray Basin, as shown in Figure 2.8.4. There is virtually no current recharge of low-salinity water to the MGL aquifer, with the current reserves of fresh groundwater being recharged about 4 000-8 000 years ago, when South Australia and much of the rest of the world experienced a much wetter climate than has existed over the last hundred years or so (Barnett 2016). There would have been significantly greater volumes of run-off flowing out of the Mount Lofty Ranges onto the plains of the Murray Basin, which would have recharged the MGL aquifer via slow downward leakage through the overlying Quaternary sediments, forming the areas of low salinity. This process of ancient recharge is supported by the uncorrected ^{14}C estimate of the age of the MGL groundwater of about 4 000-8 000 years (Cresswell & Herczeg 2004).

The onset of the current drier conditions has resulted in increased salinities in the Quaternary aquifer, now mostly in the range of 5 000-15 000 mg L^{-1}. Downward leakage of this saline groundwater into the MGL confined aquifer occurs when extractions lower the pressure surface below the level of the water table in the Quaternary aquifer. Long-term monitoring has shown that larger increases in salinity occur when extractions increase significantly, and that these increases occur locally in response to local pumping intensities rather than regionally (Fig. 2.8.4). More importantly, monitoring suggests that these increases are mostly reversible when extraction decreases again to normal levels.

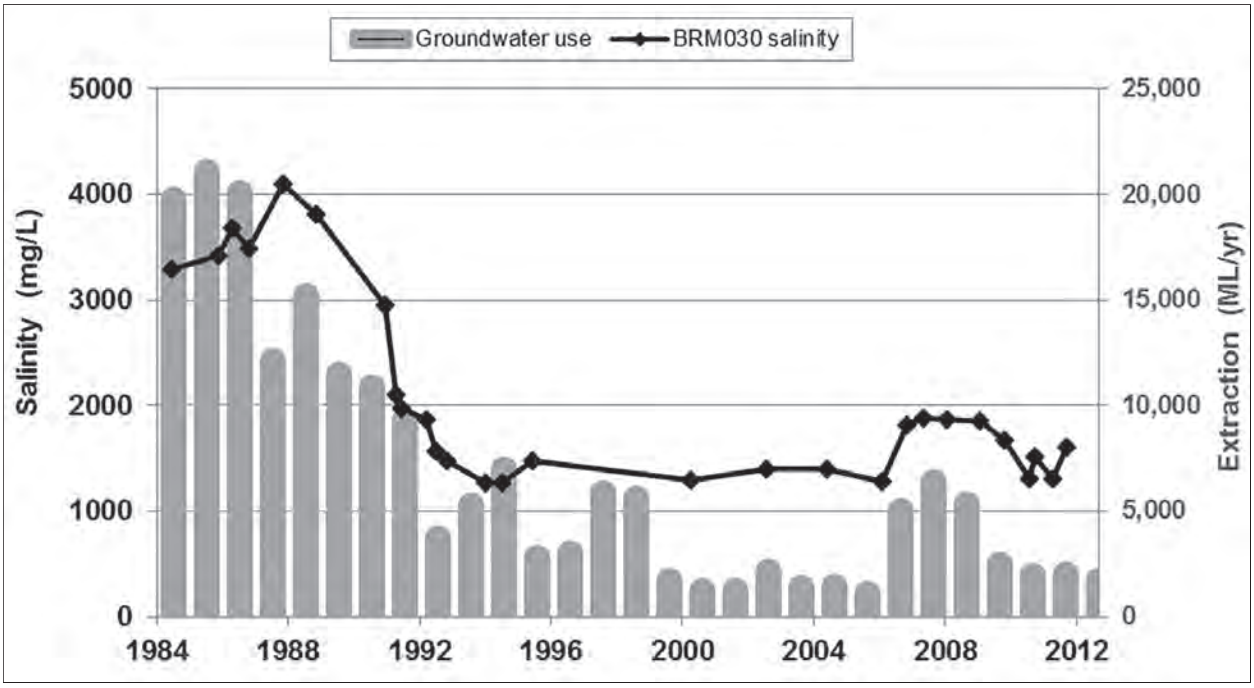

Figure 2.8.4 Groundwater salinity response to extraction from the MGL aquifer. (From Department for Environment and Water)

The most recent increases in salinity occurred during the Millennium Drought when surface water resources from Lake Alexandrina were unavailable, and groundwater extractions rose significantly. In the Langhorne Creek area, extractions rose from a seven-year average of about 1 500 ML yr^{-1} to just below the allocation limit of 6 500 ML yr^{-1} in three years, with a corresponding rise in salinity observed in observation well BRM030 (Fig. 2.8.4).

The risk of groundwater salinity increases caused by higher extractions during drought has been ameliorated by the availability of alternative water supplies. The construction of two pipelines to supply River Murray water to the area has occurred from off-takes upstream of Wellington, so that in the future, droughts will not cause the same access and salinity issues experienced previously by supply sources using Lake Alexandrina. The demand on groundwater will consequently not be as high and therefore salinity increases will not be as large. To reduce costs, the pipeline diameter was chosen to supply the irrigation demand over 12 months rather than just the summer irrigation season. This requires water that is pumped during winter to be recharged into the MGL aquifer for later extraction during summer by the process of aquifer storage and recovery (ASR).

Salinity monitoring has shown a general decline in salinity since the drought, which could reflect both decreased extraction and the influence of ASR operations (Fig. 2.8.4).

Local aquifers

Rainfall has infiltrated down through the permeable sand dunes of the Younghusband Peninsula to form a freshwater lens, which lies on top of the denser sea water, as shown in Figure 2.8.5. Small freshwater springs can emerge at the edge of the lens along the shore of the Coorong, and have been used historically by the Ngarrindjeri people as drinking water.

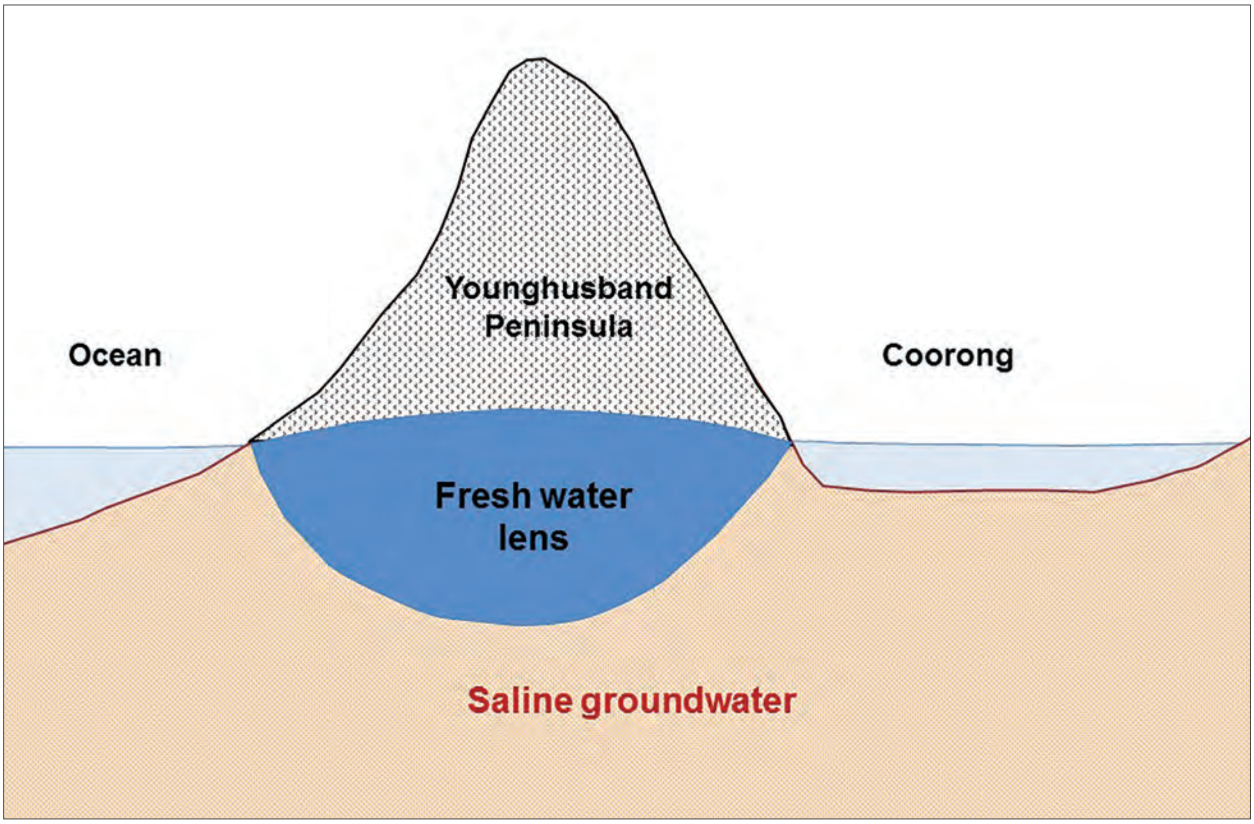

Figure 2.8.5 Occurrence of freshwater lenses on the Younghusband Peninsula. (From Department for Environment and Water)

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CHAPTER 2.9

SOILS IN THE COORONG, LOWER LAKES AND MURRAY MOUTH REGION

ROB W. FITZPATRICK[1], PAUL SHAND[2] AND LUKE M. MOSLEY[3]

INTRODUCTION

Soil is a non-renewable resource that requires constant monitoring to prevent its degradation and promote its sustainable management. There are many views of the vital role soils play in society and components that are used to characterise and map soils in the field (Box 2.9.1). The diversity of soil types in the Coorong, the Lower Lakes (Lake Alexandrina, 649 km^2, and Lake Albert, 320 km^2) and the Murray Mouth (CLLMM), which comprise the Murray-Darling Basin terminal lake-estuary system, is attributable to the wide variety of soil-forming factors over time and landscape types in the region (e.g. de Mooy 1959; Fitzpatrick & Shand 2008; Fitzpatrick et al. 2009a; Maschmedt 2009). These varied soil-forming factors are expressed over a wide range of (i) natural environments (geology, geomorphology, climate, vegetation, fresh and saline water conditions) (ii) anthropogenically modified environments (barrages, blocking banks and irrigation) (iii) changing climatic environments (e.g. increased hydrological droughts, sea-level rise and decreased winter rainfall).

This chapter summarises information on the diverse distribution, properties and management of soils from various time periods in the CLLMM, designated in 1985 as a Wetland of International Importance under the Ramsar Convention on Wetlands, reflecting the region's ecological significance. We also provide an overview of various soil change processes and management strategies, especially during drying and wetting cycles. Droughts are predicted to become more prevalent in the future, given climate change projections for the Lower Murray River region (CSIRO 2011). The protection and management of the CLLMM is dependent on a detailed understanding of the long-term temporal and spatial variations in soil subtypes, especially subaqueous and acid sulfate soils, during wetting/flooding and drying conditions.

Before European arrival, the Ngarrindjeri peoples recorded creation stories about the remarkable changes that occurred in the CLLMM — changes that were of both cultural and aesthetic value (Box 2.9.2). Today, the Ngarrindjeri also believe that '[t]he land and waters must be healthy for the Ngarrindjeri people to be healthy' (Ngarrindjeri Nation 2007). The first European explorers — such as Captain Charles Sturt, who explored the region between 1828 and 1829 — also possessed great skills of observation and were the earliest European recorders of soil information in the CLLMM (Box 2.9.2).

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BOX 2.9.1 WHAT IS SOIL?

Soils mean different things to different people. Some people regard soil as 'dirt' or 'mud', because it makes them 'dirty' when they make contact with it. Soil scientists (pedologists) view soils as being made up of different-size mineral particles (sand, silt and clay) and organic matter. Soils have complex biological, chemical, physical, mineralogical and hydrological properties that are always changing with time. Hence, soil is dynamic; it teems with organisms; and it is an integral part of the environment. Agronomists, farmers and gardeners, however, see soil as a medium for growing crops, pastures and plants — primarily in the top 50 cm of the Earth's surface. Engineers, meanwhile, regard soil as material to build on and excavate, and are usually concerned primarily with moisture conditions and the capacity for soil to become compacted or to support structures.

The upper limit of soil is the boundary between soil and air, shallow water, live plants or plant materials that have not begun to decompose. Areas are not considered to have soil if the surface is permanently covered by water too deep (typically more than 2.5 m) for the growth of rooted plants.

Subaqueous soils accommodate submerged soil materials in both inland and tidal settings and an arbitrary depth of up to 2.5 m below the water surface. Soil is characterised by one or more horizons, or layers, which are distinguishable from the initial material as a result of additions, losses, transfers and transformations of energy and matter, or by the ability to support rooted plants in a natural environment.

Pedology (from the Greek *pedon* = soil) is the soil science discipline concerned primarily with understanding the variety of soils and their distribution, and is most directly focused on the key questions concerning sampling and description of processes of soil formation, including quality, extent, distribution, spatial variability and genesis, from microscopic to megascopic scales. The description and interpretation of soils can be used in addressing the questions 'What is the soil like?' and 'Where does a particular soil come from?' (adapted from Fitzpatrick 2013a).

GEOMORPHIC SETTINGS, DISTRIBUTION AND PROPERTIES OF SOILS WITHIN LAND TYPES

Linkages between the geology, geomorphology and soils in the CLLMM have been summarised by Maschmedt (2009) and de Mooy (1959). Most soils in the CLLMM immediate catchment area are sandy and/or calcareous from aeolian (wind-derived) sources (de Mooy 1959; Fitzpatrick & Shand 2008; Fitzpatrick et al. 2008a, 2009b, 2010a, 2010b, 2011b; Maschmedt 2009). However, wherever the aeolian deposits have been eroded to re-expose the older Tertiary and Pleistocene sediments, more clayey or weakly calcareous to non-calcareous soils predominate.

Distinctive 'land types' were mapped by the SA Department of Water Land and Biodiversity Conservation (DWLBC 2007) and are displayed in Figure 2.9.1. The predominant land types and waterbodies, together with their characteristic soil types, are described in Table 2.9.1 and summarised in the following section:

- **Categories A** and **B soils** have calcrete at depths shallower than 50 cm. Category A soils are calcareous throughout, and are presumed to have undergone less leaching than the soils of Category B.
- **Category C soils** are deep calcareous sandy loams to clay loams throughout, with some being commonly calcreted.

BOX 2.9.2 PRE-EUROPEAN SETTLEMENT SOIL CHARACTERISTICS

Aboriginal peoples of Australia recorded creation stories about the remarkable changes that occurred both when the sea level began rising ~18 000 years ago and when the current sea level stabilised ~5 000 years ago. At the same time, rainfall and inland lake levels were initially low, followed by cycles of brief highs and extended dries. By 5 000 years ago, rainfall was marginally higher than it is today. During wetter periods, lake levels filled, while dune building dominated in dry periods (Bowler et al. 1976). The creation stories and oral traditions of Indigenous people have been passed down from generation to generation, especially about the detailed knowledge of the nurseries, i.e. wetlands (reed beds were much more extensive in the past), many of which contain acid sulfate soils. The Coorong is also an archaeological site of national importance with shell middens and burial sites throughout the area, giving evidence of Aboriginal occupation for >5 000 years. For example, the Ngarrindjeri believe that the land and waters is a living body and that they are a part of its existence (Ngarrindjeri Nation 2007). In the Ngarrindjeri Nation Yarluwar-Ruwe plan (Ngarrindjeri Nation 2007, p. 13) it is stated: 'The land and waters must be healthy for the Ngarrindjeri people to be healthy. We say that if wetlands/nurseries die, our Ngartji (totem or special friend) die, then Ngarrindjeri will surely die'.

Post-European settlement soil characteristics: The first European explorers possessed great skills of observation. The early explorers were usually not trained scientists, as their primary concerns were to delineate the major terrain features of the interior, and to survive. Moreover, many of the early explorers originated or worked in environments quite different from Australia. The early explorers used mainly horses for transport, and their observations and reports on soils had mainly to do with pastoral or agricultural potential rather than with the natural history of wetlands or back swamps. Nevertheless, the following observations remain of interest with regard to past and current known occurrences of inland acid sulfate soils:

Captain Charles Sturt was one of the earliest recorders of soil information in southern Australia. Following his previous experience along the Murrumbidgee, Murray and Darling Rivers from 1828 to 1829, Sturt explored from Cawndilla near the Menindee Lakes westward into the north-eastern deserts of South Australia in 1844-1846. His journals (Sturt 1833) reveal him to be an observant and inquisitive explorer. Quotations from his published journals reveal a few of his perceptions about the possible natural occurrences of inland acid sulfate soils in wetlands. Sturt was the first known European to have travelled down the Murray River to its mouth in 1830, when he noted in his journal that 'the shores of the lakes were densely covered with fresh water reeds in one continuous belt as far as the eye could see'. (These are suitable conditions for the formation of sulfidic material, because of the considerable build-up of organic matter in the dense reeds in waterlogged soils.) This was confirmed by Sturt's observations of subaqueous soils in Lake Alexandrina: 'Its bottom was one of black mud, and weeds of enormous length were floating on its surface, detached by the late gales, and which, from the shallowness of the lake, got constantly entangled with our rudder'. The black mud description is still apt today, but the aquatic plants (macrophytes) described are largely absent from the Lakes.

- **Category D soil** comprises vast accumulations of non-calcareous sands, which have formed from the winnowing of fine-grained carbonate particles from the silica sand grains, and from leaching of the partially soluble carbonates from the silica (Maschmedt 2009).
- **Category E soils** comprise sand over sandy clay loam or clay, which are commonly formed over coarse-grained sediments, notably Tertiary Loxton and Parilla Sands. This relationship does not always hold, as sandy surfaces can also result from deposition of reworked silica grains.

- **Category F soils** comprise red loamy soil with more clayey subsoil; and Category G soils comprise sandy loam to clay loam over brown clay subsoil, which are mostly formed over sediments that are more clayey than those underlying Category E soils. Profiles with loamy to clay loamy surfaces and medium to heavy clay subsoils are usually underlain by Pleistocene clays.
- **Category H soils**, or cracking clays, comprise predominant smectite and illite clay minerals derived from Murray Basin sediments.
- **Category I soils** are commonly sandy loam to clayey sand throughout, and are generally too young to have been influenced by significant aeolian carbonate accessions. They are derived from coarse-grained alluvial sediments, which give rise to soils with minimal clay translocation and little if any carbonate accumulation. These soils usually occur in modern alluvial environments with patchy occurrences.
- **Category J soils** (wetland soils) have at least part of the profile saturated for at least three months of the year, a characteristic that is significant as they have very limited commercial use unless drained. Many of these wetland soils are moderately to highly saline and comprise acid sulfate soils (Fitzpatrick & Shand 2008; Fitzpatrick et al. 2009a; and others). These soils have special biological characteristics, and hence are of high ecological value.
- **Category W soils** are subaqueous and subaqueous acid sulfate soils, which have most of the profile saturated permanently (Box 2.9.1), unless drained or dried due to drought conditions. These acid sulfate soils are typically formed in Holocene sediments in aqueous environments that provide anoxic conditions, that have high concentrations of sulfate, soluble iron and labile organic matter, and that are widespread in the region. Further, they are of freshwater origin and appear to be mostly associated with freshwater reed beds (*Phragmites australis*, *Typha* spp.) and buried detritus from reeds. In assessments of hundreds of Lower Lakes soil profiles (often to >1.5 m depth), there was no evidence of marine or estuarine organic

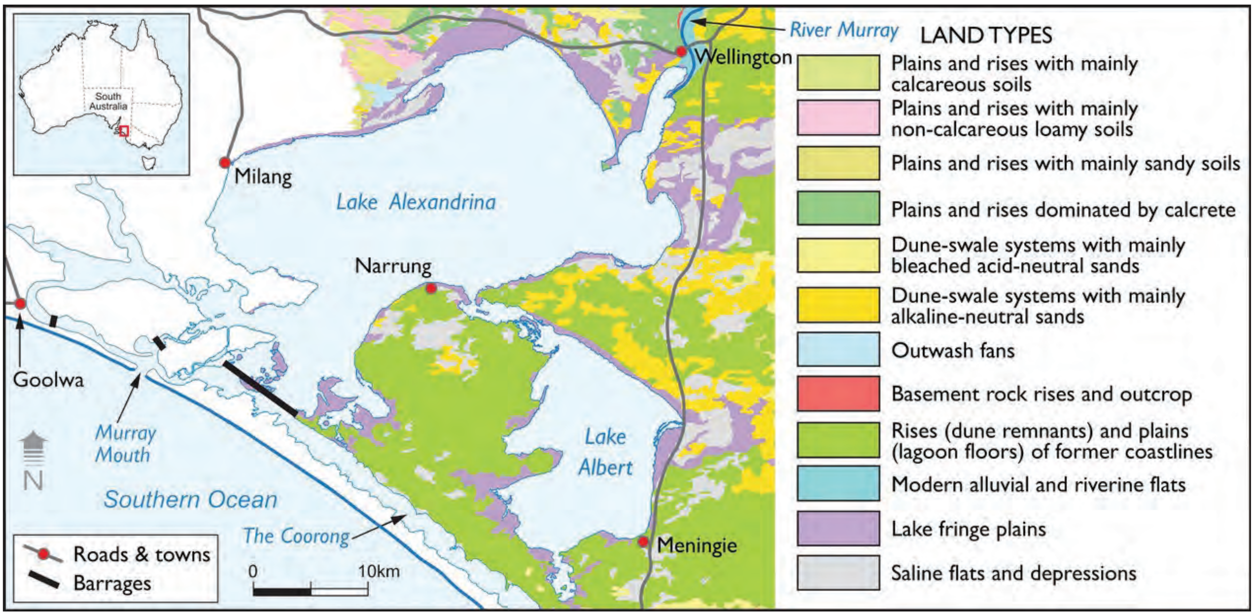


Figure 2.9.1 Land types of the Coorong, Lower Lakes and Murray Mouth region. (DWLBC 2007; Maschmedt 2009)

matter from mangroves (*Avicennia*), seagrass (*Posidonia*) or sea lettuce (*Ulva*) (Fitzpatrick et al. 2008a). However, there are contemporary mangrove features containing acid sulfate soils on the seaward side of the Murray estuary where a very small stand (~200 m^2) of *Avicennia marina* was planted in the 1960s (Spalding et al. 2010).

In summary, the dominant soil types occurring in the CLLMM, which mostly comprises the Ramsar wetland complex, are acid sulfate soils from categories J and W (Table 2.9.1 and above). The properties, distribution and management of acid sulfate soils are discussed in more detail in the sections below.

Table 2.9.1 Distribution of soil categories within land types and water bodies in the CLLMM. (Modified from Maschmedt 2009)

Land type and water bodies (lakes, rivers, streams, estuary, the Coorong)	***Typical soil categories**		
	>30%	**10-30%**	**1-10%**
Plains and rises with mainly calcareous soils	C	F,D	A,B,E
Plains and rises with mainly non-calcareous loamy soils	F	E,G,C	D
Plains and rises with mainly sandy soils	E	D,G	F,B,C
Plains and rises dominated by calcrete	A	C	B,D,F,E
Dune-swale systems with mainly bleached acid-neutral sands	D	E	G,C,F,A
Dune-swale systems with mainly alkaline-neutral sands	D	C,F	E,A,B
Outwash fans	C	F	E,I,D
Basement rock rises and outcrop	C, R	F	A
Rises (dune remnants) and plains (lagoon floors) of former coastlines	A,B	J	D,C,E
Modern alluvial and riverine flats	H	W,G	I,J,D
Lake fringe plains	-	H,I,C,B	J,D,E,G,F
Saline flats and depressions	J	C, W	G,H,D,A,E
Water bodies (lakes, rivers, streams and the Coorong)	W	J	R

Soil Category	**Brief description of soil categories** (based on key for identifying categories of vineyard soils from Maschmedt et al. 2002 and Maschmedt 2009)
A	Shallow calcareous sandy loam to clay loam over calcrete
B	Shallow non-calcareous soil over calcrete
C	Deep calcareous sandy loam to clay loam
D	Deep sand
E	Sand over sandy clay loam to clay
F	Red loamy soil with more clayey subsoil
G	Sandy loam to clay loam over brown clay
H	Cracking clays
I	Deep gradational sandy loam to clay loam
J	Wet soil, usually moderately to highly saline and acid sulfate soils with hypersulfidic material
R	Shallow soil on basement rock
W	Subaqueous acid sulfate soils with hypersulfidic, hyposulfidic, sulfuric monosulfidic materials

ACID SULFATE SOILS

The earliest research on the nature and distribution of subaqueous soils and sediments in Lake Albert was completed by Taylor and Poole (1931) prior to barrage construction. At this time the levels of both Lake Albert and Lake Alexandrina changed seasonally, periodically exposing acid sulfate soils with hypersulfidic and hyposulfidic materials (see Box 2.9.3 for definitions). Taylor and Poole were assessing the agricultural potential of Lake Albert, which was being considered for drainage and development for irrigated pastures and cropping. At that time they noted the presence of what we now call acid sulfate soils (Box 2.9.3), because one of the soils sampled

BOX 2.9.3 WHAT ARE ACID SULFATE SOILS?

'Acid sulfate soils' (ASS) is the name given to those soils or unconsolidated sediments in which sulfuric acid may be produced, is being produced, or has been produced in amounts that have a lasting effect on main soil characteristics (Pons 1973). These soils contain sulfide minerals (principally iron sulfides) or are affected by geochemical or biochemical transformations of sulfide minerals (Dent 1986). These soils may either contain acidity or have the potential to form acid in amounts that have an effect on the main soil characteristics of inland freshwater lakes, wetlands, creeks and rivers, as well as coastal water bodies such as estuaries in Australia. Other potential consequences of ASS disturbance or exposure include deoxygenation of soil or surface waters and the release of metals and nutrients which potentially pose a hazard to soils and water quality and ecosystems. They are widespread throughout the world in coastal and inland areas (Fanning et al. 2017). Areas impacted by ASS in Australia form an estimated 215 000 km^2: 58 000 km^2 is coastal ASS and 157 000 km^2 is inland ASS (Fitzpatrick et al. 2008a).

Acid sulfate soils may be acidic (i.e. contain sulfuric material) or may have the potential to generate sulfuric acid when exposed to oxygen because of the presence of sulfide minerals, principally pyrite (i.e. they contain hypersulfidic or hyposulfidic materials). The following nomenclature and definitions used for acid sulfate soil materials are defined in the second edition of Australian Soil Classification (Isbell and National Committee on Soils & Terrain 2016):

- **Hypersulfidic material**: sulfidic material that had a field pH of 4 or more and the pH dropped by at least 0.5 units to less than 4 when incubated at field capacity for at least eight weeks
- **Hyposulfidic material**: sulfidic soil material that had a field pH of 4 or more and the pH dropped by at least 0.5 units to not less than 4 when incubated at field capacity for at least eight weeks
- **Sulfuric material**: soil material that has a pH <4 (1:1 by weight in water, or in a minimum of water to permit measurement) when measured as a result of the oxidation of sulfidic materials and evidence of sulfidic material, such as underlying sulfidic material and/or the presence of yellow masses of jarosite along old root channels and faces of peds
- **Monosulfidic material**: soil material containing ≥0.01% acid volatile sulfide.

When acid sulfate soils with hypersulfidic material dry, oxidation of pyrite may cause strong acidification (pH <4) and form sulfuric material. Resaturation of acid sulfate soils with sulfuric material can lead to reformation of pyrite and pH increase (but this may take months to years) due to activity of sulfate-reducing bacteria, which also require available organic carbon.

A positive net acidity indicates an acid-generating potential greater than the acid-neutralising capacity of the soil. A negative net acidity indicates an excess acid-neutralising capacity, which in theory could prevent the soil becoming a hazard.

had a pH of 3.9 after drying, and they argued (successfully and accurately in hindsight) that the Lake should not be drained for agriculture (Taylor & Poole 1931). Their original 1930s soil samples were retrieved from the CSIRO Land and Water soil archive in 2007 and reanalysed for pH for comparison with the original measurements made 78 years previously (Fitzpatrick et al. 2008b). In this case, the original 1930s results can be taken as the original pH values (pH 8.5); the pH values for 2007 were much lower (pH 2 to 4) than when the samples were collected, confirming the acidifying effects of exposure to the atmosphere of the subaqueous acid sulfate soils (ASS) with hypersulfidic material (Box 2.9.3; Fitzpatrick et al. 2008b).

Sulfide accumulation: Hypersulfidic, hyposulfidic and monosulfidic materials

Since the 1940s, water levels in the River Murray, adjacent wetlands and Lower Lakes have been maintained and managed using locks, barrages and levee banks along the river channel, with seawater exclusion being their main function. The construction of locks, barrages and levee banks has allowed artificially stable water conditions in the Lower Murray regions to be maintained for over 80 years with a normal pool level of c.+0.75 m AHD (Australian Height Datum; 0 m AHD corresponds approximately to mean sea level). This likely resulted in considerable build-up of hyposulfidic, hypersulfidic and monosulfidic materials in the Lower Lakes and adjacent wetlands because of

- less frequent and lower-magnitude wetting and drying cycles that would have prevented build-up (particularly on the Lake margins) of acid sulfate soils (due to the fluctuations creating frequent oxidising conditions in sediments)
- the evaporative concentration of sulfate from river nutrient/salt loads during the period of stable pool level and from groundwater sources
- the lack of natural scouring and seasonal flooding, which occurred during the time prior to major pre-European water resource development (5 000 BP to 1920s)
- the plentiful supply of organic matter from *Phragmites australis* reed beds and dairy farming activities.

The following are typical contemporary features of acid sulfate soils from the Lower Lakes containing pyrite (FeS2) in clays, sands and peats:

- black clayey hypersulfidic material (e.g. Boggy Creek and Finniss River regions; Fig. 2.9.2)
- dark grey sandy hypersulfidic material (e.g. Currency Creek and Point Sturt regions)
- black organic-rich or peaty hypersulfidic material (also known as Coorongite; Box 2.9.4) (e.g. Lakes Alexandrina and Albert; Fig. 2.9.3).

These hypersulfidic and hyposulfidic materials also contain abundant live and relict plant material, mainly *Phragmites australis* (Common Reed; Fig. 2.9.2b) and/or *Typha latifolia* (Bulrush) roots and root channels, but also laminae and other detritus, which provide evidence of freshwater deposition. Other features of acid sulfate soils with hypersulfidic and hyposulfidic materials in the Lower Lakes are the widespread presence of freshwater shells and shell detritus in layers down to a depth of 1 m. This also points to a freshwater environment.

Black monosulfidic material (Box 2.9.3) with gel-like consistency is also common in areas adjacent to the barrages in Lake Alexandrina (e.g. the Tauwitchere Barrage as shown in Fig. 2.9.4) and in the Coorong (Fitzpatrick et al. 2008b, 2011c). Monosulfidic material

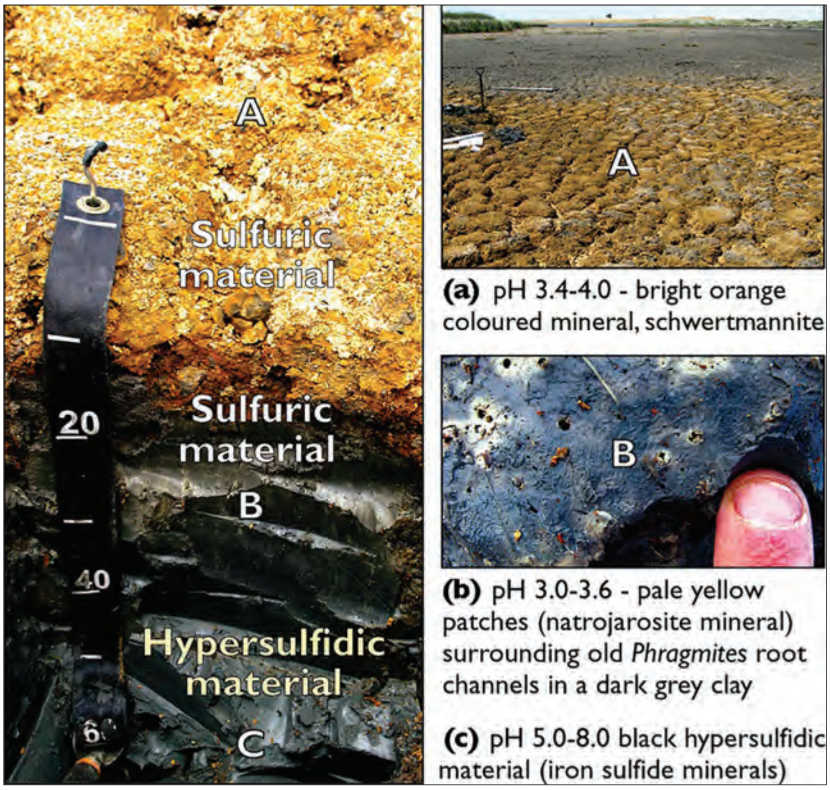


Figure 2.9.2 Acid sulfate soil showing the presence of hypersulfidic and sulfuric materials in a dry river bed of the Finniss River, South Australia. (Modified from Fitzpatrick et al. 2009b)

comprises a low-density material, which contains monosulfide minerals (FeS) that are still waterlogged (Box 2.9.3). These materials also incorporate the previously used term 'monosulfidic black ooze' (MBO). Monosulfidic material generally has a field pH of 4 or more, commonly pH >7-8, and while it may not become extremely acidic (pH <4) when drained, it can rapidly deoxygenate surface water if disturbed.

In most cases, all three of these acid sulfate soil materials are permanently saturated or are subaqueous soils, and are benign unless disturbed.

Formation and rewetting of sulfuric (pH <4) materials during the Millennium Drought

The extreme Millennium Drought period had its biggest impact in the Lower Murray from 2006 to 2010, and considerably reduced the freshwater inflows from the River Murray to the Lower Lakes. As such, water levels declined from the typical pre-drought water level of c.+0.5 m AHD to, at lowest, c.-1 m AHD for Lake Alexandrina during autumn 2009 and c.-0.8 m for Lake Albert during late summer 2010. The lowering of Lake water levels, combined with the extensive shallow fringing bathymetry of the Lakes, incrementally exposed and drained large new areas of lake margins, and with this there was widespread formation of sulfuric (pH <4) soil materials (Fitzpatrick et al. 2008a, b, c) as shown in Figure 2.9.2. Accompanying these highly acidic soil conditions there were consequent accumulations of the pale-yellow iron oxy-hydroxysulfate mineral jarosite (Fig. 2.9.2b), which is a characteristic feature of acid sulfate soils with pH <4 worldwide. In addition, there were common occurrences of greenish-yellow and

BOX 2.9.4 WHAT IS COORONGITE?

By the middle of the 1920s it was established that the black rubbery deposit known as Coorongite (Fig. 2.9.3; Broughton 1920; Cane 1977) was produced by one of the numerous kinds of green, freshwater algae — small primitive, rootless plants, which float in water and often form a scum on the surface or on submerged objects such as stones. The species was identified as *Botryococcus braunii* (Cane 1977), which has also been found to form the equivalent of Coorongite in Lake Balkash, Siberia and in Lake N'Hangella, East Africa. According to Cane (1977) Coorongite is believed to be the 'peat stage' in the formation of the high-grade oil shale known as Torbanite.

Coorongite has been identified in numerous subaqueous acid sulfate soils in Lake Albert and less frequently observed in Lake Alexandrina by Fitzpatrick et al. (2008b, 2008c, 2011a, 2011c). Coorongite had not previously been recorded from the Coorong, despite its name, but is known from drill holes near Salt Creek (Cane 1977). However, a layer of Coorongite has recently been identified in the Coorong at a site just south of Salt Creek (sites COO1 and COO2: Fitzpatrick et al. 2008c, 2011c) when resampled in May 2018 at a deeper depth (i.e. 50-85 cm; Rob Fitzpatrick & Luke Mosley unpublished data 2018).

Calibrated radiocarbon ages (expressed as calendar years Before Present) for three samples of bulk organic matter preserved as Coorongite layers (between 20 and 70 cm) in hypersulfidic material from two locations in Lake Albert and one from Lake Alexandrina range from 5 840±40 to 6 230±40 BP (Paul Shand & Rob Fitzpatrick unpublished data 2011). The two locations in Lake Albert were on the eastern and north-eastern side, and the Lake Alexandrina sample was off shore at Point McLeay (Fitzpatrick et al. 2008b, c).

In summary, the presence of Coorongite as layers of organic-rich or peaty hypersulfidic material in subaqueous acid sulfate soils (Fig. 2.9.3) provides evidence for a past freshwater environment in the Lower Lakes region. In the Lower Lakes region, relict evidence of mangrove, seagrass and sea lettuce features has never been observed in acid sulfate soils, which is especially common in several deep coastal embayment environments of Gulf St Vincent and Spencer Gulf.

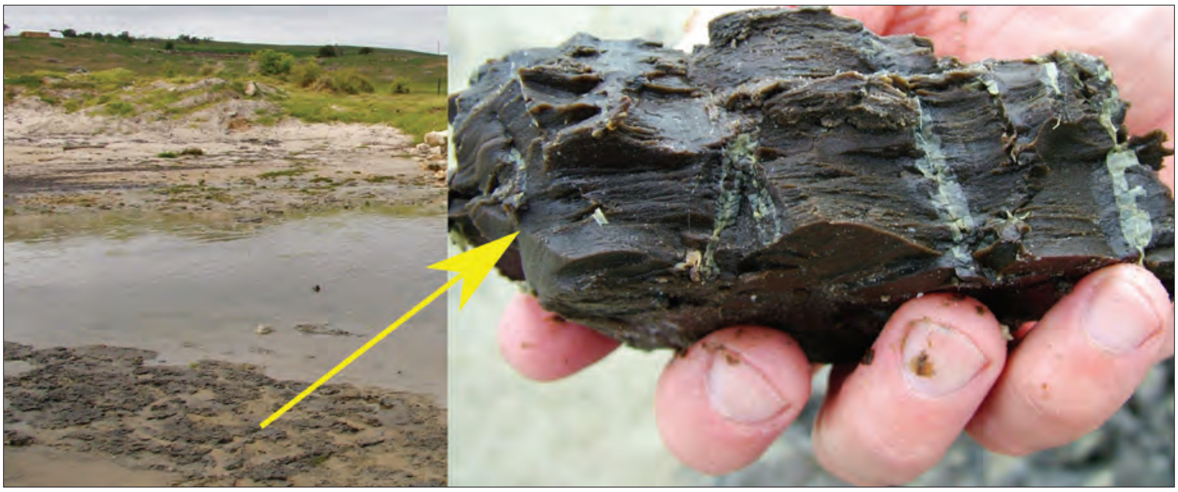


Figure 2.9.3 Black organic-rich or peaty hypersulfidic material also known as Coorongite (a black rubbery-like material) eroded out and excavated under water in Lake Albert in 2007 (by Fitzpatrick et al. 2008b, c). Note the fossil laminar structures comprising decomposed but well-preserved root and leaf materials from *Phragmites* spp. and/or *Typha* spp.

Figure 2.9.4 Monosulfidic material from under water at the Tauwitchere Barrage in Lake Alexandrina adjacent to the Coorong. (From Fitzpatrick et al. 2008b, c)

orange-yellow coloured surface crusts of salt efflorescences, comprising sulfate-rich evaporite minerals of sideronatrite (yellow) and schwertmannite (orange; Fig. 2.9.2a).

The Lower Lakes are shallow-water bodies, with a mean depth of ~2.4 m and 1.5 m, for Lake Alexandrina and Lake Albert respectively, at a normal operating level of c.+0.75 m AHD (Mosley et al. 2012). Bathymetry was used to model the extent and formation of different acid sulfate soil types as water levels declined in the Millennium Drought. As water level receded, sulfuric soil formation followed the sequence:

> subaqueous sulfidic soils (<2 m deep to near to or at the waterline, waterlogged) → sulfidic soils (near to or at the waterline, very moist to mostly waterlogged) → sulfuric soils (drying or dry).

The proportions of acid sulfate soil types and deep-water distributions for the +0.5 and -1.5 m AHD scenarios for each Lake are presented in Fig. 2.9.5. Computer projections to plot the incremental spread of acid sulfate soils with sulfuric materials by combining lake bed bathymetry and water level scenarios (normal +0.5m to -1.5 m AHD) showed the potential for 32 699 ha of shoreline and lake bed to convert from subaqueous sulfidic soils → sulfidic soils → sulfuric soils (Fitzpatrick et al. 2008a, 2008b, 2008c, 2009a, 2009b) (Figs. 2.9.5 & 2.9.6).

As a result of these predictions, grave concerns grew that without significant new river inflows to the Lakes, the ASS trajectories (Figs. 2.9.5 & 2.9.6) could eventually be realised, along with the associated environmental degradation. In August 2009 the predictions were indeed verified based on extensive field investigations and laboratory analyses across the Lower Lakes region, where 330 sites were described and sampled, resulting in 706 samples being analysed for pH and acid base accounting parameters (Fitzpatrick et al. 2010a). About 85% of the lake surface soil/sediment had a positive net acidity (i.e. total acidity minus soil-neutralising capacity; Box 2.9.3), with highest net acidities (>500 mol H^+ t^{-1}) occurring in clay-rich sediments in the middle of Lakes Albert and Alexandrina (Fig. 2.9.7). These results showed that an extensive acid sulfate soil hazard was present in the Lower Lakes. About 82% (67 087 ha) of the total lake area (82 219 ha) had potential for developing sulfuric (pH <4)

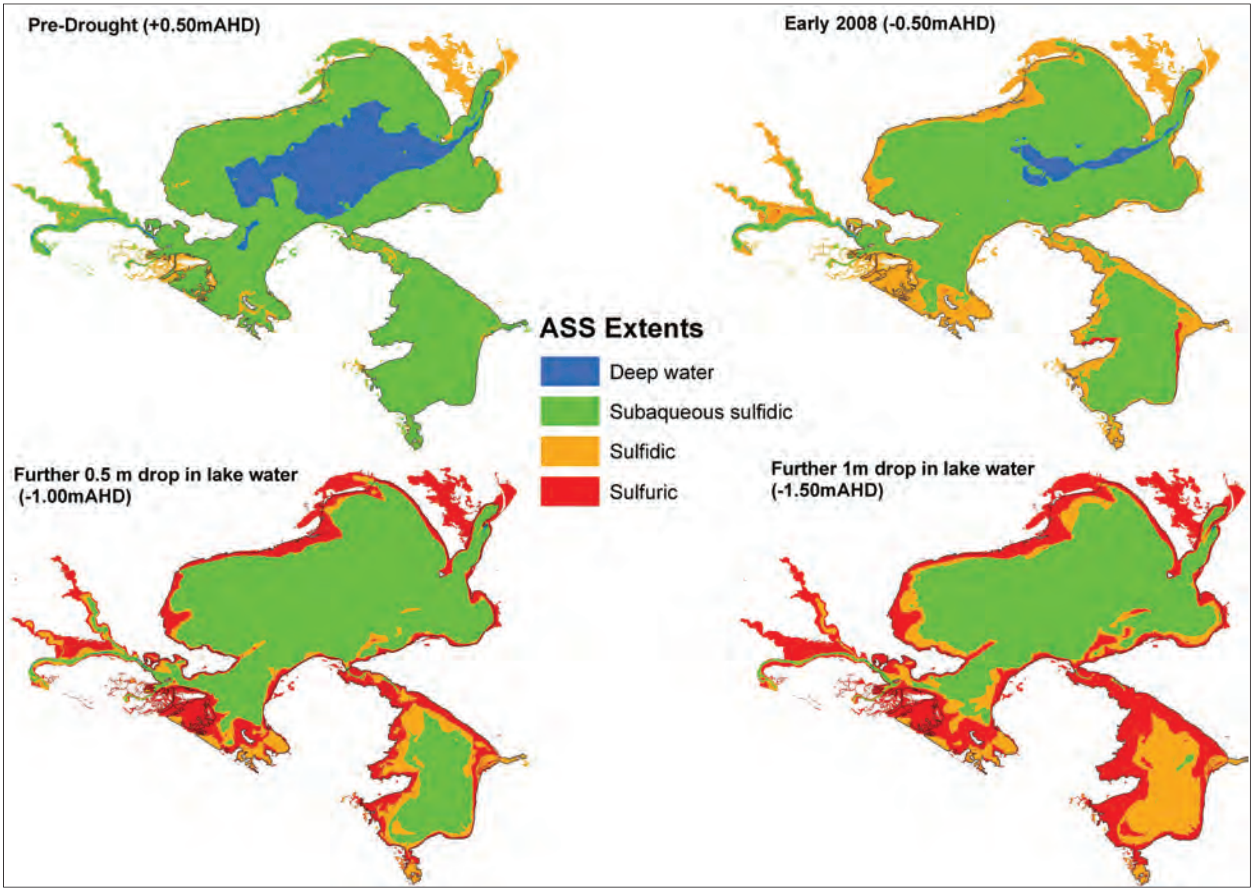


Figure 2.9.5 Predictive scenario maps depicting changes in acid sulfate soil materials at different water levels in the Lower Lakes (+0.5 m AHD, -0.5 m AHD and -1.5 m AHD), based on regional soil investigations and bathymetry (modified from Fitzpatrick et al. 2008a, 2008b, 2008c, 2009a, 2009b). Finniss River, Currency Creek and Goolwa Channel are the three extensions occurring on the left side of Lake Alexandrina. The term 'sulfidic', used in 2008, was replaced by Isbell and National Committee on Soils & Terrain (2016) with 'hypersulfidic'.

materials in the soils/sediments if water levels continued to decline. The median net acidity measured (10 mol $H^+ t^{-1}$) was below guideline levels (18 mol $H^+ t^{-1}$; Dear et al. 2002) for when management of soils is recommended. However, a large area of the inundated soil/sediments of both Lakes and tributaries, particularly Lake Albert, contained very high levels of net acidity (>250 mol H+ t^{-1}). This is well in excess of the Dear et al. (2002) guideline and indicated a very severe hazard. The southern and north-eastern regions of Lake Alexandrina and some marginal areas around both Lakes were a lower hazard.

As shown in Figure 2.9.8, there was a large variability, or heterogeneity, in the properties of acid sulfate soil types mapped. The net acidity (Fig. 2.9.7) and acid sulfate soil (Fig. 2.9.8) maps showed that sulfuric soils were especially prevalent in tributary regions with poor connection to the main lake bodies, such as Currency Creek, Finniss River, Loveday Bay, the body of water at Tolderol and Boggy Creek (Fitzpatrick et al. 2008b, 2008c, 2009b). The rate of oxidation of hypersulfidic material was found to be high, with up to 2% of available pyrite able to be oxidised per day in the sandy sediments to form sulfuric material. The rewetting of these materials via rainfall and tributary inflow resulted in widespread surface water acidification (pH 2-5) in the Currency and Finniss tributary areas and other shallow embayments around

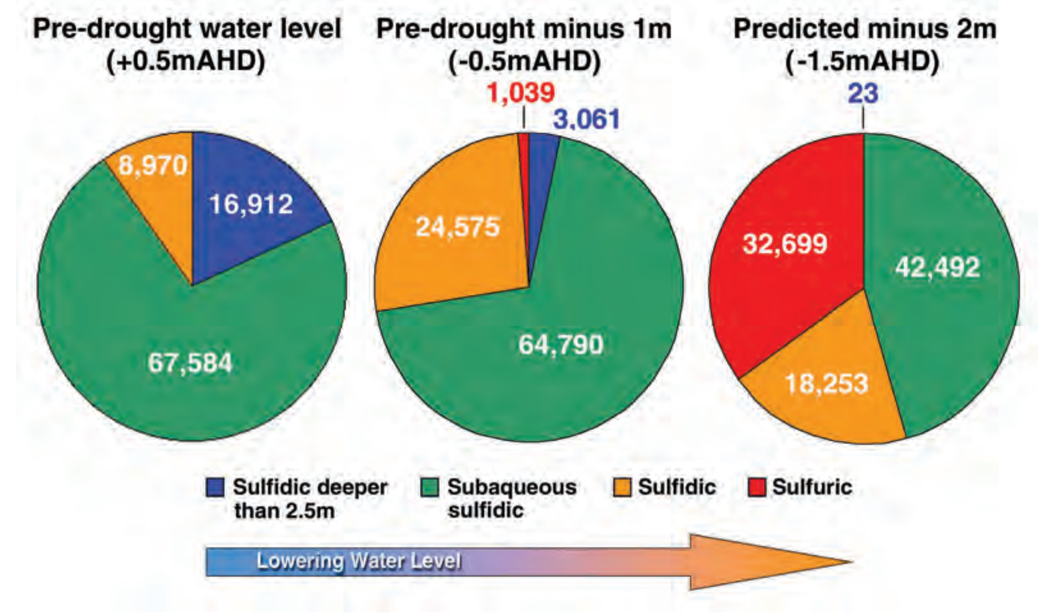


Figure 2.9.6 Pie charts showing changes in predicted areal extents for the Lower Lakes in hectares for various ASS types corresponding to pre-drought conditions (+0.5 m AHD), drought conditions in 2008 (-0.5 m AHD), and conditions that would occur were the drought to be prolonged and cause the Lower Lakes' water level to drop to -1.5 m AHD (modified from Fitzpatrick et al. 2008a, b, c). The term 'sulfidic', used in 2008, was replaced by Isbell and National Committee on Soils & Terrain (2016) with 'hypersulfidic'.

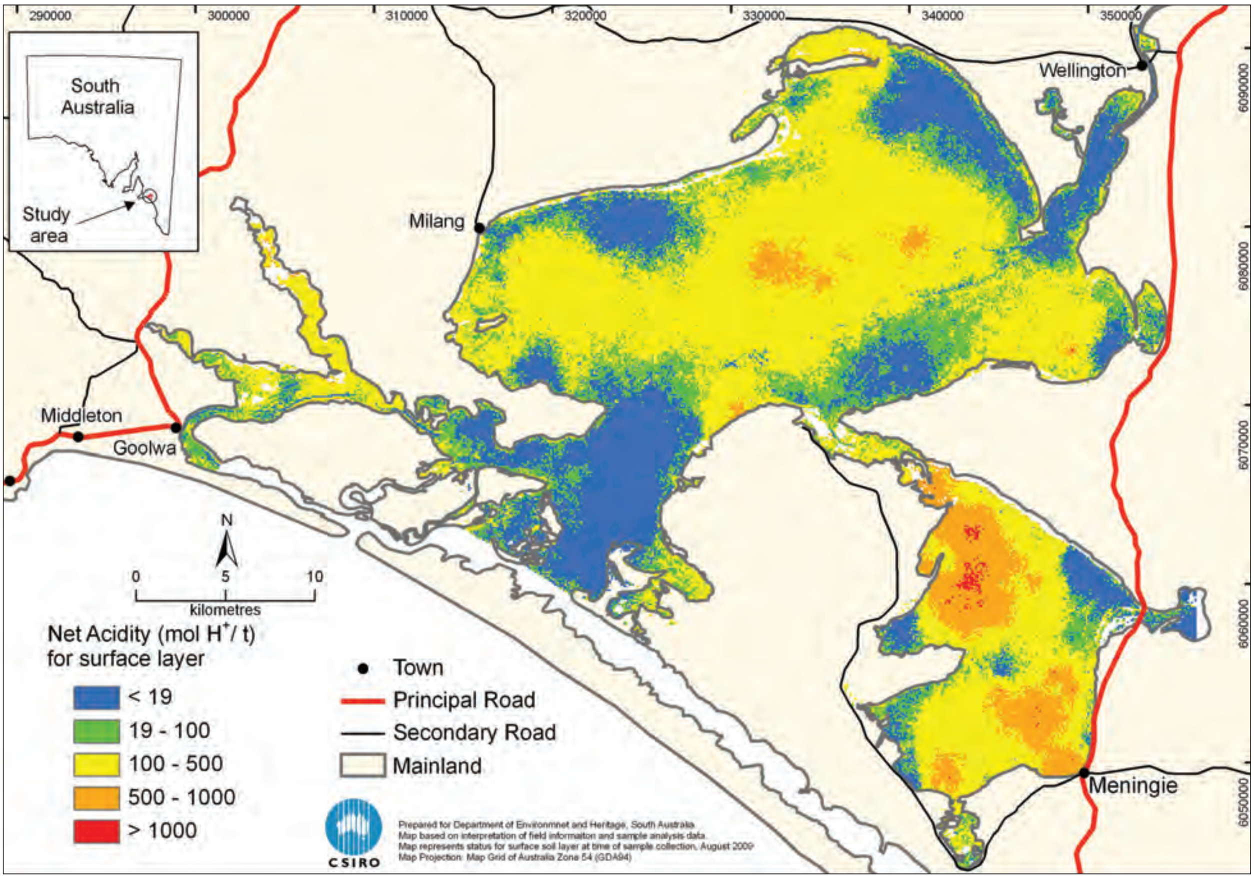


Figure 2.9.7 Net acidity map showing data grouped into five classes for the upper soil layer (0 to 10 cm). (After Fitzpatrick et al. 2010a)

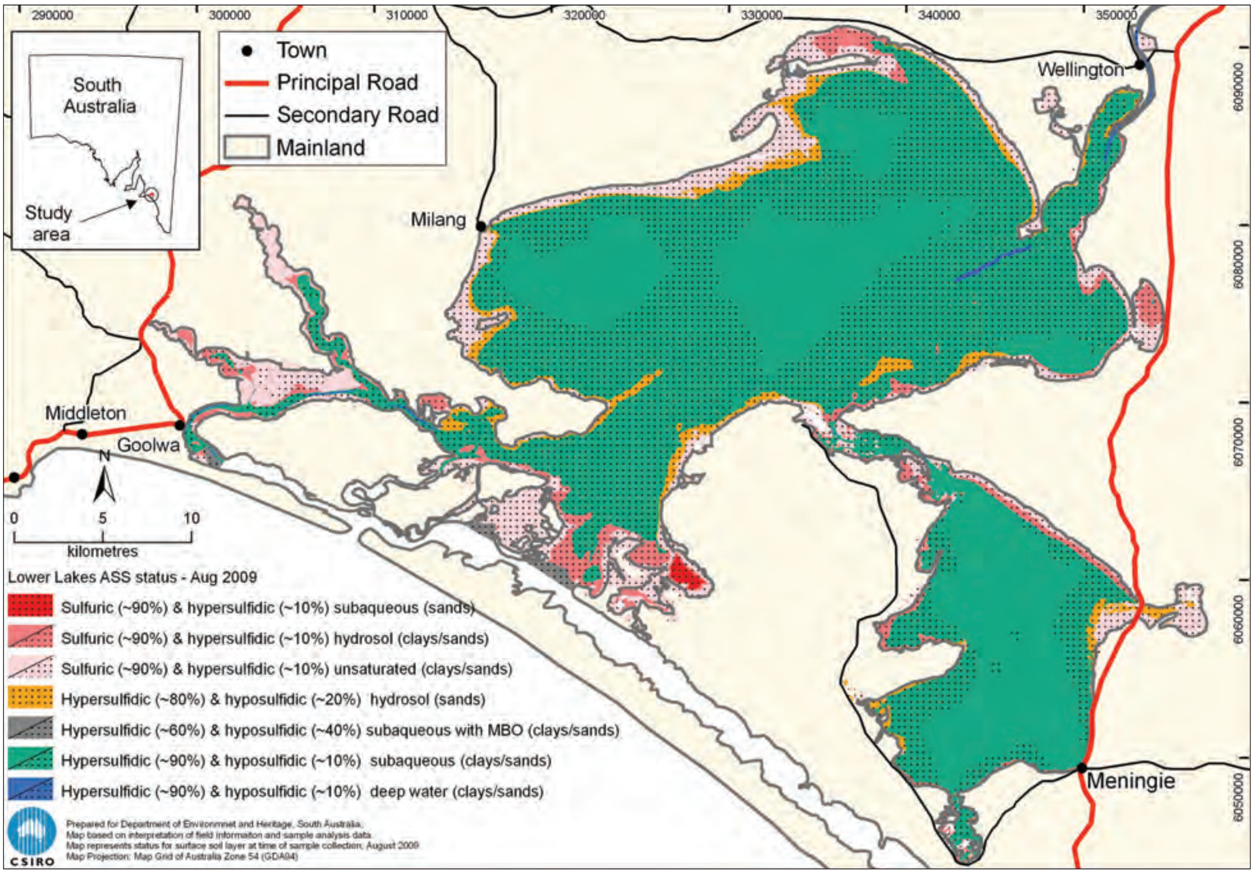


Figure 2.9.8 Soil classification map of the distribution of the following wide range of acid sulfate soil subtypes:
(i) acid sulfate soil materials with sulfuric, hypersulfidic, hyposulfidic and monosulfidic (MBO) materials
(ii) depth of water with deep water, subaqueous, hydrosols (saturated to a depth of 50 cm below the mineral soil surface) and unsaturated (unsaturated to a depth of 50 cm below the mineral soil surface)
(iii) soil texture with sands, loams and clays.
(After Fitzpatrick et al. 2010a)

the lake margins in 2009-2010 (Mosley et al. 2014a, b, c). Metal and metalloid contaminants that were released from the sediment matrix by extreme acidification (e.g. pH <2) posed risks to the public and the environment (Simpson et al. 2010a; Mosley et al. 2014a). Other hazards included noxious (hydrogen sulphide) gas release as well as mobilisation of dust from exposed acid sulfate soil areas, which led to community concern (Palmer et al. 2011).

Many research studies were undertaken during this time (see Table 2.9.2 for summary), coordinated in a major integrated acid sulfate soil research program (DENR 2010). The research program informed the geochemical modelling by Hipsey et al. (2010, 2014), which indicated that acidification of the main lake areas could occur if water levels fall below c.-1.75 m AHD for Lake Alexandrina and -0.75m AHD for Lake Albert. The risk profile was predicted to substantially increase past these lower water levels and/or with prolonged time near these levels. This was predicted to be due to the acidic groundwater seepage becoming much greater, due to an increase in exposed sediment area and higher hydraulic head gradients. Localised acidic 'hotspots' were also predicted to occur around the lake margins.

Hydro-toposequence models

All this information was used to construct general and detailed soil-regolith hydro-toposequence models, in combination with summary tables and acid sulfate soil maps to provide a comprehensive understanding of 2D, 3D and 4D (predictive) soil-landscape features along representative transects (e.g. Baker et al. 2010, 2011, 2013; Fitzpatrick et al. 2009a, b). These models also illustrate the sequential vertical and lateral changes in pedogenic processes as well as the mineralogical, hydrological and biogeochemical interactions that occur across creek, river and lake hydro-toposequences.

The generalised predictive soil-regolith model shown in Figure 2.9.9 illustrates the Lower Lakes and River Murray region, which experienced lowering of water levels due to drought, followed by winter rainfall rewetting and flooding in 2010 (Fitzpatrick et al. 2008b, 2009a, 2009b, 2011b). The soil-regolith model outlines sequential transformations progressively through five sediment/soil types from

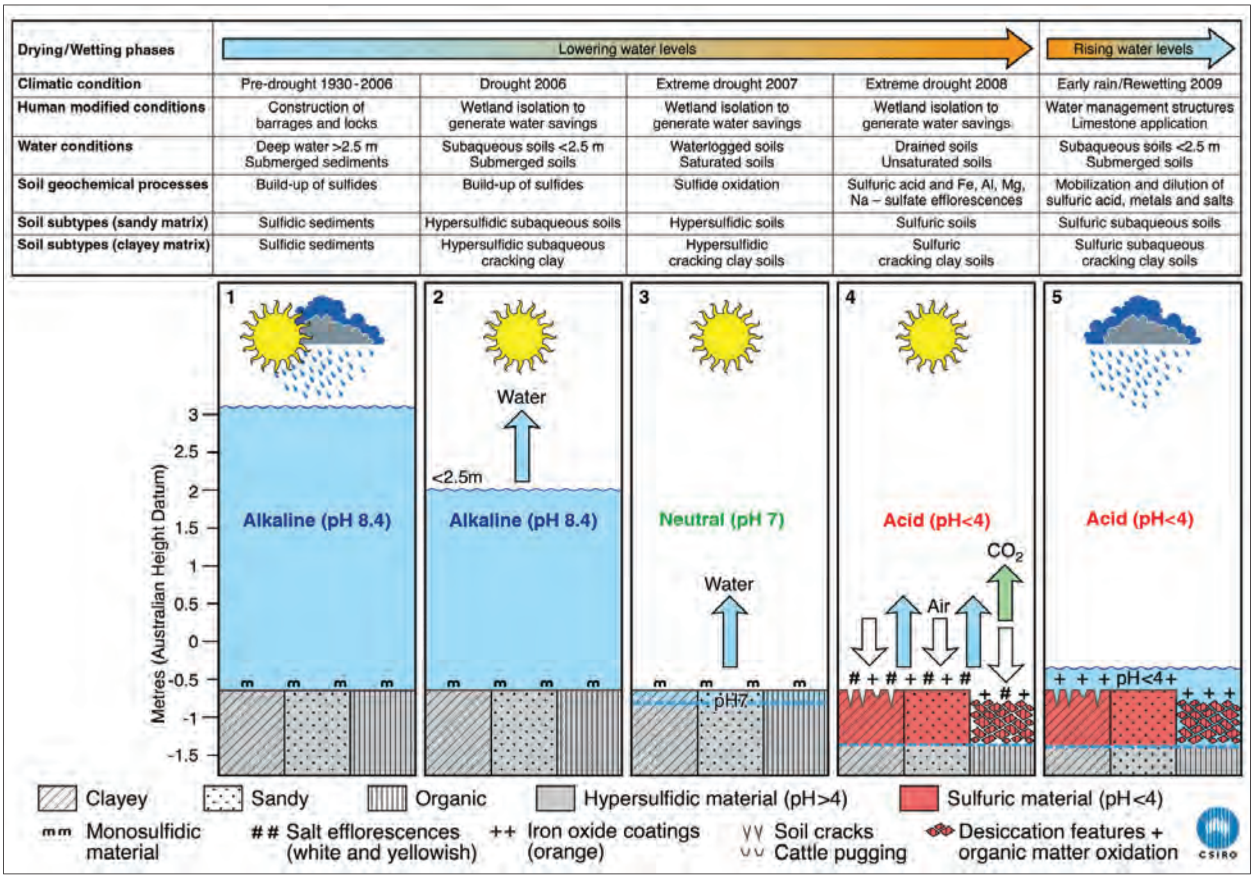
1. alkaline deeper water sediments →
2. alkaline subaqueous soils →
3. neutral waterlogged soils containing 'benign' hypersulfidic material →
4. acidic drained soils containing 'nasty' sulfuric material (pH <4) →
5. rewetted acidic subaqueous soils with sulfuric material and water.

For example, from 2007 to 2009 the partial drying of the Finniss River caused the hypersulfidic subaqueous clays to transform to sulfuric clays. On rewetting, sulfuric subaqueous clays were formed in 2009 (Fig. 2.9.9). Rewetting/reflooding caused widespread, gradual formation of acidic, sulfuric materials that persisted in subsoils, following restoration of the lake level (+0.7 m AHD) (Baker et al. 2010, 2011, 2013; Fitzpatrick et al. 2011a, b). A similar sequence occurred in Lake Albert (Baker et al. 2010; Fitzpatrick et al. 2011d). This is consistent with observations that, for several years post-drought, groundwater remained acidic under the previously (Millennium Drought) exposed lake beds (Leyden et al. 2016). This appears to be linked to a lack of available organic matter to drive sulfate and other reduction cycles, which increase alkalinity in the soil to neutralise acid present (Michael et al. 2016, 2017; Kölbl et al. 2017, 2018).

However, in some areas, prolonged inundation encouraged sulfate reduction and caused the formation of hypersulfidic subaqueous clays in summer 2011 and hyposulfidic subaqueous clays in winter 2011 (Fitzpatrick et al. 2011d). It was also established that acidity has been flushed, from several areas which contained sulfuric materials, during the early winter of 2009 (Fitzpatrick et al. 2008a, 2008b, 2009a, 2009b).

Management response, implications and strategies

While increased disturbance of hypersulfidic material is the principal cause of the formation of sulfuric materials, one would expect that the principal management option would be to reverse the situation (i.e. keep conditions anoxic or under-anaerobic, in order to slow or stop the rate and extent of pyrite oxidation). This can be achieved either by keeping hypersulfidic material anaerobic under saturated conditions or by rapid drying of hypersulfidic material to



Drying/Wetting phases	Lowering water levels				Rising water levels
Climatic condition	Pre-drought 1930-2006	Drought 2006	Extreme drought 2007	Extreme drought 2008	Early rain/Rewetting 2009
Human modified conditions	Construction of barrages and locks	Wetland isolation to generate water savings	Wetland isolation to generate water savings	Wetland isolation to generate water savings	Water management structures Limestone application
Water conditions	Deep water >2.5 m Submerged sediments	Subaqueous soils <2.5 m Submerged soils	Waterlogged soils Saturated soils	Drained soils Unsaturated soils	Subaqueous soils <2.5 m Submerged soils
Soil geochemical processes	Build-up of sulfides	Build-up of sulfides	Sulfide oxidation	Sulfuric acid and Fe, Al, Mg, Na – sulfate efflorescences	Mobilization and dilution of sulfuric acid, metals and salts
Soil subtypes (sandy matrix)	Sulfidic sediments	Hypersulfidic subaqueous soils	Hypersulfidic soils	Sulfuric soils	Sulfuric subaqueous soils
Soil subtypes (clayey matrix)	Sulfidic sediments	Hypersulfidic subaqueous cracking clay	Hypersulfidic cracking clay soils	Sulfuric cracking clay soils	Sulfuric subaqueous cracking clay soils

Figure 2.9.9 Generalised predictive soil-regolith model illustrating the role of climate variability (drought triggered and early winter rains), environmental conditions imposed by humans (i.e. modifications from barrages, isolating wetlands and weirs) and water conditions (subaqueous, waterlogged, dried and rewetted), which play a vital role in the alteration of soil geochemical processes and sequential transformation of various sandy, clayey and organic acid sulfate soil subtypes. (Modified from Fitzpatrick et al. 2008b, 2009b, 2011d)

slow the biologically mediated oxidation processes which are responsible for the formation of sulfuric acid. However, the selection of appropriate management options to prevent oxidation of sulfides depends on the nature and location of the various types of acid sulfate soil materials, their position in the landscape, and availability and ability to deliver sufficient amounts of water to either maintain or generate anoxic or waterlogged conditions. Reversing the process by rewetting, once oxidation has occurred, is not straightforward, however, because it is at this time that the risks from acid and metal mobilisation are highest. This is why reliable acid sulfate soil hazard maps, at appropriate scales, along with characterising landscapes are so important (e.g. Figs. 2.9.8 & 2.9.9). Understanding the soil properties and chemistry, rates of chemical processes and hydrogeological parameters is key to selecting the best options for drainage and the most appropriate management of the soils when they are drained. Appropriate management of acid sulfate soil types during their formation can improve discharge water quality and protect infrastructure and the environment. Such improvements can generally be achieved by applying low-cost land management strategies (e.g. Dear et al. 2002).

The main management implications and strategies due to occurrences of acid sulfate soils with sulfuric material in the CLLMM during the Millennium Drought are summarised in

Table 2.9.2 Identification, properties, distribution (mapping), geochemistry and management of acid sulfate soils.

Location	Time period and outcomes	References
Identification and properties		
Lake Albert	1930-1931; subaqueous acid sulfate soils with hypersulfidic material	Taylor and Poole (1931)
Lakes Alexandrina, Albert and Coorong	2007-2010; Drought followed by reflooding; soil and water acidification	Fitzpatrick et al. (2008a, 2008b, 2008c, 2008d, 2010a)
Finniss, Currency Creek	2008; Drought followed by reflooding; soil and water acidification	Fitzpatrick et al. (2010a)
Coorong	2008; Subaqueous acid sulfate soils with hypersulfidic material, hyposulfidic and monosulfidic materials	Fitzpatrick et al. (2008b, 2011c)
Distribution (mapping) and modelling		
Finniss, Currency Creeks	Predicted maps based on field investigations and bathometry	Fitzpatrick et al. (2008b)
Lakes Alexandrina, Albert and Coorong; Finniss, Currency Creeks	Maps based on field investigations, laboratory analyses and geostatistical interpretations	Fitzpatrick et al. (2010a, b)
Lakes Alexandrina, Albert	Three-dimensional hydro-geochemical models to assess lake acidification risk. Environmental Modelling and Software	Hipsey et al. (2014).
Monitoring		
Lakes Alexandrina, Albert	2008-2014; Drought (4 years) followed by reflooding (2 years); soil acidification in 238 inland floodplain wetlands; soil and water acidification	Fitzpatrick et al. (2011d) Baker et al. (2010, 2011, 2013)
Lakes Alexandrina, Albert	Community monitoring; citizen scientists	Thomas et al. (2011, 2016)
Geochemistry and pedogenic processes		
Lakes Alexandrina, Albert	Mobilisation of acid and metals	Simpson et al. (2010a, b)
Boggy Creek	Geochemical processes and models	Creeper et al. (2015a, b)
Finniss River	Geochemical processes and models	Fitzpatrick et al. (2012, 2011d)
Seawater contaminant mobilisation		
Boggy Creek and Point Sturt	Field-based mecocosm experiments indicate seawater-enhanced mobilisation of contaminants to surface waters	Hicks et al. (2010); Simpson et al. 2010)
Lakes Alexandrina & Albert	Laboratory experiments (as above)	Sullivan et al. (2010)
Management		
Boggy Creek and Point Sturt	Saltwater mobilisation of acidity and metals	Hicks et al. (2009)
Boggy Lake	Liming Follow-up on effects of liming	Mosley et al. (2014b) Shand et al. (2017b)
Bioremediation using plants and organic matter		
Tolderol	Effect of bioremediation (revegetation) strategies in drought	Sullivan et al. (2011, 2013)
Wally's Landing, Finniss River	Studied effect of plants on acid sulfate soil materials	Michael et al. (2016, 2017)

Location	Time period and outcomes	References
	Recovery of soil linked to organic matter availability	Kölbl et al. (2017, 2018)
Guidelines and policy		
CLLMM and elsewhere	2011; Guidelines for Assessment and Management of ASS	Fitzpatrick et al. (2011a)
CLLMM and elsewhere	2013; submission on plan for CLLMM and elsewhere	Souter et al. (2013)
Water and air quality		
CLLMM and elsewhere	Water quality screening risk assessment	Stauber et al. (2008)
Lakes Alexandrina, Albert	Water quality	Mosley et al. (2012, 2014a, 2014b, 2014c)
Lakes Alexandrina, Albert	Assessed air quality risks to the community from dust arising from acid sulfate soil areas	Palmer et al. (2011)
CLLMM and elsewhere	Climate change	Shand et al. (2017a)

the section below and in Table 2.9.2 (for more detail, see DENR 2010 and Fitzpatrick et al. 2011d). Various factors were used to determine the type and appropriateness of management actions required. A range of case studies have been highlighted below to better illustrate some of the 'unique' management options which have been applied in the CLLMM during the Millennium Drought and following reflooding. The large scale of the problem and difficulties with access (i.e. soft mud on lake margins) required novel sampling (e.g. the use of hovercraft) and management strategies.

Case Study 1. Limestone application

Applications of fine limestone ($CaCO_3$) were applied to the upper Finniss River in the form of a barrier across the river below Wally's Landing jetty, as shown in Figure 2.9.10, to neutralise potential acidic waters from the wetland and channel.

Larger areas of exposed acid sulfate soils with sulfuric (pH <4) materials and associated acid water bodies in two key 'hotspots' (Currency Creek and Boggy Lake) were managed via aerial dosing of limestone. This option involved precision application of limestone into the water body using a crop-dusting plan. The amount and location of limestone dosed was informed by measurements of acidity already present in the water body (Mosley et al. 2014b). Figure 2.9.11 shows aerial dosing operations in Boggy Lake, which is connected to Lake Alexandrina, to neutralise strongly acidic ponded water in May 2010.

Case Study 2. Embankments, regulators and pumping

As a consequence of the widespread occurrence of sulfuric material and acidic waters in the Goolwa Channel, Finniss River and Currency Creek areas (Fig. 2.9.8), the federal government, in response to a Referral under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) ('the EPBC Act')[4], gave approval for the South Australian Government to undertake

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[4] EPBC Reference Number 2009/4833; see Natural Resources SA Murray-Darling Basin 2009.

Figure 2.9.10 Applications of fine limestone in the Finniss River below Wally's Landing jetty to acidic waters flowing from the wetland and channel in May 2009. (From Fitzpatrick et al. 2011d)

Figure 2.9.11 Left: Aerial application of limestone in Boggy Lake, SA. Right: photos showing mechanism used to upload fine agricultural limestone into the aircraft in a nearby paddock. (From Fitzpatrick et al. 2011d)

a set of emergency actions to undertake management measure to mitigate acid sulfate soils (Natural Resources SA Murray-Darling Basin 2009). First, a temporary flow regulator across the Goolwa Channel at Clayton was constructed (Fig. 2.9.13) to allow water levels in the Goolwa Channel, Finniss River and Currency Creek to be raised. This strategy aimed to saturate the

Figure 2.9.12 The main temporary flow regulator across the Goolwa Channel was completed in early August 2009, allowing water levels in the Goolwa Channel, Finniss River and Currency Creek to be raised and to saturate the existing exposed sulfuric material shown in the soil map (see Fig. 2.9.8). The regulator was about 400 m long and 40 m wide, and was constructed as an earth-fill embankment. The photographs show two angles of the same public notice in the foreground, explaining the 'Goolwa Channel Water Level Management Project', with information on acid sulfate soils, which included the following statement: 'Keeping acid sulfate soils with hypersulfidic material wet is a proven and effective management technique'. (From Fitzpatrick et al. 2011d)

Figure 2.9.13 Two angles of the same notice giving public notification of risk in Boggy Lake (which is in the background) adjacent to Lake Alexandrina, because of the widespread occurrence of both acid sulfate soils with sulfuric materials (pH <2.5) on beaches and ponded acidic water (pH <4). (From Fitzpatrick et al. 2011d)

exposed sulfuric and hypersulfidic materials (Fig. 2.9.12) to minimise further sulfide oxidation and to allow the early season flows (which would have mobilised acid and heavy metals) to be held back, allowing natural in situ bioremediation to proceed. The constructed height of the regulator was c.+2.5 m AHD (to allow sufficient freeboard), but the water level was managed to a maximum level of +0.7 m AHD. The pool level was initially raised to +0.7m AHD by pumping water from Lake Alexandrina. This action required ~20 GL of water. In addition, a low-level regulator (0 m AHD) was constructed across the mouth of Currency Creek to permit continued saturation of sulfidic, hypersulfidic and sulfuric materials.

Constructing a large bund across the Narrung Narrows and pumping water from Lake Alexandrina to Lake Albert to maintain water levels successfully prevented more hypersulfidic material in Lake Albert oxidising to form sulfuric material (see Chapter 4.3 for more details).

Case Study 3. Seawater inundation

Given the falling lake levels (below sea level) and ongoing exposure of acid sulfate soils, there was focus on the potential introduction of sea water into the Lower Lakes. While seawater addition is a valid option to prevent drying out and acidification of currently submerged sediments, it was considered a higher-risk management strategy compared with fresh water, as enhanced contaminant (acid and metals) mobilisation could occur over oxidised lake marginal sediments (Hicks et al. 2009; Sullivan et al. 2010). Consequently, it was found preferable to maintain water levels with fresh water, and sea water was only to be considered as a last-resort option (if fresh water was not available) to keep high-acidity sediments from oxidising (DENR 2010). A key consideration was that recovery of water quality following acidification of the Lakes could take months to years, whereas recovery from soil acidification would take much longer, and achieving previous conditions might not be possible. Following introduction of sea water, hypersalinity was predicted to rapidly develop in the Lower Lakes under low-flow conditions, and to lead to a very long recovery time for the water quality and ecology of the historically freshwater to estuarine (in the zone south of Point Sturt) Ramsar site (see Chapter 4.3).

Development of effective monitoring strategies

Unless acid sulfate soil properties, associated groundwater levels/hydrogeochemistry and drain water quality are monitored and assessed, the need for, and efficacy of, acid sulfate soil and water management actions cannot be assessed or understood. For example, based on soil- and water-monitoring results, warning signs were erected (Fig. 2.9.13) to warn the public of the hazards present at these sites. This would not have been possible without the monitoring information to inform the risk assessment.

Consequently, the effective implementation and documentation of monitoring activities have been essential, together with appropriate interpretation, to manage the various potential risks and the assumptions made (e.g. see monitoring case studies conducted by Baker et al. 2010, 2011, 2013; Fitzpatrick et al. 2011c; Mosley et al. 2014c).

Sampling protocols for monitoring changes in acid sulfate soil conditions in the Lower Lakes region were also specifically developed for community volunteers by Thomas and Fitzpatrick (2011). Seminars and field days were held to build the capacity of 85 community group volunteers to effectively monitor acid sulfate soils four times during 2009 and 2010. This resulted in a total of 486 soil profiles and 1 458 soil layers being sampled and tested for pH in the field by community groups, and in the laboratory by CSIRO. The graphs showing pH changes and trends are available (i) on the ASRIS (Australian Soil Resource Information

System), which also contains the Atlas of Australian Acid Sulfate Soils (AAASS)[5] (ii) in a technical report (Thomas & Fitzpatrick 2011) and journal publication (Thomas et al. 2016). The engagement of citizen scientists greatly raised awareness of acid sulfate soils in the Lower Lakes, and in turn helped inform more detailed follow-up work and management in some areas.

CONCLUSION

Soil quality of the CLLMM has been dramatically altered by European settlement through changes in land use, water resource development throughout the Murray-Darling Basin, and the construction and operation of water-regulating structures. There is evidence in the CLLMM that the influence of natural and anthropogenic wetting-drying cycles and extreme drought conditions are important factors in directing changes in acid sulfate soil properties (e.g. formation of sulfides, the rate and nature of oxidation processes/changes, acid-neutralising and buffering mechanisms).

There is an extensive and considerable acid sulfate soil hazard in the CLLMM. The acidity in the soils is heterogeneous and dynamic. The research investigations highlighted particularly severe acid sulfate soil hazards in the clay-rich soils and sediments in the centre of both Lakes; consequently, these areas should be kept inundated to prevent acidification. Once exposed to the atmosphere, oxidation of the acid sulfate soils in the Lower Lakes occurs rapidly, as occurred at a large scale on the exposed Lake margins in the extreme Millennium Drought. Significant quantities of contaminants (metals, metalloids) were also formed in the sediment during the drought, at concentrations toxic to terrestrial and aquatic ecosystems. Although the oxidation and acidification of marginal acid sulfate soils occurred rapidly during the drought, subsequent monitoring has shown that recovery typically takes much longer, often several years (Shand et al. 2017a, b). Research continues on how this has impacted the ecosystem in the longer term, and whether the conditions pertaining during the drought have impacted the longer-term resilience of the Lake.

The oxidation of pyrite to form sulfuric acid and the mineral jarosite in sulfuric material, due to extreme drought conditions in the CLLMM region, may offer the first visible warning against much larger imminent environmental problems (e.g. water pollution and ecosystem impacts). Hence, acid sulfate soil materials in the CLLMM can be compared with the well-known 'canary in the mine shaft', because external drivers can render the various acid sulfate soil materials either relatively stable (i.e. wetting, reflooding or reducing), or susceptible to rapid change (i.e. under drying or oxidising conditions). Like canaries in coal mines, the types of acid sulfate soil materials in the CLLMM region can provide critical information about deteriorating environmental situations. Environmental assessment and monitoring of acid sulfate soils in the CLLMM will provide a bridge between multiple disciplines to indicate a new era in providing the needed tools to estimate soil-water and biological responses to changes in environmental conditions.

The drought-/climate-induced and/or associated resource-management-driven environmental impacts of acid sulfate soils in the CLLMM involve complex processes because

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[5] The Australian Soil Resource Information System can be accessed at http://www.asris.csiro.au.

of the following factors: (i) the location and properties of acid sulfate soils, such as their physical (e.g. depth and extent of cracking) and chemical (e.g. redox conditions) characteristics, which may not recover from extensive drought (ii) the severity of drought and/or excavation (e.g. depth of drain) (iii) the range of metals and metalloids concentrated at various depths in acid sulfate soil profiles, and their potential to be released into the environment (e.g. via preferred pathways of transport) and subsequent incorporation into iron oxidation products (e.g. schwertmannite or jarosite). These complex processes create ongoing challenges for management, but considerable progress has been made over the last decade on understanding and managing acid sulfate soils in the CLLMM region.

ACKNOWLEDGEMENTS

We especially thank other members past and present of the Acid Sulfate Soil team in CSIRO Land and Water (Dr Gerard Grealish, Richard Merry, Mark Raven, Steve Marvanek, Warren Hicks, Stuart McClure, Dr Brett Thomas, Dr Mark Thomas, Dr Nathan Creeper, Dr Andrew Baker, Dr Stuart Simpson, Dr Peter Self, Dr Nilmini Jayalath and Sonia Grocke), EPA (David Palmer, Ben Zammit, Emily Leyden, Peter Mettam, Ashley Natt, Jessica Iacopetta, Jaimi Smith, Peter Scott), and DEW/DEWNR/DENR (Russell Seaman, Dr Liz Barnett, Ann Marie Jolley, John Howard, Richard Brown, Jarrod Eaton, Andrew Beal), University of Adelaide (Prof Rob Reid, Dr Patrick Michael) and University of WA (Dr Matt Hipsey) for assistance; Greg Rinder for drafting the figures; and David Maschmedt for help with constructing Figure 2.9.1.

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CHAPTER 2.10

WATER QUALITY OF THE COORONG, LOWER LAKES AND MURRAY MOUTH

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INTRODUCTION

Water quality is a measure of the condition (physical, chemical, biological) of water relative to the requirements of one or more species and/or to any human need or purpose (adapted from Johnson et al. 1997). Many constituents (Box 2.10.1) are used to characterise the water quality of a system, and these constituents are measured by field instruments or in the laboratory. For a given water quality parameter the level that is considered tolerable varies between different aquatic organisms and the purposes that the water is used for (e.g. irrigation, recreation).

The water quality of aquatic ecosystems is governed by a number of external and internal processes, the importance of which can vary in response to changes in environmental characteristics including hydrology, climate, catchment geology and land use, and pollutant inputs. Many changes have occurred within the Murray-Darling Basin, Australia's longest river system, with impacts on the water quality in the Coorong, the Lower Lakes (Lake Alexandrina and Lake Albert) and the Murray Mouth (CLLMM), which comprise the basin's terminal lake-estuary system.

As highlighted in other chapters, the CLLMM is a region of significant ecological, economic and social value, not only for South Australia, but also for Australia and internationally. It contains a high biodiversity of aquatic and semi-aquatic plants and animals, and

- it is listed as a wetland of international importance under the Ramsar Convention
- it is a source of water for irrigated agriculture and supports a substantial fishery
- it provides recreational pursuits and aesthetic benefits
- it has high cultural value, including sacred areas for the Ngarrindjeri Aboriginal peoples.

Suitable water quality is essential not only for the economic and societal uses of water in this region, but also for shaping the aquatic ecosystems. For example, increased salinity levels can have detrimental impacts on many freshwater aquatic fauna and flora, can reduce fish abundances available to support recreational and professional fishers, and can make water unsuitable for irrigation and/or domestic stock.

The water quality in large, shallow, semi-connected, end-of-basin water bodies like the Lower Lakes and Coorong is particularly sensitive to environmental change. This is because (a) there are strong interactions between the surface waters and underlying sediments (b) Lake volumes are often relatively small compared to inflows (c) evaporation rates are high relative

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BOX 2.10.1 EXAMPLE CONSTITUENTS OF WATER QUALITY

Salinity is a measure of the amount of dissolved salts in the water. As salinity increases, water may become toxic to native freshwater organisms and unsuitable for irrigation. Salinity is often measured by Electrical Conductivity (EC).

Turbidity is a measure of the cloudiness or haziness in water caused by suspended solids (e.g. sediment, algae) and can influence the light that is available to aquatic plants for photosynthesis and growth.

Dissolved oxygen is a measure of the quantity of oxygen gas dissolved in the water. Aquatic animals, plants and many bacteria need oxygen for respiration. A low level of dissolved oxygen is harmful to aquatic life and can result in major ecosystem impacts, such as fish kills. Oxygen is replenished by photosynthesis and diffusion from the atmosphere, which is enhanced by wind action.

pH is an indicator of acidity or alkalinity of water. Neutral water has a pH of 7; acidic solutions have lower values; and alkaline solutions have higher values.

Nutrients are essential for the growth and functioning of biota. Nitrogen, phosphorus and silica often limit the primary productivity of aquatic ecosystems. Dissolved nutrients are more readily available to aquatic biota. Particulate nutrients are those bound to inorganic (sediment) or incorporated in organic material. Eutrophication is the excessive increase in nutrients that can lead to problematic growths of aquatic plants, such as phytoplankton.

Chlorophyll a is the key photosynthetic pigment in plants, algae and cyanobacteria. The concentration of chlorophyll gives an indication of the concentrations of phytoplankton present in the water column.

Metals (e.g. iron, aluminium, copper, zinc) can be toxic to aquatic biota. They are generally found in relatively low dissolved concentrations in the water column of aquatic systems, but under certain circumstances (e.g. acidified waters) can be in higher concentrations.

to water volumes and depths (d) there are strong interactions with the ocean. Over time the Murray-Darling Basin has undergone significant agricultural and commercial development, which has extracted large volumes of water, altered catchment conditions, changed run-off water quality, and modified hydrology by construction of dams, locks and barrages. Being at the downstream end of the river basin, the CLLMM region is most vulnerable to the influence of these altered conditions, and water quality in the CLLMM has varied significantly over time, with implications for aquatic biota and domestic and commercial uses. The influence of changing hydrological conditions is particularly important, with the recent Millennium Drought highlighting the sensitivity of water quality within the CLLMM to changes in hydrology, as discussed below.

This chapter summarises water quality observations and research from various time periods in the CLLMM, and provides an overview of the changing water quality characteristics, their likely causes and their future management. Knowledge of historical conditions provides important information for water managers, allowing them to assess how far aquatic systems have altered from their historical states and how those conditions may respond to future changes. Having this knowledge helps to meet community expectations of ensuring sustainability of the unique Australian landscapes and the biota they support. For water quality in the CLLMM, this knowledge helps inform the likely changes to water quality characteristics resulting from different water management scenarios and the water regime required to maintain a functioning ecosystem and human uses of the water.

PRE-EUROPEAN SETTLEMENT WATER QUALITY

Predevelopment water quality characteristics are more difficult to establish due to the absence of monitoring data, but can be inferred from historical observations, including political and social records. This is the case with the CLLMM, where the earliest records of large-scale human impacts on water quality are associated with European arrival (Box 2.10.2) and captured in early political debates (Sim & Muller 2004). There are also many significant and important Aboriginal records and evidence. The records suggest that Lake Alexandrina was predominantly fresh water above the narrow channels between the islands at the River Mouth (below Point Sturt), while Lake Albert was slightly brackish. For example, Captain Sturt also observed an extensive submerged aquatic plant community within Lake Alexandrina (Sturt 1834, p. 163):

> Its bottom was one of black mud, and weeds of enormous length were floating on its surface, detached by the late gales, and which, from the shallowness of the lake, got constantly entangled with our rudder.

Based on the contemporary understanding of shallow-lake ecosystems (e.g. Scheffer et al. 1993), these observations suggest a lake with low turbidity and low nutrient and phytoplankton levels, markedly different from conditions today.

The early European written evidence is limited to capturing only a small ‘snap-shot’ in time. Broader changes in water quality conditions can be established through paleolimnological studies, of which there have been several within the region (Chapter 2.4). Overall, these studies suggest that prior to European settlement there was a salinity continuum in Lake Alexandrina (Barnett 1994; Fluin et al. 2007). There is strong evidence of estuarine conditions near the current location of the Goolwa Barrage, whereas in the centre of the Lake Alexandrina salinity was low, and mostly freshwater conditions predominated, with the occasional salinity peak, likely during extended periods of low river inflow. Towards the north-eastern section of the Lake, there is no evidence for salinity elevated above fresh to slightly brackish conditions. These findings are consistent with the early European observations (Box 2.10.2).

Similarly, within the Coorong there is evidence of a salinity gradient — generally increasing from north to south, but with salinity levels varying depending on the extent of freshwater and marine inputs (Reeves et al. 2015). Overall, it is evident that prior to European settlement the North Lagoon was a clear estuarine system throughout, receiving direct inputs of fresh and marine water. In the South Lagoon, turbidity was lower and the water clearer than it is today, with salinities slightly above sea water with periodic tidal inputs from the North Lagoon and episodic inputs of fresh water, either from the River Murray via the North Lagoon or from Salt Creek. Furthermore, prior to European settlement, the seagrass *Ruppia megacarpa* was dominant (Krull et al. 2009; McKirdy et al. 2010; Dick et al. 2011), suggesting that the Coorong was less turbid, less saline and had lower nutrient concentrations than today, which again is consistent with the early European observations described above.

BOX 2.10.2 EARLY EUROPEAN CLLMM WATER QUALITY OBSERVATIONS IN THE LOWER LAKES ADAPTED FROM THE OFFICIAL JOURNALS OF CAPTAIN CHARLES STURT (1834) AND SIM AND MULLER (2004)

1830 Sturt (1934, p. 161):

> Thus far, the waters of the lake had continued sweet; but on filling a can when we were abreast of this point [*authors' note: this is presumed to be Point Sturt*], it was found that they were quite unpalatable*, to say the least of them. The transition from fresh to salt water was almost immediate, and it was fortunate we made the discovery in sufficient time to prevent our losing ground. But, as it was, we filled our casks, and stood on, without for a moment altering our course.

Also (p. 268):

> At about seven miles from the mouth of the river [*authors' note: the 'mouth' of the river here is presumed to be referring to near Pomanda Island where the main river channel enters Lake Alexandrina; see Figure 2.10.1*], its waters are brackish*, and at twenty-one miles they are quite salt [*sic*] [*authors' note: this is presumed to be south of Point Sturt which is approximately 21 miles across Lake Alexandrina from Pomanda Island, see Fig. 2.10.1*], whilst seals frequent the lower parts. Considering this lake to be of sufficient importance, and in anticipation that its shores will, during her reign, if not at an earlier period, be peopled by some portion of her subjects, I have called it, in well-meant loyalty, 'The Lake Alexandrina.'

1837 (Sim and Muller 2004, p. 9):

> Strangways and Hutchison travel upriver from near the Mouth to Point Sturt/ Point McLeay. 'Water here was so pure that we filled our kegs'. Cock, Finlayson, Barton and Wyatt travel down the Bremer to Lake Alexandrina (north of Milang, Fig. 2.10.1). 'The lake appears to be of vast extent, the waters being quite sweet and fresh'.

1839 (Sim and Muller 2004, p. 18):

> Another Overlander, George Hamilton, who also came via Lakes Albert and Alexandrina, lost control of his mob of cattle near Lake Albert. They had not had water for a few days and when they smelt water in the distance they rushed towards it. Hamilton who said '*the waters of which I fancied were salt*' tried to stop them but he, his men and their dogs were unable to do so. Completely exhausted and with men, horses and dogs '*knocked up*' he was forced to watch them disappear toward the lake. Upon regaining his breath he continued on: '*I crawled to the top of the knoll and looked forth. There in the distance was the lake; the head of the line had just reached it, and I drew in my breath as I saw them go into the water and bend their heads to drink. And they did drink, and as the rear came up they spread themselves on the shores and drank too. Here was the surprise — the lake's banks were not rotten, and the water was at least drinkable, for none of the cattle refused it*. Returning to my comrades, I announced to them this astonishing result. Remounting our horses we followed on the tracks of the herd, and we were soon tasting the water — it was fresh, and it was not salt; it had a vapid sweet taste, but it quenched our thirst. Millions of wildfowl must have been on the surface of this lake. As we reached its borders they rose in dense clouds, darkening the air.*

*It is important to note that unpalatable water for drinking occurs at relatively low salinities compared to sea water. The Australian Drinking Water Guidelines class water with total dissolved solids >1 200 mg L^{-1} (>2 000 Electrical Conductivity units, µS cm^{-1}) 'unpalatable'. Sea water in comparison is about 30 times saltier than this, at 35 000 mg L^{-1} total dissolved solids (~55 000 µS cm^{-1}). Brackish water is in the range of 1 000-5 000 mg L^{-1}. Beef cattle tolerate salinity up to 5 000-10 000 mg L^{-1}.

MURRAY-DARLING BASIN CATCHMENT AND WATER RESOURCE DEVELOPMENT

Water quality of the Lower Lakes and the Coorong has been dramatically altered by European settlement through changes in land use, water resource development and the construction and operation of water-regulating structures. Overall this has altered water quality (e.g. increased phytoplankton abundance; Croome et al. 2011) and hydrological regimes (e.g. total flow, water level variation) throughout the system. These changes have undoubtedly contributed to major water quality and ecological changes in the CLLMM, as discussed below.

Land use changes occurred throughout the Murray-Darling Basin after European settlement, including the development of land for agriculture, the establishment of growing urban centres, and mining activities. A major impact of these changes in both the Lower Lakes and Coorong was an increase in nutrient inputs and a shift to a system dominated by phytoplankton rather than aquatic plants (Herzeg et al. 2001; Reeves et al. 2015). Initially, European settlers ran cattle and sheep along the Lake shores from the early 1840s, allowing the stock free access to the fresh water and feed (Sim & Muller 2004). One of the first detailed scientific accounts of toxic cyanobacteria in the world was reported in Lake Alexandrina in 1878, with several hundred animal stock deaths after ingestion of *Nodularia spumigena* (Francis 1878; Codd et al. 1994). At the time this was attributed to very low flow and hot, calm conditions, but the presence of stock may also have contributed to increasing the nutrient availability to support the growth of *N. spumigena*. As agricultural development continued throughout the Basin, the use of phosphorus-containing fertilisers and copper-based fungicides increased, with superphosphate introduced to the surrounding region by the 1890s (Faull 1981). Growing urban centres also led to discharges of nutrient-rich sewerage effluent to the Murray River (Barnett 1994). Locally, copper was mined in the 1850s at Strathalbyn and along the Bremer River, which flows into Lake Alexandrina. Flood-irrigated agriculture was developed in the Lower Murray floodplains from the early 1900s, with nutrient-rich drainage water returned to the River (Mosley & Fleming 2010).

The average total annual natural flow out of the river system to the sea prior to water resource development in the Murray-Darling Basin was about 14 000 GL yr^{-1}. By the late 1800s irrigation development was occurring throughout the Murray-Darling Basin and by the 1920s total water diversions from the Murray-Darling Basin were ~2 000 GL yr^{-1}, equating to 14% of natural outflows from the Lower Lakes. Carbon isotope analyses of the sediments have shown that this resulted in reduced freshwater inputs and increased marine inputs into the system during the first half of the 20th century (Herczeg et al. 2001). Paleolimnological studies have shown that this led to increasing salinisation of the Lower Lakes (Fluin et al. 2007). This is also captured within societal records, with Lake water becoming too salty for stock and causing the loss of aquatic plants from the shoreline of the Lower Lakes (Sim & Muller 2004). The construction of the barrages reversed the trend and led to increased freshening of the Lakes. Creation of drains in the Southeast for agriculture, and diversion of this water to the ocean, have also reduced freshwater inputs to the Coorong, resulting in their salinisation (Reeves et al. 2015; Krull et al. 2009; Chapter 2.4 in this volume). The combined salinisation of the Coorong, construction of barrages and reductions in River Murray flow into and from the Lower Lakes have significantly reduced the spatial extent of the estuary.

Water extractions accelerated in the mid-1950s (up to ~4 000 GL yr^{-1} or one-third of the natural outflows from the Lower Lakes), reducing outflows and continuing to increase the salinisation of the Coorong (Reeves et al. 2015; Krull et al. 2009). In fact, the paleolimnological studies suggest that the most significant changes in salinisation and phytoplankton production occurred after the 1950s (Krull et al. 2009; McKirdy et al. 2010). The coincident loss of aquatic plants also suggests increased turbidity. It appears that these water quality changes led to significant changes in the ecology, with the South Lagoon of the Coorong switching from *Ruppia megacarpa* dominance (which has limited tolerance to elevated salinity) to *Ruppia tuberosa* (Krull et al. 2009; Dick et al. 2011).

From the 1940s the water quality of the Lower Lakes was additionally influenced by the five barrages that were constructed in 1935-1940 between the islands between Lake Alexandrina and the Murray Mouth (Fig. 2.10.1). These barrages prevented seawater intrusions into the Lower Lakes, causing them to become more permanent freshwater lakes with very little spatial and temporal variation in salinity levels as reflected within the paleolimnological studies (Fluin et al. 2007; Herzeg et al. 2001). The barrages also resulted in a more constant and higher lake water level, increasing erosion of the lake shore. Facilitated by the absence of macrophyte beds, this likely contributed to increased turbidity levels compared to pre-European settlement conditions.

Establishment of water quality monitoring and research programs (1970s-2010)

Land and water resource development and river regulation accelerated in the Basin in the 1960s and 1970s with the development of large-scale irrigation districts, and consequently water diversions continued to increase to about 12 000 GL yr^{-1} by the 1990s (i.e. ~90% of natural outflows to Lower Lakes). This resulted in river and land salinisation across the Murray Valley. The Salinity and Drainage Strategy was initiated in 1988 to combat these Basin-wide problems: the strategy included reductions in irrigation return waters and saline groundwater interception schemes. A water quality monitoring program commenced in the Lower Lakes at Milang in 1978, although initially with only a few parameters measured. The water quality monitoring of the CLLMM was progressively expanded through time, but monitoring programs were irregular, with a focus on management issues concerning domestic and agricultural water use, rather than long-term characterisation of the water quality/ecological character of the region. For the Coorong, semi-regular water quality monitoring did not begin until relatively recently (post-1998). Furthermore, other than salinity, there was little consideration of water quality in early management plans when the site was first recognised as an internationally significant wetland in 1985 (Ramsar-listed).

