UTS UNIVERSITY OF TECHNOLOGY SYDNEY

Placing Sustainability at the Centre of the Water, Sanitation and Hygiene Sector: A Transdisciplinary Inquiry

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Doctor of Philosophy

under the supervision of Professor Juliet Willetts and Emeritus Professor Cynthia Mitchell

University of Technology Sydney
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Certificate of original authorship

I, Naomi Carrard declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Institute for Sustainable Futures at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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Format of the thesis and included publications

Format of the thesis

This thesis is a 'thesis by compilation' as described in the University of Technology Sydney's *Graduate Research Candidature Management, Thesis Preparation and Submission Procedures 2021* (section 10.1.2), comprising a combination of chapters and published/publishable works.

Included publications

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2. Carrard, N., Foster, T., & Willetts, J. (2019). Groundwater as a source of drinking water in Southeast Asia and the Pacific: A multi-country review of current reliance and resource concerns. *Water (Switzerland)*, *11*(8). https://doi.org/10.3390/w11081605

3. Carrard, N., Jayathilake, N., & Willetts, J. (2021). Life-cycle costs of a resource-oriented sanitation system and implications for advancing a circular economy approach to sanitation. *Journal of Cleaner Production*, *307*, 127135. https://doi.org/10.1016/j.jclepro.2021.127135

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Declarations of co-authorship

Publication 1 — Environmentally Sustainable WASH? Current discourse, planetary boundaries and future directions

In the case of the publication *Environmentally Sustainable WASH? Current discourse, planetary boundaries and future directions* (published in the *Journal of Water, Sanitation and Hygiene for Development*), the undersigned agree that the nature and extent of the contributions to the work was as follows:

Co-author	Nature of contribution	Extent of contribution (%)	Signature	Date
Naomi Carrard	Led all aspects including conceptualisation, research, writing and revisions. Defined research questions, approach and methodology, undertook data collection and analysis, identified implications and recommendations based on research findings.	95	Production Note: Signature removed prior to publication.	10/08/2017
Juliet Willetts	Provided feedback and input during fortnightly meetings and critical review of drafts.	5	Production Note: Signature removed prior to publication.	10/08/2017

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In the case of the publication *Groundwater as a source of drinking water in Southeast Asia and the Pacific: A multi-country review of current reliance and resource concerns* (published in the journal *Water*), the undersigned agree that the nature and extent of the contributions to the work was as follows:

Co-author	Nature of contribution	Extent of contribution (%)	Signature	Date
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Tim Foster	Provided feedback and input at key points in the study design, research and writing, and critical review of drafts.	5	Production Note: Signature removed prior to publication.	02/08/2019
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Co-author	Nature of contribution	Extent of contribution (%)	Signature	Date
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In the case of the publication *Placing sustainability at the centre of water, sanitation and hygiene: Knowledge co-production for sectoral transformation* (published in *Current Research in Environmental Sustainability*), the undersigned agree that the nature and extent of the contributions to the work was as follows:

Co-author	Nature of contribution	Extent of contribution (%)	Signature	Date
Naomi Carrard	Led all aspects including conceptualisation, research, writing and revisions. Defined research questions, approach and methodology, undertook data collection and analysis. Identified implications based on research findings.	90	Production Note: Signature removed prior to publication.	01/04/2022
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Abstract

Globally, efforts to realise the human rights to water and sanitation are continuing in a context of rapid environmental change and pressing sustainability concerns. The water, sanitation and hygiene (WASH) sector has long grappled with complex challenges of ensuring safe, lasting services for all. Yet WASH sector engagement with sustainability imperatives has been partial and focused on continuity of access to services. There is opportunity for the WASH sector to both benefit from, and contribute to, thinking and action towards sustainability transformations.

The transdisciplinary inquiry documented in this thesis explored how WASH professionals can translate and implement sustainability concepts in sectoral research and practice. A problem-solving transdisciplinary orientation shaped the approach, engaging with sustainability transformations in a normative way. Application of conceptual frames and analytical heuristics reflected a pragmatic research perspective, and included planetary boundary thinking as well as frames and tools from circular economy and systems thinking scholarship.

The inquiry comprised four studies that each contribute novel research at the intersection of WASH and sustainability, and together informed synthesised insights. A review of WASH sustainability discourse with reference to the planetary boundaries framework identified four themes and four opportunities for strengthening sectoral contributions to sustainability. Analysis of groundwater reliance and resource concerns in Southeast Asia and Pacific nations demonstrated why and how WASH professionals should engage in groundwater resource management. Life-cycle costing of a resource-oriented sanitation system in Sri Lanka contributed critical data on how much it costs, and who pays, to prioritise a resource-orientation in sanitation service delivery. The fourth and final study brought a select group of WASH professionals together to co-produce knowledge about foregrounding sustainability in the WASH sector, building on findings from each of the previous studies. The process generated ideas for individual and sectoral action towards sustainability transformations, and

demonstrated the value of knowledge co-production as a mechanism for progressing WASH sustainability discourse.

Synthesis of insights across the inquiry identified three emergent themes for informing WASH professional practice: (i) *reframing* sector perspectives towards a deeper resource-orientation; (ii) *reimagining* purpose to foreground longer-term goals and imperatives, such that they inform WASH professionals' everyday actions; and (iii) *reflexively researching*, exploring how researchers can ethically shape WASH discourse in line with the ideals of sustainability transformations. The latter theme positions WASH researchers within the wider sector context, articulating a compass for future critiquing and reimagining of WASH in line with the ideals of sustainability transformations.

PART I Defining the approach and exploring the landscape

Introducing the inquiry's motivation and aims, detailing its transdisciplinary approach and presenting an analysis of WASH-sustainability discourse.

1 Chapter 1 Introduction and research aims

1.1 Overview

This is a thesis about the translation and implementation of profound, yet abstract, planetary sustainability concepts to sectoral research and practice, with a focus on the water, sanitation and hygiene (WASH) sector. The transdisciplinary inquiry documented in this thesis explored the interconnections between two global communities of thought and action: professionals working to expand water, sanitation and hygiene services in low- and middle-income countries; and those researching, advocating, and acting towards sustainability transformations that address urgent environmental concerns. This introductory chapter situates the WASH sector as the context of inquiry and presents the starting point for the research – that the WASH sector can both benefit from, and contribute to, thinking and action towards planetary sustainability. Having established the context and motivation, this chapter introduces my epistemological positioning and research questions that guided the inquiry. Finally, the chapter provides an overview of the thesis, which weaves together four studies and their associated journal publications.

1.2 Research context: the WASH sector

1.2.1 Sector characteristics and directions

The ‘WASH sector’ is a global community of professionals focused on expanding access to safe water, sanitation and hygiene services. The sector dominantly focuses on low- and middle-income countries, where 2 billion people live without safely managed water services and 3.6 billion without safely managed sanitation services (UN-Water, 2021). Access to WASH services is recognised as critical for public health (Hutton & Chase, 2016; Ray & Smith, 2021; WHO, 2018). WASH is also foundational for the achievement of a wide range of development outcomes linked to livelihoods, education, gender equality and social inclusion (Amebelu et al., 2021; Hutton & Chase, 2016).

The history and evolution of the WASH sector is intertwined with that of development aid. Since the 1950s, multilateral agencies and national governments have invested approximately USD 360 billion in water-related development initiatives (Hargrove, 2019). The influence of international agencies and development organisations is evident in shifting trends and priorities over decades (Herrera, 2019). A tendency to prioritise water evolved to encompass sanitation, as the ‘WatSan’ sector advocated for the critical role of sanitation alongside water (Daryanani, 2012; Kaguima, 2013). Sanitation was added to Millennium Development Goal 7 in 2002 (Herrera, 2019), and recognised as a human right in 2010 – eight years after the United Nations (UN) recognised the human right to water (Bartram et al., 2014). In the 2000s the sector again expanded its focus from ‘WatSan’ to ‘WASH’ to reflect and promote the importance of hygiene and handwashing in achieving WASH-related health outcomes (Huston & Moriarty, 2018). As the focus has broadened, so has the conception of what defines, and is required for, WASH services. A tendency to emphasise technologies and facilities has been supplanted by conceptions of WASH services as systems shaped by social, economic, environmental and governance dynamics (Huston & Moriarty, 2018; Pugel et al., 2022; Rosenqvist et al., 2016; Valcourt et al., 2020).

A wide range of public and private institutions at global, national and local levels constitute the WASH sector. At the global scale, United Nations agencies with a substantial role in WASH include the World Health Organization and UNICEF, which together host the Joint Monitoring Programme for Water Supply and Sanitation (JMP). Since 1990, the JMP has collated, analysed and reported country, regional and global estimates of progress on WASH, building on a history of international monitoring of drinking water and sanitation since the 1930s (as detailed by Bartram et al., 2014). Complementing access data, UN Water produces a biennial Global Analysis and Assessment of Sanitation and Drinking-Water (GLAAS) that provides country-level data on investments and policy environments. With a stronger collaboration and advocacy role, Sanitation and Water for All (SWA) is a global partnership of governments, donors, civil society organisations and research institutions coordinating high-level action towards universal clean water and adequate sanitation.

Beyond these global platforms, international organisations play advocacy, knowledge brokering and program implementation roles. Key actors include UNICEF, civil society organisations such as WaterAid (a high-profile dedicated WASH organisation) and IRC (a 'think and do tank' engaged in WASH research and advocacy). Global networks are active for water (e.g. the Rural Water Supply Network), sanitation (e.g. the Sustainable Sanitation Alliance) and handwashing (e.g. the Global Handwashing Partnership), providing platforms for diverse professionals to share and learn about research and practice.

At national and local levels, multiple public, private and community organisations are implicated in WASH. Relevant national agencies include those with remits in areas of public works, health, education, environment and resource management. At sub-national scales, local governments are often charged with responsibility for ensuring water and sanitation service delivery (Cairncross et al., 2010; World Bank, 2017), with services provided by a mix of public, private and community actors. Although many of these agencies and actors would not self-identify as part of the WASH sector given the diversity of their roles and responsibilities, they engage with WASH sector discourse through international collaborations, development programs and in national policy processes.

WASH sector knowledge is reflected in, and shaped by, organisational and scholarly literature and regular sector events. The *Journal of Water, Sanitation and Hygiene for Development* is a dedicated academic publication for WASH published by the International Water Association, with WASH research also frequently appearing in a broad range of water-, health- and development-focused publications. Prominent sector conferences include World Water Week organised by the Stockholm International Water Institute (SIWI), the Water and Health Conference organised by the University of North Carolina (UNC), the Water Engineering Development Centre (WEDC) conference hosted by Loughborough University and (since 2008) the WASH Futures conference (now the Water and WASH Futures Conference), held in Australia with support from the Department of Foreign Affairs and Trade. This latter conference, which was spearheaded by the University of Technology Sydney, the International WaterCentre and civil society organisations, reflects Australia's contribution to shaping the global community.

Normative directions for the WASH sector are described in Sustainable Development Goal (SDG) 6 which aims to ensure access to water and sanitation for all (General Assembly Resolution 70/1, UN Doc. A/Res/70/1, 2015) and the human rights to water and sanitation (General Assembly Resolution 64/292, UN Doc. A/Res/64/292, 2010). Both articulate visions for universal, equitable access to water, sanitation and hygiene, with SDG 6 incorporating WASH targets and water resource management targets under one goal. The SDG framework represents a substantial evolution compared with its Millennium Development Goal predecessor, in which access to facilities was emphasised over safely managed service delivery, and water resources were considered separately with reference to biodiversity loss. Within SDG 6, access to safely managed services and water resource management are co-located. However, they remain in separate targets and the extent to which co-location in one goal has driven practical integration is questionable (Tortajada & Biswas, 2018).

A recent sector development has been the establishment of a Lancet Commission on water, sanitation and hygiene and health. The Commission on WASH and health aims to “reimagine and reconstitute WASH not only as a central pillar of public health, but also as a pathway to gender equality and social and environmental justice” (Amebelu et al., 2021, p.1469). The Commission frames WASH from a human rights perspective. It emphasises the scale of ambition required to achieve SDG 6 (which is off-track), and how the COVID-19 pandemic has highlighted the links between WASH access and public health. Climate change, rapid urbanisation, humanitarian crises and persistent inequalities are described as compounding challenges. The Commission has identified three priority activities for its initial focus (Amebelu et al., 2021), namely, arguing the case for universal access to safely managed WASH, assessing the financial cost of achieving universal access (and associated benefits), and making recommendations to inform national systems that support professional service delivery while responding to the challenges of climate change and urbanisation. Of relevance to this inquiry is the Commission’s emphasis on social and environmental justice, with the third priority area of work seeking recommendations that centre public health, gender equality, and broader social and environmental justice (Amebelu et al., 2021). Positioning WASH as a pathway to environmental justice

recognises the deep connections between WASH and environmental dynamics, and will shape how the sector approaches these connections (discussed further in section 3.8).

1.2.2 WASH professionals

Professionals in the WASH sector are diverse in their skill sets and disciplinary foundations, playing a wide range of technical, social and regulatory roles. A historical dominance of professionals with engineering and public health qualifications has broadened with recognition of the social, economic and environmental dimensions of WASH service delivery, such that WASH professionals now include anthropologists, economists, psychologists and marketing experts (to name a few). Although no comprehensive analysis of the disciplines and skills represented in the WASH sector exists, recent work has highlighted the sector's complexity (Haque & Freeman, 2021), disciplinary diversity in studies focusing on WASH-gender connections (Macarthur et al., 2020) and disciplinary diversity in the new Lancet Commission on WASH and Health (Amebelu et al., 2021).

The diversity of disciplinary orientations in the WASH sector is not, however, matched by diversity of demographics in leading sector organisations. With an increasing focus on equity and inclusion in line with Agenda 2030 guiding principles of Leave No One Behind and Gender Equality (United Nations Sustainable Development Group, 2019), WASH professionals are increasingly reflecting on a lack of diversity within a sector shaped by colonial and postcolonial aid dynamics. A study by Worsham et al. (2021) found that older, white males from high-income countries comprise more than a third of leadership positions in 105 global sanitation stakeholder organisations, with Black, Indigenous and other Women of Colour the least represented group. Worsham et al.'s study forms part of an emerging sector focus on decolonisation of WASH knowledge, which is discussed in this inquiry in Chapters 6 (publication 4) and 7.

1.2.3 My place in the sector

In articulating the WASH sector as context for this inquiry, I locate myself as a WASH professional working within, influenced by, and influencing sector norms and

trends. My research has been shaped by my embeddedness in the sector and work I have done alongside my doctoral research, including substantial pieces of research focused on WASH-gender connections, inclusive sanitation, climate resilience and local government roles as duty bearers in realisation of the human rights to water and sanitation. I reflect the disciplinary diversity characteristic of WASH professionals, coming to the sector from a foundational background in Geography, History and Environmental Law and building expertise over a decade of transdisciplinary research across WASH, the Australian water sector and development effectiveness projects. As a white woman living in a high-income country, I also reflect the dominance of high-income country professionals driving the WASH research agenda and discourse, a fact I have reflected on throughout this inquiry.

In locating myself within the development aid WASH sector I also conceive this community as where I have greatest capacity to influence, with the sector in turn seeking to strengthen WASH service delivery in national and sub-national contexts. Acknowledging the realities and limitations of my sphere of influence, in this inquiry I intentionally focused on the development aid WASH sector, though with an ultimate aim to inform service delivery in country contexts. As such, the inquiry has sought change both within and through the WASH sector. My location and conception of WASH sector influence and concern is illustrated in Figure 1, which maps the WASH sector and my place within it using circles of control, influence and concern (after S. R. Covey, 1989).

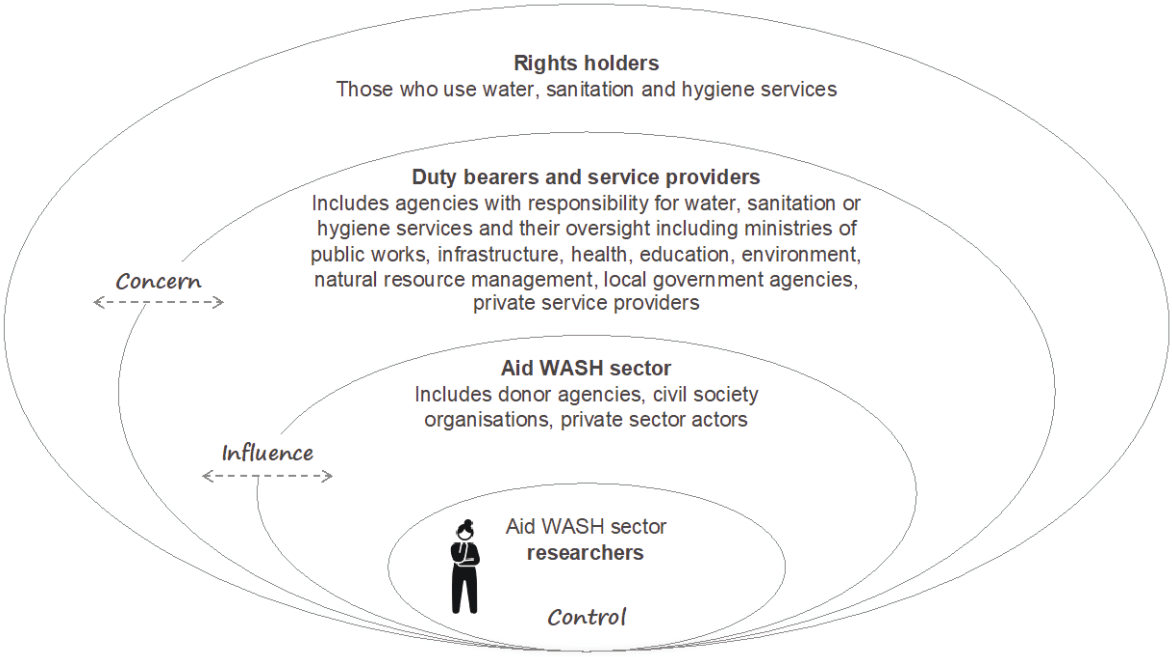

Figure 1 My position in the WASH sector and related realms of influence and concern

1.3 Research motivation and framing

1.3.1 The WASH sector and sustainability

The WASH sector has historically conceived of sustainability as being about continuity of access to services. Sustainability in WASH and the aid sector more generally has typically been considered in terms of benefits arising from investments, with a 'sustainable' initiative defined as one in which benefits of a project are sustained beyond its duration (e.g. Weststrate et al., 2019; World Bank, 2017). The WASH sector has traditionally focused on infrastructure and its management by communities (Valcourt et al., 2020), connoted by words such as durability (Jiménez et al., 2017) and functionality (Lockwood & Smits, 2011; Whaley & Cleaver, 2017). More generally, the sector has dominantly focused on social and economic needs and drivers (Bradley & Bartram, 2013) with less attention paid to the association between WASH sector activities and the natural resources and ecosystems on which humankind depends to survive and thrive. Yet the connections are profound – WASH services rely on the availability of freshwater and ecosystem services, and impact environmental processes at local and wider scales.

Sectors adjacent to WASH, such as the global water sector, have more strongly engaged with environmental sustainability. The International Water Association, for example, has several specialist groups focused on basin and water resources, as well as resource recovery and reuse (IWA, 2022). In 2016, they released a framework to guide water utilities in transitioning to a circular economy (IWA, 2016). Similarly, the Stockholm International Water Institute, which convenes World Water Week (a key WASH sector event), positions water governance as centrally connected to the climate crisis, food security and biodiversity loss (SIWI, 2022). While these examples connect to and implicate WASH actors, the WASH development aid community has tended to focus more narrowly on service delivery. More generally, global efforts to advance Integrated Water Resources Management – which is part of SDG 6 – have evolved in parallel to WASH but with limited integration (Hadwen et al., 2015; Valcourt et al., 2020).

My observation of limited engagement of the WASH sector with broader and deeper conceptions of sustainability beyond a 'continued functioning of facilities and services' idea is what led me to this doctoral inquiry. I wanted to explore and respond to a perceived contrast between global sustainability imperatives evident in both academic and popular discourse – which were important to me personally – and a lack of engagement with these imperatives in WASH.