The patchiness of the monitoring data and climatic and hydrological differences make establishing temporal and spatial patterns in water quality during this timeframe difficult. Nevertheless, important changes in water quality have been observed, as shown in the time series for salinity, the major nutrients total phosphorus (TP) and total nitrogen (TN), chlorophyll and turbidity (Figs. 2.10.2-2.10.4). In the Lower Lakes, there were observed increases in salinities between the 1970s and 1980s (Fig. 2.10.2), presumably associated with increased inputs of salt and reduced outputs to the Coorong. This was followed by decreases in salinities

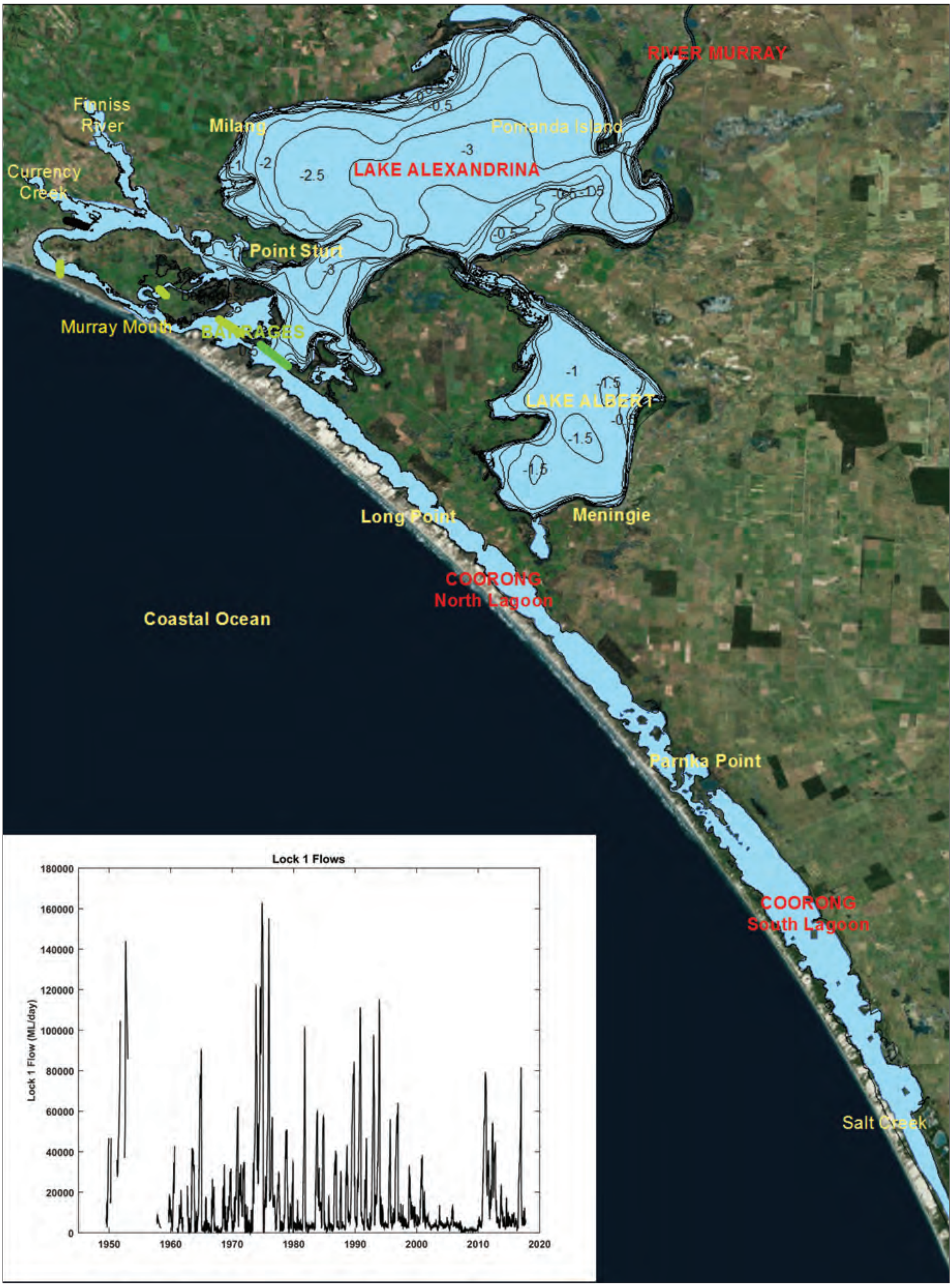

Figure 2.10.1 Map of the study area showing key water quality monitoring and other locations mentioned in the text. (From Department for Environment and Water, South Australia)

Main picture: The depth contours (in m Australian Height Datum, contours at 0.5 m intervals) are shown for Lakes Alexandrina and Albert.

Inset: flow over Lock 1 from 1950 to 2017.

Note that Lock 1 is the closest upstream monitoring station and flow generally approximates flow to the Lower Lakes well, except during low-flow conditions).

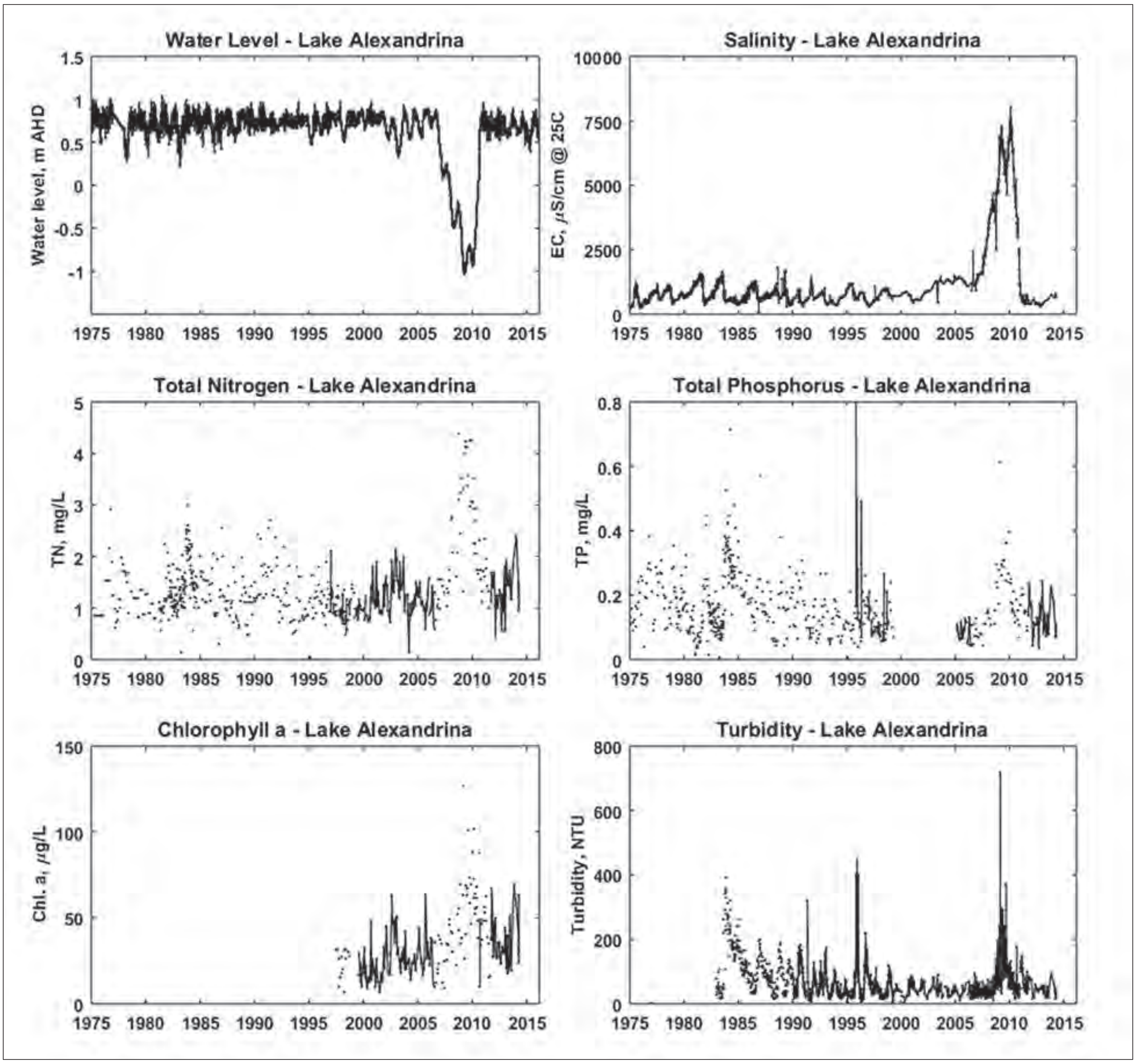

Figure 2.10.2 Water level and quality at Milang, Lake Alexandrina. Salinity is shown as Electrical Conductivity (EC). (From Environment Protection Authority and Department for Environment and Water, South Australia)

observed at Milang between the 1980s and 2000s (Fig. 2.10.2), presumably associated with implementation of the Salinity and Drainage Strategy.

However, attributing such short periods of change to particular causes can be difficult, because of the large variation in the data over timescales ranging from days to decades. A fundamental question is whether there have been significant, consistent changes in water quality through the life of the monitoring program. It is evident from the time series (Fig. 2.10.2) that the Millennium Drought of 2000-2010 had a large impact on water quality, and this is discussed separately below. Statistical analyses of the time series data indicate that changes were occurring prior to the Millennium Drought, albeit at a slower rate. Overall salinity was increasing at a rate in Lake Alexandrina of ~8 μS cm^{-1} per year, suggesting an increase of nearly 200 μS cm^{-1} over the 25-year monitoring period (Fig. 2.10.2). Median TN concentrations in Lake Alexandrina had not changed significantly over the monitoring period, whereas the

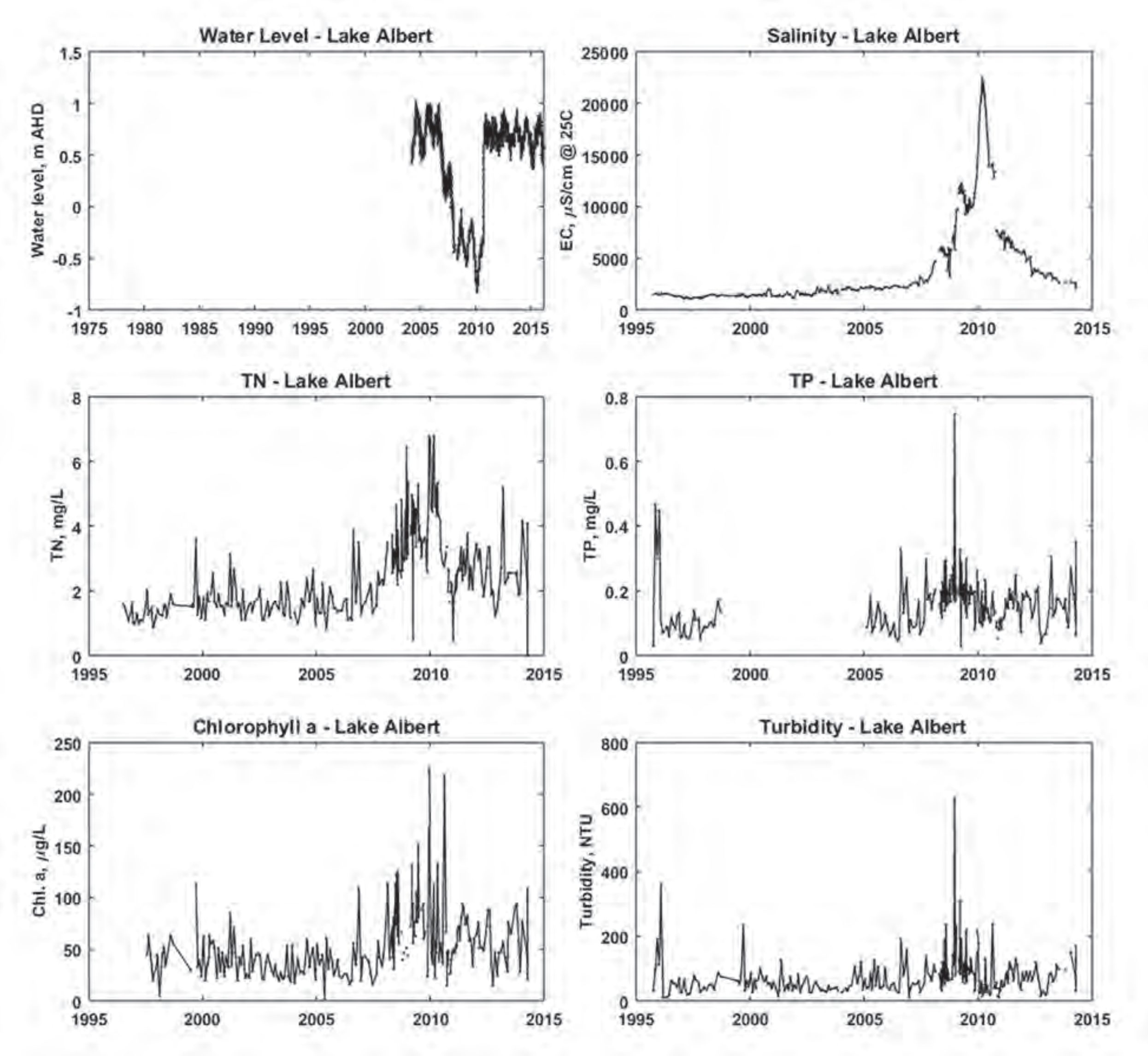

Figure 2.10.3 Water level and quality at Meningie, Lake Albert. Salinity is shown as Electrical Conductivity (EC). (From Environment Protection Authority and Department for Environment and Water, South Australia)

analyses suggested that TP and turbidity had both declined. In the case of TP the decline was at a rate of ~1.5 µg L^{-1} per year, which over the 25 years of pre-drought data equates to a decrease of 37.5 µg L^{-1}. Turbidity declined at a rate of about 5 Nephelometric Turbidity Units (NTU) per year for the 17 years of the pre-drought time series, which equates to a decline of 85 NTU (Oliver et al. 2013, 2014). It is suspected that the decline in turbidity was associated with the increase in conductivity and increased lake residence time due to reduced flows. The decline in TP over time is suspected to be associated with the parallel decline in turbidity, as much of the TP is associated with suspended particles. Consequently, the decline in TP is also associated with the increasing conductivity, and lake residence time resulted in increased sedimentation (Barnett 1994). These interconnections indicate how a change in hydrology and one parameter, such as conductivity, can potentially influence a raft of other water quality attributes. In essence, Lake Alexandrina is more saline than it was 25 years ago, but nutrient

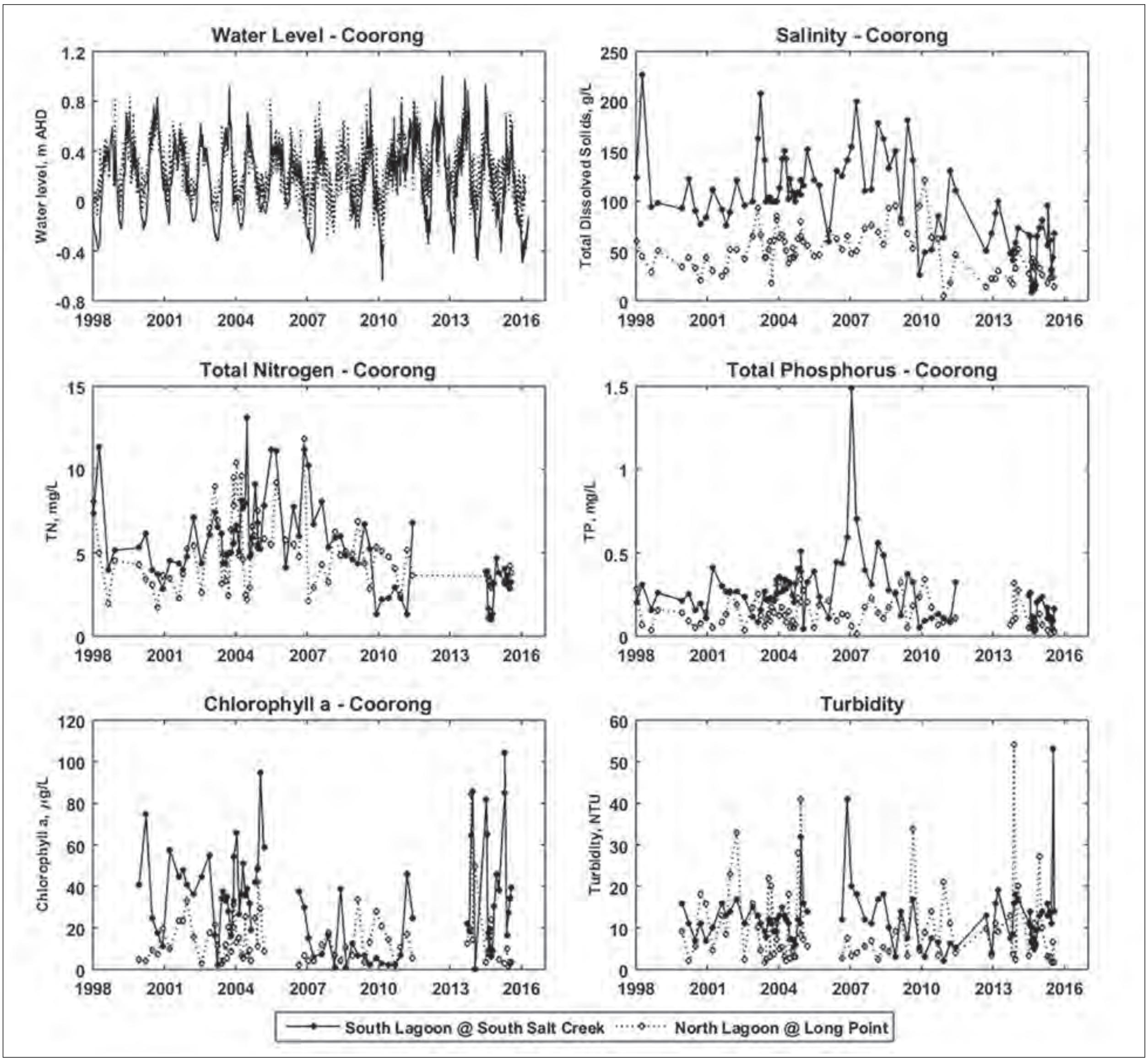

Figure 2.10.4 Water level and quality in the Coorong from 1998 to 2016. Sites shown are Salt Creek in the South Lagoon and Long Point in the North Lagoon. Salinity is shown as Total Dissolved Solids (TDS). (From Environment Protection Authority and Department for Environment and Water, South Australia)

conditions have not changed substantially. Similar analyses for Lake Albert were restricted by a lack of data (Fig. 2.10.3), but it seems that these parameters were not changing significantly.

For the Coorong, the absence of continuous water quality monitoring pre-1998 means that longer-term changes are much more difficult to establish. The earliest comprehensive water quality surveys in the Coorong appear to be those of Geddes and Butler (1982) which document water quality in the North and South Lagoons during a low-flow period in 1982-1983. In the South Lagoon, the salinities increased to 90-100 g L^{-1} during this period, TP was 0.09-0.11 mg L^{-1}, and chlorophyll *a* was 21-29 µg L^{-1}. In the North Lagoon, salinities were 20-80 g L^{-1} during this low-flow period, TP averaged 0.08 mg L^{-1}, and chlorophyll *a* was mostly <10 µg L^{-1} but increased to 20-30 µg L^{-1} during the summer of 1983. Longer-term salinity data were also analysed by Geddes and Butler (1982). During a sustained high-flow period in the mid-1970s (Fig. 2.10.1 inset), the North Lagoon was estuarine (salinity <35 g L^{-1})

and the South Lagoon salinity showed fluctuations between 40-70 g L^{-1}. More continuous post-1998 water quality results (Fig. 2.10.4) show generally higher salinity, TN, TP and chlorophyll *a* levels during the 2002-2010 low-flow period (compared to Geddes & Butler 1984 results), particularly in the South Lagoon. However, recently (post-2011) water quality improvements have occurred (Fig. 2.10.4), following higher River Murray inflows (Fig. 2.10.1 inset) and barrage and Salt Creek outflows (Mosley et al. 2017). In general, major changes in CLLMM water quality appear less associated with changes in catchment and land use in the Murray-Darling Basin, and more significantly influenced by changes in hydrology, as further detailed below for the Millennium Drought period.

THE EXTREME MILLENNIUM DROUGHT AND SUBSEQUENT FLOODS

Between 1997 and 2009 south-eastern Australia experienced the most persistent rainfall deficit since the start of the 20th century (CSIRO 2011). This, along with water extractions, resulted in a dramatic and prolonged reduction in inflows to the CLLMM (Fig. 2.10.1 inset), and a particularly extreme low-flow period between 2007 and 2010 where very low lake levels and no barrage outflow occurred (Figs. 2.10.2 & 2.10.3; Chapter 2.7; Mosley et al. 2012). This period became known as the Millennium Drought. The extreme drought conditions were immediately followed by the Murray-Darling Basin experiencing one of its largest recorded annual rainfalls, and high flows ensued from 2010 to 2012. Water levels in the Lower Lakes recovered in September 2010. The extreme climatic and hydrological conditions had a profound and prolonged effect on water quality within the CLLMM as described below.

Reduced inflows during the drought resulted in salinities rising dramatically in the Coorong (Fig. 2.10.4) due to reduced inputs of fresh water and the evapo-concentration of salt, whereby evaporation of water leaves behind the salt which accumulates. Salinities reached greater than four times that of sea water at the southern end of the Coorong, which severely constricted habitat availability for the majority of plants and animals (Brookes et al. 2009). TN and TP concentrations also increased due to reduced inflows and evapo-concentration. In comparision chlorophyll *a* and turbidity decreased. This was likely due to a very large population of brine shrimp, which would have cleared the water by grazing (Mike Geddes 2018 *pers. comm.*). It could have also been due to the lack of nutrient supply for algal production and high salinities, resulting in particle aggregation and deposition (Stone et al. 2016).

Salinities also increased within the Lower Lakes during the drought due to evapo-concentration and intrusions of saline water into the Lakes (Mosley et al. 2012). From January 2007 until March 2008, it was estimated that an additional 2.4 million t of salt entered the Lakes, the majority of which was presumably from leakage from the barrages due to water levels being significantly lower in Lake Alexandrina than the Coorong (Aldridge et al. 2011). This resulted in the large-scale death of freshwater plants and animals, including freshwater mussels.

As in the Coorong, TN and TP also increased within the Lower Lakes, but in contrast to the Coorong, chlorophyll *a* and turbidity also increased (Figs. 2.10.2 & 2.10.3; Aldridge et al. 2011; Mosley et al. 2012, 2013; Oliver et al. 2013, 2015). These increases were associated with lack of outflow concentrating material within the Lakes and increased wind-driven resuspension of sediment from the lake bed due to lower water levels, which fell by almost 2 m below normal levels within the Lake (Mosley et al. 2012; Skinner 2011). The phytoplankton community within also shifted from being more green-algae-dominated to cyanobacteria-dominated (Oliver et al. 2014), with cyanobacteria generally being viewed as a poorer quality food source for aquatic food webs. Acid sulfate soils at the margins of the Lower Lakes were also exposed and oxidised, and subsequently caused severe, but localised, extreme water quality effects when they became wet (Box 2.10.3).

BOX 2.10.3 ACIDIFICATION DURING THE MILLENNIUM DROUGHT

Receding water levels exposed large areas of lake sediments (Fitzpatrick et al. 2010). The pyrite (FeS_2) in these sediments oxidised and generated high concentrations of acidity. Upon rewetting of the exposed sediments, surface water acidification (pH 2-3) occurred in several locations (total area of 21.7 km2) (Mosley et al. 2014a, b). In the acidic conditions, dissolved metals (Al, As, Co, Cr, Cu, Fe, Mn, Ni, Zn) were mobilised, with concentrations greatly exceeding aquatic ecosystem protection guidelines (Simpson et al. 2010; Mosley et al. 2014 a, b, c).

In many areas neutralisation of the surface water acidity occurred naturally during Lake refill, but aerial limestone dosing was required in two areas to aid the neutralisation (Mosley et al. 2014 a, c).

Low pH and high dissolved metal concentrations have persisted in the submerged lake sediment and groundwater over six years after surface water neutralisation occurred in 2010 (Leyden et al. 2016, and see Chapter 2.9 in this volume).

Post-drought recovery of water quality began in late 2010 with the return of higher River Murray inflows, refilling of the Lower Lakes, and inputs to the Coorong (Fig. 2.10.2; Oliver et al. 2013, 2014.). Within the Coorong salinity, TN and TP decreased, while chlorophyll *a* and turbidity increased. In the Coorong South Lagoon, water quality improvements were also due in part to increased input of south-east drainage outflows from Salt Creek (Mosley et al. 2017). The water quality in Lake Alexandrina recovered relatively quickly (in months), being flushed via the large River Murray inflows inputs and barrage outputs (Fig. 2.10.4). Due to Lake Albert being a terminal system, water quality recovery took much longer, with salinity still elevated five years after the drought ended (Fig. 2.10.3). In both Lakes the algal community composition had not returned to pre-drought composition by 2014 (Oliver et al. 2013, 2014). Despite inputs of water with low dissolved oxygen levels associated with a widespread 'blackwater' event at the beginning of the flood period, oxygen was maintained at suitable levels within the CLLMM due to the shallow nature of the system and wind-driven re-aeration (Aldridge et al. 2012; Whitworth et al. 2013).

UNDERSTANDING HOW THE SYSTEM FUNCTIONS VIA RESEARCH AND MONITORING

Whilst the monitoring programs described above have provided critical information to managers for operational purposes, they have also helped researchers to develop a critical understanding of how the system functions. This has included establishing links between the key ecosystem drivers for the region (such as water level and salinity) and key ecological processes (such as generation of bird habitat, fish recruitment). This understanding allows for better predictions on how the CLLMM ecosystem may respond to various 'management levers', such as inflows from the River Murray, outflows through the barrages, inflows from the Upper South East Drainage scheme and dredging of the Murray Mouth. This predictive capacity relies on the development of a fundamental understanding of processes occurring within the system, and also on water quality models that are able to represent this process and predict how these processes and water quality may change under different management scenarios. Indeed, good progress has been made on such models over the past 10 years (Webster 2010; Hipsey et al. 2014). These models have relied heavily on the water quality monitoring data for calibrating and validating the outputs and have been used extensively for informing numerous critical management decisions for the region.

Overall, the Lower Lakes are now considered to be a nutrient- and algae-rich, or eutrophic, system (Geddes 1984). Indeed, increased nutrient loading from anthropogenic sources and subsequent eutrophication make up one of the greatest threats to aquatic ecosystems worldwide, with the Lower Lakes system experiencing regular occurrences of algal blooms during periods of low flow (Oliver et al. 2013). However, the Lakes act to modify the amount and form of nutrients that pass through to the Coorong and coastal ocean (Cook et al. 2009). Over an extended period the Lakes were found to retain the majority of nutrient forms (filterable reactive phosphorus 77%; nitrate 92%; total phosphorus 55%; silica 39%; total nitrogen 7%), but to be a slight net exporter of others (organic N 6%). This function of retaining and modifying nutrients reduces the availability of nutrients to algae, and when combined with high turbidity levels is thought to make the Lakes a marginal environment for algal growth (Geddes 1984). Furthermore, the high turbidity levels play an important role in structuring the Lower Lakes' ecosystem (Geddes 1988) and also likely influence the Coorong ecosystem response to the Lake inflows (Cook et al. 2009).

For the Coorong, concentrations of bio-available nutrient forms (ammonium, nitrate and phosphate) are low, but turbidity and concentrations of particulate nitrogen and phosphorus are high, due to high phytoplankton biomass and suspended detrital material (Mosley et al. 2017). Ford (2007) suggested that this is due to tight cycling of nutrients between the organic and inorganic forms, whereby inorganic nutrients are readily utilised. Many of the processes involved in the cycling of nitrogen and phosphorus are influenced by changing salinity (and associated changes in sulfur cycling), so nutrient cycling is strongly related to the salinity gradient that exists within the Coorong (Ford 2007). The concentrations of dissolved organic carbon (DOC), dissolved organic nitrogen (DON) and dissolved organic phosphorus (DOP) all increase southwards along the Coorong faster than the salinity increases, indicating that sources of these materials are in the South Lagoon. Whilst such internal sources can be important during low-inflow years, Grigg et al. (2009) found that in years with higher riverine inflows, external inputs are the dominant source of material, with most of it flushed rapidly to the ocean. Some riverine material is retained within the system, however, and fluxes of material to the South Lagoon in inflow years are considerably higher than in no-flow years (Grigg et al. 2009). During low-flow years the persistent direction of material transfer is from north to south, with a concentration of ocean-derived material within the system, since the Coorong is an inverse estuary with water drawn in from the ocean to replace evaporative losses. South-east catchment inflows via Salt Creek appear to drive export of material from the South to the North Lagoon, reducing salinity and total nutrient concentrations (Mosley et al. 2017). Lowered River Murray outflows have also reduced the input of nutrients and organic matter to the coastal ocean, reducing its productivity (Auricht et al. 2017).

THE FUTURE

The hydrological and biogeochemical complexity of the CLLMM makes future water quality conditions extremely difficult to predict, particularly given uncertainty associated with climate change. It is clearly evident from historical monitoring and research that hydrology is a primary driver of water quality. Generally, during periods of high River Murray flows the influence of external inputs dominates the water quality of the system (particularly in Lake Alexandrina), whereas during periods of low River Murray flows, internal biogeochemical processes become relatively more important.

The successful implementation of the Basin Plan, and associated restoration of 'environmental flows', is critical to maintaining suitable water in the CLLMM region into the future to protect and improve the important aquatic ecosystems and socioeconomic values of the site. Indeed, recent work assessing the contribution of environmental water provisions provided to the site as part of the Basin Plan has shown significant benefits for enhancing the transport of inorganic and organic material through the system and maintaining water quality (e.g. Ye et al. 2016). Previous studies had suggested that flow provisions across the barrages could provide significant benefits for the food webs of the Coorong and Southern Ocean (Geddes 1984; Cook et al. 2009), and more recent studies have shown this to be the case. Bice et al. (2015) found that barrage releases from the Lower Lakes to the Coorong increased productivity of the food web and supported the growth of sandy sprat, which is considered to be a critical component of the Coorong food web. The coastal water productivity will also likely be enhanced with increased environmental flows and outflows through the Murray Mouth (Auricht et al. 2017). However, the benefits of small inputs may be short-lived, not persisting within the region for much time. Increasing automation of barrage operations could enable more opportunistic barrage opening, when conditions are suitable, increasing the connectivity and size of the estuary.

Such environmental water provisions will likely become more important for the site should the future climate for the Basin be consistent with current predictions. Median river flows in the southern Murray-Darling Basin are predicted to decline further over the next 20 years (13% decrease by 2030) due to climate change (CSIRO 2008). Hence extreme low-flow periods such as occurred from 2007-2010, and resultant water quality impacts (Mosley et al. 2012), could recur. However, improved management of limited water resources in the Basin under the new Basin Plan may help mitigate some of the water quality impacts of extreme drought. For example, Mosley et al. (2014a, p. 491) found that

> [t]he deficit in the River Murray inflows (that would have maintained average water levels) to the Lower Lakes during the drought was ~400 GL yr^{-1}. During the 2007-2009 drought period an average of 4 631 GL yr^{-1} was diverted from the Murray-Darling Basin, mostly for agricultural use. Much of this water could have flowed to the Lower Lakes (60-80% of the total water diversions were from Murray, Murrumbidgee, Goulburn-Broken systems where 75-84% of flow reaches the Lower Lakes if not diverted).

Climate change is likely to affect water quality of the region, not just through changes in hydrology, but also through changes to other drivers of water quality. For example, ocean water levels are predicted to rise, which will impact upon water exchange and salinity levels. Water temperature will likely rise, which will likely impact upon the composition of the phytoplankton community, potentially favouring cyanobacterial communities. However, to date there has been little research on the likely impacts of climate on water quality within the site. In any case, significant uncertainty in the water quality response to climate change will remain, and so ongoing adaptive management of the site will be required. This adaptive management will be dependent upon having a system-wide water quality monitoring program.

BOX 2.10.4 A POSITIVE VISION FOR CLLMM WATER QUALITY IN THE FUTURE?

The successful implementation of the Basin Plan will deliver increased magnitude and frequency of environmental flows to the CLLMM region, including more water security during droughts. The South East Flows Restoration Project will increase water inflows to the South Lagoon, improve export of material to the North Lagoon and improve water quality within the Coorong. Driven by flow restoration, water quality in the Coorong and Lower Lakes improves over the longer term, sustaining improvements in ecological condition. For example, reduced turbidity and more variable Lake levels result in an increase in the abundance of submerged aquatic plants through the region, which results in further improvements to water quality. Development of new barrage infrastructure and strategies creates a larger functioning estuary to provide more diverse water quality conditions and to increase ecosystem health. Water quality monitoring is funded and continued across the region to enable management to continually adapt to a changing climate. Overall, substantial ecological, cultural, social and economic benefits are provided by enhancing the water quality of the site.

ACKNOWLEDGEMENTS

A review of this chapter by Dr Mike Geddes is gratefully acknowledged. We also thank the Department for Environment and Water and Environment Protection Authority South Australia for access to their water quality data, and for funding various previous studies on water quality that have greatly improved our knowledge in this area.

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PART 3:

BIOLOGICAL SYSTEMS

CHAPTER 3.1

PLANKTON COMMUNITIES OF THE COORONG, LOWER LAKES AND MURRAY MOUTH

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INTRODUCTION

The Coorong, Lower Lakes and Murray Mouth (CLLMM) region is quite biodiverse, due to highly variable environmental conditions over a relatively small area. The varying environmental conditions create a broad array of habitats due to physical (i.e. presence of structure), chemical (i.e. variations in water quality/salinity) and biological (i.e. presence of aquatic macrophytes) factors (Chapters 2.7 & 2.10). As such, the region is well known for the presence of a diverse array of biota, particularly bird and fish taxa. However, other biota such as plankton are also abundant and diverse in the region for the same reasons as higher trophic order animals. Plankton are a diverse group of microorganisms that live in water, ranging from unicellular organisms smaller than 0.2 µm (femtoplankton) to multicellular organisms up to 20 cm (macroplankton) (Table 3.1.1).

Autotrophic planktonic organisms, such as Cyanobacteria and microalgae, photosynthesise like plants and produce their own food from inorganic compounds, such as nutrients and minerals, using energy captured from sunlight. The importance of nutrients, cyanobacteria and microalgae to aquatic ecosystems has been well documented in the literature, and consequently they have been monitored across the CLLMM region since the 1970s, although

Table 3.1.1 Range of size for different types of plankton.

Type of Plankton	Size range	Type of organisms
Femtoplankton	<0.2 µm	viruses
Picoplancton	0.2 to 2 µm	bacteria and cyanobacteria
Nanoplankton	2 to 20 µm	small phytoplankton such as small diatoms and dinoflagellates
Microplankton	20 to 200 µm	most phytoplankton and small zooplankton such as foraminifers, protozoans, rotifers
Mesoplankton	200 µm to 20 mm	large zooplankton such as copepods, ostracods, cladocerans and larvae of invertebrates, such as barnacles, crabs, molluscs
Macroplankton	20 mm to 20 cm	amphipods, shrimps, jellyfish and larvae of fish

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irregularly and inconsistently. Also important are heterotrophic planktonic organisms, such as the zooplankton that feed on other microorganisms, e.g. bacteria and phytoplankton, as well as smaller zooplankton. The monitoring of zooplankton communities in the CLLMM region only started in 2010.

Plankton are dispersed by flowing water or transported between water bodies or regions by animals (Havel & Shurin 2004). They provide a crucial source of food for larger organisms, such as bivalves (e.g. cockles, oysters) and fish (e.g. sandy sprat, Tamar goby, small-mouthed hardyhead). The ubiquity of plankton in aquatic ecosystems, and their importance in terms of biomass and production, make them a critical component of food webs and carbon cycling. In particular, they contribute to the availability and cycling of nutrients, and they also influence the pathway of matter transfer to higher trophic levels.

The intense anthropogenic modification of the CLLMM region — largely through the alteration and reduction of flows by barrages, locks and weirs; catchment activities influencing water quality; and climate change — has seen large environmental and hence ecological changes (Lester & Fairweather 2009; Paton & Bailey 2014; Dittmann et al. 2015; Leterme et al. 2015). Therefore, an understanding of the ecosystem, including plankton, is critical in order to assess the impact of changes and to aid management into the future. The aim of this chapter is to provide an overview of our current understanding of the plankton communities in the CLLMM region, and their variations over time. Shifts in community composition may reflect natural seasonal or annual cycles in environmental conditions, such as meteorology or flow, which reoccur over longer periods of time. Such influences may form recognisable patterns in community composition that are considered representative of different habitats. In contrast, large and persistent changes in plankton community composition may reflect major shifts in environmental conditions, and are likely to impact communities of higher organisms, often detrimentally, as the planktonic food resources are altered in their type, time of occurrence and food value. Management aimed at sustaining the environmental status of the region needs to be able to identify when shifts in planktonic community composition are sufficiently extreme and persistent to reflect site degradation, as well as to have sufficient knowledge of the environmental conditions responsible for changes in order to understand how they could be improved by management actions. This review demonstrates that, despite quite extensive information for some areas of the CLLMM region, especially the Lower Lakes, our knowledge of the plankton communities is still rudimentary, and for some areas poor.

Typically, time series of changes in community composition are compared with parallel changes in environmental conditions in order to try and recognise links. Although simple in concept, the identification of such links is often difficult in practice because so many parameters vary simultaneously, so that identification of the driving variables generally requires complex statistical analyses to confirm associations. Even when this is achieved, if the time series do not include periods not impacted by external influences, then identifying a plankton community that might be a target for management actions is still fraught with difficulties. Sometimes a 'space for time' substitution approach can be helpful, where changes in the plankton communities across sites are associated with differences in the environmental conditions. It is then assumed that if the environmental conditions changed to match those observed at a particular site, the same community composition would occur. The reliability of these analyses can be undermined if sites are not fundamentally equivalent apart from the changing environmental parameter of interest. As this is not always the case, multivariate methods are generally required to tease apart the differences between sites.

This chapter draws on both time series analyses and 'space for time' substitution analyses in order to ascribe the variations in plankton communities in the CLLMM region, their responses to changing environmental conditions, and the attempts made to identify major environmental drivers that could help guide the development of management strategies.

PLANKTON BIOTA

Viruses and bacteria

Viruses are ubiquitous and abundant in aquatic ecosystems but, most importantly, they play a fundamental role in structuring the plankton food web, primarily by killing bacteria, cyanobacteria and phytoplankton. Through this process, viruses impact plankton diversity in aquatic ecosystems. However, the dynamics of viruses and their response to environmental changes are still understudied and poorly understood. Viruses and bacteria have been studied in the Goolwa Channel and the Coorong wetland in 2009 and 2010. Along the Coorong wetland, their communities became increasingly abundant towards Salt Creek, with the abundance of viruses increasing from 9.0×10^6 cells mL^{-1} (at the Murray Mouth) to 2.5×10^8 cells mL^{-1} (at Salt Creek). Viruses found in hypersaline systems such as Salt Creek are described by the term 'Halovirus'. Similarly, bacterial abundances range from 2.1×10^6 to 2.4×10^8 cells mL^{-1} along the Coorong wetland (Schapira et al. 2009; Pollet et al. 2010). The composition of bacterial communities along the Coorong wetland seemed to be mainly driven by salinity (Schapira et al. 2009).

Cyanobacteria

Cyanobacteria are photosynthetic bacteria that form significant surface blooms. They are able to do so because they contain gas-filled spaces within the cells that provide a degree of buoyancy. In calmer conditions these cells can float upwards in the water column to the well-illuminated surface layers, where they can photosynthesise and grow prolifically, provided that nutrients and other cellular requirements are also met. In some cases, the gas-vacuolated cyanobacteria can regulate their buoyancy and alter their position in the water column in order to balance their growth requirements. For example, they may move away from the damaging excessive light intensities at the very surface in order to progressively access more nutrient-enriched layers once nutrients in the surface layers have been depleted. Light intensity, nutrient availability and the intensity of turbulent mixing are the major environmental factors that influence the success of the bloom-forming cyanobacteria. Under conditions where surface blooms occur, further concentration of the cells can occur if they are pushed downwind and then accumulate against a lee shore. In these circumstances, exceptionally thick layers of phytoplankton may occur, providing concentrations of cells that, if contacted or imbibed by humans or animals, could be damaging to health.

There has been a long history of cyanobacterial blooms in the region, with one of the first ever detailed scientific accounts of toxic cyanobacteria reported in a paper in *Nature* in 1878 by George Francis, Adelaide assayer and chemist (Francis 1878). This described animal deaths attributed to ingestion of *Nodularia spumigena* by stock watering at Lake Alexandrina. The water level was very low in 1878, and during calm conditions with high water temperatures a bloom floated to the Lake surface and was blown to the shoreline where horses, cattle and sheep ingested the material, resulting in several hundred animals dying. In the 1990s blooms of *N. spumigena* again came to the attention of the public, and following confirmation of toxicity, the water supply was switched to a local reservoir and recreational use of the Lake was restricted.

Salinity and cyanobacteria in the lower River Murray are responsible for degrading the water quality to a point where it negatively impacts both the Lower Lakes and Coorong ecosystems and the water supply for irrigation and domestic supply. Cyanobacteria present a toxic threat to wildlife but also have implications for the entire food chain, as they affect the sustainable biomass of higher order organisms. In 2007, the highest cyanobacterial abundance (1.3×10^6 to 1.4×10^6 cells mL^{-1}) was recorded at salinity conditions ranging between 8.0% and 11.0%, north and south of Parnka Point (Schapira et al. 2010). Aldridge et al. (2012) found that in response to large water inflows into the Coorong in 2010-2011, first the phytoplanton community was dominated by Cyanobacteria, but as the flow continued, the abundance of Chlorophyta (green algae) and Bacillariophyta (diatoms) increased. Thus, it was assumed that the phytoplankton community was shifting towards one that would have greater nutritional benefits for the Coorong ecosystem.

Microalgae

The CLLMM water quality monitoring programs operated by the Department of Environment, Water and Natural Resources (DEWNR) used the NATA-registered laboratory of the Australian Water Quality Centre for identification and enumeration of the phytoplankton. Other research programs operated by Flinders University have used Microalgal Services (Victoria), an Australian laboratory with high-level expertise in identification and monitoring of marine phytoplankton. Different regions of the CLLMM have been monitored for different lengths of time: Lake Alexandrina from 1983; the Goolwa Channel, which is a part of Lake Alexandrina, from 2005; Lake Albert from 1997; and the Coorong only from 2006. Specific research projects have provided earlier data but only for short periods of time. In total the monitoring programs have identified 185 different phytoplankton species in 140 different genera. Even in the Coorong, despite the short period of monitoring, 131 different taxa have been identified. Most of the major phytoplankton groups are represented, with a wide array of attributes (Table 3.1.2). Consequently, as environmental conditions change, so the community composition of the phytoplankton changes to be dominated by taxa that are more suitable to the changing growth conditions.

Cyanobacteria and microalgae are critical components of aquatic food webs, their photosynthetic production providing a major food supply. Occasionally, when growth conditions are suitable, excessive growths of those photosynthetic organisms can result in ‘blooms’ that can cause a range of water quality problems. A high concentration of those organisms can be aesthetically displeasing, especially when forming a ‘pea-soup’ appearance in areas used for recreational and water sport activities. In some cases, contact with contaminated

Table 3.1.2 Phytoplankton taxa observed in the CLLMM region.

Taxa	Common name	Attribute/Characteristics
Bacillariophyceae	Diatoms (single-celled, chain-forming cells)	Cell surrounded by a frustule largely made of silica (SiO_2); two halves fit together like a pillbox
Chlorophyta	Green algae (single-celled, filamentous or colonial)	Widely distributed, pigments similar to terrestrial vegetation
Dinophyta	Dinoflagellates (single-celled, flagellated mixotrophs)	Some species present cellulose plates on top of the cell membrane that constitute the armour of the 'armoured' dinoflagellates
Cyanophyta	Cyanobacteria (also called blue-green algae)	Can be single-celled, filamentous or colonial
Cryptophyta	Cryptophytes (flagellated single celled)	Possess at least 2 flagella for locomotion
Chrysophyceae	Chrysophytes (Golden-brown algae)	Mostly in the open ocean, are part of the nanoplankton
Charophyta	Charophytes (filamentous and desmids)	Mostly in hard fresh to brackish water with very limited flow
Euglenophyta	*Euglena* (flagellated single-celled)	Mostly freshwater, no true cell wall but bound by a pellicle made of proteinaceous strips which give the cell its shape

water can be unhealthy. Large blooms often produce taste and odour compounds, especially when they begin to decay, reducing the usefulness of the water resource for consumptive purposes. Problems with consumptive use are exacerbated by the increased difficulty of treating the water. The large mass of cells readily blocks filters and requires increased chemical treatment to meet drinking water standards. In many cases these problems are annoying, but for some groups of species, especially some of the cyanobacteria and dinoflagellates, blooms can be far more problematic because some have the added attribute of toxin production. A variety of different toxins are produced by the various phytoplankton, with effects ranging from skin irritation to acute diarrhoea, neurotoxicity and liver damage, with the potential to cause death in some extreme cases.

Zooplankton

Zooplankton are a critical part of any aquatic ecosystem, including the Murray-Darling river system, where they are an important source of food for fish (e.g. Cheshire 2010; Wedderburn et al. 2013), but they also consume and control bacteria (e.g. *Brachionus* spp.; Fig. 3.1.1). There are a high number of species and endemism in Australia. For example, there are almost a thousand Rotifera species in Australian inland waters, with at least 15% endemic to Australia (Shiel & Koste 1986). Rotifera is one of the most diverse microfaunal groups in floodplains of the Murray, but only 10 rotifer species could be considered widespread in the system (Shiel et al. 1998). In spring surveys of 112 temporary floodplain waters on River Murray tributaries by Shiel et al. (1998), ephemeral pool microfaunal assemblages were distinct from those of adjacent permanent billabongs, which is apparently a function of, or response to, habitat heterogeneity (Shiel et al. 1998). In the Murray-Darling Basin, zooplankton species diversity is inversely related to salinity (Shiel 2002).

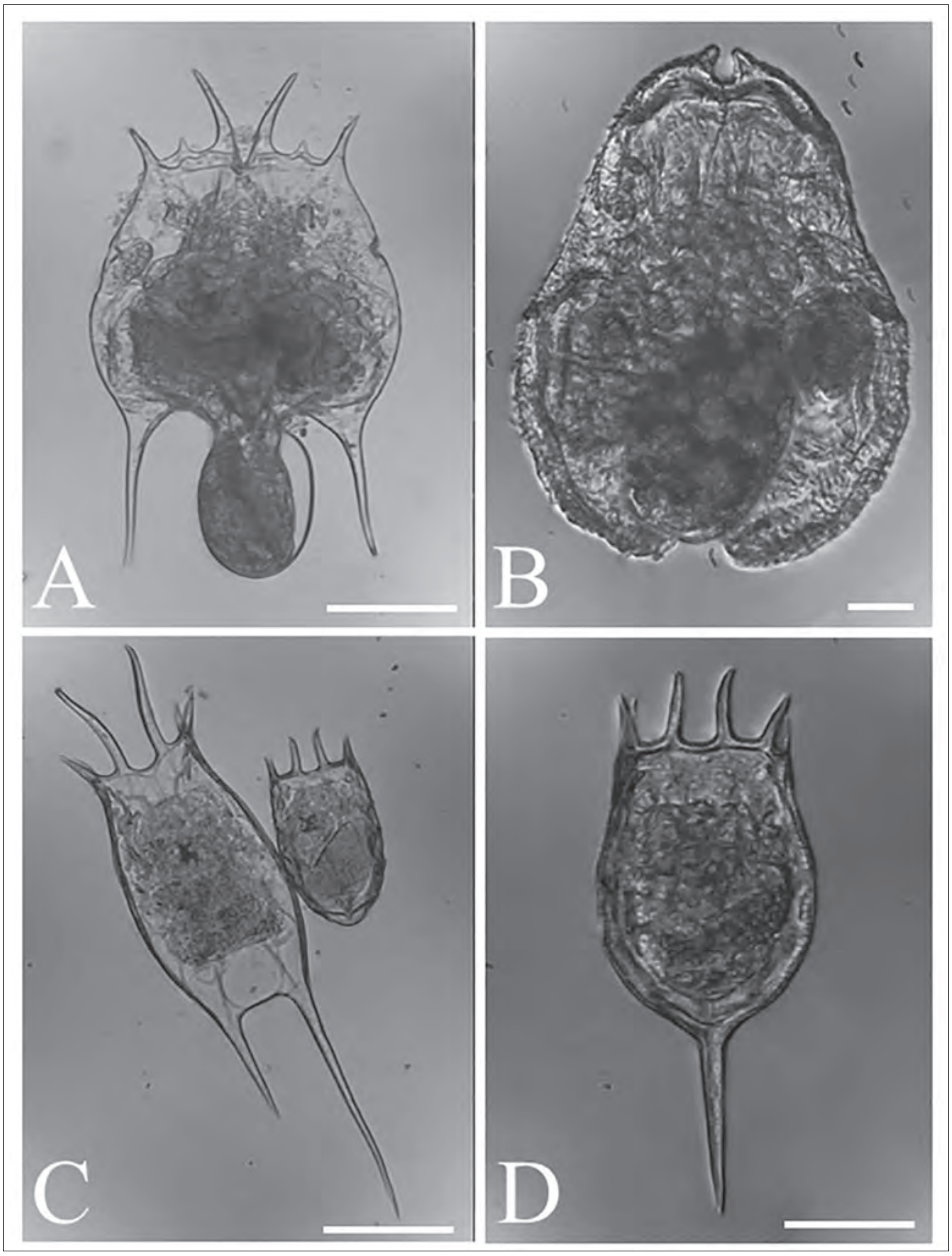

Figure 3.1.1 Rotifer species of the Murray-Darling river system (courtesy of Russel Shiel).
(A) *Brachionus quadridentatus* (scale bar: 47 μm) (C) *Keratella slacki* and *Keratella lenzi* (scale bar: 80 μm)
(B) *Brachionus keikoa* (scale bar: 12 μm) (D) *Keratella cochlearis* (scale bar: 39 μm).

IMPACT OF ENVIRONMENTAL CHANGES

Lower Lakes — Lake Alexandrina and Lake Albert

Before construction of the barrages between the Lower Lakes and the Coorong, the Lower Lakes used to fluctuate between brackish (estuarine) and fresh (lacustrine), depending on river and tide dynamics. Construction of the barrages has removed the influence of tides from the Lower Lakes and, combined with the removal of water (for anthropogenic application), this has reduced the frequency of flows into the Lower Lakes. As such, when flows are further diminished due to drought, water quality issues eventuate.

The general patterns of occurrence of phytoplankton in the Lakes were reviewed by Aldridge et al. (2012). Although mixed communities of phytoplankton species occur in the Lakes, particular groups are more likely to be dominant under certain conditions. During the periods 1965-1967 and 1972-1973, blooms of cyanobacteria were observed in the Lakes (Geddes 1984). During periods of high turbidity, low light availability and high nutrient availability, the filamentous green alga *Planctonema lauterbornii* seems to dominate the community. In Lake Alexandrina from 1975 to 1978, that species accounted for more than 95% of algal cells (Geddes 1984). The flow of fresh water into the Lake has been associated with changes in the cyanobacteria community composition, and the changes in phytoplankton dominance have been associated with changes in salinity and nutrients (Jendyk et al. 2014; Leterme et al. 2015).

Later, between 1990 and 1995, cyanobacterial blooms of *Nodularia spumigena*, *Anabaena* spp. and *Aphanizomenon* spp. (Fig. 3.1.2) occurred regularly in Lake Alexandrina and Lake Albert, and were associated with extended periods of low freshwater flow, low turbidity, low turbulence and high light availability. More specifically, the blooms of *N. spumigena* in the summer and autumn of both 1990-1991 and 1995 were associated with low flows (<10 000 ML day^{-1}), moderate turbidity (<50 Nephelometric Turbidity Units (NTU)), low electrical conductivity (40-100 mS m^{-1}) and variable nutrient concentrations (Aldridge et al. 2012). Towards the end of the Millennium Drought, between August 2008 and September 2009, when river inflows were minimal and Lake depths fell to unprecedented levels, both Lake Alexandrina and Lake

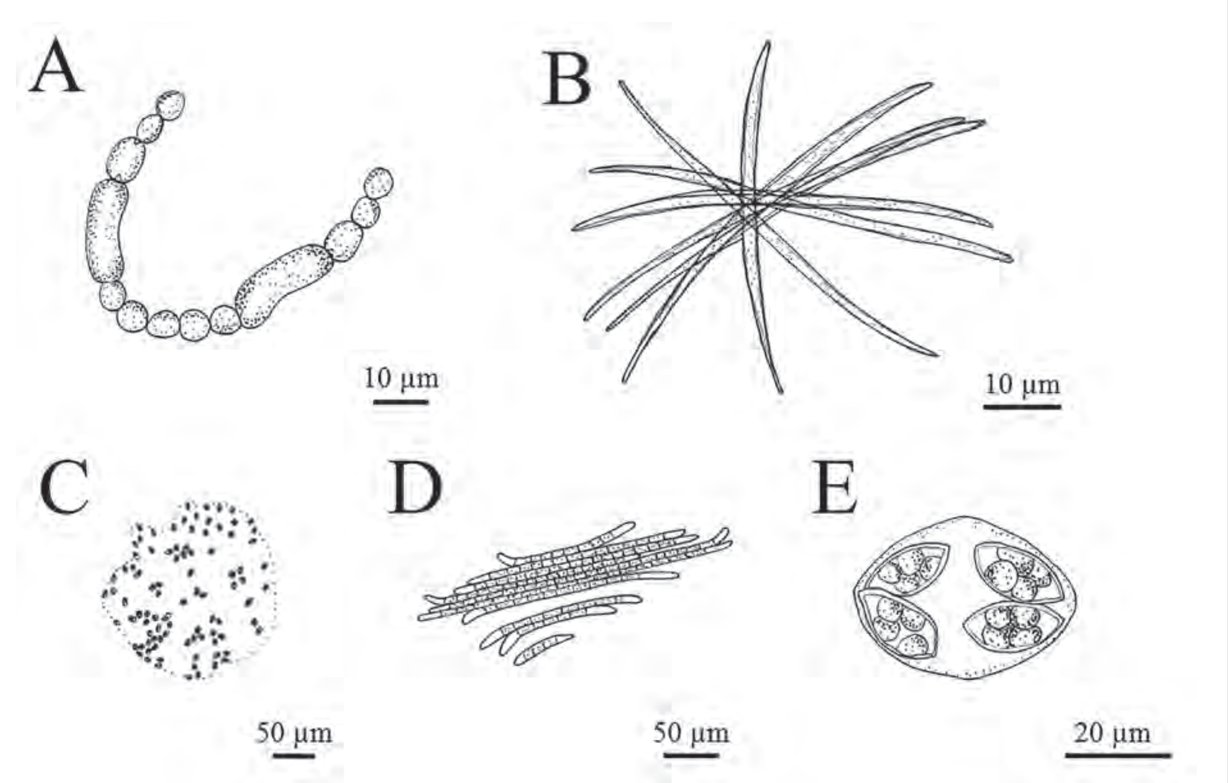

Figure 3.1.2 Cyanobacteria: (A) *Anabaena* sp., (C) *Aphanocapsa* sp. and (E) *Aphanizomenon* sp.; and green algae: (B) *Ankistrodesmus* sp. and (C) *Oocystis* sp.

Albert regularly experienced blooms of *picocyanobacteria*, notably *Aphanocapsa* spp. (Fig. 3.1.2), *Planktolyngbya* spp., *Aphanizomenon* spp. and *Pseudanabaena* spp. (Aldridge et al. 2012). It was also during the extended drought period that the first recorded bloom of *Cylindrospermopsis raciborskii* occurred in the Lower Lakes in 2006 (Cook et al. 2008).

Consistent and reliable long-term monitoring provides the data for developing dependable understanding of the functioning of ecosystems. Monitoring aims to capture the extent of change within a system and provide data amenable to statistical testing. Statistical analysis helps ensure that suggested interactions are reliable and can be used in developing management plans. Monitoring in the CLLMM has been undertaken for different purposes and for different periods of time in the various regions, but in all cases sample collection has been disrupted or altered and this makes statistical analyses difficult. However, overarching data analyses are more powerful and robust than the conceptual linking of individual studies, and recently efforts have been made to extract a standard phytoplankton data set from the DEWNR monitoring program to describe changes in the CLLMM using multivariate analyses (Oliver et al. 2013, 2014). The longest and most continuous monitoring data sets are from Lake Alexandrina, especially from a site near Milang. This has been sampled for phytoplankton since the mid-1970s, although data collection from this site has been disrupted; for example, no monitoring was carried out between 1999 and 2004 due to lack of government funding, which was unfortunate as the decade-long Millennium Drought started at this time.

Multivariate analyses of the data have enabled broad comparisons of community changes — for example, the average concentrations of the genera most responsible for the community changes before, during and after the Millennium Drought (Fig. 3.1.3). The data from Milang capture the major changes in phytoplankton abundance and confirm many of the characteristics previously reported in individual studies. In particular, they show that *Planctonema* spp. were a dominant phytoplankton for the period 1983-1997, but that during this time there were occasional blooms of cyanobacteria, largely of *Nodularia* or *Anabaena*, enhancing their average cell numbers. Monitoring at the site ceased just prior to the drought, but when it recommenced in 2006 during the drought, *Aphanocapsa* spp. and *Planktolyngbya* spp. were common, and their increases and the demise of *Planctonema* were the largest population changes. In 2011, *Planctonema* spp. made a short recovery and returned to dominance during periods of high flows associated with the breaking of the drought, and this is reflected in its contribution to the community composition post-drought (Fig. 3.1.3). However, this was short-lived as flows again declined and the cyanobacteria *Aphanocapsa* spp. and *Planktolyngbya* spp. returned.

These multivariate statistical techniques, which have become available over the last decade as increased computing power has enabled their routine application, provide a means for analysing changes in community composition and relating them to changes in water quality (Oliver et al. 2013, 2014). Such analyses suggest that the major driver of shifts in phytoplankton community composition over the Millennium Drought was the increased salinity of the Lake, a result of reduced inflows of water from the River and the evaporation from the Lake increasing the salt concentration.

Much like smaller planktonic organisms, zooplankton assemblages in the River Murray are reflective of the river water conditions: alkaline (pH 7.5-8.7), turbid (10-225 NTU) and moderately saline (0.2-1.0 g L^{-1}; Shiel 1979). All freshwater zooplankton species are sensitive to

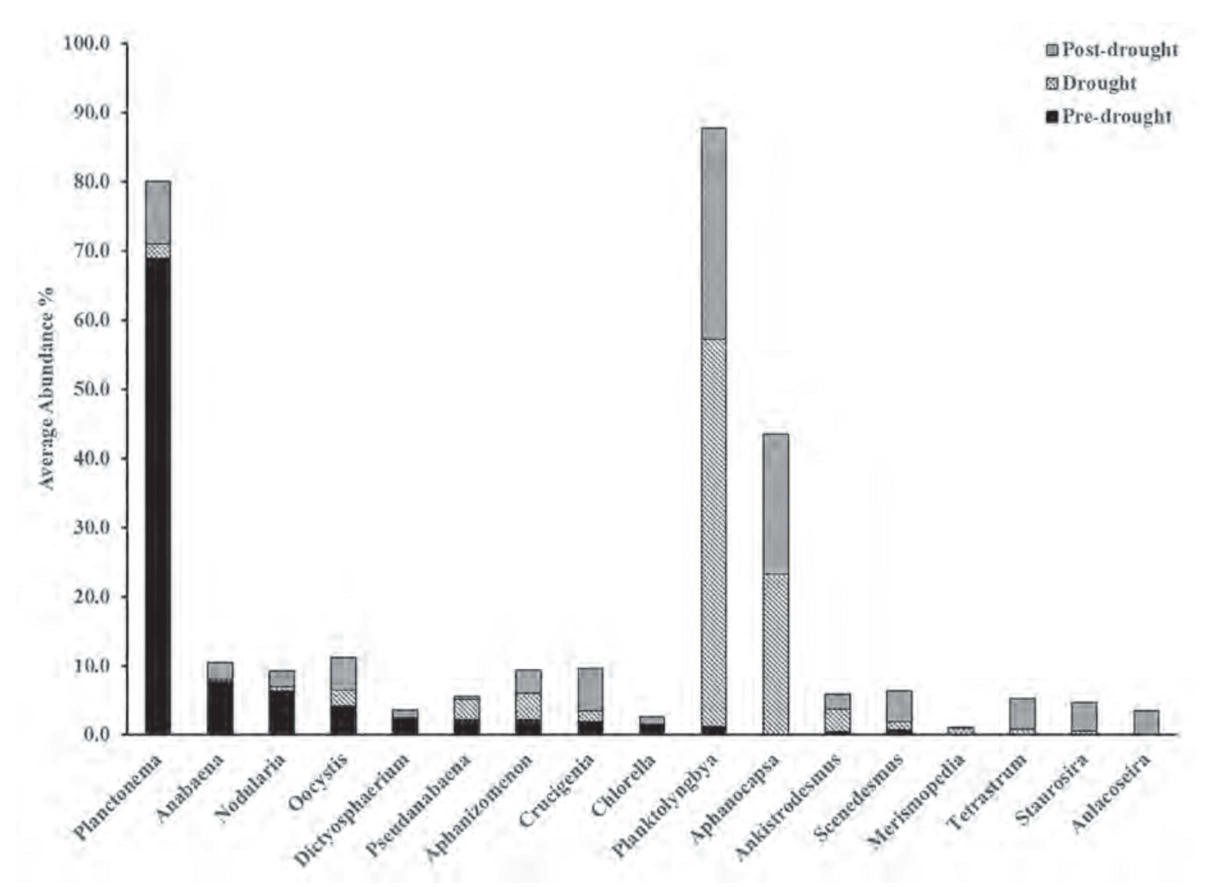

Figure 3.1.3 Average percentage abundance within each period of the microalgal genera accounting for 90% of the change across the pre-drought, drought and post-drought periods in Lake Alexandrina. (Designed by R. Oliver)

salinity increases above ~4 g L^{-1} (Shiel & Tan 2013a). In particular, the Murray regime provides more suitable conditions for phytoplankton growth, and thus favours the development of herbivorous microcrustacea with relatively long duration times (Shiel 1986; Shiel & Walker 1984). Downstream weirs and locks on the Murray River provide low- or no-flow conditions and a longer retention time, which permit reconstitution of a microcrustacean assemblage. This is referred to in European studies as the 'age' of the water, with rotifers dominating in waters of low 'age' (e.g. short retention time storages such as Lake Mulwala) and microcrustacean assemblages appearing in waters of greater 'age' (e.g. long retention time storages such as Lakes Dartmouth and Hume).

This phenomenon reflects the life cycle of the respective microfauna. At ambient temperatures in Murray River tributaries, rotifers are reproducing in days and microcrustacea in weeks. Rotifers are able to get through their life cycles in the short retention-time storages; microcrustacea are not. The latter require stable conditions for a longer period to reach adult reproductive stages, and are unable to complete life cycles in turbulent or rapid through-flow storages (Shiel 2002). Shiel et al. (1982) noted 133 species of zooplankton in the lower Murray. A mixed assemblage of protists, rotifers and microcrustaceans persists into the lower Murray, with longitudinal changes in species composition during long travel times to the River mouth (Shiel 2002). The persistent microfaunal community reflects disparate contributions from upstream impoundments, e.g. floodplain waters which may at times have a connection to the River, regions of slow flow such as backwaters or braided channels, waste stabilisation ponds from riverside communities, which may discharge into Murray tributaries — in fact, any standing water which connects to the River at any time (Shiel 2002).

Geddes (1984) also highlighted that there are notable differences between zooplankton assemblages in upstream impoundments of the Murray and Lake Alexandrina (e.g. higher zooplankton biomass), because distinct limnetic species are maintained locally, even though Lake Alexandrina receives femtoplankton from the River Murray and from the tributaries (e.g. Finniss River; Shiel & Tan 2013a). In particular, there is little seasonal pattern for rotifers in the Lower Lakes (Geddes 1984). The size of some zooplankton species (e.g. *Daphnia carinata* up to 5 mm) in Lake Alexandrina is much greater than other parts of their ranges, possibly because high turbidity makes them less prone to predation (Geddes 1984), but this requires testing.

Shiel and Tan (2013a) recorded 207 taxa of zooplankton in the Lower Lakes, Goolwa Channel and the estuarine region of the Coorong in sampling over 2011-2012, with 152 of those taxa recorded in Lake Alexandrina (Fig. 3.1.4). This compares with a total of 28 species recorded in Lake Alexandrina and Lake Albert by Geddes (1984), which partly relates to differences in sampling methods (35 μm mesh versus 158 μm mesh respectively), and also to much lower densities recorded by Geddes (1984). In 2010-2012, Lake Albert had the highest zooplankton densities in the region with 4 000-5 000 individuals L^{-1} — the halotolerant *Hexarthra brandorffi* dominated immediately following drought, but was later replaced by freshwater zooplankton species (e.g. the rotifer *Filinia pejleri*; Shiel & Tan 2013a). The return of river flows in 2011 led to a riverine, rotifer-dominated assemblage in Lake Alexandrina, and this assemblage was also reflected in samples taken from the Goolwa Channel and estuarine region of the Coorong at the same time (Shiel & Tan 2013a). Lake Albert differed from Lake Alexandrina in that there was a mix of microcrustaceans, rotifer and protist plankton that was similar to that recorded by Geddes (1984). Shiel and Tan (2013a) found that after high river flows, many zooplankton in the CLLMM region had originated from upstream (e.g. the rotifers *Brachionus angularis* and *Keratella australis* (Fig. 3.1.1)), as previously suggested (Shiel et al. 1982) and recently documented (Furst et al. 2014). The tributaries of Lake Alexandrina and the Goolwa Channel appear to be important sources of zooplankton biomass. For example, Shiel and Tan (2013a) found substantial contributions of microcrustaceans from the Finniss River and Currency Creek.

Lake Albert has an elevated salinity compared with Lake Alexandrina; hence, halotolerant or halophile plankters are present, and assemblages are similar to the marine-influenced North Lagoon of the Coorong (Shiel & Tan 2013b). During freshwater flows through the entrance to Lake Albert (Narrung Narrows), an increase in species richness due to the presence of both riverine and estuarine zooplankton has been recorded (Shiel & Tan 2013b). As well as being diverse compared to other sampling sites in the lower Murray, Lake Albert has been recorded to have the greatest density (4 000-5 000 individuals L^{-1}), compared to other lower Murray sites during a monitoring program (Shiel & Tan 2013b). Microcrustaceans, rotifers, copepods and cladocerans have been recorded in Lake Albert. Investigations into Lake Albert zooplankton fauna are few, with only four monitoring reports available in the literature.

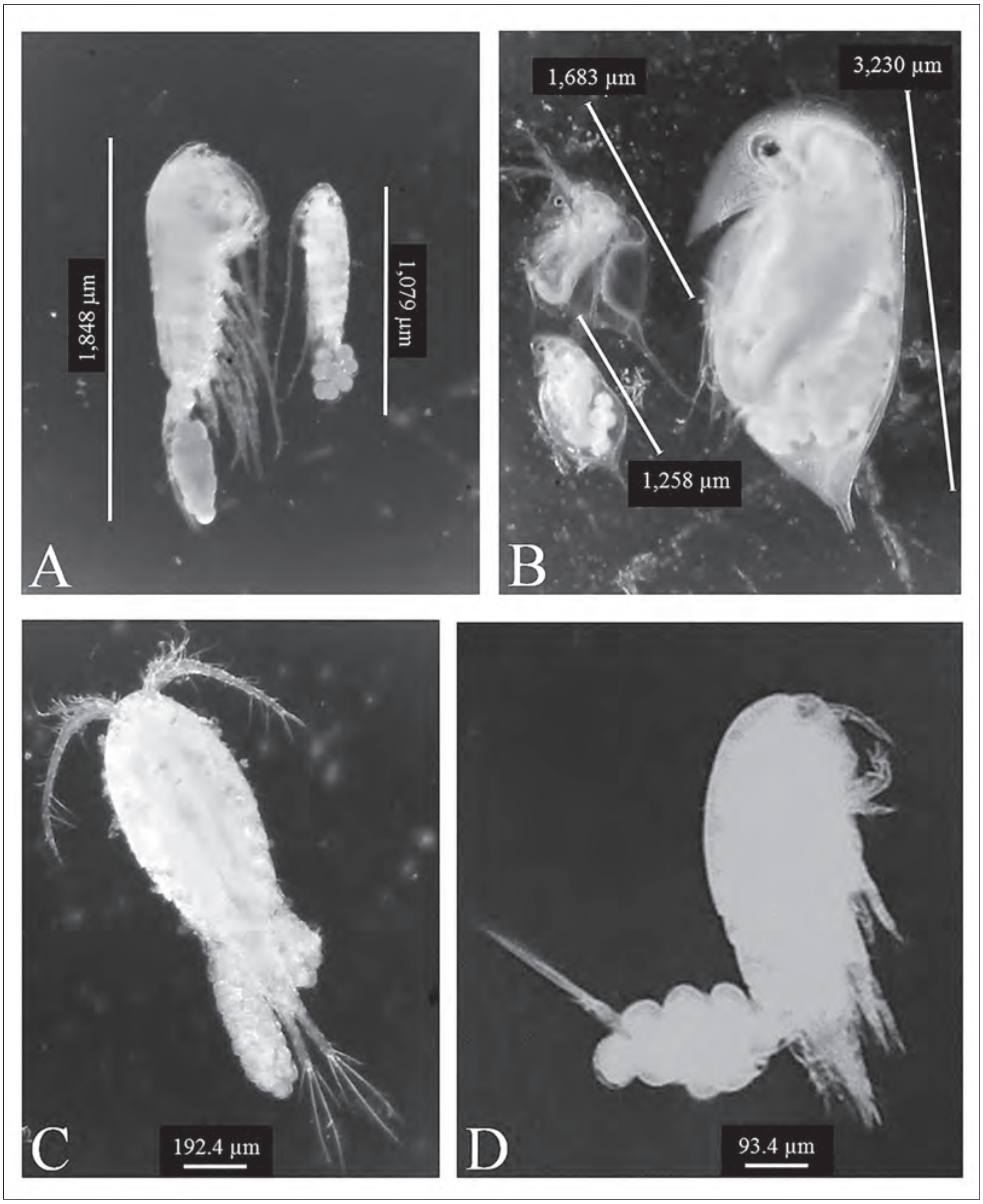

Figure 3.1.4 Zooplankton species.
(A) *Boeckella triarticulata* (left) and *Calamoecia ampulla* (right) sampled in Lake Alexandrina.
(B) *Daphnia* species sampled in Lake Albert. Lower left: *D. galeata*, an invasive species new for the continent. Top left: *D. lumholtzi*. Right: one of the many *D. carinata*, which is a species complex.
(C) *Australocyclops australis* sampled in the River Murray.
(D) *Microcyclops varicans* sampled in Lake Alexandrina.
Images were taken using Dark-Field Light Microscopy. (Micrograph by R. Shiel)

Murray Mouth/Coorong Lagoon

Monitoring in the Coorong has been restricted to recent times, but has also varied annually along the length of the waterbody. DEWNR and Flinders University, through their respective programs, monitored the Coorong between 2005 and 2016. The three sampling locations monitored in the Murray Mouth region were sampled in 2005/06, 2010/11 and 2012/13, while the northern

Coorong was sampled in 2010/11 and 2013/14 and the southern Coorong in 2013/14. Flinders University monitored the Coorong between August 2011 and 2013 on a monthly basis. This fragmented sampling regime makes data analyses very difficult. However, multivariate analyses indicated that within each of the sites the changes in phytoplankton composition over time were not significant, while differences between sites were significant. This enabled a snapshot of the longitudinal differences in average phytoplankton community composition at stations along the length of the Coorong over the monitoring period, reflected in average cell abundances for species present in 95% of the samples (Table 3.1.3). Originally in the monitoring data, *Nannochloris* was identified as *Chlorella*, but this was corrected following more detailed taxonomic assessment, and here the *Chlorella* enumerations are attributed to *Nannochloris*.

In the Coorong, phytoplankton has been monitored for its biomass (expressed in Chlorophyll *a*) and its composition. The freshwater inflow into the Coorong varies significantly on a seasonal basis and impacts the salinity levels of the water in the North and South Lagoons. The phytoplankton biomass has been observed to be constantly higher at sites with elevated salinity (Jendyk et al. 2014; Leterme et al. 2015; Hemraj et al. 2017a). The increase in phytoplankton biomass with salinity is associated with the spatial variation in phytoplankton community structure along the system, in particular, with a decrease in taxonomic richness. While salinity is the main driver of the phytoplankton community in the Coorong, the nutrient composition of the different regions (i.e. Goolwa Channel, North and South Lagoons) also affects the community structure along the system.

Jendyk et al. (2014) monitored the phytoplankton communities of the Coorong following the inflow described. Over the two years of monitoring, a total of 52 species of diatoms (Fig. 3.1.5), 27 species of dinoflagellates, 35 species of chlorophytes and 11 species of cryptophytes were identified. The distribution of those species was affected by salinity (Jendyk et al. 2014; Leterme et al. 2015), with chlorophytes dominating brackish locations and diatoms prevailing in hypersaline conditions. While a wide range of phytoplankton species was encountered throughout this study, their origin and/or preferred habitat within the estuary was highly group-dependent. Three distinct populations of phytoplankton were identified as a function of salinity:

1. chlorophyte-dominated populations, indicative of freshwater and low brackish conditions
2. diatom-/dinoflagellate-dominated populations that thrive at higher salinity
3. a transitory or euryhaline population that consists of species encountered throughout the Coorong all year round, and that seems unaffected by seasonal changes in salinity.

The zooplankton assemblages in the estuarine region of the Coorong are more variable than those in the Lakes, being subject to barrage releases and tidal influences; hence they fluctuate between riverine and estuarine microfauna in short periods of time (Shiel & Tan 2013a). Overall, about 85% of zooplankton recorded during high river flows from 2010 to 2012 were riverine in origin rather than being a lacustrine assemblage (Shiel & Tan 2013a). There are likely to be positive food chain effects from the influx of freshwater zooplankton during times of river flows, particularly for small-bodied fish or early life stages of larger fish species (Shiel & Tan 2013b), but in the CLLMM region there are only a few studies in this regard (e.g. Lamontagne et al. 2007; Wedderburn et al. 2013, 2016). During their 2013-2014 survey, Hemraj et al. (2017a) recorded

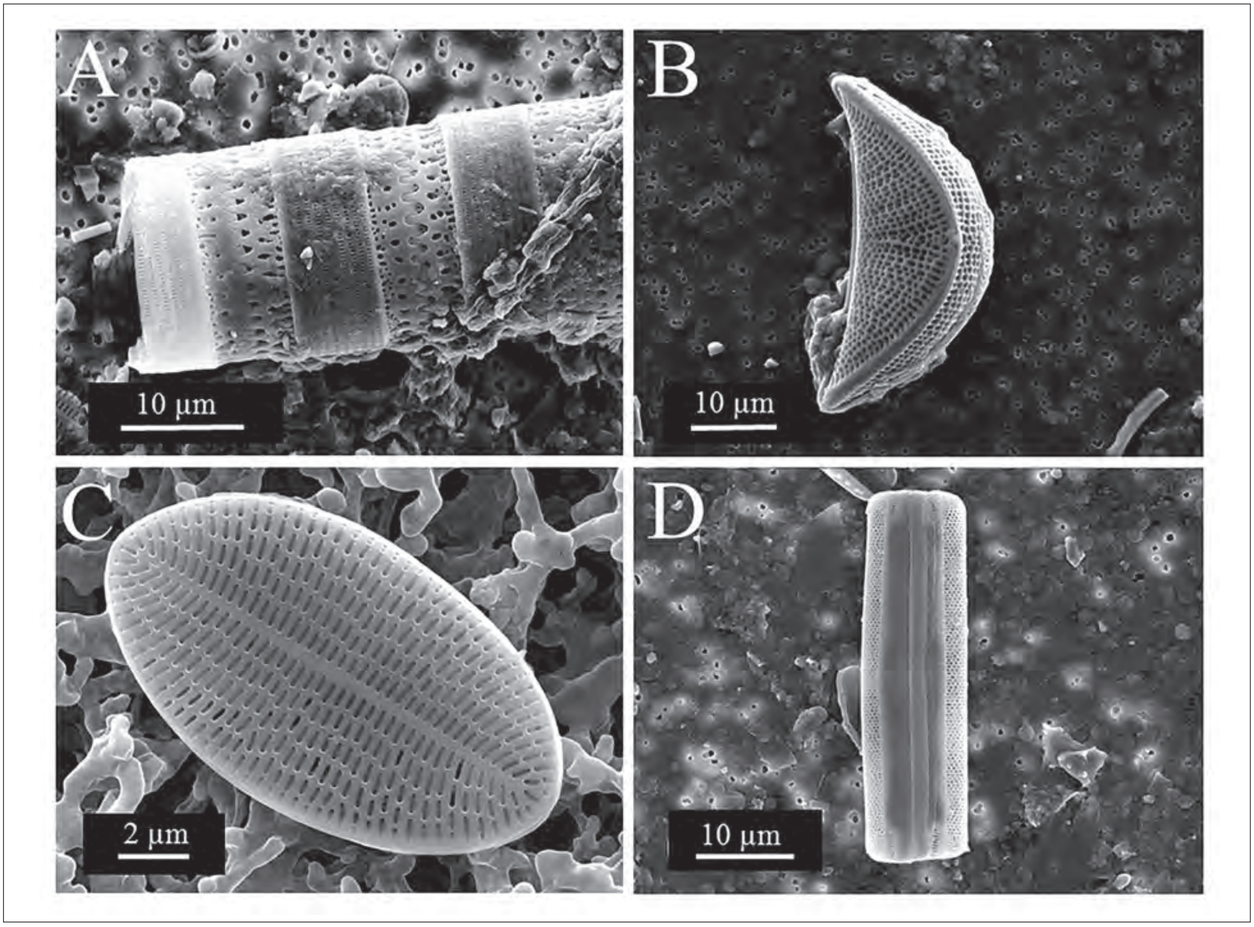

Figure 3.1.5 Diatoms.
(A) *Aulacoseira* sp.
(B) *Rhopalodia* sp.
(C) *Cocconeis* sp.
(D) *Grammatophora* sp. sampled in the Coorong.
Images were taken using Scanning Electron Microscopy. (Micrograph by S. Leterme)

30 zooplankton taxa present along the Coorong, with 18 taxa observed in the hypersaline area. The majority of these taxa included rotifers, copepods and invertebrate larvae. Seasonal and spatial variations in populations were apparent, with several species present along the length of the Coorong, while others, such as *Acartia* cf. *fancetti*, were only present in the hypersaline areas, past Parnka Point. Along the Coorong, copepod eggs and nauplii are generally extant throughout the year, although variations in abundances are apparent. However, copepodites and adults are more commonly encountered during periods of higher water levels. As emphasised by Brendonck and De Meester (2003), the structure and dynamics of the egg bank are determined by the life-history characteristics of the species (or local population), the hatching phenology of their resting stages and the characteristics of the habitat. Overlooking the egg bank as an important component of zooplankton communities may lead to erroneous interpretations in the analysis of community and population genetic structure.

Influence of river flow on plankton

Floodplains and other off-channel habitats commonly contain more diverse and abundant zooplankton communities than the river channel itself. Whilst several biotic and abiotic factors

Table 3.1.3 Average abundances (cells mL^{-1}) of the genera of phytoplankton contributing 95% of the average total cell abundance at sampling sites along the Coorong over the combined monitoring periods of DEWNR. Analysed by CSIRO (Oliver et al. 2013, 2014) and Flinders University (Microalgae Services; Jendyk et al. 2014; Leterme et al. 2015).

Group	**Genus/Species**	**Monument Road**	**Halfway**	**Sugar's Beach**	**Mundoo Channel barrage**	**Godfrey's Landing**	**Murray Mouth**	**Boundary Creek**	**Hunter's Creek**	**Ewe Island**	**Tauwit- chere**	**Pelican Point**	**Mark Point**	**Long Point**	**Noona- meena**	**Parnka Villa**	**Villa de Yumpa**	**jack Point**	**Salt Creek**
Chlorophyta	*Actinastrum*	0	0	0	127	89	5	0	0	16	10	133	16	100	667	8	0	0	0
Bacillariophyceae	*Amphora*	126	381	234	48	28	0	525	0	2	4	0	4	7	22	2	149	242	558
Chlorophyta	*Ankistrodesmus*	375	19	55	70	14	105	239	175	115	143	167	742	18	0	1	0	0	0
Cyanophyta	*Aphanizomenon*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cyanophyta	*Aphanocapsa*	484	5	0	85	0	673	0	20	376	384	0	152	0	0	0	0	0	0
Bacillariophyceae	*Aulacoseira*	34959	4551	8530	8749	0	17132	35817	20688	22298	15180	0	21544	0	0	0	0	0	0
Bacillariophyceae	*Ceratoneis/* *C. closterium*	129	0	21	155	4	77	110	98	207	174	313	57	182	325	6	0	0	0
Bacillariophyceae	cf. *Fragilaria* <15mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bacillariophyceae	*Chaetoceros*	6823	6835	2003	530	142	0	33	0	2	4	183	11	20	55	1	738	278	7692
Chlorophyta	*Chlorella*	149	261	1510	34	961	0	0	0	4	0	0	1	0	37	21	81	1067	83
Chlorophyta	*Chlorohormidium*	1124	510	414	2094	597	66	0	0	265	0	0	872	3	217	54	100	3	0
Chlorophyta	CHLOROPHYCEAE	4933	333	335	193	9	4070	1450	967	15308	442	0	227713	0	0	1612789	0	0	0
Chlorophyta	*Chodatella*	14	1	9	4367	559	0	17	0	146	179	5500	657	348	4387	242	101	0	0
Bacillariophyceae	*Cocconeis*	34	110	74	0	0	128	0	483	13	155	0	17374	0	0	36605	0	0	0
Cyanophyta	*Coelosphaerium*	166	32	18	115	232	48	0	0	632	323	117	121	70	650	12	0	0	0
Chlorophyta	*Crucigenia*	75	174	337	57	268	0	0	0	3	9	0	9	17	127	45	215	172	633
Cyanophyta	*Cyanodictyon*	1280	1887	3633	1909	0	1124	15433	10667	529	5571	0	2322	0	0	0	0	0	0
Bacillariophyceae	*Cyclotella*	883	430	284	1191	687	1575	2258	2883	1260	2968	1600	1070	970	2133	173	0	0	0
Chlorophyta	*Dictyosphaerium*	41136	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Group	**Genus/Species**	**Monument Road**	**Halfway**	**Sugar's Beach**	**Mundoo Channel barrage**	**Godfrey's Landing**	**Murray Mouth**	**Boundary Creek**	**Hunter's Creek**	**Ewe Island**	**Tauwit- chere**	**Pelican Point**	**Mark Point**	**Long Point**	**Noona- meena**	**Parnka Villa**	**Villa de Yumpa**	**jack Point**	**Salt Creek**
Chlorophyta	*Dimorphococcus*	131	323	267	225	138	11	146	167	171	170	1833	390	217	762	97	103	142	442
Dinophyta	*Gymnodinioid* <20um	111	198	79	189	74	0	0	725	165	0	0	0	1200	267	0	0	0	0
Cryptophyta	*Hemiselmis*	0	0	0	0	0	0	0	0	101	23	267	30	0	533	0	0	0	0
Dinophyta	*Heterocapsa rotundata*	554	1156	474	187	355	0	750	0	7	20	0	18	128	400	82	419	585	1042
Chlorophyta	*Kirchneriella*	158	238	231	151	705	0	0	0	15	30	433	89	247	275	173	325	202	475
Cryptophyta	*Leucocryptos*	50	57	61	21	14	0	133	0	2	0	90000	186	37	33	17	17	0	33
Cyanophyta	*Merismopedia*	0	37	0	17	76	0	0	0	104	16	0	10	0	33	17	8	0	0
Chlorophyta	*Monoraphidium*	232	587	309	174	80	0	1533	0	8	9	83	27	3	22	12	316	797	783
Bacillariophyceae	*Naviculoid*	948	1219	627	894	0	1097	14547	3933	389	1357	0	3067	0	0	0	0	0	0
Bacillariophyceae	*Nitzschia*	2	0	2	93	218	0	0	0	4	34	1400	17508	20	517	133756	13	0	0
Chlorophyta	*Oocystis*	114	201	365	129	189	10	108	0	26	61	217	95	115	832	33	273	283	867
Chlorophyta	*Pediastrum*	119	203	1156	121	1979	125	421	100	121	57	283	733	76	267	2035	225	187	767
Cryptophyta	*Plagioselmis prolonga*	371	404	284	379	96	698	1298	1445	668	916	367	455	198	217	95	0	0	0
Chlorophyta	*Planctonema*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cyanophyta	*Planktolyngbya*	41	3	0	167	11	23	0	0	94	39	53	126	200	147	67	0	0	0
Cryptophyta	*Rhodomonas lacustris*	207	587	175	265	425	0	75	0	14	17	233	36	208	498	98	336	322	408
Chlorophyta	*Scenedesmus*	1703	1008	1599	921	0	2486	5345	6217	2703	5145	0	1004	1250	0	7	0	0	0
Bacillariophyceae	*Staurosira*	53165	1269	2770	4399	0	39980	7750	9480	31241	16464	0	14089	4150	0	313	0	0	0
Cyanophyta	*Synechocystis*	0	0	0	71	0	0	0	0	0	0	0	59	0	417	0	0	0	0
Bacillariophyceae	*Tabellaria*	489	123	256	542	182	650	1458	1242	849	1144	1867	376	370	1267	147	0	0	0
Cryptophyta	*Teleaulax acuta*	463	363	310	424	0	1184	746	2778	2373	2553	0	93	1687	0	0	0	0	0
Chlorophyta	*Tetrastrum*	0	0	0	0	0	6571	0	0	7250	0	0	13111	0	0	439474	0	0	0

are significant in determining the community composition and abundance, the longer water residence time (WRT) of floodplain habitats is a major factor that determines zooplankton community structure and abundance. In addition to the higher WRTs, ephemeral off-channel sites also generally have highly abundant and species-rich egg banks (Brendonck & De Meester 2003), adding to the significance of these habitats. During times of high flow, floodplains and their conduits, such as those that adjoin the River Murray, transfer a substantial proportion of the biotic production including zooplankton (Furst et al. 2014) back to the River channel.

Due to river regulation and over-extraction, the natural flow regime within the River Murray has been significantly altered (MDBA 2015). This has led to a reduction in the frequency, extent and duration of floodplain inundation, and has thus reduced the transfer of zooplankton from floodplain to main channel habitats.

In the sampling of the CLLMM region during the period of high river flows following the drought in 2010-2011, 70% of the zooplankton taxa were recorded above the barrages in Lake Alexandrina and the Goolwa Channel (Shiel & Tan 2013b). Upper catchment (e.g. Darling River) zooplankton taxa have been recorded in the CLLMM during extended periods of high flows (see Shiel & Tan 2013b). High flows (or at least moderate increases) can also cause localised population booms in the Lower Lakes, when areas that have been dry for a period of time become inundated (Wedderburn et al. 2013). Salinity is influenced by river flows, and variations in salinity also play a role in determining the composition of zooplankton assemblages. For example, during periods of low flow, assemblages in the southern Lower Lakes are dominated by halophilic and estuarine taxa, due to the elevated salinity in such flow conditions. The Coorong estuary is now more marine-influenced since the construction of the barrages, and hence a reduction of freshwater influence (Chapters 2.7 & 2.10). As a result, the Coorong lagoons are often now hypersaline and this elevated salinity likely drives a reduction in species richness (see Shiel & Tan 2013b). Riverine zooplankton communities, including those sourced from upstream floodplains and wetlands, are transported downstream, some eventually reaching the Lower Lakes and Coorong, where they mix with the pre-existing zooplankton communities.

Diversity and abundance of the zooplankton community have been found to be highest during periods of freshwater inflow. The degree to which these freshwater communities mix, influence and persist within the Coorong is dependent upon the dynamic physico-chemistry of the ecosystem, which is driven by the interaction between freshwater discharge, weather and tidal cycles. Interestingly, freshwater zooplankton taxa have been found in the Eastern Indian Ocean, near the Murray Mouth, in times of large freshwater flows through the barrages (Shiel & Aldridge 2011). As well as modifying salinity levels, freshwater flow influences other water quality parameters, including nutrients, organic matter, pH and phytoplankton biomass and species composition. These parameters in turn play a role in determining zooplankton assemblages (Leterme et al. 2015; Hemraj et al. 2017a, b). River flow into the Coorong influences plankton trophic interactions by modifying water quality and habitat complexity (Hemraj et al. 2017b). Changes in plankton community structure (virus, bacteria, nano/picoplankton, phytoplankton and zooplankton) in relation to freshwater flow have been described by Hemraj et al. (2017b). Shifts in plankton interactions from phytoplankton-zooplankton-dominated, during higher water flow, to virus-, bacteria- and nano/picoplankton-dominated, during low water flow, have been documented along the system.

Consequences for higher trophic organisms

Plankton are a critical support for higher trophic levels, and changes in planktonic community structures and interactions are highly influential on the trophic web. In regards to the diet of fish, studies in the Murray Darling Basin (MDB) have generally considered zooplankton at a coarse (e.g. Balcombe & Humphries 2009) or moderate taxonomic scale only. Zooplankton provide a critical link within aquatic food webs through the ingestion and processing of bacteria, phytoplankton and organic material and as a food source for fish, waterbirds and macro-invertebrates (e.g. *Chaoborus*). In the Coorong, a recent study found that freshwater zooplankton, transported downstream by freshwater discharge, were subsidising the diet of sandy sprat (*Hyperlophus vittatus*), a primary prey item for larger piscivorous fishes (Bice & Zampatti 2015). Moreover, spatiotemporal variation in salinity, pH, dissolved oxygen and phytoplankton biomass has been observed to cause variations in prey diversity for smallmouth hardyhead (*Atherinosoma microstoma*), while temporal variation in prey diversity was observed for sandy sprat and Tamar River goby (*Afurcagobius tamarensis*) in the Murray Estuary and Coorong (Hossain et al. 2017). As a primary prey item for larger piscivourous fishes, increases in food resources and hence production of sandy sprat and smallmouthed hardyhead are likely to benefit the productivity of higher trophic levels throughout the Coorong.

CONCLUSIONS

Community composition of the plankton in the CLLMM is largely determined by system hydrology, primarily regulated river inflows and water level heights set by infrastructure. Sometimes the hydrological conditions directly impact the plankton communities, but often their effect is through complex influences on physical-chemical water quality conditions, including salinity, turbidity and underwater light availability. The characteristics of flow and water level in the CLLMM are controlled by water resource managers; consequently, so is the condition of the plankton communities that underpin the aquatic food webs. Recent analyses of the Lakes have suggested major shifts in community composition, particularly of phytoplankton, and these are no longer the communities that supported the Lakes during earlier periods. Similarly, in the Coorong, changes in water quality have had major impacts on the plankton, with a critical driver being the management of flows over the barrages. The plankton communities appear to be at a critical juncture, with indications that the system is moving towards a poorer-quality habitat. This sets a major challenge for water resource managers and society as the move to full system management brings with it the mantle of responsibility for its condition. Monitoring programs are critical to cataloguing the changes that are occurring, and to providing the information necessary to understand and manage change. Currently there is no comprehensive monitoring of the plankton of the CLLMM and little support for continued analyses of the historic monitoring data, a situation that will not help future decision makers.

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CHAPTER 3.2

AQUATIC AND LITTORAL VEGETATION

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INTRODUCTION

The Coorong, Lower Lakes and Murray Mouth (CLLMM) are at the terminus of the Murray-Darling system, and the junction of three of South Australia's Interim Biogeographic Regionalisation for Australia (IBRA) regions: the Western Murray-Darling Depression, Kanmantoo and Naracoorte Coastal Plain. The region contains a complex of fresh to hypersaline and temporary to permanent wetlands, and the aquatic and littoral plant communities reflect this habitat diversity.

To describe the change in vegetation, the Coorong and Murray Mouth are split into three habitats: the Murray Estuary (Goolwa Barrage to Mark Point), the North Lagoon (Mark Point to Hells Gate) and the South Lagoon (Hells Gate to Tea Tree Crossing). The Lower Lakes are split into five habitats: Lake Alexandrina, Lake Albert, Goolwa Channel (the Clayton Regulator site to Goolwa Barrage, including the lower Finniss River and lower Currency Creek), permanent freshwater wetlands and temporary wetlands.

This chapter examines the region and describes the extensive range of habitats illustrated by the presence of the functional groups proposed by Casanova (2011). It identifies the physical-chemical/hydrological characteristics that determine the distribution of aquatic and littoral plant communities and documents the composition of key plant communities. It tracks vegetation changes in response to hydrological and climatic events (either natural or anthropogenic). It considers management options in the light of scientific information and considers the long-term consequences of unsuitable or 'no action' management on the sustainability of the diversity of the region.

Vegetation characterisation

A total of 353 vascular plant and charophyte taxa (including 132 exotics and five listed as rare in South Australia) have been recorded in the CLLMM region since 1975. Due to the large number of species recorded, only key taxa and communities will be discussed in this chapter. The functional classification proposed by Casanova (2011) will be used to classify plants into three broad groups: terrestrial, amphibious and submerged.

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Terrestrial species are generally intolerant of waterlogged and inundated conditions and are split into two subgroups: 1) 'terrestrial dry' (species that are able to persist in environments with low soil moisture) 2) 'terrestrial damp' (species that require high soil moisture) (Brock & Casanova 1997; Casanova 2011). Terrestrial species typically grow above the high water mark but will colonise wetlands when water levels are drawn down (Brock & Casanova 1997). In the region, terrestrial dry species occupy the adjacent highlands around the edge of the Lower Lakes and Coorong, and terrestrial damp species exist on the edges of the Lower Lakes and associated permanent wetlands and in temporary wetlands when water levels are drawn down (Seaman 2003).

Amphibious species are adapted to wetting and drying cycles, and Casanova (2011) split this group into five subgroups based on morphology and adaptation to fluctuating water levels. 1) 'Amphibious fluctuation tolerator-emergent' species will grow in shallow water and areas that have high soil moisture but are not fully submerged. 2) 'Amphibious fluctuation tolerator-woody' are perennial woody species that tolerate partial but not full submergence (e.g. Denton & Ganf 1994). 3) 'Amphibious fluctuation tolerator-low growing' species are typically small forbs, sedges and rushes that require submergence and exposure. 4) 'Amphibious fluctuation responder-plastic' species respond anatomically to inundation and exposure. 5) 'Amphibious fluctuation responder-floating' species float on the surface, usually unattached to the sediment. Amphibious species are commonly found on the edges of permanent water bodies (in the zone that wets and dries) and in temporary wetlands (Brock & Casanova 1997; Casanova 2011). They are common around the edges of the Lower Lakes and associated wetlands and in samphire and saltmarsh habitats around the Coorong and Murray Mouth (Seaman 2003).

Submerged species represent the 'true' aquatic plants that require the presence of water to complete their life cycle (Casanova 2011). This group is divided into three subgroups depending on life history and morphology. 1) 'Submerged r-selected' species are adapted to temporary water bodies that are annually flooded to a depth of more than 10 cm and complete their life cycle whilst water is present, but can persist as dormant propagules in dry wetlands for a number of years. 2) 'Submerged-emergent' species require permanent shallow water or a permanently saturated root zone, but have emergent leaves or stems (Casanova 2011; Roberts & Marston 2011). 3) 'Submerged k-selected' taxa require permanent water, deeper than 10 cm for more than a year, to germinate and reach sufficient biomass to start reproducing (Casanova 2011; Roberts & Marston 2011). Submerged r-selected species are found in temporary wetlands around the Lower Lakes (Nicol et al. 2016a) and on seasonally inundated mudflats in the South Lagoon (Paton et al. 2015b). Submerged-emergent species are abundant around the edges of the Lower Lakes and associated permanent wetlands (Seaman 2003). Submerged k-selected taxa are typically found in Lower Lakes permanent wetlands and throughout the Goolwa Channel (Nicol et al. 2016a).

HYDROLOGICAL AND PHYSICAL-CHEMICAL FACTORS THAT INFLUENCE AQUATIC AND LITTORAL VEGETATION

The main factors that influence the composition of aquatic and littoral vegetation in the CLLMM are water regime, salinity, turbidity and wave action. The interaction of these factors and their timing differentially influences the various life stages of plants (e.g. Kim et al. 2015) and other biota and in turn the species present.

Water regime

Mitsch and Gosselink (1993) described water regime as the depth, duration, frequency and timing of inundation and exposure, and stated that it is probably the single most important determinant of biota in wetlands. Water regime determines water depth (in areas that are inundated) and soil moisture (in exposed areas) and in turn influences germination and seedling recruitment (e.g. Keddy & Ellis 1985; Nicol et al. 2003) as well as performance of existing aquatic and littoral plants (e.g. Coops et al. 1996). Therefore, water regime plays an important role in structuring the composition and zonation of aquatic and littoral vegetation as water levels rise and fall (Blanch et al. 1999), and changes to the water regime will result in changes to the vegetation.

Salinity

Salinity can affect plants directly (toxic effects of high sodium and chloride concentrations) or indirectly, by interfering with the uptake of potassium and reducing the capacity for water uptake (osmotic drought) (Ganf & Morris 2016). In addition, increased salinity can induce dormancy, render propagules inviable (Nielsen et al. 2003) or delay germination (Nicol & Ward 2010a, b). Therefore, the plant community present is determined by the salinity tolerance of plants and the effects of salinity on plant propagules.

Surface water salinity in the Lower Lakes is typically lower than 3 000 μS cm^{-1} (Chapter 2.10), which is below the reported salinity thresholds for most species present (Bailey et al. 2002). The areas that are the exception are temporary wetlands, on the eastern shoreline of Lake Alexandrina and around Lake Albert, which interact with the local shallow saline groundwater and areas in Lake Alexandrina adjacent to the barrages during periods of ‘reverse head’, when the water level is higher in the Coorong than in Lake Alexandrina, resulting in temporary seawater incursion upstream of the barrages (Chapters 2.6 & 2.10).

In contrast, salinity in the Murray Estuary and Coorong is variable and depends primarily on barrage outflows, marine incursions and evaporation. Typically, there is a salinity gradient that ranges from fresh (during periods of high barrage outflows) to marine (when the barrages are closed) in the Murray Estuary; and salinity increases with increasing distance southwards from the Murray Mouth to the hypersaline South Lagoon (Geddes & Butler 1984; Geddes 1987; Geddes & Hall 1990; Chapter 2.10).

Turbidity

Turbidity controls light availability in the underwater environment (Chapter 2.10) and in turn the maximum colonisation depth of submergent plants (Spence 1982). Turbidity is derived from three sources: suspended sediment, phytoplankton and dissolved coloured material (e.g. dissolved organic carbon) (Chapter 2.10). The Lower Lakes (due to suspended sediment) and Coorong (due to phytoplankton) are highly turbid (although the Coorong may become less turbid during periods of low barrage outflows) (Chapter 2.10). This restricts the maximum colonisation depth of submergent plants to around 1 m (Seaman 2003; Nicol et al. 2016a).

Wave action

Wave action can result in uprooting (e.g. Foote & Kadlec 1988) or physical damage (e.g. Coops & Van der Velde 1996) to plants (particularly seedlings and juveniles) growing around the shorelines of water bodies. Furthermore, wave action can result in the suspension of fine sediment, increasing turbidity (e.g. Scott & Olley 2003).

The lee (northern and eastern) shorelines of the Lower Lakes are high-energy shorelines subjected to significant wave action (PIRSA Spatial Information Services 2009). The vegetation on these shorelines is typically sparse and, when present, dominated by robust emergent species such as common reed (*Phragmites australis*) (Jellinek et al. 2016; Nicol et al. 2016b).

AQUATIC AND LITTORAL PLANT COMMUNITIES

Submergent freshwater plant communities

Submergent freshwater (surface water conductivity <5 000 µS cm^{-1}) plants were historically abundant in areas protected from wave action in the Lower Lakes (Renfrey et al. 1989; Holt et al. 2005; Nicol et al. 2006). Between 2007 and 2010, submergent vegetation was lost from the system due to low water levels (except in Goolwa Channel after August 2009 due to the Clayton regulator), but some of these species have returned to areas they historically occupied (albeit in reduced abundance) since August 2010 (Nicol et al. 2016a). The submergent plant taxa recorded in the Lakes since 2010 are water milfoil (*Myriophyllum salsugineum*), coarse water milfoil (*Myriophyllum caput-medusae*), curly pondweed (*Potamogeton crispus*) (Fig. 3.2.1), sago pondweed (*Potamogeton pectinatus*), widgeon grass (*Ruppia polycarpa*) (Fig. 3.2.2), tuberous sea tassel (*Ruppia tuberosa*), large fruit sea tassel (*Ruppia megacarpa*), hornwort (*Ceratophyllum demersum*) (Fig. 3.2.3), ribbon weed (*Vallisneria australis*) (Fig. 3.2.4), stoneworts (*Chara* spp.) and fox tail stonewort (*Lamprothamnium macropogon*). Water mat (*Lepilaena cylindrocarpa*), Austral water mat (*Lepilaena australis*), amphibious water milfoil (*Myriophyllum simulans*) and thread-leaf crowfoot (*Ranunculus trichophyllus*) were historically recorded in the Lakes (Renfrey et al. 1989; Holt et al. 2005; Nicol et al. 2006), but have not been recorded since 2007 (Nicol et al. 2017).

The main factors that influence the distribution and abundance of submergent plants in the Lower Lakes are water regime, turbidity, salinity and wave action. Submergent plants generally do not colonise areas below sea level, except in Goolwa Channel, where plants often grow in areas as low as -0.5 to -1 m AHD (Australian Height Datum, equivalent to metres above mean sea level) (Nicol et al. 2016a). The impact of salinity is less well understood. Species that were reported to have low salinity tolerances (e.g. ribbon weed and hornwort) (Bailey et al. 2002) colonised and persisted in Goolwa Channel between August 2009 and August 2010 when salinities exceeded 30 000 µS cm^{-1} at times (Gehrig et al. 2011a).

There is very little information regarding the impact of other physical-chemical factors on the distribution and abundance of submergent plants in the Lakes. The Lower Lakes are turbid water bodies and light availability will prevent submergent species from colonising deep-water habitats (>1.5 m deep) (*sensu* Spence 1982). Furthermore, all deep-water habitats (with the exception of those in Goolwa Channel) are in open water areas of Lakes Alexandrina and Albert and are often subjected to wave action.

Figure 3.2.1 Curly pondweed (*Potamogeton crispus*) near Wally's Landing in the lower Finniss River. (Photograph by Jason Nicol)

Figure 3.2.2 Widgeon grass (*Ruppia polycarpa*) in Point Sturt Wetland, Lake Alexandrina. (Photograph by Jason Nicol)

Figure 3.2.3 Hornwort (*Ceratophyllum demersum*) in Lake Alexandrina near Raukkan. (Photograph by Susan Gehrig)

Figure 3.2.4 Ribbon weed (*Vallisneria australis*) in Lake Alexandrina at Wellington Lodge. (Photograph by Susan Gehrig)

Emergent freshwater plant communities

In the Lower Lakes, extensive stands of emergent macrophytes are present around the shorelines throughout the system. Stands are often monospecific common reed or cumbungi (*Typha domingensis*); however, in some areas there is distinctive zonation of tangled lignum (*Duma florulenta*) and common reed (at the top of the elevation gradient), cumbungi (middle elevations) and river clubrush (*Schoenoplectus tabernaemontani*) (low elevation), or there is a diverse assemblage of submerged-emergent, amphibious and submerged k-selected species (diverse red beds) (Frahn et al. 2014; Nicol et al. 2016b).

Emergent plants tend to occupy elevations between +0.9 m AHD and sea level; hence, water levels need to be maintained at a minimum of +0.2 m AHD, preferably +0.4 m AHD, to maintain hydrological connection with the Lakes and ensure that there is sufficient water for plants growing at higher elevations. Between 2007 and 2010, when water levels were low, most emergent plants persisted, but they did not recruit further down the elevation gradient and were hydrologically disconnected from the Lakes (Gehrig et al. 2012). Therefore, these did not provide the same function (e.g. aquatic habitat) as emergent vegetation that is hydrologically connected. The effect of salinity is less well understood. For example, species that were reported to have low salinity tolerances (e.g. cumbungi and river clubrush) (Bailey et al. 2002) persisted in Goolwa Channel between August 2009 and August 2010 when surface water salinity exceeded 30 000 µS cm^{-1} at times (Gehrig et al. 2011a). Nevertheless, while salinities were elevated, no recruitment from seed was observed, and abundances were lower compared with abundances after water levels were reinstated and salinity reduced (Frahn et al. 2014).

Cumbungi

Cumbungi can form extensive monospecific stands around the shorelines of Lakes Alexandrina and Albert (Fig. 3.2.5) (Seaman 2003; Nicol et al. 2014). This species generally colonises areas between +0.8 and 0 m AHD but will grow in deeper water (around -0.2 m AHD) in areas that are protected from wave action (e.g. the lower Finniss River, Clayton Bay, Dunns Lagoon) (Gehrig et al. 2012). Cumbungi is probably more susceptible to wave action than common reed, as it rarely forms large stands in areas with high wave action (Nicol et al. 2014).

Cumbungi reproduces both sexually and asexually (Sainty & Jacobs 1981; Finlayson et al. 1983; Romanowski 1998; Sainty & Jacobs 2003). Plants produce large numbers of seeds (>250 000 in a single inflorescence) that are dispersed long distances by the wind (Finlayson et al. 1983) and are present in the soil seed bank (Nicol & Ward 2010a, b). Seeds germinate on wet soil and when inundated to at least 70 cm (Nicol & Ganf 2000). In addition, cumbungi forms an extensive rhizome network and, once established, can rapidly colonise areas excluding other species (Finlayson et al. 1983). Bailey et al. (2002) reported that cumbungi died when exposed to surface water conductivity of 8 000 µS cm^{-1}; however, Gehrig et al. (2011a) observed healthy plants growing in areas where the surface water salinity exceeded 30 000 µS cm^{-1} in Goolwa Channel.

Common reed

Similar to cumbungi, common reed also often forms dense monospecific stands around the edges of Lakes Alexandrina and Albert (Fig. 3.2.6) (Seaman 2003; Nicol et al. 2014). Plants tend to

Figure 3.2.5 Cumbungi (*Typha domingensis*) plants recently sprouted from rhizomes after water levels were reinstated in Clayton Bay, Lake Alexandrina. (Photograph of Jason Nicol by Rod Ward)

Figure 3.2.6 Dense monospecific stand of common reed (*Phragmites australis*) at Narrung Narrows. (Photograph by Jason Nicol)

occupy higher elevations (+09 to +0.4 m AHD), but will colonise deeper water (0 m AHD or deeper), especially in areas with steep banks that are protected from wave action (e.g. the lower Finniss River) (Frahn et al. 2014). On exposed shorelines, common reed is restricted to the upper elevations (Gehrig et al. 2011a) and important for controlling shoreline erosion (*sensu* Hocking et al. 1983). However, common reed can be invasive and can both prevent other species from establishing and restrict water flow in drains and channels (Hocking et al. 1983).

The primary mode of reproduction in the Lower Lakes is by rhizomes (asexual). Viable seeds have not been detected in the seed bank (Nicol & Ward 2010a, b); however, a small number of seedlings were observed in Lake Albert when water levels were drawn down (J. Nicol *pers. obs.*). Bailey et al. (2002) reported that common reed died at a salinity of >15 g L^{-1} total dissolved solids (TDS); however, Gehrig et al. (2011a) observed healthy plants growing in areas where the surface water salinity exceeded 22 g L^{-1} (>30 000 µS cm^{-1}) in Goolwa Channel. Common reed is a good competitor and able to rapidly colonise large areas, with clonal reproduction outcompeting other species, but it is susceptible to grazing and trampling by domestic stock. Common reed prefers high soil moisture when not inundated, but will persist for short periods when subjected to low soil moisture, and will senesce to rhizomes when subjected to extended desiccation (Hocking et al. 1983).

Tangled lignum

Tangled lignum forms large stands around the edges of Lakes Alexandrina and Albert at high elevations (>+1 to +0.8 m AHD) (Fig. 3.2.7) (Frahn et al. 2014), and because of this is generally not affected by wave action (Seaman 2003; Nicol et al. 2014). Plants are intolerant of long-term inundation but will tolerate short-term inundation, extended water logging and desiccation (Roberts & Marston 2011).

Tangled lignum reproduces sexually and asexually by fragmentation and layering, but does not form a long-lived soil seed bank (Chong & Walker 2005). Bailey et al. (2002) reported the maximum salinity tolerance of this species as 4.4 g L^{-1}; however, it persisted in Goolwa Channel whilst the Clayton regulator was in operation and surface water salinities exceeded its reported maximum salinity tolerance (Gehrig et al. 2011a).

Diverse reed beds

Diverse reed beds are characterised by a mixed assemblage of submerged-emergent, amphibious and submerged k-selected species (Fig. 3.2.8). Typically, diverse reed beds have >5% cover of native amphibious species and native emergent species (other than cumbungi and common reed) between +0.8 and +0.6 m AHD, and >5% cover of native submergent species and emergent species (other than cumbungi and common reed) between 0 and +0.6 m AHD. Taxa present include common reed, cumbungi, river clubrush, tangled lignum, sharp clubrush (*Schoenoplectus pungens*), sea rush (*Bolboschoenus caldwellii*), common rush (*Juncus usitatus*), water parsnip (*Berula erecta*), greater bindweed (*Calystegia sepium*), common spike rush (*Eleocharis acuta*), water fern (Azolla spp.), duckweed (*Lemna* spp., *Wolffia* spp., *Spirodela* spp.), water ribbons (*Triglochin procera*), mud dock (*Rumex bidens*), Australian gypsywort (*Lycopus australis*), water primrose (*Ludwigia peploides*), shield pennywort (*Hydrocotyle verticillata*), centella (*Centella

Figure 3.2.7 Tangled lignum (*Duma florulenta*) (background) with cumbungi (*Typha domingensis*) (foreground) in the lower Finniss River near Stirling Downs. (Photograph by Jason Nicol)

Figure 3.2.8 A diverse reed bed containing cumbungi (*Typha domingensis*), common reed (*Phragmites australis*), river clubrush (*Schoenoplectus tabernaemontani*), sea rush (*Juncus kraussii*), water primrose (*Ludwigia peploides*), common spike rush (*Schoenoplectus pungens*) and hornwort (*Ceratophyllum demersum*) in Lake Alexandrina near Raukkan. (Photograph by Regina Durbridge)

asiatica), sea clubrush (*Bolboschoenus caldwellii*), spiny sedge (*Cyperus gymnocaulos*), slender knotweed (*Persicaria lapathifolia*), water milfoil, ribbon weed and hornwort (Nicol et al. 2016a, b). Diverse reed beds are found at similar elevations to cumbungi and common reed monocultures (+0.9 to 0 m AHD), but generally in areas protected from wave action with gentle sloping shorelines, and often develop along shorelines where river clubrush has been planted to control erosion (Nicol et al. 2016b). It is unclear why the diversity in these areas is higher, because there are protected areas with gentle sloping shorelines with cumbungi and common reed monocultures (Nicol et al. 2014).

Species that characterise diverse reed beds require shallow inundation or high soil moisture (Sainty & Jacobs 1981, 2003; Romanowski 1998; Roberts & Marston 2011) and are restricted to areas with low salinity that are protected from wave action (Nicol et al. 2014). Most species present reproduce sexually and asexually (Sainty & Jacobs 1981, 2003; Romanowski 1998), and form a desiccation-resistant seed bank (Nicol & Ward 2010a, b).

Samphire and saltmarsh communities

Samphire and saltmarsh communities are widespread throughout the region in areas where there is moderate to high salinity (Seaman 2003). Most samphire and saltmarsh species have higher growth rates when grown at low salinities, but are out-competed by species such as cumbungi or common reed, and are therefore restricted to areas with high salinity in nature (Ungar 1991). Common taxa include samphire (*Sarcocornia* spp., *Tecticornia* spp.), seablite (*Suaeda australis*), streaked arrow-grass (*Triglochin striatum*), sea rush, sharp clubrush, round-leaf wilsonia (*Wilsonia rotundifolia*) and creeping brook-weed (*Samolus repens*) (Fig. 3.2.9) (Frahn et al. 2014). Species

Figure 3.2.9 A salt-tolerant plant community of predominantly seablite (*Suaeda australis*) and samphire (*Sarcocornia* sp.) at the mouth of Hunters Creek on Hindmarsh Island. (Photograph by Jason Nicol)

are generally intolerant of long-term inundation but grow well in waterlogged soil (Sainty & Jacobs 1981, 2003; Romanowski 1998); hence, they are typically restricted to areas above +0.7 m AHD in the Lower Lakes and above +0.2 m AHD in the Coorong and Murray Estuary. However, if water levels fall below +0.4 m AHD in the Lower Lakes and +0.1 m AHD in the Coorong, samphire and saltmarsh communities become disconnected from open water habitats, and this can result in a decline in recruitment and poor condition of existing plants (Chapter 3.3).

Reproduction of samphire and saltmarsh plants is primarily by seed (except sea rush and sharp clubrush, which also reproduce asexually with rhizomes), and all species form a soil seed bank (Nicol & Ward 2010b). Germination occurs on wet soil; however, some species (e.g. sea rush) require salinities lower than they are able to tolerate as adults to germinate and survive while juveniles (Greenwood & MacFarlane 2006; Naidoo & Kift 2006). Little is known about their dispersal; however, it is likely that they are dispersed by water and animals. The seeds of the black seed samphire (*Sarcocornia quinqueflora*) are an important component of the diet of the orange bellied parrot (*Neophema chrysogaster*), a species which has been listed as Critically Endangered under the *Environment Protection and Biodiversity Conservation Act 1999* (the 'EPBC Act') (Mondon et al. 2009).

Swamp paperbark woodlands

Swamp paperbark is the dominant tree in the region, forming small areas of closed woodlands downstream of Point Sturt in Lake Alexandrina, the southern shoreline of Lake Albert and the edges of saline wetlands around the Coorong (Fig. 3.2.10) (Seaman 2003; Marsland & Nicol

Figure 3.2.10 Swamp paperbark (*Melaleuca halmaturorum*) woodland at Kennedy Bay, Lake Albert. (Photograph by Jason Nicol)

2009). Swamp paperbark is intolerant of medium-term flooding (particularly as juveniles) (Denton & Ganf 1994), and is restricted to areas above +0.8 m AHD upstream of the barrages and +0.2 m AHD downstream of the barrages.

Reproduction is by seed, which germinates on exposed soil with high moisture content and will lose viability when inundated for longer than four weeks (Nicol & Ganf 2000). This species does not form a soil seed bank, but holds the seed in the canopy (an aerial seed bank or serotiny) (Rayamajhi et al. 2002). Swamp paperbark are highly salt-tolerant (Holliday 2004), but it is not known whether lower salinity is required for germination and juvenile survivorship.

Large-fruit sea tassel submergent herblands

In the 1980s large-fruit sea tassel was the dominant submergent macrophyte in the North Lagoon and Murray Estuary (Geddes & Butler 1984; Geddes 1987; Geddes & Hall 1990). Abundance declined throughout the 1990s and distribution was restricted to the Murray Estuary by 1995 (Edyvane et al. 1996). By 2002 it had become locally extinct downstream of the barrages due to elevated salinity (Chapter 2.10), although a viable sediment seed bank was still present (Paton 2002). Small barrage releases in 2003 (Geddes 2005a) and 2004 (Geddes 2005b) did not result in recruitment and no seed bank was detected in 2007 (Nicol 2007).

Large-fruit sea tassel reproduces sexually and asexually (rhizomes) and will develop a desiccation-resistant seed bank (Nicol & Ward 2010a, b). The longevity of seed in the seed bank under different conditions is unknown. Large-fruit sea tassel plants are intolerant of desiccation, and exposure of five hours will result in mortality (Adams & Bate 1994). The maximum salinity tolerance of large-fruit sea tassel is 46 g L^{-1}; however, plants did not flower and seeds did not germinate in water with salinity over 35 g L^{-1} (Brock 1979, 1982b, 1983).

Tuberous sea tassel saline submergent herblands

Tuberous sea tassel is one of the most salt-tolerant plants in the world, with a maximum reported salinity tolerance for adult plants of 230 g L^{-1} (Brock 1982a). It is an annual or short-lived perennial, well adapted to temporary water bodies with a persistent sediment seed bank (Brock 1979, 1982b). Seeds germinate rapidly once sediment is inundated (Porter 2007), and under favourable conditions will reproduce asexually by rhizomes, rapidly colonising large areas (Brock 1982b). Tuberous sea tassel also produces turions, desiccation-resistant asexual propagules that persist in the sediment during dry periods (Brock 1982b).

Tuberous sea tassel plants require salinity lower than 85 g L^{-1} for germination from seed and <125 g L^{-1} to sprout from turions (Kim et al. 2013). In the South Lagoon, seeds germinate in late autumn/early winter as water levels rise and inundate mudflats. Water levels need to be maintained at above +0.2 m AHD until plants are able to produce seed and replenish the seed bank (Paton et al. 2015b). Therefore, salinity in the South Lagoon needs to be below 85 g L^{-1} in late autumn to early winter to provide conditions suitable for germination, and needs to remain below the threshold for flowering and seed set, in order to ensure that the seed bank is replenished. This requires barrage flows to be maintained into early summer to ensure that water levels and salinity remain at suitable levels to enable reproduction to prevent depletion of the propagule bank (Paton et al. 2015b). However, if the salinity in the South Lagoon falls below 80 g L^{-1} towards the end of the growing season, tuberous sea tassel may be smothered by filamentous green algae (*Ulva paradoxa*) (Paton et al. 2017).

THE RESPONSE OF VEGETATION TO CLIMATIC AND HYDROLOGICAL CHANGES

The change in vegetation through time in the region is linked to changes in water regime and salinity (see Chapters 1.2, 2.4, 2.6, 2.7 & 2.10). Quantitative vegetation data from the Coorong date back to the mid-1970s, and from the Lower Lakes to the late 1980s. Information prior to these dates is primarily for the Lower Lakes from historical accounts and oral histories collated by Sim and Muller (2004).

Lower Lakes

Between European settlement and the late 1890s, accounts state that Lakes Alexandrina and Albert were surrounded by dense beds of 'reeds' (probably common reed and cumbungi) growing to 8 feet (2.4 m) tall, and half a mile (800 m) wide in places. In addition, 'fresh waterweed' (probably freshwater submergent species) grew for a mile (1.6 km) out into the Lake in places. As upstream abstraction for irrigation increased, sea water pushed further into the Lakes. Reeds were dying at Point Sturt by 1904, by 1906 at Poltalloch, and by 1933 at Nalpa Station and Wellington Lodge (Chapter 2.4) (Sim & Muller 2004).

The completion of the barrages in 1940 returned the Lower Lakes to a freshwater ecosystem, but data regarding the aquatic and littoral vegetation of the Lower Lakes between 1940 and 1989 are absent. Nevertheless, reed beds up to half a mile (800 m) wide and aquatic plants growing up to a mile (1.6 km) offshore have not been reported since the late 1890s (Sim & Muller 2004). The barrages resulted in relatively stable water levels for the Lower Lakes (Chapter 2.7), which have probably changed their bathymetry. Shoreline erosion, which would probably have been extensive shortly after barrage construction due to the absence of the once extensive shoreline reed beds, has resulted in almost vertical shorelines in places (notably the northern and eastern shorelines) (Chapter 2.1), and this does not favour colonisation of littoral vegetation.

The earliest quantitative aquatic and littoral vegetation data collected from the Lower Lakes were a snapshot of the aquatic vegetation of Hindmarsh Island in February 1989 (Renfrey et al. 1989). Transects on the northern shoreline of the Island showed zonation of the plant community, with tangled lignum and common reed the dominant species at high elevations, although there were also areas of amphibious herblands. Intermediate elevations were dominated by cumbungi, river clubrush, water ribbons and submergent species, with the lowest elevations containing only submerged taxa (Renfrey et al. 1989).

Very little information was collected between 1989 and 2004, i.e. a one-off survey of Murray Mouth Reserves in March 2002 (Brandle et al. 2002) and habitat mapping (Seaman 2003). The above studies indicated that in areas where the water depth exceeded 1 m, plants were generally absent (Seaman 2003). The areas with the greatest abundances of submerged and amphibious species were wetlands and sheltered areas along the western shoreline of Lake Alexandrina; the northern shoreline of Hindmarsh Island, Goolwa Channel and the lower

Finniss River; and lower Currency Creek (Brandle et al. 2002; Seaman 2003). The plant communities present in wetlands along the eastern shoreline of Lake Alexandrina and around the edges of Lake Albert suggested that salinity plays a role in structuring the community with samphire, saltmarsh plants and submergent halophytes — the dominant species in this area of the Lower Lakes. The shores of Lakes Alexandrina and Albert were dominated by common reed and cumbungi, with limited areas of diverse reed beds on sheltered shorelines (Seaman 2003).

In spring 2004 (Holt et al. 2005) and spring 2005 (Nicol et al. 2006) vegetation surveys in selected wetlands were undertaken. Data from these surveys showed that the wetland plant communities were similar to the broad-scale habitats mapped by Seaman (2003). However, these surveys provided more detailed information at the site scale. For example, extensive beds of ribbon weed were present at Milang Shores, Dunns Lagoon and Clayton Bay and in the channels on Hindmarsh Island (Holt et al. 2005); and milfoil was abundant near the Hindmarsh Island bridge, in Clayton Bay, Dunns Lagoon (Holt et al. 2005) and Hunters Creek (Nicol et al. 2006). Wetlands along the eastern shoreline of Lake Alexandrina and around the edges of Lake Albert (Poltalloch, Narrung, Teringie and Waltowa) were typically fringed by samphire and saltmarsh plants, with limited common reed and cumbungi stands in areas adjacent to the Lakes (Holt et al. 2005; Nicol et al. 2006). The inundated areas of these wetlands were dominated by submergent halophytes such as fox tail stonewort, water mat, tuberous sea tassel and widgeon grass (Holt et al. 2005; Nicol et al. 2006).

Regular monitoring of plant communities in the Lower Lakes (wetlands and shorelines) as part of The Living Murray condition monitoring program commenced in spring 2008 (Marsland & Nicol 2009; Gehrig et al. 2010, 2011b, 2012; Frahn et al. 2013, 2014; Nicol et al. 2016a, 2017) and continues to this day.

From 2007 to 2010 the water level in the Lower Lakes fell to unprecedented low levels (Chapter 2.6). During this period several engineering interventions were undertaken, primarily the construction of the Narrung bund and Clayton regulator (Chapters 2.7 & 4.3), in an attempt to mitigate acid sulfate soils (Chapter 2.9). Whilst in operation these structures (in conjunction with pumping) enabled water levels in Lake Albert and Goolwa Channel to be managed independently of Lake Alexandrina, which was reflected in their water levels (Chapter 2.7). Construction of the Narrung bund was completed in early 2008 and disconnected Lake Albert from Lake Alexandrina. Water was then pumped from Lake Alexandrina into Lake Albert to maintain water levels above -0.5 m AHD. Construction of the Clayton regulator was finished in August 2009 and water impounded from Finniss River, and Currency and Tookayerta Creeks. In addition, water was pumped from Lake Alexandrina to raise water levels to +0.7 m AHD in spring 2009 (Chapter 2.7). Water level in Lake Alexandrina was dependent on inflows from the River Murray and remained below sea level from 2007 to spring 2010 (Chapter 2.7).

Salinity was also influenced by the regulators during this period; surface water electrical conductivity (EC) in Lake Alexandrina remained below 7 000 µS cm^{-1} (Chapter 2.10). However, in Lake Albert electrical conductivity reached 20 000 µS cm^{-1} in February 2010 and 33 000 µS cm^{-1} in March 2010 (Chapter 2.10).

The low water levels resulted in drying of fringing habitats (wetlands and shorelines), where aquatic plant diversity was highest. Drying of these habitats resulted in the complete loss of submergent species (Gehrig et al. 2011a, b); however, a viable seed bank was present in Dunns and Shadows Lagoons (Nicol & Ward 2010a) and Goolwa Channel (Nicol & Ward 2010b). It should be noted that viable seed banks of submergent taxa were probably present throughout wetlands and fringing habitats in the Lower Lakes, but assessments were only undertaken in Dunns and Shadows Lagoons.

The extensive common reed stands, tangled lignum and samphire shrublands that were present around the edges of Lakes Alexandrina and Albert prior to 2007 were still present, and in some areas expanded their distribution down the elevation gradient to colonise areas of dry lake bed (Marsland & Nicol 2009). Cumbungi and river clubrush stands that had live plants present showed reduced extent and appeared to be in poor condition. Stands of emergent and amphibious species persisted, and were not inundated and disconnected from the Lakes (Marsland & Nicol 2009).

The construction of the Narrung bund enabled water levels to be raised in Lake Albert, but there was insufficient water to inundate fringing habitats (Chapter 2.7). In contrast, the Clayton regulator enabled water levels in Goolwa Channel to be raised sufficiently to inundate fringing habitats (Chapter 2.7). It was expected that the increased salinity in Goolwa Channel (Chapter 2.10) would result in significant mortality of fringing vegetation (Bailey et al. 2002); however, this did not occur and there was a noticeable improvement in the condition of the fringing vegetation during this period (Gehrig et al. 2011a). Submergent species also recruited in Goolwa Channel; however, the submergent vegetation was dominated by dense beds of sago pondweed (Gehrig et al. 2011a). Dense monocultures of this species occupied 1 491 ha of Goolwa Channel, with sparse sago pondweed submerged herblands occupying a further 100 ha, and mixed sago pondweed/milfoil submerged herblands occupying 572 ha (Gehrig et al. 2011a). The combined area of the above submergent plant communities covered 53% of the area of Goolwa Channel (Gehrig et al. 2011a).

Increased inflows to the Lakes and breaching of the Clayton regulator and Narrung bund in spring 2010 resulted in reconnection throughout the Lower Lakes and reinstatement of historical water levels (Chapter 2.7). Flows over Lock 1 have been sufficient to maintain water levels between +0.4 and +1 m AHD in the Lakes since spring 2010 (Chapter 2.7) and reduce surface water EC in Lake Alexandrina and Goolwa Channel to below 1 000 $\mu S\ cm^{-1}$ and Lake Albert below 2 000 $\mu S\ cm^{-1}$ (Chapter 2.10).

The inflow of fresh turbid water into Goolwa Channel resulted in the extirpation of much of the submergent vegetation that recruited after the Clayton regulator was constructed (Gehrig et al. 2011a); however, this was slowly replaced with more diverse submergent vegetation consisting of sago pondweed, milfoil, hornwort, curly pondweed and ribbon weed. Since the Clayton regulator was breached there have also been increasing trends in the abundance of amphibious and emergent species and a decline in exotic terrestrial taxa (Nicol et al. 2017).

Reinstatement of water levels in Lakes Alexandrina and Albert has also resulted in an improvement in vegetation condition. Emergent and amphibious species have increased in abundance on the shorelines of both Lakes and in fringing wetlands. Submergent species are uncommon in Lake Albert but there have been increases in the abundance of submergents in Lake Alexandrina and wetland habitats (Nicol et al. 2017).

Coorong and Murray estuary

There is information regarding the distribution and abundance of large-fruit sea tassel and tuberous sea tassel from the Coorong and Murray estuary from the mid-1970s (Nicol 2005). Geddes and Brock (1977) reported that sea tassel was the most common angiosperm growing in the Coorong and adjacent seasonal lakes. Specimens were found growing in waters of varying depth and salinity, and the growth form appeared to be taller and more robust in the deeper, less saline areas (the North Lagoon and Murray Estuary) and smaller and more delicate in the shallower, more saline areas (South Lagoon) (Geddes & Brock 1977). It was later determined that these different forms were different species, the smaller, more delicate form being the tuberous sea tassel and the larger, more robust form the large-fruit sea tassel (Jacobs & Brock 1982).

Large-fruit sea tassel

Geddes and Butler (1984) reported that large-fruit sea tassel was the dominant macrophyte in the North Lagoon from December 1981 to March 1983, and it was widely distributed in water <1 m deep. During this period the River Murray catchment was in drought and there was no outflow from the barrages. This resulted in a longitudinal salinity gradient in the North Lagoon, with the lowest salinity closest to the Murray Mouth and the highest at the southern end of the lagoon. Salinities ranged from 20-50‰ TDS in December 1981 and 40-80‰ TDS in January 1983 and showed a seasonal pattern, rising in the summer of 1981-1982, falling during May to July 1982, and rising in October 1982 to peak in January 1983 (Geddes & Butler 1984).

From March 1983 to March 1985 there was considerable discharge from the barrages, and the salinity in the North Lagoon changed dramatically during this time (Geddes 1987). Large-fruit sea tassel was the dominant macrophyte in the North Lagoon with vigorous, extensive beds flowering profusely and occupying the length of the lagoon until June 1984, after which they died back. They became extensive and vigorous again by December 1984 but no flowering was observed. The expansion and die-back corresponded with falling and rising salinity in the Coorong, and flowering also corresponded with a fall in salinity (Geddes 1987).

No investigations regarding the distribution and abundance of large-fruit sea-tassel were undertaken until August 1995, when a survey of the Murray Estuary was conducted. Extensive beds were reported from south of Long Point in the North Lagoon to Goolwa Barrage (Edyvane et al. 1996). These observations were the last reported occurrence of extant large-fruit sea tassel in the Coorong and Murray Estuary. Geddes (2005a, b) monitored the response of the biota in the Murray Estuary to controlled barrage releases in spring 2003 and autumn 2004 and reported an absence of large-fruit sea tassel from the system. Despite the absence of plants in the Coorong and Murray estuary, a seed bank was present until at least January 2001, with seed densities ranging from 100 to 2 000 seeds m^{-2} at the southern end of the North Lagoon (Paton 2001). However, Nicol (2007) found no large-fruit sea tassel plants and only one viable seed in ~1 300 sediment samples in the North Lagoon and Murray Estuary in spring 2006.

Tuberous sea tassel

Tuberous sea tassel was historically abundant throughout the South Lagoon, forming extensive submergent herblands in water depths ranging from 0.3 to 0.9 m (Womersley 1975; Paton

1982, 1996; Paton et al. 2015a, b). However, distribution and abundance were spatially and temporally variable. In July 1984, only small specimens were observed in restricted areas, but by September extensive beds were observed throughout the South Lagoon. In December that year the shallow areas of the northern and middle sections of the South Lagoon were fringed with extensive beds of flowering plants. By April 1985 mature tuberous sea tassel was only present in the northern half of the South Lagoon (Geddes 1987).

Tuberous sea tassel remained abundant throughout the South Lagoon during the late 1980s and 1990s (Paton 1996, 2000; Paton & Bolton 2001). However, since 2002 the abundance and extent of tuberous sea tassel have declined, and by 2008 plants were absent from the South Lagoon and the seed bank was depauperate compared to historical levels (Paton et al. 2015a, b). This coincided with a period of low barrage outflows that resulted in high salinities and water levels falling in mid-spring in the South Lagoon (Ye et al. 2016), exposing mudflats before plants had flowered and replenished the seed bank. During this period tuberous sea tassel established in the middle of the North Lagoon and by July 2010 extensive beds were present (Paton et al. 2015a). Barrage outflows increased in spring 2010, reducing salinity; however, water levels in the South Lagoon had fallen before outflows commenced and no improvement was observed in the South Lagoon. Furthermore, the lower salinity resulted in the loss of beds from the North Lagoon (Paton et al. 2015a, b). Recovery of tuberous sea tassel in the South Lagoon has remained slow due to the depauperate seed bank, but an increase in abundance and extent was observed between 2012 and 2014, then a decrease in 2015, followed by an increase in 2016 (Paton et al. 2017). However, the increase in extent and abundance in 2016 did not result in an improvement in the seed bank, due to reproductive failure caused by smothering of flower heads with filamentous green algae (*Ulva paradoxa*) (Paton et al. 2017).

MANAGEMENT

At the terminus of the River Murray management options for the vegetation of the Lower Lakes and Coorong are limited. Nevertheless, doing nothing or adopting a business-as-usual approach after the breaking of the Millennium Drought is not an option, as it will likely result in further degradation of the system (e.g. Lester et al. 2013). Evidence gained from recent monitoring and investigations showed that the persistence (and potential improvement) of a diverse and functional plant community are reliant on the delivery of sufficient water to the system. Other management actions to control shoreline erosion in the Lower Lakes and improve the seed bank of tuberous sea tassel in the South Lagoon have been undertaken, with varying degrees of success, but these will fail unless sufficient water is delivered to the system.

Basin Plan and water allocation

To maintain diverse aquatic and littoral plant communities in the Lower Lakes, water level fluctuations are required to provide opportunities for amphibious species to recruit in the littoral zone but provide permanent shallow water environments for submergent species. Hence, the ideal hydrological regime for the Lower Lakes has water levels in spring and early summer of +0.7-+0.8 m AHD (or higher in some years to provide opportunities for lignum and swamp paperbark recruitment), falling to no lower than +0.4 m AHD in autumn. In the Coorong and Murray Estuary, barrage outflows that will result in salinity below 35 g L^{-1} in the

North Lagoon and Murray Estuary and provide water levels above +0.2 m AHD in the South Lagoon until mid-December are required for the recruitment and persistence of large-fruit sea tassel (North Lagoon and Murray Estuary) and tuberous sea tassel (South Lagoon).

The recovery of 2 750 GL of water for the environment under the Murray-Darling Basin Plan will result in water levels in the Lower Lakes being maintained (Chapter 2.7). However, it is unlikely that this volume (in the absence of natural flows) will provide sufficient water to lower salinity in the North Lagoon to enable large-fruit sea tassel recruitment (Brock 1982a, 1982b), or maintain water levels and salinities in the South Lagoon to enable tuberous sea tassel to complete its life cycle (Webster 2007; Kim et al. 2015; Paton et al. 2017).

River clubrush planting

The relatively stable water levels in the Lower Lakes brought about by barrage construction have resulted in significant shoreline erosion (PIRSA Spatial Information Services 2009). In an effort to reduce erosion, river clubrush was planted at a site on the western shoreline of Lake Albert in 2003 (Fig. 3.2.11). Clumps of adult river clubrush were planted in water 40-60 cm deep in a zig-zag pattern 1 m apart in a band 1 m wide (Jellinek et al. 2016; Nicol et al. 2016b) (Fig. 3.2.11). Observations at this site suggested that the planted river clubrush reduced erosion, and another site in Lake Albert was planted in 2006 and two sites in Lake Alexandrina in 2006 and 2007 (Nicol et al. 2016b). Low water levels between 2007 and 2010 resulted in the planted river clubrush senescing to rhizomes, but they resprouted when water levels were reinstated (Nicol et al. 2016a, b). A further 30 km of shoreline was planted between 2012 and 2016 to reduce shoreline erosion and increase aquatic plant diversity.

Monitoring results showed that sites planted with river clubrush prior to 2008 had developed dense stands and at sites planted after 2011 stand density and width were increasing (Nicol et al. 2016b). Furthermore, planted stands provided low-energy habitats where less robust submergent and amphibious species recruited, and were more species-rich compared to adjacent unplanted shorelines (Jellinek et al. 2016; Nicol et al. 2016b) (Fig. 3.2.11).

Tuberous sea tassel seed bank translocation

The extended period of low or no barrage outflows between 2002 and 2010 caused repeated reproductive failure of tuberous sea tassel, which in turn resulted in the seed bank becoming depleted (Paton & Bailey 2012; Paton et al. 2015b). Barrage outflows in 2010-2011 resulted in favourable conditions for tuberous sea tassel (Ye et al. 2016); however, there was little response due to the depauperate seed bank (Paton & Bailey 2012). In an effort to improve the seed bank, sediment was collected from nearby Lake Cantara (a seasonal lake in Coorong National Park that has a healthy population of tuberous sea tassel) in 2013 and 2014 (Paton et al. 2016). The top 15 mm of sediment were scraped from around 1.5 ha of lake bed in both years using an excavator, and transported to mudflats on the eastern side of the South Lagoon. About 280 t of sediment were translocated in 2013 and 450 t in 2014 (Paton et al. 2016). Areas that received the sediment were lightly scarified and the sediment from Lake Cantara was scattered onto the surface. Some areas of mudflat were inundated and in these areas the sediment was scattered directly into the water. A total 20 ha of mudflats at Policeman Point and

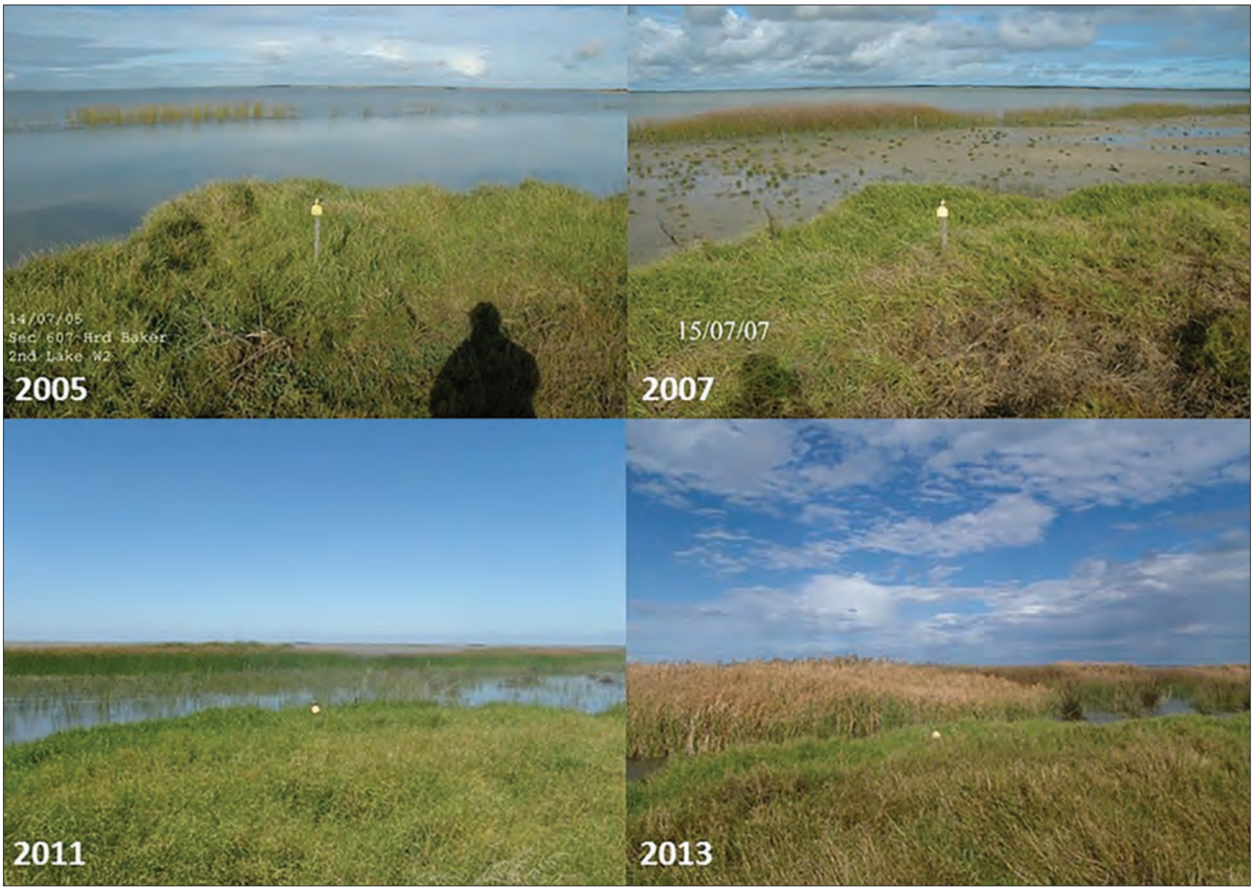

Figure 3.2.11 Series of photos showing development of shoreline vegetation at the first site planted with river clubrush (*Schoenoplectus tabernaemontani*). (Photographs dated 2005, 2007 & 2011 by Ken Strothers; photograph dated 2013 by Regina Durbridge)

Woods Well received sediment from Lake Cantara in 2013 and an additional 42 ha in 2014 (Paton et al. 2016).

There was little recruitment of tuberous sea tassel the first winter after translocation (at sites planted in 2013 and 2014); however, at the 2013 translocation sites there were vigorous populations in the winter of 2014 and 2015. Despite an improvement in the number of shoots at these sites in winter 2014 and 2015, water levels fell in mid- to late spring in both years, resulting in negligible seeds and fewer turions being produced. It was recommended that further translocation cease until there is a higher chance of water levels being maintained until late spring to early summer, and in turn a greater chance of reproductive success. In addition, the donor sites in Lake Cantara have been slow to recover (the area where sediment was removed had lower numbers of shoots compared to adjacent sediment) despite only 15 mm of sediment being removed (Paton et al. 2016).

THREATS

The greatest threats to the region are 1) water allocation planning resulting in insufficient water delivery to the system to maintain plant communities and further reduced water availability 2) sea-level rise as a result of climate change.

Water allocation planning

The 2 750 GL of environmental water to be recovered under the Murray-Darling Basin Plan by 2019 should result in water levels in the Lower Lakes that support a diverse and functional aquatic and littoral plant community. However, this volume of water is insufficient to provide conditions that will facilitate the establishment of large-fruit sea tassel in the North Lagoon (Brock 1982a, b) and the Murray Estuary, or provide sufficient barrage outflows to maintain water levels in the South Lagoon for tuberous sea tassel seed set (Kim et al. 2015; Ye et al. 2016; Paton et al. 2017). An additional threat to the vegetation of the region is the proposed Sustainable Diversion Limit Adjustments. If adopted, these will result in a reduction in the amount of water recovered under the Basin (as a result of upstream engineering interventions primarily to water floodplains) (*sensu* Pittock et al. 2013) and in turn the amount of environmental water available for the Coorong and Lower Lakes.

Climate change

Climate change predictions suggest that south-east Australia will become hotter and drier, which will result in reduced run-off and in turn reduced streamflow and higher evaporation (e.g. Pittock & Finlayson 2011). In the Murray-Darling Basin, a 1° C increase in average temperature will result in 15% reduced inflows (Cai & Cowan 2008), and even with water recovered under the Basin Plan this will result in significant changes to ecosystems (Colloff et al. 2016). Lester et al. (2013) predicted that climate change could have catastrophic consequences for the Coorong under the current levels of extraction. However, they predicted that much of the degradation could be averted by reducing upstream water extraction (Lester et al. 2013). A similar situation is likely for the Lower Lakes, with conditions similar to those observed between 2007 and 2010 more likely in the future under current levels of extraction, but avoided by reducing upstream extraction.

Sea-level rise brought about by climate change also poses a significant threat to the Coorong, Lower Lakes and Murray Mouth ecosystem, particularly the Lower Lakes. A sea-level rise of around 79 cm is predicted by 2100 (Department of Climate Change 2009), which in the short term will result in periods of reverse head occurring more frequently with longer durations, and in the long term the barrages may be over-topped (Chapter 4.3). This will result in periods of elevated salinity upstream of the barrages, which in the short term will probably have little impact on the aquatic and littoral vegetation due to the relatively short duration of the seawater incursions and the tolerance of the vegetation to elevated salinity (*sensu* Gehrig et al. 2011a). However, in the long term, as the seawater incursions become more frequent and of longer duration (or permanent in the case of the barrages being over-topped), there will be a change in the vegetation, with salt-sensitive species being replaced with salt-tolerant ones.

The impacts of sea-level rise on the vegetation of Coorong are unclear. The higher water levels in the Coorong will probably result in the decline of swamp paperbark woodlands (Denton & Ganf 1994) and samphire and saltmarsh habitats due to increased inundation. However, the increased water levels may reduce salinity and inundate mudflats for longer in the South Lagoon, which could have positive outcomes for tuberous sea tassel.

ACKNOWLEDGEMENTS

The authors acknowledge the Murray-Darling Basin Authority's The Living Murray Program, which has funded condition and intervention monitoring that has vastly improved our understanding of the vegetation dynamics of the Coorong, Lower Lakes and Murray Mouth region. We also thank Sacha Jellinek and Scoresby Shepherd for providing constructive feedback on an early draft of this chapter.

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Chapter 3.3

Terrestrial Vegetation of the Coorong, Lower Lakes and Murray Mouth Region

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THE TERRESTRIAL LANDSCAPE

The Coorong, Lower Lakes and Murray Mouth (CLLMM) region is an ecologically, economically and culturally significant region situated in the Southeast (SE) of South Australia (DEH 2000) (Fig. 3.3.1). It is located at the terminus of the Murray-Darling River, Australia's longest river system, and experiences a Mediterranean climate with wet winters and hot, dry summers and an average annual rainfall of 450 mm (BOM 2016). The topography of this landscape varies from the low hills of Mount Lofty Ranges in the north-west, the low valleys and plains surrounding Lake Alexandrina and Lake Albert, and the plains and dunes of the Coorong to the south-east (Hall et al. 2009). The pre-European vegetation would have varied across these landforms, with the Mount Lofty Ranges dominated by eucalypt forests, woodlands and grassy woodlands, the Lakes dominated by a mixture of mallee, temperate shrublands and wetland vegetation, and the Coorong dominated by coastal and wetland vegetation types (Berkinshaw 2009).

The region has experienced extensive vegetation clearance and land degradation since European settlement, and the introduction of agriculture (cropping and grazing) resulted in a substantial decline in native biodiversity. As such, the CLLMM region is now recognised as a critically endangered eco-region (Hoekstra et al. 2005; Mogoutnov & Venning 2014).

The impacts of vegetation clearance have been compounded by hydrological changes to the terrestrial and aquatic ecosystems of the region. As a result of excessive water extraction upstream and the construction of barrages between Lake Alexandrina and the Coorong, the condition of remnant native vegetation declined further (Van Dijk et al. 2013).

The Millennium Drought (1995-2009) exacerbated these environmental problems and also had significant social and economic impacts (Van Dijk et al. 2013). In response, large-scale restoration activities were undertaken. These activities formed part of a federal and state funding initiative known as the Coorong, Lower Lakes and Murray Mouth Recovery Project, which aimed to restore the resilience of the region (Fig. 3.3.1). In order to guide these restoration activities, the SA Department of Environment, Water and Natural Resources (DEWNR) collaborated with other agencies, community organisations and experts to describe the vegetation communities that currently or once occurred in this landscape. The program also sought to prioritise the restoration of vegetation communities most at risk of further decline to ensure that the CLLMM region remained resilient to future environmental disturbances.

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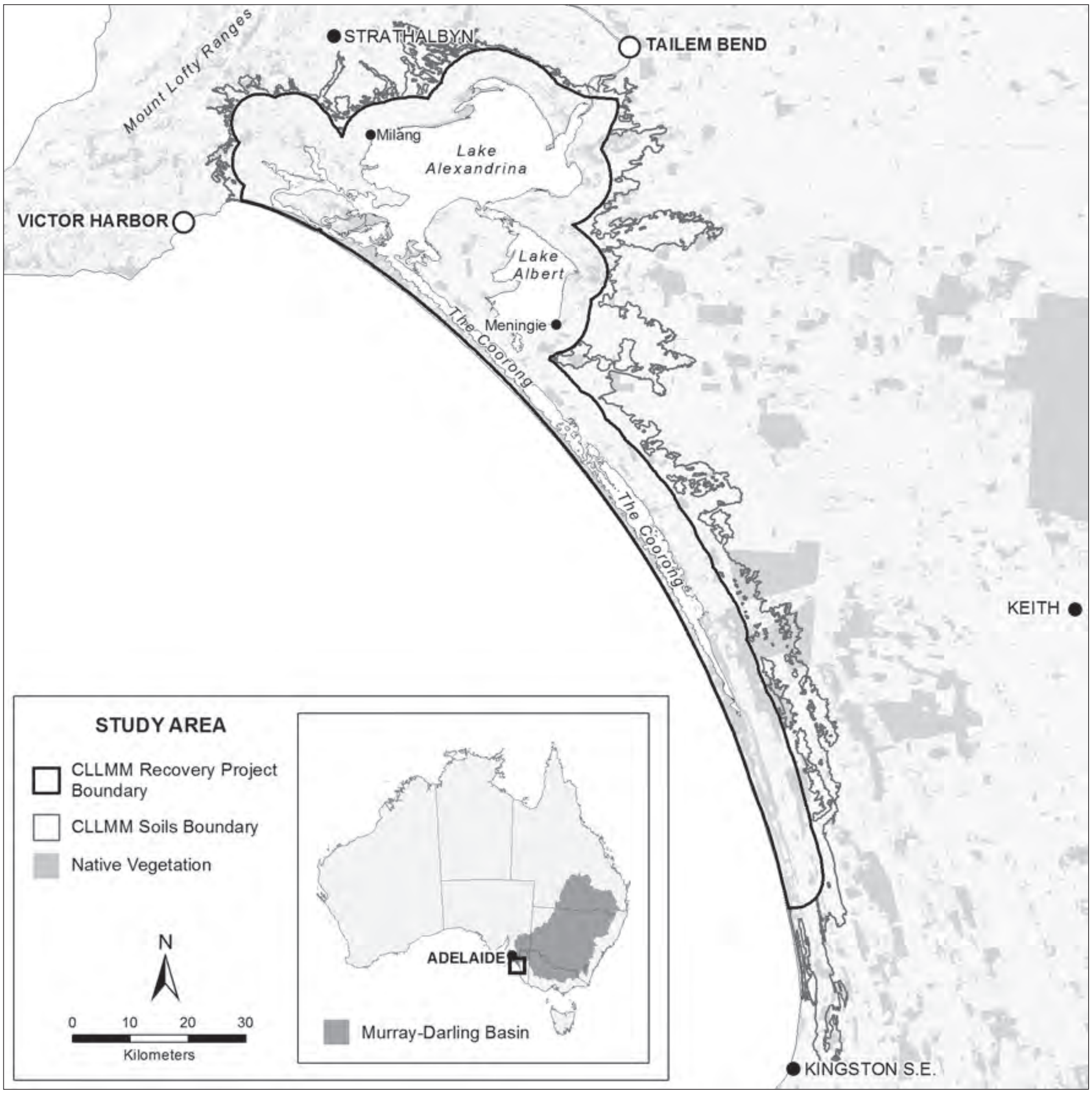

Figure 3.3.1 The CLLMM Recovery Project boundary along with the soils boundary, which was used to define the extent of the vegetation communities discussed below. (From Department for Environment and Water 2017)

The vegetation communities that were derived from this analysis are described below, including factors that influence their persistence, associated native plant species, and restoration activities undertaken as part of the CLLMM Recovery Project (2011-2016).

REMNANCY

About 278 000 ha, or 13%, of native vegetation remain in the SE region of South Australia (Foulkes & Heard 2003). Remnancy is slightly higher in the CLLMM region at ~22%, possibly due to the number of large reserves which were set aside in areas less suitable for agriculture, such as deep sands, saline soils or exposed calcrete.

The majority of the remaining native vegetation in the CLLMM region occurs within the Coorong National Park, consisting of a patchwork of different vegetation associations.

The dominant vegetation communities are *Eucalyptus diversifolia* ssp. *diversifolia*, open mallee, and *Leucopogon parviflorus*, *Acacia longifolia* ssp. *sophorae* and *Olearia axillaris* tall shrubland. More saline sites, found mainly in the south, are dominated by *Melaleuca halmaturorum* tall shrubland, and *Gahnia filum* and *Sarcocornia* spp. (low shrubland) (Heard 2003).

Smaller patches of remnant vegetation in the region occur on private property, council reserves or along roadsides, including patches of *Callitris gracilis* low open woodland on the Poltalloch Peninsula, *Eucalyptus leucoxylon* ssp. *stephaniae*, low woodland, and *Allocasuarina verticillata* low open woodland on the Narrung Peninsula, and *Melaleuca brevifolia* tall open shrubland north and south of Meningie (Kinnear et al. 2000). These native vegetation patches are islands among a sea of cleared cropping and grazing land.

However, the degree of remnancy stated above is likely to be an over-estimate. This is because the native vegetation cover has been calculated from GIS imagery that may not be accurate or up to date, and the communities identified in vegetation mapping do not have a direct correlation with those described here. Degree of remnancy can also be misleading as an indicator of ecosystem health, as vegetation mapping does not take into account the quality of the remnant area. For example, according to the mapping, 67% of the samphire vegetation community remains. However, much of this habitat has limited hydrological connectivity to other water bodies, meaning that many samphire remnants do not have the diversity of plant species representative of more hydrologically connected landscapes. Livestock grazing also impacts the quality of unfenced remnant habitats, such as temperate woodlands, as it decreases understorey species and increases weed invasion (Dorrough et al. 2004; Yates & Hobbs 1997). Grazing similarly degrades semi-aquatic habitats such as samphire and fringing wetland communities (Jellinek et al. 2016).

VEGETATION COMMUNITIES IN THE CLLMM REGION

The distribution of each plant community is influenced by a number of environmental factors, such as soil type, landform element, rainfall and location within the region. Of these, soil type has a dominant influence on vegetation composition, and can be used to predict where plant communities are likely to occur (Fig. 3.3.1) (Hall et al. 2009; Berkinshaw 2009). Analysis using existing soil mapping, vegetation data and opinions from botanical experts identified 16 dominant communities in the CLLMM region (Table 3.3.1) (Bonifacio et al. 2016). While there are issues associated with the use of spatial data to map vegetation communities, spatial data are useful to predict where these communities are likely to occur when field surveys are lacking (Franklin 1995).

Of the 16 plant communities recognised, six were considered priorities for habitat restoration and revegetation (Table 3.3.2). These communities were identified as priorities because they had been heavily cleared since European settlement and were demonstrated to provide important habitat for selected bird species (Jellinek 2017).

The plant communities are briefly described below. Detailed maps of the expected distribution of each plant community, as well as a propagation list of the species associated with each community, can be found in Jellinek and Te (2016).

Table 3.3.1 Dominant plant communities identified in the CLLMM region. ID refers to the individual number relating to that species.

ID	Plant Community
1	Pink gum (*Eucalyptus fasciculosa*) woodland
2	Cup gum (*Eucalyptus cosmophylla*) and brown stringybark (*Eucalyptus baxteri*) woodland over heath
3	Coastal shrubland of the Coorong (*Olearia axillaris*, *Leucopogon parviflorus* and *Acacia longifolia* ssp. *sophorae*)
4	Coastal white mallee (*Eucalyptus diversifolia* ssp. *diversifolia*) open mallee
5	Drooping sheoak (*Allocasuarina verticillata*) low woodland
6	Mallee box (*Eucalyptus porosa*) grassy woodland
7	Peppermint box (*Eucalyptus odorata*) grassy woodland
8	Ridge-fruited mallee (*Eucalyptus incrassata*), narrow-leaved red mallee (*E. leptophylla*) and red mallee (*E. socialis* ssp.) mallee
9	South Australian blue gum (*Eucalyptus leucoxylon* ssp.) woodland
10	Freshwater fringing wetland
11	Lignum (*Duma florulenta*) shrubland
12	Swamp paperbark (*Melaleuca halmaturorum*) and samphire (*Tecticornia* spp.) tall shrubland
13	Chaffy saw-sedge (*Gahnia filum*) sedgeland
14	River red gum (*Eucalyptus camaldulensis* spp. *camaldulensis*) grassy woodland
15	Grassland
16	Drooping sheoak (*Allocasuarina verticillata*) and native pine (*Callitris gracilis*) woodland

Table 3.3.2 Priority plant communities and the area remaining in the CLLMM region compared with pre-European mapping.

ID	Priority Plant Community	% Area Remaining (ha)
1	Pink gum (*Eucalyptus fasciculosa*) woodland	14%
6 7 9	Mallee box (*Eucalyptus porosa*) grassy woodland Peppermint box (*Eucalyptus odorata*) grassy woodland and South Australian blue gum (*Eucalyptus leucoxylon*) woodland	8%
12	Swamp paperbark (*Melaleuca halmaturorum*) and samphire (*Tecticornia* spp.) tall shrubland	67%
16	Drooping sheoak (*Allocasuarina verticillata*) and native pine (*Callitris gracilis*) woodland	2%

1. Pink gum (*Eucalyptus fasciculosa*) woodland

This plant community is found in the north and north-western parts of the CLLMM region, particularly between Currency Creek and the Finniss River, extending up to Scott Conservation Park and Mount Observation. It is usually found on lower to mid-slopes in poor (infertile) sandy soils on flats, to low sandy rises in plains and low hills, with sand over clay soils (G3 & G4 soils), and/or in dune systems with bleached siliceous sand (H3 soils) (Table 3.3.3).

This woodland community is characterised by *Eucalyptus fasciculosa* as the dominant tree species (10 m high and 10-30 % canopy cover, but can often be associated with brown stringybark (*E. baxteri*)).

The mid-layer consists of a sparse to moderate (<30 % cover) density of heathy shrubs, including *Acacia paradoxa*, *A. pycnantha*, *A. myrtifolia*, *Allocasuarina striata*, *Banksia* spp., *Bursaria spinosa*, *Callistemon rugulosa*, *Calytrix tetragona*, *Dodonaea viscosa* ssp. *spatulata*, *Exocarpos cupressiformis*, *Hakea rostrata*, *Leptospermum myrsinoides*, *Olearia ramulosa*, *Pultenaea daphnoides* and *Xanthorrhoea semiplana* ssp. *semiplana*.

The ground layer is diverse and consists of low shrub, herbs, grasses and sedges, including *Astrolomo humifusum*, *Austrostipa* spp., *Boronia coerulescens*, *Caesia calliantha*, *Correa reflexa*, *Dianella revoluta*, *Dillwynia hispida*, *Enchylaena tomentosa*, *Enneapogon nigricans*, *Epacris impressa*, *Grevillea lavandulacea*, *Helichrysum leucopsideum*, *Hibbertia virgata*, *Isopogon ceratophyllus*, *Kennedia prostrata*, *Kunzea pomifera*, *Lepidosperma* spp., *Lomandra* spp., *Muehlenbeckia gunnii*, *Neurachne alopecuroidea*, *Pimelea* spp., *Platylobium obtusangulum*, *Rytidosperma* spp., *Tetratheca pilosa*, *Themeda triandra* and *Thomasia petalocalyx*.

2. Cup gum (*Eucalyptus cosmophylla*) and brown stringybark (*E. baxteri*) woodland over heath

Found predominantly in the north-western part of the CLLMM region, from Mount Compass to Mount Observation, extending south to Tookayerta Creek and Currency Creek, this vegetation community prefers higher elevation areas that receive more rainfall than those dominated by pink gum woodland.

Cup gum and brown stringybark vegetation communities are usually found on low-fertility sandy loams to loams with lateritic influence, where some blown-in sand is present. These soils include sand over clay (G3 & G5 soils) and to a lesser extent acidic sandy loam over red clay (K3 soils), or hard loamy sand over red clay (D5 soils) (Table 3.3.3).

This woodland community is dominated by *Eucalyptus cosmophylla* and *E. baxteri* but can co-occur with *E. fasciculosa*. The mid-layer consists of a dense layer (<40% cover) of heathy shrubs, including *Acacia* spp., *Allocasuarina striata*, *Banksia* spp., *Bursaria spinosa*, *Calytrix tetragona*, *Dianella brevicaulis*, *Dodonaea viscosa* ssp. *spatulata*, *Hakea* spp., *Leptospermum continentale* and *Xanthorrhoea semiplana*.

The ground layer consists of a diverse range of low shrubs, herbs, grasses and sedges, including *Acrotriche depressa*, *Stenanthera conostephioides*, *Burchardia umbellata*, *Cryptandra tomentosa*, *Daviesia asperula*, *Dillwynia hispida*, *Eutaxia microphylla*, *Gahnia ancistrophylla*, *Hibbertia* spp., *Isopogon ceratophyllus*, *Lepidosperma* spp., *Lomandra multiflora*, *Neurachne alopecuroidea*, *Platylobium obtusangulum* and *Tetratheca pilosa*.

3. Coastal shrubland of the Coorong (*Olearia axillaris*, *Leucopogon parviflorus* and *Acacia longifolia* ssp. *sophorae*)

Coastal shrubland mostly occurs along the coastal dunes of the Coorong (Younghusband Peninsula) but may also occur near Goolwa. It is predominantly found on deep sands (H1 & H2 soils), and to a lesser extent on shallow sandy loam on calcrete (B3 soils) (Table 3.3.3).

This shrubland community is characterised by a mix of *Acacia longifolia* ssp. *sophorae*, with *Leucopogon parviflorus* and *Olearia axillaris* as the co-dominant upper layer species. Other tall shrubs include *Adriana quadripartita*, *Exocarpos syrticola*, *Melaleuca lanceolata*, *Myoporum insulare* and *Ozothamnus turbinatus*. Some emergent trees may be present, including *Allocasuarina verticillata* and *Eucalyptus diversifolia* ssp. *diversifolia*.

The ground layer has a moderate to high diversity of low shrubs and groundcovers, including *Acaena novae-zelandiae*, *Carpobrotus rossii*, *Clematis microphylla*, *Dianella brevicaulis*, *Ficinia nodosa*, *Kunzea pomifera*, *Lepidosperma gladiatum*, *Leucophyta brownii*, *Muehlenbeckia gunnii*, *Pimelea serpyllifolia* ssp. *serpyllifolia*, *Poa poiformis*, *Rhagodia candolleana*, *Spinifex hirsutus* and *Sporobolus virginicus*.

4. Coastal white mallee (*Eucalyptus diversifolia* ssp. *diversifolia*) open mallee

This plant community occurs throughout the CLLMM region, but is most common in the north-east, central and southern parts of the region. In the Mount Lofty Ranges it has a limited distribution, generally found only between Currency Creek and the Finniss River.

It predominantly occurs on shallow sandy soil on calcrete (B2 & B3 soils) and deep sands (H1 & H3 soils), and to a lesser extent on sand over clay (G3 & G5 soils). Outcropping calcrete can often be seen associated with these soil types. In rare cases, it also occurs on the upper margins of samphire vegetation in saline soils (N2 soils) (Table 3.3.3). As this mallee community can occur on a variety of different soil types across the region, it commonly co-occurs with other vegetation communities.

This open mallee community is characterised by *E. diversifolia* ssp. *diversifolia* as the dominant upper layer species to 10 m high, but can co-occur with *E. incrassata* and *E. leptophylla* with a heathy understorey.

The mid-layer species include *Acacia* spp., *Adriana quadripartita*, *Allocasuarina verticillata*, *Banksia marginata*, *Brachyloma ericoides*, *Bursaria spinosa*, *Calytrix tetragona*, *Dodonaea viscosa* ssp. *spathulata*, *Exocarpos sparteus*, *Hakea vittata*, *Leucopogon parviflorus*, *Melaleuca lanceolata*, *Myoporum insulare*, *Pomaderris paniculosa*, *Olearia axillaris* and *Xanthorrhoea caespitosa*.

The ground layer contains a sparse (<20%) cover of low shrubs and sedges, including *Astroloma humifusum*, *Carpobrotus rossii*, *Dianella revoluta* var. *revoluta*, *Dichondra repens*, *Gahnia deusta*, *Hibbertia* spp., *Kunzea pomifera*, *Lasiopetalum baueri*, *Lepidosperma* spp., *Lomandra* spp., *Muehlenbeckia gunnii*, *Pimelea serpyllifolia* and *Tetragonia implexicoma*.

5. Drooping sheoak (*Allocasuarina verticillata*) low woodland

Generally found in the north-east, central and southern parts of the region, this community grows on shallow sandy soil on calcrete (B3 & B8 soils), and to a lesser extent on bleached sand over sandy clay (G3 soils), bleached siliceous sand (H3 soils) and rarely saline soils (N2 soils) (Table 3.3.3). Much of this vegetation community has been cleared, but it was probably most commonly found on the Narrung Peninsula and east of Meningie.

This low woodland is characterised by *Allocasuarina verticillata* as the dominant upper layer species, sometimes occurring as pure stands or including *Callitris gracilis*, *Eucalyptus diversifolia* ssp. *diversifolia* and *Melaleuca lanceolata*. It has a shrubby understorey, although it may also have had a grassy understorey in its original state. In coastal areas, this community has a heath or shrub understorey, whereas elsewhere it ranges from a heathy to an open grassy understorey.

The mid-layer species include *Acacia pycnantha*, *Banksia marginata*, *Bursaria spinosa* ssp. *spinosa*, *Dodonaea viscosa* ssp. *spatulata*, *Myoporum insulare*, *Pittosporum angustifolium*, *Pomaderris paniculosa* and *Xanthorrhoea caespitosa*.

The ground layer has a rich diversity of low shrubs, grasses and herbs, including *Anthosachne scabra*, *Astroloma* spp., *Rytidosperma caespitosum*, *Austrostipa* spp., *Billardiera cymosa* ssp. *cymosa*, *Burchardia umbellata*, *Calostemma purpureum*, *Cryptandra tomentosa*, *Dianella revoluta* ssp. *revoluta*, *Dichondra repens*, *Gahnia deusta*, *Helichrysum leucopsideum*, *Kennedia prostrata*, *Kunzea pomifera*, *Lasiopetalum baueri*, *Lepidosperma* spp., *Lomandra effusa*, *Themeda triandra* and *Thomasia petalocalyx*.

6. Mallee box (*Eucalyptus porosa*) grassy woodland

Found in the northern part of the region, this community is usually associated with moderate rainfall in semi-arid areas (Berkinshaw 2009). It is not found in the wetter areas of the Mount Lofty Ranges (Nicolle 2013). Mallee box generally occurs on the Narrung Peninsula, around Wellington and Langhorne Creek, and to a lesser extent around Milang and Goolwa.

It is usually located on level to gently undulating plains, and in poorly drained depressions on clay over limestone and coastal limestone bluffs, but can also occur on rises and low hills (Nicolle 2013). In the CLLMM region it is associated with loam over poorly structured red clay (D3 soils), on shallow calcareous loam on calcrete (B2 soils) or shallow sandy loam on calcrete (B3 soils) (Table 3.3.3).

This grassy woodland is characterised by *Eucalyptus porosa* as the dominant upper layer species, but can co-occur with *Allocasuarina verticillata*, *Callitris gracilis*, *E. fasciculosa*, *E. leucoxylon* and *E. odorata*.

The mid-layer consists of sparse (<30% cover) shrubs, including *Acacia pycnantha*, *A. spinescens*, *Banksia marginata*, *Bursaria spinosa* ssp. *spinosa*, *Calytrix tetragona*, *Daviesia devito*, *Dodonaea viscosa* ssp. *spathulata*, *Eutaxia microphylla*, *Melaleuca lanceolata*, *Olearia ramulosa* and *Pittosporum angustifolium*.

The ground layer varies from a relatively dense and diverse community in open sites, to a sparser layer under more densely wooded sites. It includes *Aristida behriana*, *Arthropodium strictum*, *Austrostipa* spp., *Bulbine bulbosa*, *Clematis microphylla*, *Dianella revoluta* ssp. *revoluta*, *Enneapogon nigricans*, *Goodenia pinnatifida*, *Kennedia prostrata*, *Lepidosperma viscidum*, *Lomandra* spp., *Ozothamnus retusus*, *Rytidosperma* spp., *Senecio quadridentatus*, *Themeda triandra*, *Vittadinia cuneata* and *Wahlenbergia luteola*.

7. Peppermint box (*Eucalyptus odorata*) grassy woodland

Restricted to the north-western part of the CLLMM region, this community grows in semi-arid areas that have a moderate rainfall. It can occur around Langhorne Creek and from Milang to Goolwa (excluding between Currency Creek and the Finniss River) (Berkinshaw 2009).

The peppermint box community is generally located on undulating plains and on lower to mid-slopes (up to 30 m elevation) with shallow loamy soils (Nicolle 2013). In the CLLMM region it is associated with loam over poorly structured red clay (D3 soils) and sand over poorly structured clay (G4 soils) (Table 3.3.3). It tends to be associated with well-drained soils on hilltops, although elsewhere it can be common in drainage lines dominated by mallee box.

This grassy woodland community is characterised by *Eucalyptus odorata* as the dominant upper layer species, but can co-occur with *Allocasuarina verticillata*, *E. fasciculosa* and *E. leucoxylon* ssp. *leucoxylon* (40 % canopy cover).

The mid-layer consists of sparse (<30 % cover) shrubs, including *Acacia pycnantha*, *Bursaria spinosa*, *Dodonaea viscosa* ssp. *spathulata*, *Eutaxia microphylla*, *Exocarpos cupressiformis* and *Pittosporum angustifolium*.

The ground layer varies from a relatively dense and diverse layer in open sites to a sparse layer under more densely wooded sites, and includes *Aristida behriana*, *Arthropodium strictum*, *Austrostipa* spp., *Dianella revoluta* ssp. *revoluta*, *Goodenia pinnatifida*, *Lepidosperma viscidum*, *Lomandra* spp., *Ozothamnus retusus*, *Rytidosperma* spp., *Senecio quadridentatus*, *Themeda triandra*, *Vittadinia cuneata* and *Wahlenbergia luteola*.

8. Ridge-fruited mallee (*Eucalyptus incrassata*), narrow-leaved red mallee (*E. leptophylla*) and red mallee (*E. socialis*) mallee

Similar to peppermint box, this plant community occurs in the north-western part of the CLLMM region, although it is restricted to areas between Currency Creek and the Finniss River, and around Milang and Langhorne Creek. Here it grows on sand over clay soils (G1 & G3 soils) and bleached siliceous sand (H3 soils) (Table 3.3.3).

This mallee community is characterised by a mix of *Eucalyptus incrassata*, *E. leptophylla* and *E. socialis* as the dominant upper layer species, but can also co-occur with *E. diversifolia* ssp. *diversifolia* and *Callitris gracilis*.

The mid-layer is relatively dense (<50 % cover) with diverse shrubs, including *Acacia* spp., *Allocasuarina stricta*, *Baeckea crassifolia*, *Bursaria spinosa*, *Calytrix tetragona*, *Cryptandra tomentosa*, *Hybanthus floribundus*, *Lasiopetalum baueri*, *Leptospermum coriaceum*, *Melaleuca* spp., *Olearia ciliata*, *Pittosporum angustifolium* and *Prostanthera aspalathoides*.

The ground layer consists of low shrubs, herbs, grasses and sedges, including *Austrostipa* spp., *Boronia coerulescens*, *Clematis microphylla*, *Dampiera rosmarinifolia*, *Dianella revoluta*, *Dillwynia hispida*, *Gahnia* spp., *Glischrocaryon behrii*, *Halgania cyanea*, *Hibbertia riparia*, *Hypolaena fastigiata*, *Kennedia prostrata*, *Lasiopetalum baueri*, *Lepidosperma carphoides*, *Lomandra* spp., *Pimelea stricta*, *Rhagodia candolleana* and *Rytidosperma setaceum*.

9. South Australian blue gum (*Eucalyptus leucoxylon* ssp.) woodland

This plant community contains two subspecies that occur in different parts of the CLLMM region, *Eucalyptus leucoxylon* ssp. *stephaniae* and *E. leucoxylon* ssp. *leucoxylon*. The more commonly distributed of the two subspecies, *E. leucoxylon* ssp. *stephaniae,* is found in the north-east, central and southern parts of the CLLMM region, while *E. leucoxylon* ssp. *leucoxylon* occurs in and around Scott Conservation Park in the Mount Lofty Ranges (Nicolle 2013).

Eucalyptus *leucoxylon* ssp. *stephaniae* is usually found in undulating or hilly terrain on loam soils, including shallow calcareous loam on calcrete (B3 soils), shallow loam over red clay on calcrete (B6 soils), shallow sand on calcrete (B8 soils) and to a lesser extent on deep sand over clay (Table 3.3.3). *Eucalyptus leucoxylon* ssp. *leucoxylon* grows on loam to sandy loam soil over clay on flats and lower slopes.

Eucalyptus leucoxylon ssp. *stephaniae* co-occurs with *Allocasuarina verticillata*, *E. diversifolia* ssp. *diversifolia*, *E. fasciculosa* and *E. incrassata*, with a sparse to dense heathy understorey.

The mid-layer consists of shrubs, including *Acacia longifolia* ssp. *sophorae*, *A. pycnantha*, *Banksia* spp., *Bursaria spinosa*, *Exocarpos sparteus*, *Hakea mitchellii*, *Leptospermum myrsinoides*, *Melaleuca lanceolata* and *Xanthorrhoea caespitosa*.

Eucalyptus leucoxylon ssp. *leucoxylon* co-occurs with *E. cosmophylla*, *E. fasciculosa* and *E. porosa*, with sparse shrubs (<20%) and a grassy-herbaceous ground layer.

The mid-layer species include *Acacia* spp., *Banksia marginata*, *Bursaria spinosa*, *Exocarpos cupressiformis*, *Hakea rostrata*, *Leptospermum myrsinoides* and *Xanthorrhoea semiplana*. The ground layer consists of low shrubs, herbs, grasses and sedges.

10. Freshwater fringing wetland

Freshwater fringing wetlands grow in wet (N3) soils in inundated areas around Lake Alexandra and Lakes Albert; they require constant or regular inundation as well as some tolerance to saline and brackish water. This community is associated with low-salinity areas as distinct from samphire, which is associated with more saline (N2) soils (Table 3.3.3).

This wetland community is dominated by *Phragmites australis*, *Schoenoplectus tabernaemontani* and *Typha domingensis* (Jellinek et al. 2016) with small sedges, submerged and floating aquatic species occurring in the calm water between and among the dominant species. These include *Azolla rubra*, *Baumea juncea*, *Bolboschoenus caldwellii*, *Calystegia sepium*, *Cyperus gymnocaulos*, *Hydrocotyle verticillata*, *Juncus kraussii*, *Myriophyllum* spp., *Schoenoplectus pungens* and *Cycnogeton procerum*.

11. Lignum (*Duma florulenta*) shrubland

Located in the northern part of the CLLMM region in wetter areas around the Lower Lakes, this community occurs on wet (N3) soils as well as in loam over poorly structured red clay (D3 soils). It occurs to a lesser extent on shallow sandy loam on calcrete (B3 soils) and loam over brown or dark clay (F1 soils) (Table 3.3.3).

This shrubland community is characterised by *Duma florulenta* as the dominant upper layer species, which grows to about 2 m high, sometimes occurring as a pure stand or with scattered *Eucalyptus camaldulensis* ssp. *camaldulensis*.

The ground layer consists of low shrubs, sedges and herbs tolerant of infrequent flooding, including *Atriplex semibaccata*, *Baumea juncea*, *Bolboschoenus caldwellii*, *Carex appressa*, *Disphyma crassifolium* ssp. *clavellatum*, *Distichlis distichophylla*, *Einadia nutans*, *Eleocharis acuta*, *Ficinia nodosa*, *Frankenia pauciflora* ssp. *gunnii*, *Gahnia filum*, *Juncus kraussii*, *Lachnagrostis filiformis*, *Lawrencia spicata*, *Puccinellia stricta*, *Samolus repens*, *Selliera radicans*, *Suaeda australis*, *Threlkeldia diffusa* and *Wilsonia rotundifolia*.

12. Swamp paperbark (*Melaleuca halmaturorum*) and samphire (*Tecticornia* spp.) tall shrubland

This plant community can be found across the CLLMM region (Bonifacio et al. 2016). It is associated with sub-coastal and semi-saline swamps and wetlands, rivers, estuaries, seasonally inundated depressions and floodplains. It grows on saline clay (N2 soils) and to a lesser extent wet (N3) soil (Table 3.3.3), but can also grow on sandy clays (Hall et al. 2009).

This tall shrubland is characterised by *Melaleuca halmaturorum* as the dominant upper layer species, which grows to 10 m high, and sometimes forms dense stands.

The understorey can be dense (<60 % cover) or quite sparse (<30 % cover), depending on the canopy cover and hydrology. Species consists of low salt-tolerant shrubs dominated by *Sarcocornia* spp. and *Tecticornia* spp. The composition of species associated with this vegetation community is largely dependent on the salinity of the standing water and the quantity of freshwater run-off.

Other low shrubs include *Acaena novae-zelandiae*, *Disphyma crassifolium* ssp. *clavellatum*, *Distichlis distichophylla*, *Frankenia pauciflora* ssp. *gunnii*, *Gahnia filum*, *Hemichroa pentandra*, *Lawrencia* spp., *Maireana oppositifolia*, *Samolus repens*, *Selliera radicans*, *Suaeda australis*, *Threlkeldia diffusa*, *Wilsonia humilis* and *W. rotundifolia*.

13. Chaffy saw-sedge (*Gahnia filum*) sedgeland

Associated with wetland areas, this community occurs in low depressions and may fringe samphire and swamp paperbark communities. The distribution of chaffy saw-sedge communities is now very limited in the northern part of the region due to adjacent terrestrial vegetation clearance, which has raised the water table and increased salinity. It is more common in the southern part of the region within the Coorong National Park and areas adjoining Tilley Swamp Conservation Park.

This sedgeland community is characterised by *Gahnia filum* as the dominant upper layer species, sometime forming dense stands along with *Melaleuca halmaturorum* and *Myoporum insulare* on swamp edges.

The ground layer species are found in the spaces between *G. filum* and include *Acaena novae-zelandiae*, *Atriplex semibaccata*, *Distichlis distichophylla*, *Frankenia pauciflora* ssp. *gunnii*, *Hemichroa pentandra*, *Juncus kraussii*, *Lawrencia* spp., *Puccinellia stricta*, *Samolus repens*, *Sarcocornia* spp., *Selliera radicans*, *Suaeda australis*, *Tecticornia* spp., *Threlkeldia diffusa* and *Wilsonia* spp.

14. River red gum (*Eucalyptus camaldulensis* ssp. *camaldulensis*) grassy woodland

River red gum is associated with floodplains and freshwater swamps on wet soils (N3), especially in the north-western part of the CLLMM region in the Mount Lofty Ranges (Berkinshaw 2009). It has largely been cleared due to the high suitability of this land for agriculture. Expert knowledge indicates that much of its distribution is limited to the creek-lines of Langhorne Creek, although it is likely to occur in most landscapes where temporary freshwater inundation occurs.

This grassy woodland community is characterised by *Eucalyptus camaldulensis* ssp. *camaldulensis* as the dominant upper layer species, but can include *E. largiflorens* and

E. viminalis ssp. *cygnetensis*. The understorey in many instances has been significantly impacted and modified through drainage, stock grazing and pasture improvement.

The mid-layer has sparse (<20 % cover) tall shrubs including *Acacia* spp., *Callistemon* spp., *Duma florulenta*, *Leptospermum lanigerum* and *Melaleuca brevifolia*.

The ground layer is diverse with grasses, sedges and herbs, including *Acaena echinata*, *Baumea juncea*, *Carex* spp., *Chorizandra enodis*, *Cyperus* spp., *Dichondra repens*, *Distichlis distichophylla*, *Eleocharis acuta*, *Gahnia trifida*, *Juncus kraussii*, *J. sarophorus*, *Phragmites australis*, *Poa labillardieri*, *Lobelia concolor*, *Rumex brownii*, *Schoenus apogon* and *Typha domingensis*.

15. Grassland

Largely cleared in the CLLMM region, few examples of what this community may have resembled remain in the landscape. Generally, these are found between Wellington Lodge and Cooke Plains in the north-eastern part of the CLLMM region.

This grassland community is characterised by *Lomandra effusa* and *L. multiflora* ssp. *dura* as the dominant species in closely spaced tussocks, covering 10-70 % of the area.

The inter-tussock spaces contain a rich diversity of herbs, grasses and sedges, including *Arista* spp., *Austrostipa* spp., *Bulbine bulbosa*, *Calostemma purpureum*, *Convolvulus remotus*, *Dianella revoluta*, *Dichondra repens*, *Einadia nutans*, *Enchylaena tomentosa*, *Enneapogon nigricans*, *Eutaxia diffusa*, *Goodenia pinnatifida*, *Hyalosperma semisterile*, *Lepidosperma* spp., *Microseris lanceolata*, *Oxalis perennans*, *Pimelea glauca* and *Rytidosperma caespitosum*.

Emergent trees and tall shrubs are either absent or sparse (<10 % cover) and can include *Bursaria spinosa*, *Callitris gracilis*, *Cryptandra tomentosa*, *Dodonaea viscosa* and *Eucalyptus porosa*.

16. Drooping sheoak (*Allocasuarina verticillata*) and native pine (*Callitris gracilis*) woodland

Found in the north-eastern part of the CLLMM region (Bonifacio et al. 2016), generally on the Narrung and Poltalloch Peninsulas, this community is associated with gently undulating sub-coastal plains and dunes as well as the slopes of low hills (Berkinshaw 2009). It grows on shallow sandy loam soils over calcrete (B3 soils) (Table 3.3.3).

This woodland is characterised by *Allocasuarina verticillata* and/or *Callitris gracilis* as the dominant upper layer species, sometimes forming dense stands, with a heathy to an open grassy understorey.

The mid-layer species include *Acacia pycnantha*, *Banksia marginata*, *Bursaria spinosa* ssp. *spinosa*, *Dodonaea viscosa* ssp. *spatulata*, *Myoporum insulare*, *Pittosporum angustifolium*, *Pomaderris paniculosa* ssp. *paniculosa* and *Xanthorrhoea caespitosa*.

The ground layer has a rich diversity of low shrubs, grasses and herbs, including *Anthosachne scabra*, *Astroloma* spp., *Rytidosperma caespitosum*, *Austrostipa* spp., *Billardiera cymosa* ssp. *cymosa*, *Burchardia umbellata*, *Calostemma purpureum*, *Cryptandra tomentosa*, *Dianella revoluta* ssp. *revoluta*, *Dichondra repens*, *Gahnia deusta*, *Helichrysum leucopsideum*, *Kennedia prostrata*, *Kunzea pomifera*, *Lasiopetalum baueri*, *Lepidosperma* spp., *Lomandra effusa*, *Themeda triandra* and *Thomasia petalocalyx*.

Table 3.3.3 A summary of the dominant soil types found in the CLLMM region. (Based on Hall et al. 2009)

Soil type	Description
B2	Grey to red-brown loamy sand to light clay, but most commonly loamy, usually in a shallow to very shallow layer. Situated on gently undulating plains, rises and low hills, and often associated with dunefields, old coastal dune ranges and coastal sand spreads.
B3	Shallow (0-9 cm) brown to red sandy loam to light clay over a hard base of calcrete (~20 cm depth). As with B2 soils, B3 soils are mostly situated on level to gently undulating plains, but can occur on rises and low hills, and are often associated with dunefields, old coastal dune ranges and coastal sand spreads.
B6	Shallow, red-brown loam or clay loam over calcrete. Found in old coastal dunes or on flat to undulating land.
B8	Shallow, pale brown sand over calcrete. Found in coastal and near coastal flats, rises and dunes.
D2	Reddish brown loams over red clay and located on valley floors and gentle slopes of the Mount Lofty Ranges.
D3	Dark reddish brown loams over poorly structured red clay and located on similar landforms to D2 soils.
D5	Hard loamy sand over red clay soils.
F1	Loam over brown or dark clay. They are commonly found in the Mount Lofty Ranges on plains and rises. The top 20-30 cm are made up of dark loam soil and below that the soil is yellowish brown to light grey clay.
G3	Thick, sandy soils over clay found on flats, sandy rises and on low dunes.
G4	Dark greyish loamy sand layer in the first 8 cm, below which is a brown loamy sand (25 cm) and then a shallow yellowish red to yellowish brown clay layer (below 25 cm).
G5	Sands over acidic clay. The first 20-40 cm in this layer are made up of dark grey to pale brown loamy sand, below which is yellowish brown sandy clay loam. Found in high rainfall areas of the Mount Lofty Ranges.
H1	Carbonate sand making up coastal sand dunes. Coastal dunes found further inland may also be made up of this soil type.
H2	Siliceous sands found on inland linear dunes and coastal dunes.
H3	Deep soils, with the first 8 cm containing dark brown loose sands followed by a bleached sub-surface layer (very pale brown, 8-35 cm deep). Below this, the soil is a brownish yellow colour. These are closely associated with G3 soils.
K3	Acidic sandy loam structure over red clay. They are common in the Mount Lofty Ranges on hillsides. The first 20-30 cm are made up of a dark greyish brown sandy loam below which is red to yellowish brown heavy clay.
N2	Highly to extremely saline soils affected by shallow saline water tables and ranging from deep clays to sand over clays to deep sands. N2 soils occur where saline groundwater comes close to the land surface (~1 m) with poor to very poor drainage. They are associated with tidal flats, swamps, closed depressions and drainage depressions.
N3	Affected by prolonged wetness but are not peaty or highly to extremely saline. N3 soils are situated in low-lying and poorly to very poorly drained areas, mostly in high rainfall areas.

REVEGETATION ACTIVITIES (2011-2016)

The CLLMM project area was a 5 km buffer around the Lower Lakes and Coorong (Fig. 3.3.1) that was designed to reduce the effects of environmental impacts on the Ramsar wetland. Restoration activities as a part of the CLLMM Vegetation Program began in 2011 and were largely completed in 2015, with a smaller proportion planted in 2016, resulting in over

4.2 million plants (tube-stock) being planted on over 1 500 ha of private and public land at 148 sites (Fig. 3.3.2). The identification and mapping of the plant communities were used as a guide for restoration activities to ensure that priority communities were planted in appropriate locations. As such, the communities planted generally resembled those listed above, although they differed slightly, depending on site-specific characteristics. While terrestrial and wetland restoration was undertaken, this chapter specifically describes the terrestrial restoration.

Restoration plantings were implemented in a variety of distinct zones or vegetation communities, signifying differences in landforms and soil types including saline areas, sand hills, sandy loam soils over calcrete and sandy loam soils over clay. The topography of these areas also varied from hilly landscapes closer to the Mount Lofty Ranges, to flatter areas south-east of Lake Alexandrina and Lake Albert along the Coorong.

The CLLMM Vegetation Program worked in collaboration with the Goolwa to Wellington Local Action Planning Association (GWLAP), the Ngarrindjeri Regional Authority and

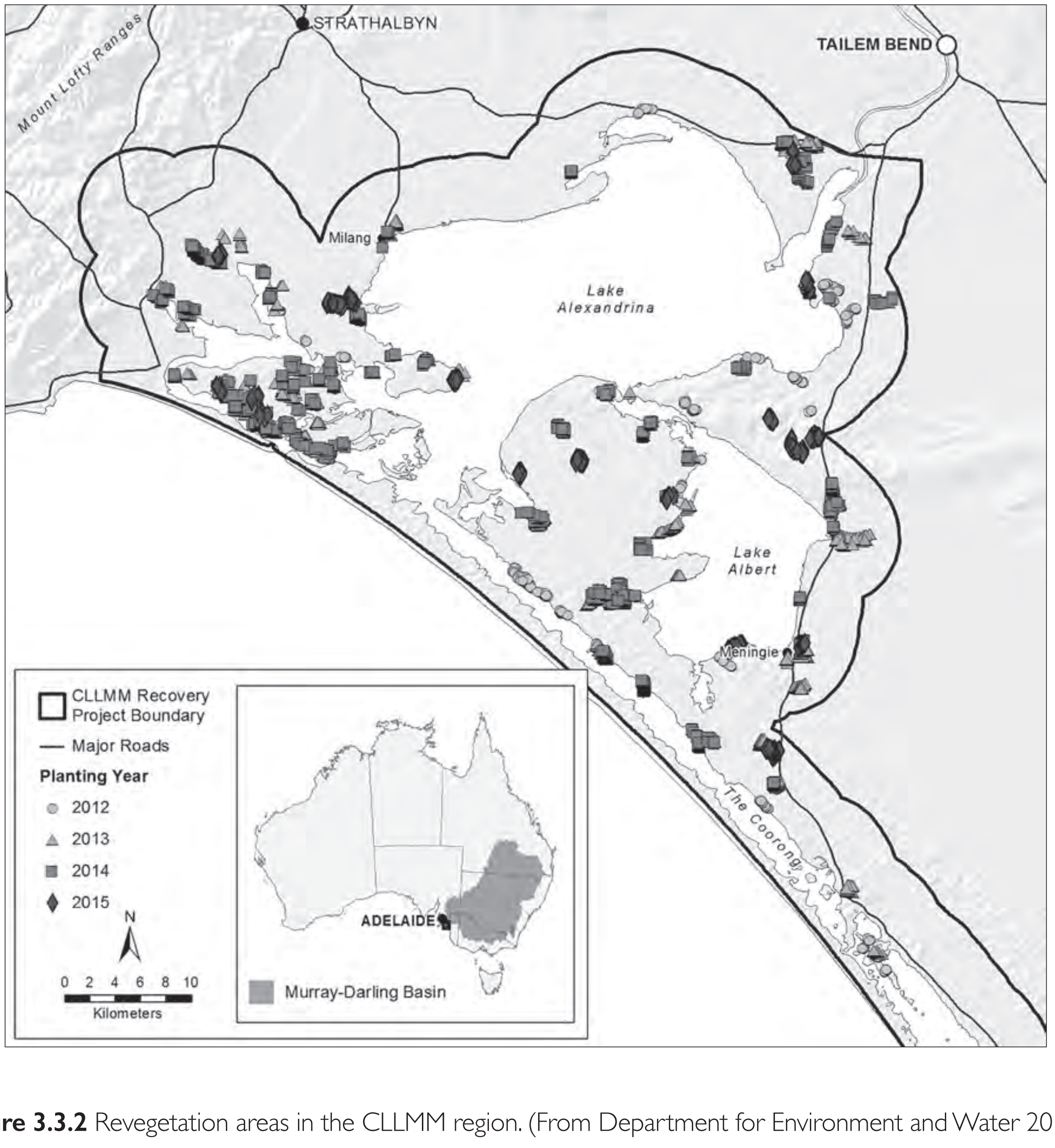

Figure 3.3.2 Revegetation areas in the CLLMM region. (From Department for Environment and Water 2017)

commercial contractors to achieve the planting of 4.2 million plants of 202 different species; these comprised ~11 % overstorey, 38 % midstorey and 51 % understorey species. They were all planted as tube-stock and were native to the surrounding landscape.

While revegetation activities were undertaken by different groups, planting methods were similar and plants were generally guarded. As the majority of the planting areas had been cleared and used for agricultural production, prior to planting all sites were fenced from livestock and sprayed with a herbicide to reduce competition from exotic grasses.

ACKNOWLEDGEMENTS

This information was developed as a part of the CLLMM Recovery Project (2011-2016), a A$137 million investment by the South Australian Government's Murray Futures program and the Australian Government to enhance the resilience of this Ramsar-listed wetland. The Vegetation Program was delivered through a partnership between the South Australian Government, local community groups and the Ngarrindjeri Regional Authority. The priority vegetation communities identified in this chapter, and the planting lists associated with these communities, were developed in order to fulfill the goals of the Vegetation Program.

We thank those who provided the expert opinion for this chapter — Kerri Muller, Susan Gehrig, Janet Pedler, Ben Simon, Will Miles, Terry Sim and Ann Prescott. We also thank the Ngarrindjeri and local landholders who allowed us access to their properties.

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CHAPTER 3.4

ESTUARINE AND LAGOON MACRO-INVERTEBRATES — PATTERNS AND PROCESSES

SABINE DITTMANN[1,2], ALEC ROLSTON[1,3] AND RYAN BARING[1]

INTRODUCTION

Sediments of estuaries and lagoons are home to a variety of invertebrates. Benthic macro-invertebrates comprise organisms, such as bristleworms, molluscs or crustaceans, which are larger than 0.5 mm in size and live in the sand and mud, or on the sediment surface. Most of these macro-invertebrates are solitary, but tubeworms can construct larger biogenic reefs. In the Coorong and Murray Mouth, larval life stages of insects are also found living associated with sediments. Benthic macro-invertebrates perform ecosystem functions through their activities, such as improving sediment conditions through bioturbation. Bioturbation, together with ecosystem engineering through the provision of biogenic habitat, constitute sediment-mediated biotic processes carried out by macro-invertebrates (Reise 2002). Macro-invertebrates are also key to trophic interactions in estuaries, as they represent various feeding modes (e.g. deposit feeder, suspension feeder, grazer, predator), and constitute one of the most important food sources for fish and shorebirds (Humphries & Potter 1993; Gamito & Furtado 2009; Verissimo et al. 2012). As prey items, macro-invertebrates are relevant in supporting fish and shorebird populations in the Coorong and Murray Mouth (Chapters 3.6, 3.7 & 4.1). The position of macro-invertebrates in the food web implies that notable changes to their abundances have flow-on effects to higher trophic levels (Finn et al. 2008; Spruzen et al. 2008). Macro-invertebrate communities that are taxonomically and functionally diverse and provide abundant harvestable prey for fish and shorebirds can support a functioning and resilient estuarine and lagoonal ecosystem (Kim & Montagna 2012; Greenfield et al. 2016).

Because of strong interactions with environmental conditions, macro-invertebrates are commonly used as indicators for changes in estuarine ecosystems. In the Coorong and Murray Mouth, drought and flood events have induced changes in the macro-invertebrate communities, and understanding of this response pattern can advance the understanding of environmental watering requirements in this highly regulated estuary. This chapter presents spatial and temporal patterns of macro-invertebrate communities in the sediments and tubeworm reefs of the Murray Mouth and Coorong, the abiotic processes driving these patterns through changing environmental conditions, and the resulting changes in biotic processes influenced by macro-invertebrates.

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MACRO-INVERTEBRATE DIVERSITY

Over 60 species of macro-invertebrates have been recorded from the Murray Mouth and Coorong (Table 3.4.1). Bristleworms (Annelida) and crustaceans are the most numerous in species, followed by insects and molluscs. Most species (50) are found in the Murray Mouth, fewer in the North Lagoon (40) and only 22 species (mostly insect larvae) in the South Lagoon. The Murray Mouth (MM) and North Lagoon (NL) have more species in common compared to the Murray Mouth and South Lagoon (SL), but the North and South Lagoons share some species as well. Several species occur only in association with tubeworm reefs or have only been found on settlement plates deployed in the Murray Mouth region. Macro-invertebrates with a more demersal life style, moving between the water column and sediment, are also found (e.g. mysid shrimp, brine shrimp and some ostracods).

The overall number of species present in the Coorong and Murray Mouth is likely to be higher than presented here, as sampling across various monitoring programs (2004 to current) has concentrated on the near-shore sediments and habitats. Furthermore, the highly abundant amphipods and small-sized hydrobiid snails can contain several species difficult to differentiate. Six morpho-species of hybrobiid snails have been differentiated (including species of the genera *Hydrobia* and *Tatea*). Rare finds (single individuals found on one or few occasions) of larval stages of insect taxa are not included in Table 3.4.1.

The number of macro-invertebrate species recorded from the Murray Mouth and Coorong is comparable to other estuaries and lagoons around southern Australia, and over one-third of the species occur in similar habitats throughout temperate Australia (Jones 1987; Edgar et al. 1999; Hirst 2004; Wildsmith et al. 2009, 2011; Tweedley et al. 2012). In addition to macro-invertebrates, over 40 genera of meiobenthic nematodes, living in between the grains of mud and sand, have been found in the Murray Mouth estuary (Nicholas et al. 1992).

Macro-invertebrates can occur in very high abundances in the Murray Mouth and Coorong (Dittmann et al. 2015). The five most abundant taxa recorded in long-term monitoring are amphipods, polychaetes (*Capitella capitata*, *Simplisetia aequisetis*), bivalves (*Arthritica helmsi*) and chironomid larvae (Fig. 3.4.1). The most abundant bivalve (*A. helmsi*) is a very small-sized species (~5 mm max. shell size). The majority of the macro-invertebrates live in the top layer of the sediments, and only some of the polychaetes (e.g. *S. aequisetis*, *Australonereis ehlersi*) and larger bivalves (e.g. *Soletellina alba*) live deeper in the sediment or build burrows reaching over 10 cm into the sandy mud. Functional classification has conveyed that many of the abundant macro-invertebrate species are deposit feeders or grazers (Table 3.4.2) (Dittmann et al. 2016). Many polychaetes have flexibility in their feeding mode and reproductive pattern (pelagic/benthic), subject to habitat conditions. Such flexibility is seen as an adaptation to changing environmental conditions in estuaries (Bernhardt & Leslie 2013).