1.3.2 Planetary boundary thinking and the doughnut as guiding concepts

The planetary boundaries framework offers a helpful way of engaging with fundamental earth system processes, and I selected this framework as an initial lens for considering how the WASH sector might strengthen its engagement with sustainability. First proposed by Rockström et al. (2009) and since refined and re-published (Steffen et al., 2015), it sets out nine inter-linked earth system boundaries in which human society can continue to thrive, thereby defining a "safe operating space for humanity" (p. 472). This 'safe operating space' is a key point of differentiation between planetary boundaries and previous framings of ecological limits; it conceptualises what 'sustainable' looks like from a planetary perspective as an alternative to sectoral approaches focused on minimising negative externalities (Rockström et al., 2009). Further, it makes clear that deep and widespread transformations are needed to remain within the 'safe operating space',

with a number of the planetary boundaries either transgressing or approaching their safe limits (as shown in Figure 2). The planetary boundaries framework is further described, including connections between WASH and five of the identified earth system processes, in publication 1 (Chapter 3).

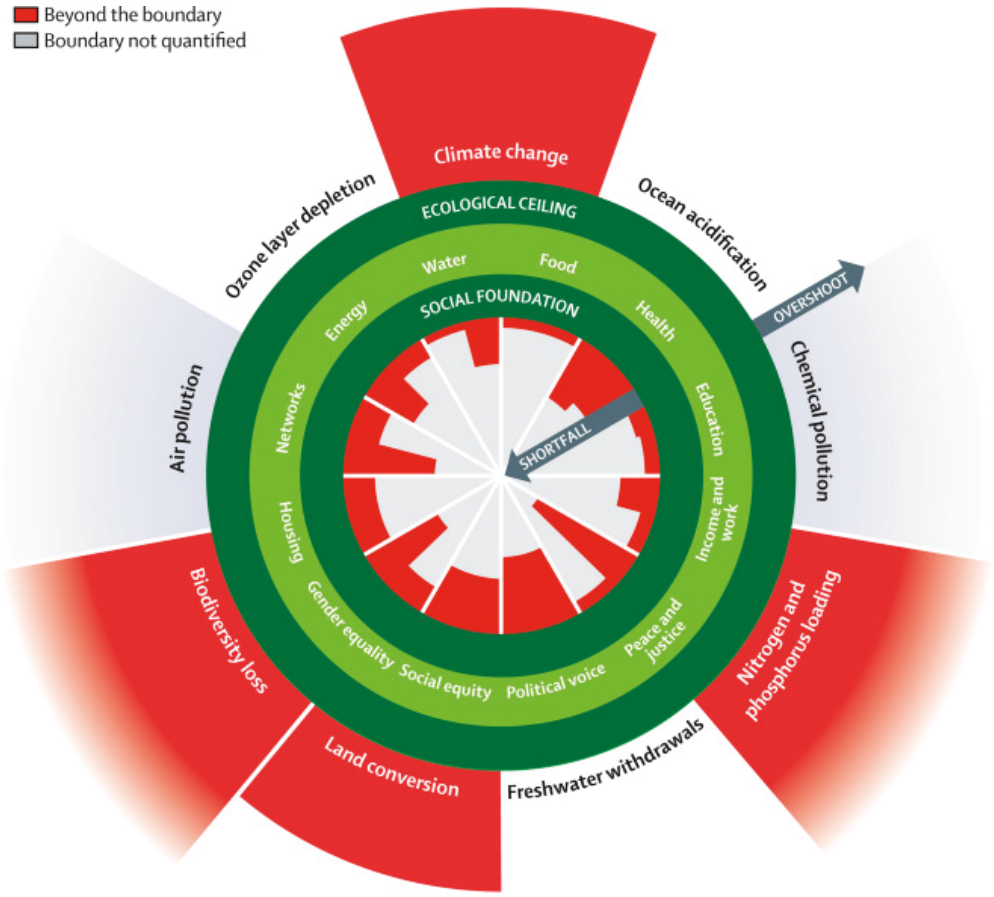

Figure 2 The planetary boundaries and 'doughnut' conceptualisation showing both ecological limits and social foundations. Source: Raworth (2017a)

I selected the planetary boundaries framework as a guiding concept for engaging with WASH-sustainability connections for three reasons. First, because of its influence in global development and sustainability platforms. The planetary boundaries framework informed global policy dialogues related to the SDGs (Griggs et al., 2013; Hajer et al., 2015; Pisano & Berger, 2013), demonstrating its resonance and legitimacy as a framework for guiding human development in line with sustainability imperatives. The planetary boundaries framework also underpins influential global research and action platforms, such as those connected with planetary health. The concept of planetary health aims to situate public health

(which is core to WASH sector agendas) within the wider context of its dependence on planetary health in the Anthropocene era, and meeting SDG targets while remaining within planetary boundaries is a “driving force of the planetary health approach” (J. Cole, 2019, p. 16).

Second, a key idea related to the planetary boundaries framework – as presented by its architects – is the idea of ‘planetary boundary thinking’ as a guiding mindset for addressing development goals within earth system boundaries. ‘PB thinking’ was an idea shared in the 2015 update of the original framework (Steffen et al., 2015) to guide interpretation of what the framework means at different levels across contexts. The scientific basis of the planetary boundaries framework cannot be downscaled, yet the authors acknowledge that changes in subsystems inevitably affect the function of the planet as a whole, which presents a challenge for application of the framework given that policy action occurs at local rather than planetary scales (Steffen et al., 2015). ‘PB thinking’ is one response, indicating an approach that recognises planetary sustainability imperatives and strives for local actions that contribute to human development within the ‘safe operating space for humanity’. This idea is similar to the conception of the planetary boundaries framework as signposting a fundamentally different route to sustainable development in its articulation of a ‘safe operating space’ (Downing et al., 2019). In this inquiry I did not seek to apply the scientific basis of the planetary boundaries framework to WASH contexts and activities, but rather adopted the concept of ‘PB thinking’ to explore the intersection of planetary boundary, human rights and development frameworks at scales relevant to WASH sector professionals.

Third, and most importantly, the planetary boundaries framework has benefited from the complementary conceptualisation of ‘the doughnut’, which brings social foundations and planetary boundaries together in one integrated vision of a safe *and just* operating space for humanity (Raworth, 2013, 2017a). As shown in Figure 2, the social foundations reflect twelve dimensions critical for human wellbeing derived from the SDGs (Raworth, 2017a). As one of the twelve social foundations, ‘water’ is defined and measured as the number of people without access to improved water and improved sanitation according to WHO/UNICEF Joint Monitoring Program (JMP) definitions, which also underpin the directions and

activities of the WASH sector (as described above in section 1.2). In offering a conceptual connection between ecological limits and social foundations, the doughnut defines a vision aligned with my research intent to consider how the dominant focus and work of the WASH sector – which addresses the 'water' social foundation – might be expanded to engage at depth with the idea of a safe (as well as just) space.

The doughnut aligns with my conceptualisation of how the human rights framework can and should guide WASH activities, with a focus on both service-related criteria (availability, accessibility, quality and safety, affordability, acceptability) and underpinning human rights principles including sustainability. The doughnut also suggests paths to rethink economic approaches in pursuit of the safe and just space, including a focus on distributive and regenerative ideals (Raworth, 2017b). Publication 1 (Chapter 3) includes further discussion of the doughnut as a guide for WASH sustainability, and publication 3 (Chapter 5) explores a regenerative approach to sanitation.

1.3.3 Sustainability transformations

Complementing the guiding role of 'planetary boundary thinking' and the doughnut, my inquiry is situated within the recently expanding field of sustainability transformations. Sustainability transformations has emerged over the past decade as a field of research concerned with societal shifts that address global environmental pressures and move us towards sustainable, equitable futures (Patterson et al., 2017). While the concept of sustainability transformations is relatively recent, it builds on established research across numerous fields focused on social and environmental change to address wicked problems including climate change, food insecurity, biodiversity loss and poverty (Salomaa & Juhola, 2020). Three bodies of literature have been particularly influential in shaping transformations scholarship, namely socio-technical transitions, transformational adaptation and resilience (Bennett et al., 2019).

Sustainability transformations research is often connected with that focused on transitions, yet while complementary, the two fields have an important distinction. Compared with ideas of socio-technical transition pathways, transformation

connotes deeper and more radical change, responding to the recognition that incremental change is insufficient to address global challenges (B.-O. Linnér & Wibeck, 2019). Reflecting the idea of more radical change, Linnér & Wibeck (2019) assert that “transformations infer profound and enduring nonlinear systemic changes, typically involving social, cultural, technological, political, economic, and/or environmental processes” (p. 4).

My inquiry engaged with sustainability transformations in a normative way, viewing fundamental societal change towards more sustainable and equitable futures as necessary and desirable – and seeing the WASH sector as subject to and playing a role in transformation processes. A normative framing of sustainability transformations is one of two approaches described by Patterson et al. (2017), the other being an analytical approach that considers, for example, what happens, how and why. In taking a normative orientation, my inquiry drew on both the visionary ideals associated with sustainability transformations, and the implied need for fundamental change across all sectors to achieve those ideals.

In initial phases of the inquiry I did not articulate an explicit alignment with sustainability transformations, but rather engaged with ideals through the planetary boundaries/doughnut conception of a safe and just space. In study 4, leveraging the substantial sustainability transformations work that had emerged since my inquiry began, I more directly located my research within the sustainability transformations space and this body of work then informed my synthesis (Chapter 7).

In more clearly situating my research in the sustainability transformations field, I applied sustainability science conceptions of knowledge co-production as a collaborative, iterative and normative means of producing science (Wyborn et al. 2019). I also critically reflected on knowledge co-production as a sustainability transformation tool, given the nature of transformations as inherently political, contested, relative and subjective (Blythe et al., 2018; B.-O. Linnér & Wibeck, 2019; Patterson et al., 2017). Knowledge co-production is introduced in Chapter 3 as aligned with transdisciplinary approaches, then defined and discussed in Part III of this thesis.

1.3.4 Leverage points for sustainability transformations and circles of influence as sensemaking heuristics for a transdisciplinary inquiry

The normative nature of this inquiry, and its intent to integrate WASH and sustainability transformations ideas – both of which are broad fields of scholarship and practice – demanded a transdisciplinary approach. The transdisciplinary approach created space for emergence, with the choice of each study and increasing engagement with sustainability transformations literature reflecting the iterative, evolving nature of transdisciplinary research. The approach also sought integrative insights by synthesising across multiple concepts, datasets, and disciplinary perspectives (further discussed in section 2.6.1).

In pursuit of integration across the whole inquiry I used two sensemaking tools: leverage points for sustainability transformations (Abson et al., 2017; Meadows, 2008; Waddock et al., 2020) and circles of control, influence and concern (adapted from S. Covey, 1998; S. R. Covey, 1989). The transdisciplinary approach and use of heuristic tools for sensemaking is described and justified in Chapter 2, building on the introduction of my epistemological perspective below in section 1.4. The application of leverage points and circles of influence to generate integrative insights across the whole inquiry is detailed in the synthesis (Chapter 7).

1.4 Researcher profile and epistemological perspective

I embarked on this inquiry having spent a decade working in the WASH sector on a range of applied and transdisciplinary research and consulting projects (section 2.3 elaborates my transdisciplinary WASH research orientation). In addition to responding to the perceived gap between WASH sector priorities and sustainability imperatives, I wanted to deepen my reflective and reflexive research skills to inform future WASH sector research and action that both aligns with and contributes to wider sustainability transformations.

An intention to strengthen reflective and reflexive practice skills through doctoral research draws from my ambition to be an ethical researcher within a normative research frame. I bring an explicit change agenda to my research to contribute – in and through my research and related actions – to a sustainable and equitable

world. This normative approach has guided my research throughout my career as I have worked in partnerships with practice and policy organisations while based in a research institute with an explicit mission to “create change towards sustainable futures”. While conscious of the limited extent to which a doctoral project can realistically influence substantial sectoral change, I approached the inquiry with an intent to drive greater focus on sustainability both through and beyond the inquiry.

In seeking change through and beyond my research, I am conscious of doing so in ways that align with established principles of research ethics and challenge (rather than reinforce) unequal power dynamics. A focus on research ethics and power within a normative research frame demands both reflective and reflexive skills. In differentiating reflective and reflexive practice, I associate the former with a learning orientation in which research activities are iterative, reflected on and adapted based on emerging insights and evolving contextual factors (Wickson et al., 2006). In complement, reflexivity is more self-focused, involving being cognisant and questioning of how research activities are shaped by my own ways of thinking, assumptions and underlying values (drawing on the definition of reflexivity by Bradbury & Divecha, 2020). Both reflective and reflexive practices are integral to ethical change-oriented research, particularly in development research characterised by deep historical asymmetries.

In taking a normative stance, and doing so reflexively, I position myself as epistemologically plural. Epistemological pluralism, as described by Miller et al. (2008), recognises that “in any given research context, there may be several valuable ways of knowing, and that accommodating this plurality can lead to more successful integrated study” (p. 45). I identify with both constructivist and pragmatic paradigms, while also valuing (and engaging in) positivist research. In line with constructivist perspectives, I see knowledge as socially constructed and mediated by power, position and experience (Crotty, 1998). Bringing this lens to my inquiry has meant paying attention to the ways in which knowledge is made, used and drives action, exemplified by my focus on discourse in study 1 (WASH sector discourse and planetary boundaries) and knowledge co-production in study 4 (co-production for WASH sustainability).

My pragmatist perspective is evident in the normative, transdisciplinary framing of the inquiry (Popa et al., 2015), and my belief that all necessary approaches should be used to understand and address the problem in question (Johnson & Onwuegbuzie, 2004; Kaushik & Walsh, 2019). The pragmatist lens also drives my valuing of positivist perspectives and preference for mixed methods approaches (evident across the studies), seeing constructive roles for quantitative, qualitative and mixed-method research to grapple with the complexities of real-world challenges defined by biophysical realities and human interactions. Figure 3 illustrates my perspective. While noting the many and inconsistent ways in which philosophical terms are used, I present this figure as a means to convey my ontological, epistemological and (to an extent in the normative framing) axiological perspectives.

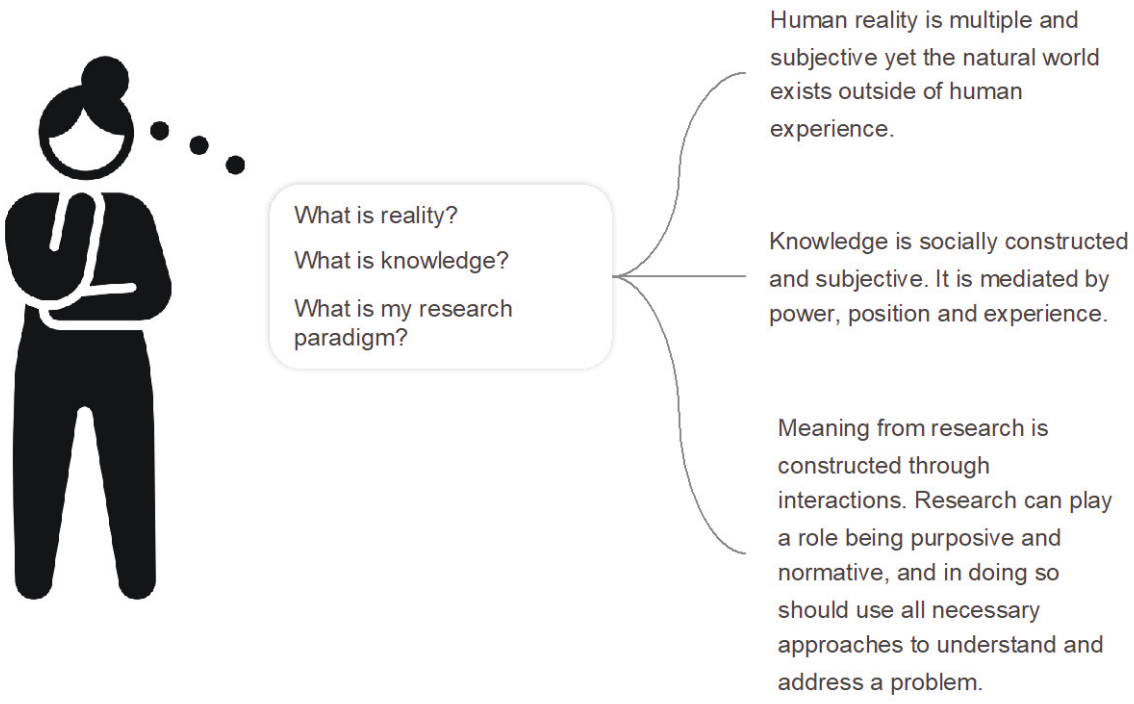

Figure 3 A plural epistemological perspective spanning constructivist and pragmatic research paradigms

In taking a plural epistemological perspective, I identify tensions between pragmatic and constructivist approaches that were experienced during this inquiry. A pragmatic lens, which drives an action-orientation, can be ethically compromised if

ideas are translated into practice without due consideration of philosophical complexities. And constructivist approaches can delay urgent action (as is demanded by sustainability crises) if excessive time and effort is diverted to philosophical debate. Such tensions are characteristic of transdisciplinary, action-oriented sustainability science, and highlighted by a trend towards relational thinking that engages humanities and social science perspectives in addressing sustainability challenges (West et al., 2020). In this inquiry, I sought to tread a defensible path between depth of conceptual reflection and reaching action-oriented conclusions, with each study moving from analysis to consideration of 'so what for WASH professionals?' in line with the overarching research question, elaborated below in section 1.5. In doing so, rather than reaching a unified epistemological position I sought to maintain a plural perspective, arguing for practical actions while also acknowledging complexity and contestation.

1.5 Research questions

Research questions that guided the inquiry were crafted to explore how sustainability concepts exemplified by ideas of 'planetary boundary thinking' and 'sustainability transformations' might be relevant for, and inform, the work of the WASH sector. Questions addressed both conceptual and practical aspects of WASH-sustainability connections, reflecting the intentional selection of sub-studies to span a breadth of relevant, understudied topics. The design of research questions was guided by the ultimate aim of the inquiry, which was to identify opportunities for strengthening WASH-sustainability connections, building evidence and generating insights that can inform sector priorities and actions. The questions – in their breadth and diversity – also reflect the transdisciplinary nature of the inquiry and its pursuit of coherence while grappling with complexity (elaborated in Chapter 2).

The overarching research question was:

How can water, sanitation and hygiene (WASH) professionals translate and implement planetary sustainability concepts within – and as a foundation for – continued efforts to expand and strengthen service delivery towards realisation of the human rights to water and sanitation?

The focus on ‘WASH professionals’ speaks to an actor-oriented approach, emphasising that the ‘WASH sector’ is an abstract concept that only exists as a community of professionals driving discourse and action in particular directions. The phrase ‘planetary sustainability’ reflects the intent to broaden the WASH-sustainability conversation beyond narrower conceptions of sustainability focused on functionality towards planetary-scale imperatives associated with human-nature interactions. The phrase is also deliberately broad to encompass the range of sustainability concepts that informed the inquiry including planetary boundaries, circular economy and sustainability transformations. Efforts to expand and strengthen service delivery include activities to reach those currently without services, as well as those seeking to strengthen existing services towards alignment with the JMP ‘safely managed’ criteria and conceptions of strong WASH systems (e.g. Huston & Moriarty, 2018; Pugel et al., 2022; Valcourt et al., 2020). Finally, the question includes reference to the ultimate sector goal of realising the human rights to water and sanitation. In referencing the human rights, the intent is to convey my position that stronger integration of sustainability must not override, but rather must occur as part of, progressive realisation of human rights.

The overarching research question sits above sub-questions associated with four included studies. Table 1 presents the questions that guided each of the included studies, and Figure 4 illustrates how the questions for each study informed the overarching research question. Each sub-question is elaborated and addressed in this thesis in subsequent relevant chapters as indicated in Table 1, with the overarching research question relevant throughout and addressed directly in Chapter 7 (synthesis).