SPATIAL GRADIENT

The Murray Mouth and Coorong Lagoons are characterised by a strong gradient in environmental conditions, particularly salinity, which is increasing towards the southern reaches of the Coorong (Chapters 2.6 & 2.7), and the macro-invertebrates' distribution and abundance reflect this gradient. Based on >10 years of monitoring, a clear pattern emerges, with diversity, abundance and biomass highest at the Murray Mouth, then decreasing southward into the

Table 3.4.1 List of macro-invertebrate taxa recorded in the Murray Mouth (MM) and the North (NL) and South Lagoon (SL) of the Coorong, based on studies by Geddes and Butler (1984), Geddes (1987, 2005), Rolston and Dittmann (2009), as well as on condition monitoring since 2004 (see, for example, Dittmann & Baring 2016), CLLMM monitoring (Dittmann et al. 2016) and several student projects (Goldschmidt 2010; Keuning 2011; Kirkpatrick 2011; Earl 2014). The taxonomy has been updated and where previous species names were no longer accepted, a higher classification or sp. indet. for undetermined identification included. Hexapoda occurred mostly as larvae or pupae.

Phyla	Class/Order	Family	Species	MM	NL	SL
Platyhelminthes						
	Polycladida	Notoplanidae	*Notoplana australis*	✓		
Annelida						
	Oligochaeta		sp. indet.	✓	✓	✓
	Polychaeta	Capitellidae	*Capitella* cf. *capitata*	✓	✓	✓
	Polychaeta	Capitellidae	*Capitella* sp.	✓	✓	
	Polychaeta	Phyllodocidae	*Phyllodoce novaehollandiae*	✓	✓	
	Polychaeta	Nereididae	*Simplisetia aequisetis*	✓	✓	✓
	Polychaeta	Nereididae	*Australonereis ehlersi*	✓	✓	
	Polychaeta	Nephtyidae	*Aglaophamus (Nephtys) australiensis*	✓	✓	
	Polychaeta	Orbiniidae	sp. indet.	✓		
	Polychaeta	Spionidae	*Boccardiella limnicola*	✓	✓	
	Polychaeta	Spionidae	*Prionospio aucklandica*	✓		
	Polychaeta	Serpulidae	*Ficopomatus enigmaticus*	✓	✓	
	Polychaeta	Sabellidae	*Euchone variabilis*		✓	
	Polychaeta	Syllidae	sp. indet.	✓		
Nemertea						
	Nemertea		sp. indet.	✓	✓	
Mollusca						
	Bivalvia	Lasaeidae	*Arthritica helmsi*	✓	✓	✓
	Bivalvia	Galaeommatidae	sp. indet.	✓	✓	
	Bivalvia	Mactridae	*Spisula (Notospisula) trigonella*	✓	✓	
	Bivalvia	Psammobiidae	*Hiatula (Soletellina) alba*	✓	✓	
	Bivalvia	Mytilidae	*Limnoperna* sp.	✓		
	Gastropoda	Hydrobiidae	sp. indet. (6 species)	✓	✓	✓
	Gastropoda	Amphibolidae	*Salinator fragilis*	✓	✓	
	Gastropoda	Pomatiopsidae	*Coxiella striatula*			✓
	Gastropoda	Nassaridae	*Nassarius pauperatus*	✓		
	Gastropoda	Bullidae	*Bulla* sp.	✓		

Phyla	Class/Order	Family	Species	MM	NL	SL
Crustacea						
	Amphipoda		sp. indet.	✓	✓	✓
	Amphipoda	Corophiidae	*Paracorophium* sp.	✓	✓	✓
	Amphipoda	Melitidae	*Melita* sp.	✓	✓	
	Amphipoda	Isaeidae	*Gammaropsis* sp.	✓	✓	
	Amphipoda	Ampithoidae	sp. indet.	✓		
	Isopoda	Scyphacidae	*Haloniscus searlei*		✓	✓
	Ostracoda		sp. indet.	✓	✓	✓
	Cirripedia	Balanidae	*Amphibalanus variegatus*	✓		
	Tanaidacea		sp. indet.	✓		
	Mysidacea		sp. indet.	✓	✓	
	Anostraca	Parartemiidae	*Parartemia zietziana*			✓
	Decapoda	Alpheidae	*Alpheus richardsoni*	✓		
	Decapoda	Palaemonidae	*Palaeomon sp.*		✓	
	Decapoda	Callianassidae	*Biffarius limosus*	✓	✓	
	Decapoda	Macrophthalmidae	*Tasmanoplax (Macrophthalmus) latifrons*	✓		
	Decapoda	Varunidae	*Paragrapsus gaimardii*	✓	✓	
	Decapoda	Varunidae	*Helograpsus haswellianus*	✓		
	Decapoda	Hymenosomatidae	*Amarinus laevis*	✓	✓	
	Decapoda	Hymenosomatidae	*Halicarcinus ovatus*	✓		
	Decapoda	Pilumnidae	*Pilumnopeus serratifrons*	✓		
Hexapoda						
	Collembola		sp. indet.		✓	✓
	Diptera	Chironomidae	sp. indet.	✓	✓	✓
	Diptera	Chironomidae	*Tanytarsus* sp.	✓	✓	✓
	Diptera	Chironomidae	*Paratendipes* sp.	✓	✓	✓
	Diptera	Chironomidae	*Demicryptochironomus* sp.	✓	✓	✓
	Diptera	Ephydridae	sp. indet.	✓	✓	✓
	Diptera	Dolichopodidae	sp. indet.	✓	✓	✓
	Diptera	Ceratopogonidae	sp. indet.	✓	✓	✓
	Diptera	Culicidae	sp. indet.	✓	✓	✓
	Diptera	Stratiomyidae	sp. indet.	✓	✓	✓
	Diptera	Empididae	sp. indet.	✓	✓	✓
	Coleoptera	Staphylinidae	sp. indet.	✓	✓	
Total number of taxa by region				50	40	22

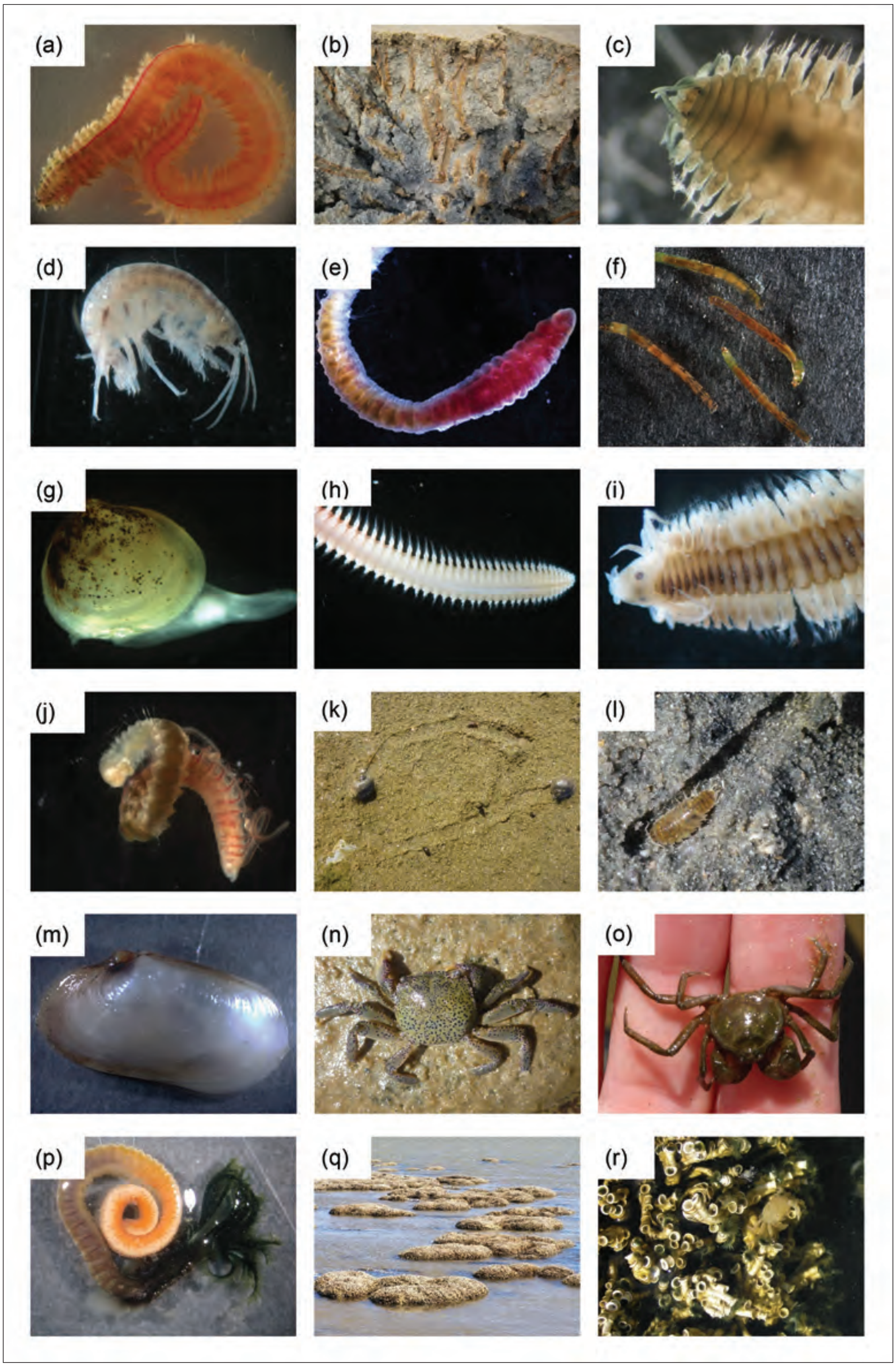

Figure 3.4.1 Macro-invertebrates occurring in the Murray Mouth and Coorong and some examples of associated biogenic structures.
(a) *Simplisetia aequisetis;* (b) burrows in sediment made by *S. aequisetis;* (c) *Australonereis ehlersi;* (d) *Amphipoda;* (e) *Capitella capitata;* (f) chironomid larvae; (g) *Arthritica helmsi;* (h) *Nephtys australiensis;* (i) *Phyllodoce novaehollandiae;* (j) *Boccardiella limnicola;* (k) snails on the sediment surface, including *Salinator fragilis* and the smaller Hydrobiidae; (l) isopod (*Haloniscus searlei*); (m) *Hiatula alba;* (n) *Paragrapsus gaimardii;* (o) *Amarinus laevis;* (p) *Ficopomatus enigmaticus;* (q) tubeworm reefs; (r) detail of tubeworm reef with juvenile *P. gaimardii*
(Photographs (a)-(q) by S. Dittmann, A. Rolston and R. Baring. Photograph (r) by M. Nelson.)

Coorong (Fig. 3.4.2). The North Lagoon has the highest rate of change in salinities, and with it, benthic communities are shifting. In years with strong river flows entering the Coorong, estuarine macro-invertebrate distributions extend further south in the North Lagoon, while in years with low flows, distributions contract to the Murray Mouth (Dittmann et al. 2015). This ecological shift in macro-invertebrate communities has been most pronounced around Noonameena (Site 7 in Fig. 3.4.2(a)). Salinity is the strongest environmental determinant for this shift, with a salinity threshold of 64 ppt separating communities in the Murray Mouth and parts of the North Lagoon from a hypersaline community found in the southern reaches of the Coorong (Dittmann et al. 2015).

As in estuaries globally (Whitfield et al. 2012), salinity is a main driver for the distribution of macro-invertebrates in the Murray Mouth and Coorong. Several species have been found over a wide range of salinities, but occur with highest abundances over a narrower range of salinities (Table 3.4.2). The tolerance of many key taxa (e.g. *Simplisetia aequisetis*, amphipods

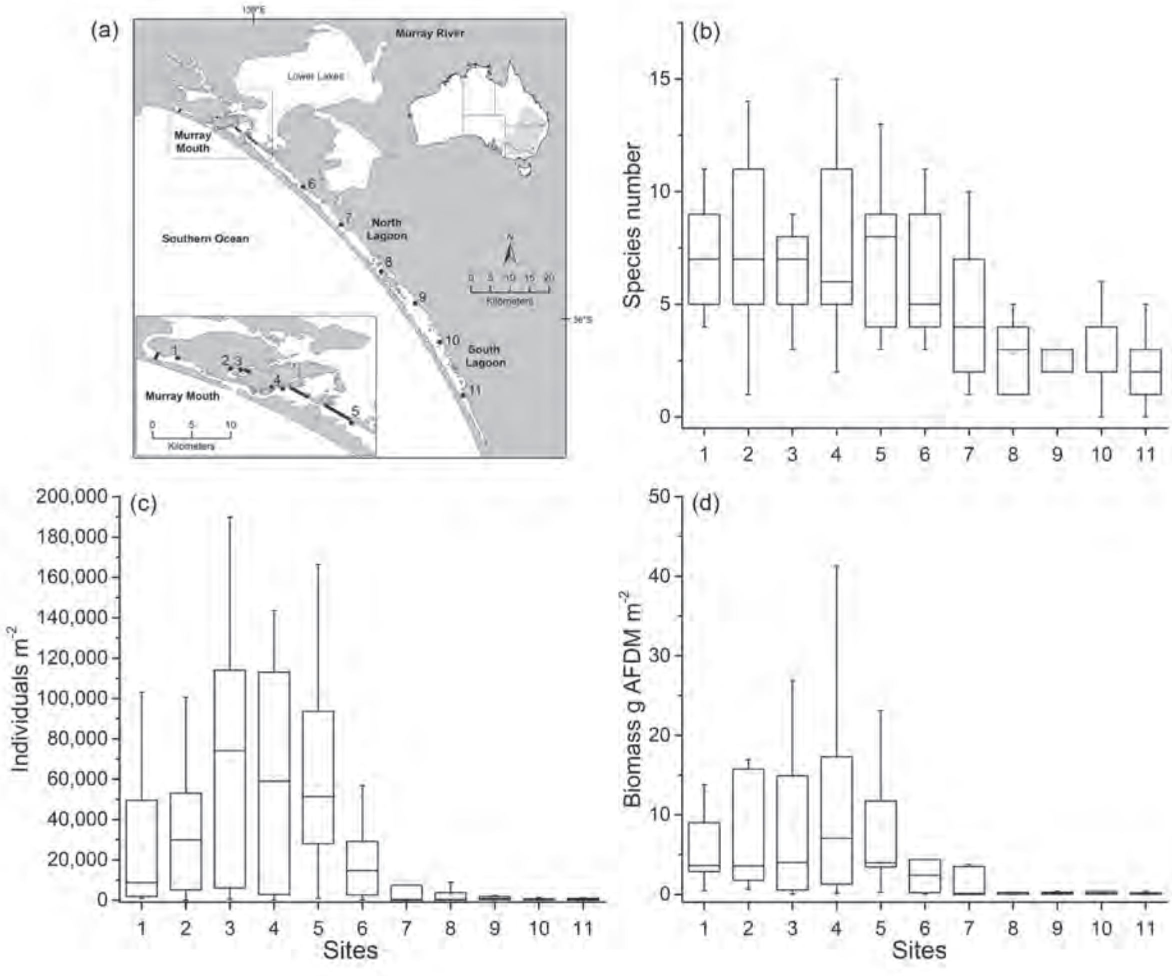

Figure 3.4.2 Spatial gradient of macro-invertebrates from long-term monitoring sites.
(a) Map showing location of sampling sites of The Living Murray condition monitoring.
(b) Species numbers.
(c) Abundance.
(d) Biomass (Ash-free Dry Mass AFDM).
Box plots are based on monitoring carried out annually in spring/early summer from 2004-2013, and 2015.

Table 3.4.2 Tolerance ranges, habitat requirements and life-history attributes for the most common macro-invertebrates found in the Murray Mouth and Coorong. DO = dissolved oxygen. (Based on long-term monitoring data, authors' observations and relevant literature. See also Rolston et al. (2010); Oliver (1971); Dorsey (1981); Glasby (1986); Beesley et al. (1998); Corfield (2000); Jumars et al. (2015).)

Species/Taxa	Habitat				Life History Strategies	
	Salinity (ppt)	**DO (mg/L)**	**Environmental tolerance**	**Sediment Interactions**	**Feeding Mode**	**Reproductive Mode (larvae)**
Capitella capitata	0-90	3-11	Tolerant of poor environmental conditions and organically enriched sediments	Construct mucus-lined burrows	Sub-surface deposit feeder (non-selective)	Pelagic planktotrophic larvae
Nephtys australiensis	0-50	5.5-11	Tolerant of acidified conditions	Burrowing	Predator	Pelagic planktotrophic larvae
Boccardiella limnicola	0-40	6-13	Tolerates freshwater habitats	Constructs small sediment tubes	Suspension and deposit feeder	Possibly reproductive variability, pelagic-planktotrophic or brooding
Australonereis ehlersi	20-50	6.5-11	Intolerant of low oxygen concentration, adverse environmental conditions	Bioturbation, ecosystem engineer (tube builder)	Omnivore and deposit feeder	Brooding
Simplisetia aequisetis	0-70	4-13	Tolerates low oxygen concentrations, organically enriched sediments	Bioturbation, ecosystem engineer (burrow or tube builder)	Omnivore and selective deposit feeder	Brooding, but reproductive variability
Oligochaeta	0-60	4.5-11.5		Sediment surface modifier	Deposit feeder, detritivore	Benthic
Amphipoda	0-105	4-13		Sediment destabilisation, can construct small burrows	Deposit and suspension feeder, omnivore, predator	Brooding
Ostracoda	30-120	4-13		Demersal, no bioturbation	Grazer	Mix of reproductive strategies
Chironomidae	0-140	4-13.5	Tolerates low oxygen concentrations	Free-living or constructing delicate sediment tubes	Deposit and detritus feeder, grazing of algae	Only larval life stage aquatic
Arthritica helmsi	0-75	4.5-13		Burrowers — surface layers, free-living	Suspension feeder	Brooding, releases benthic juveniles
Salinator fragilis	0-45	5.5-11.5		Free-living, sediment surface modifier	Deposit feeder and grazer	Eggs deposited on mud
Hydrobiidae	0-45	5.5-13		Free-living, sediment surface modifier	Deposit feeder and grazer	Pelagic-planktonic, benthic

(Kangas & Geddes 1984), chironomid larvae, *Capitella capitata*) to a wider range of salinities and to extremely high salinities can be an adaptation to the changing salinity conditions in the Murray Mouth and Coorong. Species with narrower salinity tolerance (e.g. *Australonereis ehlersi*, *Nephtys australiensis*, *Boccardiella limnicola*) have narrower spatial distribution, and lower abundances when unfavourable salinities prevail.

Spatial gradients of macro-invertebrates in estuaries can further result from sediment properties, such as grain-size composition or organic matter content, and dissolved oxygen (DO). The most common macro-invertebrate species vary in their lower DO tolerance threshold (Table 3.4.2). Lower DO concentration during the 2010 flood event also reduced abundances of macro-invertebrates at sampling sites near the barrages in the Murray Mouth (Dittmann et al. 2015).

DROUGHT AND FLOOD RESPONSE AND RECOVERY

Since the construction of the barrages and water regulation in the Murray-Darling river system, river flows reaching the Murray Mouth and Coorong have been constrained and periods occur with low or no flow over the barrages, exacerbating drought conditions. Effects of drought and flood on macro-invertebrates have been investigated in the early 1980s (Kangas & Geddes 1984; Geddes 1987) and over the last decade (Dittmann et al. 2015). During droughts, extreme hypersalinity affects a wider area of the Coorong and Murray Mouth, and lower water levels cause long-term exposure of mudflat sediments, which thus become uninhabitable for macro-invertebrates. As a consequence, distribution ranges of macro-invertebrate species become restricted, their abundances decline, and several species are no longer found if drought conditions persist over several years.

The recovery after a drought disturbance can take years, subject to species-specific responses and also to the pattern of flow intensity and flow duration following the drought. Amphipods and chironomid larvae respond quickly to freshwater inflows, and their abundances increase to very high numbers throughout most of the Murray Mouth and Coorong. For most other macro-invertebrate species, a time lag in recovery has been noted (Geddes 1987; Dittmann et al. 2015), subject to their life-history, tolerance to salinities and dissolved oxygen concentrations, and habitat suitability. The development of any conceptual link between flows and macro-invertebrates requires consideration of their response to flow volumes, the continuity of flow, and the lengths of a drought period. Dittmann et al. (2015) combined these flow characteristics in an index, showing beneficial effects for macro-invertebrates of continuous inflows of intermediate to above average flow volumes (Fig. 3.4.3). This response pattern illustrated that continuity of flow over the barrages is relevant to sustain macro-invertebrate communities and thus food supply for higher trophic levels in the Coorong.

Recolonisation pathways into near-shore sediments can be through fluctuating water levels with tides or wind seiching, but many estuarine and lagoon macro-invertebrate species have low dispersal abilities. Sampling of macro-invertebrates from deeper and shallow near-shore sediments over several years after the 2010 flood indicated that sediments in deeper sections can function as a refuge during the drought and flood event, and provide a source for macro-invertebrate recolonisation of the near-shore sediments (Dittmann et al. 2016). Yet for some species the source population for recolonisation may have been reduced within

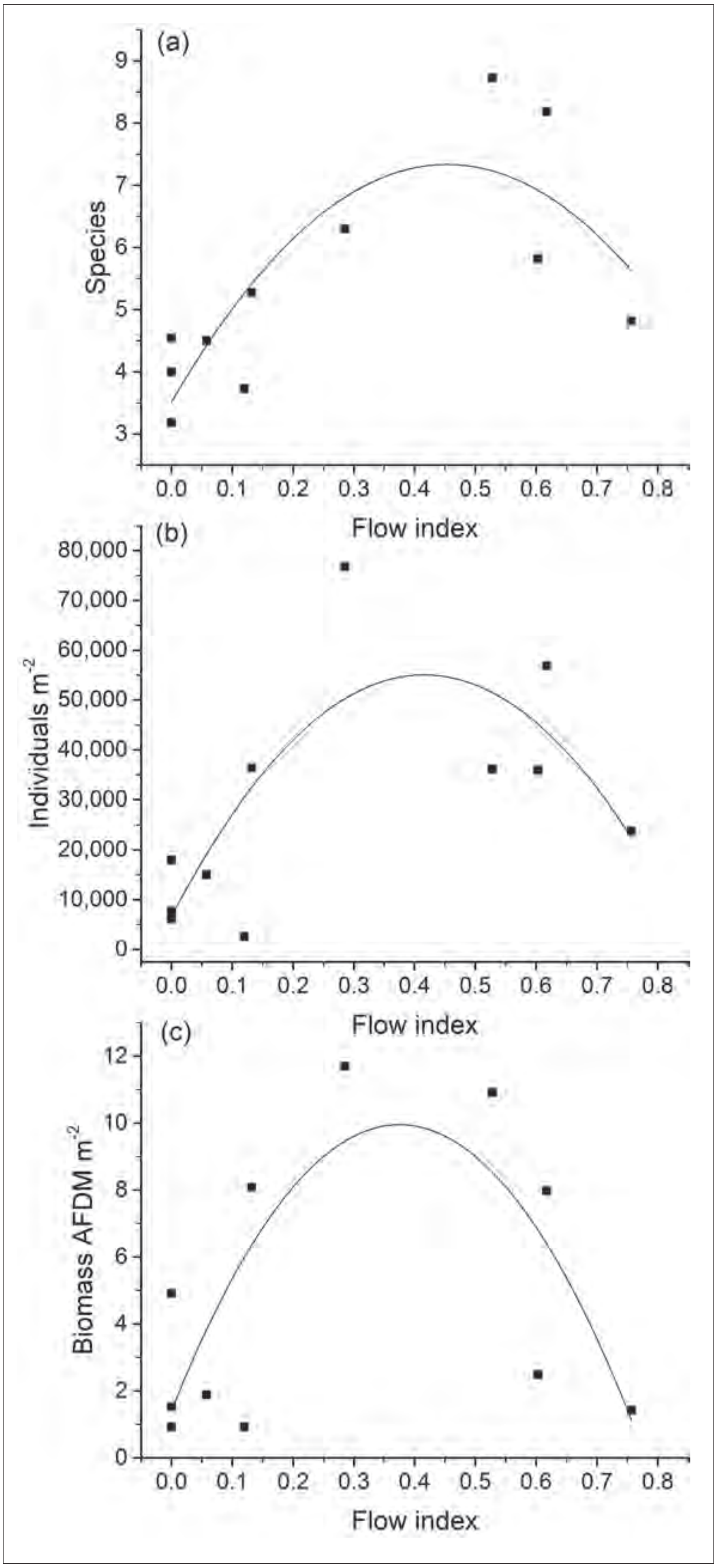

Figure 3.4.3 Scatterplots of average macro-invertebrate species and individual densities and biomass based on The Living Murray spring/early summer monitoring from 2004-2015 in relation to the flow index (see Dittmann et al. (2015) for further details). Low values of the index indicate conditions of no or low flow, but also high flows after a prolonged drought. The index is closer to 1 when inflows are continuous and exceed the long-term average flows. The lines indicate fitted curves.

the Murray Mouth and Coorong, and dispersal from estuaries further afield may account for their delayed return to the system. Even some of the key estuarine-lagoonal species, such as *Arthritica helmsi* and *Simplisetia aequisetis*, increased in abundances and distribution ranges only several years after flows were restored. In particular, the first occurrence of estuarine-lagoonal macro-invertebrates in the South Lagoon was only noted some years after the 2010 flood event. This slow recolonisation could result from a combination of unsuitable habitat in the South Lagoon and dispersal.

The taxonomic and functional composition of macro-invertebrates differs in space throughout the Murray Mouth and Coorong, and over time in relation to drought and flood periods. A conceptual model of changes in environmental drivers to drought and flood events, and during estuarine-marine conditions, illustrates macro-invertebrate responses that lead to differences not only in diversity, abundance and biomass, but also in ecological functions (Fig. 3.4.4). Few larger-bodied organisms occur under drought conditions, and overall numbers are low. Under flood conditions, small-bodied opportunistic species (e.g. amphipods, chironomid larvae, capitellid polychaetes) can be abundant and can account for some bioturbation at the sediment-water interface, which slightly improves the depth of the

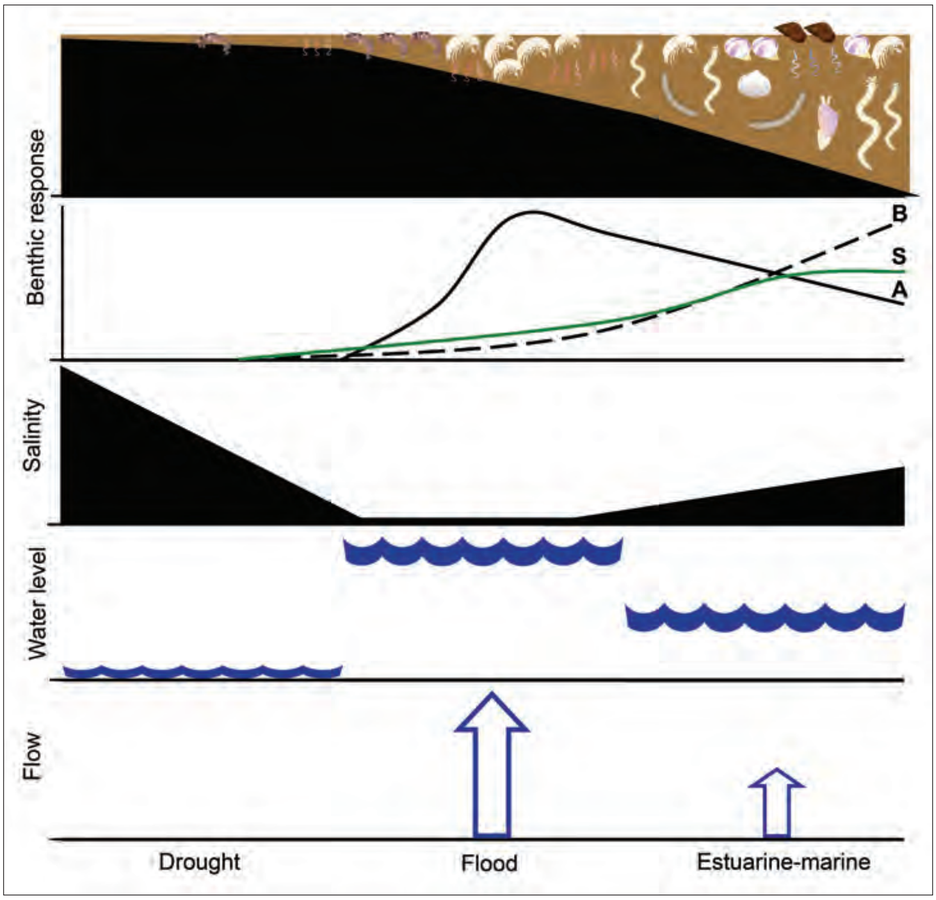

Figure 3.4.4 Conceptual diagrams of changes to the main environmental drivers (water level and salinity) and response by benthic macro-invertebrates occurring in sand or mud of the Coorong and Murray Mouth during drought, flood and estuarine-marine conditions. The black and grey shading in the top diagram indicate anoxic and oxic sediment layers respectively. B = Biomass; S = Species richness; A = Abundance. The conceptual diagrams can also be seen in a spatial context, with conditions under drought characteristic for the South Lagoon, and estuarine-marine conditions for the North Lagoon and Murray Mouth.

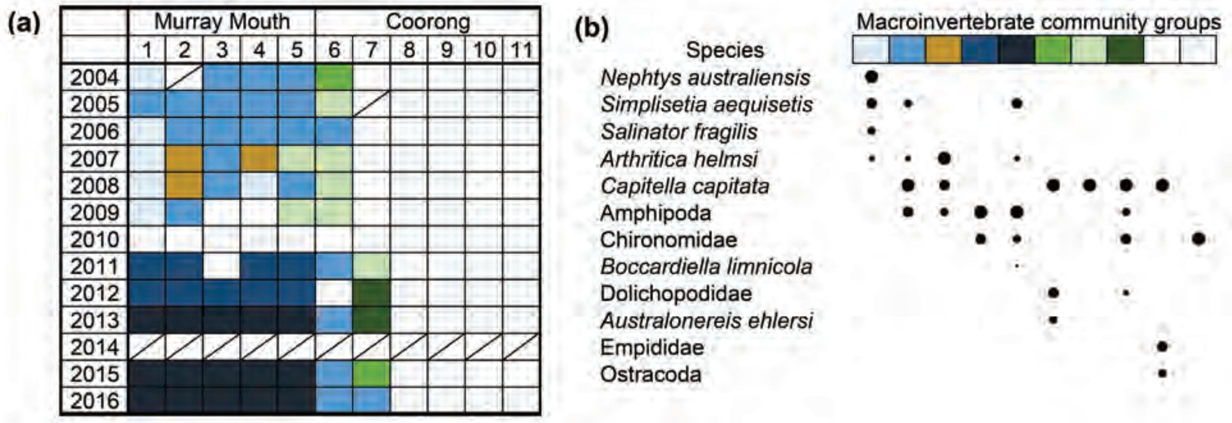

Figure 3.4.5 (a) Changes in the spatial and temporal distribution of macro-invertebrate communities in nearshore sediments of the Murray Mouth and Coorong, based on The Living Murray condition monitoring from 2004-2016. No monitoring occurred in 2014, indicated by crossed-out cells; this also applies to two further sites not sampled in single years. The different grey shadings in (a) represent significantly different communities determined by multivariate Similarity Profiles Analysis (SIMPROF) and in (b) identify the species characterising each community, with dot sizes indicating decreasing rank order of their contribution to abundances in each community. Sites 6 to 8 are located in the North Lagoon, and sites 9 to 11 in the South Lagoon of the Coorong. See also map in Fig. 3.4.2a.

oxic layer, but macro-invertebrate biomass stays low. Under estuarine-marine conditions with more continuous river flows, a more diverse and abundant benthic community occurs. This community is accompanied with higher functional diversity, including deeper bioturbation, benthic-pelagic coupling through suspension-feeding bivalves, and provision of food for higher trophic levels. The overall pattern seen in this conceptual model resembles the well-known response of benthic macro-invertebrates to disturbances (Pearson & Rosenberg 1978).

HISTORICAL AND COMMUNITY CHANGES OVER TIME

The first macro-invertebrate studies were carried out in the early 1980s (Geddes & Butler 1984), several decades after the barrages were built. Such studies intensified in the early 2000s, and 12 years of monitoring data illustrate changes to communities over time (Fig. 3.4.5). In the Murray Mouth, the changes in communities are mainly drought- and flood-related, and the North Lagoon appears as a transition area, with its own community mostly characterised by the abundance of the small polychaete *Capitella capitata*. The community found in the South Lagoon is almost exclusively characterised by chironomid (midge) larvae. Brine shrimps can also abound in the South Lagoon under hypersaline conditions, as observed during the recent and previous droughts. The main macro-invertebrate species characterising the communities in the Coorong over time are comparable between studies in the 1980s (Geddes & Butler 1984; Geddes 1987) and since 2000 (Dittmann et al. 2015).

Build-ups of bryozoans and serpulid tubeworms were recorded from the Coorong Lagoon by Bone and Wass (1990), and Bone (1991) also detected a population explosion of the encrusting bryozoan *Conopeum* (*Membranipora*) *aciculatum* in the Coorong in spring 1989 after several years of rare occurrence. Bone (1991) suggested that this bryozoan can be used as an indicator for palaeo-salinity, and sub-fossil records of this species indicate a salinity of about 38 ppt in the Coorong 700 years BP (Bone & Wass 1990). As recent salinities in the Coorong are too high for this bryozoan, Bone (1991) suggests that the sudden increase in the population was possibly related to the high freshwater inflow in 1989. Growth of tubeworms and uni-laminar layers of bryozoans were also observed in the North Lagoon after recent inflows (Dittmann *pers. obs.*). The build-ups of serpulid worms and bryozoans can be covered and stabilised by benthic cyanobacteria, leading to the formation of bryostromatolithes (Palinska et al. 1999). The serpulid tubeworms mentioned by Bone and Wass (1990) are possibly *Ficopomatus enigmaticus*, a reef-building species commonly found in the Coorong today.

TUBEWORM REEFS

The tubeworm *F. enigmaticus* builds pronounced reef structures throughout the Murray Mouth and North Lagoon of the Coorong. Near Monument Road, in the Mundoo Channel, at Long Point and Noonameena, clusters of reefs can be found, constituting single reef patches from about 50 cm to over 1 m in diameter. Tubeworm reefs can also occur in the deeper channel sections, where they can reach a greater height and become an obstacle for vessel navigation. The reefs vary over time, and their growth intensifies after freshwater inflows. The reefs are mostly noted when water levels are lower and their spatial extent becomes visible. The reef structure also persists when the worms have died, as can occur if salinities exceed their upper tolerance limit. During the Millennium Drought, when few live *F. enigmaticus* were found in the tubes, the small spionid polychaete *Boccardiella limnicola* built sedimentary lining within the empty tubes and inhabited the reefs in the Murray Mouth.

The tubeworm reefs constitute a three-dimensional biogenic structure, providing additional habitat and hard substrate in the sedimentary environment of the Murray Mouth and Coorong. Small mytilid mussels (*Limnoperna* sp.) and barnacles are found attached to tube structures in Mundoo Channel. Nemerteans rarely seen on the sediment elsewhere also occur amongst the tubeworm structures, as do snapping shrimp (*Alpheus richardsoni*). Juvenile crabs (*Paragrapsus gaimardii*) and the small-sized crab *Amarinus laevis* are found amongst the tubes, where they may find protection from predation, and larger *P. gaimardii* tend to shelter at the reef edge. A range of small mobile crustacean species (tanaids, amphipods) are common amongst the reef structures. Several other species, such as *S. aequisetis*, *C. capitata* and hydrobiid snails, regularly found in sediments, are also found among the reef structures.

Species numbers and individual densities of associated macro-invertebrates are higher in reefs than adjacent sediment (Fig. 3.4.6). At Long Point, the effect is most pronounced at the reef edge. Effects of tubeworm reefs on macro-invertebrate communities are site-specific and also vary between years, based on studies at Monument Road and Long Point in 2010, 2013 and 2015 (Goldschmidt 2010; Moyle 2016). Some of these annual changes reflect the overall recovery of the macro-invertebrate fauna after the drought.

OUTLOOK

The macro-invertebrate fauna constitutes a diverse and functionally important ecosystem component of the Murray Mouth and Coorong. Further studies are needed in order to fully

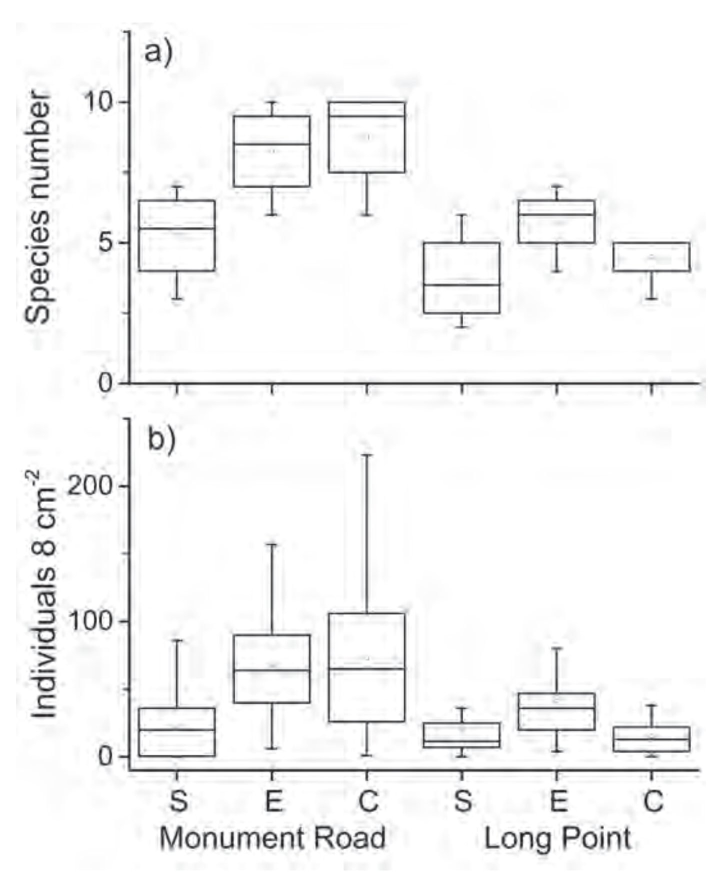

Figure 3.4.6 Box plots of species numbers and individual densities (per surface area of the corer) of macro-invertebrates associated with tubeworm reefs at Monument Road and Long Point, differentiating the location of adjacent sediment (S), the reef edge (E) and the reef centre (C). (Based on several studies from 2010 to 2015)

BOX 3.4.1 TUBEWORM COLONISATION OF THE GOOLWA CHANNEL

The tubeworm *Ficopomatus enigmaticus* occurs in the Murray Mouth and Coorong, but seepage of estuarine water through barrages allowed larval dispersal into Lake Alexandrina in the early stages of the Millennium Drought. With a wide salinity tolerance, preference for sheltered waters with weak currents, ability to cope with eutrophication and low dissolved oxygen concentrations, *F. enigmaticus* found ideal living conditions in the Goolwa Channel (Dittmann et al. 2009). In 2008, colonial growth of tubeworms became an issue of concern for freshwater turtles and bivalves, for coastal infrastructure, and for boats in the Goolwa Channel.

Settlement experiments deployed at multiple sites in Lake Alexandrina during 2008/2009 using several substrates revealed a preference for settlement on rough over smooth substrate. Antifouling paint could reduce or inhibit settlement. Colonisation was fast over the summer months and initial growth of tubes was high, slowing over time as colonies grew. Once tube structures were available, they functioned as settlement substrate for following generations of *F. enigmaticus*, enhancing the growth of the colonies (Dittmann et al. 2009). A similar experiment set up on either side of the Goolwa barrage revealed that tubeworms only colonised plates on the Lake side of the Goolwa Channel, but were outcompeted by barnacles, which colonised all plates on the Murray Mouth side of the barrage (Kirkpatrick 2011).

Further life-history attributes of this species facilitated the invasion. The worms reach maturity after several months, have the ability to spawn repeatedly in their lifetime, and change sex. Furthermore, when mature worms are damaged, gametes may be released into the water column. Physical removal is thus no option to eradicate tubeworms, as it can trigger mass spawning. It remains unknown whether it is a native species or was introduced to Australia (Styan et al. 2017).

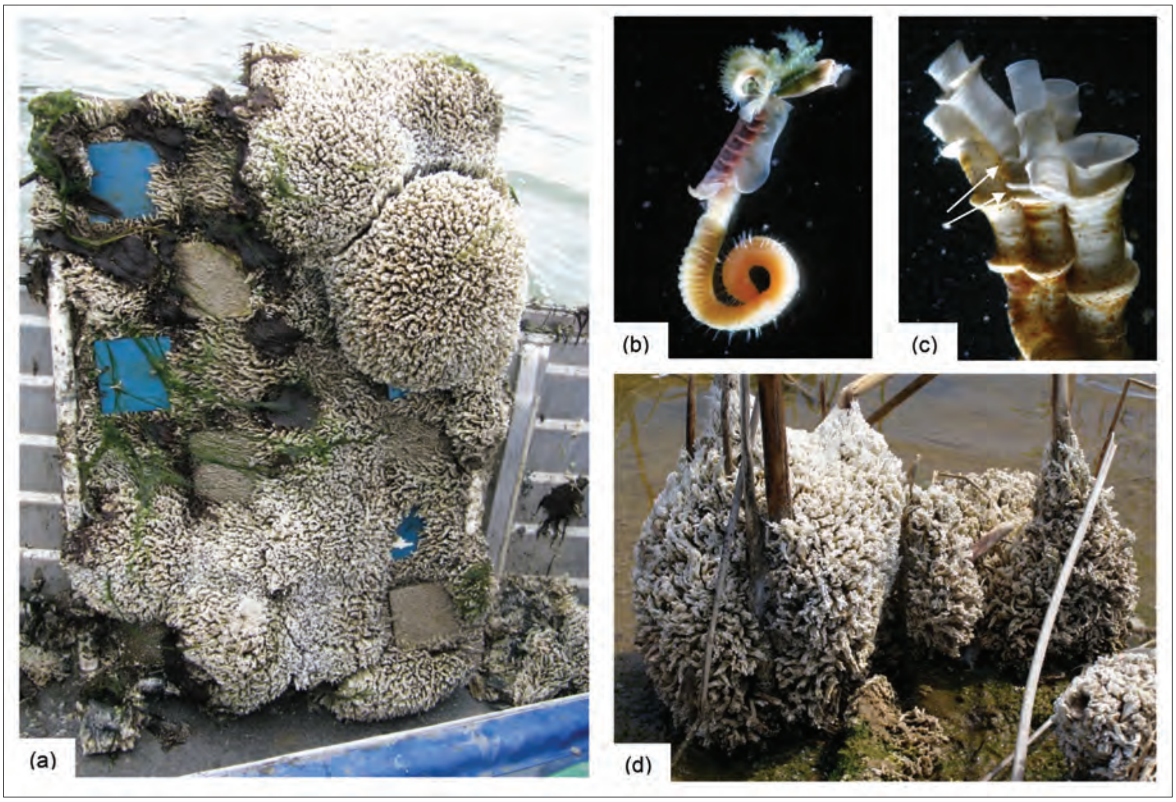

Figure 3.4.7
(a) Colonisation of settlement plates with tubeworms after four months' deployment in the Goolwa Channel. Uncolonised plates were covered with antifouling paint; plates with little colonisation had smooth surfaces and/or antimicrobial paint; the largest colonies were on plates with a rough surface.
(b) The tubeworm *Ficopomatus enigmaticus.*
(c) Small tubes of juvenile *F. enigmaticus* on a colony fragment, indicated by arrows.
(d) Tubeworms growing around reeds near Goolwa.
(Photographs by S. Dittmann and A. Rolston)

understand the functional ecology, and to go deeper into investigating macro-invertebrates in the submerged sediments of the channels and their connectivity throughout the Coorong. The macro-invertebrate communities have shown signs of recovery with continuous flows after a long drought. Such understanding can inform the management of environmental water releases with regards to relevance for continuous flows and managing salinity and water levels. Adaptable and quick response management is required to ensure that macro-invertebrate communities provide a resource base for higher trophic levels and ecological functions, such as ameliorating sediment conditions through bioturbation and biogenic habitat through ecosystem engineering. Further improvements in water quality and flow patterns are needed to improve their resilience to environmental extremes that are likely under climate change scenarios.

ACKNOWLEDGEMENTS

This chapter uses data and knowledge obtained from various research and monitoring programs supported by funding from The Living Murray initiative, the Murray-Darling Basin Authority, the Department of Environment, Water and Natural Resources, the former South Australian Department for Environment and Heritage and South Australian Department for Water, the South Australian Murray-Darling Basin Natural Resources Management Board, the South Australian South East Natural Resource Management Board, the CSIRO Flagship Collaboration Fund for CLLAMM ecology (Water for a Healthy Country National Research Flagship), and the Flinders Research Centre for Coastal and Catchment Environments. The information gathered in this chapter also includes records from several students who completed their honours and PhD theses on the Murray Mouth and Coorong, namely Jason Earl, Justine Keuning, Melanie Goldschmidt, Aaron Kirkpatrick and Shannyn Moyle. We also thank all of the research assistants and volunteers, whose contributions during field and lab work enabled the collection of data on macro-invertebrates. Comments from a reviewer helped to improve this chapter.

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CHAPTER 3.5

FRESHWATER MACRO-INVERTEBRATES

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INTRODUCTION

This chapter describes the major groups of macro-invertebrates that occur in the freshwater habitats of the Coorong, Lower Lakes and Murray Mouth region. Macro-invertebrates are animals that lack a 'backbone' and can be seen with the naked eye. This chapter does not include a detailed treatment of zooplankton — the small crustaceans that are described elsewhere in this book.

Most people are familiar with large species of macro-invertebrates, such as common yabbies and freshwater mussels, as well as the more annoying flies, midges and mosquitoes. Comparatively fewer people are aware of the wide range of sponges, flatworms, worms, mites, bivalves and snails, or crustaceans and insects that populate the many habitats that lie at the downstream reaches of the River Murray. The key habitats and macro-invertebrate species found in this region are discussed in this chapter, along with short, special-interest articles about particularly significant species and a description of how the macro-invertebrate communities were affected by the Millennium Drought, and their subsequent progress following a return to wetter and fresher conditions from mid-2010 onwards. The fragile nature of the lower River Murray has only just been revealed by the recent drought — having been masked by the effects of river regulation for the past 75 years — but it is clear that macro-invertebrate and other biological communities in the region are susceptible to catastrophic damage whenever flows cease to connect the River, Lakes and sea for extended periods of time. The chapter concludes

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[*] Keith Forbes Walker passed away suddenly on 27 February 2016, aged 70 years. Keith was a very approachable and inspirational teacher, helpful, positive, polite and calm in the face of all difficulties. Widely respected and greatly missed, his enthusiasm and passion for the environment, ecological insights and prolific writings are among his many enduring influences.

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with this theme and the need to maintain the Lower Lakes above sea level to ensure that the habitat needs of freshwater species are met into the future.

Readers seeking more will find additional information about many of these macro-invertebrates in guide books (e.g. Williams 1980; Hawking & Smith 1997; Gooderham & Tsyrlin 2002; Smith 2016) and internet sites (for example, *Identification and Ecology of Australian Freshwater Invertebrates*, with its keys to aquatic species). Both the *Australian Faunal Directory* and the *Atlas of Living Australia* provide useful search functions and distributional, habitat, biodiversity and collection locality data.[10]

ENVIRONMENTAL DIVERSITY

The River Murray at Wellington enters Lake Alexandrina, which is connected with the terminal Lake Albert, and then flows into the Coorong, before entering the sea near Goolwa. Five barrages have been installed along the seaward margins of Lake Alexandrina, constructed in 1939-1940 to manage weir pool levels for water supply and irrigation development, and also to prevent the ingress of sea water to the Lakes. The barrages raised the level of the Lakes and the channel upstream as far as Blanchetown by about 700 mm. Thus, no part of the Murray in South Australia is un-impounded (Walker et al. 1994).

Lakes Alexandrina and Albert, the lower reaches of tributary streams, such as Finniss River and Currency Creek, and numerous fringing wetlands and soaks that surround the Lakes and/or Coorong are freshwater habitats supporting freshwater species. Only the habitats of these waters, at elevations below 1.0 m AHD, are considered in this chapter. The Coorong and Murray Mouth are marine to hypersaline systems, and support saline-tolerant estuarine and lagoon species, which are covered in detail in Chapter 3.3.

The main habitats of freshwater invertebrates support a sparse *benthic* (bottom-living) community, a *pelagic* (open-water) community and a rich *littoral* (lake-edge) community. The deeper parts of the Lakes, which extend over 4 m deep in Lake Alexandrina and 2 m in Lake Albert (Mosley et al. 2012), are sparsely populated by nematodes, annelid worms, chironomids (mostly from the Subfamily Chironominae), small bivalve molluscs (*Corbicula australis*) and zooplankton such as cladocerans and ostracods. Open water areas support zooplankton, but it is along the littoral edges that most biodiversity exists. The littoral habitat is populated by emergent plants, such as common reed (*Phragmites australis*), Cumbungi (*Typha*) and a range of sedges (e.g. *Schoenoplectus* and *Bolboschoenus*) and rushes (*Juncus*). Macro-invertebrate communities vary with the extent of available aquatic vegetation, which itself varies depending on the exposure to wave action generated by the prevailing south-southwest winds in the region. Freshwater submerged aquatic plant communities were once extensive in the Lakes, but are now restricted to near-shore habitats due to light limitation in what are mostly highly turbid lake environments (Sim & Muller 2004). They include species such as ribbon weed (*Vallisneria australis*), water ribbons (*Triglochin procerum*), pondweeds (*Stuckenia* spp.), milfoils (*Myriophyllum* spp.), widgeon grasses (*Ruppia* spp.) and charophytes. Many of the shallow,

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[10] *Identification and Ecology of Australian Freshwater Invertebrates*: www.mdfrc.org.au/bugguide/index.htm. Keys to aquatic species: at www.lucidcentral.com. *Australian Faunal Directory*: https://biodiversity.org.au/afd/home. *Atlas of Living Australia*: https://www.ala.org.au/.

fringing wetlands around the Lower Lakes support emergent macrophytes and lignum, and some also include remnant areas of swamp paperbark (DEWNR 2013a). A threatened frog, the Southern bell frog (*Litoria raniformis*), inhabits freshwater wetlands, such as Pelican Lagoon, Clayton Bay and Hindmarsh Island channels (DEWNR 2013a), but little is known about the macro-invertebrates that live in these and other shallow, freshwater habitats surrounding the Lakes. An isolated pool near the north-eastern corner of Lake Alexandrina sampled in late 2010 supported low numbers of chironomid (non-biting midge) larvae (*Paratanytarsus*, *Chironomus* and *Dicrotendipes*), waterbugs (*Micronecta* sp., *Anisops thienemanni*), juvenile damselfly nymphs, caddisflies (*Triplectides australis*) and a few juvenile carp (*Cyprinis carpio*). Similar habitats probably support a wide range of aerially dispersed insect groups, as is the case in other temporary pool habitats in Australia (Dell et al. 2014).

BIODIVERSITY

Lake and lower tributary reaches

Over 140 macro-invertebrate taxa have been recorded from the Lower Lakes region, mostly in unpublished studies, collected in response to understanding the effects caused by the Millennium Drought (thought by some to have spanned the 2007-2010 period but determined by the Bureau of Meteorology to have extended from late 1996 to mid-2010.[11]) At least 45 taxa are non-insects (e.g. sponges, cnidarians, platyhelminths, nemerteans, nematodes, leeches, worms, mites, molluscs and crustaceans) and 97 are insect taxa, including chironomids (26 taxa), beetles (15), Hemiptera (13) and caddisflies (13).

Most species recorded in the Lower Lakes also live upstream in the main channel of the River Murray (Walker et al. 2009). Water in the Lower Lakes region lacks persistent currents, in common with the impounded reaches of the River Murray. This appears to not offer suitable habitat conditions for the many sensitive species of stoneflies, mayflies, caddisflies and blackflies that are usually associated with flowing-water (‘*riffle*’) habitats found further upstream in tributary streams, such as the Finniss River and Currency Creek. Thus, of the mayflies and caddisflies from this catchment, it is only the more tolerant and generalist species that occur in the Lower Lakes.

Porifera (sponges)

Freshwater sponges (Spongillidae) are sessile, filter-feeding, multicellular, colonial animals that form soft, spongy encrustations on submerged logs, bark, boulders and rocks, and in pipelines (Racek 1969; Williams 1980). They are difficult to recognise as animals, and individual species are distinguished by the size, structure and arrangement of both their gemmules (asexual resting propagules) and skeletal spicules.

Little is known about Australian species and the only sponge formally identified from the River Murray in South Australia is *Eunapius fragilis*, recorded near Morgan in 1952 (Racek 1969). This species forms small, light tan-coloured clumps on logs and rocks. It survives floods without experiencing structural damage and, like most spongillids, is well adapted to turbid,

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[11] See http://www.bom.gov.au/climate/updates/articles/a010-southern-rainfall-decline.shtml.

sediment-laden water. Unidentified species have been collected from sites on the River Murray floodplain and inflowing tributaries (Walker et al. 2009), and from the lower Finniss River and the eastern margins of Lake Alexandrina (Poltalloch and north-east shore).

Cnidaria (hydroids, jellyfish, etc)

The phylum Cnidaria is represented in fresh waters by the Order Hydrozoa, characterised by the presence of stinging cells containing nematocysts used to capture small zooplankton and other invertebrates (Williams 1980). Hydrozoa includes sessile forms with both a solitary arrangement (*Hydra*, Fig. 3.5.1a), and colonial forms (*Cordylophora*), and a group of free-floating solitary jellyfish, not yet recorded from the Lower Lakes.

Both *Hydra* and *Cordylophora* are small, elongated, soft-bodied organisms that attach to the substratum (mostly submerged logs, rocks and stems of aquatic plants) by a pedal disc, and are distinguishable by the presence of a number of simple tentacles surrounding a distal mouth (Williams 1980). While *Hydra* consists of a single organism, *Cordylophora* colonies form an interconnected network of tubes coated by perisarc, an outer protective layer containing chitin.

Hydra appears to be restricted to the eastern margins of Lake Alexandrina around Milang and Clayton and lower Currency Creek and Goolwa Channel. In contrast, *Cordylophora* has a more extensive distribution — found throughout both Lakes, and extending into the lower Finniss River and Goolwa Channel.

Nemertea (proboscis worms)

Nemerteans in Australia are represented by a single, possibly introduced, freshwater genus, *Prostoma* with two species (*P. graecensis* and *P. eilhardi*) (Williams 1980; Hawking & Smith 1997; Wells 2010). They are small, very thin, unsegmented, worm-like animals that lack appendages. Nemerteans typically have three pairs of lateral eyespots, and may be either white or brightly coloured. They are distinguished by the presence of a muscular proboscis used to capture animal prey, and have a smooth body wall covered with cilia used for movement (Williams 1980). Nemerteans occur as free-living animals throughout the Riverland (Walker et al. 2009), and were recorded from mostly sheltered, sandy, reed-covered sites from Lake Albert at Campbell Park, Lake Alexandrina near Clayton, and Loveday Bay, and the lower Finniss River and lower Currency Creek in 2003-2013.

Nematoda (round worms)

Nematodes are thin, unsegmented, elongate, colourless and translucent worm-like animals. They are circular in cross-section (the origin of their common name) with a mouth surrounded by sensory buds anteriorly, and with the posterior end appearing as a tapered point. The phylum shows wide variations in life-history and reproductive traits. Many are well adapted to dehydration, temperature extremes, poor water quality and high sediment sulphide concentrations. Free-living nematodes feed on a range of different foods: some species eat fungi, bacteria and decaying organic matter, others feed on plants, and many are active predators of small animals and even other nematodes (Wade et al. 2004). They are all poor swimmers, and move with a characteristic ‘s-shaped’, whipping motion when moving through sediments.

Despite representing one of the most species-rich groups likely to occur in the region, little is known about the species found in the Lower Lakes, estuary and Coorong. The most comprehensive account for the region is provided by Nicholas et al. (1992), with over 40 genera recorded, most being cosmopolitan or with widespread distributions. Most species were collected from marine and estuarine waters, often in high densities (>100 000 m^{-2}), contrasting with the freshwater habitats upstream of the barrages where densities in sandy habitats were much lower (up to a maximum of 10 000 m^{-2}), and comprised genera such as *Eutobrilus*, *Tripyla* and *Ironus* that are typical of similar habitats overseas. Bird (1995) found that *Eutobrilus heptapapillatus*, a cosmopolitan freshwater species, comprised over 85% of the nematode population in both Lakes Alexandrina and Albert. Another two species of free-living nematodes (*Mesacanthion alexandrinus*, *Enoploides stewarti*) from typically marine genera were recorded from Lake Alexandrina near the River Murray mouth (Nicholas 1993), indicating the contrasting influence of salinity and flow in defining the mix of estuarine and freshwater nematodes inhabiting the downstream end of the River Murray.

More recent sampling of the region in 2002-2013 suggests that nematodes have a widespread distribution throughout the expanse of waters upstream of the barrages. The highest densities have typically been recorded in sandy substrate from the many embayments and lagoons surrounding Lake Alexandrina, e.g. Dog Lake, Tolderol, Milang and Loveday Bay.

Platyhelminthes (flatworms)

The plathyhelminth classes represented in the Lower Lakes region include the Temnocephalidea and Turbellaria. The former are ectocommensal on crustaceans, including common yabbies (*Cherax destructor*), atyid shrimps and Murray prawns. They are small animals, ranging from 1-12 mm long, with a flattened oval-shaped appearance, and are distinguished by the presence of two to six finger-like anterior tentacles, which they use to capture small invertebrate prey (Williams 1980). Undescribed species of *Temnocephala* (Fig. 3.5.1b) are known from the River Murray, wetlands and anabranches from Chowilla to Mannum, and from the Marne and Somme river catchments (Walker et al. 2009), and sampling in 2004 revealed their presence in Clayton Lagoon, Lake Alexandrina.

Turbellarians (flatworms or planarians) are free-living, elongate, flattened, soft-bodied animals about 2-10 mm long, with a distinctive head and usually two anterior eyespots. They are typically found gliding over stones, bark, snags and submerged plants (Williams 1980). They are carnivorous and feed on live or decaying animal matter. They are poorly known by Australian ecologists, because they are difficult to preserve and identify, requiring histological examination (Williams 1980). Undescribed species have been recorded from the margins of the River Murray, permanent wetlands, and from perennial creeks of the Eastern Mount Lofty Ranges (Walker et al. 2009). Turbellarians have also been recorded from well-vegetated sites from the western and northern shoreline of Lake Alexandrina, Lake Albert at Waltowa and Meningie, the lower reaches of the Finniss River and Currency Creek, and the Goolwa Channel in 2002-2013.

Annelida (segmented worms)

Freshwater annelids include the common aquatic oligochaetes (related to earthworms) and the leeches. The Lower Lakes oligochaete fauna has not been investigated in detail, but

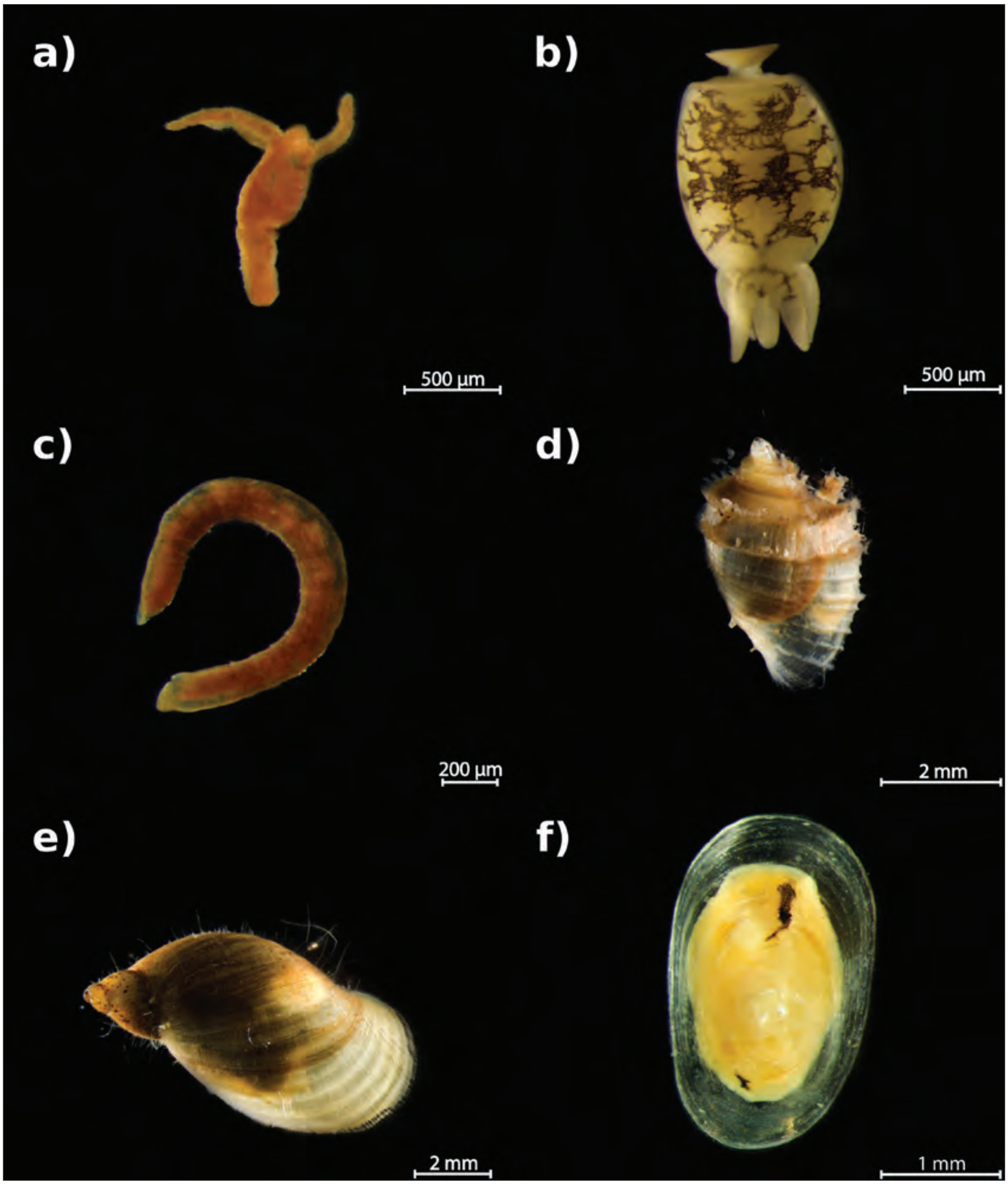

Figure 3.5.1
(a) Cnidaria, ***Hydra***.
(b) Platyhelminthes, *Temnocephala*.
(c) Oligochaeta, Naididae.
(d) Gastropoda, *Glyptophysa*.
(e) Gastropoda, Lymnaeidae.
(f) Gastropoda, limpet *Ferrissia*.
(Reproduced with permission from the Environment Protection Authority, SA)

another annelid, an estuarine polychaete, *Ficopomatus enigmaticus,* gained notoriety during the Millennium Drought after it spread rapidly and formed white encrustations on tortoises inhabiting the Lower Lakes. Among the known oligochaetes (Fig. 3.5.1c) from the region are seven taxa from the Family Naididae (mainly from subfamily Naidinae: *Pristina longiseta*, *Chaetogaster*, *Dero*, *Nais* and *Slavina*) and at least one taxon from the Enchytraeidae. Most oligochaetes feed head-down in the sediments, extending their tail into the water for respiration, whilst species of *Dero* are notable for the presence of gills in an anal chamber. Some species swim or crawl over the bottom, ingesting mineral particles and decaying organic matter in order to obtain their nutrition from the attached microorganisms. Species of *Nais* have simple eyes, a feature uncommon among the oligochaetes.

The small, oval-shaped, often cream-coloured Glossiphoniidae is the only one of the three families of freshwater leeches from South Australia recorded from the Lower Lakes.

Mollusca

The non-marine molluscs found in the Lower Lakes include freshwater mussels and gastropods (see Smith 1996 for identification keys). Few mollusc species occur in the region, probably due to the combined effects of their specialised feeding mechanisms and the local environmental conditions. The Lower Lakes represent a harsh environment for molluscs compared with other parts of the River Murray catchment; they experience high wind-generated turbulence, are managed to minimise water fluctuations, and have very poorly developed littoral zones, with relatively few plants present; and the mineral substrate is mostly fine, unstable sediments. These conditions are not ideal for freshwater molluscs to feed in, because mussels are sedentary filter feeders that need stable sediments, and snails and limpets use their *radulae* (a rasping mouthpart) to scrape food from plant and other stable surfaces.

Mussels are *bivalves*, meaning ‘two valves’, and these soft-bodied animals live inside the shell valves, which are joined together by a hinge and flexible ligament. They all have low mobility and they are usually found burrowing into compacted sandy habitats. The large freshwater mussel *Velesunio ambiguus* (Fig. 3.5.3b) and the much smaller orb-shell mussel *Corbicula australis* (Fig. 3.5.3a) are common inhabitants of Lake Alexandrina, and also occur further upstream in wetlands and slow-flowing sections of the River Murray (Walker 1981; Walker et al. 2009). Another bivalve, the river mussel *Alathyria jacksoni*, is restricted to the littoral areas of flowing sections of the mainstream, so does not occur in the lentic habitats of the Lower Lakes.

When mussels die, the ligament holding the valves closed breaks, after which the shells are commonly found on the shoreline, as occurred during the Millennium Drought when many *V. ambiguus* died around Lake Alexandrina, particularly at Point Sturt, where large beds of mussels inhabited the soft, stable sediments. It is likely that mussels died across most of Lake Alexandrina from increasing salinity, because the salt tolerance of this species is quite low, probably well below 3 000 mg L^{-1} (Walker *pers. obs.*), and salt concentrations across the Lake were much higher than that during the drought. Small, live *V. ambiguus* have subsequently been seen from the river end of Lake Alexandrina since 2014, suggesting that this species was in the early stages of recolonising the Lakes region from the river, via their larvae which parasitise fish (see Walker et al. 2009; Smith 2016).

The term *gastropod* is a Greek word meaning ‘stomach foot’, and while they do not really move on their stomach, these animals do move by sliding on a large foot. The gastropods in the Lower Lakes are mostly confined to Lake Alexandrina and the lower tributary reaches, where a range of spire-shelled snails (Figs. 3.5.1d & 3.5.1e) and a freshwater limpet (Fig. 3.5.1f) have often been recorded. The snails, comprising operculates and air-breathing pulmonates, are mostly associated with aquatic plants, and include species from at least four families (Hydrobiidae, Lymnaeidae, Planorbidae and Physidae). The operculate hydrobiids include native species from the genera *Angrobia* and *Posticobia* and the introduced *Potamopyrgus* snail from

New Zealand. The pulmonates include a record of a lymnaeid, *Austropeplea tomentosa*, from Milang in 2003; planorbids from the genera *Glyptophysa* and *Gyraulus* from the Clayton area; and an introduced physid from the genus *Physa*, which is the most common and widespread snail in the region. The limpet *Ferrissia* (Planorbidae) is commonly found attached to the leaves of macrophytes, snags or stones. Prior to the drought, the most commonly recorded gastropods were immature hydrobiids and *Physa*, but the latter species and *Ferrissia* were apparently the only species that persisted through the drought (McEvoy & Oxley 2013).

Crustacea

The major groups of macrocrustaceans found in the River Murray in South Australia are the amphipods, isopods and decapods. Three families of amphipods or scuds are present in the Lower Lakes region, often in large numbers, including *Austrochiltonia* (Fig. 3.5.3d), from the Chiltoniidae (formerly Ceinidae) and *Paracorophium* (Corophiidae, Fig. 3.5.3e), and unidentified members of the family Eusiridae. Amphipods are distinguished by the presence of gills on their thoracic appendages, and in the use of their abdominal appendages for swimming (Williams 1980). *Austrochiltonia* is the largest amphipod present and it feeds by scraping plant material and biofilms, while the smaller Corophiidae and Eusiridae are biofilm grazers and epibenthic filter feeders, consuming bacteria and fungi.

The isopods include *Heterias* from the family Janiridae, and *Haloniscus* from the family Scyphacidae, and both feed on biofilms and algae. They are distinguished by having a well-defined head and lacking a carapace; and they have seven pairs of walking legs, an abdomen with six segments, and gills on their abdominal appendages (Williams 1980). *Heterias pusilla* occurs in low numbers in freshwater habitats with silty, organic sediments from Lake Alexandrina and the lower reaches of the tributary streams, whereas *Haloniscus*, normally found in temporary habitats, has only been collected from the Goolwa Channel.

The Decapoda ('with 10 legs') all have a prominent carapace with fused segments forming a cephalothorax; eyes borne on stalks; and five pairs of thoracic legs (Williams 1980). Decapods are omnivorous but probably feed (in common with the amphipods and isopods) primarily on bacterial and fungal material in biofilms. They are well represented in the Lower Lakes by the Atyidae (shrimps), with *Paratya* and *Caridina* (Fig. 3.5.3f); the Palaemonidae, with *Macrobrachium* (the Murray prawn, Fig. 3.5.5a); the Parastacidae, with the common yabby *Cherax destructor* (Fig. 3.5.5b, Box 3.5.1); and lastly the Hymenosomatidae, with the small spider crab *Amarinus lacustris*, formerly in the genus *Halicarcinus* (Box 3.5.2).

In 2003-2004, before the start of the drought, the amphipods *Austrochiltonia* and eusirids, the isopod *Heterias* and the decapods *Paratya*, *Caridina*, *Macrobrachium*, *Amarinus* and *Cherax* were collected from Lake Alexandrina at Milang (McEvoy & Oxley 2013; EPA unpublished data). In 2009-2010, amphipods were the only crustaceans collected, probably because salinities may have been too high for most species to persist during the drought in the region. Once floodwaters entered the region in late 2010, isopods and decapods slowly recolonised the Lower Lakes, so that by about 2013-2014 the crustacea present had mostly recovered their former diversity. Amphipods numerically dominate the crustacean assemblages found in both Lakes, with eusirids particularly common in Lake Albert and lower Currency Creek. Lake Alexandrina normally provides habitat for isopods and decapods, but they are rarely collected

BOX 3.5.1 COMMON YABBIES IN THE LOWER LAKES

Common yabby *Cherax destructor* is a large, smooth-shelled freshwater crayfish widely distributed across southern Australia, including the Lower Lakes (Horwitz & Knott 1995; Lawrence et al. 2002). The species is most active over warmer months, with breeding occurring from late spring until autumn. It is a hardy, opportunistic species, tolerant of poor water quality, and can persist in dry channels and wetlands by burrowing down to reach moist soils. In this way, the yabbies can survive for several years between floods, after which booms in yabby numbers are often experienced.

The yabby is a valuable food resource for the traditional owners, the Ngarrindjeri (who name them *Meauke*), and yabby fishing is a popular local pastime. It has also long supported a small, but important, commercial fishery with a catch of >100 t yr^{-1} during the 1970s. Such was the availability and demand for the species that a restaurant specialising in serving yabby dishes and aptly named Yabby City opened at Clayton Bay and ran for over 30 years under the ownership of commercial fisherman Henry Jones and his wife Gloria. At its peak, the restaurant used 1 t wk^{-1} of common yabbies, and for a long time employed 20 full-time staff.

The commercial catch declined during the late 1970s with a number of causes implicated, including over-fishing, competition with introduced fish species, and the reduction in flooding through the regulation of water levels in the River. Nowadays, common yabbies remain broadly distributed across the region, but numbers are considerably lower than they once were — with an average commercial catch of only 6 t yr^{-1} during the past 30 years.

Figure 3.5.2 The 'big' yabby outside the Yabby City restaurant, Clayton Bay. (Photograph by Gloria Jones)

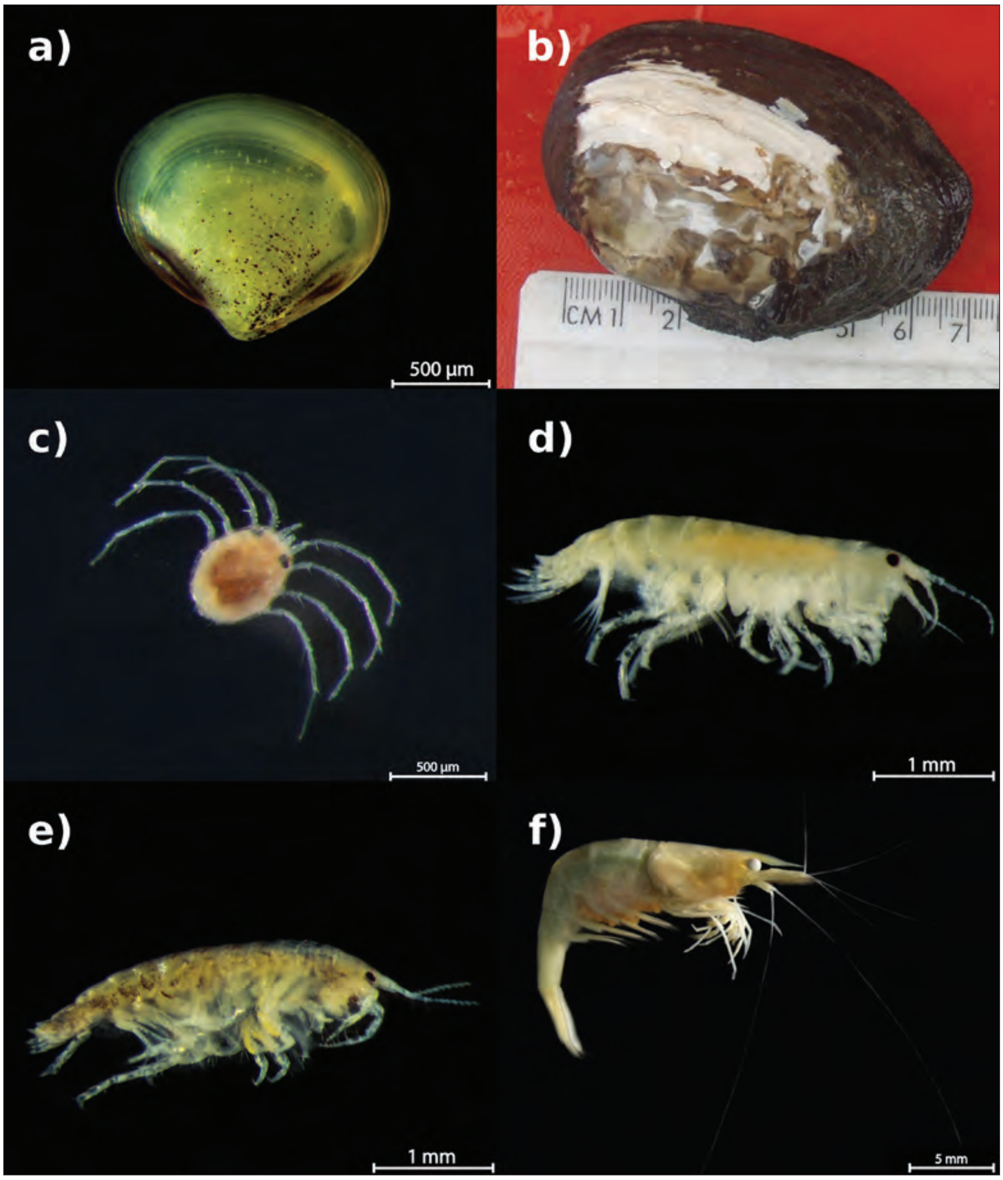

Figure 3.5.3
(a) Bivalvia, *Corbicula australis*.
(b) Bivalvia, *Velesunio ambiguus*.
(c) Arachnida, Hygrobatoidea.
(d) Amphipoda, *Austrochiltonia* (Chiltoniidae).
(e) Amphipoda, *Paracorophium* (Corophiidae).
(f) Decapoda, gravid *Caridina* female.
(Reproduced with permission from the Environment Protection Authority, SA)

from the naturally more saline Lake Albert. The only crustacean with no sign of recovery from the drought in either Lake is the spider crab, *Amarinus lacustris*, although it is still present in the tributaries (EPA unpublished data).

Arachnida (mites)

Mites are represented by four major groups: suborders Astigmata, Oribatida, Prostigmata (of the Acariformes) and Mesostigmata (Parasitiformes). Most fully aquatic mites are members of the Parasitengonina, Halacaroidea (Families Halacaridae and Pezidae) and Hydrozetoidea (Oribatida). All are relatively small macro-invertebrates with four pairs of legs, an absence of antennae, and two pairs of feeding appendages — comprising anterior clawed chelicerae, and posterior pedipalps (Williams 1980).

Oribatid mites ('beetle mites') are mostly scrapers and shredders that feed on living and dead plants, fungi, algae, bacteria and yeast. The oribatids that live along the edges of slow-flowing and still waters in South Australia are mostly small, red-brown mites with distinctive tear-drop shaped bodies that are heavily sclerotised. Oribatids are common inhabitants throughout the Lower Lakes region, and they have often been recorded in large numbers, particularly from the fresher sites in Lake Alexandrina and the lower Finniss River.

The best-known and most diverse mite group is the 'water mites' (Fig. 3.5.3c) (see Harvey 1998 for further details), which are members of Infraorder Parasitengonina. These display a variety of shapes and forms, and many are brightly coloured. While they have commonly been recorded further upstream in the Riverland and Murraylands (Walker et al. 2009), there are only a few unidentified records from Lake Albert at Meningie and Boggy Lake on Lake Alexandrina. While they are not represented in data from net sweeps and cores, five South Australian species of mites from the Unionicolidae live as parasites within freshwater mussels (Viets 1980; Harvey & Growns 1998; Smith 2016). The occurrence of mussels across the beds of the Lower Lakes is also likely to support these parasitic species, but further investigation is required to confirm this.

Peza ops (Pezidae) is a River Murray specialist (Harvey 1998), and in South Australia it is common in the slow-flowing main channel and wetland habitats (Madden & Corbin 2004), but it is apparently not found in tributaries (cf. Harvey 1990). It is characterised by large projections on the head, formed by the rostrum and modified pedipalps, and the presence of numerous setae on the body and legs. The only record from the Lower Lakes region is of an individual collected from the north-eastern shore of Lake Alexandrina in February 2012, presumably transferred by previous flooding from the River Murray. The Halacaridae are a large family of mostly marine mites that includes predators, parasites and algal feeding species. They are poorly described in Australia and a single unidentified halacarid was recorded from Milang on Lake Alexandrina in early 2004 — the only record from this family in the region.

Insecta (the insects)

The insects represent the greatest number of freshwater macro-invertebrate species. Most aquatic forms are immature larval and nymphal stages of species that become airborne as adults (e.g. dragonflies, mayflies, caddisflies, chironomid midges and other types of fly), but there are aquatic adults, especially among the beetles (Coleoptera) and bugs (Hemiptera).

The Ephemeroptera (mayflies) are one of the most primitive insect groups. The Baetidae are represented in the Lower Lakes by *Cloeon*, and the Caenidae by *Tasmanocoenis tillyardi* (Fig. 3.5.7b) and *T. arcuata*. These taxa were commonly recorded from Lake Alexandrina in 2003-2004, but were not collected towards the end of the drought and when flows first returned during 2009-2011. However, monitoring detected *T. arcuata*, normally associated with riverine habitats (Walker et al. 2009), in Lake Alexandrina at Milang in 2012 and from sites at the outfall of the River Murray into the Lake, in its north-eastern corner, as well as at Poltalloch in the following year. This temporary shift in population distribution presumably occurred in response to regular post-drought pulses from the flowing river. Similar patterns of

BOX 3.5.2 THE CRYPTIC WORLD OF THE FRESHWATER SPIDER CRAB

One of the more curious inhabitants of the region is the freshwater spider crab *Amarinus lacustris*, which occurs in fresh and slightly saline waters (Walker 1969; Johnston & Robson 2005). The range of the species includes much of south-east Australia, New Zealand and King, Lord Howe and Norfolk Islands. Yet the species goes almost unnoticed in the habitats it occupies, rarely being seen or collected, given its small size (the size of a fingernail), and the fact that it shelters among water plants, snags or under rocks. This species evolved from a marine lifestyle, and whilst it is now found in fresh water, it maintains a high tolerance to salt and is capable of surviving in almost sea water. Yet *A. lacustris* is distinct from its marine relatives in undergoing *direct development* (i.e. the eggs hatch into small crabs), as opposed to producing free-swimming larvae (Lucas 1972).

Across the region, the species has been collected from fringing habitats of Lake Alexandrina and the lower reaches of Currency Creek and Finniss River.

Figure 3.5.4 Two gravid *Amarinus lacustris* females, with a 5-cent coin for scale. (Photograph by Kerrylyn Johnston)

apparent slow recovery were shown by *T. tillyardi*, which is typically associated with vegetated wetland habitats, and *Cloeon*, which can frequent still and slow-flowing waters (Corbin & Goonan 2010), with both species recaptured from sites around Lake Alexandrina and lower Currency Creek in 2013-2014. It is likely that *Cloeon* and *T. tillyardi* occurred in Lake Albert prior to the drought, where salinities did not exceed their tolerance (Corbin & Goonan 2010), but the lack of mayflies from sampling in 2009-2014 suggests that mayflies were slow to recover from the drought, as was the salinity in this lake (Stone et al. 2016).

The odonates are represented by aquatic larval stages of damselflies (Zygoptera) and dragonflies (Anisoptera). All larvae (termed 'nymphs' in some sources) are carnivorous, and each possesses a grasping labial mask that it uses to quickly seize its small prey. Damselfly larvae are identified by their slender bodies and presence of three conspicuous gills at the far end of their abdomen, whereas dragonflies are more robust in form, and lack external gills. Only one family of damselflies, the Coenagrionidae, has been consistently recorded from the Lakes, with larvae of species such as *Austroagrion watsoni*, *Ischnura heterosticta* (Fig. 3.5.7c) and *Xanthagrion erythroneurum* occasionally collected among emergent reeds and plants on the edge of the Lakes and Currency Creek. Conversely, the long, slender-bodied larvae of *Austrolestes annulosus* (Lestidae), which is normally associated with saline waters, were collected among aquatic plants in the lower Finniss River and Currency Creek in late 2010. Only three genera from three dragonfly families have been collected from the region, i.e. *Hemicordulia tau* (Hemicorduliidae), *Hemianax papuensis* (Aeshnidae) and *Austroaeshna* sp. (Telephlebiidae). Their larvae are usually found around the bases of emergent aquatic plants and are often difficult to detect due to their slow, cryptic movements. However, the cast skins, or *exuviae*, left behind on the stems of emergent aquatic plants by adult dragonflies at the completion of their larval moult, provide conspicuous evidence of their use of aquatic habitats in the region.

One of the most abundant insect groups found in slow-moving or still water is the true bugs (Hemiptera). The Corixidae ('lesser water boatmen', Fig. 3.5.6f) include *Micronecta*, *Agraptocorixa* (*A. eurynome* and *A. hirtifrons*), *Sigara australis* and *Diaprecoris barycephala*. Only *Micronecta* is normally found in large numbers around the edges of Lake Alexandrina and the tributary streams. The Notonectidae (or backswimmers) are notable because they swim with their *ventral* (= under) surface uppermost; they are represented by species of *Anisops* (Fig. 3.5.7a) and *Enithares*, and they are uncommon in the region, inhabiting the deeper sections of littoral habitats of the Lakes and tributaries. Several aquatic bug species, only occasionally seen in the region, have been collected, including Veliidae (*Microvelia oceanica*) and Mesoveliidae (*Mesovelia*), both of which skate on the water's surface near the shoreline of the Lakes; and *Naucoris congrex* (Naucoridae), *Hebrus* (Hebridae) and *Neoplea* (Pleidae), found among vegetated wetland and lagoon habitats. Few waterbugs were recorded from the region at the end of the Millennium Drought in 2009, but most taxa reappeared from 2010 onwards. The wetland specialists are the exceptions, and were not recorded there post-drought.

Beetles (Coleoptera) are found (usually in very low numbers) at well-vegetated parts of Lake Alexandrina, in the tributaries and occasionally in Lake Albert. A range of families including the Dytiscidae ('diving beetles'), Hydrophilidae ('water-scavenger beetles'), Hydraenidae ('minute rove beetles'), Haliplidae ('crawling water beetles') and Scirtidae ('marsh beetles') are represented. Predatory larvae and aquatic adult stages of the dysticids include *Hydrovatus*, *Cybister*, *Liodessus*, *Chostonectes*, *Necterosoma* (Fig. 3.5.5c) and *Lancetes*. The hydrophilids are mostly herbivores in their adult stage, but develop from larvae which feed as carnivorous predators, and include *Berosus*, *Enochrus* and *Limnoxenus*. Hydraenids of the region are small, crawling, predacious species from the tribe Ochthebiini. The genus *Haliplus* is represented in monitoring data only by a small beetle of weak swimming ability from Currency Creek in 2013. Larval scirtids are aquatic detritivores, which have also only been recorded from Currency Creek. Other families that are not strictly aquatic — though they have affinities to wet mud

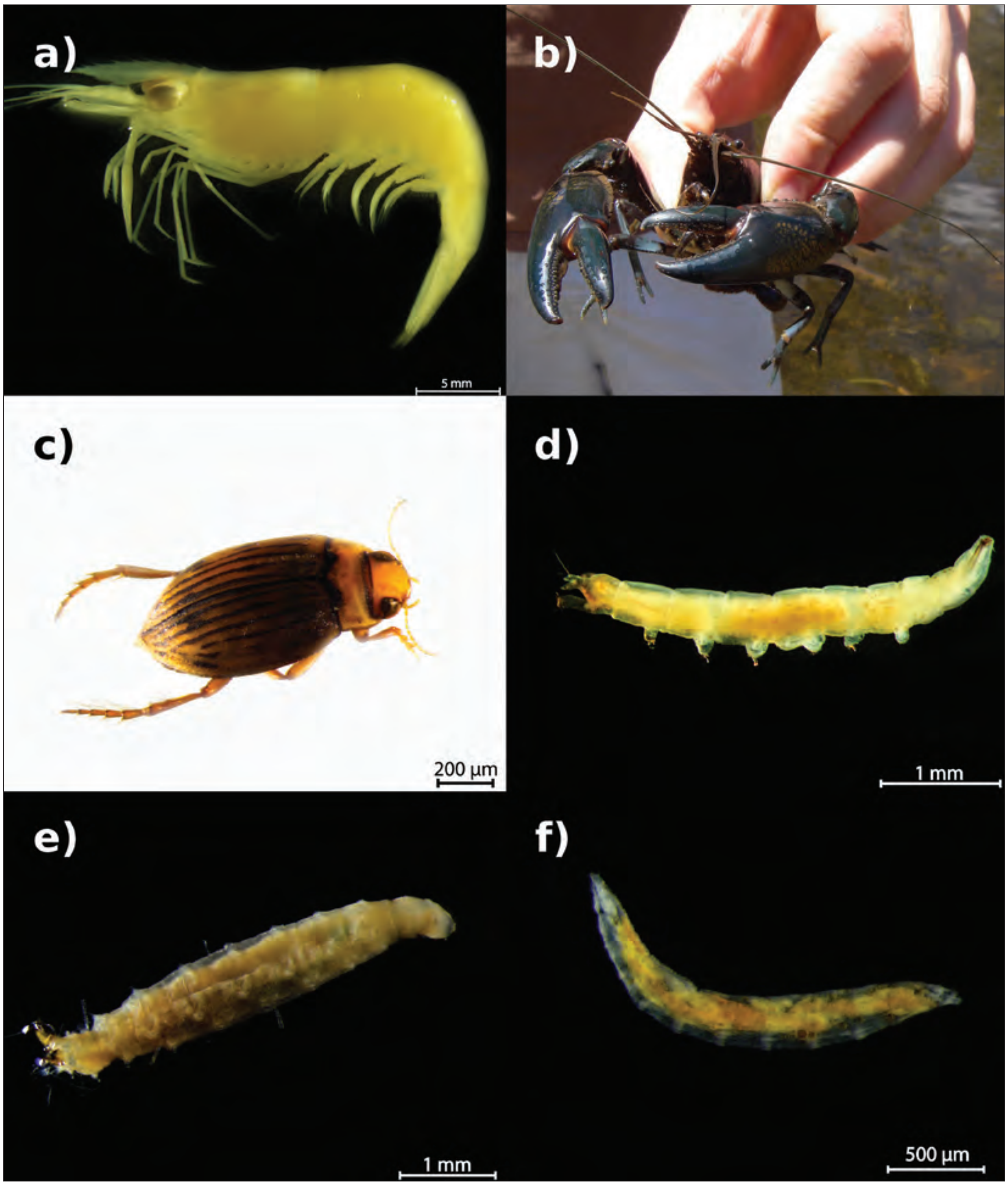

Figure 3.5.5
(a) Decapoda, Murray prawn *Macrobrachium australiense*.
(b) Decapoda, common yabby *Cherax destructor.*
(c) Coleoptera, diving beetle *Necterosoma*.
(d) Diptera, dance fly larva Empididae.
(e) Diptera, Tabanidae.
(f) Diptera, Muscidae.
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habitats — have also occasionally been collected, including larval Staphylinidae and adult Curculionidae.

The order Diptera ('true flies') is a very abundant and diverse group of freshwater insects in the region. Like other members of the order, the adult stages are terrestrial, but freshwater dipterans have aquatic larval stages. The Chironomidae or non-biting midge flies are the most abundant family with many genera recorded from collections around the Lower Lakes. *Procladius* (Fig. 3.5.6b) is one of its most widespread members, and is also tolerant of saline water, whereas other commonly collected midge larvae such as *Cricotopus* (Fig. 3.5.6c) and *Nanocladius* are not salt-tolerant. Abundant species from the tribe Tanytarsini (including *Cladotanytarsus* and *Paratanytarsus*) are present in areas of fine sediment; and in the more saline parts of the Coorong, *Tanytarsus barbitarsis* is often the only abundant insect present (Box 3.5.3). Other species have the blood pigment haemoglobin in their body fluids; this makes their larvae appear red, leading to them being commonly called 'bloodworms'. The red colour is lost when specimens are preserved for microscopic examination (Fig. 3.5.6). The haemoglobin assists in making them tolerant of poor water quality (particularly under low oxygen levels) and the presence of large numbers of *Chironomus*, *Dicrotendipes*, *Kiefferulus* and *Polypedilum* can indicate disturbed, eutrophic conditions. *Cryptochironomus* (Fig. 3.5.6d) is another red midge larva; this genus is carnivorous and feeds on smaller midges and annelid worms. *Zavreliella* larvae are only found in South Australia from the River Murray and Lower Lakes. They construct a case that is portable (see Fig. 3.5.6e); larvae such as those of Trichoptera species commonly do this, but it is noteworthy behaviour for midges — most of which spend their larval stage in cases that they fix to surface sediment grains. Chironomid larvae may be identified under a microscope using Madden's (2010) key.

Regional mosquito species (Culicidae) are well known as adults (Lee et al. 1989; Russell 1993; Russell & Kay 2004), and can be important disease vectors. This is due to the biting habits of the females (whereas the males are nectar feeders, and bite flowers). Mosquito larvae are comparatively scarce in the Lower Lakes and Coorong, owing to the fact that these bodies of water harbour species of both fish and insects, which are the predators of mosquito larvae. Instead, they favour ephemeral and semi-permanent waters at the margins of streams, and natural wetlands as well as man-made habitats containing water from rain, tidal flow, stream flow, irrigation and other sources. The most common species in the region is *Aedes camptorhynchus*. Other species that can occur are *Anopheles annulipes* and some species of the genus *Culex* (Fig. 3.5.6a), e.g. *C. annulirostris*, *C. globicoxitus*, *C. molestus* and the more urban

BOX 3.5.3 CHIRONOMIDS IN THE SOUTHERN COORONG

Tanytarsus barbitarsis is a chironomid midge about 3-4 mm long, which is widespread and abundant in saline wetlands, particularly the Coorong. Adults of the species are often attracted to lights in residential areas, but in the Coorong the adults are usually seen settled among coastal vegetation, or in the air in massed swarms (usually on the lee side of some taller vegetation) which constitute a cloudy haze of tiny moving insects. These swarms are predominantly males. Females fly into these swarms to find a mate. Once mated, the females lay their eggs on the water in littoral habitat, and the eggs drop to the bed, where they later hatch as larvae. The larvae live on the bed in protective tubes, and graze on surface algae and detritus. They are sometimes called bloodworms because they use haemoglobin to store oxygen. As they grow (over ~30 days, depending on water temperature), the larvae shed their skin multiple times, progressing through four separate stages or instars, before pupating.

The pupae may take three days to mature before hatching — by floating to the surface of the water, where the adult emerges. Adult midges only live for a few days. The larval stages of the midges are a major source of food for birds and fish in the Coorong, while adults are also taken by aerial hunting birds. In the South Lagoon of the Coorong, where elevated salinities are common, this species is fundamental to the diet of fish and birds.

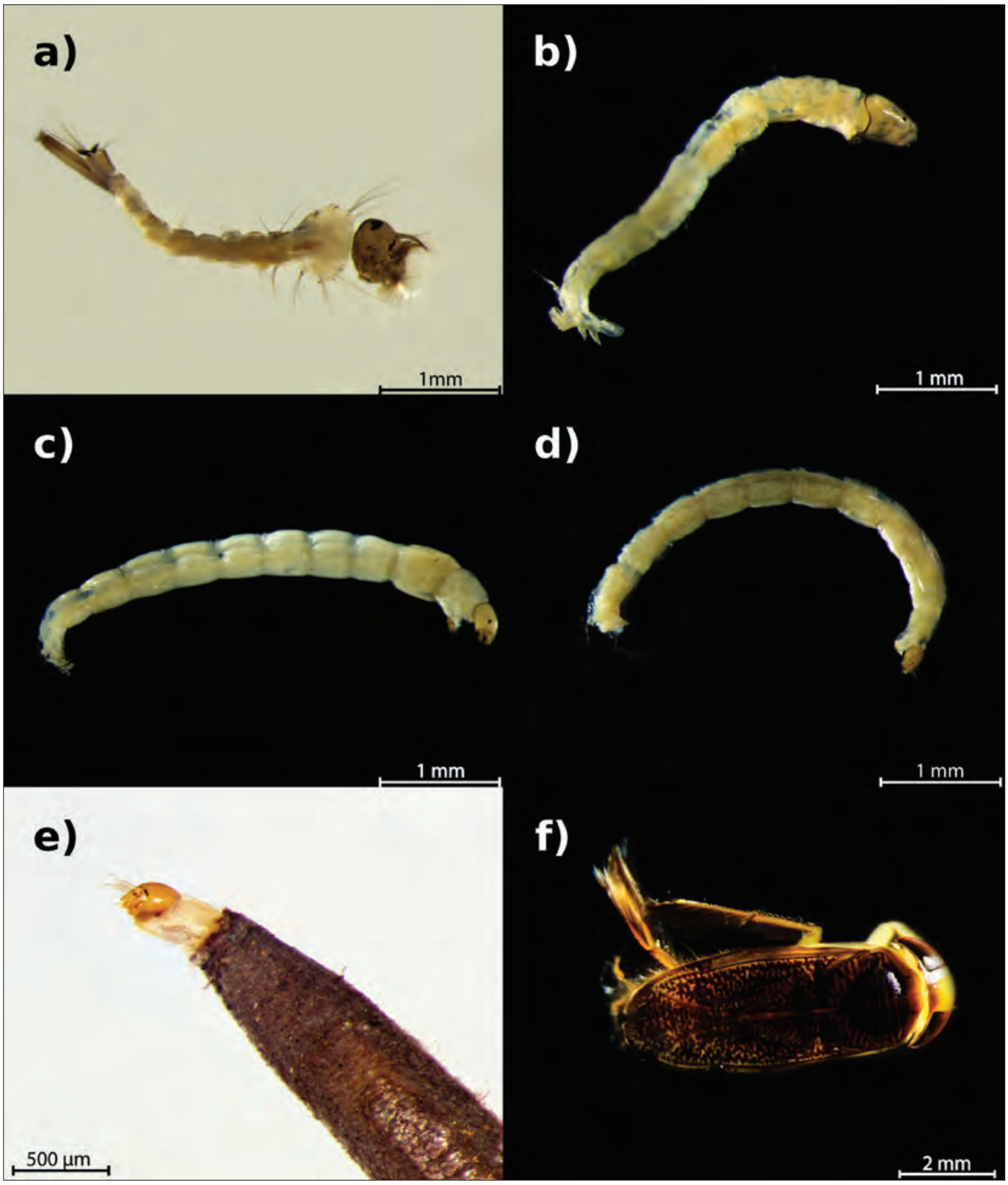

Figure 3.5.6
(a) Diptera, mosquito larva *Culex*.
(b) Diptera, chironomid larva *Procladius*.
(c) Diptera, chironomid larva *Cricotopus*.
(d) Diptera, chironomid larva *Cryptochironomus*.
(e) Diptera, chironomid larva *Zavreliella*.
(f) Hemiptera, Lesser Water Boatman *Sigara*.
(Reproduced with permission from the Environment Protection Authority, SA)

C. quinquefasciatus. Mosquito larvae usually access oxygen from above the water surface, via a breathing tube called a *siphon* (see Fig. 3.5.6a), but *Coquellittidea linealis* is notable because it has a siphon modified to pierce plant stems to source oxygen, allowing it to remain continually submerged.

The larvae of biting midges (Ceratopogonidae) resemble those of chironomids, but they lack a front pair of prolegs. Species from the genera *Dasyhelea*, *Bezzia*, *Culicoides* and others are frequently found in the region. Larvae live in the sediment as predators, but the adults can be significant nuisances when present in large numbers, because they can bite.

Of the other families of Diptera that occur in the region, few can be identified to species, as the taxonomy of the larval stages is poorly known. They include the Tipulidae, Tabanidae (Fig. 3.5.5e), Stratiomyidae, Empididae (Fig. 3.5.5d), Dolichopodidae and Psychodidae. The Tipulidae (crane flies) and Tabanidae (March flies) are more familiar as adults. The Ephydridae are another group that is saline-tolerant, and *Ephydrella* larvae are very common in the southern lagoon of the Coorong.

The Trichoptera (caddisflies) take their scientific name (which translates to 'hairy/scaly wings') from the adults — which resemble small moths and live alongside waters. The larvae, like the eggs and pupae, are fully aquatic and mainly include cased forms, though several free-living species are resident. The free-living *Ecnomus* are characterised by their sclerotised thoracic segments and lack of abdominal gills. These species are omnivores, and include *E. pansus*, *E. cygnitus* and *E. turgidus*. The Hydroptilidae (micro-caddisflies; Figs. 3.5.7d & 3.5.7e) produce early, free-living instar larvae, but as the larvae grow, different species build characteristic purse-shaped, portable cases made from a secretion of silk — which may incorporate sand, algae and/or sticks. Purse designs include wheat-shaped cases of *Orthotrichia*, rectangular silt-cased *Hellyethira* and ovoid, sandy cases of *Hydroptila*. The Leptoceridae are much larger, and their mobile larvae construct cases from sticks (hollowed out, or sewn together) or sand grains, and are represented by *Triplectides* (including *T. australis* (Fig. 3.5.8b), *T. australicus* and *T. ciuskus*), *Oecetis* (Fig. 3.5.8a) and *Notalina* (see Fig. 3.5.7f).

Aquatic caterpillars inhabit well-vegetated parts of Lake Alexandrina. They belong to Lepidoptera: Crambidae, subfamily Acentropinae, and they are characterised by filamentous external gills. A few insect families, although mostly considered terrestrial, also occur along the edges of waters and they may include aquatic species, including weevils (actually beetles from the Family Curculionidae). Clustered on the surface film of still water may be seen springtails (families Hypogastruridae, Onychiuridae, Isotomidae and Sminthuridae) from the Order Collembola; they are closely related to both Insecta and Crustacea.

FEATURES

Historical changes in response to drought

River regulation and barrage construction have resulted in comparatively static water levels within the Lakes, particularly over the past 50 years (Sim & Muller 2005). This has reduced the width and diversity of fringing vegetation, and limited potential habitat for many macro-invertebrates (Walker et al. 1994). Furthermore, the construction of the barrages resulted in the loss of a dynamic estuarine zone in the Lower Lakes (Fluin et al. 2009), further reducing the variability in habitat and water quality in the region.

More recently, the extreme conditions of the Millennium Drought (2007-2010) resulted in unprecedented low water levels throughout the Lower Lakes (-1.2 m AHD; Mosley et al. 2014). These low levels, with complete drying in some areas, exposed the lake sediments to oxygen. With subsequent rewetting, this generated acidic water conditions — pH reducing to 2-3 at some sites (Mosley et al. 2014), well below national guideline trigger values indicative of healthy aquatic environments (pH 6.5-9.0; ANZECC & ARMCANZ 2000).

A decline in the diversity and abundance of the macro-invertebrate community was detected in 2009, due to reduced habitat availability, with only open unvegetated waters

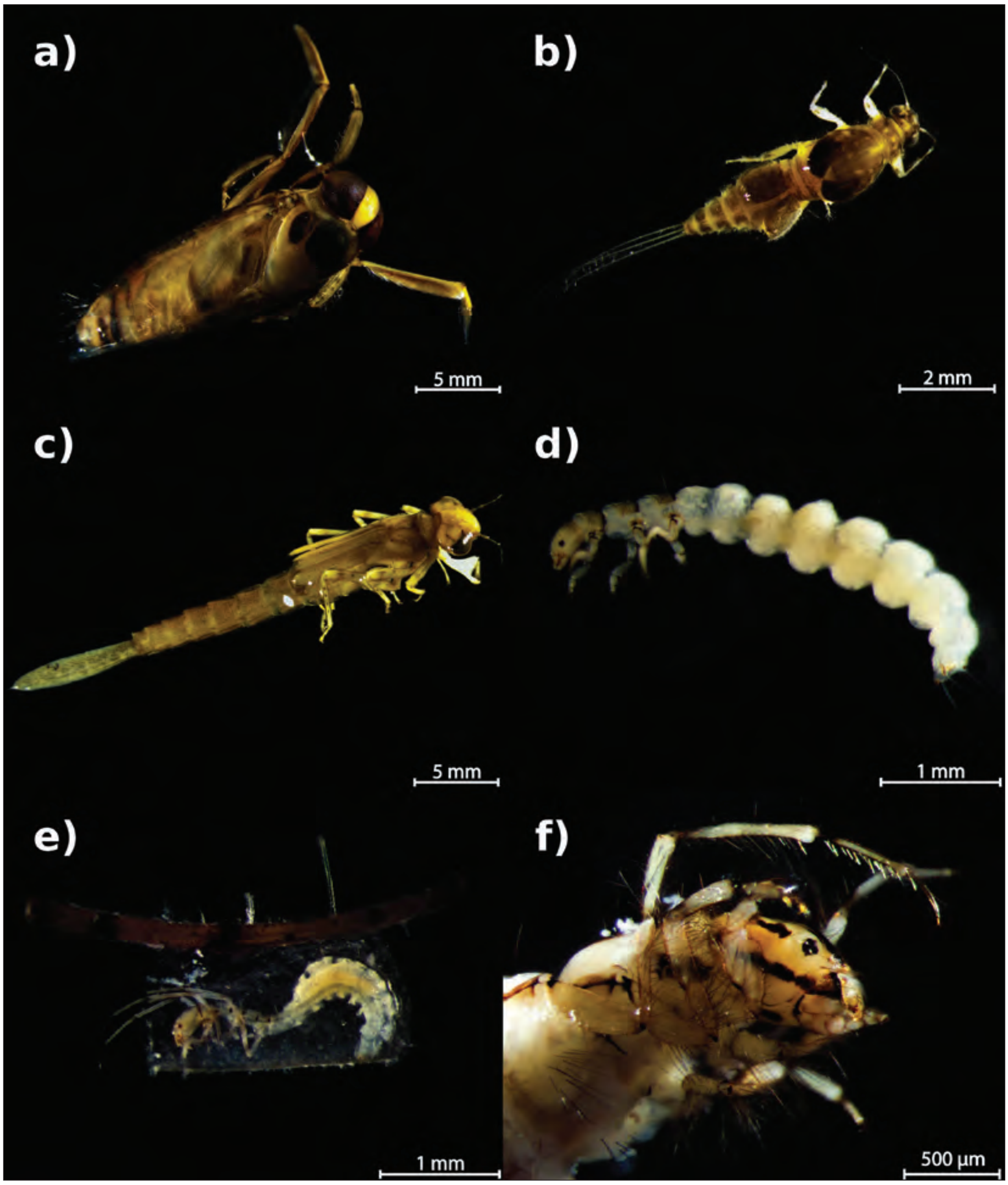

Figure 3.5.7
(a) Hemiptera, backswimmer *Anisops*.
(b) Ephemeroptera, mayfly nymph *Tasmanocoenis tillyardi*.
(c) Zygoptera, damselfly nymph *Ischnura heterosticta*.
(d) Trichoptera, caddisfly larva *Hydroptila losida* (lacking its typical sand case).
(e) Trichoptera, caddisfly larva *Hellyethira malleoforma*.
(f) Trichoptera, front section of caddisfly larva *Notalina spira*.
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available across the main bodies of the Lakes, completely dry areas in the embayments and sections of the lower tributaries, and high salinity levels in the southern areas of the Lakes and Goolwa Channel. After flows returned to the region in 2010, the community composition gradually improved. By 2013 (three years after the drought ended), pH values had returned to circum-neutral across the region, and only minor toxic effects and minor changes to the biological community were evident (McEvoy & Oxley 2013), but some pore water

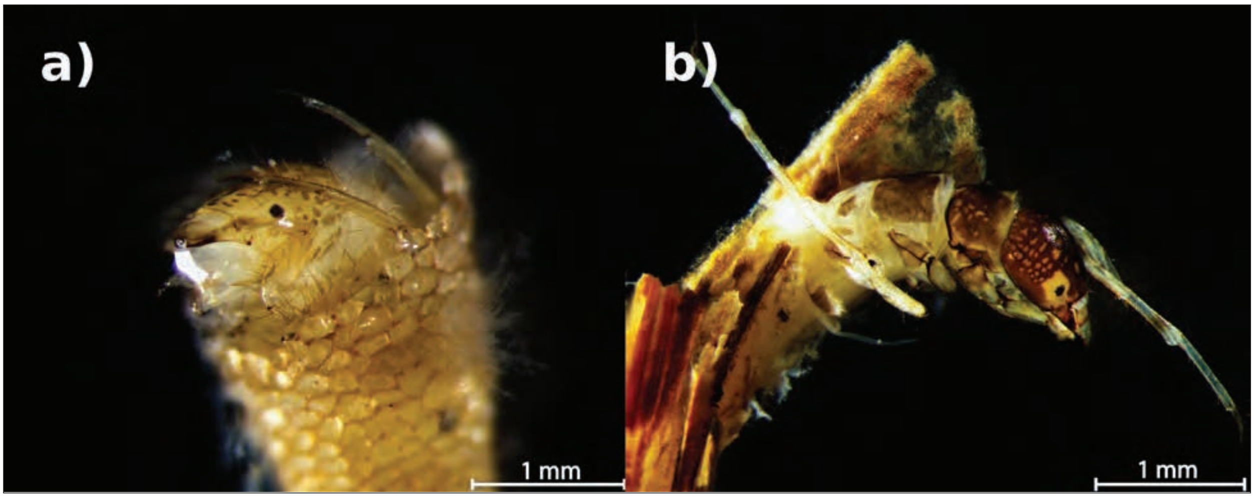

Figure 3.5.8 Front sections of the cased caddisfly larvae (Trichoptera).
(a) Leptoceridae, ***Oecetis***.
(b) Leptoceridae, *Triplectides australis*.
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metal(loid) concentrations were still above national guideline trigger values (ANZECC & ARMCANZ 2000).

In comparison with other fresh waters of the state, the freshwater macro-invertebrate community of the Lower Lakes was largely unstudied prior to this severe drought. An uncertain baseline challenged scientific evaluation of drought impact (e.g. separating recent changes from any that may be more attributable to earlier river regulation activity), including determination of the time of recovery in the affected waters. The few samples collected from Clayton and Milang on Lake Alexandrina in 2003-2004 suggested that aquatic mollusc abundance and richness had not recovered since the drought ended, especially for the snails and mussels.

Following prolonged drought, the degree of recovery of aquatic ecosystems after flow resumes varies depending on the system and severity of the drought. Recovery of a similar pre-drought community may occur over time (Ledger & Hildrew 2001), or some species may become locally extinct and a completely different community may establish from what was previously present (Ledger & Hildrew 2001; Acuña et al. 2005). In general, it appears that the longer and more severe the drought, the longer recovery will take (Lake et al. 2006). So, while the re-establishment of many aquatic species began soon after the end of an extended drought in the Lower Lakes, it is clear that recovery was incomplete after four to five years, and that many groups and species remained absent or had restricted distributions compared with what we know of the Lakes before the drought.

CONSERVATION

As noted by Walker et al. (2009), aquatic invertebrates are generally not considered high priorities for conservation, but for many decades the localised extinction of a number of species of snails (*Notopala* and *Thiara*) and the endangered Murray crayfish (*Euastacus armatus*) from the South Australian River Murray has been associated with the effects of river regulation. Such biodiversity impacts are testament to the need to manage threatening processes in the largest river system in the state. However, direct feeding connections exist between widespread, abundant and productive macro-invertebrates and the health of threatened and protected native fish and migratory wading birds. A duty to protect this biodiversity is part of state, national and international conservation agreements.

The Millennium Drought showed that when the water level of the River Murray downstream from Lock 1 and the Lower Lakes region falls over a metre below sea level and the River disconnects from the sea, salinity levels rise to a point where most freshwater species are lost and estuarine and marine species start to colonise the area. Maintaining an open river mouth and water levels above 0 m AHD for 100% of the time, and providing more flows, are key objectives of implementing the Murray-Darling Basin Plan in South Australia (Lester et al. 2011; DEWNR 2013b). If these objectives are successfully achieved, this will help ensure the continued survival of freshwater macro-invertebrates and other aquatic freshwater plants and animals in the Lower Lakes and lower reaches of the River Murray into the future.

ACKNOWLEDGEMENTS

We are grateful to the many organisations that have funded and supported the macro-invertebrate studies carried out in recent decades throughout the River Murray in South Australia. They include the Murray-Darling Basin Authority, Environment Protection Authority of South Australia, South Australian Water Corporation, Australian Water Quality Centre, Department of Environment, Water and Natural Resources SA, and the Commonwealth Department of the Environment and Energy.

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CHAPTER 3.6

FISHES OF THE LOWER LAKES AND COORONG: A SUMMARY OF LIFE-HISTORY, POPULATION DYNAMICS AND MANAGEMENT

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INTRODUCTION

As the dynamic interface between the lower River Murray and the Southern Ocean, the Lower Lakes and Coorong (LLC) provide a diversity of aquatic habitats, from freshwater wetlands to hypersaline lagoons. The region supports a diverse assemblage of fishes, unique within the Murray-Darling Basin (MDB), including threatened taxa and species of importance to commercial and recreational fisheries and to the Ngarrindjeri people (Berndt et al. 1993; Phillips & Muller 2006). Consequently, fishes contribute greatly to biodiversity and ecosystem function, and to the economic, social and cultural values of the LLC.

River regulation and water allocation for consumptive use (e.g. irrigation) have profoundly altered the flow regime of the MDB and the natural character of the LLC. In particular, the Murray Barrages, which collectively span 7.6 km, regulate river discharge, limit tidal incursion and act as a barrier to the movement of fishes and other biota between the lower River Murray and its estuary. Upstream water abstraction has led to decreases in mean annual discharge to ~39% (4 723 GL) of natural flow (12 233 GL), whilst periods of cease-to-flow occur 40% of the time compared with 1% under natural unregulated conditions (CSIRO 2008). Consequently, abiotic conditions (e.g. salinities) and ecological patterns and processes have been altered, including the distribution and abundance of fishes (Wedderburn et al. 2017). Notwithstanding anthropogenic impacts, the LLC maintain a rich fish assemblage.

Despite the importance of fishes to the Ngarrindjeri people and the presence of a commercial fishery since 1846 (Olsen & Evans 1991), the only comprehensive post-European inventories of fishes of the Coorong and Lower Lakes, respectively, were published in 1990 (Eckert & Robinson 1990) and 2003 (Wedderburn & Hammer 2003), and the general ecology of fishes

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of the region has rarely been considered (cf. Sim et al. 2000). Recent research, however, has improved knowledge of fish ecology and population dynamics, particularly with regards to the influence of river flow, salinity and connectivity (Ye et al. 2016).

This chapter provides a synopsis of the biology and ecology of fishes of the LLC, both in a contemporary context and in a manner that will support future management and conservation. Specifically, we integrate recent data with past studies in order to

- describe the aquatic habitats available to fishes in the LLC and how they are influenced by river flow and management
- provide an up-to-date inventory of fishes recorded from the LLC and assign them to 'estuarine use functional guilds'
- discuss fish assemblage dynamics in different spatial units of the LLC and the population dynamics of diadromous fishes, in association with abiotic and biotic conditions
- discuss the future management of fishes of the region.

Several species of the LLC also support commercial (i.e. the 'Lakes and Coorong Fishery', or LCF), recreational and Indigenous fisheries, with exploitation contributing to the range of factors influencing population dynamics. This topic is specifically addressed in Chapter 4.2 of this book.

AQUATIC HABITATS OF THE LOWER LAKES AND COORONG

Since the construction of the Murray Barrages in the 1930s, the aquatic habitats of the LLC have comprised two distinct spatial units, typically representing freshwater and estuarine environments. These are

a) the freshwater region, including Lake Albert, Lake Alexandrina and the lowland stream reaches/terminal wetlands of the eastern Mount Lofty Ranges (EMLR) tributaries
b) the estuarine Coorong, comprising the Murray Estuary, North and South Lagoons (Figure 3.6.1).

Each of these spatial units provides unique habitats for fish. To avoid confusion, it is important to note that the entirety of the Coorong represents the 'estuary' of the River Murray (*sensu* Potter et al. 2010), but the 'Murray Estuary' is a geographic site name given to the reach between Goolwa Barrage and Pelican Point.

Lake Alexandrina and Lake Albert are large (~760 km^2 and 168 km^2), shallow (deepest points -4.0 m and -1.7 m Australian Height Datum [AHD] respectively), eutrophic and turbid freshwater lakes (Aldridge et al. 2011). The bulk of freshwater flow to the Lower Lakes is derived from the lower River Murray (typically >98% of total annual flow), with a smaller contribution (typically <2%) from tributary streams of the EMLR (i.e. Currency Creek and Finniss, Angas and Bremer Rivers). The centres of both Lakes are characterised by largely homogenous bare sediment, whilst the littoral zones are characterised by emergent (e.g. *Phragmites australis* and *Typha domingensis*) and sparse, submerged vegetation (e.g. *Myriophyllum* spp and *Ceratophyllum demersum*) (Phillips & Muller 2006). The south-west region of Lake Alexandrina — comprising Hindmarsh I., Mundoo I. and several smaller islands, Goolwa Channel and the confluences with the Finniss River and Currency Creek — harbours a diversity of aquatic habitats, characterised by heterogeneous emergent and submergent vegetation (Phillips & Muller 2006). Lake Alexandrina

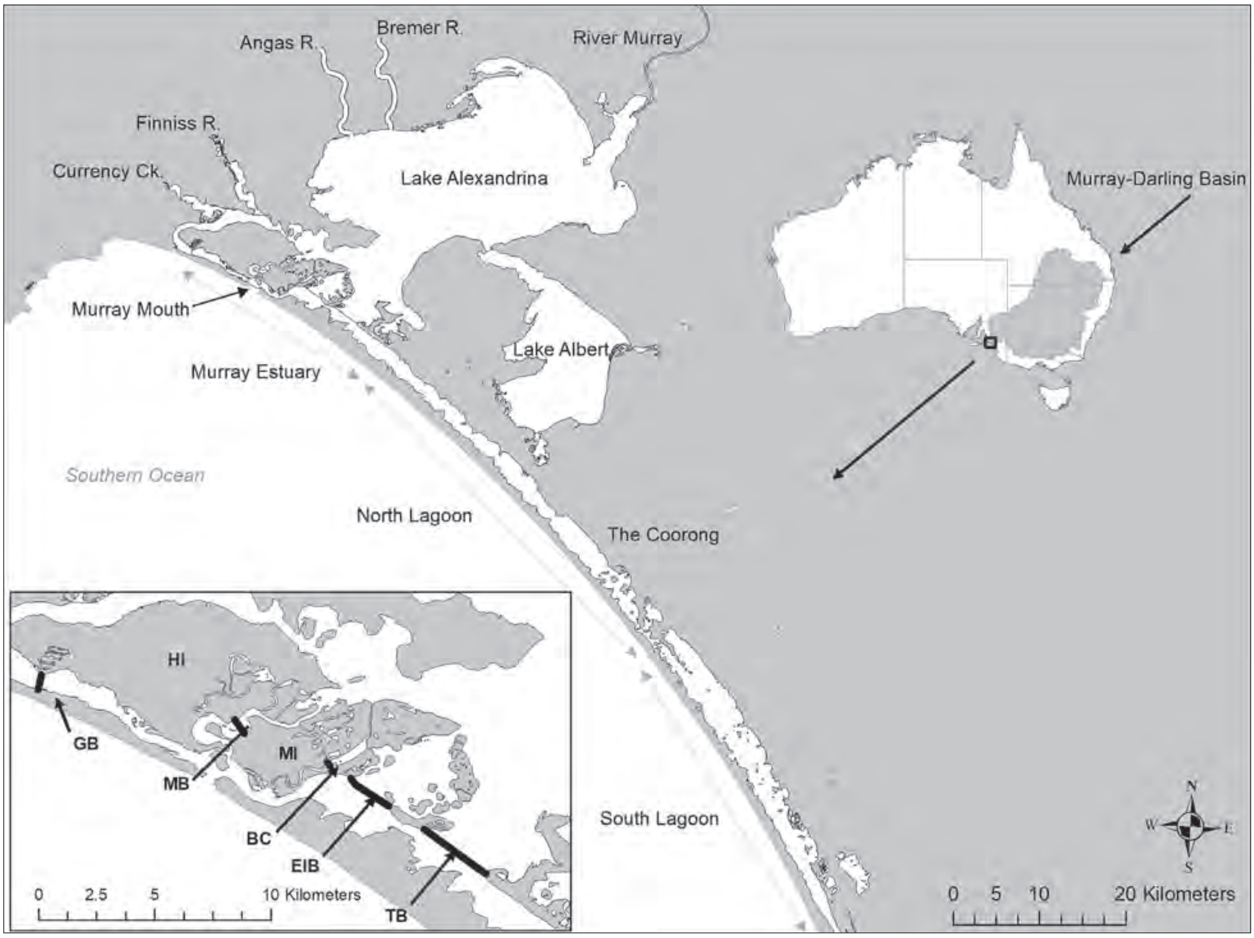

Figure 3.6.1 Map of the Lower Lakes and Coorong presenting the location of spatial subunits of the region. Illustrated are Lake Alexandrina and Lake Albert, the Murray Estuary, North Lagoon and South Lagoon. Specific detail of the interface between the Lower Lakes and Coorong is provided in the inset, presenting the location of the Murray Barrages and significant islands. GB = Goolwa Barrage, MB = Mundoo Barrage, BC = Boundary Creek Barrage, EIB = Ewe Island Barrage, TB = Tauwitchere Barrage, HI = Hindmarsh Island, MI = Mundoo island. (Map by J. Fredberg)

typically exhibits salinities, here presented as electrical conductivity (EC), of <1 000 µS cm^{-1}, whilst EC in Lake Albert is greater and more variable (typically 1 000-9 000 µS cm^{-1}) due to its restricted connection to Lake Alexandrina through the Narrung Narrows, limited water exchange and evapo-concentration (Wedderburn et al. 2014a).

The Coorong is a narrow estuarine lagoon that runs south-east from the River mouth parallel to the coast for ~140 km (Fig. 3.6.1). It is commonly divided into three subunits based upon geographical features and a persistent salinity gradient: a) the Murray Estuary b) the North Lagoon c) the South Lagoon. The Murray Estuary extends from Goolwa Barrage south-east to Pelican Point, including all five barrages, Mundoo Channel and Boundary Creek. The North Lagoon spans the area from Pelican Point to Parnka Point, and the South Lagoon from Parnka Point to 42 Mile Crossing.

Aquatic habitats within the Murray Estuary and Coorong Lagoons are dominated by permanent lagoons and intertidal mudflats, marshes and rocky shores. Physical habitats also include worm reefs formed by the polychaete *Ficopomatus enigmaticus*, and beds of the submerged macrophyte *Ruppia tuberosa* and benthic algae (i.e. *Ulva paradoxa*). The current distribution of *Ruppia tuberosa* is largely driven by the longitudinal salinity gradient and water level variability, and it is now confined to small areas of the North Lagoon and South Lagoon (Frahn & Gehrig 2015). Other submerged macrophytes were historically present, including *Ruppia megacarpa*, but have been mostly absent for the past two decades (Paton 2010).

The physical character of the Coorong is driven by discharge of fresh water through the Murray Barrages (and to a lesser degree discharge from the upper Southeast through Salt Creek) and marine water exchange through the Murray Mouth. As such, salinity in the Murray Estuary is highly variable. During times of high freshwater discharge, salinity is brackish, but variable (0.1-35 g kg^{-1}), whilst during times of low or no discharge it typically reflects marine conditions (i.e. 35-40 g kg^{-1}; Geddes 1987). Salinity increases through the lagoons, relative to the Murray Estuary, with salinity in the South Lagoon reaching >100 g kg^{-1} during extended periods of low flow (Geddes & Butler 1984; Wedderburn et al. 2016). Nonetheless, during times of high river flows, salinities in the North Lagoon are typically brackish (i.e. 5-35g kg^{-1}) with reductions in salinity in the South Lagoon also observed (Geddes 1987).

SPECIES AND ESTUARINE USE FUNCTIONAL GUILDS

The species' inventories of Eckert and Robinson (1990) and Wedderburn and Hammer (2003) have been combined with data collated from several long-term fish-monitoring programs in the Lower Lakes (e.g. Bice & Ye 2007; Bice et al. 2011, 2014; Bice & Zampatti 2011; Wedderburn & Barnes 2014) and the Coorong (e.g. Noell et al. 2009; Bice et al. 2017a; Ye et al. 2015) over the period 2005-2016, records from the Lakes and Coorong Fishery (LCF) from 1984-2014, and the SA Museum ichthyology collection, in order to develop a comprehensive list of fishes. A total of 104 fish species have been recorded to date, with 45 species from the Lower Lakes and 93 species from the Coorong (Table 3.6.1). This represents an assemblage with a diverse range of morphologies, sizes, life-histories and commercial and conservation significance.

Guild approaches, which aggregate fishes based on similarities in biology and ecology, have long been used in estuarine environments, providing a standardised approach to classifying fishes for comparison across aquatic systems, and assisting management by simplifying complex assemblages. We have adopted the 'estuarine use functional guild' (EUFG) approach (Elliott et al. 2007) as refined by Potter et al. (2015). The EUFG proposes that fishes can be grouped under four broad life-history categories, defined primarily by the environment in which spawning occurs: a) freshwater b) diadromous c) estuarine d) marine. Each category comprises two or more guilds defined by specific locations of spawning, feeding and/or refuge, and by the nature of migratory movements between different ecosystems.

Fishes of the LLC were assigned to the guilds of Potter et al. (2015) in a workshop of relevant experts in order to reach a consensus on designation of species. Assignment was based on published literature of species biology/ecology and expert opinion. All four categories and nine of a possible 14 guilds, as defined by Potter et al. (2015), are represented by fishes of the LLC. Each of these categories and guilds is described below with the general life-histories and ecology of representative species.

Table 3.6.1 List of fish species recorded from the Lower Lakes and Coorong and their guild classification. Species were designated to guilds by means of an expert workshop following the 'Estuarine Use Functional Guild' approach proposed by Potter et al. (2015). The spatial units of the site within which each species has been recorded are also presented, whilst those in bold represent spatial units within which a species is typically common.
LAx = Lake Alexandrina, LAb = Lake Albert, ME = Murray Estuary, NL = North Lagoon, SL = South Lagoon.

Common name	**Scientific name**	**Family**	**Guild**	**Spatial units where recorded**
Freshwater category				
Murray hardyhead[E, P]	*Craterocephalus fluviatilis*	Atherinidae	Freshwater straggler	LAx, LAb, ME
Unspecked hardyhead	*Craterocephalus fulvus*	Atherinidae	Freshwater straggler	**LAx**, **LAb**, ME
Oriental weatherloach[@^]	*Misgurnis anguillicaudatus*	Cobitidae	Freshwater straggler	LAx
Goldfish[@]	*Carassius auratus*	Cyprinidae	Freshwater straggler	**LAx**, LAb, ME
Common carp[@, C]	*Cyprinus carpio*	Cyprinidae	Freshwater straggler	**LAx**, **LAb**, ME, NL
Tench[@^]	*Tinca tinca*	Cyprinidae	Freshwater straggler	LAx
Carp gudgeon complex	*Hypseleotris spp.*	Eleotridae	Freshwater straggler	**LAx**, LAb, ME
Dwarf flat-headed gudgeon	*Philypnodon macrostomus*	Eleotridae	Freshwater straggler	**LAx**, LAb, ME
Mountain galaxias	*Galaxias olidus* complex	Galaxiidae	Freshwater straggler	LAx
Murray rainbowfish	*Melanotaenia fluviatilis*	Melaenotaenidae	Freshwater straggler	LAx
River blackfish	*Gadopsis marmoratus*	Percichthyidae	Freshwater straggler	LAx
Murray cod[E, P]	*Maccullochella peelii*	Percichthyidae	Freshwater straggler	LAx, LAb, ME
Golden perch[C]	*Macquaria ambigua*	Percichthyidae	Freshwater straggler	**LAx**, **LAb**, ME
Southern pygmy perch[P]	*Nannoperca australis*	Percichthyidae	Freshwater straggler	LAx
Yarra pygmy perch[E, P]	*Nannoperca obscura*	Percichthyidae	Freshwater straggler	LAx
Redfin perch[@, C]	*Perca fluviatilis*	Percidae	Freshwater straggler	**LAx**, **LAb**, ME
Freshwater catfish [P]	*Tandanus tandanus*	Plotosidae	Freshwater straggler	LAx, LAb
Eastern Gambusia[@]	*Gambusia holbrooki*	Poecilidae	Freshwater straggler	**LAx**, **LAb**, ME
Rainbow trout[@]	*Oncorhynchus mykiss*	Salmonidae	Freshwater straggler	LAx
Brown trout[@]	*Salmo trutta*	Salmonidae	Freshwater straggler	LAx
Silver perch[E, P]	*Bidyanus bidyanus*	Terapontidae	Freshwater straggler	LAx, LAb, ME
Spangled perch[^]	*Leiopotherapon unicolor*	Terapontidae	Freshwater straggler	LAx, ME
Bony herring[C]	*Nematalosa erebi*	Clupeidae	Freshwater est. opportunist	**LAx**, **LAb**, **ME**, NL, SL
Flat-headed gudgeon	*Philypnodon grandiceps*	Eleotridae	Freshwater est. opportunist	**LAx**, **LAb**, **ME**, NL
Australian smelt	*Retropinna semoni*	Retropinnidae	Freshwater est. opportunist	**LAx**, **LAb**, **ME**, NL
Diadromous category				
Pouched lamprey	*Geotria australis*	Geotriidae	Anadromous	LAx, ME
Short-headed lamprey	*Mordacia mordax*	Mordaciidae	Anadromous	LAx, ME
Short-finned eel	*Anguilla australis*	Anguillidae	Catadromous	LAx

Common name	Scientific name	Family	Guild	Spatial units where recorded
Congolli	*Pseudaphritis urvillii*	Bovichtidae	Catadromous	**LAx**, **LAb**, **ME**, **NL**, SL
Common galaxias	*Galaxias maculatus*	Galaxiidae	Semi-catadromous	**LAx**, **LAb**, **ME**, NL
Estuary perch^	*Macquaria colonorum*	Percichthyidae	Semi-catadromous	LAx, ME
Australian bass^	*Macquaria novemaculeata*	Percichthyidae	Semi-catadromous	LAx
Estuarine category				
Smallmouth hardyhead	*Atherinosoma microstoma*	Atherinidae	Solely estuarine	LAx, LAb, ME, **NL**, **SL**
Tamar River goby	*Afurcagobius tamarensis*	Gobiidae	Solely estuarine	LAx, LAb, **ME**, **NL**
Western bluespot goby	*Pseudogobius olorum*	Gobiidae	Solely estuarine	LAx, LAb, **ME**, NL
Lagoon goby	*Tasmanogobius lasti*	Gobiidae	Solely estuarine	LAx, LAb, **ME**, NL
Black bream[C]	*Acanthopagrus butcheri*	Sparidae	Solely estuarine	LAx, **ME**, **NL**, SL
Western river garfish	*Hyporhamphus regularis regularis*	Hemiramphidae	Solely estuarine	LAx, **ME**, NL
Bridled goby	*Arenigobius bifrenatus*	Gobiidae	Estuarine & marine	LAx, LAb, **ME**, NL
Estuary catfish^	*Cnidoglanis macrostomus*	Plotosidae	Estuarine & marine	ME
Soldierfish	*Gymnapistes marmoratus*	Tetrarogidae	Estuarine & marine	**ME**, NL
Marine category				
Australian herring[C]	*Arripis georgianus*	Arripidae	Marine est. opportunist	**ME**, NL
Western Australian salmon[C]	*Arripis truttaceus*	Arripidae	Marine est. opportunist	**ME**, NL
Sandy sprat	*Hyperlophus vittatus*	Clupeidae	Marine est. opportunist	LAx, **ME**, NL
Australian anchovy	*Engraulis australis*	Engraulidae	Marine est. opportunist	ME, NL
Yelloweye mullet[C]	*Aldrichetta forsteri*	Mugilidae	Marine est. opportunist	LAx, **ME**, **NL**, SL
Goldspot mullet	*Liza argentea*	Mugilidae	Marine est. opportunist	LAx, **ME**, NL, SL
Sea mullet	*Mugil cephalus*	Mugilidae	Marine est. opportunist	LAx, ME, NL, SL
Blue-spotted flathead	*Platycephalus speculator*	Platycephalidae	Marine est. opportunist	ME
Longsnout flounder	*Ammotretis rostratus*	Pleuronectidae	Marine est. opportunist	ME, **NL**
Greenback flounder[C]	*Rhombosolea tapirina*	Pleuronectidae	Marine est. opportunist	ME, **NL**, SL
Tailor^	*Pomatomus saltatrix*	Pomatomidae	Marine est. opportunist	ME
Mulloway[C]	*Argyrosomus japonicus*	Sciaenidae	Marine est. opportunist	LAx, **ME**, NL
Yellowfin whiting	*Sillago schomburgkii*	Sillaginidae	Marine est. opportunist	ME
Prickly toadfish	*Contusus brevicaudus*	Tetraodontidae	Marine est. opportunist	ME
Smooth toadfish	*Tetractenos glaber*	Tetraodontidae	Marine est. opportunist	ME, NL
Cowfish^	*Aracana ornata*	Aracanidae	Marine straggler	ME
Tasmanian blenny^	*Parablennius tasmanianus*	Bleniidae	Marine straggler	ME
Silver trevally^	*Pseudocaranx georgianus*	Carangidae	Marine straggler	ME
Bronze whaler shark	*Carcharhinus brachyurus*	Carcharhinidae	marine straggler	ME, NL
Magpie perch^	*Cheilodactylus nigripes*	Cheilodactylidae	marine straggler	ME

Common name	**Scientific name**	**Family**	**Guild**	**Spatial units where recorded**
Silver spot^	*Threpterius maculosus*	Chironemidae	Marine straggler	ME
Southern crested weedfish^	*Cristiceps australis*	Clinidae	Marine straggler	ME, NL
Ogilby's weedfish^	*Heteroclinus heptaeolus*	Clinidae	Marine straggler	ME, NL
Australian pilchard	*Sardinops sagax*	Clupeidae	Marine straggler	ME
Blue sprat	*Spratelloides robustus*	Clupeidae	Marine straggler	ME
Old wife^	*Enoplosus armatus*	Enoplosidae	Marine straggler	ME
Southern Longfin Goby	*Favonigobius lateralis*	Gobiidae	marine straggler	ME
Southern garfish	*Hyporhamphus melanochir*	Hemiramphidae	Marine straggler	ME
Broadnose shark^	*Notorynchus cepedianus*	Hexanchidae	Marine straggler	NL
Zebra fish	*Girella zebra*	Kyphosidae	Marine straggler	ME
Sea sweep	*Scorpis aequipinnis*	Kyphosidae	Marine straggler	ME
Blue groper^	*Achoerodus gouldii*	Labridae	Marine straggler	NL
Little weed whiting^	*Neoodax balteatus*	Labridae	marine straggler	ME
Longray weed whiting^	*Siphonognathus radiatus*	Labridae	marine straggler	ME
Flathead sandfish	*Lesueurina platycephala*	Leptoscopidae	Marine straggler	ME
Bridled leatherjacket	*Acanthaluteres spilomelanurus*	Monacanthidae	Marine straggler	ME
Southern pygmy leatherjacket^	*Brachaluteres jacksonianus*	Monacanthidae	Marine straggler	ME
Gunn's leatherjacket^	*Eubalichthys gunnii*	Monacanthidae	Marine straggler	ME
Six-spined leatherjacket	*Meuschenia freycineti*	Monacanthidae	Marine straggler	ME
Velvet leatherjacket^	*Meuschenia scaber*	Monacanthidae	Marine straggler	ME
Rough leatherjacket^	*Scobinichthys granulatus*	Monacanthidae	Marine straggler	ME
Red mullet	*Upeneichthys vlamingii*	Mullidae	Marine straggler	ME
Southern eagle ray^	*Myliobatus tenuicaudatus*	Myliobatidae	Marine straggler	ME
Rock ling^	*Genypterus tigerinus*	Ophidiidae	Marine straggler	NL
Common saw shark^	*Pristiophorus cirratus*	Pristiophoridae	Marine straggler	NL
Southern saw shark^	*Pristiophorus nudipinnis*	Pristiophoridae	Marine straggler	NL
Red gurnard perch^	*Helicolenus percoides*	Scorpaenidae	Marine straggler	NL
Black-spotted gurnard perch	*Neosebastes nigropunctatus*	Scorpaenidae	Marine straggler	NL
Common gurnard perch	*Neosebastes scorpaenoides*	Scorpaenidae	Marine straggler	NL
King George whiting	*Sillaginodes punctatus*	Sillaginidae	Marine straggler	ME
Snapper^	*Chrysophrys auratus*	Sparidae	Marine straggler	NL
Smooth hammerhead^	*Sphyrna zygaena*	Sphyrnidae	Marine straggler	NL
Big belly seahorse^	*Hippocampus abdominalis*	Syngnathidae	Marine straggler	ME
Rhino pipefish^	*Histiogamphelus cristatus*	Syngnathidae	Marine straggler	ME
Tucker's pipefish^	*Mitotichthys tuckeri*	Syngnathidae	Marine straggler	ME
Common seadragon^	*Phyllopteryx taeniolatus*	Syngnathidae	Marine straggler	NL

Common name	Scientific name	Family	Guild	Spatial units where recorded
Pug-nosed pipefish	*Pugnaso curtirostris*	Syngnathidae	Marine straggler	ME
Spotted pipefish^	*Stigmatophora argus*	Syngnathidae	Marine straggler	ME
Western striped grunter^	*Pelates octolineatus*	Terapontidae	Marine straggler	ME
Richardson's toadfish	*Tetractenos hamiltoni*	Tetraodontidae	Marine straggler	ME
School shark	*Galeorhinus galeus*	Triakidae	Marine straggler	NL
Gummy shark	*Mustelus antarcticus*	Triakidae	Marine straggler	NL
Red gurnard^	*Chelidonichthys kumu*	Triglidae	Marine straggler	NL

$^{@}$denotes alien species, ^{E} denotes species listed under the commonwealth *Environment Protection and Biodiversity Conservation Act 1999*, ^{P} denotes species 'protected' in South Australia under the *Fisheries Management Act 2007*, ^{C} denotes species of commercial importance within the site, ^denotes species with few records from the Lower Lakes and Coorong.

Freshwater category

Freshwater straggler guild

This guild is defined as species that occupy truly freshwater environments and that only sporadically enter estuaries and in low numbers (Potter et al. 2015). These species commonly, but not always, exhibit low tolerances to elevated salinities. The guild comprises 20 species that are characteristic of the fish assemblage of the Lower Lakes and occasionally occur in the Coorong (Table 3.6.1). The EUFG approach adopted is related to the use of estuarine habitats by these species but does not differentiate the range of life-histories exhibited by freshwater species from this guild. Differences in life-history and population dynamics will be further discussed in a subsequent section in this chapter entitled *Fish assemblage dynamics in the Lower Lakes* (p. 384).

This guild comprises several species of conservation significance (Table 3.6.2), including the small-bodied (i.e. adult length <100 mm) Yarra pygmy perch (*Nannoperca obscura*), southern

Table 3.6.2 List of fish species of conservation concern found in the Lower Lakes and Coorong, and their relevant national and state conservation status. National listings relate to the federal *Environment Protection and Biodiversity Conservation Act 1999*. State listings include protection from take under the *Fisheries Management Act 2007* and interim listings under the Action Plan for South Australian Freshwater Fishes (Hammer et al. 2009).

Common name	Scientific name	South Australian listing		National listing
		Fisheries Management Act 2007	**Action Plan for South Australian Freshwater Fishes 2009**	***EPBC Act 1999***
Murray cod	*Maccullochella peelii*	Protected	Endangered	Vulnerable
Silver perch	*Bidyanus bidyanus*	Protected	Endangered	Critically Endangered
Freshwater catfish	*Tandanus tandanus*	Protected	Endangered	-
Yarra pygmy perch	*Nannoperca obscura*	Protected	Critically Endangered	Vulnerable
Southern pygmy perch	*Nannoperca australis*	Protected	Endangered	-
Murray hardyhead	*Craterocephalus fluviatilis*	Protected	Critically Endangered	Endangered

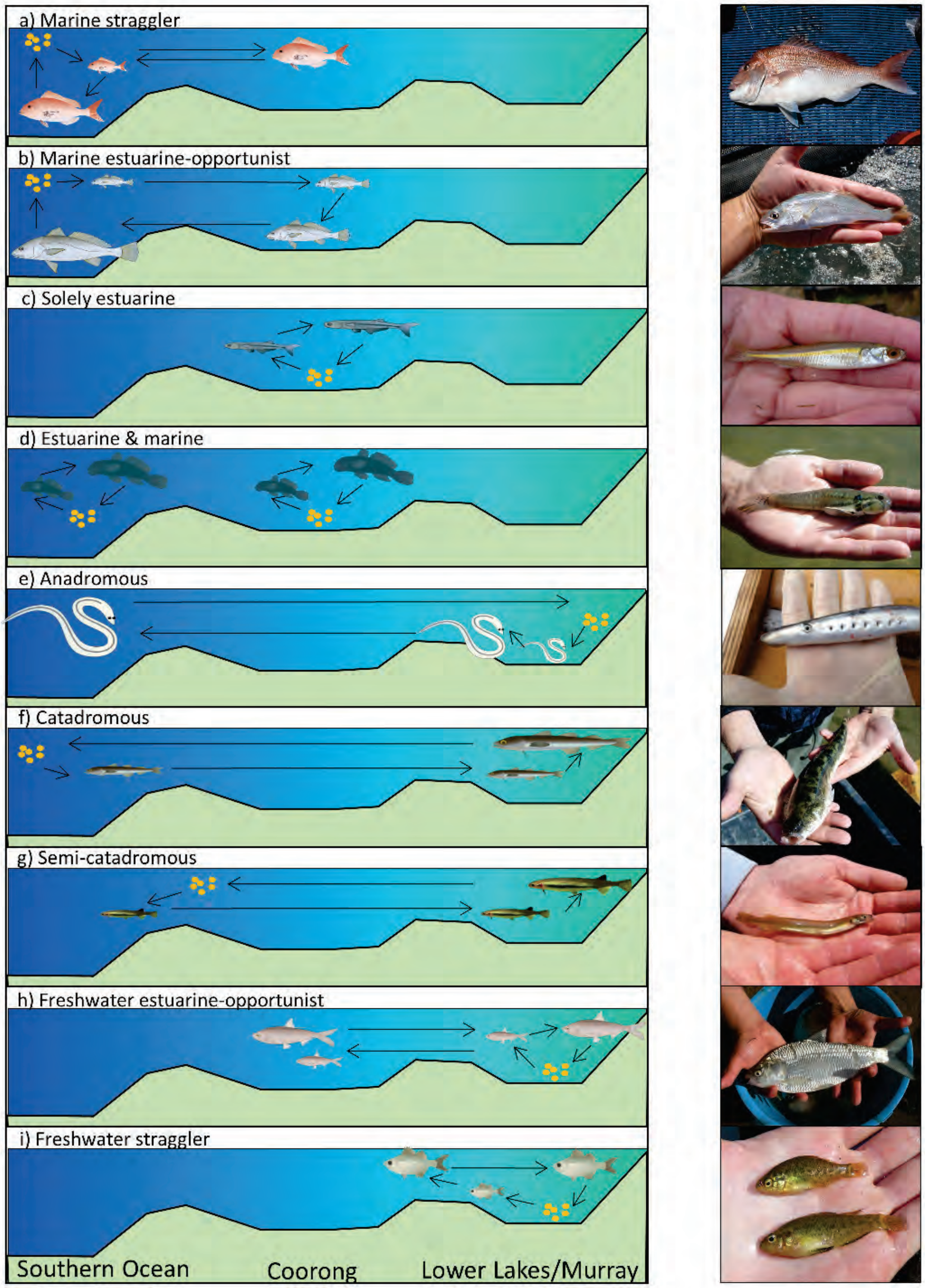

Figure 3.6.2 Conceptual diagrams of the life-histories of different estuarine use functional guilds and representative fish species from the Lower Lakes and Coorong.

(a) Marine straggler — snapper.
(b) Marine estuarine-opportunist — mulloway.
(c) Solely estuarine — smallmouth hardyhead.
(d) Estuarine and marine — bridled goby.
(e) Anadromous — pouched lamprey.
(f) Catadromous — congolli.
(g) Semi-catadromous — common galaxias.
(h) Freshwater estuarine-opportunist — bony herring.
(i) Freshwater straggler — Yarra pygmy perch.

(Adapted from Potter et al. 2015. Symbols courtesy of the Integration and Application Network, University of Maryland Centre for Environmental Science (ian.umces.edu/symbols/)).

pygmy perch (*Nannoperca australis*) and Murray hardyhead (*Craterocephalus fluviatilis*). The Lower Lakes population of Yarra pygmy perch is the only population of this species in the MDB, and as such, is a genetically distinct major lineage (Hammer et al. 2010), whilst the population of Murray hardyhead comprises a distinct genetic management unit within the MDB (Adams et al. 2011). Several other small-bodied species, including carp gudgeon (*Hypseleotris* spp) and unspecked hardyhead (*Craterocephalus fulvus*), are common and widespread in the Lower Lakes. Medium- and large-bodied species of conservation significance, namely silver perch (*Bidyanus bidyanus*), freshwater catfish (*Tandanus tandanus*) and Murray cod (*Maccullochella peelii*), have been recorded in the Lower Lakes, but are generally rare (Hammer et al. 2009). Another large-bodied species, golden perch (*Macquaria ambigua*), is common and widespread in the Lower Lakes, and commercially and culturally important, with 20-200 t harvested annually by the LCF (Sim et al. 2000; Ferguson et al. 2013; Earl 2015).

The alien species common carp (*Cyprinus carpio*), redfin perch (*Perca fluviatilis*), eastern gambusia (*Gambusia holbrooki*), goldfish (*Carassius auratus*), tench (*Tinca tinca*), brown trout (*Salmo trutta*), rainbow trout (*Onchorryhnchus myskiss*) and oriental weatherloach (*Misgurnis anguillicaudatus*) are also members of the freshwater straggler guild. The trout species and tench are now rare in the Lower Lakes but are patchily distributed in tributaries in the EMLR (Whiterod et al. 2015). Trout are stocked in some of these streams under a species exemption granted by the SA Government. Common carp, redfin perch, eastern gambusia and goldfish are common and widespread in the Lower Lakes (Wedderburn & Hammer 2003). Common carp and redfin perch are among the most abundant large-bodied fishes, and, notwithstanding their alien status, contribute 300-1 000 and 5-90 t respectively to annual landings from the LCF (Earl 2015). Oriental weatherloach is known from a single record in Lake Alexandrina (March 2018; S. Wedderburn unpublished data) but may become more common given range expansion into the lower River Murray from upstream since 2011 (Fredberg et al. 2014).

Freshwater-estuarine opportunist guild

This guild comprises freshwater species that commonly use estuarine habitats in substantial numbers; it is represented by bony herring (*Nematalosa erebi*), Australian smelt (*Retropinna semoni*) and flat-headed gudgeon (*Philypnodon grandiceps*) (Table 3.6.1). These species are ecological generalists, exhibiting flexible reproductive characteristics (e.g. protracted spawning seasons), broad physico-chemical tolerances (e.g. salinity) and flexible habitat requirements. All are widespread and abundant in the Lower Lakes and Coorong, being sampled in the Murray Estuary, North Lagoon and South Lagoon even at elevated salinities (e.g. ≥ 35 g kg^{-1}) (Ye et al. 2012). Typically, >400 t yr^{-1} of bony herring are harvested by the LCF (predominantly from the Lower Lakes), for use as bait in the Southeast rock lobster fishery (Earl 2015).

Diadromous category

This category is defined as those species that must migrate between freshwater and marine environments to complete their life cycles, and within the LLC is represented by three guilds as defined by the environment in which reproduction occurs and where the majority of adult life is spent a) anadromous b) catadromous c) semi-catadromous.

Anadromous guild

This guild incorporates species whose adult life is spent primarily in the marine environment, prior to upstream migration into freshwater environments for spawning (Potter et al. 2015). It is represented by pouched lamprey (*Geotria australis*) and short-headed lamprey (*Mordacia mordax*) (Table 3.6.1) — the only anadromous fishes in the MDB. Lamprey are primitive, jawless, eel-like fishes, and adults are parasitic feeders on marine fishes. The LLC represent a migratory pathway from adult marine habitats to freshwater spawning and nursery habitats. Migration of pouched lamprey into the Coorong and through the Lower Lakes into the River Murray occurs in winter, whilst short-headed lamprey migrates upstream in late winter-spring (Bice et al. 2017a). Historically, upstream migrations extended far upstream in the River Murray (up to ~2 000 km from the Murray Mouth) and associated tributaries (e.g. the Goulburn River) (Potter & Strahan 1968). More recently in 2015, an individual pouched lamprey tagged at Goolwa Barrage was detected three months later at Lock 11 on the River Murray at Mildura, Victoria (878 km upstream) (SARDI 2015 unpublished data). Upstream migration may take as long as 16 months in pouched lamprey (Potter et al. 1983) and 12 months in short-headed lamprey (Potter 1970), during which time adults do not feed. The early life stages (ammocoetes) are sedentary, benthic filter feeders that reside in silty and sandy substrates of freshwater environments. Metamorphosis into adult morphology occurs at ~3.5 years in short-headed lamprey and ~4.3 years in pouched lamprey, and juveniles subsequently migrate downstream to the sea (Potter 1970; Potter & Hilliard 1986). Both species were once common in the MDB (Potter & Strahan 1968) but are now rarely encountered. Declines have likely resulted from diminished river flows and obstruction of migration by flow-regulating structures, including the barrages.

Catadromous guild

This guild refers to species whose adult life is spent in fresh water, prior to downstream migration into the marine environment for spawning (Potter et al. 2015). Larvae and juveniles develop in the ocean before migrating upstream into freshwater habitats. Short-finned eel (*Anguilla australis*) and congolli (*Pseudaphritis urvillii*) represent this guild in the LLC (Table 3.6.1).

Congolli is a medium-bodied (adult female length ~300 mm) benthic species found throughout the LLC. The species exhibits both sexual dimorphism and spatial sexual segregation, with smaller males (length <150 mm) favouring estuarine habitats and larger females (length >150 mm) most abundant in freshwater habitats (Hortle 1978). During winter, females undertake rapid downstream spawning migrations from the lower River Murray, EMLR tributaries and Lower Lakes, through the Coorong and into the ocean (Bice et al. in press). Females are thought to be semelparous, with spawning followed by mortality (Crook et al. 2010). Larvae and juveniles enter the Coorong from the ocean and migrate upstream into freshwater habitats in spring-summer at sizes ranging from 20 to 70 mm in length and ~90 days old (Bice et al. 2012). Whilst common and widespread across the LLC, it appears that the species was more abundant prior to barrage construction, when it comprised a notable seasonal component of the LCF (Olsen & Evans 1991).

Semi-catadromous guild

This guild refers to species with a generally catadromous life-history, but whose downstream spawning migrations cease in estuarine environments (Potter et al. 2015). In the LLC this guild is represented by estuary perch (*Macquaria colonorum*), Australian bass (*Macquaria novemaculeata*) and common galaxias (*Galaxias maculatus*) (Table 3.6.1). While the LLC represents the western extremity of the range of estuary perch, the species was anecdotally common in the region prior to construction of the barrages. However, there have been <10 confirmed records of this species in the last two decades (last record 2014 from the North Lagoon), suggesting that initial barrage construction impacted on this species. The closely related Australian bass was unknown from the region until a confirmed record in 2017, but the origin of this fish is unclear (e.g. translocated or wild vagrant).

The common galaxias is a small-bodied species (adult length ~100 mm) that is common in the Lower Lakes (Wedderburn et al. 2014a) and the EMLR tributaries (Whiterod et al. 2015). Downstream migrations and spawning may occur over a protracted period from June to November (Bice et al. 2012), with eggs spawned on littoral vegetation on spring tides and development occurring largely out of water, before hatching on the following spring tide (McDowall 1996). Larvae are commonly washed out to sea, where they develop, before upstream migrations of juveniles (whitebait) occur in spring-summer. Despite typically exhibiting a semi-catadromous life-history, common galaxias display flexible reproductive strategies and may form self-sustaining landlocked populations (Pollard 1971; Chapman et al. 2006), with some evidence of this occurring in the Lower Lakes during times of extended barrage closure (Zampatti et al. 2011).

Estuarine category

Solely estuarine guild

This guild refers to species whose reproduction is confined to estuarine habitats; it includes black bream (*Acanthopagrus butcheri*), smallmouth hardyhead (*Atherinosoma microstoma*), river garfish (*Hyperhamphus regularis*), Tamar River goby (*Afurcagobius tamarensis*), lagoon goby (*Tasmanogobius lasti*) and blue-spot goby (*Pseudogobius olorum*) (Table 3.6.1). These species, with the exception of smallmouth hardyhead, are typically most common in the Murray Estuary and North Lagoon, and are occasionally sampled in the South Lagoon and Lower Lakes. Smallmouth hardyhead is typically abundant in the South Lagoon, where it is often the only fish present.

Black bream is a medium-bodied (adult size to ~500 mm), long-lived species (up to 30 years; see Morison et al. 1998) that tolerates a broad range of salinities (0-60 g kg^{-1}) (Hoeksema et al. 2006). It is most abundant in the Murray Estuary and North Lagoon but is also found in the South Lagoon and in Lake Alexandrina. The species is an opportunistic omnivore, consuming a range of food items, including molluscs (e.g. mussels), crustaceans (e.g. crabs), polychaetes, small-bodied fishes (e.g. gobies) and plant matter (Norriss et al. 2002). Spawning likely occurs in spring-summer in the Coorong (Cheshire et al. 2013), and is associated with freshwater flow and the formation of a 'salt wedge', typically at salinities of 10-25 g kg^{-1} (Nicholson et al. 2008). While the species completes its life cycle within the Coorong, there is evidence of inter-estuarine movements to the nearby Hindmarsh River (Hall 1984; unpublished data), suggesting that its population dynamics may be influenced by processes occurring over broader spatial scales.

Estuarine and marine guild

This guild refers to species that may form discrete self-sustaining populations in estuarine and marine environments (Potter et al. 2015). The estuarine and marine guild is represented by three species in the LLC (Table 3.6.1): estuary catfish (*Cnidoglandis macrostomus*) and soldier fish (*Gymnapistes marmoratus*), which are uncommon, and bridled goby (*Arenigobius bifrenatus*), which is abundant and broadly distributed. Bridled goby is a benthic species, which grows to ~150 mm in length and is most commonly found in the Murray Estuary, but also at times in the Lower Lakes and North Lagoon. Males in particular can be strikingly coloured with a distinct black stripe across the cheek and small iridescent blueish dots along the flanks. Bridled goby uses burrows and physical habitat (e.g. rock) for shelter and preys upon a variety of invertebrates and small fishes (McDowall 1996).

Marine category

Marine-estuarine opportunist guild

Marine-estuarine opportunists are marine fishes that enter estuaries regularly, in substantial numbers, often as juveniles, but use marine waters to varying degrees as alternative nurseries (Potter et al. 2015). This guild is represented by 15 species within the LLC (Table 3.6.1), and these species are typically common either throughout the year or during well-defined seasons, particularly in the Murray Estuary and North Lagoon. This guild includes several species of importance in commercial, cultural and recreational fisheries, including mulloway (*Argyrosomus japonicus*), greenback flounder (*Rhombosolea tapirina*) and yelloweye mullet (*Aldrichetta forsteri*), and others that are important in the trophic dynamics of the Coorong (e.g. sandy sprat, *Hyperlophus vitattus*) (Bice et al. 2016a).

Mulloway is an iconic large-bodied (adult length >1 m) species, which uses the Coorong as a nursery, typically entering the system from the ocean at ≤1 year of age and length <150 mm, and emigrating to the ocean and coastal marine adult habitats at ~5 years of age (Ferguson et al. 2014). During their time in the Coorong, mulloway are most commonly encountered in the Murray Estuary and upper part of the North Lagoon, and are the apex piscivorous predator in the region. At small sizes (<400 mm), individuals prey upon small-bodied fishes (e.g. sandy sprat) and small crustaceans (e.g. mysid shrimps), before progressing to larger fishes (e.g. congolli, gobies and bony herring) and crustaceans (i.e. *Paragrapsus gaimardii*) (Giatas & Ye 2015). At >700 mm in length, mulloway in the Coorong have a diet consisting largely of yelloweye mullet (Giatas & Ye 2015). Importantly, recruitment and the strength of adult age classes of mulloway are positively correlated with freshwater discharge to the Coorong (Ferguson et al. 2008). The Coorong and its role as a nursery for this species have a large influence on regional population dynamics (Ferguson et al. 2008).

Marine straggler guild

This guild is defined as marine species that enter estuaries sporadically and typically in low numbers (cf. Potter et al. 2015). Despite this, species from this guild represent ~50% of fishes recorded from the LLC (Table 3.6.1). They are commonly stenohaline and thus only found occasionally in areas of the Coorong where salinities are similar to sea water.

This guild is represented in the LLC by 30 families with a range of different morphologies and trophic levels. It includes small fishes, such as the delicate pipefishes of the Syngnathidae and bait fishes of the Clupeidae (e.g. Australian pilchard, *Sagax sardinops*, and blue sprat, *Spratelloides robustus*), larger predatory fishes (e.g. snapper, *Chrysophrys auratus*), and several species of shark (e.g. bronze whaler, *Carcharhinus brachyurus*). Most species have been recorded from the LLC on only a few occasions, although others, including bronze whaler, King George whiting (*Sillaginodes punctatus*) and several leatherjacket species of the family Monacanthidae, are more commonly encountered. Nonetheless, they are typically captured in low numbers. The LLC do not play a large role in the population dynamics of these species at regional or broader spatial scales.

FISH ASSEMBLAGE DYNAMICS IN THE LOWER LAKES

Paleolimnological and geomorphological studies suggest that prior to European settlement the Lower Lakes were a dynamic, but largely freshwater environment (Fluin et al. 2007; Chapter 2.2 in this volume). Construction of the Murray Barrages, in the early 1930s, in response to declining River Murray flow, fragmented the LLC, and 'secured' the freshwater environment upstream. As such, the Lower Lakes currently support a distinct assemblage of fishes, dominated by freshwater species (Wedderburn & Hammer 2003). Despite fragmentation of the LLC, variability in River Murray flow, albeit much reduced from a natural state, has a large influence on fish population dynamics. This influence may be direct, by influencing critical life-history processes (e.g. spawning, larval drift, migration), or indirect, by influencing water level and salinity in the Lower Lakes, and in turn fish habitat and resource availability. The freshwater fishes of the Lower Lakes can be delineated by the spatial scales of their life-histories. A primary distinction exists between those whose life-histories operate at the spatial scale of the Lower Lakes and are reliant on specific habitats therein (e.g. Yarra pygmy perch) and those whose life-histories operate over greater spatial scales, and whose population dynamics within the Lower Lakes are influenced by processes occurring in other regions of the MDB (e.g. golden perch).

Three ecological specialists that complete their life cycles within the Lower Lakes and are reliant on specific littoral and off-channel habitats are Murray hardyhead, southern pygmy perch and Yarra pygmy perch. A broad-scale survey of littoral fish assemblages in 2002-2003 identified state and nationally significant populations of these species coexisting with numerous common freshwater and catadromous fishes, and low numbers of euryhaline estuarine fishes (e.g. gobies) (Wedderburn & Hammer 2003). This led to a series of monitoring programs targeting small-bodied fishes (i.e. Higham et al. 2005; Bice et al. 2011, 2014; Wedderburn & Barnes 2014) that continued throughout and beyond the Millennium Drought (Van Dijk et al. 2013). These programs found substantial variability in small-bodied fish assemblages, including critical declines in threatened species, driven by water level, salinity and connectivity.

As the Millennium Drought progressed through 2007-2010, reduced river flows led to water level recession in the Lower Lakes, desiccating fringing littoral and off-channel habitats, critical to Murray hardyhead, southern pygmy perch and Yarra pygmy perch (Fig. 3.6.3). Remnant water bodies were fragmented, salinity increased, and freshwater aquatic vegetation was replaced by salt-tolerant species or bare sediment (Nicol et al. 2016). There was a corresponding decline in the abundance of threatened freshwater and catadromous species,

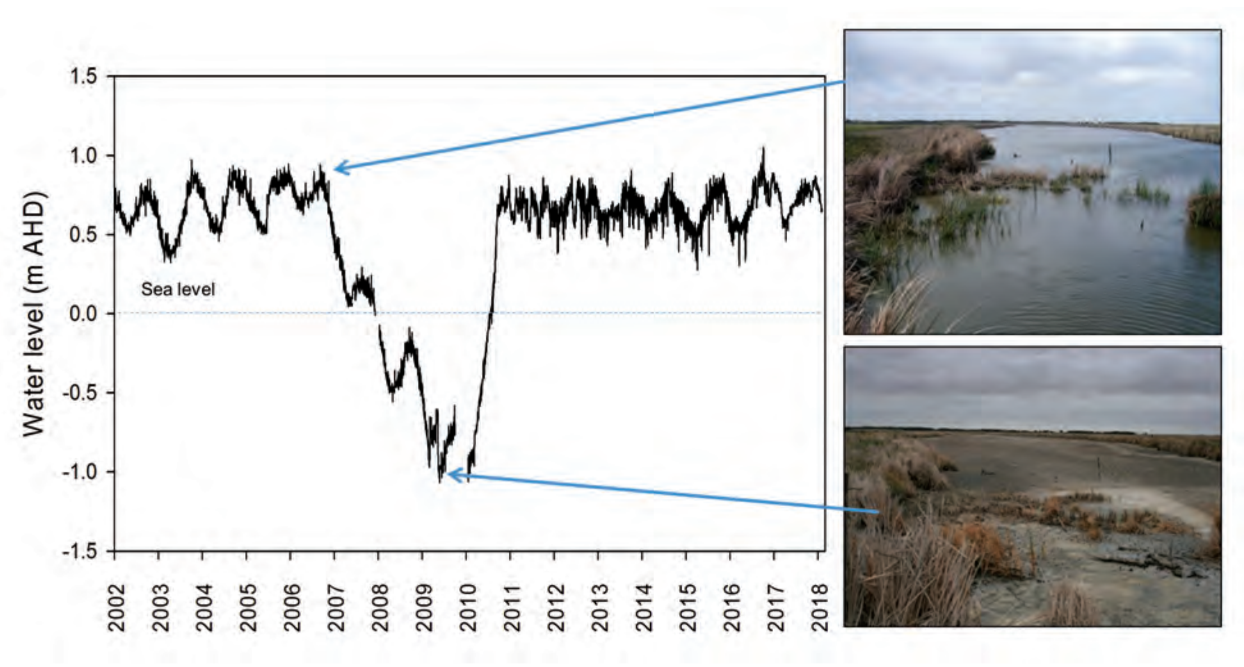

Figure 3.6.3 Water level (m AHD, Australian Height Datum) in Lake Alexandrina from 2002-2018 and images of Boggy Creek on Hindmarsh Island from 2007 and 2009, depicting the water level recession and habitat desiccation that occurred over this period. (From www.waterconnect.sa.gov.au, Department for Environment and Water. Photograph by C. Bice)

due to the loss of obligate habitats and connectivity between the LLC respectively, and an increasing dominance of generalist freshwater (e.g. Australian smelt) and estuarine species (e.g. lagoon goby) (Wedderburn et al. 2012). In light of these substantial changes to habitats and the character of freshwater fish assemblages, several management actions (e.g. environmental watering, fish capture and captive maintenance/breeding) were implemented to ensure the survival of threatened species (Hammer et al. 2013) (Box 3.6.1).

The sudden return of higher river flow and water levels (>0.5 m AHD) in the Lower Lakes in late 2010 resulted in a range of responses from populations of small-bodied fishes. Estuarine species became less abundant, whilst generalist freshwater species, including non-native fishes (e.g. common carp) and catadromous species (e.g. congolli), dominated the assemblage. This reflected reduced salinities and improved connectivity between the Lower Lakes and Coorong, reinforcing the influence of these factors on the structure of fish assemblages in the Lower Lakes. Small-bodied threatened species, however, exhibited variable responses: the salt-tolerant Murray hardyhead persisted throughout the drought and showed signs of population recovery in the south-western region of Lake Alexandrina (Bice et al. 2014; Wedderburn et al. 2014a); but Yarra pygmy perch, and potentially southern pygmy perch, were extirpated from the Lower Lakes. All three species were reintroduced to the Lower Lakes from captive populations (Box 3.6.1), and, despite evidence of self-sustaining populations of Murray hardyhead and southern pygmy perch, as of 2018, Yarra pygmy perch remains absent (Box 3.6.1).

Large-bodied freshwater fishes also characterise the fish assemblage of the Lower Lakes, with bony herring and golden perch the most abundant native species. Golden perch migrate within freshwater habitats (potamodromy), with long-distance movements (up to thousands of

BOX 3.6.1 SMALL-BODIED THREATENED FISH CONSERVATION

Yarra pygmy perch, southern pygmy perch and Murray hardyhead are small-bodied (<80 mm length), short-lived (typically 1-2 yr), threatened freshwater fishes (Table 3.6.2), which depend on specific vegetated littoral and wetland habitats in the Lower Lakes. Water levels in Lake Alexandrina and Lake Albert decreased to approximately 1 m below sea level during the latter stages of the Millennium Drought (Fig. 3.6.3), desiccating habitats critical to these species. A range of management actions were undertaken to prevent local extinctions, including environmental watering of refugia (e.g. Boggy Creek: Wedderburn et al. 2013), captive breeding from local wild fish (Attard et al. 2016) and establishment of populations in farm dams (Hammer et al. 2013). Following the return of stable water levels and favourable habitat in the Lower Lakes (c. spring 2011), approximately 5 850 Yarra pygmy perch, 1 350 southern pygmy perch and 7 500 Murray hardyhead were reintroduced into Lake Alexandrina from 2011 to 2013 (Bice et al. 2014). A further 900 Yarra pygmy perch were released in spring 2016 and a further 12 000 Murray hardyhead were released into Lake Albert in 2016-2017. Murray hardyhead has recovered in Lake Alexandrina, but despite recent releases has yet to re-establish in Lake Albert. There are also signs of population recovery of southern pygmy perch at discrete wetland habitats, resulting from the reintroduction program. However, as of 2018, Yarra pygmy perch remain undetected by monitoring, so further reintroductions are necessary (Wedderburn & Barnes 2018).

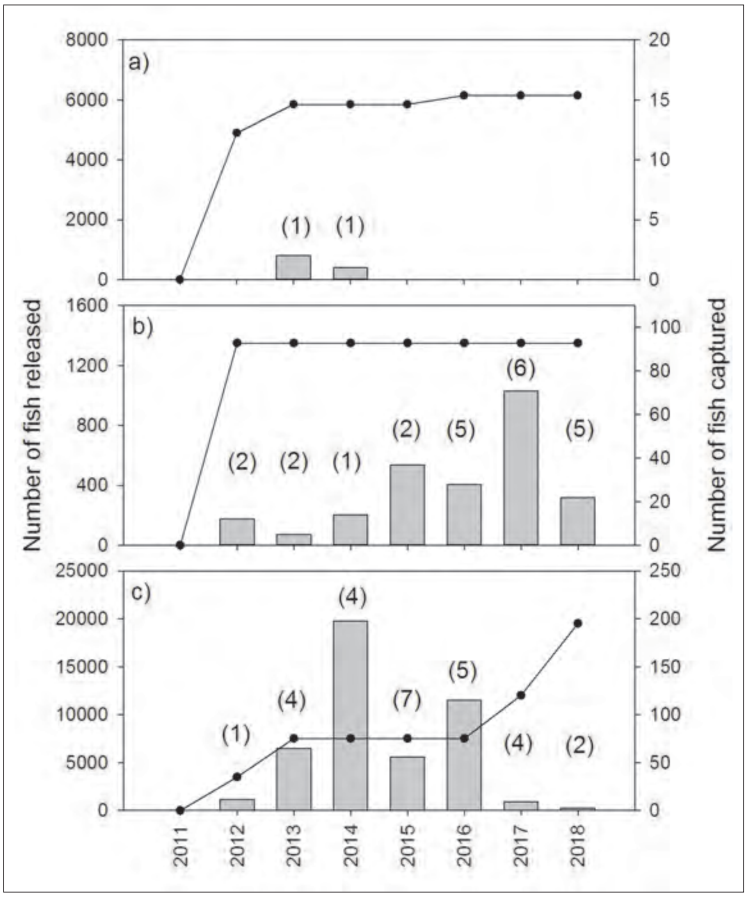

Figure 3.6.4 Cumulative number of fish released (line) and total number of fish captured during standardised monitoring in the Lower Lakes for
(a) Yarra pygmy perch.
(b) Southern pygmy perch.
(c) Murray hardyhead.
Values in brackets represent the number of sites at which the species were captured.

kilometres) by adult fish previously recorded in the MDB (Reynolds 1983). Golden perch is one of few native species in the Murray-Darling Basin that are cued to spawn by elevated flow or flooding, when coinciding with temperature thresholds (Mallen-Cooper & Stuart 2003; Zampatti & Leigh 2013). Furthermore, eggs and larvae are neutrally buoyant and undergo an obligate downstream drifting phase, whilst juveniles have also been shown to undertake considerable active downstream migrations into the lower River Murray (Zampatti et al. 2015); hence populations in given areas, like the Lower Lakes, may be influenced by spawning and immigration from upstream areas. Recent population age structure data for the Lower Lakes (Ferguson & Ye 2016) indicate similar population demography to other areas of the lower River Murray (Zampatti et al. 2015), particularly dominance of the population by individuals spawned during recent high-flow years from 2010-2013. Whilst this suggests a level of interaction between the Lakes and lower River Murray, the relative importance of local and broader population processes on population dynamics of golden perch within the Lower Lakes remains unclear.

Other large-bodied native freshwater species, including Murray cod, silver perch and freshwater catfish, inhabit the Lower Lakes in low numbers. Murray cod were once more common; historically, they formed a component of the commercial fishery (Ferguson & Ye 2016). However, general declines in abundance throughout the lower River Murray (Sim et al. 2000; Ferguson et al. 2013; Zampatti et al. 2014) resulted in a corresponding decline in fishery catches, and ultimately the species was listed under the commonwealth *Environment Protection and Biodiversity Conservation Act 1999* ('the EPBC Act') and protected from harvest in 2003. Data on the current status of Murray cod in the Lower Lakes, as well as silver perch and freshwater catfish, are limited; nonetheless, these species now likely favour upstream riverine habitats.

Alien species are commonly attributed with negative impacts on aquatic habitats and/or native fishes, and these impacts likely extend to the Lower Lakes. Interactions between common carp and native species in the Lower Lakes are unstudied, but damage to aquatic macrophytes and associated decline of aquatic habitat quality are often attributed to this species (Roberts et al. 1995). In addition, common carp may directly compete with native species for food and habitat (Koehn et al. 2000). Recent studies on redfin perch in the Lower Lakes have shown predation on small-bodied native fishes by individuals as small as 9 cm long and <6 months old, as well as the potential for competition between redfin perch and golden perch through dietary overlap (Wedderburn et al. 2014b; Wedderburn & Barnes 2016). Furthermore, the small-bodied eastern gambusia is abundant in littoral and off-channel habitats of the Lower Lakes, and outside of its natural range has been associated with declines in several native fishes globally, through competition for food resources and aggressive interaction (Pyke 2008). While knowledge of the specific impacts of alien species on native fishes in the Lower Lakes is limited, the large abundance/biomass of common carp, redfin perch and eastern gambusia suggests that impacts may be considerable.

FISH ASSEMBLAGE DYNAMICS IN THE COORONG

Salinity is a primary driver of fish distributions and assemblage dynamics in estuaries (Elliott & Whitfield 2011), influencing fishes both directly, through physiological tolerance/preference, and indirectly, by determining the availability of structural habitat (e.g. aquatic macrophytes), and distribution and abundance of food resources (e.g. invertebrates). The fish fauna of the

Coorong illustrates well the influence of river flows and salinity on the distribution of estuarine-associated fishes (Bucater et al. 2013; Hossain et al. 2016; Wedderburn et al. 2016).

The persistent longitudinal salinity gradient from the Murray Estuary to the South Lagoon dictates a gradient in fish species richness. Areas with salinity <35 g kg^{-1} typically have greater richness, due to the presence of species from a range of life-history guilds, and this zone most commonly occurs in the Murray Estuary, due to its proximity to the barrages and the Murray Mouth. In the North Lagoon, where salinity begins to increase, species richness begins to decline, but several euryhaline species typically persist (e.g. smallmouth hardyhead, several gobies, black bream, yelloweye mullet, congolli). In the South Lagoon, salinities increase further, and species richness continues to decline until only smallmouth hardyhead — a species among the most salt-tolerant of fishes globally (Nordlie 2009) — persists. Whilst this gradient in species richness is generally maintained, its exact position shifts NW-SE, dependent on freshwater discharge and its influence on the spatial position of the salinity gradient (Geddes 1987; Ye et al. 2014; Hossain et al. 2016; Wedderburn et al. 2016).

Whilst the Murray Estuary typically exhibits the greatest overall species richness within the region, species composition and abundance vary greatly. Monitoring during 2006-2017 demonstrated that species richness varied little temporally, but during periods of low or no discharge (e.g. 2007-2010) and predominantly marine salinities (35-40 g kg^{-1}), marine species (particularly marine stragglers, e.g. Australian pilchard) were more prevalent, whilst few freshwater species were present (Zampatti et al. 2010). However, the converse occurs during periods of greater discharge (e.g. 2010-2013) and reduced salinities (Ye et al. 2016; Bice et al. 2017a) (Fig. 3.6.5). In contrast, species richness of the estuarine life-history category is typically constant, reflecting the broad salinity tolerance of these species.

Fish abundances are substantially reduced during low freshwater discharge and enhanced during high discharge. Indeed, overall annual fish abundance in the Murray Estuary during the drought from 2007-2010 was typically <10% of annual abundance recorded over the subsequent high-flow period from 2010-2013 (Bice et al. 2017a). The increase in overall abundance during high discharge and associated reduced salinity was driven primarily by the increase in abundances of freshwater and catadromous species, but species from the estuarine and the marine life-history categories (e.g. sandy sprat) also contributed significantly. This suggests a response not only to reduced salinity, but also to enhanced productivity and ecosystem carrying capacity with increased river flows (Brooks et al. 2015; Chapter 3.9 of this volume). In the Murray Estuary, predation of freshwater zooplankton and assimilation of carbon of riverine origin have been demonstrated for the marine estuarine-opportunist sandy sprat, providing direct evidence of subsidy of the estuarine food web by river flows (Bice et al. 2016a). Indeed, within the Murray Estuary, where sandy sprat is typically the most abundant small-bodied fish, it is preyed upon by larger piscivorous fishes (i.e. Australian salmon, *Arripis truttaceaus*, and juvenile mulloway) (Giatas & Ye 2015) and potentially piscivorous birds (e.g. tern species) (Taylor & Roe 2004). Subsequently, factors influencing the abundance of sandy sprat may also affect the abundance of higher trophic levels, including commercially and recreationally important fish species (Bice et al. 2016a).

Similar responses to variable salinity and freshwater discharge occur in the North and South Lagoons. Perhaps most notably, salinity plays a pivotal role in the distribution and abundance

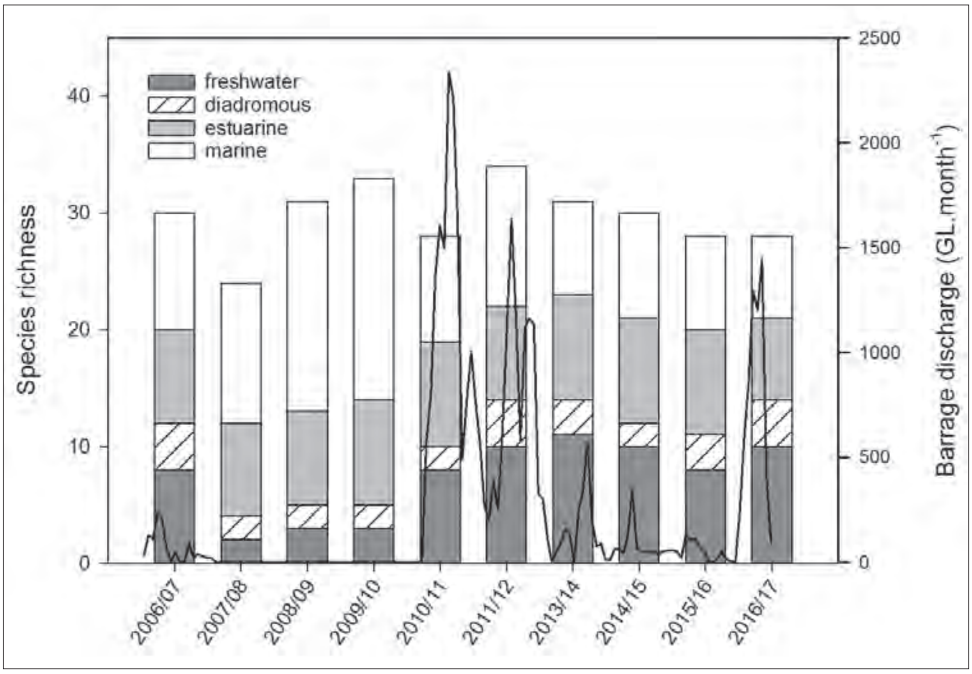

Figure 3.6.5 Fish species richness from standardised fish monitoring in the Murray Estuary from 2006-2017, including the contribution of species from different life history categories, i.e. freshwater, diadromous, estuarine and marine (Bice et al. 2017a). Barrage discharge (GL month^{-1}) is overlaid (black line).

of estuarine species, including smallmouth hardyhead. The species is fundamental to food webs in the North and South Lagoons, and represents a key prey item of the south-eastern fairy tern (*Sterna nereis nereis*), which is listed as vulnerable under the EPBC Act (Paton 2010). During extended periods of low or no freshwater discharge, salinity in the South Lagoon can rise to >120 g kg^{-1}, which largely precludes the highly euryhaline smallmouth hardyhead, while periods of high discharge and reduced salinity enhance its distribution and abundance (Wedderburn et al. 2016). Indeed, in 2008/09, during an extended period of no discharge and elevated salinity, the distribution of smallmouth hardyhead contracted to ~40% of its prior range (Wedderburn et al. 2016), while its abundance was substantially reduced relative to subsequent periods of high (2011/12) and low freshwater discharge (2014/15) (Ye et al. 2015) (Fig. 3.6.6). The diminished distribution and abundance of smallmouth hardyhead in the South Lagoon of the Coorong over the period 2007-2010 disadvantaged the population of fairy tern, which uses breeding islands in the South Lagoon, due to increased energetic demands and predation risk for eggs and chicks resulting from increased travel required for adult foraging (Paton 2010).

CONNECTIVITY AND POPULATION DYNAMICS OF DIADROMOUS FISHES

The population dynamics of diadromous species are dependent on migration between marine and fresh waters. Whilst data on diadromous fish populations prior to construction of the Murray Barrages are scarce, the now infrequent occurrence of estuary perch, pouched lamprey and short-headed lamprey, and anecdotal evidence of reduced abundance of congolli (Olsen & Evans 1991), all likely reflect the impact of the barrages on fish migration. The barrages, however, are low-level structures (~1 m above sea level), and consequently, during periods of

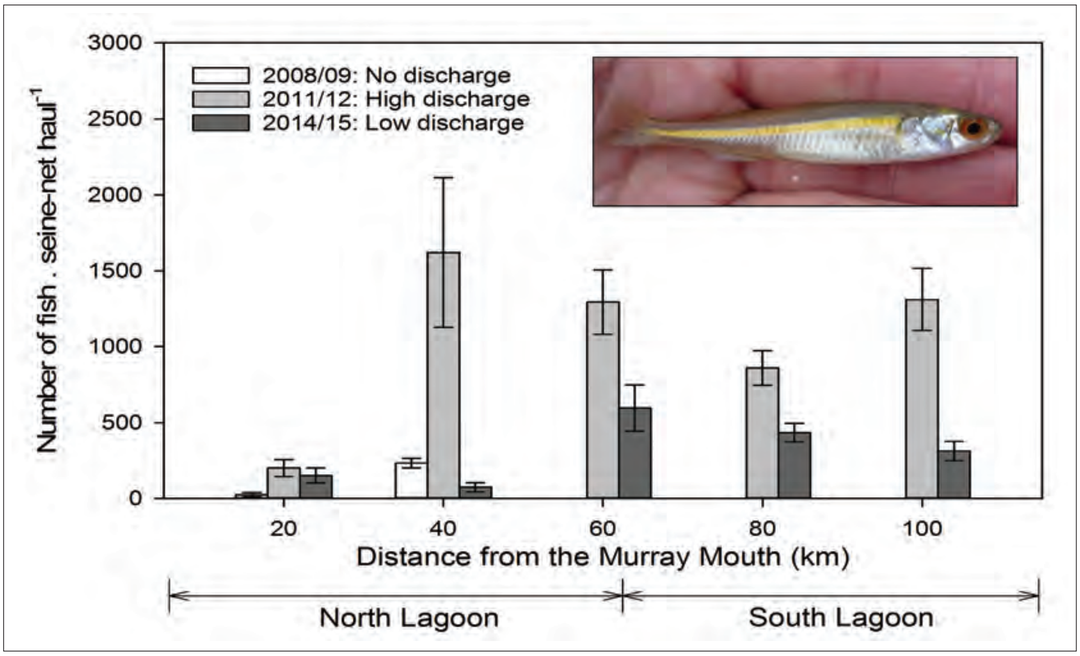

Figure 3.6.6 The abundance (number of fish.seine-net haul^{-1}) of smallmouth hardyhead at sites in the North Lagoon and South Lagoon of the Coorong approximately 20 km (Mark Point), 40 km (Noonameena), 60 km (Hells Gate), 80 km (Jack Point) and 100 km (Salt Creek) from the Murray Mouth, during spring/summer in 2008/09 (0 GL freshwater discharge), 2011/12 (8 800 GL freshwater discharge) and 2014/15 (~1 000 GL freshwater discharge). (Adapted from Ye et al. 2015)

freshwater discharge, when water levels are similar upstream and downstream of the structures, some passage of fish between the Coorong and Lower Lakes is possible. Furthermore, since 2003, several fishways have been constructed on the Murray Barrages to facilitate the upstream movements of diadromous species (Box 3.6.2). Despite the presence of fishways, contemporary hydrology and barrage operation exert a substantial influence on connectivity and population dynamics of diadromous fishes, as demonstrated by long-term (2006-2017) monitoring of fish migration at fishways on Tauwitchere and Goolwa Barrages (Bice et al. 2017a).

In response to declining inflows and water levels in the Lower Lakes during the Millennium Drought, the barrages (including fishways) were shut in March 2007, disconnecting the Lower Lakes from the Coorong until September 2010. Following the closure of the barrages, the abundance of upstream migrating juveniles of the catadromous congolli in the spring-summer periods of 2007-2010 declined to just 0-5% of their abundance in 2006/07, immediately prior to barrage closure (Zampatti et al. 2010) (Fig. 3.6.7). A study of the movement of adult female congolli in Lake Alexandrina in 2009 suggested that reproductively mature fish were attempting to undertake downstream spawning migrations in winter, but were obstructed by the closed barrages (Bice et al. in press), resulting in failure to reach spawning grounds. In association, there were substantial reductions in the abundance of juveniles. Recruitment was diminished over a number of years, resulting in the absence of several annual cohorts and reducing the resilience of the population and threatening its persistence.

In contrast, the period 2010-2017 was characterised by continuous freshwater discharge and connectivity. From September 2010, freshwater discharge and connectivity allowed adults undertaking downstream spawning migrations to pass through the barrages before exiting the

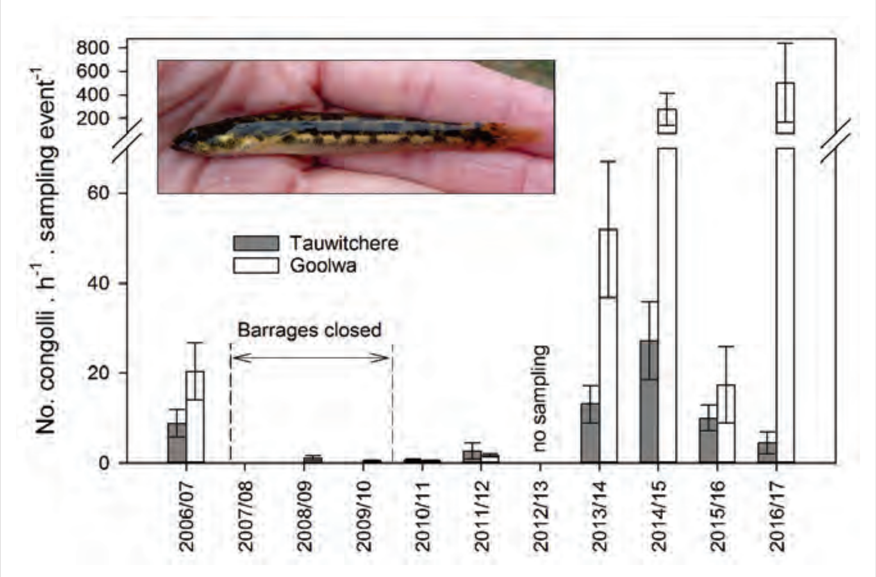

Figure 3.6.7 The abundance of juvenile congolli sampled migrating upstream at vertical-slot fishways on Goolwa (white bar) and Tauwitchere Barrages (grey bar) during spring/summer, annually from 2006-2017. (Adapted from Bice et al. 2017a)

Coorong and entering the ocean (Bice et al. in press). Subsequently, abundances of upstream migrating congolli increased significantly in spring/summer 2010/11, and continued to increase in subsequent years (Fig. 3.6.7). Indeed in 2016/17, following seven consecutive years of freshwater discharge and connectivity, the abundance of upstream migrating congolli at Goolwa Barrage was the greatest since the inception of long-term fishway monitoring in 2006. Congolli typically mature at 3-4 years of age (Hortle 1978), hence the adult spawning population in winter 2016 had increased in abundance, due largely to the presence of fish that had recruited over the period 2010/11 to 2012/13. These trends in abundance of congolli highlight the importance of freshwater discharge and maintenance of connectivity between the Lower Lakes and Coorong on an annual basis and the influence of consecutive 'favourable' years on population dynamics of catadromous fishes.

Pouched and short-headed lamprey are anadromous, a life-history characterised by adult migration into freshwater habitats to spawn. Whilst this is the opposite life-history strategy to that of congolli, lamprey are equally influenced by hydrology and connectivity. Whilst less common than congolli, abundances of lamprey also fluctuated during 2006-2017, with both species undetected by monitoring from 2007 to 2011. The presence of physico-chemical (e.g. salinity) and olfactory cues of riverine origin (e.g. pheromones from juveniles) in the marine environment is believed to be vital in stimulating upstream migrations in lamprey species from the northern hemisphere (Meckley et al. 2014). This is also likely for populations of pouched and short-headed lamprey in the southern hemisphere because, in the context of the Lower Lakes and Coorong, they are only encountered at the barrages during years when fresh water is released in winter-spring (Bice et al. 2017a).

MANAGEMENT AND RESTORATION OF FISH POPULATIONS

The LLC is recognised internationally as a unique ecosystem and harbours a diverse and dynamic fish assemblage of substantial conservation, commercial and cultural significance. The persistence

BOX 3.6.2 MURRAY BARRAGE FISHWAYS

Fishways are engineered structures used to facilitate fish movement past instream barriers (Clay 1995). Recognition of the importance of fish migration between the Coorong and Lower Lakes prompted the construction of three experimental fishways at Tauwitchere and Goolwa Barrages in 2003 under the Murray-Darling Basin Authority's *The Sea to Hume* fishway program. The fishways were designed primarily for the passage of large fish (i.e. >150 mm in length), but subsequent monitoring indicated that small fish (<100 mm in length), including juvenile congolli and common galaxias, comprised 95% of the migratory fish assemblage (Zampatti et al. 2010). Consequently, in 2009, two more fishways were constructed, at Tauwitchere Barrage and Hunters Creek causeway, specifically to facilitate the passage of small fish (Bice et al. 2017b). A further six fishways were constructed during 2014-2018, including at least one fishway on every barrage (i.e. Goolwa, Mundoo, Boundary Creek, Ewe Island and Tauwitchere), specifically designed to pass a range of species and size classes during a range of flows (Bice et al. 2016b). This program has substantially enhanced connectivity between the Coorong and Lower Lakes to benefit the restoration and sustainability of freshwater and diadromous fish populations.

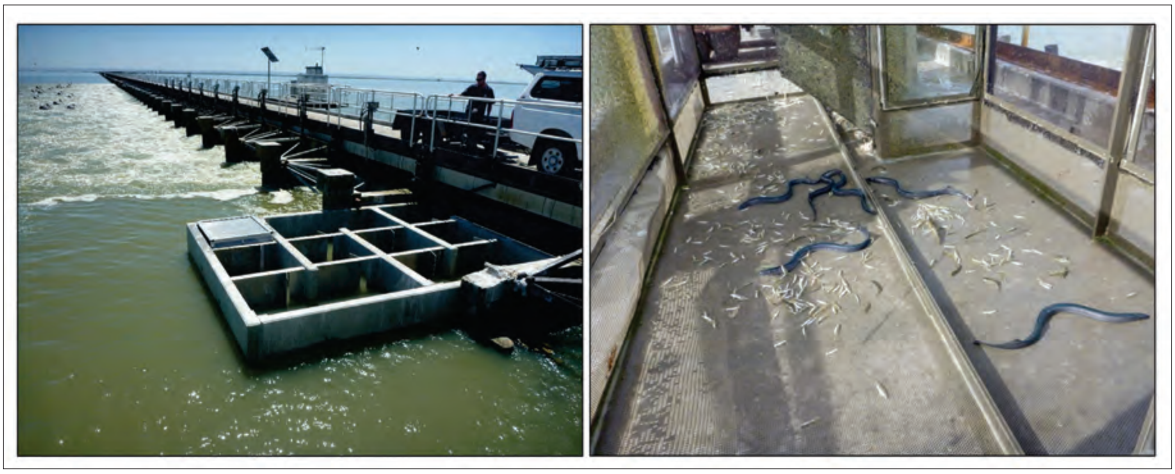

Figure 3.6.8 The small vertical-slot fishway at Tauwitchere Barrage and upstream migrating pouched lamprey sampled from the fishways during winter 2015. (Photograph by C. Bice)

and integrity of fish populations, however, are threatened by a number of anthropogenic factors. Primary factors are altered river flow, salinity and connectivity, but altered land use, harvesting and interactions with alien species also impact native fish populations. Management that mitigates these threats provides the most promise for future sustainability of fishes of the region. Encouragingly, flow restoration under the Murray-Darling Basin Plan and fishway construction, and other initiatives (e.g. the South East Flows Restoration Project), are actions that contribute to mitigating key threats to native fishes.

Ecological research on fishes in the LLC has provided a strong basis to inform management of the recovery of environmental water for ecological outcomes under the Basin Plan. Key ecological objectives within the Basin Plan include

- maintenance of water levels in the Lower Lakes to preserve key habitats and populations of threatened freshwater species

- maintenance of appropriate salinities in the South Lagoon and North Lagoon to facilitate, amongst other objectives, broad distributions of estuarine fishes including smallmouth hardyhead
- maintenance of an 'open' Murray Mouth to allow water exchange and the movement of biota, including fish
- maintenance of discharge through fishways during key seasons to facilitate the obligate migrations of diadromous fishes.

Whilst increased freshwater flow to the LLC represents the fundamental management need for future sustainability of fishes of the region, complementary actions are also required. One such action is the mitigation of fragmentation caused by the Murray Barrages, through fishway construction and environmentally sensitive barrage operation. The Murray Darling Basin Authority's Sea to Hume Program and the CLLMM Recovery Program have collectively facilitated the construction of 11 fishways on the Murray Barrages from 2003-2017 (Box 3.6.2). These fishways now facilitate the upstream passage of thousands of diadromous, freshwater and estuarine fishes on an annual basis (Zampatti et al. 2010; Bice et al. 2017b). Furthermore, barrage operation that is sensitive to fish behaviour and migration is enhancing bi-directional movement of fishes at the barrages. Discharge of low volumes of water in winter is now an annual priority to allow downstream spawning migrations of congolli (catadromous) and upstream spawning migrations of lampreys (anadromous). Barrage discharge is also prioritised to areas of the barrages that maximise attraction of fish to fishway entrances, improving the ability of fish to locate the fishways. These fundamental changes in barrage operation are a result of effective collaboration between scientists, natural resource managers and river operators (i.e. SA Water and the MDBA). Nonetheless, there is scope for further improvement in barrage operations with respect to enhancing connectivity and fish migration. This could include the reinstatement of limited tidal fluxing, which is being trialled at some tidal barriers in the Northern Hemisphere (Brink et al. 2018), but which remains unexplored at the Murray Barrages.

Restoration of fish populations in the LLC requires persistence of these populations. Unfortunately, the sole population of Yarra pygmy perch in the MDB was extirpated from the Lower Lakes in 2009 as water levels decreased due to over-allocation and drought. Despite several reintroduction attempts, the species is yet to re-establish a self-sustaining population (Box 3.6.1). Consequently, its continued presence in the Lower Lakes will rely on further reintroduction attempts. The loss of Yarra pygmy perch provides an example of the way that the impact of anthropogenic pressures can extend an ecosystem beyond its natural limits of variability and cause subsequent loss of critical habitat. It also provides a prudent lesson on the need to be prepared for emergency conservation situations, or, ideally, the need to avoid reaching the point where they are required.

A comprehensive understanding of species biology and ecology is fundamental to ecosystem management. Whilst knowledge of the biology and ecology of fishes of the LLC has improved greatly in recent years, many gaps still exist. In particular, there is a paucity of knowledge regarding the habitat requirements, diet, and spawning and recruitment dynamics for many species, but particularly those that are not commercially harvested. Furthermore, the influence of variability in freshwater flow and associated physico-chemical conditions on critical life-history processes remains poorly understood for many fish species and is required to better inform environmental flow delivery. For some species, population dynamics within the LLC may be influenced by processes occurring beyond the region (e.g. upstream in other regions of the MDB or marine waters and adjacent estuaries) and may warrant further research, particularly as environmental management moves from a site-focused approach to a larger-scale, holistic approach that considers the scales of individual species' life-histories.

ACKNOWLEDGEMENTS

Much of the research summarised here was funded under the SA Department for Environment Water and Natural Resources (DEWNR) CLLMM Recovery Project and the Murray-Darling Basin Authority's The Living Murray Initiative. The authors thank, collectively, the various project managers from these agencies that have supported research and conservation of fishes in the region. The authors also thank Greg Ferguson, Jason Earl, George Giatas and Luciana Bucater for their contribution to the expert workshop and designation of species to estuarine use functional guilds; Josh Fredberg for generating Figure 3.6.1; and Greg Ferguson and Ian Potter for formal review of this chapter.

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CHAPTER 3.7

WATERBIRDS OF THE COORONG, LOWER LAKES AND MURRAY MOUTH

DAVID C. PATON[1], FIONA L. PATON AND COLIN P. BAILEY

INTRODUCTION

Waterbirds are a key component of the Coorong, Lower Lakes and Murray Mouth (CLLMM) region, and one of the main reasons the area is listed as a Wetland of International Importance under the Ramsar Convention. Large numbers of small migratory and non-migratory waders (sandpipers, plovers and stilts), piscivorous birds (pelicans, cormorants, grebes and terns) and waterfowl (swans and ducks) use this wetland system. These wetlands are particularly important summer and drought refugia for waterbirds, with greater abundances and diversities of species present during summer and autumn than winter and spring (Paton 2010). During summer, the Coorong, which includes the hypersaline South Lagoon, North Lagoon and estuarine areas between the barrages and Murray Mouth, generally supports twice as many individual waterbirds compared to the freshwater wetlands of the Lower Lakes.

The waterbird communities of the Coorong also differ from those of the Lower Lakes. The major differences are that large numbers of shorebirds (sandpipers, stints, plovers, stilts, avocets) use the saline wetlands of the Coorong but not the freshwater wetlands of the Lower Lakes. Both areas support large and comparable numbers of waterfowl (ducks, swans), as well as large numbers of waterbird species that primarily feed on fish (cormorants, grebes, pelicans, terns). However, the composition of these two major groups of birds differs between the fresh and saline habitats; some species are largely found in the Coorong (e.g. hoary-headed grebes (*Poliocephalus poliocephalus*) and chestnut teal (*Anas castanea*)), while other species are prominent in the Lower Lakes (e.g. great cormorants (*Phalacrocorax carbo*), pied cormorants (*Phalacrocorax varius*) and Pacific black ducks (*Anas superciliosa*)). A few species, like Australian pelicans (*Pelecanus conspicillatus*) are prominent around the shores of both the Coorong and Lower Lakes (Fig. 3.7.1). Such differences in the waterbird communities of the Coorong and Lower Lakes are largely a reflection of differences in abiotic (e.g. water level and salinity) and associated biotic (e.g. food resources) factors. For example, reeds are prominent around the freshwater shorelines of the Lower Lakes, while the saline wetlands of the Coorong are shallow and gently sloping, and provide extensive mudflats for foraging shorebirds.

The abundances of waterbirds using the CLLMM can vary dramatically from one year to the next. Such changes in abundances are influenced not just by the ecological conditions in the CLLMM, but also by the conditions in the other wetlands that these birds use at other times of the year. Thus, assessing the value of this wetland just on the numbers of birds present

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Figure 3.7.1 Australian Pelicans, Coorong. (Photograph by Fiona Paton)

is difficult. However, the behaviour of the birds when using the CLLMM wetlands can refine that assessment. For example, the amount of time birds allocate to foraging can help assess the habitat suitability for a range of waterbirds. Species that allocate substantially more time to foraging are likely to be exploiting poorer food resources than those that allocate less time. For the CLLMM wetlands, some shorebirds (e.g. the red-necked stint *Calidris ruficollis*, the sharp-tailed sandpiper, *Calidris acuminata,* and herbivores (e.g. black swans, *Cygnus atrata*) have allocated 60-90% of their day to foraging in recent years, suggesting that their food resources were thinly spread or difficult to harvest. This is consistent with finding dead, emaciated stints and sandpipers on islands in the Coorong in recent years. In contrast, piscivorous bird species only allocate 20-40% of their time to foraging, indicative of readily harvestable food.