Table 1 Sub-research questions associated with each of the four included studies

Study	Questions	Chapter addressed
1 Environmentally sustainable WASH? Current discourse, planetary boundaries and future directions	How has recent WASH sector discourse engaged with environmental sustainability? What does the planetary boundaries concept mean for future priorities and pathways to support more meaningful engagement of WASH sector researchers/knowledge leaders with planetary sustainability?	Chapter 3 - publication 1
2 Groundwater as a Source of Drinking Water in Southeast Asia and the Pacific: A Multi-Country Review of Current Reliance and Resource Concerns	To what extent are households in Southeast Asian and Pacific case study countries reliant on groundwater for their primary source of drinking water? In case study countries, how do groundwater resource issues currently influence water services for groundwater-reliant households, and how are they likely to do so in future? How can WASH sector professionals at national and sub-national scales meaningfully engage in groundwater resource management as a foundation for universal, sustainable service delivery?	Chapter 4 - publication 2
3 Life-cycle costs of a resource-oriented sanitation system and implications for advancing a circular economy approach to sanitation	What are the life-cycle costs, and who pays, for an established resource-oriented sanitation system in urban Sri Lanka? How can a comprehensive understanding of the costs of resource-oriented sanitation advance a circular economy approach to sanitation in Sri Lanka and more widely?	Chapter 5 - publication 3

Study	Questions	Chapter addressed
4 Placing sustainability at the centre of water, sanitation and hygiene: Co-production for sectoral transformation	How does engaging WASH professionals in deliberation about planetary sustainability concepts contribute to new knowledge, shared understandings and new competencies? In pursuit of sectoral sustainability transformations, how does knowledge co-production work in practice and what considerations might inform its nuanced application?	Chapter 6 - publication 4

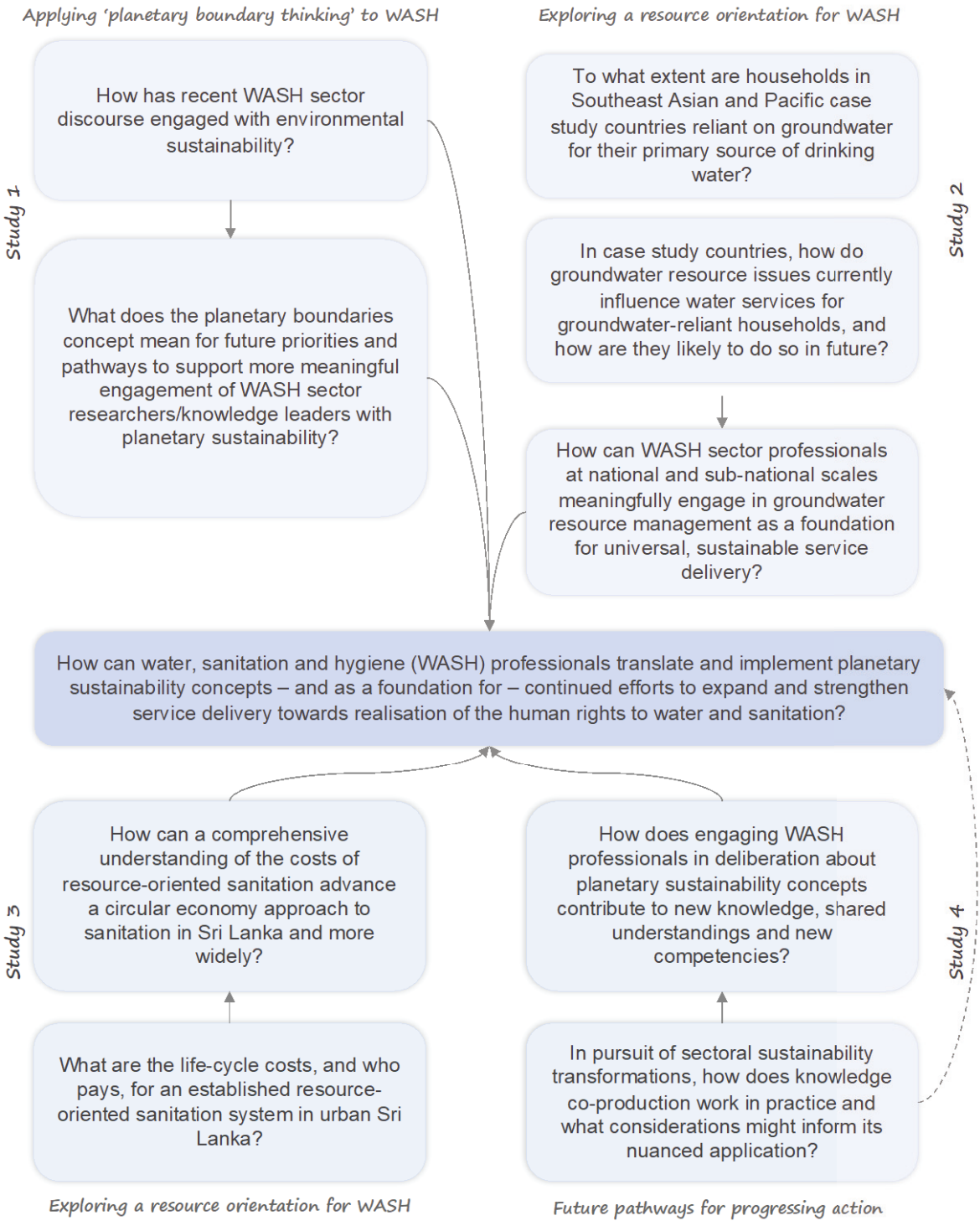

Figure 4 The inquiry's research questions and how they informed responding to the overarching research question

1.6 Research overview

This thesis has been structured as a 'thesis by compilation' as described in the University of Technology Sydney's *Graduate Research Candidature Management, Thesis Preparation and Submission Procedures 2021* (section 10.1.2). The thesis comprises four published journal articles, of which I was the lead author and researcher (see co-authorship declarations), and supporting chapters. The included publications each stand alone as scholarly contributions documenting distinct studies with their own theoretical, methodological, and analytical bases. Table 2 presents an overview of included publications including their respective approaches, intended audiences and contributions (which are also articulated in section 7.8). The supporting chapters and orientation sections frame and synthesise the studies as a coherent set, and contribute:

- Positioning the inquiry within the field of transdisciplinary research.
- An expanded and updated review of literature at the intersection of WASH and sustainability.
- Justification of the choice of studies included in the inquiry, and critical reflections on their contributions.
- A synthesis of insights and implications of the inquiry as a whole.
- Supplementary material associated with studies in the appendices.

The thesis is structured in three parts. **Part I** details scholarly foundations and scopes the field of inquiry. Following this introduction, *Chapter 2* details and justifies the transdisciplinary research approach, locating the conceptual frameworks, research methods and analytical tools used across the studies within the problem-solving discourse of transdisciplinarity. *Chapter 3* presents a systematic literature review of WASH discourse related to sustainability (publication 1) and an updated analysis of how sector literature has evolved since the review's publication.

Part II presents two in-depth studies focused on aspects of the WASH-sustainability nexus across water and sanitation subsectors. An orientation explains

and justifies the choice of topics for in-depth studies and articulate how they respond to the inquiry's overarching research question. *Chapter 4* presents the study of groundwater reliance and resource concerns in Southeast Asia and Pacific countries (publication 2). *Chapter 5* presents the analysis of life-cycle costs of a resource-oriented sanitation system and implications for advancing a circular economy approach to sanitation (publication 3). Both publications are followed by critical reflections on the studies in light of the inquiry as a whole.

Part III expands focus back to the sectoral level, presenting a co-production study and synthesising insights across the inquiry. An orientation explains and justifies the decision to include a knowledge co-production process in the inquiry, then *Chapter 6* presents the co-production study (publication 4) and critical reflections on pathways from co-production to sustainability transformations. Finally, *Chapter 7* synthesises and concludes the inquiry by identifying three meta-level themes, articulating the inquiry's transdisciplinary contributions, and identifying future directions for research that progresses WASH sector engagement with sustainability.

Appendices include supplementary material for each of the included publications.

Figure 5 illustrates the thesis structure in three parts.

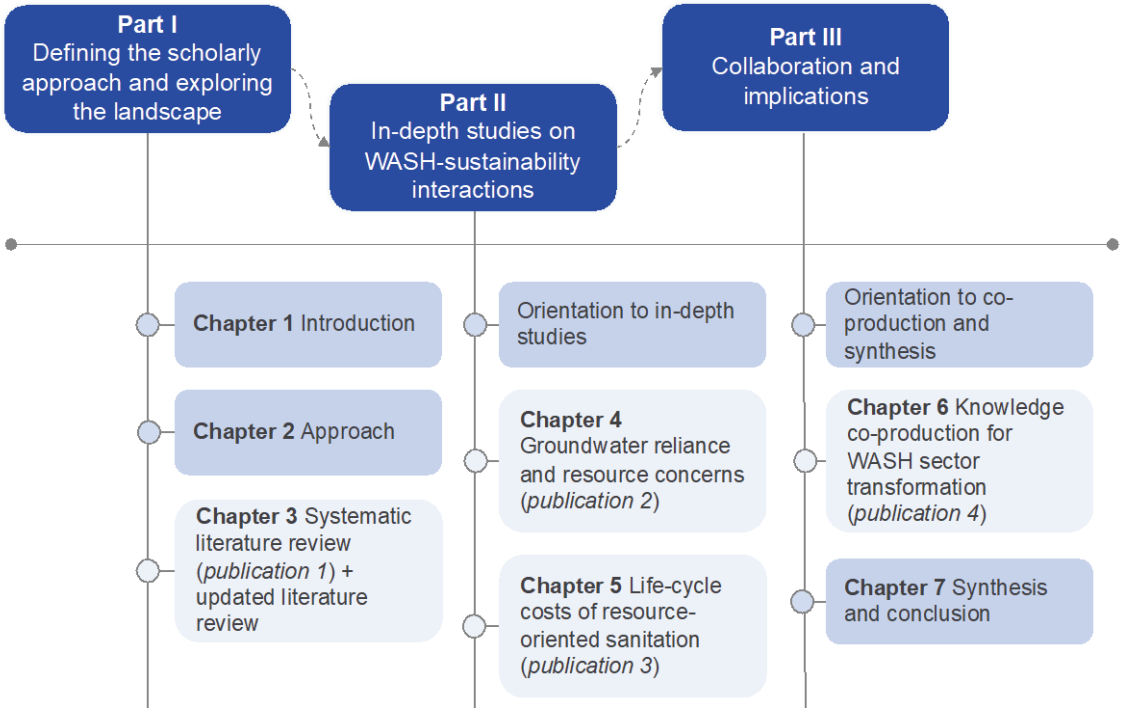

Figure 5 Structure of the three-part thesis

Table 2 Summary of publications

Title	1—Environmentally sustainable WASH? Current discourse, planetary boundaries and future directions	2—Groundwater as a Source of Drinking Water in Southeast Asia and the Pacific: A Multi-Country Review of Current Reliance and Resource Concerns	3—Life-cycle costs of a resource-oriented sanitation system and implications for advancing a circular economy approach to sanitation	4—Placing sustainability at the centre of water, sanitation and hygiene: Knowledge co-production for sectoral transformation
Journal of publication	*Journal of Water, Sanitation and Hygiene for Development* (published 2017)	*Water* (published 2019)	*Journal of Cleaner Production* (published 2021)	*Current Research in Environmental Sustainability* (published 2022)
Research methods	Systematic literature review; content and thematic analysis	Secondary data synthesis and analysis; systems diagramming	Life-cycle costing (informed by Integrated Resource Planning)	Transdisciplinary co-production of knowledge
Conceptual frameworks/ analytical heuristics	Planetary boundaries framework and the doughnut; Multi-level perspective (transition studies)	Systems thinking diagramming; criteria of the human right to water; the water service delivery approach framework	Life-cycle costing, Circular Economy concepts	Co-production for sustainability principles and theory of change, Sustainability transformations
Relevant for	WASH sector researchers and knowledge leaders within international WASH sector organisations	Researchers and professionals in international WASH organisations (direct audience) and through them, partners at national government and service authority levels	Researchers and professionals in international WASH organisations (direct audience) and through them agencies responsible for urban sanitation planning and management	WASH sector researchers and knowledge leaders (within international WASH sector organisations), transdisciplinarity and co-production scholars

Key contributions	-Comprehensively maps how WASH sector researchers and other professionals are engaging with environmental sustainability. -Demonstrates the relevance and usefulness of the planetary boundaries framework for WASH. -Articulates key gaps and opportunities for strengthening focus on environmental sustainability in WASH: i) Foster 'do more good' instead of 'do less harm'; ii) Focus on synergies and minimise trade-offs; iii) Identify and address gaps in current focus; iv) Transition reuse from niche to regime scale.	-Establishes a baseline of populations using groundwater for drinking in ten Southeast Asian and Pacific nations, demonstrating the importance of groundwater resources for meeting the human right to water. -Identifies groundwater resource issues that must be planned for to sustain water services. -In focusing at regional scale, provides comparative data and captures diversity of experiences that can inform global and local action and advocacy around the risks and concerns raised, as well as inform the scope and focus of future studies at local scales.	-Contributes empirical cost analysis of a resource-oriented system, a novel contribution given most studies are prospective or hypothetical. -Refines a replicable costing methodology for exploring costs and equity considerations. -Positions sanitation within circular economy discourse, highlighting opportunity to broaden focus from business models to systemic change. -Argues for a shift in sector discourse from economic analysis comparing resource-oriented sanitation with traditional forms towards a purposive approach supported by full-cost analysis.	-Contributes new knowledge on WASH-sustainability priorities and methodological insights on transdisciplinary knowledge co-production. -Demonstrates the relevance and usefulness of co-production for WASH sector development, including design features that underpin effective short-form processes. -Contributes methodological insights for co-production, arguing that future co-production processes could beneficially emphasise purpose, work across scales and contexts, and take a reflexive approach to power.
Journal and citation metrics[1]	Impact Factor 1.250 Citations 21	Impact Factor 3.530 Citations 95	Impact Factor 9.297 Citations 2	Impact Factor n/a (new journal, companion to *Current Opinion in Environmental Sustainability*)

[1] Google Scholar citations as of 7 September 2022. I use Google Scholar (rather than SCOPUS or Web of Science) due to the database's more comprehensive coverage of disciplines and document types that may be relevant to WASH research and practice, and the fact that studies have countered doubts regarding the accuracy of citation counts (Harzing & Alakangas, 2016).

2 Chapter 2 A transdisciplinary research approach

2.1 Overview

This chapter presents the methodological approach to the inquiry by situating the research within transdisciplinary scholarship. I first articulate the rationale for a transdisciplinary approach given the nature of the inquiry's research question. I then briefly describe my career as a transdisciplinary WASH researcher, which informed my approach in this doctoral inquiry. I locate the inquiry within the 'problem-solving' transdisciplinary discourse (Thompson Klein, 2015) and consider the relevance of alternative framings of transdisciplinarity as a theory, methodology and 'way of being'. Drawing on published criteria for assessing quality in transdisciplinary postdoctoral research (Willetts & Mitchell, 2017), I critically reflect on the iterative methodological and conceptual choices made, demonstrating my approach to ensuring research rigour and coherence within a multi-method, conceptually diverse, and yet coherent inquiry. Finally, I introduce conceptual frameworks used in the inquiry and flag their application and critical consideration in subsequent chapters.

2.2 A transdisciplinary approach to address a complex, real-world problem

The question at the heart of this inquiry – how to translate and implement planetary sustainability concepts within and through the WASH sector – demanded a transdisciplinary approach. Transdisciplinarity emerged and developed in the 1970s as a critique of narrow disciplinary perspectives, and opportunity to reimagine the relationship between science and society under a set of common axioms (Gibbs & Beavis, 2020; Thompson Klein, 2015). While definitions vary, distinguishing features of transdisciplinary approaches are their problem focus, evolving methodology and collaborative nature (Wickson et al., 2006). More specifically, transdisciplinary approaches are characterised by:

- A real-world ‘problem’ framing or focusing on socially relevant issues that transcend disciplinary boundaries (e.g. Pohl, 2010; Thompson Klein, 2017; Wickson et al., 2006).

- A normative intent to improve or transform the situation (e.g. Marshall et al., 2018; Mitchell et al., 2015).

- Transcending disciplinary paradigms, taking an epistemologically pluralist stance (e.g. Carew and Wickson, 2010; Pohl, 2010; Willetts and Mitchell, 2017).

- Evolving methodologies (e.g. Carew and Wickson, 2010; Wickson et al., 2006).

- Collaborative, consultative and/or participatory practice, involving meaningful collaboration between researchers and other stakeholders (e.g. Hernandez-Aguilar, 2018; Mobjörk, 2010; Pohl, 2010; Rigolot, 2020; Schmidt et al., 2020; Wickson et al., 2006). Increasingly, such collaborative processes are framed as ‘knowledge co-production’ (Pohl et al., 2021; Schneider et al., 2019).

- Valuing of different knowledge types, such that practical, local and personal knowledge is integrated with scientific and academic knowledge (Bammer et al., 2020; Gibbs & Beavis, 2020; Jahn et al., 2012).

While all these characteristics are evident in this inquiry’s methodology (and discussed throughout this chapter), the first two drove the decision to take a transdisciplinary approach. Firstly, the complexity of both WASH and sustainability ‘problems’ required exploration through multiple, complementary lenses to achieve a sufficiently rich picture. While the inquiry is inclusive of disciplinary lenses and methods, which offer substantial value within WASH and sustainability research, the scope of my research question required a broader approach. Its sector-wide perspective, and layering of sustainability onto already complex WASH challenges, warranted a research design suited to real-world complexity and well-placed to generate integrative insights.

Secondly, transdisciplinarity offered a frame to support rigour while undertaking values-based research. The normative, problem-solving intent of the inquiry – seeking stronger WASH sector engagement with sustainability – is driven by my belief in the importance of sustainability transformations in pursuit of sustainable, equitable futures. Such an approach requires reflection and reflexivity to ensure change-creation intentions guide, but do not dogmatically drive, the research. Transdisciplinarity offers scaffolding to support rigorous, values-based research by demanding responsiveness, collaboration and the valuing of multiple perspectives. My alignment with the problem-solving discourse of transdisciplinarity is discussed further in section 2.4, and my application of transdisciplinary quality criteria as scaffolding for rigorous research is described in section 2.6.

2.3 Building on previous transdisciplinary research experience

The decision to take a transdisciplinary approach was also informed by my prior and ongoing research experience with its emphasis on collaboration, addressing real-world challenges and adapting (and evolving) methods to suit unique situations. Having spent a decade working on collaborative WASH research projects prior to commencing my PhD, I came to doctoral research with an appreciation of both the purpose and practical realities of transdisciplinary approaches. Working on the real-world challenge of access to WASH services supports my ability to engage with complex situations and consider the potentially limitless ways in which ‘problems’ can be framed and reframed. In articulating and seeking a change agenda for research projects, I navigate purposeful, ethical approaches and identify pathways between research activities and their outcomes. Many of the projects I contribute to demand an epistemologically pluralist stance – for example, conceiving a quantitative measure of WASH-related gender outcomes based on a socially constructed view of gender equality (Carrard et al., 2022) – which has supported my development of reflexive skills. Similarly, evolving research approaches to match contextual and practical realities is characteristic of collaborative research projects, which have all been driven by a central focus on partnership between researchers and a diverse set of WASH stakeholders.

A partnership approach is characteristic of ISF-UTS WASH research, and was central in driving my focus on WASH professionals in this inquiry. Through collaborative research projects I work closely with water and/or sanitation service providers (utilities, private operators, community groups), government agencies involved in WASH policy and planning, civil society practitioners and bilateral and multilateral donor agencies. I brought these experiences to my doctoral research, seeking to build from and strengthen my transdisciplinary research skills, depth of thinking about WASH challenges, and ability to generate insights relevant and useful for the WASH professionals I partner with.

2.4 A problem-solving transdisciplinary inquiry

Synthesising and reflecting on almost 50 years of scholarly work developing the field of transdisciplinarity, Thompson Klein (2015) identifies three major discourses: transcendence, problem-solving and transgression. The transcendence discourse advocates unity, holism and the importance of moving beyond disciplinary worldviews (Thompson Klein, 2015). The problem-solving discourse is centrally focused on the potential for transdisciplinary research to address societal challenges, captured in Jantsch's (1970) vision of a transdisciplinary university structure framed by purpose, and since promulgated by numerous transdisciplinary organisations and scholarly outputs (Thompson Klein, 2015). Finally, the transgression discourse emphasises the role of transdisciplinarity in public critique and debate, moving "beyond instrumental integration to critique, reimagine, and reformulate the status quo". While the boundaries between discourses are fluid and evolving, Thompson Klein (2015) argues for their likely persistence given the relative focus on epistemological (transcendence), knowledge production (problem-solving) and critical interrogation (transgression) questions.

While acknowledging boundary fluidity, this doctoral inquiry was primarily aligned with the problem-solving discourse of transdisciplinary research. In articulating this alignment, I emphasise two features of the discourse evident in the inquiry. First, the inquiry was purposeful, with an explicit agenda to shift WASH sector focus towards a foregrounding of planetary sustainability concepts and ideals. This normative approach reflects my integrative worldview, belief in the ideal of a

sustainable and equitable future, and pragmatic epistemological orientation (as described in Chapter 1). The purposive approach was also guided by Mitchell et al.'s (2015) outcome spaces framework for transdisciplinary research, which prompts transdisciplinary researchers to identify and plan outcomes from their projects across three realms: (i) an improvement in the situation, (ii) generation of stocks and flows of knowledge, and (iii) mutual and transformational learning by researchers and research participants. Throughout the inquiry, I used these outcome spaces as a tool for reflection about the situation and optimal directions of change, my contribution to knowledge in the form of peer-reviewed publications and presentations, and my mode of engaging with sector stakeholders (throughout) and research participants (in studies 3 and 4). I articulate the contributions of the inquiry with reference to the outcome spaces in section 7.8.

Second, the inquiry adopted an iterative, generative approach in the selection of conceptual frames and methods for each included study. Such an approach is characteristic of the problem-solving discourse of transdisciplinarity, which both draws on established methods and tools from diverse disciplines and applies heuristic techniques to generate integrative and contextualised insights (Thompson Klein, 2015). A heuristic approach emphasises the situational demands of a transdisciplinary inquiry rather than focusing on methodological norms, making sense of situations as best suits their nature and the research purpose (Huutoniemi, 2014). I made use of heuristics – or "thinking tools" as termed by Carew & Wickson, (2010) – to grapple with the breadth of issues implicated in this inquiry, and an associated need for tools that support sensemaking given the impossibility of investigating every relevant implication. Tools and methods used for analysis are introduced in section 2.8 and detailed in subsequent chapters. As a set, the methods and heuristic techniques reflect a fit-for-purpose methodological approach, iteratively developing and applying tools best suited to answering research questions and generating meaningful insights to address the 'problem' in focus.

2.5 Transdisciplinarity as a way of being

While the problem-solving discourse of transdisciplinarity best characterises my doctoral inquiry, perspectives of transdisciplinarity as a 'way of being' – which span Thompson Klein's three discourses – also resonate and have shaped my approach. Rigolot (2020) conceives transdisciplinarity as both a discipline and way of being, with the latter signifying the inseparability of professional research activities and personal life. Such a perspective is captured by Gibbs and Beavis (2020), who also emphasise the idea of emergence:

> … transdisciplinarity is more than a methodology grounded in conventional logics: it is an ideology; a disposition; a way of addressing the world in which one is emergent. (p. 4)

Over its 50-year history, transdisciplinarity has been variously conceived as a methodology, discipline, practice and researcher orientation. Conceptions are often characterised dualistically as 'mode 1' and 'mode 2' transdisciplinarity, with mode 1 referring to discursive theoretical explorations of transdisciplinarity (commonly associated with the work of Nicolescu, e.g. 2008, 2014) and mode 2 more practically oriented and focused on the building of knowledge about societal challenges (Rigolot, 2020).

In aligning myself with the problem-solving discourse of transdisciplinarity I view transdisciplinarity as a practice. Yet I also reject the dualistic distinction between philosophical and practical interpretations. Conceiving transdisciplinarity as a 'way of being' resonates with my approach, which pragmatically responds to a problem while acknowledging plural perspectives, emphasising relational over mechanistic responses and the need to transcend a problem-solving perspective to achieve deep and broad transformations to sustainability. My alignment with relational perspectives on sustainability (as articulated by West et al., 2020) is evident in publication 4 (Chapter 6). The inquiry's synthesis (Chapter 7) identifies meta-level insights that transcend problem-solution framings in favour of process-oriented themes and directions. In doing so, an outcome of the inquiry is my emerging alignment with the transdisciplinary discourse of transgression, which "moves

beyond instrumental integration to critique, reimagine, and reformulate the status quo" (Thompson Klein, 2015, p. 14).

2.6 Scaffolding the approach: criteria for quality in transdisciplinary doctoral research

In pursuit of research rigour, I shaped the inquiry with reference to five criteria for assessing quality in transdisciplinary doctoral research (Willetts & Mitchell, 2017), namely, (i) contribution to knowledge, (ii) reflexivity and responsiveness, (iii) research integrity, (iv) appropriate engagement with research context and literature, and (v) coherence. The criteria reflect a decade of work adapting traditional research quality criteria for transdisciplinary research and for the doctoral process (Willetts & Mitchell, 2017). An original set of seven criteria (Mitchell & Willetts, 2009) was informed by, and updated in response to, Belcher et al.'s (2016) systematic review of assessment of transdisciplinary research. In this section, I demonstrate my alignment with the quality criteria, describing how each informed and is reflected in included studies.

2.6.1 Criterion 1: Substantial, significant research as an original contribution to knowledge and other broader societal outcomes

The inquiry sought three levels of knowledge contribution. The first is in the scholarship of integration, involving synthesis across different disciplinary perspectives and interpreting research in context (Boyer, 1997). Contributions to integrative knowledge are evident in each of the included studies, which connected insights from different disciplinary lenses and applied them to the WASH sector as context. Integration is also core to the inquiry's synthesis (Chapter 7), which makes sense of findings across the four studies to identify three meta-level themes that address the overarching research question.

Second, the inquiry contributes 'discovery' knowledge (Boyer, 1997) through its two in-depth studies focused on groundwater reliance and resource concerns (study 2) and life-cycle costs of resource-oriented sanitation (study 3). Both studies addressed gaps in existing knowledge: the extent of groundwater reliance and connections between resource concerns and drinking water services in study 2

(publication 2, Chapter 4); and empirical data on the life-cycle costs (and their distribution) for resource-oriented sanitation systems in study 3 (publication 3, Chapter 5).

Third, study 4 contributed collaborative knowledge generation through a process of knowledge co-production with a diverse set of WASH professionals (see publication 4, Chapter 6). The co-production process collaboratively explored insights associated with prior studies, strengthening their legitimacy and significance for the sector. The process also created a space for mutual, transformative learning – one of the three transdisciplinary outcome spaces (as described in section 2.4, after Mitchell et al., 2015).

Beyond knowledge contributions, the pursuit of societal outcomes shaped my approach within each study towards articulation of priorities and pathways for action. Study 1 (publication 1, Chapter 3) identified four priorities for research and knowledge leadership to strengthen WASH engagement with sustainability. Study 2 (publication 2, Chapter 4) proposed actions for water service providers, service authorities and national governments to integrate groundwater resource management imperatives within water service delivery efforts. Study 3 (publication 3, Chapter 5) explored how life-cycle costing can inform circular economy approaches to sanitation. Study 4 (publication 4, Chapter 6) collaboratively produced ideas about sector priorities for foregrounding sustainability. While claiming societal impact from the inquiry is unrealistic given the scale and timeframe of doctoral research (as discussed in Chapters 6 and 7), foregrounding implications for WASH professionals throughout the inquiry offers a foundation for broader societal contributions.

2.6.2 Criterion 2: Demonstrated reflexivity and responsiveness

Responsiveness in the inquiry is demonstrated by the iterative nature of study selection, and close engagement with research participants and stakeholders in studies 3 and 4. My research questions and approach evolved as the inquiry progressed, informed by reflection about the scholarly value, feasibility and practical benefit of each study. In these ways, the in-depth studies (studies 2 and 3) responded to priorities that were identified in the discourse analysis (study 1) and

built on my experiences in the sector. The rationale for in-depth study topic choices, and how they were informed by related research, are detailed in the orientation to Part II of this thesis. Study 4 engaged WASH professionals in discussion about emerging insights, with findings and synthesis themes responding to the perspectives and priorities shared in the co-production processes (described in Chapters 6 and 7).

Study 4 and my approach to the inquiry's synthesis also demonstrated reflexivity. Publication 4 (Chapter 6) directly explored the ways in which my position as researcher-facilitator shaped the process of knowledge co-production. Similarly, in identifying a theme of 'reflexively researching' in the inquiry's synthesis (Chapter 7), I grappled with researcher roles in normative, and aspiringly transformative, processes of sectoral change. I identified how my plural epistemological perspective shaped this inquiry, and argued for reflexivity as an ethical imperative in normative, collaborative South-North research partnerships.

2.6.3 Criterion 3: Research integrity as demonstrated by credibility, legitimacy and alignment

Credibility and legitimacy in the inquiry are demonstrated by the research being published, shared and refined at multiple points. Peer review processes attested to the robust and trustworthy nature of study findings, with the four included studies each published as articles in reputable WASH, water and sustainability journals. Sharing insights at conferences (*WASH Futures* 2018, *International Conference on Sustainable Development* 2021), with WASH sector networks (e.g. Sustainable Sanitation Alliance, Rural Water Supply Network) and during the study 4 co-production process also confirmed the legitimacy of emerging insights and elicited constructive feedback to inform subsequent stages of inquiry.

My approach to integrity was also evident in my engagement with research ethics processes. I submitted two separate applications to the UTS Human Research Ethics Committee, one for study 3 (empirical research in Sri Lanka) and one for study 4 (knowledge co-production with WASH sector stakeholders). Going through the ethics approval process twice was important given the differences between studies, and allowed for nuanced engagement with the research context for each to

ensure a responsive, respectful process. A key part of my approach was feeding back findings to participants and stakeholders, for example, study 3 findings were shared with government representatives in Sri Lanka to inform their ongoing sanitation initiatives and study 4 was shared in draft and final forms with participating WASH professionals for feedback and approval.

Alignment in the inquiry was informed by consideration of the ways in which my axiological, ontological and epistemological perspectives shaped my research. While included studies differ in their topics and methods, they align in their contextual focus on the WASH sector, consequent relevance to the overarching research question, normative intent, and pragmatic epistemological orientation. The emphasis on discourse and constructed meanings evident in studies 1 and 4 was also influenced by my constructivist orientation, as was my critically reflexive approach to the generation of meta-level insights in the inquiry's synthesis (see Chapter 7).

2.6.4 Criterion 4: Appropriate breadth and depth of engagement with both research context and literature

Breadth and depth are evident across the inquiry's four distinct yet connected studies, which explored different dimensions, scales and contexts relevant to WASH-sustainability interactions. Studies 1 and 4 took a global sectoral focus, while studies 2 and 3 addressed specific, contextualised questions relevant to water and sanitation respectively. The rationale for choice of these particular in-depth topics is presented in Part II of this thesis. Each study was informed by engagement with relevant literature spanning natural, technical, policy and practice fields.

2.6.5 Criterion 5: Coherent argument across diverse conceptual and methodological approaches and perspectives

Coherence is demonstrated within each of the included publications, which are stand-alone pieces of scholarly work. Coherence of the inquiry overall is evident in the mapping of study-specific sub-questions to the overarching research question (see section 1.5, Figure 4) and in the synthesis (Chapter 7) with its presentation of meta-level themes that emerged from cross-study analysis. The coherent argument

presented in this thesis was emergent rather than foreseen (as described in Chapter 7), which is a characteristic feature of transdisciplinary inquiry (Klenk & Meehan, 2017) and its grappling with complexity (Carew & Wickson, 2010) of problem and research process. In identifying meta-level insights, the synthesis articulated points of convergence across included studies while avoiding over-simplification of complex processes of sectoral change in line with sustainability transformations.

2.7 Reflections on transdisciplinary stakeholder engagement in the context of doctoral research

As this inquiry progressed, an ongoing question was if, and how, the research was appropriately collaborative given that a defining feature of transdisciplinary research is the inclusion of diverse knowledge types through engagement between researchers and non-academic stakeholders (Hernandez-Aguilar et al., 2020; Mobjörk, 2010; Pohl, 2010; Rigolot, 2020; Schmidt et al., 2020; Wickson et al., 2006). Studies 3 (life-cycle costs of resource-oriented sanitation) and 4 (knowledge co-production for WASH sustainability) were conducted with stakeholders, and study 4 explicitly used transdisciplinary knowledge co-production as a method. However, the overall inquiry was conceived, designed and conducted as an individual endeavour with collaborative components, rather than a collective project involving stakeholders in problem definition and design. In reflecting on my approach with reference to transdisciplinary ideals, three features highlight both the strengths and limitations of the research as a transdisciplinary inquiry, related to (i) my prior and ongoing experience as an applied WASH researcher in complement to my doctoral studies, (ii) components of the inquiry that explicitly sought collaboration, and (iii) balancing doctoral drivers and limitations with transdisciplinary ideals.

First, in conceiving and designing the inquiry, I drew from my 10 years' experience working in partnership with WASH professionals from civil society, government, donor, private sector and research realms. My close engagement with a range of WASH professionals informed the way I approached doctoral research, particularly in striving to translate research findings into relevant, useful insights for the sector

(see section 2.6 criterion 1). This close engagement continued throughout my doctoral studies, during which time I led a partnership with a civil society organisation focused on rural sanitation services in Bhutan and Lao People's Democratic Republic and rural water supply in Nepal. I also contributed to a range of projects focused on gender equality outcomes associated with WASH interventions. While these collaborative endeavours did not form part of my doctoral studies, they ensured my continued connection with the perspectives and practical realities shaping WASH professional practice in multiple contexts.

Second, as the inquiry progressed, I sought greater involvement of stakeholders by pursuing empirical research (study 3 in Sri Lanka) and co-production of knowledge (study 4). Undertaking research in Sri Lanka provided opportunity to work closely with researchers at my host institution (the International Water Management Institute) and with their support, government stakeholders at national and local levels. Engaging with government stakeholders was critical in how the study was framed and scoped (responding to an expressed need for cost information), for validating data and assumptions, and connecting research to practice by sharing and discussing findings.

Study 4 built on the collaborative approach taken in study 3, including a process of engagement with WASH sector professionals. This collaboration was conceived and occurred at a later stage of the inquiry, which is a limitation of my approach given the ideal of transdisciplinary research involving stakeholders from the outset in problem framing and question definition (Chambers et al., 2021; Jagannathan et al., 2020). I justify this limitation with reference to my third point of reflection, which focuses on the structure and expectations of a traditional PhD program as individually driven and bounded by disciplines (Lazurko et al., 2020). In incorporating a knowledge co-production process, I sought to honour transdisciplinary ideals while acknowledging my reasons for not doing so earlier given the time, resources and individual leadership characteristic of doctoral research. The co-production process of study 4 therefore represented a culmination of doctoral research up to that point, and opportunity for me to engage more deeply with transdisciplinary methods as a foundation for future transdisciplinary research endeavours.

2.8 Conceptual frames and their place in the transdisciplinary inquiry

In this section, I introduce the fields of scholarship, conceptual frameworks and heuristic analysis techniques employed in the inquiry. Subsequent chapters further discuss each of the included elements with reference to the studies in which they were applied. In this orientation, they are situated within the overall transdisciplinary approach to highlight their connections, distinctions and how they informed a coherent approach. Figure 6 illustrates and locates underpinning theories and concepts as fields of scholarship, conceptual frames, heuristic analysis tools and methods employed.

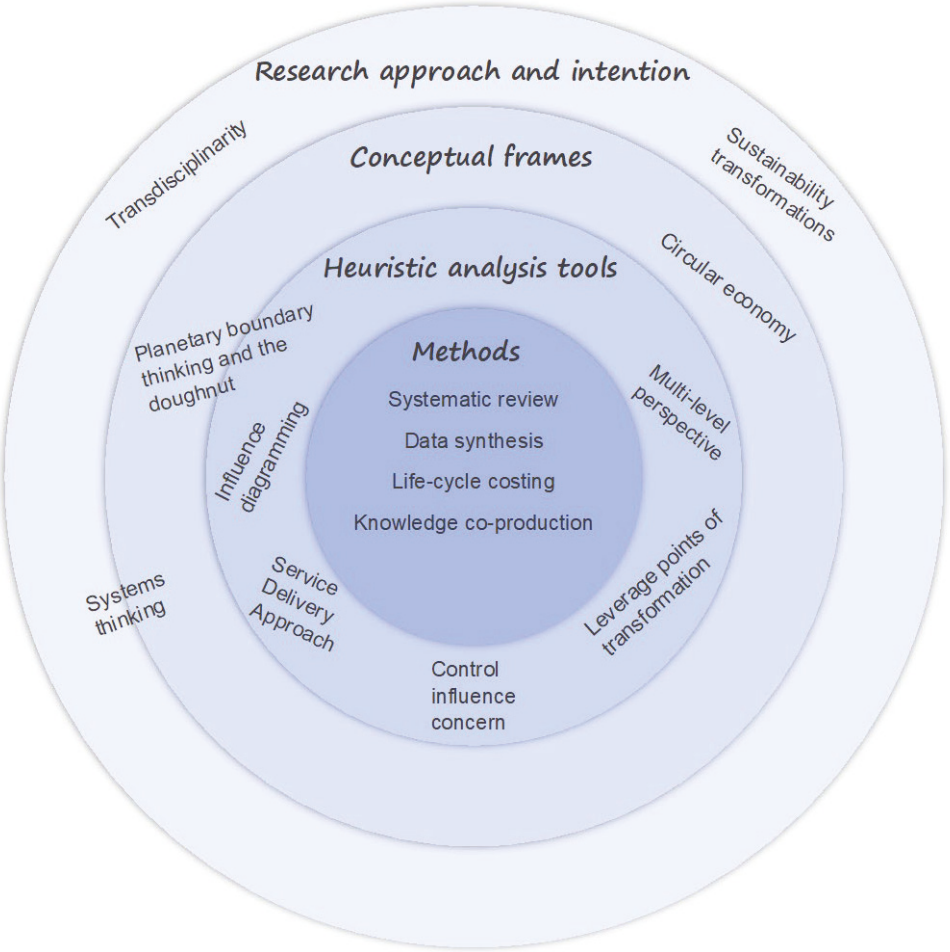

Figure 6 Conceptual frames, heuristic tools and methods used in the inquiry

Transdisciplinarity is identified as the research *approach*, with sustainability transformations the research *intention*. Planetary boundary thinking and the doughnut shaped the inquiry's conception of sustainability, and provided an

heuristic tool in study 1. The concept of circular economy underpinned study 3's normative orientation, and is a defining feature of the envisioned economic shifts that can drive our transition to a 'safe and just space for humanity' within planetary boundaries. Systems thinking concepts including interconnections, feedbacks and emergence informed my conception of the problem situation, as well as approach to identifying responses using a leverage points lens (as detailed in section 7.2).

The systems method of influence diagramming served as a heuristic for sensemaking about connections between groundwater resource concerns and the human right to water (study 2). Study 2 also used the service delivery approach framework of three institutional levels as a sector-relevant heuristic to identify implications of the analysis for national WASH agencies, service authorities and service providers. Study 1 applied the multi-level perspective – a way of conceptualising socio-technical transitions – as a heuristic for generating insights about reuse-related literature. Heuristics used in the inquiry's synthesis (introduced in section 1.3,4 and detailed in section 7.2) included leverage points of transformation and circles of control, influence and concern.