Although most birds use the Coorong as a summer or drought refuge, there are a variety of bird species that also breed regularly within the CLLMM region, including ibis, cormorants, terns, pelicans, swans and duck. The breeding colony of Australian pelicans on islands in the South Lagoon, for example, is one of the few permanent breeding colonies for this species. Furthermore, the Coorong is a critical breeding area for fairy terns (*Sternula nereis*), which are listed as endangered within South Australia.

FACTORS THAT INFLUENCE THE DISTRIBUTIONS AND ABUNDANCES OF WATERBIRDS

The vast majority (>90%) of waterbirds using both the Coorong and Lower Lakes use the margins of the Lakes and Lagoons. The margins are the areas where water depths are typically

<1 m, coinciding with the most productive parts of these wetlands. The high turbidity of the water is assumed to prevent benthic submerged aquatic plants from securing sufficient light to grow in deeper water. For the Lower Lakes, the margins support a mix of shallow open water, reeds of varying density, and other emergent vegetation, all of which provide foraging habitat as well as cover for waterbirds. These fringing habitats are only available in areas with flat, broad beaches. Shoreline erosion, however, has led to the loss of some flat shoreline areas in the Lower Lakes, creating steep Lake margins which are of poor habitat value for waterbirds. This limits the diversity of waterbirds that can use the Lower Lakes (see below). In the Coorong, provided that water levels are not too high, there are extensive areas of gently sloping shoreline, suitable for waterbirds that wade in shallow water when foraging. The presence of extensive mudflats covered with shallow water, at least during the warmer months of the year, makes the Coorong particularly important for shorebirds (migratory and endemic waders). Within the CLLMM, the wetland habitats of the Lower Lakes and Coorong, with their differing water levels and salinity regimes, provide a range of complementary habitats for waterbirds.

Lower Lakes

The Lower Lakes are freshwater systems, where the same habitat features are repeated around the margins of the two lakes. Reeds of various species (*Typha*, *Phragmites* and *Schoenoplectus*) are prominent around the shorelines, but the density, composition and width of these vary (e.g. Gehrig et al. 2012). Amongst the reed beds, and between them and the shoreline, are often areas of open shallow water, where submerged aquatic plants are abundant. More generally, areas with reeds are interspersed with areas without reeds, and, in these latter areas, the margins of the Lower Lakes are usually grassy verges. These grassy areas tend to be more exposed and have steeper banks. Importantly, very few areas around the Lower Lakes provide shallow mudflats suitable for wading birds when Lake water levels are in the range of 0.5-0.8 m AHD.

Coorong and Murray Mouth

In contrast, the Coorong is an estuarine to hypersaline wetland with extensive areas of shallow, gently sloping shorelines without emergent reeds. The salinity of this system prevents reeds from establishing, except in a few isolated pockets, where fresh water seeps into the Coorong from the dunes of Younghusband Peninsula. In the northern regions of the Coorong, near the Murray Mouth, the mudflats become variously exposed during the tidal cycle, whereas in the southern Coorong, seasonal shifts in water level of up to 1 m expose the mudflats in summer. Importantly, most shorebirds do not exploit mudflats that are fully exposed, instead foraging in shallow water (a few centimetres deep) at or near the shoreline (e.g. Rogers & Paton 2009; Paton 2010). The only exceptions are a few species of plover (e.g. red-capped plover, *Charadrius ruficapillus*), which forage primarily on exposed mudflats, particularly if they are damp (Fig. 3.7.2).

For the last 30-40 years (at least), a key feature of the Coorong has been the salinity gradient that increases southwards. In a typical year, salinities may range from 10-70 g L^{-1} in winter and spring to 30-110 g L^{-1} in summer and autumn along the length of the Coorong. As a consequence of the salinity gradient, the Coorong supports different ecosystems and food chains along its length and these differ from the food chains of the Lower Lakes, although the

Figure 3.7.2 Red-capped plover foraging on a damp mudflat, Coorong. (Photograph by Thomas Hunt)

food chains of waterbirds when using the Lower Lakes are poorly documented. In general, the richness of aquatic invertebrates and fish decreases along the salinity gradient in the Coorong, with fewer species at higher salinities (e.g. Paton 2010). For example, in the northern estuarine regions of the Coorong, various species of polychaetes are prominent benthic invertebrates, but in the higher salinities of the southern Coorong, only the chironomid (*Tanytarsus barbitarsis*) is prominent (Rolston & Dittmann 2009; Paton 2010; Dittmann et al. 2014). Similar patterns exist for fish, with many more species present in the estuarine regions, and just one species, the small-mouth hardyhead (*Atherinosoma microstoma*), prominent in the South Lagoon (Noell et al. 2009; Paton 2010; Wedderburn et al. 2016). However, this reduction in species' richness with salinity does not indicate that the overall availability of food resources is reduced at the higher salinities (e.g. Paton & Bailey 2014).

The other key component of the aquatic ecosystems and food chains of the Coorong is submerged aquatic plants. There have been marked changes in the species' composition, distribution and abundance of submerged aquatic plants in the Coorong over recent decades (Paton 2010; Paton et al. 2015a). Several species are now no longer functionally present (e.g. *Ruppia megacarpa*, *Lamprothamnium papulosum*) and others are far less abundant than they have been historically. A key, submerged, aquatic plant in the southern Coorong is *Ruppia tuberosa*, one of the few plants that can tolerate hypersaline salinities. This species was largely eliminated from the southern Coorong during the Millennium Drought (Paton et al. 2015a). While there have been some signs of recovery since the drought (e.g. in plant cover), this species has not recovered its seed bank and therefore has not regained any resilience to perturbations (e.g. another drought; Paton et al. 2017b). The critical factor for this annual plant is being able to complete its reproductive cycle. For this to happen water levels in the southern Coorong have to be maintained throughout spring and into summer. Substantial flows of water over the barrages are required to deliver this, but such flows happen rarely now because of over-extraction of water from the Murray-Darling Basin. For the first 16 years of this century there has been only one year, 2016, when there were substantial flows over the barrages and water levels were maintained throughout spring (Paton et al. 2017b). Unfortunately, though, interference from filamentous green algae (*Ulva* sp.) disrupted seed production for *R. tuberosa* in this year (Paton et al. 2017b).

In the North Lagoon, a key species historically, *R. megacarpa*, disappeared prior to the Millennium Drought. However, a red alga — *Gracilaria chilensis* — may now provide some substitute ecological functions (food resources for herbivorous waterfowl, dampening of wave actions on shorelines) in the predominantly estuarine areas and northern sections of the North Lagoon of the Coorong.

KEY FEATURES OF THE CLLMM WATERBIRD COMMUNITIES

Key features of the CLLMM waterbird communities include the richness and abundance of the CLLMM waterbird species, the inter-annual variability in abundances and distribution, their breeding and their foraging behaviours.

Species richness and abundance

Annual counts in January (conducted from 2000 onwards for the Coorong and 2009 onwards for the Lower Lakes) indicate that the Coorong generally supports twice as many individual waterbirds as the Lower Lakes in summer. The number of waterbirds supported in the Coorong in January averaged >167 000 for the 16 years from 2000 to 2015, while the average number for the Lower Lakes has been a little over 79 000 for the seven years from 2009 to 2015, and a little over 71 500 for the three years from 2013 to 2015. Initial counts, in 2009-2012, in the Lower Lakes were during and immediately following a period of exceptional conditions when the water levels were the lowest on record. Consequently, the waterbird numbers in those years are unlikely to be typical of waterbirds using this system. The waterbird communities were still recovering several years after the Millennium Drought broke (Paton & Bailey 2013, 2014). Counts from 2013-2015, however, are likely to be typical of the waterbird communities using the Lower Lakes during non-drought periods. Although >80 species of waterbirds have been detected using the Coorong and over 70 species using the Lower Lakes during these counts, more than half the species are only present in small numbers. Of the 72 species counted in the Lower Lakes since 2009, only 33 were detected in all seven years and only 22 of these had >100 individuals present. For the 82 species detected during counts in the Coorong, 35 species were present in all years, with another five species present in all but one year. Of these species, 33 species were in abundances of >100 birds.

In line with the complementary habitats provided by the Lower Lakes and Coorong, the waterbird communities that use the Lower Lakes and Coorong are markedly different. The key differences are that the Coorong supports large numbers of waders, particularly red-necked stints, banded stilts (*Cladorhynchus leucocephalus*), sharp-tailed sandpipers and, to a lesser extent, red-necked avocets (*Recurvirostris novaehollandiae*), curlew candpipers (*Calidris ferruginea*) and red-capped plovers (Table 3.7.1). These species are only in very small numbers in the Lower Lakes (typically <1% of the numbers in the Coorong). A range of other waders are also largely, if not entirely, restricted to the Coorong, including black-winged stilt (*Himantopus*

Table 3.7.1 Median abundances of major groups of waterbirds and selected individual species using the Coorong and Lower Lakes in January. Data for the Coorong are based on 16 annual counts from 2000-2015, while those for the Lower Lakes are based on three counts from 2013-2015. Species are arranged in order of median abundances within major groups and subgroups.

COORONG	LOWER LAKES
Shorebirds 62 720	***989***
Red-necked stint (26 286) Banded stilt (15 125) Sharp-tailed sandpiper (13 179) Red-necked avocet (3 007) Curlew sandpiper (2 256) Red-capped plover (1 234) Masked lapwing (468) Common greenshank (434) Black-winged stilt (417) Pied oystercatcher (158) + 21 other species (156)	Masked lapwing (565) Sharp-tailed sandpiper (214) Black-winged stilt (85) Red-kneed dotterel (56) Red-necked stint (30) + 13 other species (39)
Waterfowl 29 731	***28 715***
Grey teal (11 848) Australian shelduck (8 426) Chestnut teal (7 231) Black swan (1 647) Pacific black duck (228) Musk duck (172) Cape Barren Goose (97) Eurasian coot (75) + 7 other species (7)	Australian shelduck (13 249) Pacific black duck (4 981) Grey teal (3 912) Eurasian coot (3 339) Black swan (1 799) Cape Barren goose (1 010) Hardhead (874) Australasian shoveler (143) Pink-eared duck (84) Australian Wood Duck (70) Chestnut teal (56) Freckled duck (56) Musk duck (9) + 2 other species (7)
Fish-eaters 17 586	***37 613***
Great cormorant (1 287) Little black cormorant (1 253) Pied cormorant (271) Little pied cormorant (258) Black-faced cormorant (130) Darter (1) Australian pelican (3 410) Hoary-headed grebe (4 222) Great Crested grebe (201) Whiskered tern (5 371) Greater crested tern (3 897) Caspian tern (598) Fairy tern (337)	Great cormorant (14 963) Pied cormorant (8 759) Little black cormorant (907) Little pied cormorant (84) Darter (73) Australian pelican (6 239) Great crested grebe (128) Hoary-headed grebe (103) Whiskered tern (4 497) Caspian tern (609) Greater crested tern (490) + 2 other terns (2)

leucocephalus), common greenshank (*Tringa nebularia*), oystercatchers, godwits, far eastern curlew (*Numenius madagascariensis*), hooded plover (*Thinornis rubricollis*) and sanderling (*Calidris alba*).

However, waterfowl and fish-eating species are prominent in both wetland systems (Table 3.7.1). For the Coorong, grey teal (*Anas gracilis*), Australian shelduck (*Tadorna tadornoides*), chestnut teal and black swans are prominent species of waterfowl, while Australian shelduck, Pacific black duck, grey teal, Eurasian coot (*Fulica atra*) and black swan are the most abundant waterfowl using the Lower Lakes (Table 3.7.1). A key compositional difference between the two wetland systems is in the prominence of chestnut teal in the Coorong and Pacific black duck in the Lower Lakes. The cause of this difference in use of the Coorong versus the Lower Lakes by these two anatid ducks is not known. Musk duck (*Biziura lobata*) are present in relatively low numbers and are predominantly found in the Coorong now (Table 3.7.1). In the 1980s, musk duck were still being reported widely from around the Lower Lakes (e.g. Paton et al. 1994). However, that is not the case in recent years, particularly in 2017, when not a single musk duck was recorded using the CLLMM region in January (Paton et al. 2017a). Eckert (2000) attributes the appearance of the European carp (*Cyprinus carpio*) in the Lower Lakes in the late 1960s to the demise of the musk duck from the Lakes, suggesting that the carp led to a loss of aquatic plants and associated aquatic invertebrates that formerly supported musk ducks. Other waterfowl, including Australasian shovelers (*Anas rhynchotis*), pink-eared ducks (*Malacorhynchus membranaceus*) (Fig. 3.7.3) and hardheads (*Aythya australis*), use both wetland systems when present in the region, while freckled ducks (*Stictonetta naevosa*) mainly use the Lower Lakes.

Figure 3.7.3 Pink-eared ducks, Salt Creek. (Photograph by Thomas Hunt)

In the Lower Lakes, great cormorants, pied cormorants, Australian pelicans and whiskered terns (*Chlidonias hybrida*) are the most prominent piscivorous species, while whiskered terns, hoary-headed grebes and Australian pelicans are the most abundant members of these groups in the Coorong. Greater crested terns (*Thallasius bergii*) are also prominent in the Coorong and breed on islands in the South Lagoon (Fig. 3.7.4). However, greater crested terns also fish in the adjacent ocean while breeding in the Coorong, and so are not dependent on the Coorong for food. Five species of cormorants use the Coorong, with great cormorants and little black cormorants (*Phalacrocorax sulcirostris*) the most abundant of these. Other fish-eating species using these wetlands include Caspian terns (*Hydroprogne caspia*), great crested grebes (*Podiceps cristatus*), great egrets (*Ardea alba*) and white-faced herons (*Egretta novaehollandiae*), and these species use both wetlands to comparable extents. One other important fish-eating species is the fairy tern, which is restricted to the Coorong region.

The Coorong and Lower Lakes also support significant numbers of royal spoonbills (*Platalea regia*), Australian white ibis (*Threskiornis moluccus*), straw-necked ibis (*Threskiornis spinicollis*) and silver gulls (*Chroicocephalus novaehollandiae*). Silver gulls are widespread in both the Coorong and Lower Lakes, while the spoonbills and ibis are more abundant around the margins of the Lower Lakes. Although present in small numbers, yellow-billed spoonbills (*Platalea flavipes*) are also present and primarily associated with the Lower Lakes.

The freshwater swamps and reeds of the Lower Lakes also support a suite of largely cryptic birds, including Australasian bittern (*Botaurus poiciloptilus*), Latham's snipe (*Gallinago*

Figure 3.7.4 A pair of greater crested terns feeding a fish to their chick at a breeding colony on an island in the South Lagoon, Coorong. (Photograph by Fiona Paton)

hardwickii), and various rails (crakes) and water hens (e.g. O'Connor et al. 2013). The most conspicuous of these are the purple swamphen (*Porphyrio porphyrio*), little grassbird (*Megalurus gramineus*), Australian reed warbler (*Acrocephalus australis*) and golden-headed cisticola (*Cisticola exilis*), which are also associated with the emergent and fringing vegetation of these freshwater systems. Obtaining total counts of most of the cryptic and reed-dwelling species using the Lower Lakes is impractical. However, their presence at selected points around the Lower Lakes has been assessed in recent years with effort (O'Connor et al. 2013).

Inter-annual variability in abundances

The number of waterbirds using the wetlands from one year to the next can vary substantially. An extreme example is the banded stilt. In January 2009, >210 000 banded stilts used the Coorong, but in the three years from 2013-2015, <2 000 have been present in January (Paton et al. 2015b). The factors influencing the variations are poorly understood. However, factors outside the Coorong and Lower Lakes (e.g. flooding rains in inland Australia), as well as factors in the wetlands themselves, are likely to be influential.

The variability in the abundances of many species of waterbirds using the Coorong and Lower Lakes reflects the services that these wetlands provide the birds. Most species of waterfowl (ducks, swans) do not breed to any extent in the Coorong or Lower Lakes and move away from the Coorong, and to a lesser extent the Lower Lakes, during winter and spring to breed. The likely breeding areas for these waterfowl are assumed to be ephemeral freshwater swamps in the adjacent Southeast of South Australia, which dry out over summer but refill during winter. Many Australian waterfowl are stimulated to breed by the refilling of wetlands and prospects of abundant aquatic food that follow (Frith 1982). Before the barrages were constructed, the margins of the Lower Lakes were likely to have provided breeding opportunities for many waterfowl, but the management and maintenance of water levels at higher levels and within a narrow range may no longer provide a sufficient change in water levels and food resources to stimulate breeding. The numbers of waterfowl that return to the Coorong and Lower Lakes from breeding areas in the following summer will depend on the extent of successful breeding, and the timing of their arrival will be influenced by the quality and availability of the breeding (and any transitional/staging) wetlands, and if and when these dry out. For these birds, the permanent wetlands of the Coorong and Lower Lakes function as a critical 'summer' refuge, and this importance increases in dry years.

For the migratory shorebirds that use the Coorong over the summer months, a similar argument holds. These birds breed in the northern hemisphere and migrate annually between there and wetlands such as the Coorong in the southern hemisphere. The abundances of migratory species in any one year in the Coorong are likely to be influenced by the extent of breeding and successful migration and by whether other potential ephemeral wetlands hold water and are available for them to use on arrival. Annual variability in breeding success, measured as the percent of juvenile birds captured in Southeast Australia during the following austral summer, can vary up to 10-fold for the abundant calidrine waders using the Coorong. For example, juveniles have accounted for 7-35 % of the red-necked stints, 3-39% of the curlew sandpipers and 4-42% of the sharp-tailed sandpipers caught each year since summer 1998-1999 in south-eastern Australia (Minton et al. 2014). The endemic banded stilt and red-necked avocet rarely breed in the Coorong and also move away from the Coorong to exploit inland saline wetlands for breeding when these fill with water. Black-winged stilts, too, may shift to nearby freshwater swamps when these hold water to breed. Hoary-headed grebes, whiskered terns and Eurasian coots are other species that do not breed in the Coorong and that show dramatic reductions in abundances when the availability of inland wetlands increases.

Breeding

Most of the waterbirds that regularly breed within the CLLMM are piscivorous species that breed in colonies. These include the Australian pelican, fairy tern (Fig. 3.7.5), greater crested tern and Caspian tern, which breed on islands in the southern Coorong, and the pied cormorant in the Lower Lakes (O'Connor et al. 2013). Although greater crested terns breed in the southern Coorong and forage to an extent in the Coorong and Lower Lakes, they mainly fish in the adjacent marine environment when breeding. Caspian terns and Australian pelicans also forage substantial distances (probably at least 100 km) from their breeding colonies in the southern Coorong. Breeding for these species in the Coorong still occurred even when the South Lagoon supported no fish. Fairy terns, in contrast, vacated their breeding islands in the South Lagoon when fish were absent in the southern Coorong. Although this species attempted to breed near the Murray Mouth at these times, these breeding events were prone to human disturbance and predation by foxes. Their long-term existence is concerning because of poor recruitment, in addition to declines in their population from ~1 300 in the South Lagoon in 1985 (Paton 2010), to ~600 birds for the whole of the Coorong at the turn of the millennium, to ~400 birds in recent years (Paton et al. 2017a).

Pied cormorants still breed regularly in colonies established in reed beds (e.g. near Tolderol) and fringing terrestrial vegetation, particularly on islands in Salt Lagoon within the

Figure 3.7.5 Fairy terns at a breeding colony on an island in the South Lagoon, Coorong. (Photograph by Thomas Hunt)

Lower Lakes. During the late 2000s, pied cormorants did not breed when exceptionally low water levels disconnected the reeds from the water line. Although little black cormorants, little pied cormorants (*Microcarbo melanoleucos*) and great cormorants have all bred historically in the Lower Lakes (Close et al. 1982; O'Connor et al. 2013), in recent decades, these species have not been detected breeding in the Lower Lakes, apart from one small colony of little pied cormorants in 2017 near Wellington (Paton et al. 2017a). Individuals of these species of cormorants must now move away from the CLLMM to breed.

A range of other colonial nesting waterbirds also bred in modest numbers (usually <100 nests) prior to the 1980s (Close et al. 1982). These included yellow-billed and royal spoonbills, great egrets and glossy (*Plegadis falcinellus*), straw-necked and Australian white ibis. Of these, only the Australian white ibis, straw-necked ibis and royal spoonbill (Fig. 3.7.6) have been found breeding in recent years. Australian white ibis and straw-necked ibis forage predominantly in adjacent pastures, harvesting terrestrial invertebrates away from wetland areas, so their abundances in any one year are likely to be influenced by rainfall and by the extent to which nearby areas are irrigated. For these two species, the CLLMM wetlands provide suitable habitat (reed beds) for nesting and some foraging opportunities. A range of other species also exploit terrestrial sources of food (pasture, grain and invertebrates) while using the CLLMM during summer. These include, at least to some extent, Cape Barren goose (*Cereopsis novaehollandiae*), Australian shelduck, Pacific black duck, whiskered tern and white-faced heron.

Figure 3.7.6 Royal spoonbill with breeding plumes, Lake Alexandrina. (Photograph by Fiona Paton.)

The only other colonial-nesting species recorded as breeding regularly in the CLLMM is the silver gull, which breeds on islands in the southern Coorong. Silver gulls are adaptable and feed on a variety of foods, and their breeding may be linked to the breeding of pelicans and terns, as they can scavenge food at those sites.

A range of other waterbird species, including black swan, Pacific black duck, chestnut teal, purple swamphen, pied oystercatcher (*Himantopus longirostris*), red-necked avocet, red-capped plover, hooded plover and masked lapwing (*Vanellus miles*), as well as probably many of the cryptic reed-dwelling species, have bred in the CLLMM and are likely to continue to breed in small numbers in most years, but the actual numbers of nests and nesting success is not known.

Foraging behaviours and habitat quality in the CLLMM wetlands

The historical and current assessments of the importance of the CLLMM for waterbirds are based on the abundances of various species using the wetlands (e.g. O'Connor et al. 2012; Paton & Bailey 2014). However, numerical statistics alone do not adequately summarise the quality of these wetlands from a waterbird perspective. To function as an effective refuge in most summers, and particularly during droughts, the quantity and quality of the food and habitat resources, and access for birds to those resources, are critical.

One method of assessing the quality of the habitats in terms of providing food, and hence the capacity of the CLLMM to service the needs of waterbirds, is by assessing the birds' behaviour. Birds will allocate more time to foraging when food resources are thinly spread and difficult to harvest than they would when those resources are more available. For the Coorong, where such data exist, a range of piscivorous species spend typically c.20-50% of the day foraging. These data indicate that these fish-eating species have no difficulty securing food. Breeding by a range of fish-eating species in the Coorong and Lower Lakes is also consistent with good availability of food. However, some herbivorous species (e.g. black swans) and many of the shorebirds usually allocate over 50% of their day to foraging, and sometimes as much as 80% in some years. This suggests that their food resources, various aquatic plants and aquatic invertebrates, are not as rich or as easily harvested as fish. Although additional work relating food abundance to the time allocated to foraging is required, these data direct managers to focus on the provision of suitable habitats with aquatic plants and aquatic invertebrates in the Coorong for these birds rather than on managing fish populations for fish-eating species.

Challenges for waterbirds using the CLLMM wetlands

The waterbirds of the CLLMM have been challenged over recent decades as a consequence of over-extraction of water for human uses in the Murray-Darling Basin. Most waterbird species occur at much lower abundances now than they did 30-40 years ago (Paton et al. 2009; Paton 2010). The issue of over-extraction of water was highlighted during the Millennium Drought when limited Murray-Darling Basin flows reached the region between 2002 and 2010. Water levels in the Lower Lakes dropped to unprecedented levels and, during 2009 and most of 2010, were consistently below sea level (-0.5 m AHD in Lake Albert; and -0.7 m to -0.9 m AHD in Lake Alexandrina). This resulted in the waterline disconnecting from the fringing vegetation, along with an increased risk of acid sulfate soils being exposed to the air, leading to potential acidification. With these changes in water levels, there were dramatic changes in the waterbird communities using the Lower Lakes (Paton & Bailey 2013). During the latter half of 2010, extensive rains within the Murray-Darling Basin brought floods to the River Murray and flows returned to the Lower Lakes, and the more typical managed water levels of between 0.6 m and 0.8 m AHD re-established in 2011 and have remained on or around this level since then. Once the water levels returned to the Lower Lakes, the waterbird communities were still recovering several years later (Paton & Bailey 2013, 2014).

During the drought, the Murray Mouth and associated channels also had to be dredged to keep the Mouth open. The lack of flows also affected the ecology of the Coorong, severely disrupting seasonal patterns to water levels and resulting in the accumulation of excessive amounts of salt in the South Lagoon (Paton 2010). These hydrological changes led to changes in the distributions and abundances of key aquatic food resources (plants, invertebrates and fish) used by waterbirds in the Coorong. As the salinities increased, the distributions of the salt-tolerant fish, the smallmouth hardyhead, and the salt-tolerant chironomid, which are prominent in the southern Coorong, retracted northwards. From 2007 onwards, both were absent from the South Lagoon, when salinities exceeded 150 g L^{-1}. However, brine shrimps (*Parartemia zietziana*) thrived in the South Lagoon and southern reaches of the North Lagoon during this period. The other major change to food resources was the loss of the key aquatic macrophyte — *R. tuberosa* — from the southern Coorong. These ecological changes in turn affected the distributions and abundances of waterbirds, with many piscivorous and herbivorous bird species forced to vacate the South Lagoon (Paton 2010). One species that took advantage of the abundance of brine shrimps, however, was the banded stilt (Fig. 3.7.7).

With the return of flows to the Murray Mouth in spring 2010, the northern channels of the Murray Estuary were quickly freshened, before flows continued down the Coorong, diluting the high salinities in the South Lagoon as well. The general consensus was that this freshening of the Coorong would be beneficial, allowing a wide range of different taxa, including plants, invertebrates, fish and birds, to rebuild their population sizes. In January 2011 chironomids had recolonised the South Lagoon and were abundant, yet only small numbers of smallmouth hardyheads were in the South Lagoon, and there was no detectable recovery of *R. tuberosa*. However, *R. tuberosa* and chironomids were still abundant in the middle and southern sections of the North Lagoon, where they had established during the previous five years (Paton & Bailey 2011). Brine shrimps, however, continued to be abundant throughout the South Lagoon. The other key food resources, various polychaete worms (particularly *Capitella* sp.), were still mainly restricted to the northern sections of the North Lagoon and the Murray Estuary (Paton & Bailey 2011). With the continuation of flows and the maintenance of lower salinities throughout 2011, there were further changes in the distributions and abundances of food resources. By July 2011, there were no brine shrimps detected in the Coorong, and by January 2012, smallmouth hardyhead were extremely abundant in the southern Coorong (Paton & Bailey 2012a; Wedderburn et al. 2016).

However, there was no immediate recovery of *R. tuberosa*. In fact, *R. tuberosa* had declined further by January 2012, as the extensive beds that were present in the North Lagoon in January 2011 were absent, having vanished by June 2011 (Paton & Bailey 2012b). While

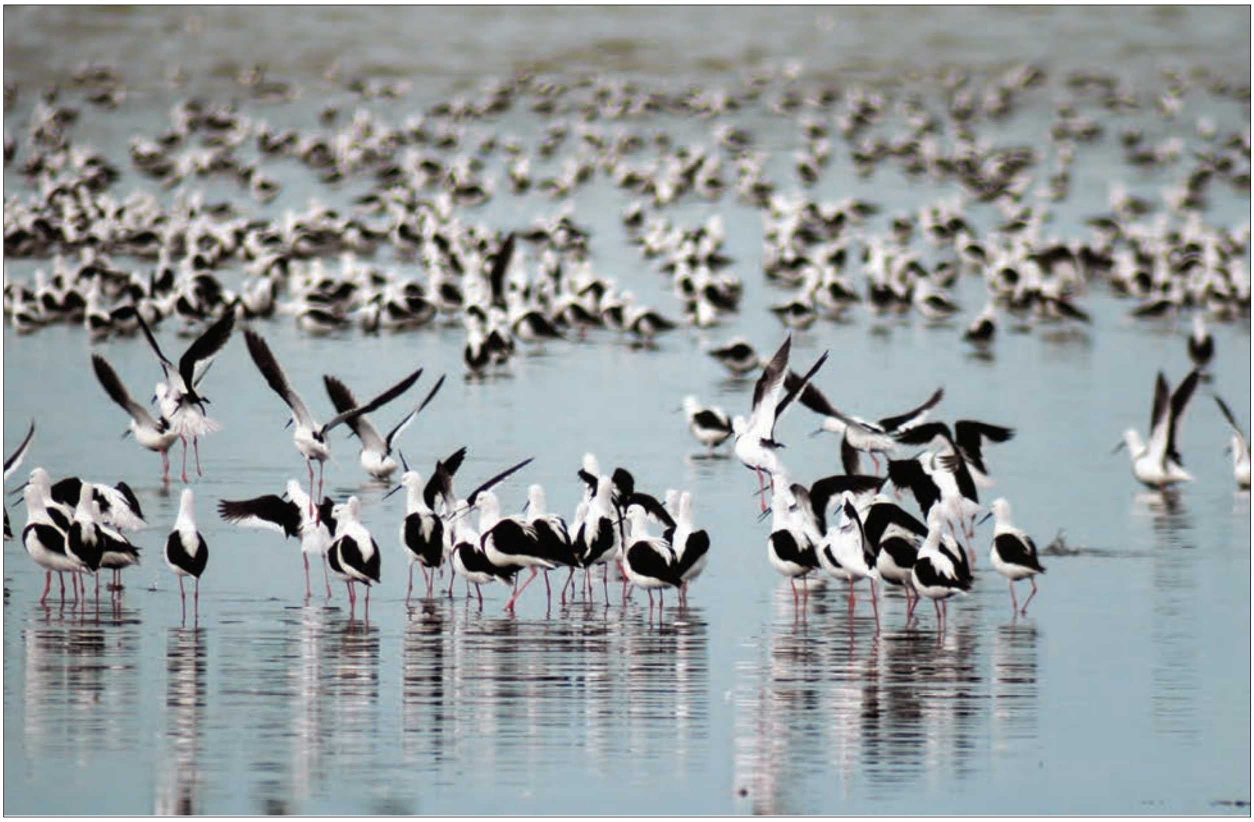

Figure 3.7.7 Banded stilt were present in the Coorong in large numbers during the Millennium Drought. (Photograph by Fiona Paton)

R. tuberosa has now recovered its former range, it has not reached the same level of vigour (cover, productivity) as existed prior to the Millennium Drought (e.g. Paton et al. 2016) and the seed banks for this species are still to be replenished (Paton et al. 2017b). Consequently, *R. tuberosa* continues to lack any long-term resilience in the Coorong (Paton et al. 2016, 2017b). These systems are still vulnerable to droughts, and if these increase in the future the quality of these wetlands may further erode and they may become less capable of supporting waterbirds, ultimately resulting in further reductions in their diversity and abundances.

Adaptive management of the CLLMM region is required to better protect and conserve the habitats that waterbirds depend on, particularly given that future climatic conditions may reduce water availability. For *R. tuberosa* (a key component of the unique ecological character of the South Lagoon), there is an urgent need to fix falling water levels in spring and into summer to provide conditions that allow this annual plant to rebuild its depleted seed bank and regain some resilience before the next drought. Historically, water levels would have been maintained in most years because River Murray flows would have, in most years, been great enough to prevent water from draining out of the South Lagoon during spring. Flows over the barrages of ~1 000 GL per month in spring and into summer are required to maintain water levels in the South Lagoon. Such flows, even when the Murray-Darling Basin Plan is fully implemented, will not eventuate in most years. The projected flows may also be lower because the current plan does not incorporate the impacts of climate change on flows. Therefore, finding alternative, innovative solutions is a key requirement to secure the Coorong as habitat for waterbirds to meet international obligations under the Ramsar Convention and migratory bird agreements, namely the Japan-Australia Migratory Bird Agreement (JAMBA), the China-Australia Migratory Bird Agreement (CAMBA) and the Republic of Korea-Australia Migratory Bird Agreement (ROKAMBA). If these solutions are not found, then alternative habitat outside the CLLMM region may need to be found or constructed, and then managed to ensure that waterbirds have suitable habitat.

Doing this requires significant investment in documenting the movements of waterbirds into and out of the CLLMM region so as to identify the wetlands that are used by CLLMM waterbirds at other times of the year. Identifying these other wetlands is important to ensure that they, too, are managed effectively for waterbirds. This is particularly the case for species that breed on these other wetlands away from the CLLMM. In addition, research needs to identify possible locations for reconstructing wetlands that can support waterbirds during summer, particularly migratory shorebirds, to provide a safety net for waterbirds should the Coorong continue to deteriorate.

ACKNOWLEDGEMENTS

In recent years (2008-2017), the census of waterbirds and assessment of waterbird resources have been commissioned and funded by the Murray-Darling Basin Authority and the South Australian Department of Environment, Water and Natural Resources (DEWNR). Prior to 2008, part-funding for the annual census of waterbirds and their resources in the Coorong was provided by the South Australian Department for Environment and Heritage (2000-2006), the Nature Foundation of South Australia (2007), and Earthwatch Australia (2001-2007). DEWNR provided permits for this monitoring, with the monitoring conducted under Animal Ethics approvals from the University of Adelaide. The waterbird censuses were conducted with the assistance of staff, students and volunteers from the University of Adelaide and, from 2001-2007, Earthwatch Australia volunteers. We would particularly like to acknowledge Daniel Rogers for his contribution to this body of work and his review of the chapter, and the many people who have assisted us to count waterbirds in the Coorong and Lower Lakes.

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CHAPTER 3.8

FROGS OF THE LOWER LAKES, COORONG AND MURRAY MOUTH

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Frogs are an integral element within food webs in the Coorong, Lower Lakes and Murray Mouth region (CLLMM), providing services throughout all stages of their dual aquatic and terrestrial life cycles, such as contributing to limiting algae growth, insect consumption, and acting as prey for many water-dependent and terrestrial species (Robinson 2000; Baldwin et.al 2005; Hocking & Babbitt 2014). Frogs are also considered to be major contributors to ecosystem functions, such as decomposition and nutrient cycling, and to ecosystem structure through aquatic bioturbation (interactions between sediment particles and the water column), and soil burrowing (Hocking & Babbitt 2014).

Twelve species of frog are known to occur within the Murray Valley region (Tyler & Walker 2011), and eight of these have been recorded in the CLLMM region since 2009 (Mason & Durbridge 2015):

- Common froglet (*Crinia signifera*)
- Eastern banjo frog (*Limnodynastes dumerilii*)
- Long-thumbed frog (*Limnodynastes fletcheri*)
- Spotted grass frog (*Limnodynastes tasmaniensis*)
- Brown tree frog (*Litoria ewingi*)
- Peron's tree frog (*Litoria peronii*)
- Southern bell frog (*Litoria raniformis*)
- Painted frog (*Neobatrachus pictus*).

Two species, which are known to occur regionally but not are not detected regularly in the CLLMM area, include Bibron's toadlet (*Pseudophryne bibronii*), and Sudell's frog (*Neobatrachus sudelli*). Of the eight species regularly recorded in the CLLMM, two of these are considered true burrowing frogs (*Limnodynastes dumerilii* and *Neobatrachus pictus*) and six are generally considered to be above-ground dwellers (Mason & Durbridge 2015) that shelter within deep organic matter or under forms of structure.

Frog call monitoring has been undertaken across the CLLMM in spring and summer each year since 2009, with the aim of better understanding species' distribution and their response to regional events, such as environmental water management and conditions over time. The observation of frog calls provides a non-intrusive form of determining the species present and the relative abundance of male frogs (as only male frogs call). Frogs respond rapidly to changing conditions, and the calling of male frogs provides an indication of breeding behaviour,

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although not necessarily recruitment success. In 2009 these surveys were initially undertaken in response to prolonged drought, referred to as the Millennium Drought. Sampling continued in successive years following the recovery period from 2010, with the return of freshwater flows to the CLLMM region and the reinundation of fringing wetlands of Lakes Alexandrina and Albert.

The most widespread and abundant species recorded since 2009 has been the common froglet (*Crinia signifera*), a small frog up to 30 mm long (Mason & Durbridge 2015; Tyler & Walker 2011). *Crinia signifera* rapidly takes advantage of damp and wet areas and can take as little as one month to complete metamorphosis from tadpole (water-dependent) to juvenile frog (terrestrial). Also common and abundant in the CLLMM region are *Limnodynastes dumerilii* and *Limnodynastes tasmaniensis*. The males of these three species call in greatest abundance in winter and early spring. *Limnodynastes dumerilli* is the second-largest frog in the region, measuring up to 90 mm in length, and is a burrower with a distinct call, hence its common name, the Eastern banjo frog (Tyler & Walker 2011). Visually, *Limnodynastes tasmaniensis* can easily be confused with its relative *Limnodynastes fletcheri*, the long-thumbed (or barking marsh) frog. Both species are similar in size (up to 55 mm in length) and of mottled colouring. Individuals may have a lighter-coloured stripe along the back, with a dusty rose-coloured patch sometimes found on the eyelid of *L. fletcheri*. The simplest distinction between species is the call of the male frogs. *L. fletcheri* has increased in abundance and spatial distribution (Mason & Durbridge 2015) in recent years. However, as is the case of frog communities in general within the CLLMM region, the full extent of their abundance and distribution pre-Millennium Drought is not well known. This is in part an artifact of the timing of historic frog surveys, which generally occur in early spring (September) and are aligned with the period when the majority of species are known to call (Walker 2002).

Amongst those species known to often call outside of the early spring period, *Litoria ewingi* is a small tree frog (up to 50 mm in length), which can call during many months of the year, often responding to autumn and winter rains (Tyler & Walker 2011). A tree frog in name, *L. ewingi* is a common species in the CLLMM area utilising the dense reed beds of bulrush (*Typha domingensis*) and common reed (*Phragmites australis*) that are common to Lakes Alexandrina and Albert. Peron's tree frog (*Litoria peronii*) is the only other tree frog within the CLLMM region. Sparsely distributed and up to 65 mm in size with distinctive cross-shaped pupils, *L. peronii* has generally been found to call in later spring and early summer.

The painted frog (*Neobatrachus pictus*) and the Sudell's frog (*Neobatrachus sudelli*) are burrowing species with a large distribution across southern South Australia (Tyler & Walker 2011). Emerging from underground following heavy rain, these species are not readily detected in traditional frog-monitoring programs. Since 2009, the painted and Sudell's frog have generally only been detected by spotlighting, not by call recognition (Mason & Durbridge 2015).

Southern bell frogs

The Southern bell frog (*Litoria raniformis*) is listed as nationally 'vulnerable' under the *Environment Protection and Biodiversity Conservation Act 1999* ('the EPBC Act') and 'vulnerable' in South Australia under the *National Parks and Wildlife Act 1972* ('the NPWA Act'). It is a large ground-dwelling frog in a closely related group of frogs referred to as the *Litoria aurea* complex. The species was once common and widespread throughout much of Southeast Australia, but has suffered noticeable and documented declines in distribution and abundance over the past 25-30 years (Clemann & Gillespie 2010; Stratman 2007).

During the recent Millennium Drought, prolonged low water levels resulted in the drying of fringing wetlands, and subsequently extensive areas of aquatic and riparian habitat were lost. Previously submerged sulfidic soils became exposed, presenting the threat of acidification. An inventory of *L. raniformis* distribution was undertaken in 2009, coinciding with the inundation of the Goolwa Water Level Management Area (GWLMA), a management response to exposure of acid sulphate soils encompassing the Goolwa Channel between the barrage and Clayton Bay and the lower reaches of the Finniss River and Currency Creek. The response by frog communities following the pumping of water from Lake Alexandrina into the area was rapid as fringing wetlands were reinundated, signifying their ability to persist during drought conditions (Mason 2010). *L. raniformis* was recorded at three locations during the inventory. The largest population (10-50 individuals) was recorded at Clayton Bay, and smaller populations were detected in the Finniss River and Mundoo Island. While surveys were also undertaken within the broader CLLMM region, Mundoo I. was the only location outside the GWLMA where *L. raniformis* were detected during this time. In 2010 the return of freshwater inflows to the region heralded extensive frog breeding of large magnitude across the CLLMM region. During this time, *L. raniformis* was detected in high abundance in the north of the region at Pelican Lagoon, south of Wellington, and in low to moderate abundances in Finniss River, Hindmarsh I. and Clayton Bay (Mason & Hillyard 2011).

Although signs of recovery of the CLLMM region have been observed since the Millennium Drought, such as the increases in abundance and distribution of many frog species (notably *Limnodynastes fletcheri*), and the expansion and diversification of submerged and emergent plant communities (Frahn et. al. 2014), *L. raniformis* is among those species that have not experienced the same level of recovery. There has, however, been a response by *L. raniformis* to water level management in 2015-2017 (Mason 2018). The species' readiness to prefer newly inundated areas, and the abundances observed following water level changes, suggest that water levels have been the primary driver in *L. raniformis* occupancy between 2013 and 2017 (Mason & Durbridge 2015; Mason 2018).

General habitat requirements

Frog species found within the CLLMM area occupy water bodies with a range of hydrological characteristics, including permanent wetlands, inundated ephemeral and temporary wetlands and creeks, and highly modified environments such as irrigation channels (Gonzalez et al. 2011). Although most species are associated with a range of water regimes, they are highly dependent on inundated vegetation and/or physical habitat, such as snags or fallen timber, which are important for shelter and for the anchoring of eggs (Gonzalez et al. 2011).

The following table, adapted from Bice et al. (2014), outlines the habitat and breeding requirements of seven of the most common species found in the CLLMM area.

Table 3.8.1 Habitat and breeding requirements of frogs of the CLLMM region.

Species	Requirements
Common froglet	Preferred habitat: • Positive association of adults with vegetation along the River Murray in SA (Healy et al. 1997). • Occurrence among dense aquatic vegetation at the water's edge (Tyler 1994). Breeding cues: • Prefers cooler temperatures and generally breeds through autumn, winter and spring, but will breed at any time of the year depending on the availability of habitat and temperature (Anstis 2002). • Described as 'frequent breeders' with eggs laid throughout the year (Anstis 2013).
Eastern banjo frog	Preferred habitat: • Lives in small holes beneath damp wood or stones; aestivates in a sealed burrow during summer (Tyler 1977). Breeding cues: • Calling is most intense after heavy rains, and mass spawning can occur on the same one or two nights (Anstis 2002). • Breeding is most likely to occur in spring and summer but species can be active at any time of the year (Tyler 1977). Spawning is typically communal, with large numbers of individuals breeding simultaneously at a site, usually on warm, wet nights (Ulkrin 1980).
Long-thumbed frog	Preferred habitat: • Aquatic species found in water or sheltering in moist places (Amey & Grigg 1995). • Only occurs among dense aquatic vegetation at the water's edge along the River Murray (Tyler 1994). • Shelters during the day under large rocks, logs and other debris, and in cracks and ground crevices, including yabby burrows (Barker et al. 1995; Cogger 2000). Breeding cues: • Most likely to breed in spring and summer, but can also be active during warmer late-winter weather and into autumn (Anstis 2013).
Spotted grass frog	Preferred habitat: • Found under stones and debris on the beds of dry creeks, pools and dams during summer (Tyler 1977). • Occurs in a range of microhabitat types, but frequently in beds of *Cyperus* spp., and *Paspalum distichum* (Healey et al. 1997); however, other studies have found occupancy of sites by adults to be unrelated to any of the measured habitat or water quality variables (Wassens & Maher 2011). • Has limited capacity to burrow. Adults congregate around permanent water during droughts, and distribution is restricted to areas with some permanent water (Wassens 2011). Breeding cues: • Breeding is opportunistic and may occur at any time of year, with males calling through spring to autumn, and mild winter weather, especially after rain (Wassens 2011), but it usually peaks in summer and autumn (Anstis 2013).
Brown tree frog	Preferred habitat: • Habitat generalist documented from a range of habitat types, such as wet and dry sclerophyll forest, farmland, heathland, semi-arid areas, alpine regions and suburban gardens (Anstis 2002). Breeding cues: • Does not have a distinct breeding season; calls and breeds at any time of the year (Anstis 2013).
Peron's tree frog	Preferred habitat: • Able to utilise vertical landscape (e.g. floodplain trees) with distribution closely linked to the availability of standing timber, in particular river red gum forests (Wassens 2011). • Greater vegetation diversity is a predictor of presence (Lane et al. 2007). Breeding cues: • Although calling and spawning are restricted to spring and summer, tadpoles may linger within water bodies until April (Wassens 2011).

Species	Requirements
Southern bell frog	Preferred habitat: • Presence of permanent water is important for populations in semi-arid landscapes due to lack of water-conserving adaptations, such as burrowing; the low rainfall, combined with high evaporation rates, limit the availability of moist terrestrial habitats (Pyke 2002). • Has a very limited capacity to survive dry periods and must move to permanent refuge sites (Wassens 2011). • Probability of occupancy increased with increasing cover of emergent and submerged vegetation (Wassens et al. 2008). Breeding cues: • Shown to breed over a protracted season, i.e. August-February, in response to flooding (M. Schultz *pers. comm.*).

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CHAPTER 3.9

FOOD WEBS OF THE COORONG

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INTRODUCTION

Estuaries are among the most productive ecosystems on Earth because they produce and receive nutrients and organic matter, the carbon-based remains of plants and animals, from a variety of sources (i.e. terrestrial, freshwater, estuarine and/or marine origin) (Schelske & Odum 1962). Food webs describe how this organic matter or 'energy' flows though the ecosystem (Odum 1971). More than a diagram of 'who eats what', food webs represent tools that aid understanding of ecosystem function and how biota can respond to change. This is especially important in estuaries, where species of economic, cultural and/or conservation significance (including fishers) are often at or near the top of the food web and can react in a complex fashion to a change in the ecosystem. Critical to the management of estuaries is maintaining species or taxonomic groups that play fundamental roles in maintaining food web structure or function ('keystone species'), because their removal may have a substantial impact on the stability of the food web (Paine 1969; Mills et al. 1993).

The Coorong supports a range of biota of conservation, economic and cultural significance (Phillips & Muller 2006). These biota do not occur as random assemblages but as interdependent functional groups that interact through complex food webs. In this chapter we synthesise available information on the food web in the Coorong by 1) providing background information on food web components, common to estuarine environments 2) describing the key components of the Coorong food web 3) describing the influence of the salinity gradient 4) describing the influence of freshwater inflow on food web structure and productivity 5) discussing implications for management. Our focus is on the contemporary Coorong food web where data are present; however, historical aspects are also briefly discussed. Food webs for the Lower Lakes and adjacent high-energy marine environment are not discussed here due to the lack of empirical data. Reference is made to biota described earlier in Chapters 3.4 and 3.6.

FOOD WEB COMPONENTS IN ESTUARIES

Food webs have three basic components: 1) primary producers — autotrophic plants, algae and bacteria that synthesise new organic matter from inorganic nutrients 2) consumers — animals that consume primary producers or other consumers 3) the microbial loop — heterotrophic

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bacteria and fungi that recycle organic matter through the breakdown of detritus (dead plant and animal material) (Fig. 3.9.1). These are briefly reviewed below for estuarine ecosystems.

Within estuaries, energy is photosynthetically produced by rooted (or epiphytic) aquatic plants (herein macrophytes, e.g. sedges and seagrasses) and macroalgae (e.g. filamentous green), and microalgae in the water column (phytoplankton) or on substrates (microphytobenthos). Primary production by phytoplankton is often described as pelagic production (occurring in open water) as opposed to benthic production (associated with substrates), attributable to benthic macrophytes and algae. Energy produced by primary producers is available to consumers in the form of living tissue ('grazing' food web) or as decaying material, i.e. detritus/organic matter ('detrital' food web) (Kennish 1986; Day et al. 2013). In estuaries, organic matter, in particulate (POM) or dissolved (DOM) forms, may be derived from autochthonous (in situ production) and/or allochthonous (imported) sources (Kennish 1986; Crump et al. 2013). Allochthonous organic matter enters estuaries via river discharge or tidal exchange and can thus originate from primary production on land, in fresh water or in the marine environment (Peterson 1999; Crump et al. 2013).

Primary consumers feed on primary producers or detritus and can be grouped into functional guilds based on their feeding mechanisms and particular food sources (e.g. Jumars et al. 2015). For example, suspension feeders consume phytoplankton and suspended POM, and can be found either in the water column (i.e. zooplankton), attached to substrates (e.g. barnacles), or as benthic infauna (e.g. bivalves). Secondary consumers are animals that prey on primary consumers; tertiary consumers prey on secondary consumers; and so on (Fig. 3.9.1). These consumers can also be pooled into feeding guilds based on those that feed predominantly on zooplankton (zooplanktivores), benthic macro-invertebrates (zoobenthivores) and fishes (piscivores) (e.g.

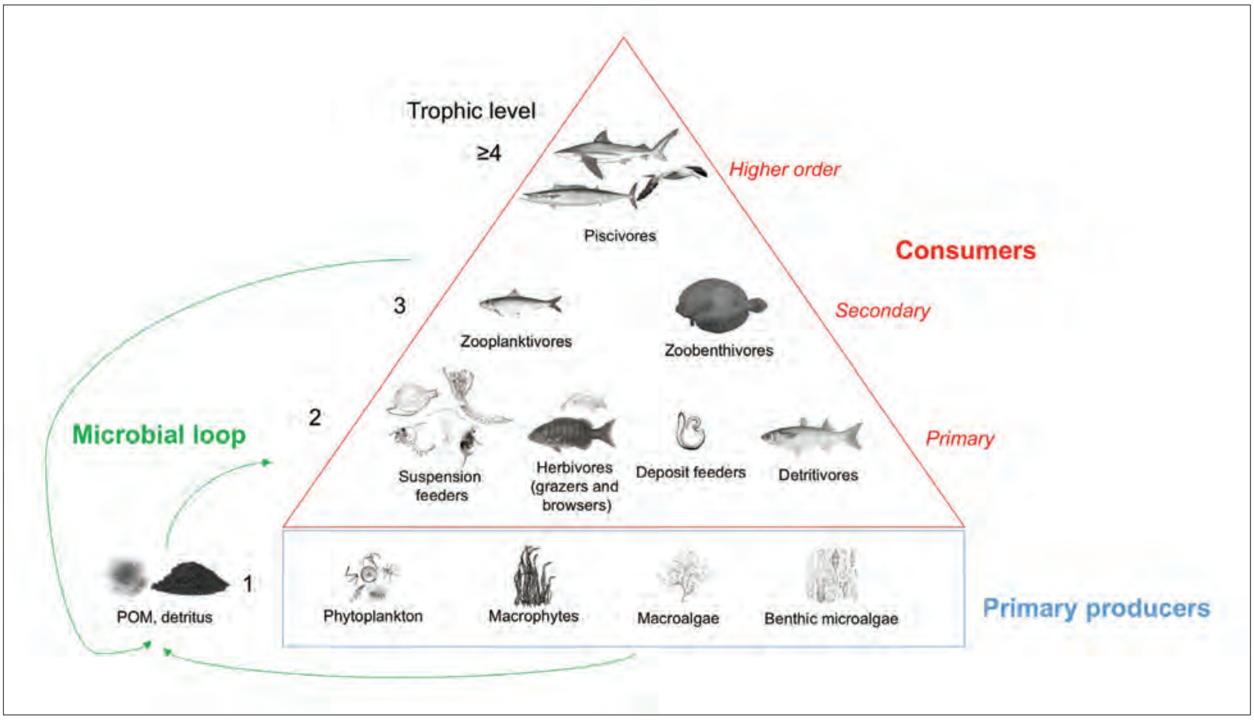

Figure 3.9.1 Simplistic aquatic food web pyramid showing the three basic food web components and examples of the common feeding types (within the pyramid) that are allocated into trophic levels (left side of pyramid). POM = particulate organic matter.

Elliot et al. 2007). Interactions between different guilds represent different pathways for the propagation of energy. It is common to refer to primary producers as the first trophic level in the food web, primary consumers as the second trophic level and so on (Fig. 3.9.1). Some consumers may feed on prey at different trophic levels and occupy positions between two trophic levels. For example, between trophic levels 2 (primary consumers) and 3 (secondary consumers), there are biota (omnivores) that may consume both plant/algal and animal material. The path of utilisation from a particular source of organic matter to a particular top consumer is typically termed a 'food chain' or 'trophic pathway' (Elton 1927; Odum 1971).

Whilst not as well understood, the microbial loop pathway is often an important component of productivity (Box 3.9.1) in estuaries because of the large proportion of benthic plant and algal biomass that is converted to detritus (Kennish 1986), and because of inputs of organic matter from river discharge (Crump et al. 2013). The decomposition of detritus produces microbial biomass that can be consumed by some primary consumers and thus can re-enter the food web (Crump et al. 2013). In addition, organic matter decomposition recycles essential inorganic nutrients (especially nitrogen and phosphorus) that can be used to promote primary production (Blum & Mills 2013).

BOX 3.9.1 WHAT IS ECOSYSTEM 'PRODUCTIVITY'?

Simply put, ecosystem productivity can be defined as the amount of new biomass produced at a given trophic level per year in a given area. Primary production at trophic level 1 dictates resource availability for higher trophic orders and ultimately determines the biotic carrying capacity of ecosystems (Fig. 3.9.3). As such, high primary production supports higher abundances (and often diversity) of biota. How much productivity one trophic level passes on to the next ('trophic transfer efficiency') depends on the proportion consumed, assimilated during digestion, respired (that is, used as energy to move around, etc.) and converted into new growth — this is rarely more than a few percent for most food webs (Slobodkin 1960; Pimm 1988). As food chains in aquatic ecosystems tend to be relatively long (more than three trophic levels), small changes in transfer efficiency from one level to the next can result in significant variations in productivity at the top levels.

TROPHIC COMPONENTS OF THE COORONG FOOD WEB

The Coorong food web comprises four main trophic groups: primary producers, primary consumers, secondary consumers and higher order consumers (trophic level 4 or greater) (Fig. 3.9.2). Within each consumer group, biota with similar feeding modes/diets and similar ecological function can be allocated into feeding guilds (Cummins & Klug 1979; Elliott et al. 2007; Jumars et al. 2015). In this chapter, we allocated biota into the following guilds: suspension-feeding micro- and macro-invertebrates; deposit-feeding and herbivorous macro-invertebrates; herbivorous waterfowl; herbivorous/detritivorous fishes; omnivorous fishes; carnivorous invertebrates; zoobenthivorous shorebirds; zooplanktivorous fishes; zoobenthivorous fishes; piscivorous birds; piscivorous fishes; piscivorous mammals; and humans/fishers (Tables 3.9.1 & 3.9.2). Where possible, feeding guild allocation (Table 3.9.2) and trophic links (Fig. 3.9.2) were based on diet inferred from empirical gut-content data from the Coorong, whilst approximate trophic levels that biota occupy (Fig. 3.9.2) were based on stable isotope analyses from the Coorong (Deegan

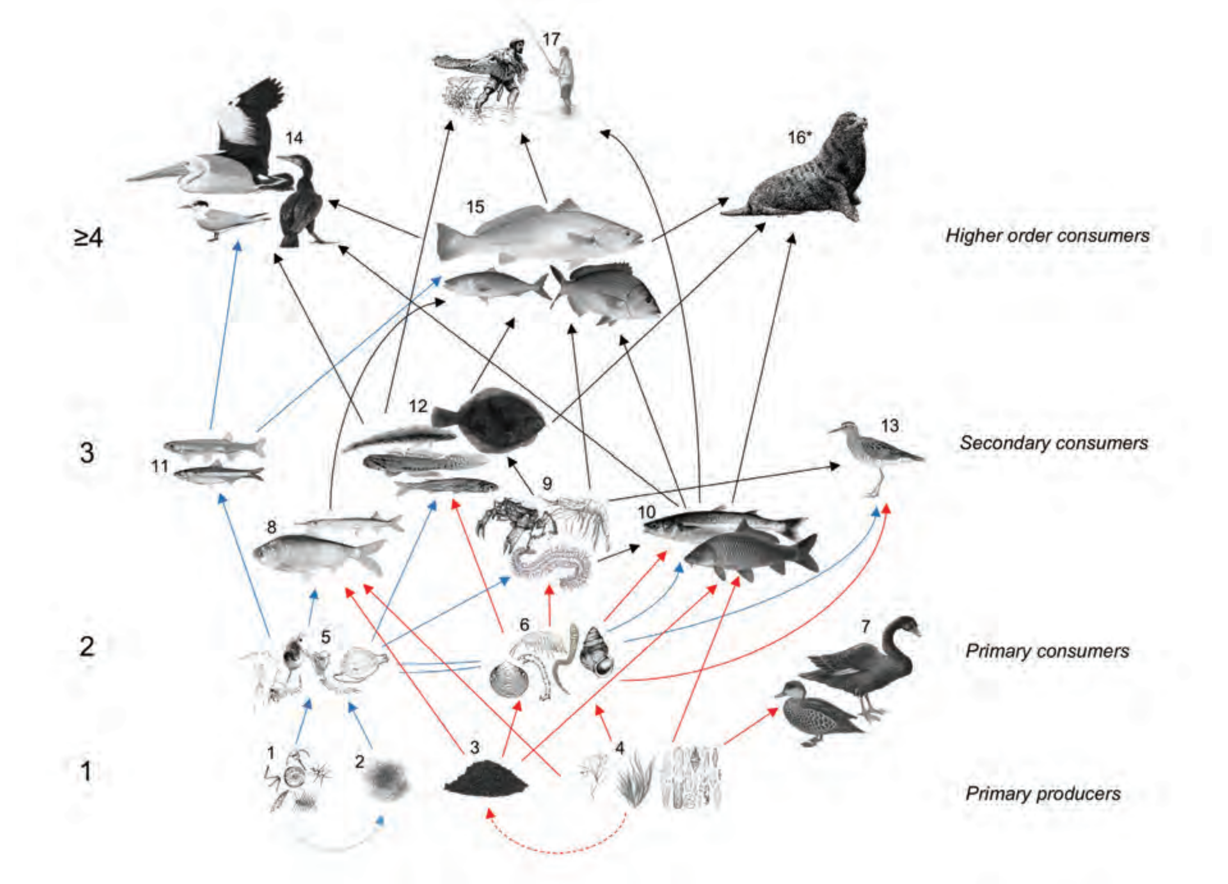

Figure 3.9.2 Conceptual food web of the Coorong using feeding functional guilds in Tables 3.9.2 and 3.9.3, and building on Giatas and Ye (2016). Red trophic links represent those supported by benthic production (benthic algae/plants), while blue trophic links represent those supported by pelagic production (phytoplankton). Primary producers and organic matter material are

(1) phytoplankton
(2) suspended particulate organic matter
(3) benthic detritus
(4) benthic macrophytes, micro- and macro-algae.
Feeding guilds are
(5) suspension-feeding micro- and macro-invertebrates
(6) deposit-feeding and herbivorous macro-invertebrates
(7) herbivorous waterfowl
(8) omnivorous fishes Part 1
(9) carnivorous invertebrates
(10) omnivorous fishes Part 2
(11) zooplanktivorous fishes
(12) zoobenthivorous fishes
(13) zoobenthivorous shorebirds
(14) piscivorous birds
(15) piscivorous fishes
(16) piscivorous mammals*
(17) humans.

Refer to Table 3.9.2 for members within feeding guilds (refer to the descriptions in Table 3.9.1). Omnivorous invertebrates (e.g. polychaete *Simplisetia aequisetis* and crab *Paragrapus gaimardii*) have been grouped into the carnivorous invertebrates guild for the purpose of this schematic view. Organic matter and benthic detritus are not primary producers and represent the microbial loop (dotted trophic links). *Long-nosed fur seals were largely undocumented in the Coorong prior to 2007.

et al. 2010; Giatas & Ye 2015). Individuals of certain species can change feeding guilds because of shifts in diet related to their life cycle, and this phenomenon is particularly prevalent in fishes (Box 3.9.2). For example, most fishes have a zooplanktivorous larval stage, but several transition to piscivory in the adult life stage. For simplicity, we have emphasised the typical adult diet when allocating biota (e.g. fishes) into feeding guilds.

Table 3.9.1 Feeding functional guild descriptions, adapted from Elliot et al. (2007) for vertebrates, and Jumars et al. (2015) for invertebrates. For vertebrates, carnivory is divided into zooplanktivore, zoobenthivore and piscivore categories.

Feeding functional guild	Description
Suspension (or 'filter') feeding invertebrates	Micro- or macro-invertebrates that feed on food particles (e.g. phytoplankton and particulate organic matter) suspended in the water column. May actively feed on particles using cilia to produce feeding currents, or feed with mucous webs.
Deposit-feeding and herbivorous macro-invertebrates[1]	Macro-invertebrates that are either 1) deposit feeders — feed on food particles (e.g. detritus) at the sediment surface ('surface deposit feeders') or suspended in sediment ('deposit feeders'/'burrowers'); or 2) herbivorous[2] — selectively feed on algae and macrophytes ('grazers') or feed indiscriminately on algae, macrophytes and detritus ('browsers').
Herbivorous waterfowl	Birds that feed predominantly on aquatic macroalgae, macrophytes or microalgae.
Herbivorous/ detritivorous fishes	Fishes that exclusively feed on macroalgae, macrophytes and/or microalgae ('herbivore'), or detritus ('detritivore').
Omnivorous fishes (two parts)	Fishes that feed on macroalgae, macrophytes, microalgae or detritus, and animal items. These fishes can be divided into two parts, depending on whether the animal proportion of their diet is dominated by 1) pelagic microcrustaceans 2) benthic macro-invertebrates.
Carnivorous invertebrates	Predatory invertebrates that feed on other animals. This guild also includes omnivorous scavengers that feed on dead/decaying animal and/or plant material.
Zooplanktivorous fishes	Fishes that feed predominantly on zooplankton.
Zoobenthivorous fishes	Fishes that feed predominantly on benthic macro-invertebrates, but diet may include fish or pelagic invertebrates.
Zoobenthivorous shorebirds	Birds that feed predominantly on aquatic benthic macro-invertebrates, but diet may include fish, aquatic pelagic invertebrates or plant material (e.g. seeds).
Piscivorous fishes	Fishes that feed predominantly on fish, but diet may also include large invertebrates.
Piscivorous birds	Birds that feed predominantly on fish, but diet may also include large invertebrates.
Piscivorous mammals	Mammals that feed predominantly on fish, but diet may also include large invertebrates or other vertebrates.

[1] The deposit-feeding and herbivorous macro-invertebrate group may also include benthic and epi-benthic micro-invertebrates (e.g. ostracods) and meiofauna. These taxa have not been sampled using appropriate methods in the Coorong and are thus not included in the food web diagram.
[2] The herbivorous macro-invertebrate group includes 'shredding', 'scraping' and 'piercing' feeding modes defined in Cummins & Klug (1979).

Primary producers

Energy is photosynthetically produced through pelagic production via phytoplankton, and benthic production via benthic macrophytes, macro- and microalgae (Fig. 3.9.2). The relative contribution of some primary producers (e.g. benthic microalgae) to the overall primary production in the Coorong is poorly understood. Benthic macroalgae (e.g. filamentous Ulva) are widespread (Geddes 2005; Geddes & Tanner 2007) and possibly an important source of benthic production (Krull et al. 2008). Like other estuaries, a large proportion of benthic production is likely converted to detritus (Kennish 1986). Historically, the macrophytes *Ruppia megacarpa* and *R. tuberosa* were widespread in the North and South Lagoons respectively (Geddes & Butler

Table 3.9.2 Coorong taxa allocated to feeding functional guilds described in Table 3.9.1. Feeding mode information for benthic invertebrates, which supports assignment to feeding guilds, is based on external literature, e.g. Cannon (1932); Oliver (1971); Jumars et al. (2015); Dorsey (1981); Felgenhauer et al. (1989); Beesley et al. (1998, 2000) and references). The source of feeding mode information for fish is provided in Table 3.9.3, for birds from references in Marchant and Higgins (1990), Higgins and Davies (1996) and Paton (2010), and for seals from SARDI unpublished data. Trophic group information is based on stable isotope analyses in Deegan et al. (2010) and Giatas and Ye (2015) for invertebrates and fishes. Not enough information is available to allocate species or families of microcrustaceans into feeding guilds. Nevertheless, many are considered to be suspension feeders, except for ostracods, which are herbivorous grazers. * indicates invertebrate taxa that also belong in another feeding mode.

Feeding functional guild	**Taxa**	**Trophic group**
Suspension-feeding invertebrates	Bivalvia — *Arthritica helmsi*, *Soletellina alba**, *Spisula* (*Notospisula*) *trigonella*, Mytilidae; Polychaeta — *Ficopomatus enigmaticus*, *Boccardiella limnicola**, *Australonereis elhersi**; Amphipoda* — *Paracorophium* sp.; Malacostraca — Mysidacea*.	Primary consumer
Deposit-feeding and herbivorous macro-invertebrates	Deposit feeders: Bivalvia — *Soletellina alba**; Oligochaeta; Polychaeta — *Capitella capitata*, *Boccardiella limnicola**, *Australonereis elhersi**, *Simplisetia aequisetis**; Sipuncula; Malacostraca — Amphipoda*; Diptera — Ceratopogonidae*, Chironomidae*, Ephydridae*, Gastropoda — *Salinator fragilis**.	Primary consumer
	Herbivorous grazers and browsers: Gastropoda — Hydrobiidae, *Salinator fragilis**, *Coxiella striata*, Glacidorbidae; Malacostraca — Amphipoda*; *Macrobrachium intermedium**; Diptera — Chironomidae*, Ephydridae*.	Primary consumer
Herbivorous waterfowl[1]	e.g. black swan (*Cygnus atratus*), Australian shelduck (*Tadorna tadornoides*), grey teal (*Anas gracilis*), chestnut teal (*Anas castanea*).	Primary consumer
Carnivorous invertebrates	Omnivorous scavengers: Polychaeta — *Simplisetia aequisetis**; Malacostraca — Amphipoda*, *Macrobrachium**, *Paragrapsus gaimardii*, *Helograpsus haswellianus*, *Amarinus laevis*.	Omnivorous[2]
	Carnivores: Polychaeta — *Phyllodoce novaehollandiae*, *Nephtys australiensis*; Malacostraca — Mysidacea*, Diptera — Ceratopogonidae*.	Secondary consumer
Omnivorous fishes	Group 1, Zooplanktivore: bony herring (*Nematalosa erebi*), river garfish (*Hyporhamphus regularis*).	Omnivorous[2]
	Group 2, Zoobenthivore: yelloweye mullet (*Aldrichetta forsteri*), common carp (*Cyprinus carpio*), bridled goby (*Arenigobius bifrenatus*), bluespot goby (*Pseudogobius olorum*).	Omnivorous[2]
Zooplanktivorous fishes	Sandy sprat (*Hyperlophus vittatus*)[3], Australian smelt (*Retropinna semoni*).	Secondary consumer
Zoobenthivorous fishes	Greenback flounder (*Rhombosolea tapirina*), smallmouth hardyhead (*Atherinosoma microstoma*), Tamar goby (*Afurcagobius tamarensis*), congolli (*Pseudaphritis urvillii*), Australian herring (*Arripis georgianus*), flathead gudgeon (*Philypnodon grandiceps*).	Secondary consumer
Zoobenthivorous shorebirds[1]	e.g. red-neck stint (*Calidris ruficollis*), banded stilt (*Cladorhynchus leucocephalus*), sharp-tailed sandpiper (*Calidris acuminata*), black-winged stilt (*Himantopus himantopus*), red-capped plover (*Charadrius ruficapillus*), red-necked avocet (*Recurvirostra novahollandiae*), black tailed godwit (*Limosa limosa*), eastern curlew (*Numenius madagascariensis*).	Secondary consumer
Piscivorous fishes	Mulloway (*Argyrosomus japonicus*), Australian salmon (*Arripis trutta* and *A. truttaceus*), black bream (*Acanthopagrus butcheri*)[4].	Higher-order consumer

Feeding functional guild	**Taxa**	**Trophic group**
Piscivorous birds	e.g. Australian pelican (*Pelecanus conspicillatus*), cormorants (*Phalacrocorax* spp.), terns (*Sternula* spp.), hoary-headed grebe (*Poliocephalus poliocephalus*).	Higher-order consumer
Piscivorous mammals	Long-nosed fur seal (*Arctocephalus forsteri*).	Higher-order consumer

[1] Herbivorous waterfowl have been classified as such, but their diets (except for black swan) may also include animal material. Shorebirds have been classified as zoobenthivorous, but their diets may also include fish or plant material such as *Ruppia tuberosa* seeds. Consequently, trophic levels for bird species within individual guilds may vary greatly, depending on their diets.

[2] 'Omnivorous' refers to a group situated between primary consumers and secondary consumers.

[3] Benthic microcrustaceans may be important in the diet of sandy sprat in the Coorong (Bice et al. 2016).

[4] While black bream could be classified as an omnivore because it may consume algae or macrophytes, the greatest proportion of its diet in the Coorong is made up of large benthic decapods (e.g. *Paragrapus gaimardii*) and fishes such as gobies (Table 3.9.3). Stable isotope analysis has confirmed this species to be a higher-order consumer (≥ trophic level 4) (Deegan et al. 2010).

1984; Paton 2010), and an important food source for waterfowl (Delroy 1974; Paton 1986). The extirpation of *R. megacarpa* and declines in *R. tuberosa* distribution and abundance in recent decades (Paton 2010) may have resulted in an overall reduction in primary productivity. Quantifying this impact is complex because *Ruppia s*pp. was an 'ecosystem engineer': shoots expanded from the benthic habitat into the water column, providing structure for epiphytes (algae that grow on other plants), habitat for invertebrates, and a direct food source for grazers (shoots) and birds (seeds and turions) (Paton 1986, 2010).

Primary consumers

Micro- and macro-invertebrates are the dominant primary consumers in the Coorong (Deegan et al. 2010; Giatas & Ye 2015; Fig. 3.9.2). These include 1) suspension feeders, e.g. many pelagic microcrustaceans (e.g. copepods and cladocerans), the sessile tubeworm *Ficopomatus enigmaticus* (Jumars et al. 2015) and bivalve *Arthritica helmsi* (Ponder 1998) 2) deposit feeders, e.g. the polychaete *Capitella capitata* (Jumars et al. 2015) 3) herbivorous macro-invertebrates, e.g. amphipods (MacNeil et al. 1997) and chironomid larvae (Oliver 1971) (Fig. 3.9.2; Tables 3.9.1 & 3.9.2). Some of these species may exhibit multiple feeding modes (Table 3.9.2), e.g. the polychaete *Australonereis ehlersi* may deposit or suspension feed (Dorsey 1981). Similarly, there may be inter-specific differences in feeding modes within broader taxonomic groupings, e.g. amphipods (MacNeil et al. 1997) and chironomid larvae (Oliver 1971).

The primary consumer trophic group also comprises herbivorous waterfowl (e.g. black swan, *Cygnus atratus*, and grey teal, *Anas gracilis*) (Frith et al. 1969; Delroy 1974; Paton 1986). Whilst specialist detritivorous fishes occur in the Coorong in low abundance (e.g. goldspot mullet, *Liza argentea*) (Chapter 3.6), herbivorous fishes are absent, which is common in dynamic environments such as temperate estuaries (Whitfield 1998; Elliot et al. 2002; Buchheister & Latour 2015). The major trophic pathway for suspension feeders is considered to be through the pelagic pathway, while energy for deposit feeders, grazers/browsers and herbivorous waterfowl is provided through the benthic pathway (Fig. 3.9.2). However, unlike a well-stratified deep lake or ocean, the Coorong is shallow and prone to sediment resuspension, and thus benthic primary production may also support suspension feeders (Threlkeld 1994). In the Coorong, there is uncertainty behind what particular primary producers are used as food resources by particular primary consumers, especially micro- and macro-invertebrates.

Omnivores, defined here as consumers feeding between trophic levels 2 and 3, include omnivorous scavenging invertebrates (e.g. the crab *Paragrapsus gaimardii* and polychaete *Simplisetia aequisetis*, Dorsey 1981; Deegan et al. 2010; Giatas & Ye 2015) and omnivorous fishes (Table 3.9.2). For the Coorong, we have divided the omnivorous fishes guild into two parts — species whose animal prey are dominated by 1) pelagic microcrustaceans, e.g. bony herring (*Nematalosa erebi*) (Atkins 1984) 2) benthic macro-invertebrates, e.g. yelloweye mullet (*Aldrichetta forsteri*) (Geddes & Francis 2008; Deegan et al. 2010; Giatas 2012) and invasive common carp (*Cyprinus carpio*) (Hall 1981) (Tables 3.9.2 & 3.9.3). Most of these omnivorous fishes demonstrate ontogenetic shifts in diet (Box 3.9.2).

Secondary consumers

Polychaetes *Nephtys australiensis* and *Phyllodoce novaehollandiae* (Jumars et al. 2015), zooplanktivorous fishes (e.g. sandy sprat, *Hyperlophus vittatus*; Bice et al. 2016; Hossain et al. 2017), zoobenthivorous fishes and zoobenthivorous shorebirds represent the secondary consumer trophic group (Deegan et al. 2010; Giatas & Ye 2015; Fig. 3.9.2). 'Forage fishes' is a term that has been used to describe many small pelagic fishes in the secondary consumer group of food webs, due to many of them being a suitable size for piscivorous predators.

Benthic invertebrates such as amphipods, polychaetes and insect larvae form important components of the diet of shorebirds (Tulp & de Goeij 1994; Paton 2010; Keuning 2011) and many zoobenthivorous fishes such as greenback flounder (*Rhombosolea tapirina*), smallmouth hardyhead (*Atherinosoma microstoma*) and Tamar goby (*Afurcagobius tamarensis*) (Geddes &

BOX 3.9.2 ONTOGENETIC DIETARY SHIFTS

Ontogenetic shifts in diet are common among fishes (Werner & Gilliam 1984). These shifts are linked to changes in energy requirements during growth and they are potentially associated with a number of factors, including changes in morphology (e.g. mouth gape or digestive system), mobility, habitat, predation pressure and intraspecific competition (Elliott et al. 2002). As a consequence of ontogenetic shifts, a species may belong to different trophic levels and feeding guilds throughout its life.

Mulloway demonstrate a pronounced ontogenetic shift in diet typical of many large-bodied fishes, with trophic level increasing through ontogeny. In the Coorong, small benthic and epibenthic crustaceans (i.e. amphipods and mysid shrimp) and small forage fishes (e.g. sandy sprat) are common in the diet of mulloway <400 mm total length (Hall 1986; Giatas & Ye 2015). With increasing predator size, mulloway tend to consume larger prey, such as the crab *Paragrapsus gaimardii* and other fishes (e.g. bony herring, and congolli, *Pseudaphritis urvillii*) at 400-599 mm total length, and yelloweye mullet at >600 mm total length (Giatas & Ye 2015).

Yelloweye mullet exhibit a more atypical ontogenetic dietary shift, with trophic level decreasing with ontogeny. In the Coorong, juveniles (50-99 mm total length) may be classified within the zoobenthivorous fishes guild (trophic level c.3-3.5), feeding predominantly on animal prey items (e.g. larval fishes, amphipods, other crustaceans and polychaetes) (G. Giatas unpublished data). As adults, the species transitions into the omnivorous fishes guild (trophic level c.2.5-3) (Deegan et al. 2010), with the importance of animal prey items declining, while the proportion of filamentous algae and detritus in the diet increases (Giatas 2012).

Table 3.9.3 Summary of the diet of common fishes of the Coorong. Species have been allocated into feeding functional guilds (FFG) (Table 3.9.2) based on adult diet literature from the Coorong presented there, and external literature where data are absent from the Coorong. P = piscivore, Zb = zoobenthivore, Zp = zooplanktivore, OI = omnivore group 1, OII = omnivore group 2.

Species	**FFG**	**Main diet items**	**Diet literature**
Mulloway (*Argyrosomus japonicus*)	P	Atherinids, gobies, mugilids, sandy sprat, bony herring, congolli, crabs, mysid shrimp, palaemonid shrimp, amphipods.	Hall 1986; Geddes & Francis 2008; Deegan et al. 2010; Giatas & Ye 2015
Australian salmon (*Arripis trutta* and *A. truttaceus*)	P	Sandy sprat, smallmouth hardyhead, gobies, copepods, amphipods, mysid shrimp.	Giatas & Ye 2015
Black bream (*Acanthopagrus butcheri*)	P	Crabs, gobies, bivalves, polychaetes, filamentous algae.	Weng 1970; Deegan et al. 2010
Greenback flounder (*Rhombosolea tapirina*)	Zb	Amphipods, polychaetes, copepods, mysid shrimp, bivalve siphons, insect larvae.	Deegan et al. 2010; Earl 2014
Congolli (*Pseudaphritis urvillii*)	Zb	Amphipods, polychaetes, mysid shrimp.	Johnson 2014; Giatas & Ye 2015
Tamar goby (*Afurcagobius tamarensis*)	Zb	Amphipods, polychaetes, copepods, ostracods, mysid shrimp, teleosts.	L. Silvester unpublished data; Geddes & Francis 2008; Hossain et al. 2017
Smallmouth hardyhead (*Atherinosoma microstoma*)	Zb	Amphipods, polychaetes, copepods, insect larvae, mysid shrimp, ostracods.	L. Silvester unpublished data; Geddes & Francis 2008; Deegan et al. 2010; Hossain et al. 2017
Sandy sprat (*Hyperlophus vittatus*)	Zp	Copepods and nauplii, cladocerans, amphipods, ostracods, crab zoea, mysid shrimp, rotifers.	Bice et al. 2016; Hossain et al. 2017
Yelloweye mullet (*Aldrichetta forsteri*)	O_{II}	Polychaetes, amphipods, copepods, mysid shrimp, palaemonid shrimp, crabs, bivalves, detritus, filamentous algae.	Geddes & Francis 2008; Deegan et al. 2010; Giatas 2012
Common carp (*Cyprinus carpio*)[1]	O_{II}	Filamentous algae, amphipods, chironomid larvae, gastropods, cladocerans and copepods.	Hall 1981
Bony herring (*Nematolosa erebi*)[1]	O_{I}	Detritus, filamentous algae, copepods, cladocerans and ostracods.	Atkins 1984

[1] Dietary data for freshwater species (i.e. common carp and bony herring) are from the Lower Lakes, not the Coorong.
In the Coorong, no dietary data exist for other abundant fish species, i.e. lagoon goby (*Tasmanogobius lasti*), Australian smelt (*Retropinna semoni*), Australian herring (*Arripis georgianus*), river garfish (*Hyporhamphus regularis*) and flathead gudgeon (*Philypnodon grandiceps*). Feeding guild allocation in Table 3.9.2 was based on external literature for these species.

Francis 2008; Deegan et al. 2010; Earl 2014; Hossain et al. 2017) (Table 3.9.3). Prey use in shorebirds is determined by leg length and beak length, where benthic invertebrates burrow into the sediments, e.g. in the Murray Estuary and North Lagoon (Paton 2010; Keuning 2011). Thus the longer-legged and longer-beaked shorebirds (e.g. black tailed godwit, *Limosa limosa*, and eastern curlew, *Numenius madagascariensis*) can usually access mudflats covered with deeper water and probe deeper into the sediments than the shorter-legged and shorter-beaked species (e.g. red-necked stint, *Calidris ruficollis*, and sharp-tailed sandpiper, *Calidris acuminata*) (Paton 2010; Keuning 2011).

Zooplanktivorous fishes generally rely on pelagic production to support zooplankton biomass, while many zoobenthivorous species obtain their food resources (e.g. benthic macroinvertebrates) via benthic production (Fig. 3.9.2). However, benthic primary production may also support pelagic zooplankton and zooplanktivorous fishes due to sediment resuspension in shallow habitats (Threlkeld 1994).

Higher-order consumers

The majority of higher-order consumers in the Coorong are piscivores that feed on zooplanktivorous, zoobenthivorous or omnivorous fishes (Deegan et al. 2010; Giatas & Ye 2015) (Table 3.9.2; Fig. 3.9.2; Box 3.9.3). In addition, large predatory or omnivorous benthic invertebrates (e.g. the crab *Paragrapsus gaimardii*) and other piscivorous fishes may be consumed by higher-order consumers (Deegan et al. 2010; Giatas & Ye 2015; SARDI unpublished data) (Table 3.9.3; Box 3.9.3).

Mulloway (*Argyrosomus japonicus*), the largest piscivorous fish in the Coorong, demonstrates a distinct ontogenetic shift in diet (Box 3.9.2). This species, along with piscivorous birds (e.g. Australian pelican, *Pelecanus conspicillatus*, cormorants and terns), is capable of feeding on a variety of fishes (McNally 1957; Smith 1994; Giatas & Ye 2015) (Table 3.9.2). In the South Lagoon of the Coorong, smallmouth hardyhead is an essential prey item for piscivorous birds (e.g. fairy tern, *Sternula nereis*) as this is often the only fish species present (Paton 2010). Long-nosed fur seals (*Arctocephalus forsteri*) (Box 3.9.3), along with humans (i.e. fishers), are considered to be the apex predators in the Coorong (Fig. 3.9.2). Mulloway, yelloweye mullet, black bream (*Acanthopagrus butcheri*) and greenback flounder are the most commercially harvested fishes (Chapter 4.2).

Identifying the energy flow to higher-order consumers in the Coorong is complex, given the potential for numerous trophic pathways (Fig. 3.9.2). At times, the diets of higher-order consumers (e.g. piscivorous fishes) may heavily comprise zooplanktivorous species, whose abundances are supported primarily by pelagic production.

BOX 3.9.3 LONG-NOSED FUR SEAL

The occurrence of seals in the Coorong dates back to the 1800s (Sturt 1833), but they were largely undocumented between then and 2007. Since 2010, there has been increasing interaction between the long-nosed fur seal and commercial fishers (Mackay 2016). The majority of individuals in the Coorong are considered to be juveniles and sub-adults, which are more abundant in coastal haul-out areas, particularly during winter (Shaughnessy et al. 2015). This species is described as an opportunistic piscivore whose diet is comprised mostly of fishes but may also contain birds and large invertebrates (e.g. crustaceans and molluscs) (Page et al. 2005; Reinhold 2015). Major prey items (reconstructed biomass) from both scat and stomach-content analyses in the Coorong include common carp, bony herring, gobies (e.g. Tamar goby), mulloway and golden perch (*Macquaria ambigua*) (SARDI unpublished data). Given that foraging of seals is not limited to the Coorong, they may derive a significant proportion of their diet composition from other environments, such as the Lower Lakes and adjacent marine environment.

INFLUENCE OF SALINITY GRADIENT ON FOOD WEB STRUCTURE IN THE COORONG

As described in Chapter 2.7, the Coorong is an inverse estuary that has an extensive and persistent salinity gradient, typically spanning from brackish in the Murray Estuary to hypersaline in the South Lagoon, although salinities are greatly influenced by freshwater inflows and seasonality (e.g. wind, tides and evaporation). As the Coorong is shallow, relatively small variations in water level also result in large areas of sediments being either flooded or exposed at daily to seasonal timescales. These two features combine to produce a complex mosaic of habitats, food webs and overall species diversity across the Coorong (Phillips & Muller 2006). Whilst it is difficult to generalise, at least four distinct food webs have been described for the Coorong along its salinity gradient (Deegan et al. 2010; Giatas & Ye 2016), in part based on the presence or absence of keystone species (Box 3.9.4). As salinities increase from marine (~40 ppt), there is a general decline in the diversity of species (Ye et al. 2015; Chapters 3.4 & 3.6) and feeding guilds, and food chain length (Deegan et al. 2010), driven by species' salinity preferences and tolerances. Furthermore, as the salinity gradient is influenced by freshwater inflow, so, too, are the presence and extent of the following distinct food webs.

1) Fresh-brackish

These are associated with the Murray Estuary region during high inflows where salinities are typically <20 ppt. This food web is characterised by high relative abundances of freshwater zooplankton (Shiel & Aldridge 2011; Shiel & Tan 2013), benthic invertebrates (albeit at low diversity), zooplanktivorous and omnivorous freshwater fishes (bony herring, common carp, Australian smelt), and a zooplanktivorous marine forage fish (sandy sprat), and moderate abundances of omnivorous marine (yelloweye mullet) and piscivorous marine fishes (Australian salmon and mulloway) (Giatas & Ye 2016). Sandy sprat, which tends to be found in highest abundance during periods of freshwater discharge (Bice et al. 2016), is a keystone species that likely transfers a significant amount of energy from primary producers and consumers (e.g. zooplankton) to higher-order consumers (Giatas & Ye 2015; Bice et al. 2016).

BOX 3.9.4 KEYSTONE SPECIES IN THE COORONG

Keystone species are fundamental to maintaining food web structure or function. The macrophyte *Ruppia tuberosa* is a keystone primary producer in the hypersaline food webs of the Coorong. Sandy sprat (zooplanktivorous fish) and smallmouth hardyhead (zoobenthivorous fish) have been identified as keystone prey species for piscivores (e.g. mulloway, Australian salmon and piscivorous birds) (Fig. 3.9.2). Similarly, mulloway is considered to be a keystone piscivorous species as it is the highest-ordered fish in the food web and supports a commercial fishery and other larger piscivores (i.e. piscivorous birds and seals) (Fig. 3.9.2). The removal of any of these keystone species will likely have a substantial impact on the stability of the food web.

2) Brackish-marine

This food web is typically associated with the Murray Estuary region and northern part of the North Lagoon with salinities typically c.30-50 ppt. It is associated with the most diverse habitat for fish, with freshwater (bony herring), estuarine (smallmouth hardyhead) and marine (sandy sprat, yelloweye mullet, mulloway, Australian salmon) fishes from a variety of feeding guilds present (Giatas & Ye 2016). High diversities of benthic macro-invertebrates also occur at these salinities, characterised by polychaetes (*Capitella capitata* and *Simplisetia aequisetis*), bivalves (*Arthritica helmsi*) and crustaceans (amphipods) (Chapter 3.4).

3) Hypersaline

This food web is associated with areas with salinities typically c.70-120 ppt, normally associated with seasonally inundated mudflats. The South Lagoon was historically characterised by the extensive development of *Ruppia* spp. on mudflats (Geddes & Butler 1984), a high abundance of salt-tolerant forage fish (smallmouth hardyhead), a diversity of bird species including waders (e.g. red-neck stint and banded stilt) and grazers (e.g. black swan) (Paton 2010). *Ruppia tuberosa* is considered to contribute greatly to the primary production in this food web, providing living plant tissue for grazers and recycled organic matter (e.g. detritus) for chironomid larvae (*Tanytarsis barbitarsis*) and brine fly larvae (*Ephydrella* sp.) (Geddes & Butler 1984; Chapter 3.4). These invertebrates support the only fish prey species (smallmouth hardyhead) present for piscivorous birds (Noell et al. 2009; Paton 2010). Piscivorous fishes are absent in this food web, and other zoobenthivorous species with quite high salinity tolerances (e.g. yellow-eye mullet) occur occasionally (Giatas & Ye 2016).

4) Extremely hypersaline

During the Millennium Drought (2001-2010), the development of extreme salinities (>120 ppt) in the South Lagoon and part of the North Lagoon led to the partial or complete extirpation of seagrasses and even salt-tolerant fishes (Noell et al. 2009; Rogers & Paton 2009; Paton 2010; Wedderburn et al. 2016). This 'new' food web was characterised by an overall low species diversity, high densities of phytoplankton and ostracods, and the presence of the Australian brine shrimp (Paton & Rogers 2008; Paton 2010; Geddes et al. 2016), the latter probably able to colonise this habitat once fishes (including smallmouth hardyhead) were extirpated. This was also associated with the nesting of salt-lake specialist bird species in the Coorong (Paton 2010).

FOOD WEB RESPONSES TO FRESHWATER INFLOW

In estuaries, the balance between autochthonous and allochthonous production shifts with hydrology (Fig. 3.9.3); for example, a large proportion of the production in estuaries typically originates from local sources (autochthonous) during low inflows (Jassby et al. 1993; Hoffman & Bronk 2006). In contrast, during high inflows, estuaries benefit from a greater proportion of primary production that has already occurred elsewhere (e.g. riverine production) and that is transported to the estuary (Jassby et al. 1993; Hoffman et al. 2008). Consequently, there is often more potential for primary production during high inflows, which in turn may promote a greater biomass of higher-order consumers (e.g. predatory fishes) (Fig. 3.9.3). However, there may be other factors that limit or delay improved ecosystem production. For example, increased turbidity from high inflows may initially hinder macrophyte and phytoplankton production, before inflows begin to subside and turbidity declines (Congdon & McComb 1979; Cadée 1986; Jassby et al. 1993).

Freshwater inflows also influence water physico-chemistry (e.g. salinity, dissolved oxygen, turbidity), and hydraulic (e.g. velocities) and structural habitat (e.g. morphology) (Drinkwater & Frank 1994; Gillanders & Kingsford 2002; Kimmerer 2002; Gillson 2011). Changes in these parameters affect species presence, distribution and abundance, and consequently modify trophic interactions in food webs. The influence of freshwater inflow on the source and magnitude of production, the spatial variation in food web types, and energy flow in trophic pathways are described below for the Coorong.

Freshwater inflows from upstream ecosystems are considered to be essential for the overall productivity in the Coorong for a number of reasons. First, inorganic nutrient input supports in situ primary production. Alternatively, these nutrients (and transported organic matter) may be stored in the Coorong following high-flow periods, and recycled and reutilised during low-flow periods (Grigg et al. 2009; Dias et al. 2016). However, transported nutrients and organic matter may have short residence times and be flushed out of the Coorong during high inflows (Ye et al. 2018), but may benefit nearshore marine communities (Auricht et al. 2017). Second, freshwater inflow directly transports riverine and terrestrial food resources (e.g. organic matter, phytoplankton and zooplankton) (Shiel & Aldridge 2011; Shiel & Tan 2013; Geddes et al. 2016) to the Coorong, potentially leading to enhanced secondary productivity

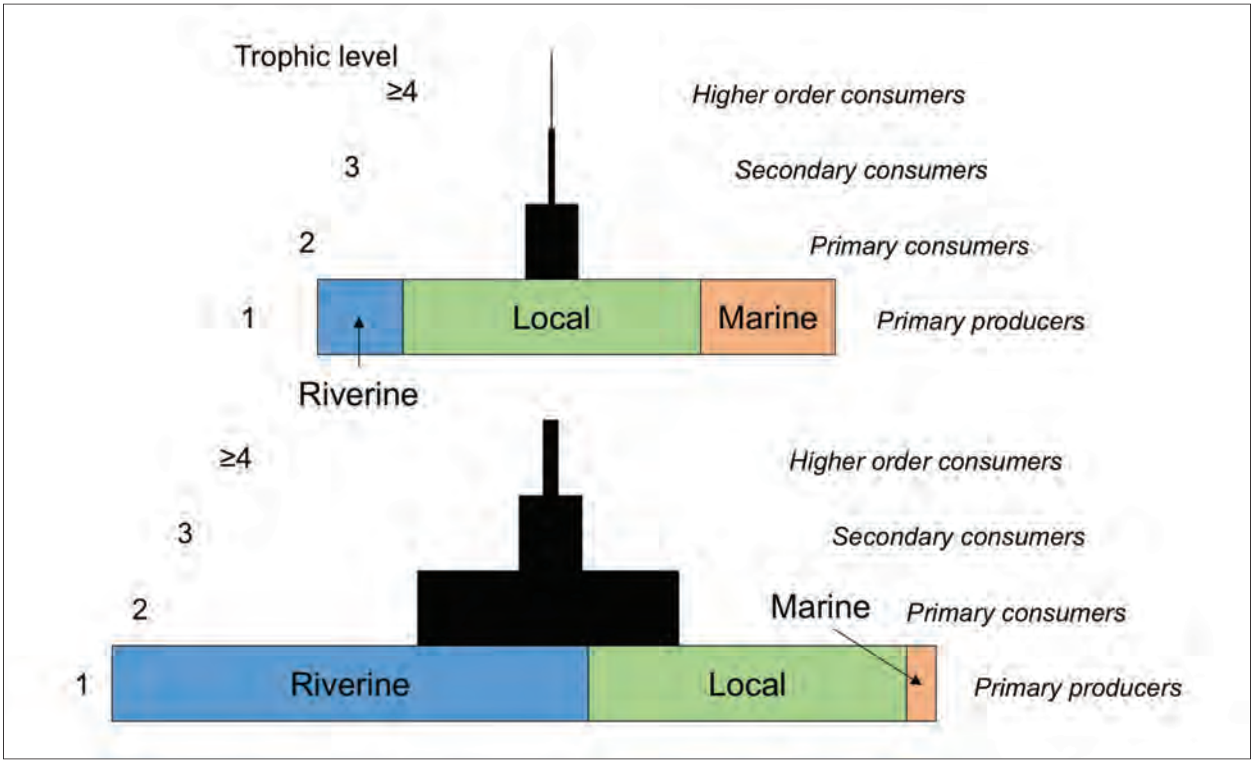

Figure 3.9.3 Conceptual representation of production in estuaries during low (top) and high (bottom) freshwater inflows. 'Riverine', 'local' and 'marine' refer to the origin of primary production, whilst width of the bars indicates the magnitude of relative production.

(e.g. sandy sprat) which is propagated progressively up the food chain (Fig. 3.9.2; Bice et al. 2016; Giatas & Ye 2016). During high freshwater inflows, there is a greater contribution of pelagic components of the food web towards production in the Murray Estuary and North Lagoon. This is the result of increased zooplankton abundance (dominated by freshwater species) during high inflows, presumably due to transportation from the River Murray and Lower Lakes to the Coorong or from increased local primary productivity of phytoplankton, stimulated by allochthonous nutrient input. Conversely, benthic production and energy propagation through benthic-based trophic pathways become relatively more important during lower inflows, particularly in the North and South Lagoons (Fig. 3.9.2; Giatas & Ye 2016). A recent isotopic investigation indicated that both benthic and pelagic pathways contributed to the diet of large-bodied fish during a prolonged low-inflow period (Lamontagne et al. 2016).

Third, freshwater inflow to the Coorong may result in increased water levels, reduced salinities and a shift in the salinity gradient in a southwards direction (Chapters 2.6 & 2.7). The shift in salinity gradient affects the spatial positioning and presence of food web types (e.g. Geddes 1987; see above). For example, during high inflows, the extremely hypersaline food web is often absent, and the spatial area where the hypersaline food web operates is restricted to the South Lagoon. The fresh-brackish and brackish-marine food webs cover a wide area spanning the Goolwa Barrage through the North Lagoon and seasonally into the South Lagoon. The wide spatial coverage of these two food webs is considered beneficial from a conservationist, economic and ecological perspective because all feeding guilds are present (including piscivorous fishes) (Deegan et al. 2010; Giatas & Ye 2016), and these food webs support the greatest biomass and diversity of biota. During prolonged periods of low freshwater inflow, the fresh-brackish food web is absent from the Coorong, and the brackish-marine food web is restricted to the Murray Estuary and northern end of the North Lagoon. Due to mostly marine salinities present in the Murray Estuary under low flows, freshwater species are absent or abundance is low (Noell et al. 2009; Geddes et al. 2016) and they play a negligible role in food web function. Extended periods of little or no freshwater inflow may lead to prolonged mouth closure and disconnection between the estuary and freshwater environments, resulting in increased salinities (Chapters 2.6 & 2.7). In turn, this can potentially lead to 1) decreased species diversity and biomass, including fisheries production 2) the loss of feeding guilds and simplification of food webs 3) extirpation of estuarine biota from the ecosystem.

CONCLUSION AND IMPLICATIONS

Maintaining a diverse and healthy food web in the Coorong is important, given the ecological, social and economic significance of the region (Phillips & Muller 2006). This importance, however, also extends beyond the region as broader population dynamics of some species, such as mulloway and migratory wader birds, are influenced by processes occurring at the site scale (Ferguson et al. 2008; Bamford et al. 2008; Barnes et al. 2015). Critical to the preservation of diverse estuarine food webs is the maintenance of connectivity between the estuarine environment and freshwater and marine environments. As for many other ecosystems associated with the River Murray, the Coorong is still adjusting to the significant changes to its hydrological regime, particularly the reductions in magnitude and frequency of inflows, which have occurred during the 20th century (Chapters 2.6 & 2.7). At present, a key concern is the loss or restriction in distribution of keystone species; indeed, some are now almost functionally absent from the system. For example, the loss of *Ruppia megacarpa* and decline of *R. tuberosa* have likely had a profound impact on primary production in the system, but the extent remains unknown. Whether or not this is a permanent change reflecting the new hydrological regime is unclear. The recent increased prevalence of the long-nose fur seal, a key top predator, may also affect food webs in the Coorong.

Recent work suggests that small increases in riverine discharge, which can be achieved through environmental water management, may benefit the Coorong food web, particularly during years of low flow in the lower River Murray where inflow to the Coorong would otherwise be absent (Bice et al. 2016; Geddes et al. 2016; Ye et al. 2017). Environmental flow management typically focuses on other ecological outcomes, but productivity benefits are valid objectives. Small increases in discharge are likely to enhance food web function, given the anticipated reduction in salinities and subsequent expansion of suitable habitat, and the increase in phytoplankton and zooplankton abundance that support zooplanktivorous fishes and higher-order consumers. Enhanced ecosystem productivity has many flow-on effects, including improved recruitment of biota, such as large-bodied fishes, which may lead to improved population demography and resilience, as well as associated economic benefits (i.e. greater mulloway biomass to support fisheries). Despite the potential benefits associated with environmental water, ecological responses to low volumes of water are likely to be localised and short-lived, and longer durations and higher frequencies of inflows are likely required for long-term benefits, particularly to benefit the hypersaline habitats and food webs in the North and South Lagoons of the Coorong (Geddes 1987; Geddes et al. 2016).