Methods applied in the inquiry comprised systematic literature review (study 1), data synthesis and targeted literature review (study 2), life-cycle costing (study 3) and transdisciplinary co-production of knowledge (study 4). Methodological choices for each study are justified and elaborated in each relevant publication (Chapters 3–6). Table 3 indicates where each field, concept, heuristic tool and method is presented and critically discussed in the thesis.

Table 3 The application of concepts, heuristics and methods in included studies and relevant thesis chapters

Concepts, heuristics and methods	Studies applied in	Where addressed in the thesis
Transdisciplinarity	Overarching research approach	Chapter 2 (this chapter)
Sustainability transformations	Implicit intention across all studies, explicitly addressed in study 4 (knowledge co-production for WASH sustainability)	Chapter 1: introduced Chapter 6 (publication 4): the aspiration of co-production Chapter 7: informing synthesised insights and future research directions
Systems thinking	Informed the inquiry's focus on interconnections and complexity. Influence diagramming used as a heuristic tool in study 2 (groundwater reliance and resource concerns). The systems concept of leverage points informed sensemaking for the inquiry's synthesis	Chapter 4 (publication 2): presented as sensemaking method Chapter 7: informing synthesised insights
Planetary boundary thinking and the doughnut	Conceptual framing for inquiry overall, heuristic analysis technique for study 1 (WASH discourse and planetary boundaries)	Chapter 1: introduced and situated with reference to sustainability transformations Chapter 3 (publication 1): defining sustainability and heuristic tool for analysis of WASH discourse
Circular economy	Conceptual framing for study 3 (life-cycle costing of resource-oriented sanitation)	Chapter 5 (publication 3): situating sanitation within circular economy concepts and critically reflecting their application in the inquiry

Concepts, heuristics and methods	Studies applied in	Where addressed in the thesis
Service Delivery Approach framework	Applied as a sector-relevant heuristic tool for identifying implications of groundwater analysis for WASH professionals	Chapter 4 (publication 2): presented as sensemaking method to identify action pathways for WASH professionals
Transition studies multi-level perspective	Heuristic tool applied in study 1 (WASH discourse and planetary boundaries)	Chapter 3 (publication 1): applied to generate insights related to resource-oriented sanitation literature, including critical reflection on the perspective in light of more recent discourse and developments
Leverage points of transformation	Heuristic tool for sensemaking across studies	Chapter 1: introduced Chapter 7: informing synthesised insights
Circles of control/influence/concern	Heuristic tool for sensemaking across studies	Chapter 1: introduced Chapter 7: informing synthesised insights
Systematic literature review	Method for study 1 (WASH discourse and planetary boundaries)	Chapter 3 (publication 1)
Data synthesis and targeted literature review	Method for study 2 (groundwater reliance and resource concerns)	Chapter 4 (publication 2)
Life-cycle costing	Method for study 3 (life-cycle costing of resource-oriented sanitation)	Chapter 5 (publication 3)
Transdisciplinary co-production of knowledge	Method for study 4 (knowledge co-production for WASH sustainability)	Chapter 6 (publication 4)

2.9 Summary

In this chapter I have justified and presented my transdisciplinary research approach. A transdisciplinary approach was justified with reference to the inquiry's focus on a complex, real-world 'problem' and its normative intent to improve the

situation. I identified the inquiry as most closely aligned with the problem-solving discourse of transdisciplinarity based on its purposeful and iterative approach, and described my complementary conception of transdisciplinarity as a 'way of being' – a conception that is driving emerging alignment with the discourse of transgression. To assert and demonstrate the rigour of my approach I explained how the inquiry met five criteria for assessment of quality in transdisciplinary doctoral research, before reflecting on strengths and limitations of the inquiry with reference to transdisciplinary ideals of stakeholder engagement. Finally, I presented an overview of the conceptual frames, heuristic tools and methods applied in the inquiry, each of which are detailed in relevant chapters and publications. In the next chapter, which concludes Part I of the thesis, I present the inquiry's exploration of WASH-sustainability literature in the form of a discourse analysis (publication 1) and updated review.

3 Chapter 3 WASH discourse and sustainability

3.1 Overview

This chapter reviews WASH discourse related to sustainability. A systematic review of literature at the intersection of WASH and environmental sustainability was published in the *Journal of Water, Sanitation and Hygiene for Development* in 2017 and forms the first of four journal articles included in this 'thesis by compilation'. The review analysed the inclusion and presentation of environmental sustainability concepts in academic and non-academic WASH sector literature published between 2010–2016. Literature was analysed inductively to identify themes, and through the lens of planetary boundaries to identify future priorities. Following a brief note on terminology, this chapter presents the journal article and shares critical reflections on the review in light of the overall inquiry. I then explore how WASH sector discourse has evolved since the review's publication, identifying a key shift from consideration of climate change as a threat towards widespread acknowledgement that climate change is the operating context for service delivery. Finally, I critically reflect on my published and updated literature reviews with reference to sustainability transformations concepts, identifying a tendency for WASH discourse to view sustainability in instrumental rather than interdependent – and potentially more transformative – terms. The systematic review established the foundation for subsequent in-depth studies that form Part II of this thesis, each of which also contain reviews of literature more closely related to their topics (Chapters 4 and 5). Together, the literature reviews informed insights presented in the synthesis (Chapter 7) about the power of discourse in reflecting and shaping collective perspectives.

3.2 A note on terminology

The phrase 'environmental sustainability' was used in the systematic review. At the time of researching and writing the review, 'environmental sustainability' was in common use in international development (as it had been since publication of the Brundtland report [WCED, 1987]) and was helpful in distinguishing literature of interest from WASH discourse focused on other dimensions of sustainability

including functional, economic and social sustainability. Since the systematic review was published, use of the word ‘sustainability’ has evolved in WASH and in development and transformations discourse, increasingly conveying integrative perspectives on human development and flourishing in the biosphere (e.g. Griggs et al., 2013; Lim et al., 2018; United Nations, 2015; Waddock, 2020). This thesis reflects wider trends in terminology, with ‘planetary sustainability’ or simply ‘sustainability’ used in later parts of the work.

3.3 Publication 1 — Environmentally sustainable WASH? Current discourse, planetary boundaries and future directions

Publication 1 is included in Author Accepted Manuscript format in this thesis. The published version is available at https://doi.org/10.2166/washdev.2017.130 and is free to read online under IWA Publishing’s open access arrangements established in 2021.

Environmentally sustainable WASH? Current discourse, planetary boundaries and future directions

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ABSTRACT

The significant challenge of achieving safe, reliable and continuous service delivery has been a focus of the water, sanitation and hygiene (WASH) sector in recent years, with less attention given to other important sustainability considerations such as environmental sustainability. The agenda set by the Sustainable Development Goals (SDGs) prompts a wider lens, bringing water resource management and ecosystem conservation together with water and sanitation access targets in one integrated goal. As we grapple with our approach to this new agenda, it is timely to reflect on how we, as a sector, engage with environmental sustainability. This paper reviews recent literature at the intersection of WASH and environmental sustainability to identify current themes and future directions. Analysis of academic and non-academic sources was undertaken and then situated with reference to the planetary boundaries framework as a useful lens to ground the socio-ecological systems and processes upon which environmental sustainability depends. Findings point to both opportunities and gaps within current sector thinking, which can drive leadership from knowledge and research institutions towards better integration of access and environmental sustainability imperatives.

KEYWORDS Environmental sustainability; planetary boundaries; reuse; sustainable development goals; WASH; water security

INTRODUCTION

Within international development aid, the dominant focus of the water, sanitation and hygiene (WASH) sector has been on social, health and economic needs and drivers, with "sustainability" often defined as continuation of services (Mehta and Movik 2014). The environmental sustainability implications of improving access are given less focus. Yet they are significant; if we continue to use dominant paradigm approaches to expanding service delivery for the 663 million people currently without access to safe water and the 2.4 billion without access to improved sanitation (WHO/UNICEF 2015) while keeping pace with population growth, there will be significant impacts across a range of ecological systems and the resources they provide. This will threaten our ability to provide equitable services for all into the future.

To date, service delivery paradigms have been informed by the experiences of developed countries and typically focused on extractive water infrastructure and "end of pipe" sanitation solutions. These models have addressed access issues, but with costs to ecosystem and resource integrity (Gleick 2003; Poustie and Deletic 2014). In the global water sector there is a shift occurring towards solutions that improve the productivity and efficiency of water use (Brooks and Brandes 2011). This approach has the potential to better integrate ecosystem and resource sustainability concerns compared with historic approaches, but is a relatively recent shift in developed countries and is yet to be meaningfully taken up in the international development WASH sector (Brooks and Brandes 2011). For this sector, it is imperative to consider ways to move beyond business as usual approaches to better integrate environmental considerations with access objectives.

In 2015 the most recent global development agenda emerged, embracing new visions and objectives in the form of the Sustainable Development Goals (SDGs) (United Nations 2015). In the SDG framework, WASH-related targets (within SDG6) have been broadened as compared with their Millennium Development Goal (MDG) predecessors. There is a stronger emphasis on universal and equitable access (informed by the human rights to water and sanitation) and the need to consider service access imperatives with reference to broader water resource management considerations. The broader agenda encompassed in SDG6 reflects a recognition of the central importance of environmental considerations in sustainable water and

sanitation service delivery, with a particular focus on the interlinked areas of water quality, water efficiency, integrated water resource management (IWRM) and water-related ecosystems.

As policy makers, practitioners and researchers widen their focus in line with the SDG agenda, it is timely to reflect on the way the WASH sector engages with environmental sustainability. This paper offers a review of current discourse at the intersection of WASH and environmental sustainability to identify themes and consider future directions that might best support, rather than threaten, a safe and sustainable planet. First, the approach is described. This includes articulating how environmental sustainability has been defined for the purposes of the review. We introduce the planetary boundaries framework (Rockström et al. 2009) as a means to ground this definition, and we describe the process of discourse analysis. Themes identified in current literature are then presented and critically discussed. Finally, future directions for the sector are proposed, informed by an assessment of current themes against the planetary boundaries framework. The planetary boundaries framework sets out nine interlinked earth system boundaries in which human society can continue to thrive, thereby defining a "safe operating space for humanity" (Rockström et al. 2009; Steffen et al. 2015). For this review, this framework both offers a synthesizing framework for engaging with critical questions of environmental sustainability, and advocates an imperative to do so.

APPROACH

Defining environmental sustainability and planetary boundaries

The definition of environmental sustainability adopted for this review incorporates conservation of both natural *resources* and *ecosystems*. A resource lens prompts consideration of the need to manage the natural resources on which human societies depend in a way that enables continuity of services in perpetuity for future generations. Including ecosystem conservation reflects both the interdependencies of ecosystems and natural resources, and their intrinsic value. This definition draws on the well-recognized Brundtland report conception of environmental sustainability as "meeting the resource and services needs of current and future generations without compromising the health of the ecosystems that provide them"

(WCED 1987), and that of Morelli (2011) with its explicit addition of the need to conserve biological diversity:

> *environmental sustainability could be defined as a condition of balance, resilience, and interconnectedness that allows human society to satisfy its needs while neither exceeding the capacity of its supporting ecosystems to continue to regenerate the services necessary to meet those needs nor by our actions diminishing biological diversity.*

For the WASH sector, contributing to environmental sustainability therefore requires managing the quantity and quality of resources (such as fresh water) in a way that ensures their ongoing availability now and for future generations, and does not threaten the health of ecosystems. It is important to note that this requires consideration of both local and wider-scale processes, given resource and ecosystem dynamics occur locally, regionally and globally.

The planetary boundaries framework aligns with this definition in its recognition that the health of earth system processes (across scales) dictates the capacity for human populations to survive and thrive. First proposed by Rockstrom et al. (2009) and since refined and re-published (Steffen et al. 2015), it sets out nine interlinked biophysical processes that regulate earth system functioning: climate change; biosphere integrity (biodiversity loss); freshwater availability; land use change; biochemical flows (nitrogen and phosphorus); ocean acidification; stratospheric ozone depletion; atmospheric aerosol loading; and novel entities (chemical pollution). The framework is informed by significant bodies of work across ecological economics, earth system science and resilience (Rockstrom et al. 2009). For each of the nine earth system processes, ongoing research is attempting to define thresholds of human impact beyond which abrupt environmental changes may threaten the earth's capacity to support human populations (Steffen et al. 2015). Figure 1 presents the planetary boundaries framework and current assessment, showing that four of the nine boundaries have been crossed as a result of human activity: climate change; biosphere integrity; land-system change; and biochemical flows (Steffen et al. 2015).

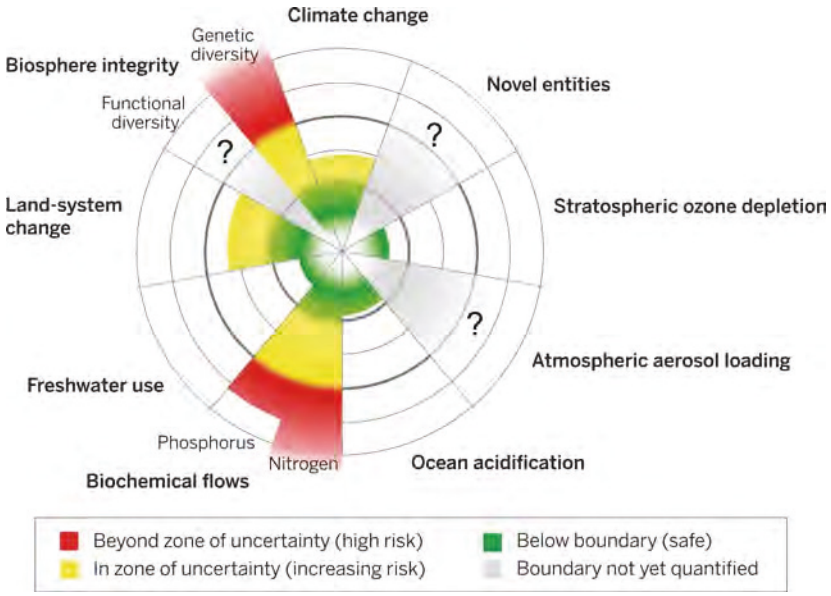


Figure 1 The planetary boundaries framework and current assessment (Steffen et al. 2015)

By quantifying these thresholds of human impact, the framework defines a "safe operating space for humanity" (Rockstrom et al. 2009). This "safe operating space" is a key conceptual advancement on previous framings of ecological limits as it provides a way to conceptualize what "sustainable" looks like from a whole-of-planet perspective as an alternative to sectoral approaches focused on minimizing negative externalities (Rockstrom et al. 2009). Further, it makes clear that deep and widespread transformations are needed to remain within the "safe operating space", with four of the earth system processes included within the framework already transgressing their safe limits (Steffen et al. 2015).

In identifying a set of tangible earth system processes critical for planetary health, the planetary boundaries framework also grounds the otherwise slightly illusive concept of environmental sustainability. Reflecting this, the framework is becoming more widely used in sustainable development discourse including in global policy dialogues related to the SDGs (Griggs 2013; Pisano and Berger 2013; Hajer et al. 2015). In line with this and taking a sectoral lens, this review draws on the framework as an analytical tool for promoting consideration of future needs and directions for WASH. Five of the nine planetary boundaries are closely connected to WASH, as described in detail below, including three that have already been transgressed.

Importantly, the authors believe that the need to strive for environmental sustainability does not override the urgent and critical need to improve the

situation for those currently without water and sanitation services. Rather, we assert that progressive realisation of the human rights to water and sanitation must continue apace, within a framework that supports environmental sustainability.

Literature analysis

Our approach was to review and analyse environmental sustainability concepts in recent (2010–2016) academic and non-academic WASH sector literature. Recognizing the role that literature, and the discourse contained within it, play in constructing our realities (Phillips and Hardy 2002 cited in Onwuegbuzie and Frels 2014), a review of this nature helps us to reflect on what we (as a sector) are focusing on and making meaningful. Specific analysis techniques included both content analysis (deductive and inductive coding and counting of codes) and thematic analysis (identifying relationships and their links to the overall context), as described by Onwuegbuzie et al. (2012) and explained in further detail below.

The first stage involved extensive searching of academic (peer reviewed journal articles) and non-academic (grey) literature to identify relevant material. Journals with a particular WASH focus were targeted, as were the sites of 18 sector institutions known for undertaking research and/or knowledge management activities. In addition, searches in a variety of academic databases and through both Google Scholar and Google were undertaken to identify further material. Search strings included combinations of phrases relating to “environmental sustainability”, “water supply”, “sanitation” and “WASH” depending on the target site. The initial search identified more than 2400 sources, of which 176 were found to be relevant to our inquiry based on appraisal of titles, abstracts and (if necessary) introductory content. During this appraisal process, an initial identification of themes was undertaken for use in subsequent coding.

Documents selected for this stage of analysis were those that provided commentary on, or insight into, the ways the WASH sector approaches research, policy and programming with respect to environmental sustainability. In other words, they enabled an analysis of what topics and ideas are considered important as well as accepted “ways of doing things” at a sector or programmatic level. Excluded from the analysis were project design documents and reports as well as highly technical papers about specific aspects of technologies. Some material that focused on technologies

was included in instances where technologies were explored within a broader discussion of environmental sustainability. We maintained a core focus on literature that was substantially concerned with domestic water supply and sanitation in the developing world, rather than material that incidentally mentioned services within a discussion of water resource allocations and management or climate change. Unsurprisingly however, many of the sources selected do sit at the interface of WASH and water resource management or climate change, given the close relationship between service delivery and these environmental dynamics.

The second stage involved content analysis and coding of each of the 176 sources based on titles, abstracts, executive summaries and a rapid scan of full text using: (i) themes identified during the initial search phase; (ii) additional content-driven themes that emerged during the coding process (using an iterative process to apply emerging themes to previously coded material); and (iii) themes relating to selected analytical lenses including SDG6 targets and planetary boundaries. Coding was done by one researcher using Mendeley reference management software and Excel, and reviewed by a second researcher. In total 62 codes were used, which were later grouped into a smaller number of themes based on similarities between codes. This coding process facilitated a quantitative assessment of themes present in the literature to identify patterns in topics of interest and co-occurrence. Also during this stage, a subset of the 40 sources that provided more in-depth insight into identified themes were selected for closer reading and analysis.

The final thematic analysis stage, based on in-depth review of the 40 selected sources, elucidated themes to enable nuanced analysis of how areas of interest were presented and discussed. These were then considered with reference to the planetary boundaries framework to prompt identification of areas where opportunities exist to increase focus and action on environmental sustainability. This process was also supported by reflecting on the relevance of themes and proposed future directions with reference to SDG6.

Limitations

A first limitation of the review is that it only includes English language literature and therefore may have missed relevant and insightful material. Related to this, the focus was on aid and development WASH literature, so sources from national and subnational levels that may present different

themes and discourses, informed by different cultures and contexts, were not considered. In addition to the necessity of reviewing a manageable quantum of material, the rationale for this focus was the fact that across diverse international contexts, aid sector literature is influential in driving how WASH service delivery is approached, so it is worthy of analysis in its own right.

A further limitation is the inherent risk in any literature search process that relevant sources may be missed. This is particularly the case for a topic as broad as environmental sustainability. Efforts were made to triangulate search results by using variations of keywords in search strings (across target databases and organisational sites) to check whether any new relevant material emerged. Despite these efforts, it is reasonable to assume that some relevant material was missed.

Finally, the analysis leans more towards practice than theory, given that this is the dominant focus of WASH sector literature. As such, the review offers valid and valuable insight into sector discourse, but does not engage with potentially relevant theoretical explorations of, for example, the links between water, the natural environment, politics and power.