Unlike many other large rivers of the world, the significance of River Murray discharge to the productivity of nearby marine habitats has not been thoroughly investigated (Auricht et al. 2017). Promoting a greater return of flows to the Coorong may also increase production in nearby marine habitats, including valuable fisheries (e.g. mulloway and pipi, *Plebidonax deltoides*) (Ferguson et al. 2013).

ACKNOWLEDGEMENTS

This chapter used data and knowledge obtained from a number of research and monitoring programs in the Coorong, particularly the CLLAMM Ecology Research Cluster supported by CSIRO Flagship Collaboration Fund, the SA Government's Murray Futures program funded by the Australian Government; the Goyder Institute for Water Research, and The Living Murray initiative of the Murray-Darling Basin Authority. The authors thank the various project managers from these agencies that have supported research in the region. Empirical data from several Flinders University Honours and PhD projects (Luke Silvester, Jason Earl, Justin Keunning, Rhys Johnson and Afzal Hossain) contributed to informing the allocation of species into feeding functional guilds. The authors also thank Mike Geddes and Chris Hallett for formal review of this chapter.

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PART 4:

MANAGEMENT, RESOURCE USE AND CONSERVATION

CHAPTER 4.1

WATER PLANNING AND ENVIRONMENTAL WATER MANAGEMENT

ADRIENNE RUMBELOW[1]

INTRODUCTION

Each year the Department for Environment and Water (DEW) develops annual environmental watering priorities for key South Australian River Murray assets, including the Coorong, Lower Lakes and Murray Mouth (CLLMM). This information is provided to the major environmental water holders to assist in planning and implementing the delivery of environmental water across the Murray-Darling Basin. Environmental water planning is critical in ensuring that water can be delivered appropriately to key wetlands, such as the Coorong and Lower Lakes, so that the volume, seasonality, duration and magnitude (flow regime) will support the key fauna and flora of the sites. Environmental water planning is guided by legislation and the supporting associated planning frameworks; predicted climate scenarios and water availability; and the results of long-term ecological monitoring programs.

LEGISLATION

The Water Act 2007

The Water Act 2007 (Cth) ('the Act') established the Murray-Darling Basin Authority (MDBA) (previously the Murray-Darling Basin Commission) with functions and powers to manage the water resources of the Basin. The Act requires the MDBA to prepare and oversee a Basin Plan — a legally enforceable document that provides for the integrated and sustainable management of water resources in the Basin.

The Basin Plan

The Basin Plan (MDBA 2012) guides governments, regional authorities and communities to sustainably manage and use the waters of the Murray-Darling Basin. The plan came into effect in November 2012 after an extensive period of consultation and development. The aim of the Basin Plan is to ensure that water is shared between all users, including the environment, in a sustainable way.

The Basin Plan provides direction not only on what water recovery is required, but also on the objectives and outcomes that should be achieved with this water.

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Part 2.8 of the Basin Plan outlines several specific objectives for the CLLMM. These relate directly to Murray Mouth openness (for salt export and Coorong water quality outcomes), and water levels in the Lower Lakes (to ensure discharge through the barrages, to prevent riverbank collapse in the Lock 1 to Barrages weir pool, and to avoid acidification). Other objectives that are significant for the CLLMM include the maintenance of ecological character for declared Ramsar wetlands; protection of the Bonn Convention, international migratory bird agreements, and other listed threatened species; water quality (in particular target salinity values); connectivity and resilience.

Basin Plan supporting documents

As a legislative document, the Basin Plan provides high-level direction on mechanisms, outcomes and governance, but relies on supporting documents to provide the detail around target species, regions and processes. The documents that provide guidance on the use of environmental water for the CLLMM are as follows:

Basin-wide environmental watering strategy

The Basin-wide environmental watering strategy (MDBA 2014a) guides environmental water holders and Basin governments in planning the management of environmental watering over the long term to meet environmental objectives. Importantly, the strategy describes specific environmental outcomes for the CLLMM that should be possible through broader water reforms associated with full implementation of the Basin Plan. These outcomes relate to populations of estuarine and diadromous fish, *Ruppia tuberosa*, waterbirds (in particular the migratory shorebirds curlew sandpiper, greenshank, red-necked stint and sharp-tailed sandpiper) and hydrology.

Basin annual environmental watering priorities

The Basin annual environmental watering priorities are developed by the MDBA each year, and guide the planning of environmental watering across the Basin by building on local, regional and state priorities. They aim to achieve the most effective use of environmental water, promote better environmental outcomes across the Basin, and coordinate watering between environmental water holders and water managers.

SA River Murray long-term environmental watering plan

The long-term environmental watering plan for the South Australian River Murray (DEWNR 2015) was completed in accordance with the requirements of the Basin Plan. It guides environmental water delivery to support the health of South Australian River Murray priority environmental assets, including the CLLMM. Eight ecological objectives and 29 nested ecological targets have been identified for the CLLMM. Four Environmental Water Requirements for the CLLMM are also described in the long-term environmental watering plan (Table 4.1.1), which brings together the annual barrage release volumes, return intervals, timing, water level and duration required to achieve optimal salinity regimes in the Lower Lakes (*sensu* Heneker 2010) and healthy ecosystem states in the Coorong (*sensu* Lester et al. 2011).

Table 4.1.1 Environmental Water Requirements for the CLLMM. (Adapted from DEWNR 2015 and O'Connor et al. 2015)

EWR #	Annual return interval (years)	Maximum interval (years)	Annual barrage flow (GL/year)	Barrage flow timing	Lakes water level range (mAHD)
CLLMM1	1-in-1	N/A	>650[1]	July-June, with peak barrage outflows in October-December	0.4-0.75
CLLMM2	1-in-2	N/A	>3 150[2]	July-June, with peak barrage outflows in October-December	0.4-0.83
CLLMM3	1-in-3	5	>6 000	July-June, with peak barrage outflows in October-December	0.4-0.83
CLLMM4	1-in-7	17	>10 000	July-June, with peak barrage outflows in October-December	0.4-0.9

[1] A total average barrage flow of 2 000 GL/yr over a three-year rolling period, i.e. not less than 6 000 GL over three years, and not less than 650 GL/yr in any one of the three years (Heneker 2010; Lester et al. 2011).

[2] A total average barrage flow of 4 000 GL/yr over a three-year rolling period, i.e. not less than 12 000 GL over three years, and not less than 3 150 GL/yr in any one of the three years (Heneker 2010; Lester et al. 2011).

ENVIRONMENTAL WATER MANAGEMENT

South Australian environmental water management

The planning, delivery, reporting and evaluation of environmental water within the Murray-Darling Basin in South Australia are coordinated by DEW in partnership with other government agencies including the MDBA, Commonwealth Environmental Water Office (CEWO), research organisations, non-government organisations and community groups.

Environmental water delivered within South Australia is primarily from two major environmental water holders: the Commonwealth Environmental Water Holder (CEWH) and The Living Murray (TLM) Initiative of the MDBA. The CLLMM is one of six designated 'icon sites' under the TLM Initiative (MDBA 2014b), meaning that the site is one of six wetlands that also has access to the TLM environmental water portfolio. At the time of developing this chapter (July 2018), the long-term average annual yield volumes of environmental water available in the southern connected Basin are 1 434 GL from the CEWH and 480 GL from TLM. These volumes are shared between all wetlands or assets in the southern connected Basin, and a proportion of the water may be carried over into the next water year, subject to operational rules and at the discretion of the water holders. These volumes will also vary in relation to resource availability, much as irrigation allocations are managed.

Additional environmental water for use in South Australia is available from the South Australian Minister for Water and the River Murray (up to 44 GL in a given year), donations from private irrigators, return flows from the Victorian Environmental Water Holder (VEWH) and from New South Wales from upstream environmental watering actions.

As such, the volumes required to achieve a healthy Coorong environment as described in South Australia's long-term watering plan (6 000-10 000 GL yr^{-1} delivered through the barrages every three and seven years respectively — Table 4.1.1), cannot be met by current environmental water portfolios. Significant volumes of unregulated flow are required to achieve target outcomes, particularly in the Coorong South Lagoon.

Basin-wide environmental water planning

Over recent years the total volume of environmental water available in the southern connected Basin has increased. To make the most of the delivery of environmental water, the Southern Connected Basin Environmental Watering Committee was established. This committee comprises Basin State and Australian Government environmental water holders, who manage planned environmental water, and key river operators. This group helps to ensure that environmental watering is coordinated, between water holders and river operators, to maximise environmental outcomes in the southern connected Basin.

Coordination is critical for aligning the needs of large upstream sites (such as Barmah-Millewa Forest and the Chowilla Floodplain) so that the return flows can be delivered to the CLLMM at appropriate times of the year. In this way, multiple ecological outcomes can be achieved with the same volume of environmental water.

Water availability scenario planning

When undertaking their planning, environmental water managers use a modelled scenario-based approach that takes into account the variety of possible future resource conditions (e.g. climate, storage levels and water availability). Water availability scenarios (or Annual Operating Probabilities — AOPs) are based on the averages of more than 100 years of flow data recorded in the Murray-Darling Basin (Fig. 4.1.1). Modelled flow scenarios (in megalitres per day) at the South Australian border provide the basis for managers to plan the best patterns of delivery of additional water.

Certain objectives and outcomes are achievable under different water availability scenarios in the CLLMM, in that only limited outcomes can be achieved under dry conditions, yet benefits to the entire CLLMM can be achieved under wet conditions. Under entitlement flow only (i.e. a dry water availability scenario), even with the addition of environmental water, only localised outcomes can be achieved in the Lower Lakes and parts of the Coorong North Lagoon. However, under wet conditions when a large volume of unregulated flow is received, environmental water can be strategically used to deliver outcomes to all parts of the wetland system, and in particular the Coorong South Lagoon. The objectives and actions outlined in Table 4.1.2 are typical of those developed annually by DEW when submitting annual environmental watering priorities to the major water holders.

Ecological monitoring

Long-term monitoring programs are critical to informing the development of annual environmental watering priorities. Water managers need to know which species, communities or processes are thriving and which are struggling, so that water delivery and barrage operations can be planned accordingly.

For the CLLMM, the TLM program funds long-term condition and intervention monitoring, which is designed to inform progress against a set of high-level ecological targets and

Table 4.1.2 Example objectives for the Coorong, Lower Lakes and Murray Mouth region, and the required timing of environmental water delivery to support these objectives, under different annual water availability scenarios.

Water Availability Scenario	Example objectives	Actions to be achieved with the addition of environmental water
Dry (90%) — River Murray entitlement flow	Provide seasonal wetting and drying in fringing Lower Lakes wetlands to enhance breeding and recruitment in threatened small-bodied native fish and frogs (Murray hardyhead, southern pygmy perch, Yarra pygmy perch, Southern bell frog).	Surcharge Lower Lakes in spring/early summer up to 0.85 mAHD. Autumn drawdown to a minimum of 0.5 m AHD.
	Maintain year-round connectivity between Lake Alexandrina and the Coorong estuary, to facilitate movement and recruitment of diadromous fishes.	Ensure, as a minimum, that all barrage fishways are operated year-round.
Moderate (75%) — small spring unregulated flow	Provide winter freshwater releases to the estuary and through the Murray Mouth to facilitate upstream lamprey migration and recruitment.	Larger barrage releases during June-August, with a bias from Goolwa. Where possible, water to be protected from source storages and tributaries to the barrages without reregulation, to protect olfactory cues.
	Extend the period of suitable salinity conditions in the Coorong North Lagoon in late spring to enhance migratory wader habitat and promote estuarine fish recruitment.	Additional flows added following a small unregulated flow event to extend the duration of higher barrage releases in spring/summer, with a bias from Tauwitchere barrage.
Near Average (50%) — moderate spring unregulated flow	Extend the period of suitable salinity and water level conditions in the Coorong South Lagoon through spring and summer, to promote *Ruppia tuberosa* growth and recruitment, and to extend suitable feeding habitat for estuarine fish.	Additional flows added following a moderate unregulated flow event to extend the duration of higher barrage releases in spring/summer, with a bias from Tauwitchere barrage.
Wet (25%) — large spring/early summer unregulated flow	During early autumn, reduce the salinity in Lake Albert and provide barrage flows to mitigate Coorong salinity following the reconnection of the North and South Lagoons in late autumn.	Undertake lake level cycling (water level manipulation facilitated by large volumes released from the barrages) to assist in the export of salt from Lake Albert, and the dilution of the South Lagoon.
	Provide flows to scour the Murray Mouth prior to the large unregulated flow event, to avoid the 'saturation' of the Coorong and flooding of mudflats, as a result of a constricted Murray Mouth and large volumes of water trapped in the Coorong.	Use water stored in the Lake to make large releases biased from Goolwa and Mundoo barrages, prior to the arrival of large unregulated flows.

objectives focused on fish, vegetation, waterbirds and hydrology (MDBA 2014b). Condition monitoring tracks trends in condition over time, while intervention monitoring determines the ecological response to management actions, such as environmental water delivery. These monitoring programs have recently undertaken a thorough statistical review, and the data collected can now populate specific quantitative indices (DEWNR 2017).

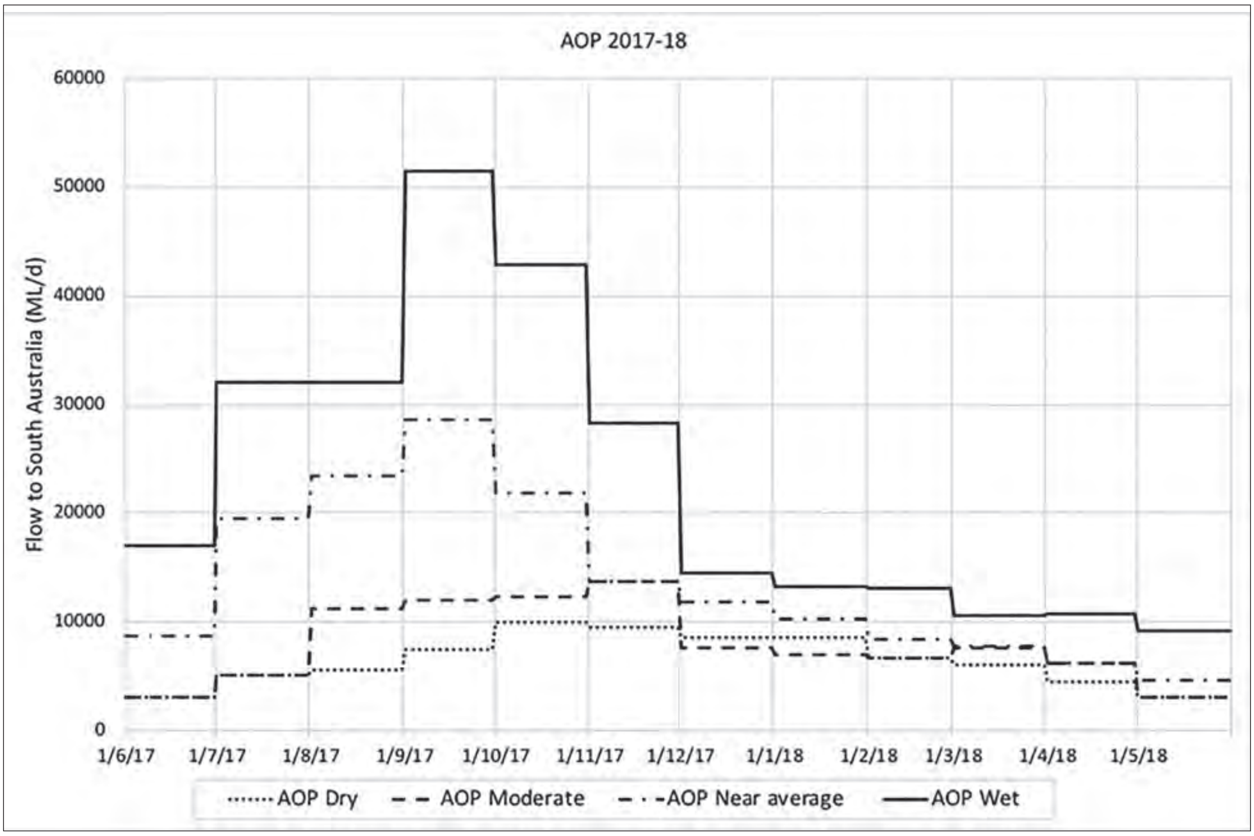

Figure 4.1.1 Annual Operating Probabilities for 2017/18 — the probability of receiving a predicted flow at the South Australian border as defined by dry (90%), moderate (75%), near average (75%) and wet (25%) conditions. (Based on data from MDBA)

Many of the targets and objectives developed through the TLM program align with those outlined in the Basin-wide environmental watering strategy (MDBA 2014a) and the South Australian River Murray long-term environmental watering plan (DEWNR 2015). As such, the TLM data collected can be used to report on and track progress against a number of initiatives, at both a state and federal level.

Condition and intervention monitoring programs can influence not only annual priority setting, but also real-time delivery of environmental water and specific barrage operations. In recent years, input from scientists assessing the flowering of the tuberous seatassel *Ruppia tuberosa* in the Coorong South Lagoon has influenced the decision to release more environmental water in an effort to sustain water levels and allow the plant to complete its life cycle. Similarly, in summer 2017/18, monitoring in relation to black bream recruitment informed which barrages to open and suitable flow rates to target, to create suitable salinity gradients conducive to spawning and recruitment.

Consultation

DEW seeks advice and feedback on environmental water use in the CLLMM from three key reference groups: the Community Advisory Panel, the Scientific Advisory Group and the Ngarrindjeri Regional Authority. Social, ecological and cultural considerations are critical in planning and implementing appropriate water resource management in the region.

Progress to date

Since the Millennium Drought ended in 2010, more than seven consecutive years of continuous barrage releases have been achieved, largely due to the delivery of environmental water. A river that flows to the ocean provides biological connectivity; salt export; nutrient and propagule transport; and cues for migration, spawning and recruitment. While some aspects of the ecology of the Coorong and Lower Lakes, such as the species *Ruppia tuberosa*, have shown only limited signs of recovery, other biota such as diadromous fishes have shown an immediate and highly positive reproductive response to continuous barrage releases, and to the delivery of water through barrage fishways.

The post-drought water management period has provided many lessons. While the volume of water delivered via the barrages has the greatest impact on the ecology, the timing, or seasonality of that delivery, is also highly critical. Water managers and scientists are also exploring the importance of the source of the water (i.e. water released from storages, via large upstream floodplain wetlands, upstream tributaries or local tributaries) and concepts such as longitudinal connectivity (i.e. protecting water from reregulation and keeping it 'green to the sea').

While much has been achieved over the last decade, water managers, scientists and the community must continue to work together and advocate for effective water delivery and management of the CLLMM.

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CHAPTER 4.2

THE HISTORY OF FISHERIES IN THE LOWER LAKES AND COORONG

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INTRODUCTION

Fishing has a long history as an important activity in South Australia's Lower Lakes and Coorong. Examination of middens has shown that finfish and shellfish have been important in the diet of Ngarrindjeri and other Aboriginal people in the Lower Lakes and Coorong for at least 10 000 years (Godfrey 1989; Luebbers 1978). Following European settlement, fishing has provided an important food resource for a growing human population. In a contemporary context, commercial, recreational and Indigenous fisheries continue to be important in this region and to complement agriculture, viticulture, manufacturing and tourism in supporting the regional population. The region is also a highly significant conservation area, with Lake Alexandrina, Lake Albert and the Coorong providing an important refuge for internationally significant migratory waders, as well as waterfowl and fishes of state and national concern (e.g. Murray hardyhead, *Craterocephalus fluviatilis*) and waterfowl. For this reason, the area was listed in 1985 as a 'wetland of international importance' (Phillips & Muller 2006), under the Convention on Wetlands (known as the Ramsar Convention and originally adopted in Ramsar in Iran in 1971).

The Lower Lakes and Coorong (LLC) is a small (975 km^2) water body, compared to the other major embayments in South Australia that support fisheries such as Spencer Gulf (~21 500 km^2 and 22 times larger) and Gulf St Vincent (~6 950 km^2 and 7 times larger) (Fig. 4.2.1). The region comprises an environmentally complex and highly dynamic aquatic system. In years when high flows occur in the River Murray, fresh water flows through Lake Alexandrina into the Murray estuary via a series of barrages, then out through the Murray Mouth, creating a plume into the eastern Indian Ocean.

Under the definition of Potter et al. (2010, p. 499), estuarine habitat occurs throughout the Coorong:

> An estuary is a partially enclosed coastal body of water that is either permanently or periodically open to the sea and which receives at least periodic discharge from a river, and thus while its salinity is typically less than the that of natural sea water and varies temporally and

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> along its length, it can be hypersaline in areas when evaporative water loss and freshwater and tidal influences are negligible.

In this chapter the Coorong is subdivided into three sections: Murray estuary and River Mouth, and the North and South Coorong Lagoons, all of which comprise estuarine habitat (Fig. 4.2.1).

Within this dynamic system, fish species that are important for commercial, recreational and Indigenous fisheries utilise a range of habitats in permanent freshwater lakes and marshes, seasonally flooded agricultural land, estuarine waters, coastal brackish/saline lagoons and adjacent marine waters. The abundance of fishes is highly variable over a range of temporal and spatial scales, because freshwater inflows, or their absence, and associated physical-chemical conditions (e.g. salinity) strongly influence available habitat, resource availability and spawning, and subsequent recruitment.

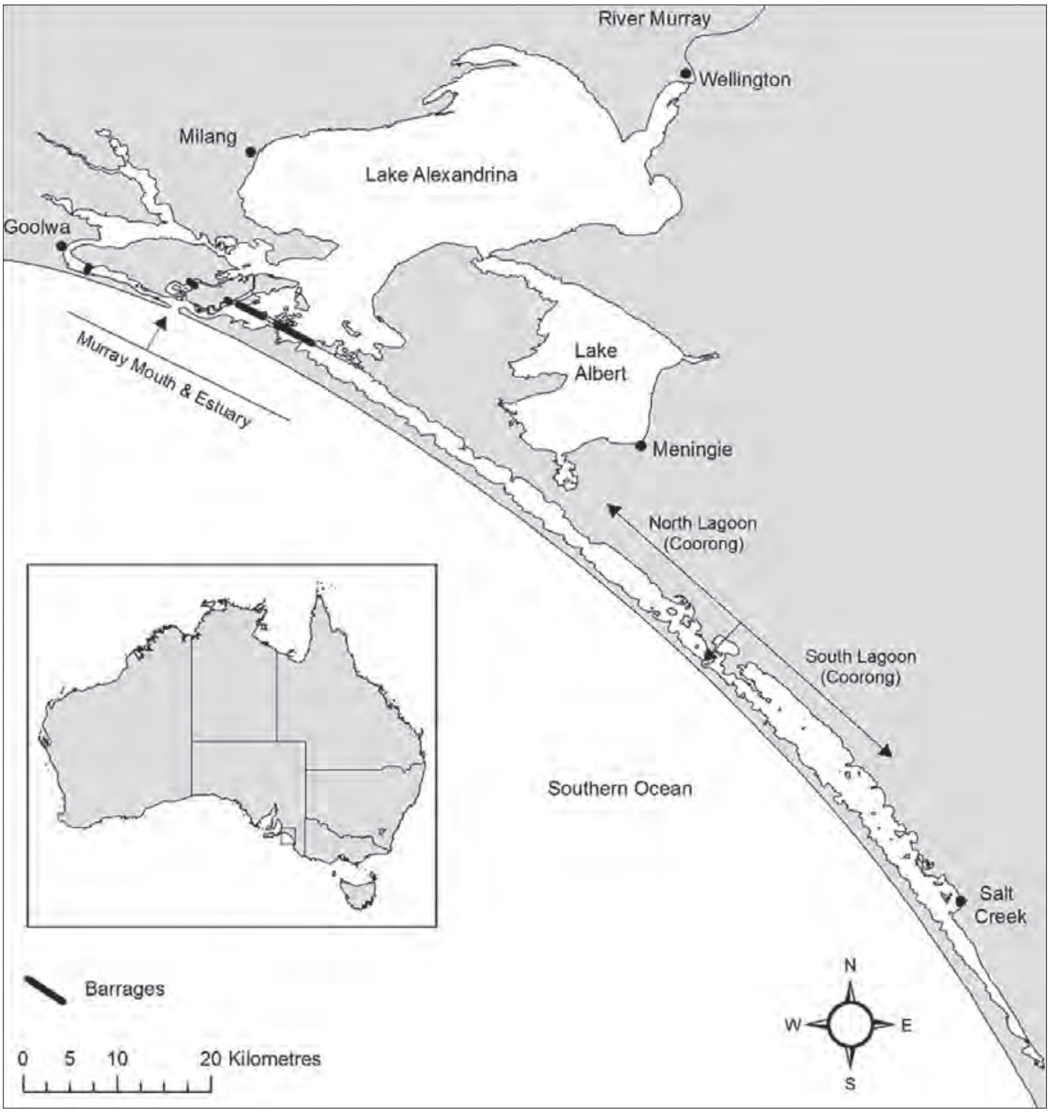

Figure 4.2.1 Map of Australia showing the location of the Lower Lakes and Coorong (inset). Main map shows the Lower River Murray Region including freshwater habitat in the River Murray and Lower Lakes (Lake Alexandrina and Lake Albert); estuarine habitat in the Murray estuary and Coorong lagoons; and nearshore marine habitat along the adjacent Southern Ocean beaches. Also shown are barrages separating freshwater and estuarine/marine habitats. (Map courtesy of Luciana Bucater, SARDI)

The commercial, recreational and Indigenous fisheries across the lower River Murray system are unique in South Australia because of the wide range of ecological values in the region and the close relationship between freshwater inflows and fishery production. These factors result in unique challenges for fishers, resource managers and researchers working toward sustainable use of the fishery resources.

This chapter reviews the available information on the Indigenous, recreational and commercial fisheries in the Lower Lakes and Coorong and describes

- their early and recent histories
- the factors influencing productivity of the fishery resources
- the life-history and fishery biology of key species supporting the fisheries
- approaches to sustainable exploitation of these species.

THE FISHERIES

Indigenous fishery

The physical character, natural resource base and overall health of the LLC harbours significant cultural and spiritual importance for the Ngarrindjeri people (Hemming et al. 2002). Throughout this region, traditional camp sites, meeting places, rock formations, burial sites and middens containing the remains of fish, terrestrial animals and pipi shells are found in higher numbers than elsewhere in Australia (Luebbers 1981). Radiocarbon dating of the bivalve mollusc pipi *Donax deltoides*, found in middens, suggested that use of fishery resources has occurred for the last 6 000-10 000 years, as Indigenous occupation of the southern Australian coast occurred (Luebbers 1981; Godfrey 1989). The number of Ngarrindjeri inhabiting this area prior to European settlement (in the early 1800s) is estimated at around 3 000 people.

The main species targeted by the Ngarrindjeri include mulloway, *Argyrosomus japonicus*; black bream, *Acanthopagrus australis*; greenback flounder, *Rhombosolea tapirina*; yelloweye mullet, *Aldrichetta forsteri*; and pipi (Ngarrindjeri Nation 2007; Disspain et al. 2015). In the Coorong, the Ngarrindjeri historically used an extensive array of techniques to harvest fish, including netting and baskets, spearing from canoes and watercraft (Berndt et al. 1993; Clarke 2002), along with the construction of intricate fish traps, some of which still exist today (Ross 2009). Each type of net in use was tailored to target a specific fish species. For example, nets with small mesh were used to target yelloweye mullet, while larger mesh was used to target bony herring, *Nematalosa erebi* (Clarke 2002). The Tangani group of the Ngarrindjeri people used haul nets to catch yelloweye mullet and mulloway in the Coorong (Clarke 2002). Following the arrival of Europeans, fishing with line and hook was also adopted (Gerritsen 2001).

Fishing was seasonal, with freshwater fish available from the River Murray through spring, summer and autumn when the river flows were low, while saltwater fish were caught mostly during summer through autumn to avoid winter storms (Berndt et al. 1993). Smoked and dried fish were stored and traded with people living in other Aboriginal settlements, along with commodities such as nets, clothing, baskets and mats (Jenkin 1979). Traditional fishing and food-gathering methods are currently practised by the Ngarrindjeri people, with the tradition passed on through Camp Coorong, which engages in cultural and traditional fishing for educational purposes.

Recreational fishery

Recreational fishing is a significant economic and social contributor to South Australian communities. By the 1950s, large numbers of recreational fishers were targeting Murray cod, *Maccullochella peelii peelii*, and a survey in 1982 found that almost 290 000 South Australians undertook some form of recreational fishing during the warmer months (Sims 1984; Wallace-Carter 1987). Between 277 463 and 317 223 South Australians engaged in recreational fishing each year, across three statewide surveys in 2000/01, 2007/08 and 2013/14, i.e. 16.2-23.3% of the population (Jones & Doonan 2005; Jones 2009; Giri & Hall 2015). In 2000/01, recreational fishing activities accounted for an expenditure of more than A$148 million (Jones & Doonan 2005). Across South Australia, annual recreational fishing effort ranged from 0.97-1.9 million days (Jones 2009). Fishing effort in the lower River Murray and LLC contributed c.11-12% of the total South Australian effort from 2007/08 to 2013/14 (Giri & Hall 2015). A decline in statewide participation and fishing effort in 2007/08, compared to 2000/01, was attributed to lower fishing effort in freshwater and estuarine habitats, due to the impacts of the Millennium Drought from 2000 to 2010 (Jones 2009).

Recreational fishers primarily use rod and line to target fish species in the freshwater, brackish and marine habitats of the LLC. In the Lower Lakes, fishers use rod and line to target the native golden perch, *Macquaria ambigua ambigua*, and the alien species common carp, *Cyprinus carpio*, and redfin perch, *Perca fluviatilis*. Mulloway, black bream, yelloweye mullet and Australian salmon, *Arripis truttaceus*, are targeted in the Murray estuary and Coorong lagoons with rod and line, while greenback flounder are caught with hand spears. Recreational fishers may also use registered gill nets to target yelloweye mullet.

During spring and summer, in years of high river flow, large mulloway aggregate in the freshwater plume that occurs in the nearshore marine environment adjacent the Murray Mouth (Hall 1986; Ferguson et al. 2008). These large mulloway are highly regarded as an 'icon' species by recreational fishers, who use heavy rod and line to target them in the surf zone. Also on the ocean beach, west of the Murray Mouth, hand gathering of pipi is a popular pastime for many recreational fishers.

Recreational fishing surveys in 2000/01, 2007/08 and 2013/14 have shown that the relative contributions of species comprising the recreational harvest in the River Murray system have changed over time (Jones & Doonan 2005; Jones 2009; Giri & Hall 2015). For freshwater species, estimates of recreational catch include all catches from the River Murray and the Lower Lakes. In all years, the total recreational harvest from the River Murray and LLC was dominated by freshwater species from the River Murray. The highest contributor to the recreational harvest was common carp, which contributed 44% of the harvest in 2000/01, increasing to 67% and 75% in 2007/08 and 2013/14, respectively (Fig. 4.2.2). Conversely, golden perch comprised 15% of recreational catches in 2000/01, decreasing to 10% and 6% in 2007/08 and 2013/14 respectively. It was estimated that most catches of golden perch were taken from the River Murray, with minor catches (0-2.5%) from Lake Alexandrina (Jones & Doonan 2005; Jones 2009). Similarly, Murray cod comprised 4% of the recreational harvest in 2000/01, with all catches from the River Murray. Catches of Murray cod were not reported in 2007/08 and this species has been protected since 2008/09.

Among estuarine-associated species, mulloway comprised 14% of the total South Australian recreational harvest (all species) in 2000/01 and 2007/08, declining to 9% in 2013/14 (Fig. 4.2.2). In 2000/01 and 2007/08, most mulloway harvested from the Coorong region were adults caught from the ocean beach (Jones & Doonan 2005; Jones 2009). The contribution to catches by yelloweye mullet followed a similar trend to mulloway, declining from 13% of the annual catch in 2000/01 to 3% in 2013/14. Black bream contributed 5% to recreational catches in 2000/01 and 1% in 2013/14. Many recreational anglers practised 'catch and release' fishing, with release rates varying among species: (i) silver perch, *Bidyanus bidyanus* (caught mainly from stocked dams, 100% released) (ii) black bream and mulloway (>70%) (iii) golden perch (51-70%) (iv) yelloweye mullet (10-30%) (v) greenback flounder (<10%) (Giri & Hall 2015).

The recreational harvest is an important component of the overall harvest (recreational and commercial catches combined) of several finfish species in the lower River Murray and LLC (Table 4.2.1). In freshwater habitats, the recreational harvest of golden perch was 28-35% of the total catch (i.e. commercial and recreational catches combined). The recreational harvest of common carp comprised 30-53% of the total catch, although this was partly due to the legal requirement preventing return of this species to the water. In the Murray estuary and Coorong lagoons, recreational angling comprised 40-62% and 58-82% of the overall harvest of mulloway and black bream respectively.

Commercial fishery

Historical

The multi-species, multi-method Lakes and Coorong Fishery (LCF) has accessed resources in freshwater, estuarine and adjacent marine habitats in the LLC since before 1846, when two fishers operated in the Coorong and Murray Mouth (Olsen & Evans 1991). Commercial fishing activities were stimulated by the development of the steamer-barge trade through the ports of Goolwa and Milang in 1853, and by completion of a rail link to Adelaide in 1885, with the number of fishers increasing to 30 in 1912 (Wallace-Carter 1987). In the late 1800s, the LCF contributed 11-14% of the state's annual catch, with increasing contributions in the early

Table 4.2.1 Estimated recreational catches for key species in the Lower Lakes and Coorong, including ocean beaches adjacent to the Murray River mouth from surveys in 2000/01, 2007/08 and 2013/14. Numbers in brackets are the percentage contribution to the total harvest by the recreational sector.

Species	2000/01	2007/08	2013/14
Golden perch	91.1 t (34.5%)	46.5 (28.4%)	37.4 8 (29.8%)
Murray cod	22.7 t		
Common carp	273.5 t (49.9%)	302 t (29.8%)	482.8 t (53.3%)
Redfin perch	10.1 t (28.8%)	2.0 t (6.5%)	2.0 t (20%)
Mulloway	90.2 t (39.8%)	61.7 t (61.7%)	59.5 (46.3%)
Black bream	31.9 t (82%)	5.9 (49.4%)	5.8 (80.6%)
Yelloweye mullet	82.9 t (40.8%)	27.6 t (10.1%)	19.4 t (9%)
Greenback flounder	0.2 t (1%)	0.25 t (11.2%)	0.27 t (21.2%)
Pipi	22.9 t (2.6%)	5.0 t (0.8%)	33 t (7.5%)

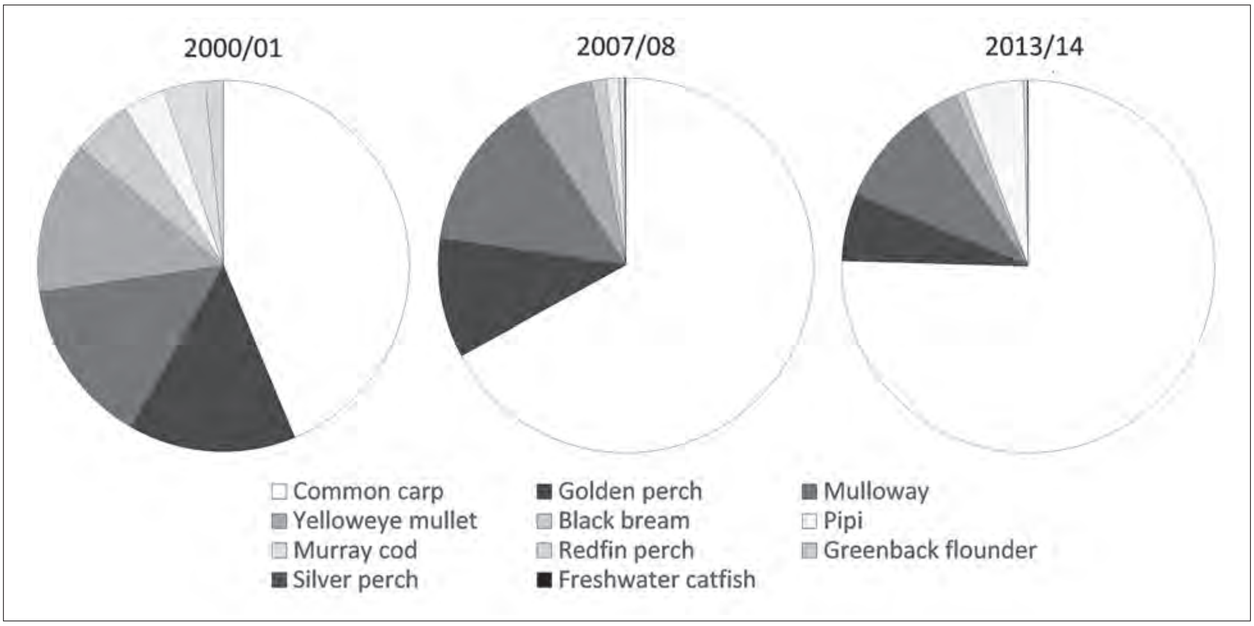

Figure 4.2.2 Proportional contribution by species from recreational catch surveys in 2000/01, 2007/08 and 2013/14. Note that catches of freshwater species include the River Murray and Lower Lakes. (From Jones & Doonan 2005; Jones 2009; Giri & Hall 2015)

1900s (29-58% during 1935-1939). The number of licensed LCF fishers reached a maximum of ~70 in 1930, before progressively declining to 13 fishers in 1970 due to a combination of enlistments and introduction of manpower regulations (Olsen & Evans 1991).

In the early- to mid-1900s, catches from the Lower Lakes and the lower River Murray consisted mainly of Murray cod, golden perch and bony herring, with smaller catches of silver perch, freshwater catfish (*Tandanus tandanus*), common yabby (*Cherax destructor*), and the alien species tench, *Tinca tinca*. Bony herring were commonly targeted for bait to supply the southern rock lobster fishery, while Murray cod and golden perch were considered high-quality table fish. Small quantities of congolli, *Pseudaphritis urvillii*, were also landed in the Lower Lakes and often kept alive for several weeks in sunken boxes before being used as live bait by fishers angling for large mulloway at the Murray Mouth (Noye 1974; Olsen & Evans 1991).

The composition of commercial catches in the Lower Lakes changed significantly in the 1970s, following the introduction of common carp to the Murray-Darling river system in the late 1960s (Koehn et al. 2000). From that time, catches of carp by the LCF increased rapidly and contributed ~42% of the total commercial catch (across all species) from the Lower Lakes in 1978/79. While bony herring remained a dominant fishery species through this period, the progressive expansion of carp populations throughout the lower River Murray and Lower Lakes occurred concurrently with declines in production for several native species including Murray cod, silver perch, freshwater catfish and the crustacean species common yabby.

Catches from the Murray estuary and Coorong lagoons in the early 1900s comprised mostly mulloway, yelloweye mullet, black bream, Australian salmon and greenback flounder (Wallace-Carter 1987). Mulloway, in particular, were taken in large quantities (e.g. ~600 t in 1938 and 1939), mainly for their swim bladders which were dried to produce isinglass for clarifying (fining) beer and stout (Olsen & Evans 1991). Salted fish was exported to Tasmania as early as 1936, making fish South Australia's first export commodity (Wallace-Carter 1987). Congolli were taken in small quantities in the estuary and Coorong (Olsen & Evans 1991), along with a range of other species including jumping mullet, *Liza argentea*; Australian herring (tommy ruff), *Arripis georgianus*; and the freshwater species bony herring displaced from Lake Alexandrina during river outflows (Noye 1974).

Gear used historically to target different species includes (i) set gill nets (mulloway, yelloweye mullet) (ii) drifter nets (golden perch, mulloway, yelloweye mullet and black bream) (iii) haul nets (golden perch, mulloway, yelloweye mullet, black bream), swinger nets (mulloway) (iv) ring nets (mulloway) (v) flounder nets (greenback flounder) (vi) floating long-line (line with hooks at regular intervals, used to target mulloway in the Murray mouth) (vii) drum nets (traps made of wire netting, congolli, golden perch) (viii) crosslines (long-lines set across a channel, Murray cod) (Wallace-Carter 1987; Olsen & Evans 1991).

Mesh and hauling nets have been in common use in the LLC since the early 1930s, accounting for most of the landings of mulloway, yelloweye mullet, tommy ruff and flounder (Olsen & Evans 1991). Prior to the 1950s, when nets were made of hemp or cotton, they were picked up daily, dried and then reset. After the 1950s, when nylon gill nets, which did not need to be dried each day, became available, fishing efficiency increased by a factor of 10 (Olsen & Evans 1991). Depending on target species and flow conditions, mesh nets can be set, using an anchor or post, or drifted.

Contemporary

The contemporary commercial LCF remains a small-scale, community-based fishery, with 36 licences (since 2006) targeting a range of species with a variety of gear types in freshwater, estuarine and marine waters across the LLC region. In Lakes Alexandrina and Albert, most catches (>95%) are taken using large mesh gill nets (115-150 mm stretched mesh) which are used to target golden perch, bony herring, common carp and redfin perch. In the Murray estuary and Coorong lagoons, large mesh gill nets (65% of total commercial effort) are used to target mulloway, black bream and greenback flounder. Small mesh gill nets (50-64 mm stretched mesh), which account for most of the remaining estuarine effort, are used to target yelloweye mullet. In the surf zone adjacent the Murray Mouth, a specialised mesh gill net, known as a 'swinger net' (>150 mm stretched mesh) is drifted out from the shore to target the spring/summer aggregations of large mulloway. In addition to finfish species, the LCF targets pipi on the ocean beach using handheld rakes.

Over the ~30 years from 1984/85 to 2014/15, average annual production from the LCF was ~2 007 t (Fig. 4.2.3). Production from the estuary remained relatively constant, contributing c.13-14% of total annual harvest, while the relative contributions from freshwater and marine habitats varied. For the 15-year period from 1984/85 to 1998/99, 70% of catches came from freshwater habitat, while 16% came from marine habitat. From 1999/2000 to 2014/15, the contribution from freshwater habitat fell to 53%, while that from marine habitat grew to 36%.

The alien species, common carp and redfin perch, contributed about half of the total catch from freshwater habitats in Lakes Alexandrina and Albert (long-term average 49%), with the highest contribution from common carp during the Millennium Drought from 2000 to 2010 (Fig. 4.2.4). Most other catches from the Lower Lakes were contributed by bony herring

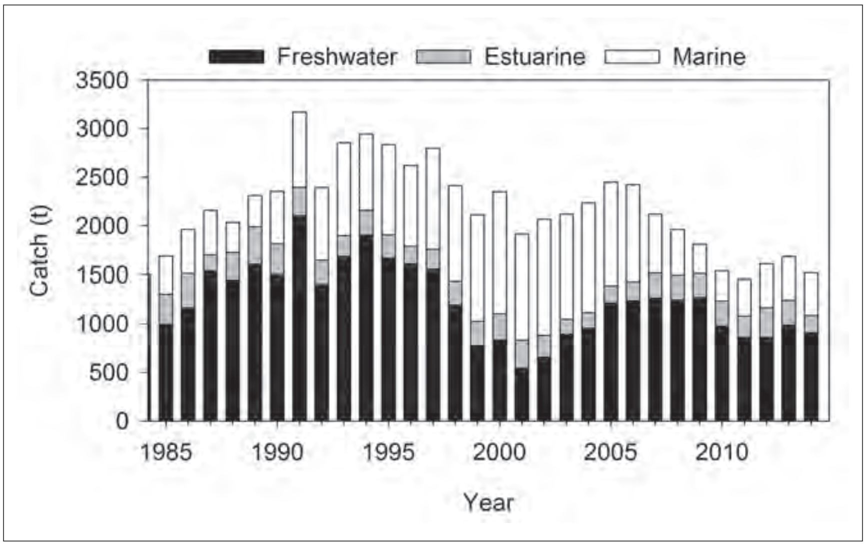

Figure 4.2.3 Annual production from the Lakes and Coorong Fishery (commercial) from Lakes Alexandrina and Albert (freshwater), the Murray estuary and Coorong lagoons (estuarine), and Coorong beach (marine). X-axis scale is in financial years, i.e. 1985 represents 1985/86.

(long-term average 47%), with smaller contributions from golden perch (long-term average 7%).

In the estuarine habitat of the Murray estuary and Coorong lagoons, catches were dominated by yelloweye mullet (long-term average 63%), with mulloway the next most important contributor (long-term average 16%; Fig. 4.2.4). The proportional contributions by yelloweye mullet and mulloway were inversely related, i.e. in years when catches of mulloway were high, those of yelloweye mullet were lower, and vice versa. In marine habitat, catches were dominated by pipi in all years, with small contributions by catches of mulloway (<5%) and yelloweye mullet.

Value

From 2005/06 to 2013/14, the contribution of the LCF to the state gross product ranged from A$15-20 million (Rippin & Morrison 2015). Of the A$20 million in 2013/14, A$5.2 million was generated directly by fishing, A$3 million by downstream activities (i.e. transport, business services, gear sales), and A$11.5 million by other sectors (i.e. trade, manufacturing) in the economy (Rippin & Morrison 2015). Total employment attributed to the LCF in 2013/14 was estimated at 153 full-time equivalent (FTE) jobs, with 40 FTE jobs generated directly by the fishery, 32 FTE jobs in downstream activities and a further 81 FTE jobs in other sectors in the economy.

In 2013/14, the Lower Lakes contributed 58% of the LCF total catch, with most of this comprising catches of the low-value species — common carp (25%) and bony herring (28%) (Fig. 4.2.5). While these species contributed more than half of the fishery harvest, they contributed a lower proportion (31%) of the total value. In contrast, also in the Lower Lakes, catches of the high-value golden perch contributed 5% of the total harvest, but 18% of the value.

Catches from the Murray estuary and Coorong lagoons contributed 16% to the total harvest in 2013/14, and 24% of the total catch value. Most catches from the Murray estuary

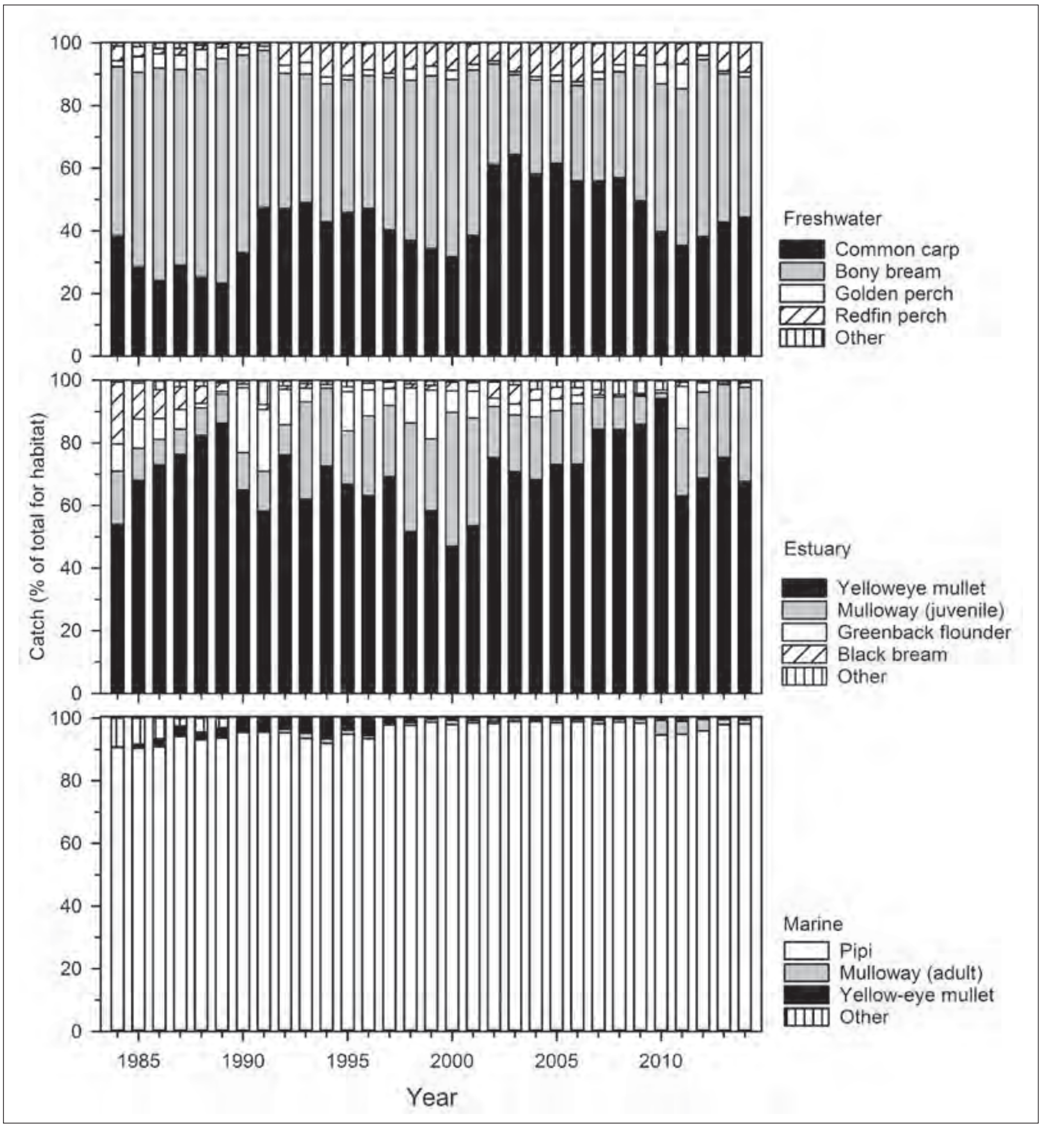

Figure 4.2.4 Percentage contribution by species to annual catches in freshwater, estuarine and marine habitats in the Lakes and Coorong Fishery. X-axis scale is in financial years, i.e. 1985 represents 1985/86.

and Coorong lagoons comprised yelloweye mullet (12% of the total catch), which contributed 13% to the total catch value. Mulloway comprised 4% of the total catch and contributed 10% to the value. In the marine environment, catches of pipi comprised 26% of the total catch and contributed 45% of the value. The high value of the pipi catch reflects the increasing proportion of annual catches that were supplied to the high-value human consumption market since the mid-2000s (57% in 2013/14), rather than the traditional bait market (Box 4.2.1; Ferguson et al. 2015).

THE ENVIRONMENT AND FISHERY PRODUCTION

Environmental influences on productivity

The flow regime of the River Murray strongly influences the fish population dynamics in the LLC. Significant droughts occurred in 1841, 1860, 1864, 1910 (with large incursions of saltwater and marine life into the LLC), 1914, 1943-1946 and during the disastrous drought

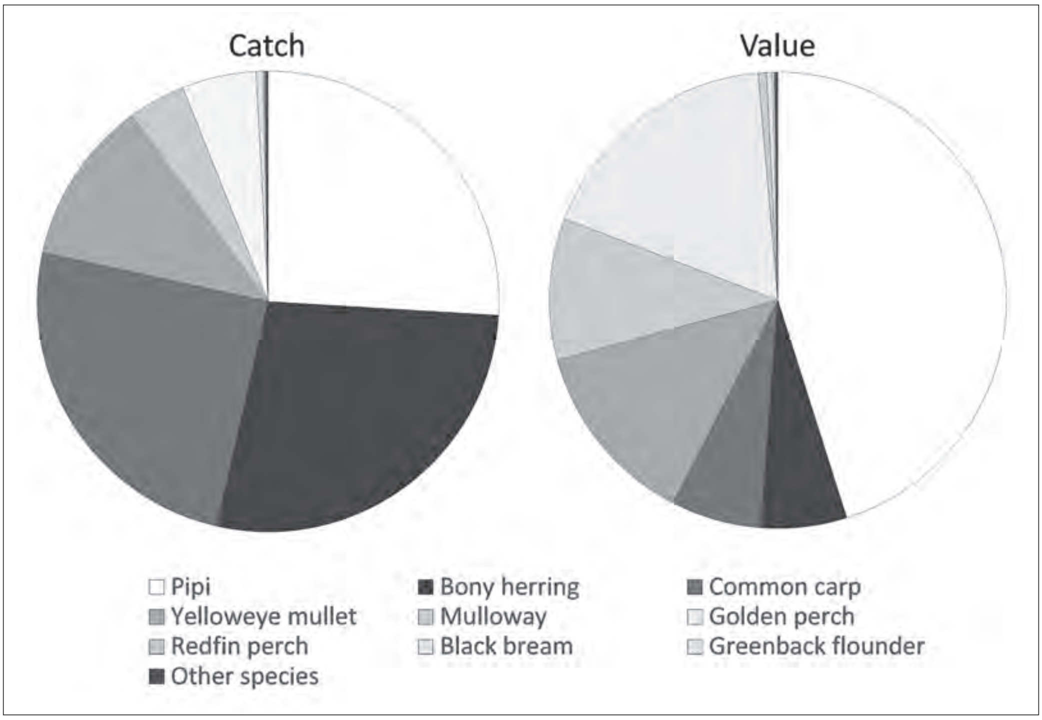

Figure 4.2.5 Distribution of commercial catch and value by species in 2013/14.

of 1964-1965 (Olsen & Evans 1991) and the Millennium Drought (2000-2010), which latter was the most severe drought since records began in the late 19th century (Leblanc et al. 2012; Van Dijk et al. 2013). Major flooding occurred in 1956, 1973-1974, 1996 (Olsen & Evans 1991) and 2010 (Leblanc et al. 2012). The River Murray has been extensively regulated to provide water for consumptive use and primarily irrigated agriculture, with average annual flow at the Murray Mouth now reduced by up to 61% (CSIRO 2008). The average period between the occurrence of flood events that are required to flush the Murray Mouth and help sustain ecosystems in the Lower Lakes, Murray estuary and Coorong lagoons has almost doubled, with the extent and frequency of the natural spring floods reduced and the River Murray ceasing to flow through the mouth 40% of the time, compared to 1% under natural conditions (CSIRO 2008). Such anthropogenic alterations to the flow regime have had a generally negative impact on the overall health of the LLC, and abrupt changes to salinity levels, temperature and other factors can affect the overall water quality in the Murray estuary, which disrupts the natural reproductive cycles and movement patterns of many fish species. The net result of these factors and other external impacts on the fishery is that varied and acute pressures are placed on fish stocks and their supporting ecosystem, particularly during periods of drought (PIRSA 2016).

Freshwater inflows from the River Murray influence water levels, salinity and connectivity among habitats, which in turn influence the dynamics of fish populations in the LLC. Freshwater inflows affect fishes through three mechanisms: (i) by changing the area of favourable habitat and the connectivity among those habitats (e.g. River Murray and Lower Lakes; Lower Lakes and Murray estuary/Coorong lagoons; Murray estuary/Coorong lagoons; and open ocean) (ii) by influencing productivity (iii) by influencing critical life-history processes (e.g. spawning and/or recruitment) for some species.

BOX 4.2.1 FISHERY BIOLOGY OF PIPI, *DONAX DELTOIDES*

Surf clams, from the family Donacidae, support fisheries worldwide. In Australia, the pipi, *Donax deltoides*, is found along the south coast from Eyre Peninsula to Kingston in South Australia, from Victoria through Tasmania, and on the eastern coast to Fraser Island in south-eastern Queensland (King 1985; McLachlan et al. 1996). One of the most productive populations of pipi in Australia occurs on the ocean beaches of the Coorong and supports commercial, recreational and Indigenous fisheries.

Pipi are a highly productive fishery species due to their fast growth, early maturity and high fecundity. In South Australia, pipi reach sexual maturity at 28 mm when they are 12-18 months old. Spawning occurs in spring-summer with a peak in October-November (Ferguson 2013) with larvae spending approximately two weeks in the water column before settling onto sandy habitat (Gluis & Li 2014). Juvenile pipi grow rapidly, reaching 12-15 mm in their first year and 25-30 mm the following year, with a maximum size of 55-60 mm at approximately 3-4 years.

The pipi resource on Younghusband Peninsula supported annual catches in excess of 1 000 t from 1999/2000 to 2005/06. From 2005/06, catches rapidly declined and there was a sequential decrease in the proportion of large pipi in the population, suggesting that the resource was over-exploited (Ferguson et al. 2015). From 2009/10, annual catches were constrained by conservative total allowable commercial catches (TACC) which, combined with the successful recruitment and growth of those recruits, allowed the stock to rebuild. From the mid-2000s, an increasing proportion of the catch has supplied the high-value human consumption market, increasing the value of the fishery while catches remain low compared to the historical peak.

Although pipi are highly productive, sustainable management of these fisheries is challenging due to the 'r-strategist' life-history which is characterised by high variability in recruitment and mortality and a short lifespan (McLachlan et al. 1996). Sustainable exploitation of the resource requires well-informed, conservative management. Since 2007/08, management of the fishery has been informed by fishery-independent (research) estimates of the available biomass and sizes of pipi with conservative TACCs set using a harvest strategy framework which aims to maintain the pipi biomass at a conservative level. Additionally, a legal minimum size is in place to allow pipi to spawn at least once prior to harvest.

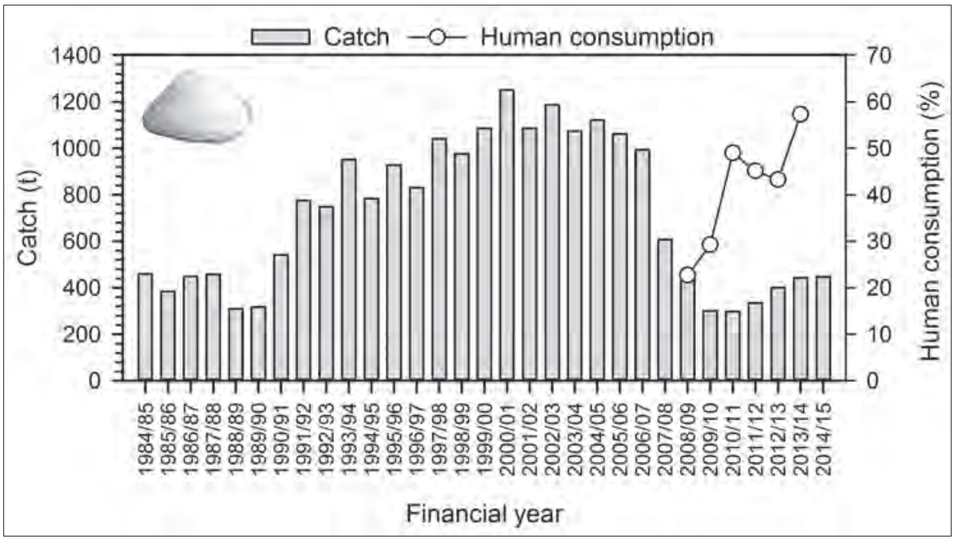

Figure 4.2.6 Historical catches of pipi from 1984/85 to 2014/15. From 2009/10 to 2014/15 the catches were constrained by the annual total allowable commercial catch. Also shown is the percentage of the catch that was sold to the high-value human consumption market from 2008/09 to 2014/15.

The relative levels of production for key fishery species have fluctuated considerably between years in relation to changes in the environment (Ferguson et al. 2013). Variation in the timing, magnitude and duration of freshwater inflows to the system drives changes in the water levels in the Lower Lakes and to salinity and turbidity in the Murray estuary and Coorong lagoons, which directly influence the quality and size of the area available for fish to occupy within the spatial constraints of the fishery (Ye et al. 2013). The connectivity between the Coorong and the sea is important to the fishery's success, as access through the Murray Mouth is critical for the movement of mulloway, yelloweye mullet and greenback flounder, and many other marine or estuarine species.

Freshwater inflow significantly affects fish assemblage structure, recruitment and abundance in the Murray estuary and Coorong lagoons, with salinity a key determinant of the distribution and abundance for fish (Zampatti et al. 2010; Ferguson et al. 2013; Ye et al. 2015) and prey species such as macro-invertebrates (Dittmann et al. 2015). The Murray estuary and Coorong lagoons rely on freshwater flow from the River Murray to maintain the salinity gradient that contributes to a range of aquatic habitats required to support a variety of fish and invertebrate communities. During low-flow periods, salinity increases and the habitable area for fish and prey contracts toward the Murray Mouth (Zampatti et al. 2010; Ferguson et al. 2013; Dittmann et al. 2015). Conversely, during inflows the area of low salinity increases and the spatial extent of fish and prey habitat increases.

The export of nutrients from rivers to estuaries is a key driver of coastal productivity (Gillanders & Kingsford 2002). Productivity in the Murray estuary and Coorong lagoons is influenced by changes in freshwater inflows from the River Murray, which affect the way that resources are delivered and modify the salinity regime (Brookes et al. 2015). Low flows decrease nutrient input to the estuary, and increased salinity changes the distribution and abundance of organisms, affecting the transfer of nutrients through the food web (Brookes et al. 2015). In general, as freshwater inflows decrease, salinity increases and the system generally becomes less productive (lower nutrient concentrations and loads, lower chlorophyll and primary productivity), with a concurrent decrease in abundance of organisms and overall biodiversity of the fish community (Ye et al. 2015).

The commercial fish species in the Murray estuary and Coorong lagoons have varying spawning cues, habitat preferences and food resources, all largely impacted by flow (Ferguson et al. 2008, 2013; Brookes et al. 2015). In particular, increased freshwater flow facilitates recruitment and increased abundances of commercially important estuarine species (e.g. black bream); marine and estuarine opportunist species (e.g. greenback flounder and mulloway); diadromous species (e.g. congolli and common galaxias, *Galaxias maculatus*); and 'small pelagic fishes' (e.g. sandy sprat, *Hyperlophus vittatus*) that form important trophic links in estuarine/marine ecosystems (Bice et al. 2016b).

Life-histories and habitat use of key species

The life-history of a fish population determines its response to environmental drivers; consequently, it is fundamental to fisheries management (King & McFarlane 2003). There are a range of life-history strategies among the key fishery species in the LLC (Fig. 4.2.7).

Periodic strategists have a life-history characterised by lower growth rates, high longevity, large body size and late maturity, allowing them to maximise lifetime fecundity, i.e. egg

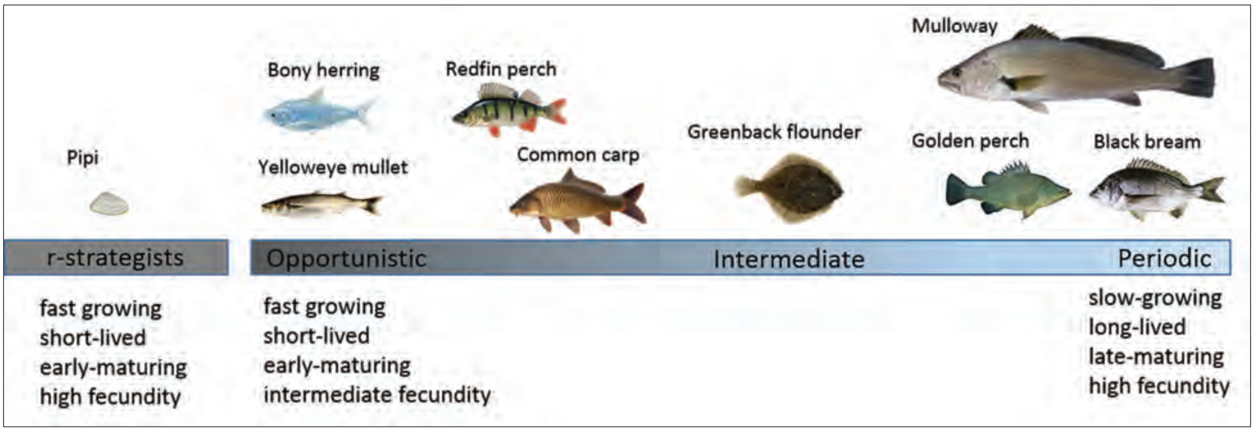

Figure 4.2.7 Life-history strategies of key fishery species in the Lower Lakes and Coorong. Periodic strategists: mulloway, black beam and golden perch; opportunistic strategists: common carp, bony herring, yelloweye mullet and redfin perch; and the r-strategist: pipi.

production (Winemiller & Rose 1992). Examples of periodic strategists are golden perch, mulloway and black bream. These large-bodied species have relatively low growth rates; they mature at a large size and age; and they have high longevity compared to many other species (Table 4.2.2). Such species require favourable environmental conditions to establish infrequent strong year classes. For example, mulloway has delayed maturity (5-6 years), large body size (138 cm), high longevity (41 years) and a prolonged juvenile stage that requires protected juvenile habitat in estuaries and inshore reefs (Ferguson et al. 2013; and see Boxes 4.2.2 & 4.2.3 for examples of periodic and intermediate life-history strategies). For species with periodic life-history strategies, responses to changes in productivity in the LLC may be complex, and increases in adult biomass following freshwater inflows and favourable environmental conditions may not occur for several years following the improved environmental conditions.

Opportunistic strategists are typically small-bodied, rapidly maturing and short-lived fishes (Winemiller & Rose 1992) (Fig. 4.2.7). Species such as bony herring and yelloweye mullet have high growth rates; they mature at a small size and age; and they spawn annually with less dependence on favourable environmental conditions than periodic strategists (Table 4.2.2). Although the alien species, common carp and redfin perch, may have life-histories that are consistent with a periodic strategy in their countries of origin (Bergerot et al. 2015), in the Lower Lakes they are able to spawn and recruit annually, which is more consistent with an opportunistic life-history strategy. Yelloweye mullet is a habitat generalist with an opportunistic life-history strategy including early maturation (2 years), small maximum size (27 cm) and low longevity (4 years). This highly productive species has contributed more than half of all catches from the Murray estuary and Coorong lagoons over the last 31 years.

The life-history of the bivalve mollusc pipi includes rapid growth, early maturity and low maximum age (Table 4.2.2; Fig. 4.2.7). Such highly productive species are described as having an r-strategist life-history (Table 4.2.2; Fig. 4.2.7; Box 4.2.1). A characteristic of r-strategist species, which include other sandy beach bivalve species, is high variability in recruitment and abundance. Such fluctuations have been observed for pipi in the Coorong region of South Australia but the reasons for these fluctuations are poorly understood.

Table 4.2.2 Functional groups and life-history strategies of key fishery species in the Lower Lakes and Coorong. Functional groups: (F) freshwater, (FEO) freshwater estuarine opportunist, (MEO) marine estuarine opportunist, (E) estuarine, and (M) marine. Life-history strategies: (P) periodic strategist, (O) opportunistic strategist, (r) r-strategist. Alien species identified with (a). Where available, estimates of life-history parameters are for populations from the Lower Lakes and Coorong (i.e. golden perch, mulloway, black bream, greenback flounder, yelloweye mullet and pipi). For other species, information was obtained from relevant sources. Life-history parameters: SAM_{50}, size at which 50% of individuals are mature; AAM_{50}, age at which 50% of individuals are mature; *k* and Linf are parameters of the von Bertalanffy growth equation representing, respectively, the intrinsic rate of growth and asymptotic (i.e. average maximum) size of the species.

Species	**Habitat functional group**	**Life-history strategy**	**SAM_{50} (cm)**	**AAM_{50} (years)**	**Max. age (years)**	**Max. size (cm)**	***k***	**L_{inf}**
Golden perch	F	P	40	4-5	26	-	0.25-0.45	76
Common carp (a)	F	O	27.3-32.8	1.4-2.7	32	120	0.38-0.48	120
Redfin perch (a)	F	O	16.8	3-4	22	60	0.19-0.24	25-35
Bony herring	FEO	O	10.8	1-2	3	48	-	48
Black bream	E	P	28.9	1.9-4.3	29	54	0.04-0.08	54
Mulloway	MEO	P	78-85	5-6	41	143	0.14	138
Greenback flounder	MEO	O/P	19.8	1	4	39	0.09	35
Yelloweye mullet	MEO	O	24.2	2	4	29	0.08	22.7
Pipi	M	r	2.8	1.8	4.5	6	0.99	6.0

BOX 4.2.2 FISHERY BIOLOGY OF MULLOWAY, *ARGYROSOMUS JAPONICUS*

Mulloway, *Argyrosomus japonicus*, is associated with estuaries and inshore waters throughout the Indo-Pacific (latitudes 40°N-39°S) including the temperate coasts of Australia. In South Australia, separate populations of mulloway occur on the western and south-eastern coasts (Ferguson et al. 2011; Barnes et al. 2015) with the south-eastern population occurring at the southernmost part of the species' global distribution (Ferguson et al. 2013).

Mulloway have a periodic life-history strategy characterised by large maximum size (>138 cm), high longevity (41 years) and delayed maturity at a large size and age (c.85-100 cm, 5-6 years) (Ferguson et al. 2008, 2013). The extended lifespan allows them to survive long periods of sub-optimal environmental conditions, while large body size allows large numbers of progeny (high fecundity) to be produced when environmental conditions are suitable for successful reproduction and recruitment. Delayed maturity and a prolonged juvenile stage likely evolved under conditions of low natural mortality of juveniles (Griffiths 1996). For mulloway in south-east South Australia, low natural mortality of juveniles is achieved through their marine-estuarine opportunist habitat association, with juveniles using protected estuarine habitat within the Murray estuary and Coorong lagoons before migrating into nearshore marine habitat when they reach sexual maturity.

For the population of mulloway in south-eastern South Australia, periodic strong year classes are associated with successive years of high freshwater inflows to the Murray estuary and Coorong lagoons (Ferguson et al. 2008). During spring/summer, large, mature mulloway aggregate to feed in the freshwater plume from the River Murray, with spawning also occurring during this period. Larvae develop rapidly in the marine environment and use the freshwater plume to locate protected habitat with small juveniles (<5 cm) found in the estuary from March onwards. Freshwater input to the Murray estuary and Coorong lagoons generates a salinity gradient and increased turbidity. Low salinity provides small juveniles (<40 cm) with protection from predation by adult mulloway and other species, while increased turbidity is associated with the production of prey species such as mysid shrimp and amphipods (Giatas & Ye 2016). Larger juveniles (>40 cm) are an apex predator in the Murray estuary and feed on yelloweye mullet; sandy sprat, *Hyperlophus vittatus*; smallmouthed hardyhead, *Atherinosoma microstoma*; congolli; bony herring; gobies; and crabs (Giatas & Ye 2015).

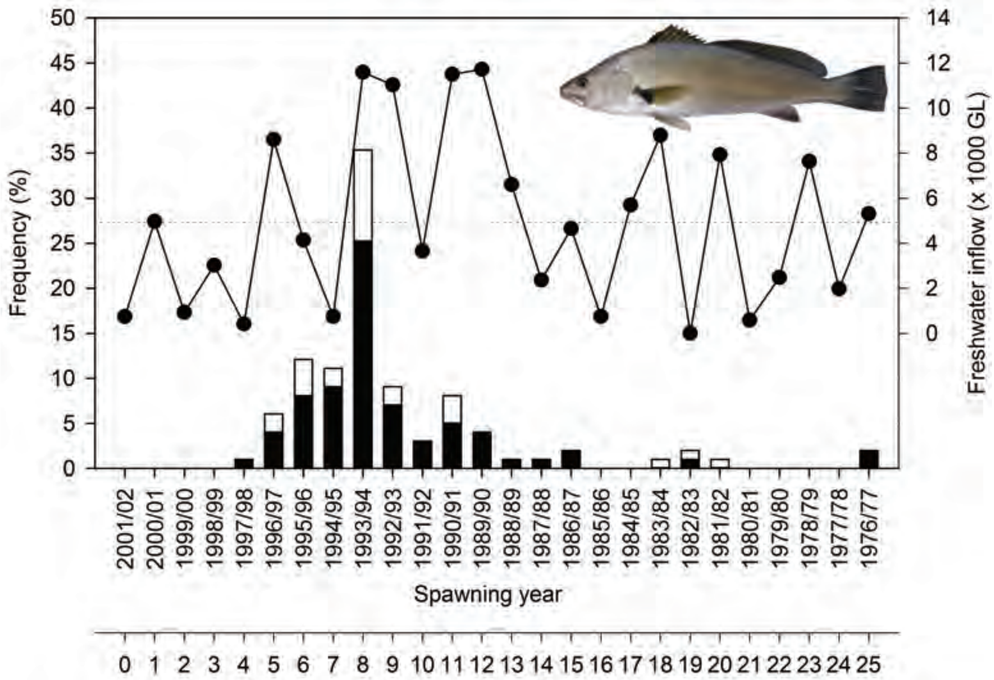

Figure 4.2.8 Age class strength for mulloway from commercial (black bars, n = 73) and recreational (white bars, n = 26) catches taken near the mouth of the River Murray in 2001/02. (Data from commercial and recreational catches were from the same distribution and were combined.) The outer x-axis shows age classes and the inside x-axis shows the spawning year for each age class. Superimposed are the annual freshwater inflows (black line and dots, courtesy of the Murray-Darling Basin Authority) and long-term average inflows (dotted line) to the Murray estuary and Coorong lagoons during the spawning year.

The key species in the commercial, recreational and Indigenous fisheries of the LLC region include representatives of several habitat use guilds (Table 4.2.2). The freshwater straggler guild includes species that occupy truly freshwater environments and only sporadically enter estuaries in low numbers (Potter et al. 2015). Such species that occur in the Lower Lakes include Murray cod, golden perch, redfin perch and common carp. The freshwater-estuarine opportunist guild is composed of freshwater species that commonly use estuarine habitats, often in substantial numbers, and is represented by bony herring. The solely estuarine guild refers to species whose reproduction is confined to estuarine habitats and includes black bream. The marine-estuarine opportunist guild includes marine fishes that enter estuaries regularly in substantial numbers

BOX 4.2.3 FISHERY BIOLOGY OF GREENBACK FLOUNDER, *RHOMBOSOLEA TAPIRINA*

Greenback flounder, *Rhombosolea tapirina*, is the most common flatfish in Australian waters (van den Enden et al. 2000), occurring in estuaries and marine waters along Australia's southern coast, as well as in New Zealand. Throughout their range, large greenback flounder are found over unvegetated substrates to depths of 100 m, while juveniles prefer sandy, sheltered inshore habitats (Jenkins et al. 1997).

Greenback flounder has an intermediate life-history strategy characterised by medium size (max. length 50 cm), moderate longevity (10 years; Sutton et al. 2010), fast growth (Earl et al. 2014), high fecundity and early maturity (~1 year, ~21 cm; Earl 2014). For the population in SE South Australia, the Murray estuary and Coorong lagoons provide important nursery habitat during the first 2-3 years of life. Because greenback flounder within the Coorong are mostly <3 years old and the species is known to live up to 10 years, it is likely that emigration to the ocean occurs around this age (Earl et al. 2014). Acoustic tagging of adult greenback flounder has shown that this species undertakes movements up to tens of kilometres between the North Lagoon and Southern Ocean (Earl et al. 2017).

The abundance and distribution of greenback flounder in the Murray estuary and Coorong lagoons are strongly influenced by the availability of estuarine habitat with favoured salinities, i.e. the area influenced by freshwater inputs where a salinity gradient of 20-40 ppt occurs (Earl 2014). Under consistent seasonal flows, extensive areas of estuarine habitat support high densities of greenback flounder, particularly in the North Lagoon (Earl & Ye 2016). Conversely, during drought, greenback flounder is restricted to areas adjacent the Murray Mouth, because it is unable to tolerate the high salinities in the lagoons (Ye et al. 2013). Spatial contractions of suitable habitat in the estuary likely force a proportion of the population to utilise alternative habitat in the marine environment. This environmentally driven variability in population size is reflected in the high inter-annual variation in fishery production for this species (Earl & Ye 2016).

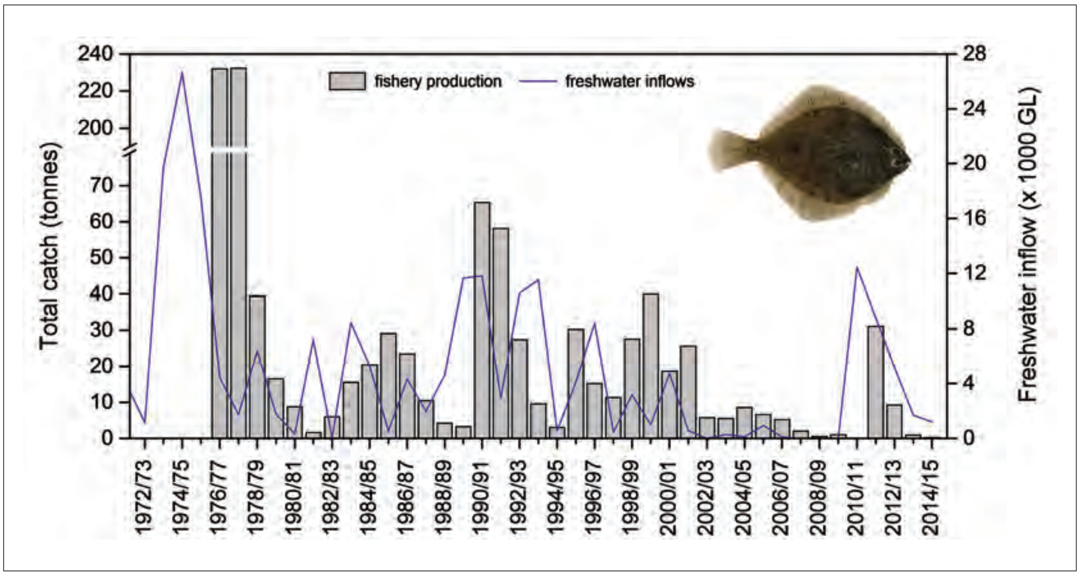

Figure 4.2.9 Figure showing total annual commercial catches of greenback flounder from the Murray estuary and Coorong from 1976/77 to 2014/15. Estimates of total catch are not available for years prior to 1976/77. Superimposed are annual freshwater inflows to the Murray estuary and Coorong from 1972/73 to 2014/15. (Courtesy of the Murray-Darling Basin Authority)

and often as juveniles. These species are also able to use marine waters as alternative nurseries (Potter et al. 2015), and include mulloway, yelloweye mullet and greenback flounder.

MANAGEMENT OF THE FISHERIES

The State Department of Primary Industries and Regions South Australia (PIRSA) is responsible for managing fisheries resources on behalf of the community. The aim of fisheries management is to ensure that harvests are sustainable — which requires a balance of biological, environmental, social and economic factors. In South Australia, sustainable resource management is supported by the *Fisheries Management Act 2007*. Under this Act, the Management Plan for the LCF allocates fishery resources among the commercial, recreational and Indigenous sectors, and describes the management tools that are available for sustainable management of the resources (PIRSA 2016). Each of the fishery sectors is managed with a combination of input (limiting fishing effort) and output (limiting harvest) controls, which vary depending on the particular fish species and the areas where they occur. These controls are determined through a consultative process between industry and other stakeholders, fisheries managers and fisheries scientists.

Indigenous and recreational fisheries

Early management of the recreational fishery was achieved under the *Fisheries Act 1917*, which introduced controls on recreational fishing in closed waters, including a ban on the use of dynamite, and the later introduction of size limits and the requirement for undersized fish to be returned to the water (Wallace-Carter 1987). Current management controls on the recreational sector include limitations on the type and amount of fishing gear, spatial and temporal closures, legal size limits for individual species (which are consistent with those in place for the commercial sector), as well as daily bag and boat limits for individual species. Gill nets may also be used by recreational fishers in the LLC. Recreational nets have small meshes (50-64 mm stretched mesh), with numbers limited to ~692 registered nets in 2014. The Indigenous fishery is able to harvest fishery resources from the Lower Lakes, Murray estuary and Coorong lagoons, and is subject to the same regulations as the recreational fishery.

Commercial fishery

The Management Plan for the South Australian commercial LCF provides a strategic policy framework for the management of the fishery (PIRSA 2016). Key components of the Management Plan are the harvest strategies for finfish and pipi. In its simplest form, a harvest strategy provides a structured framework to guide fishery management decision-making processes (Sloan et al. 2014). The implementation of a harvest strategy ensures that fishery managers, fishers and key stakeholders document how they will respond to various fishery conditions (desirable or undesirable) before they occur (Sloan et al. 2014). Typically, a harvest strategy has a number of biological performance indicators that trigger predetermined management action, which is directed by decision rules when the fishery falls below established biological reference points.

The LCF harvest strategy for finfish is unique in that it aims to manage sustainable exploitation in line with environmental conditions. Because environmental processes play a significant role in the production of finfish species in the LLC, the harvest strategy includes performance indicators based upon the amount of available habitat for these species, which is linked to fishery production. In the Lower Lakes, the area of available habitat for golden perch is represented by the mean annual water level (metres, Australian Height Datum, AHD) in Lake Alexandrina. When the water level declines below one of a set of predefined levels (target, trigger or limit reference points) in a particular year, the total allowable commercial effort (TACE) is reduced in the following year (i.e. the number of fishing nets available to the fishery is reduced for that year).

In the Murray estuary and Coorong lagoons, the area of available habitat for mulloway and yelloweye mullet is represented by the area of favourable salinity for each species, based on salinity tolerances established through field and laboratory observations (Ye et al. 2013). Estimates of salinities in the Murray estuary and Coorong lagoons are provided by a hydrodynamic model (Webster 2010). In years when the area of available habitat is reduced below the target, trigger or limit reference points in the harvest strategy, the TACE is decreased in the following year. Conversely, when freshwater inflows from the Murray River result in increased area of habitat, and thus increased production for these key species, the TACE is increased.

The harvest strategy for pipi differs from that for finfish, by being based on the results of fishery-independent surveys. To determine sustainable levels of harvest for pipi, researchers and fishers work together to conduct three surveys each year. These surveys provide two indicators of the biological status of the stock: relative abundance of pipi (the weight of pipi that can be caught in a given area), and whether recruitment has occurred that year (based on the presence of small juveniles). The harvest strategy uses these indicators to recommend a biologically acceptable total allowable commercial catch (TACC) for the following year. A third economic performance indicator is then used to analyse economic returns over a range of sustainable TACCs. From 2012/13 to 2016/17, this process resulted in four out of five TACCs being significantly lower than the maximum biologically acceptable TACC.

The LCF held third-party accreditation under the Marine Stewardship Council's sustainable seafood certification program during the period from 2008 to 2015. Golden perch, mulloway, yelloweye mullet and pipi were assessed under this program. The LCF is currently undergoing reassessment for certification of golden perch, mulloway and yelloweye mullet. In 2016, the LCF for pipi was reassessed independently of the finfish species and has been recertified. The accreditation of the fishery under the MSC assessment framework has provided improved opportunities for commercial fishers to increase domestic and overseas market demand for species harvested by the fishery.

RESEARCH

Scientific research is fundamental to fisheries management, and research into the fishery resources and environmental health of the LLC has been conducted since 1991 by the South Australian Research and Development Institute (SARDI). Other key research is conducted by CSIRO and by the state's universities for state and federal government research programs administered by the Murray-Darling Basin Authority, Department of Environment, Water and Natural Resources, and others.

SARDI (Aquatic Sciences) is the principal government fisheries research agency and provides assessments of the fishery resources in the LLC. Key advice to PIRSA (Fisheries and Aquaculture) to support ecologically sustainable development of fisheries resources is primarily funded by the Government's 'cost recovery' policy, whereby commercial licence fees are set at a level to cover management costs. Scientific outputs include (i) stock assessment reports for key fishery species, which analyse commercial catch and effort data and key demographic information (ii) brief annual fishery statistics reports (iii) detailed studies of life-histories, ecology and population dynamics of a wide range of fish species.

Assessment of fishery status relies heavily on fishery catch and effort data. Since 1 July 1984, fishers have been required to provide daily catch and effort data to SARDI on a monthly basis. These data include fishing location, targeted species, species caught, catch weight, fishing gear used and fishing effort (days, nets). Estimates of catches and catch per unit effort (CPUE) are used as a proxy for abundance in stock assessments of exploited species. In addition to fishery-dependent data, fishery-independent studies provide supplementary information on life-history (such as growth rates, age and size at maturity, movement, habitat use and demographic information), which provides a snapshot of the sizes and ages present in the population at a known time (see Ye et al. 2016 for a summary of research, and Chapter 3.6 of this volume).

STOCK STATUS

Assessment of the resource status of species in the LCF is scheduled in the Management Plan, with annual fishery statistics and performance indicator reports and formal stock assessment of key species every three years (PIRSA 2016). Fishery resources in South Australia are classified under the framework of the Status of Key Australian Fish Stocks (Flood et al. 2014). The fishery for pipi is managed under an annual TACC based on fishery-independent resource assessment, and in 2014 it was classified as 'sustainable' (Ferguson 2013; Flood et al. 2014).

Among finfish species, the status of golden perch in the Lower Lakes was classified as 'uncertain' in 2010/11, but, with increasing complexity of age structures after this time suggesting that recruitment had occurred, in addition to migration of adults from the River Murray, the status was revised to 'sustainable' in 2012/13 (Ferguson & Ye 2012; PIRSA 2015). For black bream, the population in the Murray estuary and Coorong lagoons was in a weakened state, based on trends in catch and effort, low levels of recruitment to the fishable biomass since the early 1990s, and lack of older individuals in age structures (Ferguson & Ye 2008). Despite the recruitment of several year classes since the mid-1990s, recruitment levels have remained low, as measurable improvements in adult biomass have not been detected (Ye et al. 2015). In 2016, the black bream stock was classified as 'overfished' because the low levels of recruitment appear to relate primarily to low spawning biomass, rather than to environmental conditions (Earl et al. 2016).

For mulloway, the presence of several relatively strong age classes in the spawning biomass, high annual catch rates and catches of juveniles (2-5 year olds) in the Murray estuary and Coorong lagoons during the period 2011/12-2013/14 indicated that recruitment had occurred, and this species was classified as 'sustainable' in 2013/14 (Earl & Ward 2014; PIRSA 2015). Age structures of adult mulloway from the marine environment had reduced, along with contraction of the range of ages from 2000/01 to 2011/12 (Ferguson et al. 2014). Due to the species' late maturity (>6 years), determining whether the new age classes from 2011/12-2013/14 have persisted to enter the adult population will not be possible before 2017/18.

For greenback flounder, high inter-annual variation in fishery production since the 1970s has been associated with fluctuations in freshwater inflows to the Murray estuary and Coorong lagoons, and this species was classified as 'environmentally limited' (Earl & Ye 2016). For yelloweye mullet, relatively stable annual catches and high CPUE during the period 2007/08-2012/13, and the presence of numerous strong year classes in the population, indicated that regular strong recruitment had occurred over recent years, so this species was classified as 'sustainable' in 2011/12 and 2012/13 (Earl & Ferguson 2013; PIRSA 2015)

FUTURE DIRECTIONS

Fishing in the LLC has contributed significantly to the local and state economy. In recent years, the fishery potential and marketability of pipi have been a significant component of the value of the fishery, and continued market development will potentially increase the resource value.

Interactions between fishing operations and long-nosed fur seals, *Arctocephalus forsteri*, have recently impacted fishers using gill nets in the Murray estuary, Coorong lagoons and Lower Lakes (McLeay et al. 2015). Research has been initiated to investigate methods to mitigate the impact of these interactions on the LCF, including the use of seal deterrent devices (e.g. underwater firecrackers) and alternative fishing methods (e.g. power haul netting).

There has been a recent move to implement ecosystem-based fishery management around the world. The Management Plan for the LCF and associated harvest strategy for finfish species provide a framework for informing fishery management using indicators of ecosystem status. There is potential for further development of hydrological and other indicators of the environmental condition of the Lower Lakes.

Knowledge gaps exist around the relative importance of habitat for fish species within the Lower Lakes, Murray estuary and Coorong lagoons, because fishes may use different habitats throughout their life-history or during different environmental conditions. For example, changes in the age structures of golden perch coincident with inflows to the Lower Lakes suggest that individuals move between the Lakes and the River Murray, although the extent to which this occurs is unknown. Also, among marine estuarine opportunists, mulloway and greenback flounder use estuarine and marine habitats. For the population of mulloway in south-east South Australia, strong year classes are associated with inflows to the Murray estuary and Coorong lagoons (Ferguson et al. 2008). During favourable environmental conditions, when inflows occur, juvenile mulloway use protected habitat in the Murray Estuary and Coorong lagoons, but may also use other habitat in the adjacent nearshore marine environment. The proportion of the population using these habitats is not known, although natural mortality is likely to differ. Similarly, use of marine and estuarine habitats by greenback flounder is not well understood.

Age structures of key species, in particular those with periodic life-histories such as mulloway, golden perch and black bream, provide information that improves understanding of population dynamics and life-history for each species. Further development of existing time-series of age structures provides the opportunity to improve understanding of how these fish populations change with changes in the environment. Investigation of movement patterns of fishes based on chemical signatures in bony structures, telemetric movement studies and satellite tagging has potential for improving understanding of habitat use.

The productivity of resources in the Lower Lakes, Murray estuary and Coorong is dependent on delivery of environmental flows. Flow restoration under the Murray-Darling Basin Authority's Murray-Darling Basin Plan, among other initiatives (e.g. the South East Flows Restoration Project), aims to maintain salinities in the North and South Coorong Lagoons which are consistent with habitat for fishes and birds, and maintain an 'open' Murray Mouth to allow water exchange and the movement of biota, including fish. These actions are intended to mitigate environmental impacts on fishes, supporting commercial, recreational and recreational fisheries. In addition to water delivery, a better understanding of the linkages between environmental conditions, particularly freshwater inflows and productivity, is needed. For example, benefits may accrue from the development and reinstating of natural flow paths by (i) introducing ecologically sensitive barrage operation (ii) increasing the number of fish-ways (slot-ways and rock ramps) on the Murray barrages (iii) evaluation of options for the lower Southeast of South Australia to contribute freshwater to the Coorong (Creighton 2013; Creighton et al. 2015). Increased connectivity among habitats, including that provided by fish-ways, supports populations of several small-bodied species that are important components of food webs, which include key commercial species (Bice et al. 2016a).

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CHAPTER 4.3

MANAGEMENT IN A CRISIS: RESPONSES TO THE MILLENNIUM DROUGHT

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INTRODUCTION

Managers of the modern, regulated Lakes Alexandrina and Albert were able to keep water levels relatively stable, and provide security of freshwater supplies for more than 60 years before the effects of a decade-long drought across the Murray-Darling Basin, now known as the Millennium Drought (2001-2009; Van Dijk et al. 2013), became apparent.

Regulation of water levels in the Lakes, and the connected river pool below Lock 1, commenced in the early 1940s through the construction of a series of five barrages between Lake Alexandrina and the Coorong. The barrages were built in response to government and community concerns about salinity incursion risks, navigation hazards and diminished flows to South Australia due to upstream water resources development (Sim & Muller 2004). Lake water levels were stabilised at around +0.75 m Australian Height Datum (AHD, nominally 75 cm above sea level) across a range of river flow conditions by controlling freshwater outflows and seawater ingress.

Until 2002, water levels oscillated around +0.75 m AHD except for during several, short-lived periods of low river flow in the 1960s and 1970s, but levels did not drop below +0.35 m AHD. These relatively static water levels over many decades provided certainty, and this 'sense of security' meant that industries, communities, plans and policies developed based on 'typical' operating ranges.

Particularly in the extremely dry years (2007-2009) of the Millennium Drought, everything changed. Lake water levels dropped to unprecedented lows, resulting in systemic environmental changes that were outside any management experience, including that of the Traditional Owners, and creating a crisis situation for the State and Federal Governments. The consequent management responses were necessarily rapid and based on using the best available knowledge and collective experience at the time to predict what might happen. This chapter summarises these emergency responses to inform future drought management and public debate about the need for water resource security in the Murray-Darling Basin.

DESCRIPTION OF CHALLENGES FACED IN MILLENNIUM DROUGHT

South-eastern Australia experiences severe droughts as part of long-term climate cycles. The Millennium Drought (2001-2009) is, however, widely regarded as the worst drought on record

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(Van Dijk et al. 2013), having greater impact on the rural communities and ecosystems of the Murray-Darling Basin than the previous 'Federation Drought' (1895-1902) that ultimately led to the creation of the *River Murray Waters Agreement* (1915) that became the Murray-Darling Basin Agreement in 1987. Lakes Alexandrina and Albert (Lower Lakes) lie at the terminus of the River Murray and thus are vulnerable to impacts of diversions for consumptive use and drought arising from upstream parts of the Murray-Darling Basin.

The natural hydrological features of the Basin have been highly modified by river regulation, water extraction and the placement of infrastructure over the last 200 years (Walker 2006). Inflows into Lake Alexandrina predominantly occur from the River Murray and to a much lesser extent from the Eastern Mount Lofty Ranges tributaries. Prior to the Millennium Drought, these inflows were sufficient to meet evaporative losses from the Lakes and provide for barrage releases on an annual basis, and thus lake water levels were relatively static. Sustained low rainfall and run-off across headwater catchments in Victoria and New South Wales during the Millennium Drought led to the lowest recorded inflows to major Murray-Darling Basin water storages in the previous 111 years (MDBA 2010; Van Dijk et al. 2013). Early warning signs came in October 2002 when an increasing volume of sand inside the Murray Mouth from a lack of barrage flows necessitated the use of two dredges to enhance and maintain connectivity between the Southern Ocean and the Coorong (see below). In summer 2006/07, river flows over Lock 1 were no longer sufficient to meet evaporative and supply losses and water levels in the barrages' weir pool (Barrages to Blanchetown) began to drop (Mosley et al. 2012), dropping further each spring-summer-autumn with minor recovery each winter from local tributary inflows (Fig. 4.3.1).

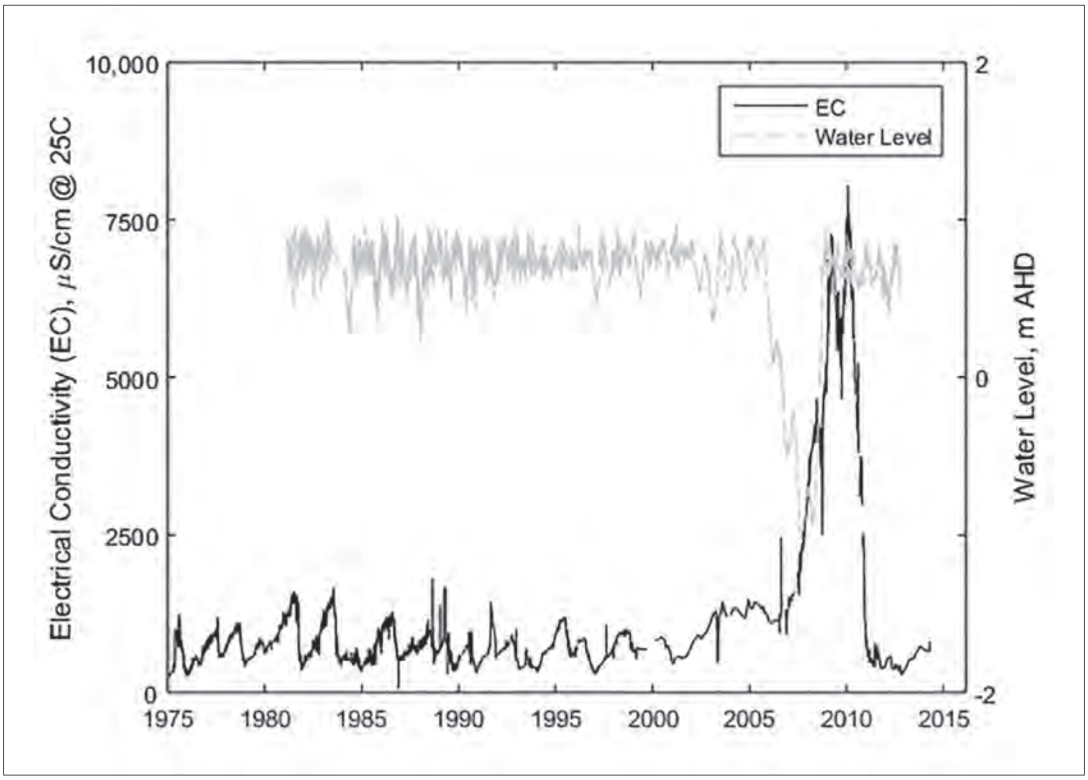

Figure 4.3.1 Lake Alexandrina water levels and Electrical Conductivity (EC) for the period 1975-2015, showing the impacts of the Millennium Drought on increasing conductivity and lowering water levels. (From Department for Environment and Water (DEW), South Australia)

River flows over the SA Border were at their lowest (<1 000 ML day^{-1}) for the period June to September 2007, compared to the normal daily entitlement of 3 000 ML day^{-1}. The lowest daily water levels averaged -1.04 m AHD in Lake Alexandrina (Fig. 4.3.1) and -0.5 m AHD in Lake Albert in April 2009. Lake Albert water levels would have dropped lower except that water was being pumped in from Lake Alexandrina over a temporary embankment near Narrung (see below). In Lake Alexandrina, the lowest levels during the drought represented a drop of almost 2 m below 'normal' operating levels, to approximately 1 m below mean sea level. This was well below any water levels previously experienced in the system for the 7 000 years since the current Coorong sand dunes formed, partly because flows were always sufficient to maintain flows in the lower River Murray (see Mallen-Cooper and Zampatti (2018) and Chapter 2.3 in this volume) and also because prior to the construction of the barrages, the ocean acted as the hydraulic control.

The very low water levels stranded irrigator and town water pumps, leading to losses or disruptions to previously secure supplies. The fringing vegetation and wetlands around both Lakes became disconnected and desiccated, resulting in loss of all inundated, vegetated habitats. A less-expected impact was the exposure of vast areas of acid sulfate soils (ASS), most of which had been previously inundated for probably thousands of years (Fitzpatrick et al. 2010), releasing acid, metals and other hazardous products that put ecosystems and residents at risk. At the system scale, one of the greatest impacts of the low lake levels was the complete disconnection of the freshwater lakes from the estuarine Murray Mouth and saline Coorong areas and complete cessation of outflows to the ocean for nearly four years. The previous connectivity (from river to lake to estuary to saline lagoons to the sea) was essential to the ecological health and hydrological functioning of the whole system and its loss during the drought soon led to systemic ecological and biogeochemical changes (see summary in Box 4.3.1). The system had been taken to the brink of complete ecological collapse.