OVERVIEW OF LITERATURE

The 176 sources reviewed through the second stage process gave relatively equal attention to water and sanitation, with approximately 30% focused on each and the remaining 40% covering both. The split between academic and grey literature was relatively equal. The representation of different regions in the reviewed literature shows 42% of sources taking a global or cross-regional perspective, 22% focused on Africa, and smaller proportions considering other regions across South Asia (13%), East Asia (12%), Latin America (8%), the Middle East (2%) and the Pacific (1%). There was a slightly stronger focus on urban (22%) compared with rural areas (14%), though 39% addressed both. It is noteworthy that a quarter of all sources did not explicitly focus on either urban or rural contexts, indicating a more conceptual focus.

From the coding process, six topic areas emerged as the most strongly represented in reviewed sources: water security; water resource management; climate change; environmental pollution arising from

inadequate sanitation; reuse; and environmentally oriented technologies (for instance technologies represented as having strong environmental credentials such as use of locally sourced materials, low energy use or the facilitation of reuse). The numbers of sources that focused on each topic, and the proportions of the reviewed literature that focused on each topic, are shown in Figure 2. Figure 3 shows the proportions of academic and grey literature for each topic, indicating a stronger representation of academic material across technology, reuse and sanitation pollution topic areas, and a greater contribution from grey literature sources on climate change, water resource management and water security.

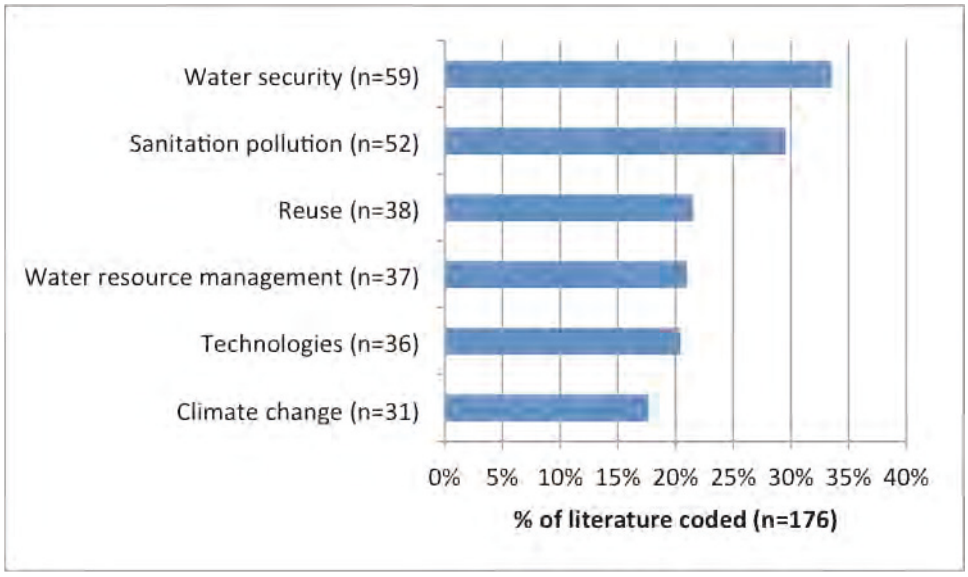


Figure 2 Common topics in reviewed literature (note that documents may be represented across multiple categories where applicable)

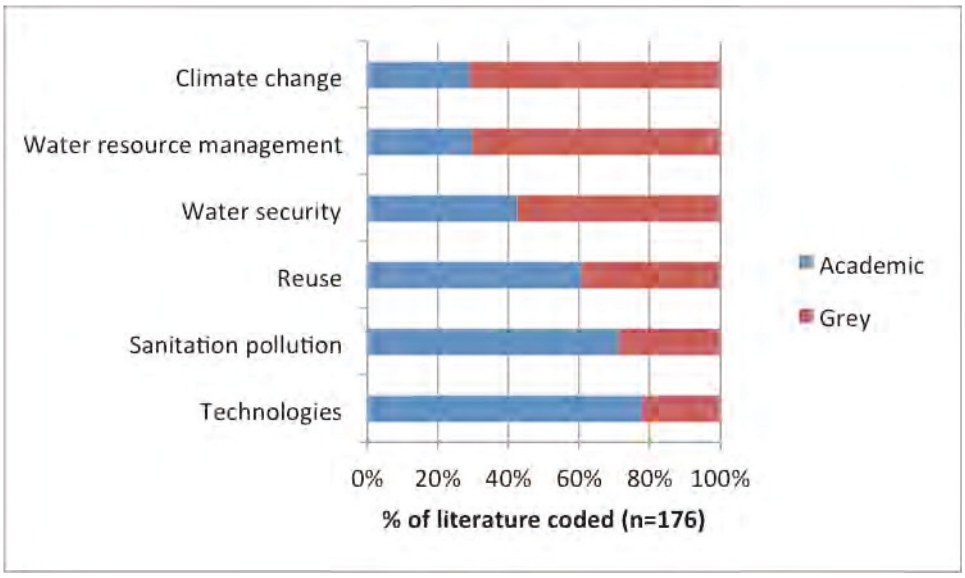


Figure 3 Proportions of academic and grey literature for common topics

These topics informed identification of themes in current literature, and as such most of them are elaborated below. It is, however, important to note two points. Firstly, while technologies were represented in a fifth of the reviewed literature, there was strong overlap between this material and other themes including reuse (with more than half these sources also discussing reuse opportunities) and limited additional insight was offered by a more specific review of technology-focused material, so we did include this as an emerging theme. Secondly, the distinction made between water security and water resource management requires explanation. While these two topic areas obviously overlapped, WASH literature typically focused on water security for people (as discussed below) and only a third of the water security literature (n=21) explicitly considered water security as linked to water resource management. For this reason they were treated as two distinct topic areas, however insights from sources with a specific water resource management focus did not add value to the in-depth analysis, and this material is therefore reflected within the elaboration of water security.

EMERGING THEMES

This section presents and discusses four themes which relate to the topic areas described above and draw from the in-depth analysis of the 40 most relevant sources: (i) the perceived tension between environmental sustainability and development imperatives; (ii) water security as a potential bridge between service delivery and environmental sustainability; (iii)

responding to environmental threats such as climate change; and (iv) water and sanitation services offering opportunities to contribute to environmental sustainability. These themes are interlinked and in some aspects cover related content, yet each offers a distinct perspective on how WASH sector literature engages with concepts of environmental sustainability. Following the analysis of themes, we consider them with reference to the planetary boundaries framework.

Development and environment in tension

Despite "sustainable development" being a decades-old concept which brings together economic, social and environmental goals with a view to providing for both present and future generations (WCED 1987), economic and social development and environmental sustainability have often been seen as being in competition with each other (Melamed et al. 2012; Atkinson et al. 2014). Considering environmental outcomes along with development and poverty reduction has been seen as "too hard" in situations where simply meeting basic needs is challenging. The time dimension is also important here, with human development an urgent concern and environmental protection often presented as something to be resolved or "dealt with later".

The WASH sector reflects this dichotomy, with both the "too hard" and "deal with it later" perspectives evident in the reviewed literature. In analysing the role of the environment as a "silent partner" in Latin-American urban WASH programs, Keatman (2012) observed that environmental considerations were given far less emphasis than issues of finance, technology, equity and poverty alleviation, and were seen as complicating the already significant challenge of improving access. In this context, despite general recognition that environmental protection would benefit upstream and downstream users, it was considered "something to tackle at a later stage" (Keatman 2012). Similarly, Batchelor et al. (2011) described the WASH sector as slow to respond to risks due to the focus on "more immediate challenges", Mehta and Movik (2014) noted the tendency for those promoting water service delivery to neglect environmental considerations despite recognizing the importance of the natural resource base, and Bradley and Bartram (2013) asserted that for some in the sector, the urgency of household sanitation provision overrides the need for full excreta management.

Factors contributing to the perceived tension between environment and development in the WASH sector and beyond relate to the physical and time

scales at which we typically conceive the two. The international development sector has predominantly measured progress with reference to individuals, whereas environmental dynamics are often analysed at global, regional or local (beyond household) scales (Melamed et al. 2012). A similar disjunct relates to time, with service delivery a short-term urgent need for current populations, in contrast with often longer-term environmental issues that will most likely affect future generations (Melamed et al. 2012; Keatman 2012).

For the WASH sector, it is important to recognize these tensions if we are to better contribute to environmental sustainability through current approaches. There is promise in the renewed SDG agenda, which is substantially broader in scope than its MDG predecessor and includes a number of beyond-household objectives within the integrated water and sanitation goal. This optimism was reflected in the post-2015 consultation on WASH and environmental sustainability, which found that "the environmental and development communities are gradually superseding their respective misperceptions that WASH and environmental sustainability are unconnected and/or may compete for resources and political attention" (Post-2015 Water Thematic Group 2013). The challenge is to embrace this agenda as a prompt to move beyond our current focus on individuals and their urgent needs, such that realisation of the rights to water and sanitation achieves sustainable services for future, as well as current, generations and does not adversely impact ecosystems.

A helpful way of conceptualizing how we can achieve human development and environmental sustainability is offered by Raworth (2012) in her adaptation of the planetary boundaries framework. Raworth (2012) proposed the addition of "social boundaries", advocating the need to define a "safe *and just* operating space for humanity" (emphasis added) that accounts for both earth system limits (described as the "environmental ceiling") and basic human rights (the "social foundations"). The resulting framework offers a doughnut-shaped "safe and just space", bounded at the centre by a set of social foundations (Figure 4). Further work is required to develop the social dimensions within this framework, which are at present only illustrative (Raworth 2012; Raworth 2013). For the WASH sector, there is an opportunity to develop ideas about how to link the "safe" and the "just" at the local level, where the connections are most meaningful for people and the environments that support them.

Figure 4 A safe and just operating space for humanity (Raworth 2012)

Water security as a bridge between WASH and environmental sustainability

The second theme relates to the concept of water security. The way water security is defined and discussed in WASH literature is critiqued here, and we consider its potential to bridge service delivery and environmental sustainability goals with reference to limitations apparent from the reviewed material.

In recent years use of the term "water security" has been increasing in policy and academic circles across the water sector (Cook and Bakker 2016). In the WASH sector, the term emerged within post-2015 discussions as a conceptual tool to help us move beyond the narrowly focused MDG "access" agenda towards a broader understanding of service delivery within a wider water management framework (Bradley and Bartram 2013). Many concepts associated with water security are not new, given the close relationship between water security and Integrated Water Resource Management (IWRM). Yet in recent WASH sector literature, water security has attracted more

interest than IWRM, perhaps because "security" terminology conveys a sense of urgency related to water crises and the scale of unmet needs, and therefore has the capacity to raise the issue on the political agenda (Pahl-Wostl et al. 2016).

There is no one agreed definition of water security, with interpretations ranging from an emphasis on meeting basic human needs through to incorporation of ecosystem needs (Pahl-Wostl et al. 2016). The reviewed WASH literature reflected this, with definitions spanning those emphasizing access to water (e.g. Calow et al. 2011) and those encompassing broader livelihood, development and environmental goals (e.g. Chiappe et al. 2015). In the latter, water security was presented both as a driver (at the political and practical levels) for integrated approaches to WASH service delivery and water resource management, and as a conceptual tool that can help us find practical ways to implement those approaches. It was seen as useful when considering services at multiple scales, including local contexts on which WASH programs typically focus (Bunclark et al. 2011).

An exploration of the potential for the concept of water security to contribute to improved domestic water and sanitation was provided by Bradley and Bartram (2013), who adopted Grey and Sadoff's (2007) often cited definition of water security as "the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environment and economies". Bradley and Bartram (2013) argued that the MDG focus on the household as a unit of analysis diverted attention away from both "upstream" (water source reliability) and "downstream" (sanitation pollution) concerns. They asserted that a definition of water security that addresses both *provision* and *risk* offers an opportunity to promote increased access to water and sanitation in a way that encompasses previously neglected areas of critical importance to the sector, including water source management (which requires, among other things, responding to pressures such as climate change) and environmental contamination related to pollution from inadequate sanitation. Importantly, the concept of water security is linked to the human rights to water and sanitation, with Bradley and Bartram (2013) arguing that benefits arising from applying a water security lens to domestic water and sanitation challenges will only arise if "enlightened by human rights insights".

In reflecting on the potential of water security to strengthen the links between WASH and environmental sustainability, it is helpful to consider three limitations evident in the reviewed literature. Firstly, there was a common perception that WASH service delivery does not present a threat to water security for people or nature at the global scale. Some studies have argued that physical water scarcity has been overemphasized in the sector (Bunclark et al. 2011; Calow et al. 2011; Mason and Calow 2012) with scarcity of basic services seen as being more appropriately conceived of as resulting from issues of access, equity and governance (Calow et al. 2011). This view derived from the fact that non-domestic sectors such as agriculture account for the vast majority of current freshwater demand (Corcoran et al. 2010) and from estimates that the quantity of water required to meet basic water and hygiene is <1% of available freshwater resources in most countries (assuming delivery of 50 litres/capita/day) (Doczi et al. 2013).

Yet this calculation neglects the fact that domestic water use in low-income countries already averages 8% of total freshwater removal (UNEP 2007 cited in Rognerud et al. 2016), and the important consideration that the availability of water for domestic consumption depends greatly on the levels of service provided (Doczi et al. 2013). Community-scale programs are unlikely to put significant pressure on freshwater resources (except in water scarce environments), but ever-increasing quantities of water delivered to rapidly growing urban populations will, with demand from these populations likely to be significantly higher than 50 litres/capita/day (LCD). For example, in urban contexts recent literature has reported much higher water demand figures of, for example, ~150 LCD in Can Tho, Vietnam (Retamal et al. 2011) and ~200 LCD in Port Vila, Vanuatu (Poustie and Deletic 2014). As economic development progresses, it is likely that higher demand will follow (Rognerud et al. 2016), given that domestic water consumption in developed countries is approximately six times that in developing countries (Shiklomanov 1999 cited in Corcoran et al. 2010). Compounding the problem is the fact that the collective impacts of increasing water demand on a particular water resource are rarely assessed (Bunclark et al. 2011).

A second possible limitation to the potential of water security to bridge service delivery and environmental sustainability is the relatively limited overlap of water security/WASH literature with literature focused on sanitation pollution. While sources focused on water security note risks to water quality and hence water security resulting from poor management of

excreta and wastewater (e.g. Bradley and Bartram 2013), "water security" as a potentially useful concept has yet to strongly enter literature more directly focused on sanitation pollution. Only a small proportion of the sources that focused on sanitation pollution mentioned water security (12%, n=7 of 58). Whether the concept of water security can contribute to improved models of wastewater and excreta management (towards meeting SDG6 targets) is yet to be determined.

The third limitation is that it remains to be seen how the WASH sector's embracing of water security will translate into practical outcomes. To date literature on water security has tended to focus at a theoretical level, exploring its boundaries and potential but with somewhat limited relevance to policy and practice (Bakker 2012; Mason and Calow 2012). Water security needs to be transformed from an abstract concept into meaningful and practical approaches or tools, but this is a challenging task. It requires developing ways to measure water security, which is problematic given the spatial and temporal variability inherent to water systems and given that "indicators are usually only relevant at a particular spatial or temporal scale" (Mason and Calow 2012).

Despite these limitations, the increasing presence of water security as a relevant concept in WASH discourse holds promise in that it reflects a move to encompass both human and environmental water resource management objectives. As we strive to achieve the integration agenda presented by the SDGs there is an opportunity to both draw on and shape ideas about water security to inform environmentally sustainable approaches to service delivery. For this to be effective, we need to promote a sector-wide conception of water security that embraces services for people as well as upstream and downstream concerns.

Responding to environmental threats

Related to concepts of water security, the idea of services being threatened or at risk due to environmental pressures has emerged as a theme within WASH literature. This is relevant to understanding the WASH sector's engagement with environmental sustainability, as the ways we respond to threats and risks will have implications for resources and ecosystems. The focus of the literature was predominantly on climate change and associated threats, though issues of freshwater availability and quality more generally

also featured (and are strongly associated with the water security discourse discussed above).

With reference to climate change, the WASH sector was depicted as vulnerable to current climatic variability (Doczi 2013) and under significant threat from climate change impacts – such as changes in rainfall, groundwater recharge and climate extremes – in the medium to longer terms (e.g. Batchelor et al. 2011; Calow et al. 2011; Heath et al. 2012; Doczi 2013; Oates et al. 2014). Impacts were presented as well-acknowledged and inevitable, though the location, scale and timing of threats is uncertain (Batchelor et al. 2011; Heath et al. 2012; Doczi 2013). The literature strongly focused on risks to water systems, and Calow et al. (2011) noted an absence of material exploring the specific links between climate change and sanitation. Nevertheless, increasing awareness of vulnerability to climate change across the sector has prompted a proliferation of tools to support adaptation and resilience, though as (Doczi 2013) pointed out, many of these are supply-driven and there is little evidence of user demand (for a review of tools see Doczi 2013).

Of interest in this literature are the types of service delivery and management responses advocated, which fall broadly into two categories: “climate proofing” and integrated adaptation measures. Each of these has implications for environmental sustainability and for service sustainability, so they are relevant to this discussion.

Literature promoting “climate-proofing” solutions has presented climate change risks as relevant due to their capacity to disrupt water and/or sanitation services. This framing is reactive, dominated by strategies for fostering more robust and resilient services. Responses advocated have included increasing redundancy in water supply systems by augmenting storage capacities (e.g. UNICEF/GWP 2015; Batchelor et al. 2011), adapting technologies to be resilient to climate impacts (Calow et al. 2011), and relying more on apparently less vulnerable sources such as deeper groundwater aquifers (Calow et al. 2011). Calow et al. (2011) noted that in national adaptation plans, supply-side solutions (such as increased water storage) were favoured over demand-side alternatives (such as improved efficiency or more equitable allocation). This aligns with Mehta and Movik's (2014) observation that “often technology is evoked to solve problems of water scarcity”.

Yet ironically, while these solutions have been proposed in response to environmental pressures, there was little evidence that the environmental implications of suggested technological fixes have been considered. "Climate proofing" solutions that rely on building bigger, stronger infrastructure will inevitably have flow-on environmental effects including both local (e.g. over-extraction of water) and diffuse (e.g. GHG) impacts. One example is that of groundwater, which is promoted by some authors as a potentially more reliable source with capacity to offset increasing scarcity of surface water, despite acknowledgement that groundwater risks from climate change are poorly understood (Bunclark et al. 2011; Calow et al. 2011) and already 20% of the world's aquifers are over-exploited (WWAP 2015 cited in Rognerud et al. 2016). Potential impacts were given less prominence in a discourse framed around "solving" environmental problems, but there is opportunity for the WASH sector to take a more nuanced approach, thinking not only about protecting services from threats, but also about how services can either exacerbate or ameliorate environmental pressures.

Some WASH literature takes a more environmentally sensitive approach, asserting that to achieve resilient services we need to embed WASH within resource management, focus on demand-side solutions, and strengthen links between governance of WASH and environment. Hadwen et al. (2015) proposed considering WASH within an IWRM approach as a means of bringing together economic efficiency, equity and environmental sustainability goals, noting that WASH has typically focused on equity (services for all) while IWRM has emphasized economic and environmental drivers. Examples of interventions to protect water quality which can both reduce health risks and achieve environmental outcomes include riparian restoration and improved land management practices (Dosskey et al. 2010 cited in Hadwen et al. 2015). Demand-side solutions to relieve pressures on water supply systems were proposed by Poustie and Deletic (2014) including rainwater capture, increased water efficiency and demand management. Interestingly, both Hadwen et al. (2015) and Poustie and Deletic (2014) focused on Pacific Island countries, which perhaps reflects the more immediate environmental pressures faced by these communities and the consequent need to position WASH within broader environmental sustainability endeavours. A complementary approach was suggested by Batchelor et al. (2011) who emphasized the importance of governance reform for effective integration and adaptation. This includes rethinking

institutional arrangements to address current constraints associated with environment departments (who typically oversee climate change initiatives) being on the periphery while WASH departments are more central (Batchelor et al. 2011).

Common in this literature (across both "climate proofing" and "integration" perspectives) is the assertion that to better manage environmental risks and uncertainties, we need improved data and knowledge, with climate change in particular putting a premium on information about water resources (Doczi 2013; Hadwen et al. 2015; Calow et al. 2011). As Calow et al. (2011) assert, "few countries know about the quantity, quality, distribution and reliability of their water resources, about how they are being used, or which water sources are functional". To appropriately respond to the threats presented by climate change and other environmental pressures, it will be critical to improve the ways in which we collect and share data to ensure our solutions don't become future environmental problems.

WASH as an environmental opportunity

The fourth theme in the current discourse frames sanitation and water service delivery as presenting opportunities to contribute to environmental sustainability. This literature goes beyond the harm minimisation perspective evident in sanitation pollution literature and promotes potential contributions to critical sustainability concerns related to nutrients, energy and water scarcity. Central to this discourse is literature on ecological sanitation, though the potential for WASH to contribute to sound watershed and ecosystem management is also evident (for example Edmond et al. 2013). Around 60% of documents coded as reflecting an "environmental opportunity" theme come from academic sources, which is an interesting contrast to material focused on links between WASH and water security or climate change, of which 60% and 73% respectively are from non-academic sources. This likely reflects the emphasis to date within "environmental opportunity" literature on theory or pilot-scale programs rather than more widespread practice, as discussed below.

The potential benefits of reusing wastewater and excreta were described as significant for water, food, nutrient and energy security. With reference to water security, the use of wastewater for irrigation is proposed as a solution to increasing water scarcity and competition (Hanjra et al. 2012) in a context where 70–90% of global available fresh water is used for agriculture (WWAP

2014 cited in Rognerud et al. 2016). This links to food security, as does literature promoting the potential of using nutrients from sanitation to reduce our dependence on increasingly scarce mineral reserves (Cordell et al. 2009; Rosenqvist et al. 2016) while simultaneously reducing pollution by preventing the return of nutrients to the environment. Corcoran et al. (2010) presented typical nutrient concentrations in effluent, asserting that effluent has the capacity to provide all the nitrogen and much of the phosphorus and potassium needed for agricultural crop production, in addition to other beneficial micronutrients and organic matter. With reference to energy security, some literature focuses on biogas from human waste as a potential alternative to fossil fuels (e.g. Doczi et al. 2013), however this was less prevalent in the reviewed literature.

The benefits of reuse were typically presented with words of caution related to health, behavioural and economic aspects, and these are important areas to consider when exploring how to capitalize on the potential contribution of sanitation and water services to environmental sustainability. As noted by Hanjra et al. (2012) frameworks for protecting human health and the environment when planning wastewater reuse are lacking in most developing countries, and many of the potential impacts (such as imbalances in microbiological communities) are not yet well understood. On the behavioural side, proper management and user acceptability (particularly in cultural contexts in which reuse of human waste is taboo) are noted as significant constraints (Kennedy-Walker et al. 2014). With reference to economic aspects, the literature is mixed. Some sources pointed to potentially higher costs associated with reuse infrastructure (e.g. Abraham et al. 2011), while others asserted that reuse actually presents a value proposition with sales from products such as faecal sludge able to generate profits that could in turn be used to support the sanitation service chain (e.g. Diener et al. 2014; Tilmans et al. 2014).

Across the literature, two scales of focus were evident: conceptual big-picture material extolling the potential of resource reuse (e.g. Cordell 2009; Corcoran et al. 2010), and reports of highly localized pilot programs, with little in between. Although reuse has been promoted in the sector for more than 15 years, including through the Principles for urban environmental sanitation (2000) and the ecological sanitation “toolbox” released by GIZ in 2003, the impact of this in driving stronger adoption of “ecological” technologies in cities is not evident (Kennedy-Walker et al. 2014). Similarly, reports from rural

areas are often small scale and confined to a few locations, with limited attention given to the potential for more widespread application (e.g. Arafat and Rahman 2010; Abraham et al. 2011; Kamuteera 2011; Okem et al. 2013). In keeping with ideas from the field of transition studies about the scales at which socio-technical shifts occur (as described in Geels 2011; Lawhon and Murphy 2012), current discourse indicates that resource reuse approaches currently operate at the "niche" (micro) scale and are yet to move into the "regime" (meso) or "landscape" (macro) scales that would reflect wider adoption in the sector and society at large. This is discussed further below under future directions.

Nevertheless, the presence of this theme in WASH discourse is promising. If we can identify strategies to support a shift in the practical application of ecological sanitation approaches from the niche level to the landscape scale (including in growing urban centres), then the potential for WASH to contribute to environmental sustainability will be significant. As Bradley and Bartram (2013) assert:

> *in water and sanitation beneficial use of wastewater and excreta is the great scientific, technological and environmental challenge or opportunity of the coming quarter-century and is of special relevance to poor rapidly developing countries. There are doubts about the economic feasibility of classical sewerage and about its logic: to dilute excreta with precious water and then separate the two again is costly and energy-intensive.*

FUTURE DIRECTIONS – INSIGHTS FROM A PLANETARY BOUNDARIES PERSPECTIVE

This section considers current themes in WASH discourse with reference to the planetary boundaries framework. The assessment helps us gauge the extent to which our focus as a sector aligns (or not) with a clear set of earth system processes fundamental to environmental sustainability, and prompts us to contemplate what else we could or should be considering. The discussion then proposes four "future directions", which are areas where opportunities exist for the WASH sector to increase focus and action to strengthen our contribution to environmental sustainability as we ramp up efforts towards progressive realisation of the human rights to water and sanitation. Where relevant, reference is also made to SDG6 and its water resource management targets.

Planetary boundaries and themes in reviewed literature

As noted earlier, the planetary boundaries framework offers a useful way of engaging with fundamental socio-ecological systems and processes that constitute environmental sustainability. The framework is relevant and useful for sustainable development discourse (Griggs et al. 2013; Pisano and Berger 2013), but further thinking needs to be done about what it might mean in practice for different sectors, actors and scales. For the WASH sector, there is potential to explore how the planetary boundaries framework might prompt more environmentally sustainable approaches. Five of the nine boundaries are directly affected by flows and processes associated with WASH service delivery, particularly given the dominant paradigm of water-borne sanitation (Ross et al. 2015).

Table 1 presents the five planetary boundaries most relevant to WASH and assesses how each of the boundaries is reflected in the reviewed literature. It is important to note that this assessment is preliminary and based on a review of general "environmental sustainability" literature rather than a detailed analysis of the overlaps between boundaries (with each boundary having its own terminology) and WASH resources, and each could reasonably be the subject of an entire review. Nevertheless, the assessment is helpful for prompting consideration of potential future directions for the sector.

Table 1 Planetary boundaries, their relevance for WASH and representation in reviewed literature

Planetary boundary	**Relevance for WASH services**	**Reflection in reviewed literature**
Global freshwater use	Centrally implicated in water supply (including for hygiene needs) and water-based sanitation. While the global freshwater use boundary remains classified within the "safe" space, the spatial distribution of freshwater determines varying regional thresholds for safe use (Rockström et al. 2009). Many regional water systems are already experiencing scarcity (Gleick and Palaniappan 2010) and it is forecast that by 2050, 40% of the global population will live in areas facing water stress (Rognerud et al. 2016).	Reflecting SDG6 targets, emerging literature highlights the need for WASH professionals and communities to better manage water resources at local scales in terms of both upstream and downstream considerations. Concerns about declining freshwater availability and quality were expressed in discussions related to water security and climate change. To date, the emphasis has been on potential risks to WASH services and the need to consider water resources as part of the service delivery landscape, with less focus on practical ways to address emerging challenges related to freshwater availability and quality. Further, potentially important considerations such as efficiency of water use have not received attention.

Planetary boundary	**Relevance for WASH services**	**Reflection in reviewed literature**
Nitrogen and phosphorous cycles (biochemical flows)	Sanitation presents both a challenge and opportunity for the safe functioning of these biochemical flows. Recent research estimates that sanitation treatment systems in 108 low- and middle-income countries remove only 11% of nitrogen and 17% of phosphorous from human excreta, with the balance discharged into the environment (Fuhrmeister et al. 2015) where it contributes to eutrophication of aquatic and marine systems (Rockström et al. 2009). Intentional reuse of N and P from excreta has the potential to both reduce this environmental impact and help meet demand for P fertilizers to support food security (and livelihood) needs in the context of increasing scarcity of mineral rock phosphate reserves (Cordell et al. 2009).	The potential for sanitation approaches that take account of nitrogen and phosphorous cycles was described in the literature, however the focus was limited to smaller scale local or pilot activities. Further, the literature focused on sanitation pollution did not specifically note issues related to nitrogen and phosphorous flows, which is a limitation given low removal ratesz from current treatment systems.
Climate change	WASH services contribute to climate change through the energy intensity of water and sewage systems (Ross et al. 2015). Greenhouse gases (GHGs) including methane are emitted by water reservoirs (Deemer et al. 2016), municipal wastewater treatment plants (Campos et al. 2016), pit latrines (Reid et al. 2014) and septic tanks (Trular et al. 2016). Recent research in the United States found that GHG emissions from domestic septic tanks account for 1.5% of a person's annual carbon footprint (Truhlar et al. 2016).	The risks posed by climate change to WASH services were a significant area of concern in literature, though a focus on "climate proofing" approaches has potentially negative consequences. There is opportunity to develop responses that are environmentally sensitive and to more strongly consider the energy intensity and GHG emissions of water and sanitation infrastructure solutions.

Planetary boundary	Relevance for WASH services	Reflection in reviewed literature
Novel entities	Novel entities are defined by Steffen et al. (2015) as "new substances, new forms of existing substances, and modified life forms that have the potential for unwanted geophysical and/or biological effects…These potentially include chemicals and other new types of engineered materials or organisms." Examples are endocrine disruptors and persistent organic pollutants. Novel entities can be added to domestic wastewater through human excreta (e.g. pharmaceuticals) or household chemicals (Kinney et al. 2006; Ross et al. 2015).	Novel entities were not considered at all in reviewed literature, yet they are relevant to how we approach sanitation services (including treatment and reuse/disposal). This is of particular concern for urban areas with growing middle-income populations, where the use of household chemicals, personal care products and pharmaceuticals is increasing.
Biosphere integrity	Over-extraction of water and inadequate sanitation threaten freshwater and coastal ecosystems (Gleick 2003; Corcoran et al. 2010).	There was limited explicit discussion in reviewed literature on water-related ecosystems. Freshwater ecosystems were noted to be beneficiaries of improved sanitation, but drivers were more often related to the availability of freshwater for human consumption than ecosystem integrity.

Future directions

Reflecting on both identified themes and their relevance to planetary boundaries, this review concludes by proposing four future directions for strengthening the contribution of the WASH sector to environmental sustainability:

(i) Foster a "do more good" instead of "do less harm" approach
(ii) Focus on synergies and minimize trade-offs
(iii) Identify and address gaps in current focus
(iv) Support a transition of the reuse agenda from niche to regime scale.

Each of these is explained and we propose ideas on starting points for the WASH sector. Suggestions are primarily directed at knowledge leaders (within

international WASH sector organisations) and researchers rather than practitioners, acknowledging that translating ideas into meaningful on-the-ground actions will take thought and time. The intention is to flag the need for research and prompt creative thinking to inform these future directions in WASH.

Do more good instead of do less harm

The idea of fostering a "do more good" instead of a "do less harm" approach is implicit within the planetary boundaries framework. It dictates that we move beyond governance and management approaches based on limits to growth and minimizing negative externalities (Rockström et al. 2009), towards cross-sectoral consideration of strategies for remaining within a safe space for human development. The related imperative to "do more good" (in contrast to simply minimizing negative impacts) has been advocated by McDonough and Braungart (2002 cited in Corcoran et al. 2010) with reference to cradle to cradle production systems, and by Mitchell (2015) with reference to infrastructure.

There is no blueprint for what this kind of approach might look like. There is an opportunity to start thinking in this way to prompt the development of new decision-making processes and metrics (Mitchell 2015). For the WASH sector, this will require carefully defining our objectives to include both access and environmental considerations, and remembering that *how* goals are achieved matters as much whether they are achieved. There are links here to water security and reuse agendas. Ecosystems (and the resources they support) can benefit from WASH programs that explicitly consider upstream and downstream dynamics, and undertaking freshwater conservation and WASH together can foster environmental stewardship (Edmond et al. 2013). Using nutrients extracted from human waste as an alternative to commercial fertilizers has positive flow-on effects for water quality (by reducing pollution), food security and mineral resource scarcity (Cordell 2009).

Maximize synergies and minimize trade-offs

Related to the idea of "doing more good", the second recommendation calls for a shift in mindset and approaches towards emphasizing synergies and minimizing trade-offs. This recognizes the interdependence of earth systems, as transgressing one planetary boundary will shift others (Rockström et al. 2009), and this reflects the interconnectedness of the SDGs. Ignoring the

overlaps between SDGs and focusing on meeting individual targets risks perverse outcomes (Nilsson et al. 2016). For example, increasing food production will likely increase diffuse water pollution which can negatively impact on water quality targets (Doczi et al. 2013). But conversely, as Nilsson et al. (2016) assert, if "mutually reinforcing actions are taken and trade-offs minimized, the agenda will be able to deliver on its potential". There are numerous examples of potential synergies within the SDGs (as described by Nilsson et al. 2016) and the interdependencies between water goals and goals related to energy, food security and natural resource management are well recognised (Merrey et al. 2015).

For the WASH sector, this thinking drives us in two directions. Firstly, we need to ensure that in striving to achieve water and sanitation access targets (6.1 and 6.2) we don't inadvertently undermine the achievement of related water resource management targets (6.3–6.6) or other SDGs with explicit environmental sustainability agendas (such as clean energy, sustainable cities and communities, climate action, life below water, and life on the land). This requires considering interconnections when designing our approaches. For example, sanitation solutions need to align with locally available water resources, so flush toilets might not be a preferable option in certain locations, even if this is the option desired by users. User preferences are a critical consideration, but resource availability is equally important. Another example is the need to account for energy requirements and GHG emissions associated with infrastructure solutions. This thinking can lead to further benefits. For example, designing systems that require less pumping and therefore have lower energy demands can result in significant cost savings over the life-cycle of water supply or sanitation systems (e.g. Willetts et al. 2010).

Secondly, we need a shift in mindset away from considering environmental sustainability as too hard or not urgent (as discussed above) towards thinking creatively about potential win-wins and how to capitalize on them. Many synergies between service delivery and environmental sustainability are evident in concepts such as integrated urban water management (e.g. Bahri 2012) and the water-energy-food nexus (e.g. Weitz et al. 2014; Bhaduri et al. 2015). There is also potential for multiple-use water systems to bring benefits across service delivery, food security and livelihoods. However, support for environmental sustainability efforts is also needed to better integrate resource and climate resilience into current approaches (Srinivasan et al.

2012). Finally, opportunities exist to integrate environmental sustainability into our advocacy of the human rights to water and sanitation. These rights include the obligation to provide services in a way that respects the environment and protects resources from overexploitation or pollution in order to ensure their availability for future generations (UN Special Rapporteur 2014). While acknowledging the magnitude of the challenge of getting basic services to those currently without them, approaching this task by seeking to maximize synergies between service delivery and environmental sustainability may prompt new thinking towards mutually beneficial outcomes.

Identify and address key gaps

Consideration of both planetary boundaries and the SDG targets reveals gaps in WASH sector considerations related to environmental sustainability, for example in areas of climate change mitigation, novel entities, biosphere integrity and water use efficiency (as a key component of freshwater management). Here, attention is given to novel entities and water use efficiency as examples.

The presence of novel entities in water sources and wastewater is an area of concern in water sector literature globally, and particular risks for developing country contexts have been noted due to weaker regulatory frameworks (Tijani et al. 2013). Micro-pollutants relevant to domestic contexts derive from pharmaceuticals, personal care products and household chemicals, with the use of these increasing as populations and wealth grow (particularly in urban areas). These contaminants are not always or easily biodegradable and their effects are poorly understood. However, serious negative impacts on ecosystem and public health have been documented, including endocrine disruption, brain damage, cancer and reproductive disorders (Tijani et al. 2013). As the WASH sector progresses initiatives to improve wastewater treatment and excreta management, we need to acknowledge the presence of novel entities and consider potential responses – including, for example behaviour change programs which include strategies for reducing their discharge, working with governments to strengthen regulations, and keeping abreast of advances in treatment approaches that may be applicable to developing country contexts.

Water use efficiency is another area of opportunity currently neglected within WASH sector literature that can contribute to sustainable management of

freshwater resources. SDG6 target 6.4 calls for a substantial increase in water-use efficiency, with proposed indicators collating efficiency improvements across significant water-using sectors including municipal water supply (IAEG-SDGs 2015). The proposed measure relates to unaccounted for water (network losses), and WASH initiatives can both contribute on this front and go beyond to also consider the promotion of water efficient technologies and behavioural strategies for enhancing water use efficiency through demand management, particularly in urban areas. This is an area in which significant work has been done by the wider water sector (e.g. Butler and Memon 2006; Araral and Wang 2013; Bao et al. 2013) that can inform WASH sector initiatives, particularly as per capita consumption rates rise and local experiences of water scarcity become more common. Increasing the focus on water efficiency is also relevant for water abundant areas, as managing demand achieves reductions in energy use and costs related to transport and treatment.

Support a transition of the reuse agenda from niche to regime

A final future direction is about supporting the transition of wastewater/excreta reuse initiatives from local to wider scales to capitalize on the environmental and food security opportunities presented by such approaches. For these initiatives (and for other changes we seek to make) it is appropriate to draw on ideas from transition studies and transition management literature. Transition studies is an emerging field that brings together insights from complexity science, innovation studies, sociology and environmental science to better understand and develop strategies for influencing the direction and pace of systemic change in societies (Loorbach et al. 2015). As described above, it characterizes a typical trajectory of socio-technical shifts from niche to regime and ultimately landscape scales (Geels 2011; Lawhon and Murphy 2011). Niche scales are areas of innovation and learning often operating independently of regime dynamics (Geels 2011). The regime level refers to established systems, practices, values, habits and institutional structures (Geels 2011). The institutions at this level play normative and regulatory roles and in doing so offer stability, but can limit innovation to incremental improvements (Geels 2005 cited in Haxeltine et al. 2008).

For the WASH sector, conceptualizing reuse opportunities in this way may assist in ultimately moving them beyond niche experimental scales towards

wider uptake. This requires reframing reuse as a necessary transition towards sustainability and positioning pilot initiatives (whether successful or not) within this transition, acknowledging that the path of change might be slow and challenging. It also requires targeting investment and research towards reuse with a view to enabling wider and longer-term uptake, for example by further developing strategies for minimizing health risks and investigating emerging concerns such as the presence of novel entities in excreta and wastewater.

Two ideas from transition management could inform this shift. The first is co-evolution, which recognizes that processes in technology, economy and society progressively build towards systemic change in the long term (Loorbach et al. 2015). For reuse programs, this creates a need to engage and align with the regime institutions that steer economic and social processes to maximize the impact of niche-level innovation, for example by working closely with governments at multiple levels to generate the social learning essential for transitions to succeed (Loorbach et al. 2015).

The second idea refers to "tipping innovation's cascade" and involves prioritizing actions that can trigger larger changes (Loorbach et al. 2015). In developing countries, investing in technologies and social programs that support reuse can avoid path dependencies that limit innovation and potentially trigger "technological leapfrogging" as has been seen in industries such as telecommunications but not yet in water (Poustie and Deletic 2014). The challenge for the WASH sector is to identify opportunities that progress innovation without compromising on core health and social outcomes. The barriers are many and the pathways are not always clear, but increasing risks to global sustainability as demonstrated by the planetary boundaries framework are a clear reminder of the need to try.