BOX 4.3.1 SUMMARY OF KEY ENVIRONMENTAL CHALLENGES DURING THE MILLENNIUM DROUGHT AT THE COORONG AND LAKES:

- exposure of acid sulfate soils. Up to 20 900 ha exposed at minimum water levels in spring 2009 (Fitzpatrick et al. 2010; Mosley et al. 2014a)
- markedly increased electrical conductivity (EC)/salinities (see Figure 4.3.1) to >8 000 EC in Lake Alexandrina and >22 000 EC in Lake Albert in spring 2009, which was above the thresholds for key species of conservation significance in the Lakes (e.g. Southern pygmy perch, Yarra pygmy perch, and freshwater macro-invertebrates; Muller 2011), and which prevented use for irrigation and severely limited stock watering
- desiccation and loss of connection of Lakes, fringing macrophyte beds and wetland habitats
- prolonged cessation of freshwater flows to the Southern Ocean (four years of no flow), disconnection of fresh and estuarine habitats and seawater intrusion into Lake Alexandrina
- physical damage due to sand movement and dust from the exposed margins of the Lakes
- colonisation of Lakes by tubeworms that grew on any hard surface, including jetties and freshwater turtle shells. Local school students caught turtles, cleaned them of tubeworms and returned them to fresher areas
- saline lake water penetration up the River towards Tailem Bend.

See other chapters in this volume for more details of the water quality and ecological impacts of the drought.

The Millennium Drought ended with heavy summer rains in late 2009 in the upper Murray-Darling Basin catchments. The long travel distances and losses along the way meant that lower River Murray weir pools and the Lakes took a period of about nine months to refill (Fig. 4.3.1). The refilling to 'normal' operating levels of around +0.75 m AHD was completed by September 2010.

EMERGENCY RESPONSES

Not only were the challenges of the drought unprecedented, but there was also very little warning that an ecological catastrophe was unfolding. There had always been an expectation that, under regulated conditions, lake water levels would fluctuate with weather patterns and rainfall in the headwaters but that overall river flows would exceed evapo-transpiration. Planning had largely assumed that run-off in the Murray-Darling Basin would be sufficient over years to decades to keep water levels in the Lakes above sea level at all times. A timeline of key events and management responses to the Millennium Drought is provided below and discussed in more detail in subsequent sections.

Governance

In response to the drought, the Minister for Water Security established the Water Security Council and, reporting to it, the Water Security Technical Working Group. Together the Water Security Council and Technical Working Group developed a Drought Response Strategy which had the following goals (ICEWARM 2012):

- *Primary Goal:* The supply of potable-quality water was to be maintained in order to meet the critical human needs of all South Australians living in the (River Murray) Water Security Zone, at all times.
- *Secondary Goal:* Once Critical Human Needs had been guaranteed for a given current year, additional River Murray flows were to be shared between a strategic reserve for critical human needs for water throughout the next water year, for the environment, for irrigation and for external domestic uses; and they were also to be adjusted to take into consideration any special accounting surplus/deficit.

As part of the overall drought response strategy, a Lower Murray Drought Contingency Plan was developed, which identified a series of triage actions (see ICEWARM 2012). These actions included items that the Government commenced planning for, but which it hoped would not have to be implemented. The whole-of-government approach created by the cross-agency council and taskforce was very successful.

There were also Senior Officials Group meetings at the Basin level to discuss water security and management actions during this period.

Dredging

Flows over the barrages, in terms of volume and timing, are critical to maintaining an open Murray Mouth, which in turn is essential to maintaining the ecological and water quality health of this Ramsar site (Close 2002; Yu 2014). It is also critical for exporting salt from the whole Murray-Darling Basin. In 2002, near the beginning of the Millennium Drought, the Murray Mouth was

Table 4.3.1 Timeline of important dates and actions during and after the Millennium Drought.

Date	Important dates and actions
2001	Official start of the Millennium Drought
2002	Dredging begins at the Murray Mouth Lower than average Basin rainfall from 2002-2003
2006	Storage levels fall in Murray-Darling Basin Lower Lakes levels begin to decline in spring-summer
2007	Lower Lakes levels fall below -0.4 m AHD in January Seepage from sea back through barrages commences Lower than average Basin rainfall
2008	Acid sulfate soil and high water salinity issues become apparent Severe water restrictions placed on irrigations (2-15 % of allocation for many water classes) Narrung embankment constructed with pumping of water into Lake Albert from Lake Alexandrina
2009	Lowest water levels on record occur (-1.04 m AHD average in Lake Alexandrina) 20 900 ha ASS exposed at minimum water levels, aerial and ground limestone application in Currency Creek and Finniss River Clayton and Currency Creek embankments constructed Late 2009 high rainfall event in Murray-Darling Basin ends the Millennium Drought
2010	Electrical conductivity reaches >8 000 µS cm^{-1} in Lake Alexandrina at Milang, >22 000 µS cm^{-1} in Lake Albert at Meningie, and salinity >150 g L^{-1} in Coorong South Lagoon (>4 x seawater salinity) Aerial limestone dosing in Boggy Lake Inflows to South Australia increase and Lake Alexandrina levels increase Lakes refill to normal operating levels in September, Narrung embankment breached to allow Lake Albert to refill
2011	High inflows from Murray-Darling Basin flooding
2012	High inflows continue Clayton Bay regulator fully removed in October
2013	Currency Creek regulator fully removed
2016	Salinity recovers in Lake Albert to pre-drought levels

rapidly silting up and was at a heightened risk of closure without management intervention. As a consequence, dredging of the accumulated sand in the Murray Mouth and adjacent Goolwa and Tauwitchere channels commenced in October 2002 and continued for eight years until high river flows in 2011, which meant dredging was no longer required. Dredging recommenced in January 2015 and is continuing as at June 2018 other than a break from the 2016 high-flow event to early 2017 when dredging recommenced due to insufficient duration of flows to scour the channels and Murray Mouth of accumulated sand. The duration of high barrage flows is critically important to improving the condition of the channels adjacent to the Murray Mouth and for the net export of sand from inside the Murray Mouth.

Dredging is considered the most effective method of keeping the mouth open in the absence of sufficient scouring flows through the barrages. It is, however, a key indicator that end-of-system flows are inadequate for sustaining environmental processes.

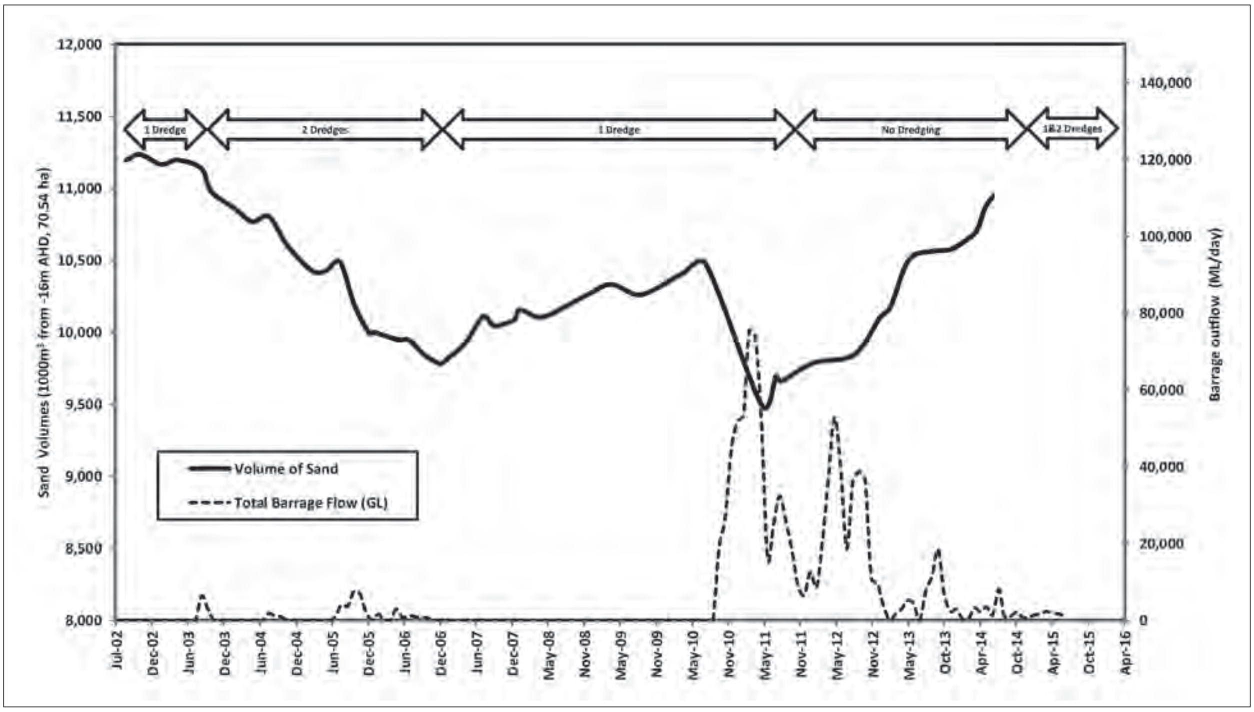

Figure 4.3.2 Sand volumes at the Murray Mouth versus barrage flow from 2002-2016, with dredging periods indicated also. (Department for Environment and Water, (DEW) South Australia)

Saltwater intrusion and 'sealing' of barrages

Seawater intrusion into the Lakes was driven by permanent 'reverse head' conditions (seawater level higher than lake levels) from 2007 to 2009 (Aldridge et al. 2009). This, coupled with evapo-concentration (Mosley et al. 2012), led to salinity in both Lakes being much higher than 'typical' values. At the peak of the drought (2009), salinity in the Goolwa Channel of Lake Alexandrina exceeded 25 000 EC, due to leakage through the barrages, but was more typically in the order of 5 000 EC in the main body of the Lake (Fig. 4.3.1).

Barrage leakage was reduced by sealing gaps at the barrages with bentonite and constructing a small 300 mm high concrete wall across the barrage spillways to reduce seawater ingress. These actions reduced, but did not eliminate, the seawater ingress, which only ceased when lake levels recovered to normal operating levels.

Construction of embankments and pumping

The construction of blocking embankments to hold water in conjunction with pumping to inundate ASS in high-risk acidification areas was another important response. Two temporary embankments were built in the Goolwa Channel at the southern end of Lake Alexandrina: one near the township of Clayton (completed August 2009; Fig. 4.3.3) and another at the confluence with Currency Creek (completed September 2009). Construction involved creating earthen embankments (Fig. 4.3.4). The objective was to capture spring flows from Currency Creek and the Finniss River, which, together with initial pumping of water over the Goolwa embankment from Lake Alexandrina, would resubmerge ASS within the Goolwa

Figure 4.3.3 Temporary embankments to manage acid sulfate soils under construction.
Left: At Clayton.
Right: The bund and pumps at Narrung (right). (Photographs by Benjamin Zammit)

Channel, Currency Creek and Finniss River, preventing further oxidation and acid release. The embankments successfully prevented further acidification (Hipsey et al. 2014), and existing acidification was managed via limestone application (see below).

In September 2010 the Clayton embankment was partially removed and the Currency Creek embankment was over-topped after increased river flows raised lake water levels. This allowed reconnection so that water could flow between Lake Alexandrina and the Goolwa Channel and Currency-Finniss tributary region for the first time in more than a year. The Clayton Bay embankment was fully removed by October 2012, and the Currency Creek regulator by August 2013.

Due to the imminent disconnection of Lake Albert from Lake Alexandrina, a third embankment and pumping infrastructure was built at Narrung in 2008 (near the current ferry; see Fig. 4.3.3). The aim was to pump water into Lake Albert from Lake Alexandrina and keep Lake Albert from drying and hence exposing a large-scale and severe acid sulfate soil hazard (see Chapter 2.9). To achieve this, multiple high-volume diesel pumps lifted up to 900 ML d^{-1} from Lake Alexandrina to Lake Albert to maintain water levels above a predicted acidification trigger (-0.5 m AHD; Hipsey et al. 2014). Dredging was required to maintain a suitable flow through the shallow channel to the pump site from Lake Alexandrina. There was also a risk that pumping to Lake Albert would push Lake Alexandrina below its own acidification trigger level (-1.5 m AHD). Fortunately, river flows into the Lakes returned before this happened and a 100 m section of Narrung Bund was removed in September 2010, with the remaining section removed around March 2011.

Limestone dosing

The receding water exposed large areas of ASS around the lake margins (>25% of lake surface area), resulting in large areas of sulfuric (pH<4) soils (Fig. 4.3.5; Fitzpatrick et al. 2010; Chapter 2.9). Surface water acidification (pH 2-3) occurred in several locations (total area of 21.7 km^2) upon rewetting of the exposed sediments by rainfall or lake refill. High concentrations of dissolved metals (Al, As, Co, Cr, Cu, Fe, Mn, Ni, Zn), which greatly exceeded aquatic ecosystem protection guidelines, were mobilised in the acidic conditions (Mosley et al. 2014a).

Aerial limestone dosing was required in two areas to assist in restoring pH and alkalinity in the acidic regions of Currency Creek and Boggy Lake. A crop-dusting plane was used to dose Currency Creek with ultrafine limestone (Fig. 4.3.4) in June-July 2009 and Boggy Lake in May-August 2010, based on precise application rates determined from water acidity measurements. This was successful in neutralising the acidity (Mosley et al. 2014b). Low porous limestone embankments were also constructed across the lower reaches of Currency Creek and Finniss River to increase the neutralising capacity and prevent acid inflows. In total, 2 029 tonnes of limestone were applied by air and 1 978 tonnes of limestone were used in the construction of the embankments.

Bioremediation

Another emergency response was the Bioremediation and Revegetation Project. Bioremediation refers to actions that aim to promote microbial activity (specifically sulfate-reducing bacterial activity) to convert dissolved sulfate to sulfide minerals, while consuming acid and immobilising metals (Sullivan et al. 2011, 2013). This is essentially a reversal of the oxidation reactions that generate acidity in exposed ASS.

Given that low lake levels had desiccated most of the aquatic vegetation, there was a strong imperative for using native plants for bioremediation to re-establish plants and habitat resources around the lake shore. Site surveys and mapping in 2008-2009 showed, however, that it was not feasible to plant the entire exposed area (c.15 000-20 000 ha) with local native species. Organic matter needed to be added to the exposed ASS as quickly as possible to control acidic hot spots and delay the decision to undertake larger-scale interventions such as letting sea water into Lake Alexandrina to inundate the acidified areas (see below). Extensive trials were undertaken which led to a combination of direct seeding (aerial and surface) and tube-stock planting being used. Seeds of native wetland plants and some terrestrial species used on the margins of the Lakes were sourced and grown locally (e.g. at community nurseries established for this project) with selection based on the plant's capacity to

Figure 4.3.4 An expanse of dry lake bed containing acid sulfate soils (left) and aerial dosing of limestone into acidic water in Currency Creek (right) in 2009. (Photographs by Luke Mosley)

- tolerate dynamic and extreme conditions
- create cover to reduce soil temperature and evaporation
- maintain soil moisture (e.g. via selecting plants with shallow rooting depths)
- reduce soil erosion by trapping sand
- improve visual appearance
- improve subsequent revegetation success
- contribute to long-term ecological improvement.

Bevy Cereal Rye was the cover crop used for aerial seeding because of its shallow root structure; fast growth; tolerance to waterlogging, salinity and acidity; and existing local use; and because of the ability to prevent reseeding (non-viable seed was utilised) to ensure that no ongoing environmental hazard was created. The organic matter left after die-off in summer was a driver of sulfate reduction and protected the lake bed from further wind erosion and moisture loss.

A range of revegetation treatments (different species and timing of plantings) and unvegetated controls were assessed at several locations around the Lakes. Sullivan et al. (2011, 2013) showed that planting on exposed lake beds promoted microbial activity by providing carbon and reduced mobilisation of metals and metalloids to the water body by physically binding these toxins. The four sedges in the trial accumulated similar rates of carbon (between 580-1 050 kg C ha^{-1} y^{-1}). Plant growth also increased pH in the surface sediments compared to bare soil, bringing the pH up from acidified conditions (<4) to near neutral (pH ≥6; Fig. 4.3.5).

Figure 4.3.5 Photograph taken from the Lake Alexandrina exposed lake bed near Tolderol showing the revegetated/bioremediated area. (Department for Environment and Water, (DEW) South Australia)

The effect of the vegetation persisted to approximately 30 cm soil depth, below which pH dropped again in some soils depending on the rate and depth of acidification. Different soil types affected the depth of acidification in exposed soils, with acidification occurring at deeper layers in the cracking clay at Tolerdol compared to the sands at Campbell Park. Perennial species that survived inundation (e.g. reeds such as *Phragmites australis*) continuously supplied organic matter to the sediments before and after the Lakes refilled. By contrast, annual or relatively short-lived plants that did not survive inundation (e.g. Bevy rye, rushes, colonising species like *Cotula coronopifolia*) supplied limited organic matter, mostly at die-off. Sullivan et al. (2011) concluded that the ongoing supply of organic carbon to the sediments was more likely to drive effective bioremediation and establish new habitats.

In only a few years the Bioremediation and Revegetation Project achieved the following:

- aerial seeding of 7 453 ha of exposed sulfidic lake bed
- planting of 665 848 sedges over 618 ha of exposed sulfidic lake bed
- revegetation of 162 ha of priority biodiversity area with local native species
- pest plant control on 200 ha of priority biodiversity areas
- revegetation of over 2 334 ha with a total of more than 5 million native plants
- fencing of more than 60 km to protect lake shore and important habitats.

Bioremediation was highly successful, not just in effectively treating the exposed ASS, but also in providing social benefits to the local communities and Indigenous contractors, who were making a tangible difference by growing plants to revegetate these problem sediments. It also helped negate the need to let sea water into Lake Alexandrina, which would have likely caused significant ongoing environmental and social issues, as discussed below.

Scoping potential for letting sea water into Lake Alexandrina

Environmental managers were implementing a range of emergency measures to manage acidification in 2009 (above) but lake water levels were still dropping and decisions had to be made about regional water level management from the following three options:

1. Do nothing and allow evaporation and acidification to occur (‘*Do Nothing*’).
2. Introduce sufficient sea water into Lake Alexandrina through the barrages to maintain water levels just above the acidification trigger levels (‘*Introduce Sea Water*’).
3. Deliver additional fresh water (i.e. River Murray flows) to maintain lake levels above the trigger levels (‘*Deliver Fresh Water*’).

With each of these three options was the additional choice of whether to continue pumping water from Lake Alexandrina to Lake Albert over the Narrung bund (see above), or conserve water in Lake Alexandrina by ceasing to pump. This gave a total of six management options. The drought and the Basin water-sharing framework meant that no river water was available to refill the Lakes with fresh water and thus the only feasible next options were to *Do Nothing* or *Introduce Sea Water*.

An assessment of the likely ecological consequences of implementing each of these options was undertaken for a nominal drought period (2009-2015) and a nominal 10-year recovery period after the drought (2015-2025; Muller 2011). The models were run for three key variables:

salinity, pH and water levels, under drought conditions of 650 GL yr^{-1} over the SA border for five years and two recovery flow scenarios of either Entitlement flows (1 850 GL yr^{-1}) or Average flows (4 000 to 5 000 GL yr^{-1}) for 10 years. It should be noted that when the assessment began in 2009, the ecosystem was in very poor condition relative to the Ramsar-listed ecosystem state (Phillips & Muller 2006). Water levels in the Lakes were very low and still dropping, large areas of ASS were exposed, salinities were higher than the Limits of Acceptable Change (Phillips & Muller 2006), and the aquatic plants and wetlands that had formerly fringed the Lakes were disconnected and desiccated, resulting in loss of all inundated, vegetated habitats.

Do Nothing

The assessment showed loss of aquatic biota in both Lakes for the *Do Nothing* scenarios. The models predicted that impounded Lake water would become progressively more saline, and then acidic, as it evaporated. If pumping to Lake Albert ceased, it would dry to a few, isolated pools of highly saline and acidic water within two years. All Lake Albert biota would be lost. Water in Lake Alexandrina, however, would be conserved such that only acidified 'hot spots' would occur each autumn around the fringes when water levels dropped to c.-1.4 m AHD, rather than widespread acidification. Regardless, all freshwater plants and most freshwater animals in Lake Alexandrina would be progressively lost from the combined impacts of reduced lake area, increased salinity (Fig. 4.3.6), acidification, trophic interactions and disruption of sensitive life stages. Disconnection from the Coorong and Murray Mouth would limit or prevent colonisation by most estuarine biota (e.g. fish) that might replace declining or lost freshwater taxa under this scenario if there was connectivity.

If pumping from Lake Alexandrina to Lake Albert continued, acidification in Lake Albert was prevented but high salinities (>60 g L^{-1}) would lead to serial losses of all but the hardiest taxa within 18 months. The 'mining' of water from Lake Alexandrina meant that it would acidify within three to four years (Fig. 4.3.6) to a pH of 4, being fatal for all biota except those fish or plankton that were able to tolerate the high salinity levels and avoid the acid by retreating to deep-water habitats they were able to survive (red areas in Fig. 4.3.6 top right). Birds would probably experience periods of high food availability, especially during fish kills, but would ultimately leave the site.

Introduce Sea Water

Introducing sea water into Lake Alexandrina through the barrages to maintain target water levels (around -1.3 m AHD) was predicted to prevent the widespread acidification seen in the *Do Nothing* scenarios. Only short-lived patches of low pH water were predicted for the Lake fringes in some years, suggesting that it was a viable management option, although there were serious concerns over the potential for enhanced metal release due to cation exchange processes with seawater inundation (Sullivan et al. 2010). Salinities, however, were predicted to increase rapidly after sea water was introduced each spring, reaching estuarine concentrations (~ 20 g L^{-1}, or 31 000 EC) in the first year, before salinities increased to marine and then hypersaline concentrations (up to 100 g L^{-1} or 157 000 EC) (Fig. 4.3.6). This would lead to serial losses of all freshwater and any colonising estuarine taxa (including fish).

Pumping to Lake Albert would have no significant effect on the ecological consequences in Lake Alexandrina other than to slow the rate of rise in salinity to hypersaline conditions, thereby delaying the loss of any one biotic group by several months (Muller 2011). Maintaining Lake Albert water levels just above its trigger level was predicted to prevent acidification but Lake Albert would also become saline because the water pumped in from Lake Alexandrina was being progressively salinised by sea water (110 g L^{-1} after three years of seawater pumping; Fig. 4.3.6). If pumping ceased, Lake Albert would undergo widespread acidification and desiccation as in the *Do Nothing* scenario. Either way the introduction of sea water would lead to the ecological collapse of both Lakes Alexandrina and Albert. The Murray Mouth and Coorong biota were unlikely to experience further salinity stress because the background salinity was so high. Adverse water level changes and unfavourable periods of sediment drying were predicted for some estuarine biota and there was increased risk of scouring and deposition of sediments around the barrages.

Deliver Fresh Water

The models showed that delivering enough River Murray water to keep the Lakes above their respective trigger levels would prevent widespread acidification. Ecological harm from increasing salinity was not entirely avoided, however, which is consistent with the need to provide more than Entitlement flows over the long term to keep the Lakes healthy (Lester et al. 2011). Modelled salinities in Lake Alexandrina increased to 8 to 10 g L^{-1} without pumping to Lake Albert (Fig. 4.3.6), which is more than 10 times the Ramsar salinity target (0.64 g L^{-1}; Phillips & Muller 2006). Given that pumping to Lake Albert would require additional river water to keep both Lakes at their target levels and that salt would be exported to Lake Albert, the salinity regime in Lake Alexandrina was fresher when pumping to Lake Albert continued (5 to 7.5 g L^{-1}). Salinities under the *Fresh Water* scenarios were predicted to remain much lower than in any of the *Do Nothing* or *Introduce Sea Water* options, except for Lake Albert, which would dry completely if pumping ceased as in the other scenarios.

The ongoing disconnection of the Lakes if water levels were maintained just above the trigger levels for a long time would lead to other ecological problems. For example, diadromous fish that rely on connection between fresh and saline habitats would be lost, even though the lake salinities may be suitable for adults. Invasive tubeworms would not be able to tolerate winter freshening from river inputs, which would lead to their decline over time. Other estuarine taxa, with the exception of highly dispersive plankton, would be unlikely to establish.

Recovery

With regards to recovery potential, the seawater scenarios showed the lowest potential to recover, due to the need to flush hypersaline water from the Lake. In particular, for Lake Albert there would be a very long recovery (>decadal) time to flush salt due to its limited ability to exchange and dilute water through the Narrung Narrows. It should be noted that all the above scenarios involve extreme drought management conditions and scenarios. The natural

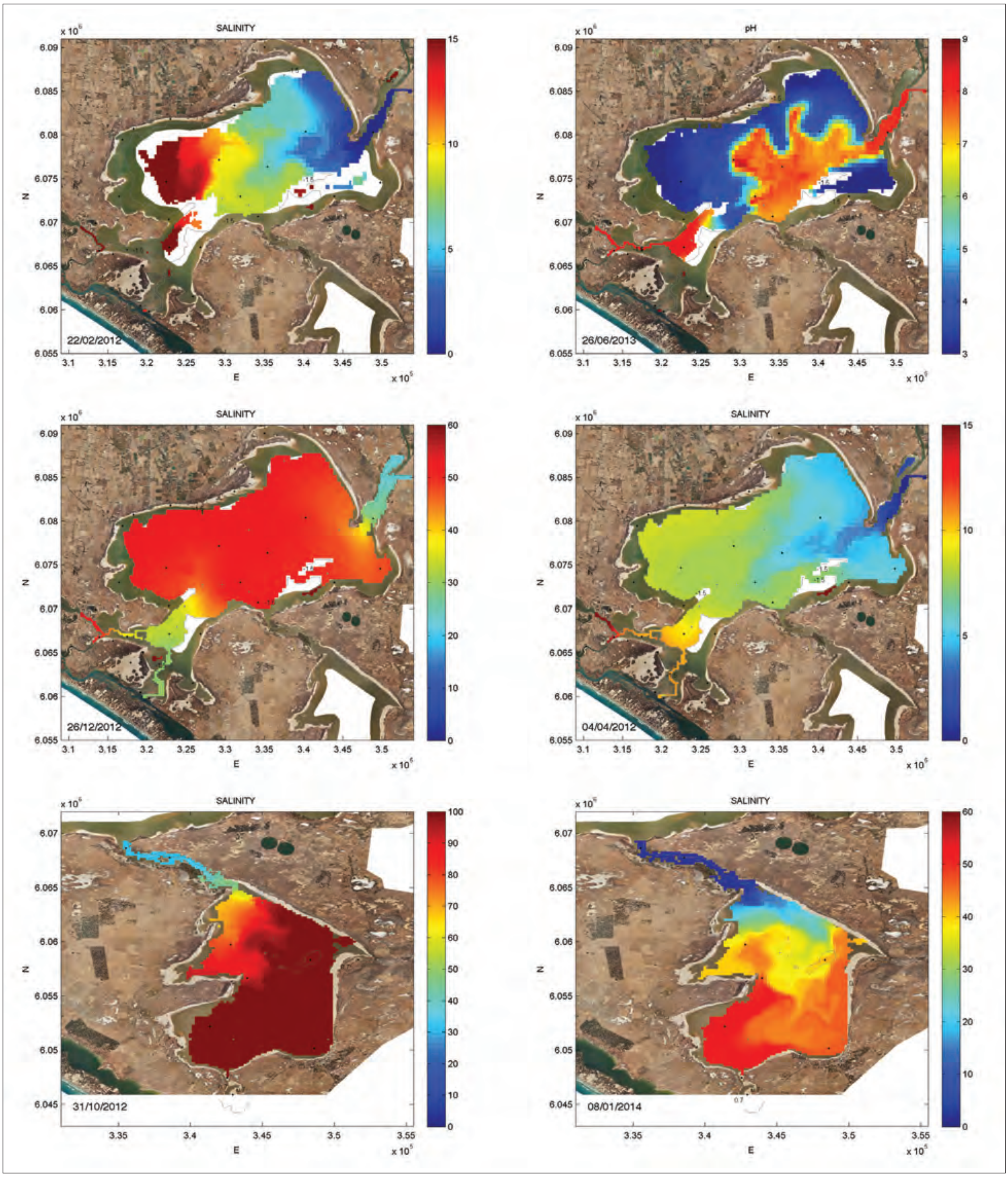

Figure 4.3.6 Modelling outputs after three years of various treatments.
Top: Lake Alexandrina *Do Nothing* salinity (dark red >15 g L^{-1} on the left) and pH (blue pH 4 on the right).
Middle: Lake Alexandrina salinity seawater pumping (red >60 g L^{-1} on the left) and Lake Alexandrina freshwater cease pumping to Lake Albert (green 10 g L^{-1} on the right).
Bottom: Lake Albert salinity seawater pumping (on the left) and salinity freshwater pumping (dark red >100 g L^{-1} on the right).
(Reproduced with permission from Dr David Wainwright, WBM Pty Ltd for Department of Environment and Water, (DEW) South Australia)

pre-barrage conditions involving seawater connection to the Lower Lakes were prior to large-scale water extraction from the Murray-Darling Basin and there is no evidence of even seawater salinities, let alone hypersalinity, persisting in the Lakes historically (see Chapter 2.4).

Other responses

Other emergency actions not detailed here:

- Licensed water allocations for irrigators were severely reduced to conserve water throughout the Murray-Darling Basin. Water shortages and the simultaneous Global Financial Crisis led to widespread economic hardship for rural communities, especially Indigenous communities and those that depended on irrigation (MDBA 2010).
- Irrigators and the SA Government purchased additional water from the very limited water market to keep permanent irrigated crops alive.
- A new pipeline was built around Lakes Alexandrina and Albert to bring potable water from the river upstream of the Lakes to lake shore water users that were no longer able to access water directly from the Lakes.
- River Murray wetlands that had regulating infrastructure in place were disconnected from the river to reduce evapo-transpiration.
- The building of an additional weir adjacent to Pomanda Island (near Wellington) was investigated as an option to control river outflows to Lake Alexandrina in an attempt to secure and protect urban and rural water supplies.
- Severe urban and industrial water restrictions were implemented for Metropolitan Adelaide and other areas.
- Pump off-takes for Adelaide city and country town water supplies were modified to enable pumping to continue to -2.2 m AHD.
- A desalinisation plant was constructed at Port Stanvac (for Metropolitan Adelaide drinking water supply).
- Investigations were carried out into stormwater harvesting and reuse to reduce River Murray water demands.
- River Murray ferries that were stranded by dropping water levels were modified.
- Critical infrastructure (e.g. roads, power lines, levee banks) and riverside housing ('shacks') were repaired when riverbanks collapsed.

MANAGEMENT AFTER THE MILLENNIUM DROUGHT

Greater than average rains in the catchment in 2009 led to unregulated summer flows that refilled the Lakes by September 2010, enabling flows out of the Murray Mouth to recommence. Improvements in soil, water quality and ecosystem condition began after that but may not return to pre-drought status (see other chapters in this volume). For example, salinity in Lake Albert only returned to pre-drought averages in 2016. These long-lasting and severe effects, and the high costs of the various management actions, highlighted that a new paradigm in Basin water management was required.

The Murray-Darling Basin Plan under the *Water Act 2007* ('the *Water Act*') came into effect in 2012 and the recovery of 3 200 GL of water for the environment is now being implemented. The return of environmental water through the Basin Plan and The Living Murray program has resulted in more water being available for the Coorong, Lower Lakes and Murray Mouth, which, coupled with new management thinking, has enabled a more flexible, risk-based approach to managing water levels. Although this water provides multiple environmental and socioeconomic benefits to SA, it has also increased the complexity of decision making. The future predicted impact of climate change reducing end-of-system River Murray flows and increasing sea levels is also a major uncertainty that is not factored into the current water recovery targets under the Basin Plan.

The Drought Emergency Framework (MDBA 2014) was formulated post-drought and is an excellent example of how the science and learnings from drought were incorporated into policy and governance. The purpose of the Drought Emergency Framework is to guide decision-making processes for the management of the Lower Lakes during any future extreme drought. Central to the framework is the development of an early warning indicator, which will be triggered when water levels are predicted to fall below 0.0 m AHD. When this trigger is reached, a Murray-Darling Basin jurisdictional High Level Steering Committee will be formed to provide sufficient lead-time to facilitate a timely response to a future drawdown event. The triggers comprise two phases — a planning phase (lake levels +0.4m to 0.0m) and an emergency actions phase (lake levels 0.0 m to -2.7 m) — which incorporate four levels delineating likely impacts and potential management actions. The Murray-Darling Basin Ministerial Council is the approval body for the development and amendment of this Emergency Framework, consistent with s26(1)(b) and (c) of the Murray-Darling Basin Agreement as outlined in sch 1 of the *Water Act*.

Another clear management improvement since the drought has been the development of the Barrage and Water Level Management Policy and the Barrage Operating Strategy through the Department for Environment and Water (DEW)'s Commonwealth-funded Variable Lakes Project. This provides a decision-making framework for prioritising multiple, potentially competing objectives that can be achieved through barrage operation, which include governance arrangements, consultation processes, operational considerations, water availability, climate and tide assessments, trade-offs, drivers and legislative considerations. The preferred water level operating regime for the Lower Lakes, under normal conditions, is now seasonally variable and ranges between +0.5 and +0.85 m AHD annually, whilst allowing for continued barrage releases that provide connectivity and assist in maintaining a degree of Mouth openness. It is understood (Muller 2011) that operating the barrages over a more variable water level range will support more complex ecosystems by supporting diverse and interconnected mosaics of aquatic flora and directly providing for threatened fauna (e.g. timely connections for small-bodied native fish and cued inundation of habitat for the Southern Bell Frog, *Litoria raniformis*). This water level range will allow fishways that connect the Lakes to the Coorong to be operated all year, whilst delivering fresh water to the estuary and exporting accumulated salt to the Southern Ocean.

The drought provided an opportunity for adaptive learning by all agencies and individuals involved and highlighted the need for caution in relying upon status-quo thinking for management. Initiatives such as The Living Laboratories program convened by the then South

Australian Department for Water, Land and Biodiversity Conservation (now Department for Environment and Water) were important mechanisms for reviewing South Australia's response to the drought. The focus of Living Laboratories (ICEWARM 2012) was on the role of South Australian Government agencies, although there was also much to be learnt from how affected communities responded at local and property scales (Muller 2012). If there is a 'silver lining' to the Millennium Drought, it is that management agencies and the community are much better prepared to help prevent such an extreme event occurring, and to manage when droughts inevitably occur again in the future.

ACKNOWLEDGEMENTS

We would like to acknowledge the government, scientific, Indigenous and local communities of the Lakes and Coorong region for their willingness to share knowledge and work together under the extreme conditions of the Millennium Drought and with high levels of uncertainties. Andrew Beal (DEW), the former Chair of the Water Security Technical Working Group and principal advisor to the Water Security Council, is thanked for a review of this chapter.

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CHAPTER 4.4

NGARRINDJERI VISION FOR THE ECOLOGICAL CHARACTER DESCRIPTION OF THE COORONG AND LOWER LAKES

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NGARRINDJERI AND RAMSAR MANAGEMENT

The Ngarrindjeri Vision for Country contains long-standing principles of 'wise use' of their 'Country', supporting healthy rivers, lakes, estuaries and coastlines. Fundamental to this vision is an understanding that everything is connected and that both cultural and natural wellbeing require healthy lands, waters and all living things (Ngarrindjeri Nation 2007, p. 5). Ngarrindjeri use the term '*Ruwe*/*Ruwar*' to describe this interconnectivity. Ngarrindjeri and Indigenous peoples internationally understand their humanity and their Indigenous sovereignty as being constituted in inextricable relations with the non-human world. For Ngarrindjeri, this philosophy is embodied in the concept and practice of *Yannarumi,* or 'Speaking as Country'. This philosophy expresses the interconnectivity between the lands, waters and all living things. As part of the living body of their Country, Ngarrindjeri believe they have an abiding right and responsibility to sustain what Western science understands as 'ecological health'.

In 1985 the Coorong and Lakes Alexandrina and Albert regions of Ngarrindjeri Country were declared wetlands of international significance under the Ramsar Convention (1971). This area includes the 'Meeting of the Waters', which has been recognised in State legislation as a location where the cultural and spiritual significance of the area is especially crucial for Ngarrindjeri wellbeing. Since this time, Ngarrindjeri have sought a meaningful contribution to the formal management of the Ramsar site. In 1998 Ngarrindjeri leaders established a formally constituted Ngarrindjeri Ramsar Working Party to develop a Nation-endorsed position paper for inclusion in a proposed Coorong, Lakes Alexandrina and Albert Ramsar Management Plan (DEH 2000; Hemming et al. 2002; NRWG 1998). However, the South Australian Government excluded this from the final Ramsar Management Plan, thereby blocking formal recognition of deep Ngarrindjeri connection to Country. In 2006 the then SA Department of Environment and Heritage published an Ecological Character Description (ECD) of the

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Coorong, Lakes Alexandrina and Albert wetland (Philips & Muller 2006). Ngarrindjeri input into its development was largely limited to a 'long-term "oral history" data-set of wetland system change over the past 50 to 60 years … ' (Phillips & Muller 2006, p. 224). Since the 2006 ECD, Ngarrindjeri have created a new relationship with the State of SA through a number of agreements and partnerships, establishing a framework for consultation and negotiation, enabling Ngarrindjeri engagement in Natural Resource Management (NRM). This Ngarrindjeri strategy of engagement, outlined below, has provided the framework for better Ngarrindjeri involvement in the latest version of the ECD, and is a first attempt at comprehensively bringing Ngarrindjeri understandings of the relationship between healthy lands and waters and all living things into Ramsar wetland planning and management.

NGARRINDJERI STRATEGY FOR ENGAGEMENT

In a continuing attempt to change the character of contact between their Nation and Australian government agencies, Ngarrindjeri leaders and elders developed their own management plan — the *Ngarrindjeri Nation Yarluwar-Ruwe Plan* (2007) (henceforth, the *Yarluwar-Ruwe Plan*, or 'the plan'), which details a broad vision for Country and a set of strategic directions for better care of Ngarrindjeri Country (Ngarrindjeri Nation 2007). The release of the *Yarluwar-Ruwe Plan* coincided with the establishment of the Ngarrindjeri Regional Authority (NRA) as a peak regional organisation to represent the Ngarrindjeri Nation, built upon a long history of Ngarrindjeri political organisation and resistance to colonisation (Rigney et al. 2015). The NRA provides a centralised point of contact between non-Indigenous interests and the Ngarrindjeri Nation and negotiates with government on a leader-to-leader basis to create policy that guarantees improved health for their Country. This is an Indigenous-led pathway to engagement with the State that utilises 'key political technologies created by the Ngarrindjeri Nation to enable its successful influence in matters affecting their country and community … firmly grounded in Ngarrindjeri ways of knowing, being and doing' (Rigney et al. 2015, p. 334).

In 2009 Ngarrindjeri negotiated a formal agreement with the State to begin a process of non-Indigenous recognition of the importance of Ngarrindjeri *Ruwe*/*Ruwar* (Country) to Ngarrindjeri wellbeing (Hemming & Rigney 2008; Hemming et al. 2002; KNYA 2009). The negotiation process is founded upon a respectful ethos of '*kungun Ngarrindjeri yunnan*' (KNY), or 'listening to Ngarrindjeri people talking', which is formally protected by legal accords co-signed by the Ngarrindjeri leaders and authorised State Ministers on behalf of the Crown of South Australia (SA) (KNYA 2009). The contract law process provides a starting point for negotiations that require State recognition of Ngarrindjeri interests in lands and waters (Rigney et al. 2015). The landmark 2009 *Kungun Ngarrindjeri Yunnan Agreement* (KNYA) created a mechanism for building Ngarrindjeri Nation capacity to become a critical contributor to regional Natural Resource Management (NRM) impacting their Country. The KNYA also provided a framework through which Ngarrindjeri were able to secure A$6 million from the SA and Australian Governments to carry out their Caring as Country work and engage in the SA Government's Murray Futures program (see Chapter 4.5). This involved the Department of Environment, Water and Natural Resources (DEWNR) and NRA co-designing the Ngarrindjeri engagement strategy for the CLLMM Recovery Project through a Ngarrindjeri Partnerships Project, which supported Ngarrindjeri to build their core capacity to meaningfully engage in the project's management actions, and included a review of the ECD (Hemming et al. 2017; NRA & DEWNR 2012).

In mid-2013 a working party of Ngarrindjeri and State Government officials was established to jointly develop a Statement of Commitment (SOC) to frame Ngarrindjeri engagement in the update of the ECD. This SOC was finalised and signed in 2014, committing the SA Government and the NRA to a series of principles, objectives and processes that provide protection for Ngarrindjeri cultural knowledge (NRA & DEWNR 2014). This framework provided Ngarrindjeri with the opportunity to engage at a deeper level with the national ECD framework and gain a better understanding of the ECD assessment process, and its limitations (Hemming et al. forthcoming). Ngarrindjeri 'ecological' knowledge of the Ramsar site stretches back before the last ice age, including its connectivity with surrounding regions; and Ngarrindjeri have documented changes in the ecological character of the region over millennia. The integration of core Ngarrindjeri values into the updated ECD is thus a crucial step for Ngarrindjeri knowledge of *Yarluwar-Ruwe* to be a formally acknowledged part of ongoing management planning and implementation, thus radically transforming a policy-writing process that is usually contracted to a non-Indigenous 'expert'.

NGARRINDJERI CONTRIBUTION TO THE 2017 ECD

In recent years the Ramsar Convention has made progress in its advocacy work, calling for contracting parties to consider cultural values in the wise and sustainable use of Ramsar wetlands and the need for meaningful engagement of Indigenous peoples in Ramsar site management (Pritchard 2013; Ramsar Convention 1999, 2002, 2005; RCN 2014). This recognition has materialised in the resolutions and guidelines prepared by the Convention and in the *Fourth Ramsar Strategic Plan 2016-2024* through Target 10 (Ramsar Convention 2015). Change was also made to the Ramsar Information Sheet (RIS) format to incorporate a set of four cultural criteria to support greater consideration of cultural values (including Indigenous cultural values) in Ramsar site listing (Ramsar Convention 2012). Despite this work, there are still no criteria that specifically recognise the cultural values of Ramsar wetlands. This means that it is up to contracting parties, such as Australia, to interpret the Convention in its fullest form.

Ngarrindjeri, through the NRA, have worked closely with DEWNR with the aim of transforming the ECD from a narrow ecological perspective to a broader one that incorporates Ngarrindjeri values and perspectives throughout the whole document. The partnership with DEWNR has supported this process, but the document — which is owned by the Commonwealth — is still under consideration, and the impact of this work is yet to be determined. This highlights the powerful influence that the multiple actors engaged in the interpretation of the Ramsar Convention and the application of the National framework (DEWHA 2008) in Australia can have on consideration and integration of Indigenous values and perspectives into ECDs (Hemming et al. forthcoming).

Ngarrindjeri have found that the ECD framework, as it currently stands, is inadequate for truly engaging with the Ngarrindjeri worldview based on principles of connectivity, responsibility, reciprocity and mutuality — where humans are connected as part of the whole 'ecosystem'. In the first instance, the ECD framework compartmentalises Ngarrindjeri lands and waters into ecosystem components, processes and services (CPS). This does not align with Ngarrindjeri rights and responsibilities, which rely on the connectivity between lands and waters and all living things: for Ngarrindjeri, all CPSs are interconnected and are an embodiment of *Ruwe/Ruwar*. The model relies on the hierarchical classification of CPSs into 'critical' and non-critical elements that comprise the ecological character, a classification which is also alien to Ngarrindjeri. As such, Ngarrindjeri philosophy poses complex challenges for Western models of compartmentalised ecosystems, particularly for the notions of 'critical services' and 'Limits of Acceptable Change'.

The ECD uses an 'ecological services' framework that breaks down the ecological system into 'services' for humans — thereby prioritising humans as unique and superior within the framework and focusing on the service benefits that the wetland can provide to humans, rather than on the interconnected benefits that flow between people and Country through wise environmental management. Additionally, Indigenous values are compartmentalised under 'cultural services', thereby reinforcing the stereotype that Indigenous culture is 'static' and properly located in the past as an aspect of environmental heritage. This undermines Ngarrindjeri emphasis on connectivity and insistence that all parts of the ecosystem are inherently cultural for Ngarrindjeri.

Furthermore, 'critical services' are conceptualised in terms of a linear progression of intermediate services, final service and benefits — rather than in Ngarrindjeri terms of cyclical and interconnected benefit or reciprocity. The concepts of interconnected benefit and flow help to explain the fundamental interdependence and cyclical relationship that Ngarrindjeri have with *Yarluwar-Ruwe*. In addition, it is evident that the benefits identified in the ECD model leave out Ngarrindjeri benefits (such as fishing) and exclude Ngarrindjeri human capital and agency. For Ngarrindjeri worldviews to be effectively integrated in the ECD, beyond history and 'cultural' stories, Ngarrindjeri also need to be recognised as a 'critical service' for the wetland. The clear trend in the majority of Australian ECDs produced under the National Framework to date, however, aside from two in the Northern Territory, is that 'cultural services' are not listed as critical (Hemming et al. forthcoming).

Ngarrindjeri understandings of long-term, resilient, wise use provide a deep knowledge of the Coorong and Lakes Ramsar site, which is being shared through the development of respectful and healthy partnerships between the Ngarrindjeri Nation and the non-Indigenous government agencies. However, recognition is only slowly emerging that Ngarrindjeri should be key decision makers in this process of setting Limits of Acceptable Change. This is in part tied up in the limitations of the current national framework — Limits of Acceptable Change (LACs) are only defined for 'critical' CPSs in ECDs and, as mentioned, the general trend amongst Australian ECD content is that 'cultural services' are not included as critical (Hemming et al. forthcoming).

Although Ngarrindjeri support the overall need to define LACs to drive an improvement — and not a worsening — of the current health of Ngarrindjeri lands and waters, this approach focuses on Western quantitative parameters (like salinity levels), with limited (if any) recognition and contribution from Ngarrindjeri science. Ngarrindjeri consider given definitions under the model problematic — for example, approaching or reaching 'the point of no return' can have severe consequences for Ngarrindjeri, but this is not currently recognised.

For Ngarrindjeri, effective LACs require an appropriate alignment with Ngarrindjeri concepts of flow, interconnectivity and reproduction, as well as with the principles of 'wise use' that are at the centre of Ngarrindjeri law and form the backbone of Ramsar philosophies. From this perspective, and keeping to the language of the ECD, a 'threat' to the system that could lead to a detrimental 'change of state' could potentially be a reduction in respectful engagement with Ngarrindjeri, which lessens their capacity to speak as Country. From a Ngarrindjeri perspective, LACs need to be measured/assessed by Ngarrindjeri themselves, rather than by other 'experts'. Genuine Ngarrindjeri engagement in defining LACs would involve a commitment under the existing KNY framework to develop an agreed set of values, negotiated by Ngarrindjeri, scientists and local non-Indigenous people. This could provide the basis for agreements relating to critical features, sustainable benefits and services and the agreed limits of acceptable change (Hemming et al. forthcoming).

TOWARDS A MORE EQUITABLE MANAGEMENT FRAMEWORK?

The ECD tool is a fundamental driver for determining how the Coorong and Lakes Alexandrina and Albert Wetland Ramsar site will be managed. When the 'ecological character' of Ngarrindjeri Country is described in a particular way, then that description affects the flow of funds for managing the area. Using a different description, based on the equitable sharing of worldviews in its development, would lead to different priorities for management and a different funnel of funding. The ECD is influential, as it determines what counts in management decisions, whose approach to management is considered important, and who is resourced. Ngarrindjeri have engaged in the current ECD process as partners, seeking to incorporate Ngarrindjeri worldviews where possible. However, the existing ECD approach does not, and cannot, incorporate or value Ngarrindjeri worldviews appropriately.

Ngarrindjeri argue that a separate Ngarrindjeri assessment of the health of the ECD should be conducted alongside the ECD approach and integrated into the *Ramsar Management Plan* as the translator for both approaches (see Hemming et al. forthcoming). Ngarrindjeri have long practised a traditional ecological assessment process known as a *Yannarumi* (Speaking as Country) assessment. Ngarrindjeri *Yannarumi* has a historical meaning which is currently being articulated by Ngarrindjeri leaders in a contemporary form that takes into account the impacts and changes that have occurred to Ngarrindjeri *Yarluwar-Ruwe* as a result of colonisation. In its engagement with the development of the redrafted ECD, the NRA is conducting a *Yannarumi* (Speaking as Country) assessment of the health of the Ramsar site, addressing the overall wellbeing of Ngarrindjeri *Yarluwar-Ruwe*. This incorporates an assessment of the health-giving effects of the ECD process that has been collaboratively developed with the SA Government. Ngarrindjeri have used the *Yannarumi* framework to assess the capacity of the Ramsar site to reproduce Ngarrindjeri wellbeing through what can be translated as a philosophy of interconnected benefit and responsibility (Hemming & Rigney 2016). *Yannarumi* assessments could provide a basis for sharing Ngarrindjeri worldviews into the ECD development as part of the Ramsar Management Plan, and could be used on an ongoing basis as part of the co-governance and co-assessment process for Ramsar site monitoring on Ngarrindjeri Country. To further translate Ngarrindjeri philosophy, Ngarrindjeri have further developed the KNY framework to include Speaking as Country agreements, which acknowledge that

Ngarrindjeri speak as/for, control and care for their Country. The 2014 Speaking as Country Deed, for example, specifically commits the Government to working with Ngarrindjeri to further improve the health of the culturally and spiritually significant 'Meeting of the Waters' area, which is crucial to Ngarrindjeri wellbeing (NRA & MSEC 2014).

Ngarrindjeri are establishing themselves as sovereign partners in wetland management, thus demanding that the State Government respond by sharing power in decision making, by foregrounding Indigenous involvement in environmental policy creation, and by prioritising opportunities for Indigenous employment in policy implementation. This is required to safeguard the meaningful, well-resourced involvement of Indigenous agents throughout the whole process, so that Ngarrindjeri Country, and thus Ngarrindjeri themselves, can be healthy. As Ngarrindjeri leaders and elders have consistently and publicly stated: 'The lands and waters are a living body. We the Ngarrindjeri people are part of its existence. The lands and waters must be healthy for the Ngarrindjeri people to be healthy' (see Trevorrow in Hemming et al. 2002, p. 3).

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CHAPTER 4.5

TOWARDS NGARRINDJERI CO-MANAGEMENT OF *YARLUWAR-RUWE* (SEA COUNTRY — LANDS, WATERS AND ALL LIVING THINGS)[1]

STEVE HEMMING[2,3] AND DARYLE RIGNEY[2,4]

> The land and waters is a living body. We the Ngarrindjeri people are part of its existence. The lands and waters must be healthy for the Ngarrindjeri people to be healthy
>
> (see Trevorrow in Hemming, Trevorrow & Rigney, 2002, p. 3).

> We argue that because Ngarrindjeri water, wetlands and floodplains are so intimately tied to Ngarrindjeri wellbeing there must be a holistic, long-term program for Ngarrindjeri to address the impacts of extensive environmental degradation of Ngarrindjeri lands and waters. This means developing research, employment, education/training, planning, cultural and spiritual processes. In this way Ngarrindjeri can hope to achieve wellbeing in a globalising economy, a twenty-first century world and on Yarluwar-Ruwe that is affected by global warming and destructive non-Indigenous land and waters practices.
>
> (Birckhead et al. 2011, p. 42).

INTRODUCTION

For Indigenous peoples living within settler democracies such as Australia, Canada, the United States and New Zealand, securing rights to Country and gaining recognition of Indigenous values and knowledges have taken various pathways, usually through some form of treaty process (Langton et al. 2004). In Australia, land rights, native title and cultural heritage protection have produced the key legislative frameworks through which rights, responsibilities and values associated with Country have been negotiated. In South Australia, new approaches to Ngarrindjeri engagement in Natural Resource Management (NRM) and Cultural Heritage Management (CHM) have emerged from a particular set of environmental, historical, cultural and political circumstances (DEWNR & NRA 2012b; Hemming & Rigney 2008; Hemming & Rigney 2012; Hemming et al. 2007; NRA & DEWNR 2012; Rigney et al. 2015). Since colonisation, Ngarrindjeri have struggled for recognition as the true custodians of their lands and waters (Ngarrindjeri Nation 2007). Over a century of non-Indigenous NRM and land use

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[1] This chapter is based on Hemming & Rigney (2016) and Hemming & Rigney (2014).

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policy in Australia has effectively excluded Indigenous interests, creating a significant obstacle for the Ngarrindjeri Nation to meet their customary obligations to Care for/as Country. In recent years, the Coorong Lower Lakes and Murray Mouth (CLLMM) region, as part of the Australia's Murray-Darling Basin, has been at the centre of extensive environmental management programs emerging from government policies seeking to address ecological degradation caused by the Millennium Drought, induced by climate change, and the over-allocation of water (see DEH 2009). The intensification of government intervention on Ngarrindjeri lands and waters amplified the need for negotiations to occur between Ngarrindjeri and the State of South Australia regarding possible solutions that begin a process of non-Indigenous recognition of the importance of Ngarrindjeri *Ruwe/Ruwar* (the connectivity between lands, waters, people and all living things) to Ngarrindjeri wellbeing (Hemming et al. 2002).

Foundational to a new approach to engagement was the development of the contract law *Kungun Ngarrindjeri Yunnan Agreement* (listen to what Ngarrindjeri have to say — KNYA) (see Hemming et al. 2010, 2011; KNYA 2009). This strategy developed from a long history of Ngarrindjeri political organisation and resistance against colonisation and it has been central to the development of the Ngarrindjeri Regional Authority (NRA), the Ngarrindjeri Nation's peak body (Hemming & Rigney 2008; Rigney et al. 2015). The landmark 2009 KNYA created a mechanism for building Ngarrindjeri Nation capacity to become a critical contributor to regional NRM through partnership projects with the Department of Environment, Water and Natural Resources (DEWNR) and framed Ngarrindjeri engagement in the State Government's *Murray Futures* CLLMM Recovery and Riverine Recovery Projects. This chapter provides an overview of the development of the innovative Ngarrindjeri-led Indigenous engagement strategies in NRM that emerged from this context with a focus on the *Murray Futures* Ngarrindjeri Partnerships Project, a key management action under the CLLMM Recovery Project (see Hemming & Rigney 2012). We argue that the shift towards Indigenous 'inclusion' in NRM and recognition of Ngarrindjeri leadership in 'co-management' of Country are fundamental to healing damaged ecological systems such as the Coorong, Lower Lakes and Murray Mouth region. They are also crucial factors in healing the Ngarrindjeri, who are a part of *Yarluwar-Ruwe* (Sea Country), and the ongoing legacy of colonialism and racism in Australian society. Importantly, this chapter is written from the perspective of a theorised Indigenous engagement with Western NRM — from the First Nation context looking outward. The shifts in NRM policy and practice outlined in this chapter are in line with Australia's obligations as a signatory to the *United Nations Declaration on the Rights of Indigenous Peoples* (UN 2007).

THE HISTORICAL CONTEXT TO NGARRINDJERI ENGAGEMENT WITH NATURAL RESOURCE MANAGEMENT (NRM) IN THE CLLMM REGION

Since South Australia's establishment as a British colony in 1836, Ngarrindjeri and other Indigenous people have struggled to protect their cultures, communities, lands and waters — in short, to 'Speak as Country' (see Berg 2010; Mattingley & Hampton 1988). As a result of the colonial history of dispossession and oppression, Indigenous Nations across Australia have very limited 'rights' to water and other natural resources except indirectly through a weakened native title regime and even more indirectly through state legislation such as the *Aboriginal Heritage Act 1988* (SA) (see Hattam et al. 2007; Jackson 2012; Jackson et al. 2012; McFarlane

2004; Turner & Neale 2015; Tan & Jackson 2013; Weir 2009, 2012). This situation differs significantly from the experiences of Indigenous peoples in comparable settler democracies such as Canada, the USA and New Zealand. In all these examples there exists significantly stronger recognition of Indigenous rights to lands and waters (see Hemming et al. 2007; Langton et al. 2004; Strelein 2006; Veeder 1964).

Nonetheless, Ngarrindjeri have maintained a strong connection to Country through a cultural tradition of *Ruwe/Ruwar*. Ngarrindjeri have continued to draw attention to the damaging changes being made to Ngarrindjeri Country through ongoing colonisation (see Bell 2008; Ngarrindjeri Nation 2007). Ngarrindjeri argue that the draining of South Australia's Southeast has had damaging effects on the flow of water into the Coorong and into the Lower Murray region more generally. The draining of wetlands/nurseries along the Murray and the building of levee banks and barrages to facilitate industries such as dairy farming and fruit growing have had devastating impacts on the health of the South Australian Murray-Darling Basin (MDB) and the lives of Ngarrindjeri people. With changing freedoms after the famous 1967 Referendum, Ngarrindjeri began a new strategy of building better 'race' relations with the non-Indigenous community. The Ngarrindjeri (re)conciliation strategy has continued to the present and became a focus in the 1980s with the establishment of Camp Coorong: Race Relations and Cultural Education Centre (see Hemming & Rigney 2008; Rigney & Hemming 2014). Always at the centre of this Indigenous communication and educational program have been Ngarrindjeri stories, histories and lessons with a message for non-Indigenous people to develop a respectful, health-giving relationship with Ngarrindjeri lands and waters. Ngarrindjeri have continued to exercise responsibility to 'Speak as Country' to preserve the reproductive health of Ngarrindjeri *Yarluwar-Ruwe*.

In the early 1990s, using new Aboriginal heritage legislation, Ngarrindjeri men and women argued that the waters around *Kumarangk* (Hindmarsh Island) are spiritual waters and crucial for the life of the Ngarrindjeri Nation. They argued that building a bridge between the mainland at Goolwa and Kumarangk would do irreparable damage to the spiritual context of the region and therefore the health of the River, the Lakes and the Coorong and all connected living things (see Bell 1998, 2008; Saunders 2003; Stevens 1995; Trevorrow & Hemming 2005). They attempted to communicate the core Ngarrindjeri cultural principles associated with *Ruwe/Ruwar*. The litigation around the Hindmarsh Island bridge issue was fought in multiple courts and in both state and federal jurisdictions. In 1995 a Royal Commission was established to investigate these traditions, and its findings rejected the Ngarrindjeri traditions (see Simons 2003; Stevens 1995). In 2001 a decision by Justice von Doussa in the Federal Court of Australia supported the Ngarrindjeri claims to the cultural and spiritual significance of the 'Meeting of the Waters' and the *Kumarangk* area (von Doussa 2001). This was after the bridge had already been erected and the desecration of Ruwe/Ruwar had occurred. As a consequence of difficult and extended negotiations and agreement making, the Meeting of the Waters 'site' has been registered under the *Aboriginal Heritage Act 1988* (SA) and has been recently recognised as significant to NRM and water planning in South Australia and the broader MDB (Hemming 2009; MDBA 2014).

At the start of the new millennium south-eastern Australia was plunged into a serious climate-induced drought, and over-extraction of water in the MDB severely restricted the flow of water through Ngarrindjeri *Ruwe*, impacting the health of the lower River Murray, Lakes Alexandrina and Albert, and the Coorong. The region supports a fragile ecology where the 'Meeting of the Waters' takes place, as fresh water combines with ocean salt water in the tidal flows of the river mouth (see Bell 1998, 2014; Hemming et al. 2002; Kampf & Bell 2014). This area is a vital cultural and creation place for the Ngarrindjeri, and a habitat and breeding ground for many Ngarrindjeri *ngartji* (totems — friends). In 1998 the Ngarrindjeri Ramsar Working Group produced a Nation-endorsed position paper that lamented the degradation of waters in the region:

> Too much water has been diverted from the river system and not enough water now reaches the Lakes and Coorong. The quality of the water has also fallen. The water is cloudy, polluted and not fit for drinking. The Murray, the Lakes and the Coorong are no longer environmentally healthy and this is partly why the Ngarrindjeri people are not healthy. The Ngarrindjeri know that the Coorong, Lakes and River are dying.
>
> (NRWG 1998, p. 5)

The Ngarrindjeri position paper was referred to, but not included, in the final Ramsar Management Plan as a key discussion paper, after promises were made by the South Australian Government (DEH 2000). The disrespectful approach to Ngarrindjeri values, aspirations and knowledges was compounded by the degraded health of the river system. The unhealthy state of the system was a direct counterpoint to the Ngarrindjeri 'Vision for Country', which encapsulates the Ngarrindjeri philosophy of being (Ruwe/Ruwar) at the centre of Ngarrindjeri Caring for their lands and waters:

> Our Lands, Our Waters, Our People, All Living Things are connected. We implore people to respect our Ruwe (Country) as it was created in the Kaldowinyeri (the Creation). We long for sparkling, clean waters, healthy land and people and all living things. We long for the Yarluwar-Ruwe (Sea Country) of our ancestors. Our vision is all people Caring, Sharing, Knowing and Respecting the lands, the waters and all living things.
>
> (Ngarrindjeri Nation 2007 in MDBA 2014, p. 25).

In a continuing attempt to change the character of contact between themselves and Australian government agencies, Ngarrindjeri leaders and elders decided to develop their own management plan — the Ngarrindjeri Nation *Yarluwar-Ruwe Plan* (2007) (henceforth, 'the plan'). The plan's vision makes clear the essential link between the wellbeing of individuals, families, communities, their unique worldview and their right and responsibility to Care for Ngarrindjeri lands and waters. It articulates a broad vision and a set of strategic directions for Caring for Ngarrindjeri Country, emphasising that 'the river, lakes, wetlands/nurseries, Coorong estuary and sea have sustained us culturally and economically for tens of thousands of years' (Ngarrindjeri Nation 2007, p. 6). It is important to appreciate that the Ngarrindjeri Nation *Yarluwar-Ruwe Plan* is both a policy document and a constitutional statement by the Ngarrindjeri Nation (Hemming et al. 2016). Importantly, the plan provided Ngarrindjeri with a vital negotiating tool used to challenge the South Australian Government to provide Ngarrindjeri with the capacity to take a leading role in Caring for/as Country under South Australia's Murray Futures initiative (see Hemming & Rigney 2010; Maclean & The Bana Yarralji Bubu Inc. 2015). The *Yarluwar-Ruwe Plan* has been crucial in the process of critiquing and rewriting discriminatory elements of what we refer to as the contemporary ‘contact zone’, such as fundamentally racist archival sources; out-of-date management plans; and government policies (see Hemming & Rigney 2010; Maclean & The Bana Yarralji Bubu Inc. 2015).

NEW THEORETICAL AND METHODOLOGICAL TRAJECTORIES: TOWARDS NGARRINDJERI CO-MANAGEMENT OF YARLUWAR-RUWE

The Ngarrindjeri approach to NRM prioritises Indigenous Nation building principles and asserts a cultural responsibility to Speak as Country (Yannarumi) (Cornell 2015b; Cosens & Chaffin 2016). This strategy has gathered pace since the 1995 Hindmarsh Island (Kumarangk) Bridge Royal Commission but can be identified as starting in its contemporary form in the mid-1980s with the establishment of organisations such as the Ngarrindjeri Tendi Inc. and the Ngarrindjeri Land and Progress Association Inc. (see Ngarrindjeri Nation 2007; Stevens 1995). A collective of Ngarrindjeri leaders, scholars and non-Indigenous supporters has contributed to its development, using insights from Ngarrindjeri philosophy and experience, along with ideas from cultural studies, Indigenous standpoint theory, postcolonial theory, critical race theory and other contexts (see, for example, Barad 2007; Berg 2010; Braidotti 2009; Bignall 2010; Byrd 2011; Gammage 2011; Haraway 1988; Hemming 2006; Moreton-Robinson 2007, 2013; Nakata 2007; Rose 1996; Rigney et al. 2015; Smith 1999, 2012). This list reflects the complexity of theory and ideas brought together in the South Australian context to address the challenges faced by Indigenous leaders when attempting to develop the best strategies for producing healthy futures for their people, their lands and waters. The results of this work have produced significant changes in relations between Ngarrindjeri and the South Australian Government.

Challenges of sustainability have in recent years prompted an important shift within Western environmentalism towards ‘posthumanism’ — a shift away from a human-centred understanding of being (see Barad 2007; Braidotti 2009; Latour 2004; Weir 2009). For example, Felix Guattari, influential French ‘post-humanist’ philosopher, posed questions to generate thinking about new futures where responsibility for wellbeing brings with it a more ethical and accountable relationship between people, lands, waters and all living things (Guattari 2000). This vision for human and non-human life resonates with Ngarrindjeri strategies for engaging with NRM and other interventions in Ngarrindjeri Country. It can be argued that ‘post-humanist’ objectives such as Guattari’s share common ground with Indigenous ‘decolonising’ projects or, in the Ngarrindjeri context, with Nation (re)building work (see Bignall et al. 2016; Rigney & Hemming 2014; Rigney et al. 2015; Smith 1999, 2012).

Whilst this conceptual framework shares many features in common with Indigenous ontologies, epistemologies, axiologies and ethologies, it typically fails to acknowledge Indigenous knowledges as a prior form of this ‘new’ paradigm. What is otherwise a promising move in environmental theory continues a long colonial tradition of the non-recognition of Indigenous agency and authority. For example, baseline drafts of the Coorong and Lakes Alexandrina and Albert wetland Ramsar site Ecological Character Description (ECD) assumed that in 1836 the Ramsar site was in a ‘natural’ state, untouched by human interaction — obscuring Ngarrindjeri agency. Since British colonisation there is a story of human-induced degradation of the ecological health of the wetlands as a consequence of agriculture, irrigation and other interventions. Ngarrindjeri survival through the most intensive periods of colonisation is invisible in this account and the only human interactions with the lands and waters are identified as non-Indigenous. Although the developing guidelines and protocols emerging from the Ramsar Convention are incorporating ideas such as biocultural diversity, reflecting an increasing influence of contemporary cultural theory, philosophy and Indigenous perspectives, these shifts are yet to be reflected in Australian Ramsar guidelines (DEWHA 2008; Hemming et al. forthcoming). However, when these conceptual innovations do make an appearance in Australian Ramsar planning and management, they will need to take into account Indigenous critiques of posthumanism and associated calls for a more sophisticated system of valuing of 'ecosystems services' and engaging with Indigenous conceptualisations of Country (see Weir 2009; Birckhead et al. 2011; Byrd 2011; Comberti et al. 2015; Coombes et al. 2014; Ens et al. 2015; Hill et al. 2013; Hoogeveen 2016; Howitt et al. 2013; Jackson & Palmer 2015; Pert et al. 2014; Pröpper & Haupts 2014; Sullivan 2010; Tadaki et al. 2015; Winthrop 2014). It is therefore important to understand limits inherent in the principal framework for conceptualising the relationships between the 'environment' and humans: this is the ecosystem services model which brings capitalist systems of valuing and Caring to bear in a reductionist approach to describing and managing 'Country'.

A recently published Murray-Darling Basin case study, conducted by Rosalind Bark and other high-profile Australia water policy researchers, applies cultural Ecological Services (ES) typologies to the famous Brewarrina fish traps. These researchers make important points about concepts such as connectivity, cultural landscapes and system holism that clearly illustrate the direction that Indigenous and non-Indigenous researchers and leaders are attempting to take in order to shift the current Australian water management and NRM regimes:

> Taking the issue of connectivity more broadly, it can be understood in a range of ways in terms of cultural ES — hydrological and ecological connectivity between the Ngemba billabong and the fish traps, between people and the river, between cultural practices and hydrological knowledge of water flows and waterway ecologies, and between Dreamtime (Creation) stories and their encoded rules and current management practices. These aspects of cultural value expand the importance of the fish trap site from one that is significant for its archaeological value to one with multiple social, cultural, ecological and economic values, as well as recognition of the key stewardship role of traditional owners and custodians. System holism is central to indigenous water cultures from the Darling River region (Muir et al. 2010) and elsewhere (Barber 2005; Bradley 2010), yet it is difficult to place within current typologies that demarcate categories of value (economic, cultural, ecological) and/or posit oppositions such as those made by Chan et al. (2012): self-oriented vs. other-oriented, individual vs. group, physical vs. metaphysical, etc. Future research could field test these value dichotomies and address the value of system holism (see Johnston et al. 2011 for an example) or what has become known in heritage circles as a cultural landscape approach (Byrne et al. 2003).
>
> (Bark et al. 2015, p. 8)

It took Ngarrindjeri over 15 years to convince the South Australian Government that the 'Meeting of the Waters' area at the mouth of the River Murray is a sacred cultural landscape that is vital to the reproduction of life and that encapsulates the Ngarrindjeri philosophy of *Ruwe/Ruwar* — interconnectivity (see Bell 1998, 2008, 2014; Simons 2003; Birckhead et al. 2011; Hemming 2009; Hemming & Rigney 2014). As journalist David Nason reported in the *Australian* in July 2010, 'When it was over[,] the Hindmarsh Island affair had become one of the most complex and bitterly litigated racial conflicts in Australian history' (Nason 2010). The contract law KNYA strategy and a combination of legal, interdisciplinary and multidisciplinary research were required to produce a successful outcome in these negotiations (see Hemming et al. 2011).

The trajectories, strategies and theoretical innovations developed and adapted by Ngarrindjeri to create a 'decolonial' shift in NRM put into practice recent calls for a more nuanced approach to engaging with concepts such as 'ecosystem services' and 'cultural ecosystem services' being deployed in Australian contexts, such as Ramsar ECDs (see Appadurai 1990; Bark et al. 2015; Hemming & Rigney 2008; Jackson & Palmer 2015). Ngarrindjeri have understood the application of these concepts and practices to have potentially detrimental effects to Ngarrindjeri wellbeing and connectivity, and to be part of the continuing colonisation of Ngarrindjeri lands and waters (see Hemming & Rigney 2008; Hemming et al. 2011; Jackson & Palmer 2015; Mignolo 2011; Sullivan 2010). The Ngarrindjeri Regional Authority (NRA) has developed a strategic, theorised form of negotiation and Nation building which uses contract law to reframe the discourse, power relations, ontologies, epistemologies and practices that flow into Ngarrindjeri *Yarluwar-Ruwe* with globalising forms of environmental management and commodification. For Ngarrindjeri, a *Yannarumi* process provides a mechanism for creating and assessing the impacts on Ngarrindjeri wellbeing resulting from interactions with settler-state policies, program and practices.

KUNGUN NGARRINDJERI YUNNAN: INNOVATIONS IN INDIGENOUS ENGAGEMENT IN NRM

Ngarrindjeri Nation (re)building accelerated in 2007 with the official incorporation of a centralised governing body, the NRA, tasked with representing and acting for Ngarrindjeri interests. The establishment of the NRA — the first Indigenous peak body representing an Indigenous Nation in South Australia — emerged from the Ngarrindjeri leadership's long-term aim of continually improving the wellbeing of Ngarrindjeri *Ruwe/Ruwar* — the inseparable relation between lands, waters, body, spirit and all living things. As stated above, the NRA has developed a strategic, theorised form of negotiation and Nation building which uses contract law to reframe the discourse, power relations, ontologies, epistemologies and practices that flow into Ngarrindjeri *Yarluwar-Ruwe* with globalising forms of environmental management. This way of doing business is formally recognised by government at local, state and federal levels though the signing of KNY agreements and Indigenous Regional Partnership Agreements based around Caring for Country and economic development. Establishing the NRA was a vital first step in the Nation (re)building process, allowing Ngarrindjeri to identify authoritatively as a Nation, and to be identified as such by settler powers. This primary moment of National identification then allowed Ngarrindjeri to organise politically and to act more effectively as a consistent and representative power in the South Australian political landscape (Cornell 2015a). The NRA continues to reinforce the need for a shift in the use of government resources for Indigenous NRM programs to long-term support for the development of the NRA's capacity to effectively respond to government demands on Ngarrindjeri 'informed consent', and Ngarrindjeri 'participation' in the state's environmental programs.

In 2007, following in the footsteps of earlier Ngarrindjeri NRM and cultural heritage programs, the NRA established a Caring for Country Program (later renamed the NRA Yarluwar-Ruwe Program) to implement and further develop the visions of the *Yarluwar-Ruwe Plan* (see Hemming et al. 2007). The *Yarluwar-Ruwe* program was responsible for coordinating and supporting holistic Ngarrindjeri heritage and Caring for/as Country activities. Through the program, the NRA worked with government and local communities to develop new forms of NRM that recognised Ngarrindjeri values and incorporated Ngarrindjeri expertise and capacity. Much of the energy in this process was directed towards improving governance, towards Caring for Country programs with associated economic development opportunities, and towards creating new relationships with government at all levels to achieve these objectives. The NRA was critical in this process, providing a centralised point of contact between non-Indigenous interests and the Ngarrindjeri Nation. The NRA's Research, Policy and Planning Unit, hosted by Flinders University, led the development of the policy and research strategies underpinning the new *Yarluwar-Ruwe* Program.

As a program, it was the conduit for all external and internal projects and programs associated with Ngarrindjeri *Yarluwar-Ruwe*. First contact from outside organisations was made via the NRA Board, and a joint Ngarrindjeri and government taskforce was established under the 2009 KNYA. Once ideas, projects and programs were presented through these channels they were referred to the NRA *Yarluwar-Ruwe* Program for detailed assessment, engagement and consideration. Importantly, the *Yarluwar-Ruwe* Program brings NRM, CHM and other related issues together. This is a unique feature of the Ngarrindjeri approach to Caring for/as Country, putting into practice the Ngarrindjeri philosophy of being, Ngarrindjeri Ruwe/Ruwar. The NRA vision that Ngarrindjeri lands and waters need to be healthy for Ngarrindjeri to be healthy is at the centre of this approach. Key features of the *Yarluwar-Ruwe* Program included

- formal representation of all appropriate Ngarrindjeri bodies such as the Ngarrindjeri Heritage Committee, Ngarrindjeri Native Title Management Committee, Ngarrindjeri Tendi (traditional governance) and others
- devolved decision making — the NRA Board has formally established the program to provide a best-practice model for 'Caring for *Yarluwar-Ruwe*'
- prioritisation of the establishment of a program of Statement of Commitments (formal terms of reference) and associated working groups that frame and direct Ngarrindjeri/government projects and programs
- development and use of cultural knowledge protection clauses in all NRA contracts, KNY agreements (these are contract law agreements) and research projects (with outside bodies)
- decision making that is culturally appropriate to Ngarrindjeri
- empowerment of Ngarrindjeri and a coordinated, long-term capacity building program
- the ability to deal with multiple issues and projects, including direct engagement in conduct and development of research projects
- development of strategies that support cultural change in government policy, programs and practices — abolition of whiteness in government policy

- stakeholder involvement through presentations and small working groups
- innovative use of technology, with a Ngarrindjeri media team producing award-winning documentaries and reports on film and digital formats
- diverse engagement and partnership building with research, educational and business sectors — partnerships with Flinders University, national and international universities, local businesses, government at all levels, NRM Boards, community groups
- the support and development of Ngarrindjeri Caring for Yarluwar-Ruwe with regards to economic development and employment securing of NRM contracts, employment, training and education.

The Ngarrindjeri *Yarluwar-Ruwe* Program has resisted and transformed the contemporary 'contact zone' in natural resource and cultural heritage management to produce new 'actor networks' that carry life-giving flows that sustain Indigenous Nation building. Importantly, the *Yarluwar-Ruwe* Program provided a culturally appropriate and strategic Indigenous engagement mechanism to support a number of major regional NRM partnership projects such as the *The Living Murray Program* and the *Murray Futures* CLLMM and Riverine Recovery Programs, and the development and implementation of the Murray-Darling Basin Plan in the South Australian Murray-Darling Basin (NRA 2012). It also facilitated an ongoing and developing partnership between the NRA and the four regional NRM Boards and the NRM programs of the regional local councils. It was a successful mechanism for discussion, analysis and decision making and has been influenced by best practices in leading First Nation contexts internationally (see Hemming et al. 2011).

In 2009, the Ngarrindjeri Nation negotiated a new KNYA with the State of South Australia that established a process for negotiating and supporting rights and responsibilities for Country (see Hemming et al. 2011). This whole-of-government contractual agreement between the Ngarrindjeri Nation and the State was set in place to frame the Ngarrindjeri strategy for negotiating Ngarrindjeri interests in NRM and in particular the South Australian Government's long-term plan for the Coorong, Lower Lakes and Murray mouth (see DEH 2009; KNYA 2009). The agreement includes a recognition of Ngarrindjeri traditional ownership; recognition of the NRA as the Ngarrindjeri peak body; and an agreement to negotiate on key, long-held Ngarrindjeri objectives, such as the co-management of parks and reserves within the Ngarrindjeri and others' Native Title Claim and the 'hand-back' of the Coorong National Park. The KNYA is a legal, binding agreement entered into between Ngarrindjeri leadership and four Ministers of the Crown in South Australia (the Minister for Sustainability, Environment and Conservation, the Minister for Water and the River Murray, the Minister for Agriculture, Fisheries and Forestry, and the Minister for Aboriginal Affairs and Reconciliation) to articulate specific rights and obligations that provide the beginnings of a new, more just relationship. Recitals D and E provide an indication of the intentions of the agreement:

> D. The Ministers have expressed a desire for a new relationship between the State of South Australia and Ngarrindjeri based upon mutual respect and trust acknowledging that Ngarrindjeri consider protection and maintenance of culture and cultural sites upon its land and water central in every respect to Ngarrindjeri community well being and existence.

> E. By this Agreement the Ministers wish to provide support and resources to the Ngarrindjeri Regional Authority Inc and enter into negotiations and consultations with the Ngarrindjeri about the maintenance and protection of Ngarrindjeri culture and cultural sites and the natural resources of the Land [lands and waters].
>
> (KNYA 2009, p. 1).

The Ngarrindjeri's first *Kungun Ngarrindjeri Yunnan Agreement* (KNYA) was entered into with Alexandrina Council in the early 2000s, but the 2009 KNYA with the South Australian Government brought all government agencies to the table. The 2009 KNYA established quarterly leader-to-leader meetings between the signatory Ministers and Ngarrindjeri leadership, providing a resourced, formal structure for meetings and negotiations between the Ngarrindjeri Nation, as represented through the Ngarrindjeri Regional Authority, and government, universities and other non-Indigenous organisations (Rigney et al. 2015). It also included the establishment and funding of a joint taskforce that created a formal context for the NRA to negotiate regarding South Australian Government programs on Ngarrindjeri Ruwe/Ruwar. Monthly taskforce meetings were held between the NRA and relevant State agencies and statutory authorities representing environment, natural resources, Water, Aboriginal Affairs and State Development. The KNYA Taskforce, which was established in 2010, met 75 times throughout the CLLMM Project (DEWNR & NRA 2012a, 2012b, 2013, 2015) and was the key driver to implementing the KNYA, providing a forum for the parties to engage on natural and cultural resource management issues, including

- coordination of Ngarrindjeri engagement across departments
- support of early engagement
- provision of an opportunity for government to seek Ngarrindjeri advice and input to its proposals
- development of collaborative initiatives.

Guiding the taskforce was the KNYA Strategic Implementation Plan (SIP), which was developed by NRA and South Australian Government representatives from the KNYA Taskforce in 2011. The SIP had five objectives covering issues such as capacity building, education, economic development, NRM and research, and it was reviewed by the KNYA Taskforce on an annual basis. SIP actions were integrated into the monthly KNYA Taskforce meetings to ensure that a focus on strategic issues was maintained (DEWNR & NRA 2012a). As an example, the KNYA Taskforce pursued its stated objectives through initiatives such as the organisation of a series of workshops focusing on Indigenous people and water issues. This led to the development of a Water Resource Planning Statement of Commitment (SOC) that was entered into by the NRA and South Australian Government for the South Australian Murray-Darling Basin (SAMDB) region (NRA et al. 2015). The SOC was developed in line with the KNYA strategy to support the incorporation of Ngarrindjeri aspirations, values and knowledges in regional water planning. It was a positive step towards both clarifying relationships and activities to implement the MDB Plan and progressing Ngarrindjeri water interests.

The taskforce in particular played a significant role in establishing a formal relationship with DEWNR, which underpinned the Ngarrindjeri engagement strategy in the CLLMM

Recovery Project. For Ngarrindjeri, a key strategic purpose of the KNYA was to create a formal mechanism enabling Ngarrindjeri cultural values to become integral to all planning and future management arrangements impacting Ngarrindjeri Yarluwar-Ruwe. As a key commitment under the KNYA, DEWNR (formerly DEH) and the NRA began working closely to co-develop the Ngarrindjeri Partnerships Project (NPP), one of 19 management actions under the CLLMM program and its key Aboriginal engagement strategy, aligned with the overall CLLMM Recovery Project objective 4: 'The culture of the traditional owners, the Ngarrindjeri, is preserved and promoted through partnerships and involvement in projects' (NRA & DEWNR 2012, p. 5). The NPP worked across the other CLLMM program management actions and supported the development of core capacity within the NRA to ensure that Ngarrindjeri knowledge, experience and cultural values were appropriately incorporated into regional NRM. A funding and service agreement for the project was entered into between the NRA and DEWNR in 2011, ceasing in June 2016. The NRA identified several long-term Caring for/as Country objectives guiding the CLLMM NPP, developed to align with the objectives of the Ngarrindjeri *Yarluwar-Ruwe Plan* (NRA & DEWNR 2012, p. 5):

1. Protect Ngarrindjeri cultural heritage and unique relationship with, and responsibilities for, the region;
2. Develop and nurture strong and productive partnerships between Ngarrindjeri, industry, government and others;
3. Build professional and culturally appropriate Ngarrindjeri capacity to engage meaningfully with current and future actions to restore the health of the Coorong, Lower Lakes and Murray Mouth;
4. Ensure Ngarrindjeri participation in governance mechanisms and integrate their interests and perspectives into planning, research and policy development;
5. Ensure Ngarrindjeri play a major role in implementing strategies to develop a resilient and healthy future for the lands and waters and all living things;
6. Increase economic and social wellbeing within the Ngarrindjeri community; and
7. Support Ngarrindjeri enterprises within a growing contemporary Ngarrindjeri economy.

These funded long-term objectives clearly outline the Ngarrindjeri program of reassembling, or transforming, the contemporary 'contact zone' in NRM and CHM, to shift from ingrained, colonising characteristics towards a respectful set of relationships that reproduce Ngarrindjeri wellbeing. Unfortunately, the NRA was left out of the original business case for the South Australian Government's second project under *Murray Futures*, the Riverine Recovery Project. The NRA's engagement in the RRP, which focused on 'water savings' and increasing river and wetland health, was only secured under a funding and service agreement in mid-2013 (see Hemming et al. 2017).

The CLLMM NPP agreement also included clauses specifically protecting Ngarrindjeri cultural knowledge as a category separate from intellectual property (see Hemming et al. 2011). The following is an example of a key definitional clause, which relates to the principle of cultural knowledge protection enabling Ngarrindjeri to safely share knowledge:

> Cultural Knowledge means all and any cultural knowledge, whether such knowledge has been disclosed or remains undisclosed of the Indigenous group, including but not limited

> to: (a) traditions, observances, customs or beliefs; (b) songs, music, dances, stories, ceremonies, symbols, narratives and designs; (c) languages; (d) spiritual knowledge; (e) traditional economies and resources management; (f) scientific, spatial, agricultural, technical, biological and ecological knowledge; and includes documentation or other forms of media arising therefrom including but not limited to archives, films, photographs, videotape or audiotape.
>
> (Hemming et al. 2010, p. 100)

Under the NPP, the NRA provided input into six of the CLLMM Management Actions (MAs), including five on-ground project areas: the Ruppia Translocation, the Lake Albert Scoping Study, the Meningie Foreshore, Monitoring and Research (MA13) and the Vegetation Program (MAs 1-5). The NRA also provided input into the review process for the Ecological Character Description (MA13). The following list, although not comprehensive, provides some examples of Ngarrindjeri contribution to key MAs:

- *Ruppia translocation*: The NRA provided input into the implementation plan, assisted in the selection of sites, provided support for sample collection and monitoring work, provided cultural heritage assessment and received the commercial contract to bag sediment for translocation and delivery to reseeding locations.
- *Lake Albert Scoping Study (LASS)*: The NRA developed a position paper, participated in a field trip and provided cultural heritage assessment.
- *Meningie Foreshore project*: The NRA provided input into interpretative elements of the project (signage, artwork, pathway design), provided a cultural heritage assessment, selected plant species, received the contract to undertake revegetation works and produced a video production of the project.
- *Ecological character description*: The NRA provided detailed content to include into the ECD.
- *Research and monitoring*: The NRA reviewed the annual program, gave input into the development of a cultural heritage assessment process, provided cultural heritage assessment, participated in monitoring activities with contractors (CSIRO, SARDI), and delivered contractor inductions and a Yarluwar-Ruwe protocols workshop.
- *Vegetation program*: The NRA provided input into the development of a cultural heritage assessment process, provided cultural heritage assessment, provided input into site plans and into the regional prioritisation process, participated in joint site visits to identify high-interest restoration sites, provided input into the Marks Point restoration plan, and revegetated key culturally significant sites (through separate funding and service agreements with DEWNR between 2011-2016).

These activities were supported by the 16 NRA employees funded by the CLLMM NPP. This included 10 staff (Coordinator, GIS Officer, Planning Officer, Research Officer, Training Officer, Heritage Manager, Heritage Specialist, two Cultural Rangers, half-time Heritage Trainee) and six nursery/on-ground staff employed through various Vegetation Program grants, supplemented by a pool of casual Ngarrindjeri employees. Through the project, the NRA supported in excess of 20 Ngarrindjeri to complete accredited vocational training to complete Certificate III, Certificate IV and the Associate Diploma in Conservation and Land Management across the CLLMM NPP, Aboriginal Learning on Country (ALoC) and Working on Country (WoC). The NRA has also facilitated an ongoing heritage training program for over 20 Ngarrindjeri, which has incorporated cultural knowledge transmission with elders, as well as intensive training related to repatriation (developed and delivered by the NRA, Flinders University and the Australian National University). In addition, through a partnership with *Change Media*, Ngarrindjeri have been trained in film and media production, producing various projects focusing on communicating Ngarrindjeri participation in Caring for their lands and waters. This training, delivered by the NRA over the course of the Partnerships MAs, has also contributed a significant skill base for Ngarrindjeri to apply in protected area management, most importantly supporting the transition to co-management of the Coorong National Park. This work created strong relationships and an organisational awareness in the NRA regarding how parks are operated in the region.

Participation in the CLLMM program has significantly increased Ngarrindjeri knowledge and understanding of how NRM works in the region, including knowledge of legislation, policy, management and planning processes, and the role of science in setting policy. Further, participation in the program has developed Ngarrindjeri capacity and skills to conduct on-ground Caring for Country work in nurseries, revegetation projects, pest and weed control and site monitoring. There has also been a significant increase in Ngarrindjeri knowledge in water policy, planning and delivery, leading to Ngarrindjeri engagement in annual and long-term environmental water planning for the state and for the Murray-Darling Basin plan. This knowledge provides Ngarrindjeri with the capacity to develop a long-term future in NRM and the ability to engage in planning, policy, business case development and strategic training to secure this future. The increase in knowledge in NRM has occurred alongside the opportunity for younger people to work with Elders, providing opportunities for teaching cultural traditions, laws and responsibilities.

Fundamental to the KNY strategy has been the program of Statement of Commitments (SOCs) (formal terms of reference) and associated working groups that frame and direct Ngarrindjeri/government projects and programs and protect Ngarrindjeri cultural knowledge. SOCs were developed as crucial ‘tools’ for articulating the KNYA principles with specific projects and programs. Like a KNY agreement, an SOC can define engagement principles and agreed actions. Of the six MAs, four were identified by the NRA for further partnership throughout the duration of the CLLMM Project. SOCs and working groups were established to frame project activities such as Ruppia translocation; CLLMM Research and Monitoring; and Vegetation Management Planning for the CLLMM Project. They were also tasked with updating the Ramsar Ecological Character Description (see, for example, NRA & DEWNR 2014). They ensured clarity of process and provided protection for Ngarrindjeri cultural knowledge. Working groups were also established for other MAs, including the Lake Albert Scoping Study, SE Flows and the Meningie Foreshore project.

The CLLMM project has provided the opportunity for Ngarrindjeri and regional NRM organisations, local councils, and the State Government to develop a long-term mechanism for regionally resourcing Ngarrindjeri to carry out their responsibilities to speak and Care for Ngarrindjeri Country as recognised in the KNY Agreement 2009. This federally funded Partnership project was identified by Ngarrindjeri as an opportunity to create a legacy for the region which addresses the need to identify mechanisms that change the way Australian NRM supports Indigenous people to take cultural responsibility for their Country. NPP resources supported the development of the Ngarrindjeri Regional Authority, *Yarluwar-Ruwe* program which in turn has provided the model for the newly developed statewide Indigenous Regional Authority program (Department of State Development 2016).

NGARRINDJERI YANNARUMI — NGARRINDJERI SPEAKING AS COUNTRY

Non-Indigenous Natural Resource Management (NRM) tends to focus on maintaining what might be understood as the ecological health of Ngarrindjeri *Yarluwar-Ruwe* without taking into account the Ngarrindjeri philosophy of interconnectedness (*Ruwe/Ruwar*). For the Coorong and Lakes region this means a form of adaptive management designed to stabilse the 'ecological character' of the system in order to maintain its capacity to produce ecosystem services largely exclusive of Ngarrindjeri values and interests. The ecological health of Ngarrindjeri *Yarluwar-Ruwe*, using this model, is managed to produce services for non-Indigenous interests such as sustainable fisheries, irrigation-based industries and wetlands suitable for tourism. This can result in managing for artificial ecosystem stability to produce maximum or predictable yields rather than ecosystem resilience and sustainability (see Armitage et al. 2010; Berkes 1999; Shiva 1993). The NRA, however, invests in a holistic approach that understands Ngarrindjeri as part of the living body of the lands and waters and all living things — with a cultural responsibility to 'Speak as Country' (*Yannarumi*). Ngarrindjeri livelihoods, culture and wellbeing depend on exercising their cultural responsibility.

In 2014, Ngarrindjeri further embedded Ngarrindjeri cultural principles in the agreement-making process and extended the concept of Speaking as Country (*Yannarumi*), underpinning governing responsibility, into a Ngarrindjeri Speaking as Country deed (NRA & MSEC 2014). This agreement provides recognition in a more explicit way of the deep interconnectedness between Ngarrindjeri agency and responsibility, health of Country and health of people and cultural life. That is, Ngarrindjeri *Ruwe/Ruwar* (lands, waters, body, spirit and all living things) needs to be healthy for Ngarrindjeri to be healthy; and for this reason Ngarrindjeri Care for, speak as and exercise cultural responsibility as Ngarrindjeri *Ruwe/Ruwar*. The deed specifically commits the government to working with Ngarrindjeri to promote an improved understanding of the meaning and significance of the 'Meeting of the Waters' site. In signing an agreement, parties commit to listening to Ngarrindjeri 'Speaking as Country'. This shift in message from simply listening to Ngarrindjeri to a deeper understanding of Ngarrindjeri philosophy signalled a seismic shift in NRM in South Australia (Hemming et al. 2016).

Healing programs — Healthy flows (Restoring Ngarrindjeri *Yarluwar-Ruwe*)

Considering the continuing impacts of colonisation on Ngarrindjeri *Yarluwar-Ruwe*, the NRA has developed a *Yannarumi* assessment framework which is used to determine the health-giving potential of partnerships, agreements, projects, policies and activities. The framework uses criteria such as the following:

- *Ngiangiampe*: projects/engagements that build respectful relationships between Ngarrindjeri and other parties such as the State Government

- *Yannarumi*: projects/engagements that build Ngarrindjeri capacity to Care for/Speak as Country — lands, waters and all living things
- *Kaldowinyeri*: projects/engagements that respect Ngarrindjeri knowledge, law, tradition and expertise
- *Miwi*: projects/engagements that bring energy, health and wellbeing into Ngarrindjeri lives
- *Ruwe/Ruwar*: projects and programs that increase the health of Yarluwar-Ruwe and that understand and respect the principle of interconnection, which is expressed as follows: 'The lands and waters is a living body and Ngarrindjeri are part of this living body' (Hemming et al. 2015).

The NRA's KNYA engagement strategy is an innovative response to 'colonial governmentality', which subverts and seeks to correct the structural conditions underlying the continuing dominance of colonising social forms and their associated epistemologies. Resulting interactions on projects such as the Ramsar ECD then reinforce Ngarrindjeri Nationhood and agency in protecting Ngarrindjeri lands and waters, by sharing in knowledge production that respects rights to cultural knowledge as a form of intellectual property. Through this method of relationship building, including in the domain of scientific research conducted on Ngarrindjeri *Ruwe* (Country), the NRA has been able to take an active and progressive role in the development of environmental policy and in decision making around water and Natural Resource Management in the Murray-Darling Basin region.

CONCLUSION

For many Indigenous Nations, interactions with the Natural Resource Management (NRM) institutions of the settler-state can be characterised as a contemporary 'contact zone' where deep knowledge of 'Country' is becoming understood to be a form of Indigenous cultural property — sometimes carrying labels such as Traditional Ecological Knowledge (TEK); Indigenous Cultural and Intellectual Property (ICIP); and Indigenous Biocultural Knowledge (IBCK) (see Barker 2005; Battiste 2008; Hemming et al. 2010; Ens et al. 2015; Fourmile 1999; Janke 1998; Mignolo 2011; Nakata 2007; Smith 1999, 2012; Stewart-Harawira 2005). For some Western scientists and environmental managers, Indigenous knowledge is understood as a valuable 'data-set' that needs to be 'captured' and added to the stock of information to be utilised by the settler-state to improve environmental management. This kind of thinking, and the discourse and the practices that it produces, are still present in key non-Indigenous agencies identified as responsible for NRM in southern South Australia. Subsequently, a regional move towards Ngarrindjeri co-management is requiring a fundamental structural shift and recognition of Ngarrindjeri as valuable leaders in the management of their lands and waters — Speaking as *Yarluwar-Ruwe*. Resources secured through major programs such as the CLLMM Ngarrindjeri Partnerships Project have provided Ngarrindjeri with the capacity to lead these structural transformations (Hemming & Rigney 2012).

Emerging from this context, and driven by the devastating impacts and challenges presented by the Millennium Drought, Ngarrindjeri have developed an integrated river management framework which locates at its centre the fundamental relationship between people, lands, waters and all living things (*Ruwe/Ruwar*) with a focus on First Nation capacity building. From this framework, Ngarrindjeri have emerged as critical partners with the South Australian Government in managing the Lower River Murray — shifting towards a form of joint river management. In 2009, a new relationship was formed between the State Government and Ngarrindjeri which paved the way for Ngarrindjeri involvement in the implementation of the *Murray Futures* CLLMM Recovery Project. Underpinning this strategy were the vision, principles and objectives articulated in the *Ngarrindjeri Nation Yarluwar-Ruwe Plan* (Ngarrindjeri Nation 2007). The CLLMM Recovery Ngarrindjeri Partnerships Project created strong working relationships with the NRA, through frequent and detailed working group arrangements, site meetings and negotiation of engagement approaches.

This chapter describes the complex work required by a regional Indigenous Nation to bring traditions, values, knowledges and philosophies into the future. This work is being conducted in partnership with universities, non-Indigenous governments, other Indigenous Nations and local non-Indigenous people. These transformations have emerged from a reconfiguration of relations between the Ngarrindjeri Nation and the settler-state in south-eastern Australia. These engagements can be mutually enriching, as Indigenous philosophies come to inform new non-Indigenous understandings that better respond to the health needs of both people and environment, and so translate to more effective policy solutions.

In southern South Australia, natural resource management has been transformed through a sustained Indigenous-led strategy focused on Indigenous Nation building. The Ngarrindjeri KNYA process has produced a unique working relationship between an Indigenous Nation and non-Indigenous interests represented by the government at all levels, universities and other groups. Key to the Ngarrindjeri strategy has been good governance; increased research, policy and planning capacity; and strong local, regional and international partnerships (see Hemming & Rigney 2012; Lui et al. 2016). As a marker of the success of this strategy, the Ngarrindjeri Yarluwar-Ruwe Program, in partnership with DEWNR, recently won the Australian River*prize* 2015 for delivering excellence in Australian river management. The success of the NRA model has also inspired a radical and unique policy shift in Indigenous affairs in South Australia, with the official introduction in 2016 of Aboriginal Regional Authorities (see Department of State Development 2016). This new policy direction should help support the further development of Ngarrindjeri capacity to meaningfully contribute to regional NRM. The centrality of the unique Indigenous relationship with 'Country' remains critical to the Ngarrindjeri vision for a healthy Indigenous Nation, and engaging with this vision through the NRA programs is now a proven pathway for non-Indigenous projects and programs similarly aimed at fostering the health of communities and their environments. The NRA stresses the need for governments to understand and respect Ngarrindjeri responsibilities to Speak as Country (Yannarumi) and to act as an Indigenous Nation.

Such acknowledgement of Indigenous political and cultural authority in key State policy and planning processes and resources is evidence that an Indigenous-led, highly innovative model for engagement between Indigenous people and the State is developing in the MDB region. We have described how the Ngarrindjeri *Yarluwar-Ruwe* Program treats 'Caring as Country' as a holistic Nation-building project designed to create a healthy Ngarrindjeri future. This unique Indigenous governance model, combined with the high-level KNYA engagement strategy, provides this part of the MDB with structures and practices designed to support just and effective Indigenous engagement in water research, policy development and management. It has achieved this because the political and legal technologies introduced by the NRA have been instrumental in starting the transformation of the colonial nature of NRM in South Australia. By providing new conditions of interaction, the NRA has created a new political disposition in South Australia, characterised by increased willingness to listen for culturally diverse expressions of interest, and to respond to such expressions in ways that mutually enhance governing agencies. Importantly, this reshaping of the contemporary 'contact zone' has produced vital opportunities for increased Ngarrindjeri agency in water research, policy and planning (Hemming & Rigney 2012; Kirby et al. 2013).

ACKNOWLEDGEMENTS

The Ngarrindjeri Regional Authority's *Yarluwar-Ruwe* Program has received substantial support from the CLLMM Ngarrindjeri Partnership Project and Riverine (*Murrundi*) Recovery Project — components of the South Australian Government's *Murray Futures* program funded by the Australian Government's *Water for the Future* initiative. We also acknowledge the following support: Office of Indigenous Strategy and Engagement, Flinders University; the Goyder Institute for Water Research; the Australian Research Council — ARC Linkage Project (LP140100376): 'Indigenous nationhood in the absence of recognition: Self-governance strategies and insights from three Aboriginal communities'; and the Melbourne University School of Government Project — 'Indigenous Nation Building: Theory; Practice and its emergence in Australia's public policy discourse'.

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