CONCLUSION

The significant challenge for the WASH sector in coming decades is to continue to promote safe, equitable service delivery for those living without, while not transgressing planetary boundaries or embarking on a path that will do so in the future. The ways we conceptualize and act on environmental sustainability will determine our success in this respect, including our capacity to achieve the integration agenda prompted by the SDGs. Taking stock of current WASH approaches to environmental sustainability, this paper

reviewed recent literature at the intersection of WASH and environmental sustainability, identifying and discussing four themes: a perceived tension between environmental sustainability and WASH development imperatives; the idea that water security is a helpful concept for bridging service delivery and environmental sustainability; different attitudes about how best to respond to threats such as climate change; and promotion of the opportunities offered by WASH to contribute to environmental sustainability.

Themes from recent literature were considered with reference to the planetary boundaries framework as a comprehensive and helpful lens for grounding the socio-ecological systems and processes that constitute environmental sustainability. From this analysis, we proposed four future directions to strengthen the WASH sector's focus on and contribution to environmental sustainability: fostering a "do more good" instead of "do less harm" approach; focusing on synergies and minimizing trade-offs; identifying and addressing gaps in current focus; and supporting a transition of the reuse agenda from niche to regime scale. In proposing these future directions, the intention is to encourage researchers and knowledge institutions to adopt more ambitious and creative service delivery approaches that better integrate access and environmental sustainability imperatives.

REFERENCES

Abraham, B., Kakumbi, G. M., Alam, M. & von Muench, E. 2011 Alternative solutions for challenging environments : a look at UNICEF-assisted ecosan projects worldwide. In *The future of water, sanitation and hygiene: Innovation, adaptation and engagement in a changing world, 35th WEDC International Conference, Loughborough, UK,* July 6-8, 2011.

Arafat, I. & Rahman, Z. 2010 Ecosanitation: Importance and experience from Bangladesh. In *Proceedings Regional Conference on Appropriate Water Supply, Sanitation and Hygiene (WASH) Solutions for Informal Settlements and Marginalized Communities, Kathmandu, Nepal,* May 19-21, 2010.

Araral, E., & Wang, Y. 2013 Water demand management: review of literature and comparison in South-East Asia. *International Journal of Water Resources Development* **29** (3), 434–450. http://doi.org/10.1080/07900627.2013.826413.

Atkinson, G., Dietz, S., Neumayer, E. & Agarwala, M. (eds) 2014 *Handbook of sustainable development*. Edward Elgar Publishing Limited, Cheltenham, UK.

Bakker, K. 2012 Water Security: Research Challenges and Opportunities. *Science*, **337**, 914–915. http://doi.org/10.1126/science.1226337.

Bao, P. N., Aramaki, T., Otaki, M., & Otaki, Y. 2013 Water Demand Management: A Strategic Approach towards a Sustainable Urban Water System in Hanoi. *Journal of Water and Environment Technology* **11** (5), 403–418. http://doi.org/10.2965/jwet.2013.403.

Bahri, A. 2012 *Integrated Urban Water Management*. Global Water Partnership Technical Committee (TEC) Background Paper 16. http://www.monroban.org/public/documents/outils/uploaded/lts46ngv.pdf (accessed 8 July 2016).

Batchelor, C., Smits, S. & James, A. J. 2011 *Adaptation of WASH services delivery to climate change and other sources of risk and uncertainty. (Thematic Overview Paper 24).* The Hague: IRC International Water and Sanitation Centre http://www.irc.nl/top24 (accessed 25 May 2016).

Bhaduri, A., Ringler, C., Dombrowski, I., Mohtar, R. & Scheumann, W. 2015 Sustainability in the water–energy–food nexus. Water International **40** (5-6), 723–732. http://doi.org/10.1080/02508060.2015.1096110.

Bradley, D. J. & Bartram, J. K. 2013 Domestic water and sanitation as water security: monitoring, concepts and strategy. *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences* **371** (2002), 20120420. http://doi.org/10.1098/rsta.2012.0420.

Brooks, D. & Brandes, O. 2011 Why a Water Soft Path, Why Now and What Then? *International Journal of Water Resources Development*, **27** (2), 315–344. http://doi.org/10.1080/07900627.2011.571235.

Bunclark, L., Carter, R., Casey, V., Day, St J. & Guthrie, D. (2011). *Managing Water Locally*. The Institution of Civil Engineers, Oxfam GB, WaterAid, England, pp. 96.

Butler, D., & Memon, F. A. (eds.) 2006. *Water Demand Management*. IWA publishing, London.

Calow, R., Bonsor, H., Jones, L., Meally, S. O., Macdonald, A. & Kaur, N. 2011 *Climate change, water resources and WASH: A scoping study*, *working paper 337*. British Geological Survey, London, pp. 59.

Campos, J. L., Valenzuela-Heredia, D., Pedrouso, A., Val Del Río, A., Belmonte, M., & Mosquera-Corral, A. 2016 Greenhouse Gases Emissions from Wastewater Treatment Plants: Minimization, Treatment, and Prevention. *Journal of Chemistry*, 2016. http://doi.org/10.1155/2016/3796352.

Chiappe, F., Mujica, A., Ross, I. & Savage, M. 2015 *Climate finance and water security: Inception report.* Oxford Policy Management, Oxford, UK.

Cook, C. & Bakker, K. 2016 Water security: critical analysis of emerging trends and definitions. In: *Handbook on Water Security*, (C. Pahl-Wostl, J. Gupta, & A. Bhaduri, eds). Edward Elgar Cheltenham, UK, pp 19-37.

Corcoran, E., Nellemann, C., Baker, E., Bos, R., Osborn, D. & Savelli, H. 2010 *Sick Water? The Central Role of Wastewater Management in Sustainable Development*. *Water*. United Nations Environment Programme http://doi.org/10.1007/s10230-011-0140-x.

Cordell, D., Drangert, J. O. & White, S. 2009 The story of phosphorus: Global food security and food for thought. *Global Environmental Change* **19** (2), 292–305. http://doi.org/10.1016/j.gloenvcha.2008.10.009.

Deemer, B.R., Harrison, J.A., Li, S., Beaulieu, J.J., DelSontro, T., Barros, N., Bezerra-Neto, J.F., Powers, S.M., dos Santos, M.A. & Vonk, J.A. 2016 Greenhouse gas emissions from reservoir water surfaces: a new global synthesis. *BioScience* 66 (11), 949-964. http://dx.doi.org/10.1093/biosci/biw117.

Diener, S., Semiyaga, S., Niwagaba, C. B., Muspratt, A. M., Gning, J. B., Mbéguéré, M., Ennin, J. E., Zurbrugg, C. & Strande, L. 2014 A value proposition: Resource recovery from faecal sludge - Can it be the driver for improved sanitation? *Resources, Conservation and Recycling* **88** (2014), 32-38. http://doi.org/10.1016/j.resconrec.2014.04.005.

Doczi, J. (2013). *Climate Risk Management Tools for the Water, Sanitation and Hygiene Sector*. Overseas Development Institute, London, pp. 60.

Doczi, J., Dorr, T., Mason, N., & Scott, A. (2013). *The post-2015 delivery of universal and sustainable access to infrastructure services services*. *ODI Working Paper*. Overseas Development Institute, London, pp. 67.

Edmond, J., Sorto, C., Davidson, S., Sauer, J., Warner, D., Dettman, M. and Platt, J., 2013. Freshwater Conservation and WASH Integration Guidelines: A Framework for Implementation in sub-Saharan Africa. Africa Biodiversity Collaborative Group, Conservation International, and The Nature Conservancy, Washington, DC, USA.

Fuhrmeister, E. R., Schwab, K. J. & Julian, T. R. 2015 Estimates of Nitrogen, Phosphorus, Biochemical Oxygen Demand, and Fecal Coliforms Entering the Environment Due to Inadequate Sanitation Treatment Technologies in 108 Low and Middle Income Countries. *Environmental Science & Technology* **49** (19), 11604–11. http://doi.org/10.1021/acs.est.5b02919.

Geels, F. W. 2011 The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation and Societal Transitions*, **1** (1), 24–40. http://doi.org/10.1016/j.eist.2011.02.002.

Gleick, P. H. & Palaniappan, M. 2010 Peak water limits to freshwater withdrawal and use. *Proceedings of the National Academy of Sciences of the United States of America*, **107** (25), 11155–11162. http://doi.org/10.1073/pnas.1004812107.

Gleick, P. H. 2003 Global freshwater resources: soft-path solutions for the 21st century. *Science (New York, N.Y.)* **302** (5650), 1524–1528. http://doi.org/10.1126/science.1089967.

Griggs, D, Stafford-Smith, M., Gaffney, O., Rockström, J., Öhman, M. C., Shyamsundar, P., Steffen, W., Glaser, G., Kanie N. & Noble, I. 2013 Policy: Sustainable development goals for people and planet *Nature* **495** (7441), 305–307.

Hadwen, W. L., Powell, B., MacDonald, M. C., Elliott, M., Chan, T., Gernjak, W. & Aalbersberg, W. G. L. 2015 Putting WASH in the water cycle: climate change, water resources and the future of water, sanitation and hygiene challenges in Pacific Island Countries. *Journal of Water, Sanitation and Hygiene for Development*, **5** (2), 183-191. http://doi.org/10.2166/washdev.2015.133.

Hajer, M., Nilsson, M., Raworth, K., Bakker, P., Berkhout, F., de Boer, Y., Rockström, J., Ludwig, K and Kok, M. 2015 Beyond cockpit-ism: Four insights to enhance the transformative potential of the sustainable development goals. *Sustainability (Switzerland)*, **7** (2), 1651–1660. http://doi.org/10.3390/su7021651.

Hanjra, M.A., Blackwell, J., Carr, G., Zhang, F. & Jackson, T.M. 2012 Wastewater irrigation and environmental health: Implications for water governance and public policy. *International journal of hygiene and environmental health* **215** (3), 255-269.

Haxeltine, A., Whitmarsh, L., Bergman, N., Rotmans, J., Schilperoord, M. & Köhler, J., 2008. A Conceptual Framework for transition modelling. *International Journal of Innovation and Sustainable Development* **3** (1-2), 93–114. http://doi.org/10.1504/IJISD.2008.018195.

Heath, T.T., Parker, A.H. & Weatherhead, E.K. 2012 Testing a rapid climate change adaptation assessment for water and sanitation providers in informal settlements in three cities in sub-Saharan Africa. *Environment and Urbanization* **24** (2), 619-637.

Inter-Agency and Expert Group on Sustainable Development Goals Indicators (IAEG-SDGs) 2015 *Compilation of Metadata Received on Indicators for Global Monitoring of the Sustainable Development Goals and Targets*. *IAEG-SDGs*. http://unstats.un.org/sdgs/files/Metadata Compilation for SDG Indicators 23 October 2015 Update.pdf (accessed 30 June 2016).

Kamuteera, E. 2011 Promoting ecological sanitation: sharing NKKD WATSAN experiences. In *35th WEDC International Conference*, Loughborough, UK (pp. 1–4).

Keatman, T. 2012 *The silent partner: The role of the environment in multi-stakeholder partnerships for urban and peri-urban water and sanitation supply*. Building Partnerships for Development in Water & Sanitation, London, UK ,pp. 104.

Kennedy-Walker, R., Evans, B., Amezaga, J. & Paterson, C. 2014 Challenges for the future of urban sanitation planning: critical analysis of John Kalbermatten's influence. *Journal of Water Sanitation and Hygiene for Development* **4** (1), 1–14. http://doi.org/10.2166/washdev.2013.164.

Kinney, C. A., Furlong, E. T., Zaugg, S. D., Burkhard, M. R., Werner, S. L., Cahill, J. D. & Jorgensen, G. R. 2006 Survey of organic wastewater contaminants in biosolids destined for land application. *Environmental Science & Technology* **40** (23), 7207–7215. http://doi.org/10.1021/es0603406.

Lawhon, M. & Murphy, J. T. 2012 Socio-technical regimes and sustainability transitions: Insights from political ecology. *Progress in Human Geography* **36** (3), 354–378. http://doi.org/10.1177/0309132511427960.

Loorbach, D., Frantzeskaki, N., & Huffenreuter, R. L. 2015 Transition Managment: Taking Stock from Governance Experimentation. *The Journal of Corporate Citizenship* **58**, 48–66.

Mason, N. & Calow, R. 2012 *Water security: from abstract concept to meaningful metrics: An initial overview of options*. Working Paper 357. Overseas Development Institute, London, UK.

Mehta, L. & Movik, S. 2014 Liquid Dynamics: Challenges for Sustainability in the Water Domain. *Wiley Interdisciplinary Reviews: Water*, **1** (4), 369–384. http://doi.org/10.1002/wat2.1031.

Melamed C., Scott A. & Mitchell T. 2012 *Separated at birth, reunited in Rio? A roadmap to bring environment and development back together,* Background Note May 2012. Overseas Development Institute, London, UK.

Merrey, D., Awulachew, S. B., Saruchera, D., & Lautze, J. (2015). *The Critical Role of Water in Achieving the Sustainable Development Goals : Synthesis of Knowledge*

and Recommendations for Effective Framing , Monitoring , and Capacity Development Paper (draft), Paper prepared for: United Nations Department of Economic and Social Affairs.

Mitchell, C. 2015 Liveability? Resilience? Or something more? What ought we expect from the infrastructure of the future? *Water 21, pp*. 12.

Morelli, J. 2011 Environmental Sustainability: A Definition for Environmental Professionals. *Journal of Environmental Sustainability* **1** (1), 1–27. http://doi.org/10.14448/jes.01.0002.

Nilsson, M., Griggs, D. & Visbeck, M. 2016 Map the interactions between Sustainable Development Goals. *Nature* **534**, 320–322.

Oates, N., Ross, I., Calow, R., Carter, R. & Doczi, J., 2014. *Adaptation to climate change in water, sanitation and hygiene: assessing risks, appraising options in Africa*. Overseas Development Institute London, UK, pp. 82.

Okem, A. E., Xulu, S., Tilley, E., Buckley, C. & Roma, E. 2013 Assessing perceptions and willingness to use urine in agriculture: a case study from rural areas of eThekwini municipality, South Africa. *Journal of Water Sanitation and Hygiene for Development* **3** (4), 582–591. http://doi.org/10.2166/washdev.2013.036.

Onwuegbuzie, a, Leech, N. & Collins, K. 2012 Qualitative Analysis Techniques for the Review of the Literature. *Qualitative Report* **17** (56), 1–28.

Onwuegbuzie, A. J. & Frels, R. K. 2014 A Framework for Using Discourse Analysis for the Review of the Literature in Counseling Research. *Counseling Outcome Research and Evaluation* **5** (1), 52–63. http://doi.org/10.1177/2150137813515905.

Pahl-Wostl, C., Gupta, J., & Bhaduri, A. 2016. Water security: a popular but contested concept. In: *Handbook on Water Security*, (C. Pahl-Wostl, J. Gupta, & A. Bhaduri, eds). Edward Elgar Cheltenham, UK, pp 1-18.

Pisano, U. & Berger, G. 2013 *Planetary Boundaries for SD. From an international perspective to national applications*. European Sustainable Development Network Quarterly Report No. 30. European Sustainable Development Network, Vienna, Austria.

Post-2015 Water Thematic Group (2013). *WASH and environmental sustainability Framing Paper: Integration for sustainable development*. http://www.unwater.org/downloads/worldwewant/WASH-4-EnvSust-Framing-Paper%20.pdf (accessed 10 June 2016).

Poustie, M. S. & Deletic, A. 2014 Modeling integrated urban water systems in developing countries: case study of Port Vila, Vanuatu. *Ambio* **43** (8), 1093–1111. http://doi.org/10.1007/s13280-014-0538-3.

Raworth, K. 2012 *A safe and just space for humanity: Can we live within the doughbnut?* Oxfam Discussion Paper, February 2012. https://www.oxfam.org/en/research/safe-and-just-space-humanity (accessed 28 Sep 2015).

Raworth, K. 2013 Defining a Safe and Just Space For Humanity. In *State of the World 2013: Is Sustainability Still Possible?* Washington, DC: Island Press/Center for Resource Economics. pp. 28–38. http://doi.org/10.5822/978-1-61091-458-1 (accessed 30 June 2016).

Reid, M. C., Guan, K., Wagner, F. & Mauzerall, D. L. 2014 Global methane emissions from pit latrines. *Environmental Science and Technology*, **48**(15), 8727–8734. http://doi.org/10.1021/es501549h.

Retamal, M.L., Nguyen Dinh Giang Nam, Willetts, J.R., Mitchell, C.A. & Carrard, N.R. 2011 Comparing household water end-use data from Vietnam and Australia: Implications for water and wastewater planning, in *Proceedings from Efficient 11 - 6th IWA Specialist Conference on Efficient Use and Management of Water*, ed International Water Association, International Water Association, London, UK, pp. 1-12. 29 March– 2 April 2011.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E., Lenton, T., Scheffer, M. , Folke, M., C. Schellnhuber, C., Nykvist, H., De Wit, C. A. , Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R. W., Fabry, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P. & Foley J. 2009 Planetary boundaries:exploring the safe operating space for humanity. *Ecology and Society* **14** (2), 32.

Rognerud, I., Fonseca, C., van der Kerk, A., & Moriarty, P. 2016 *IRC Trends Analysis, - 2016 – 2025*. IRC, The Netherlands.

Rosenqvist, T., Mitchell, C. & Willetts, J. 2016 A short history of how we think and talk about sanitation services and why it matters. *Journal of Water Sanitation and Hygiene for Development* **6** (2) 298-312. DOI: 10.2166/washdev.2016.118.

Ross, K., Abeysuriya, K. & Mitchell, C. 2015 Developing principle-based targets and indicators for the SDGs', paper presented at the *2015 International Conference on Sustainable Development*, Columbia University New York City, September 23-24 2015.

Srinivasan, V., Palaniappan, M., Akudago, J., Cohen, M. & Christian-Smith, J. 2012 *Multiple-Use Water Services (MUS): Recommendations for a Robust and Sustainable Approach Multiple-Use Water Services (MUS): Recommendations for a Robust and Sustainable Approach About the Pacific Institute*. The Pacific Institute, Oakland, California.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A. and Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L.M., Ramanathan, V., Reyers, B. & Sörlin, S. 2015 Planetary boundaries: Guiding human development on a changing planet. *Science*, **347** (6223), 1259855. http://doi.org/10.1126/science.1259855.

Tijani, J. O., Fatoba, O. O. & Petrik, L. F. 2013 A review of pharmaceuticals and endocrine-disrupting compounds: Sources, effects, removal, and detections. *Water, Air, and Soil Pollution* **224** (11), 1 -29. http://doi.org/10.1007/s11270-013-1770-3.

Tilmans, S., Diaz-Hernandez, A., Nyman, E. & Davis, J. 2014 The potential for financing small-scale wastewater treatment through resource recovery: experience from Bocas del Toro, Panama. *Journal of Water Sanitation and Hygiene for Development* **4** (3), 449–459. http://doi.org/10.2166/washdev.2014.138.

Truhlar, A. M., Rahm, B. G., Brooks, R. A., Nadeau, S. A., Makarsky, E. T. & Walter, M. T. 2016 Greenhouse Gas Emissions from Septic Systems in New York State. *Journal of Environmental Quality* **45**, 1153-1160. doi:10.2134/jeq2015.09.0478.

UN Special Rapporteur on the human right to safe drinking water and sanitation 2014. *Realising the human rights to water and sanitation: A Handbook by the UN Special Rapporteur Catarina de Albuquerque* http://www.righttowater.info/handbook/ (accessed 5 July 2016).

UNICEF/GWP (Global Water Partnership) 2015 *WASH Climate Resilient Development: Integrating climate resilience into national WASH strategies and plans*. http://doi.org/http://www.unicef.org/wash/files/Strategic_Framework_WEB.PDF.

United Nations 2015 *Transforming our world: The 2030 agenda for sustainable development*. https://sustainabledevelopment.un.org/content/documents/7891Transforming%20Our%20World. pdf.

WCED (World Commission on Environment and Development) 1987 *Our Common Future: Report of the World Commission on Environment and Development*. *United Nations*. Oxford Univeristy Press Oxford.

Weitz, N., Nilsson, M. & Davis, M. 2014 A Nexus Approach to the Post-2015 Agenda: Formulating Integrated Water, Energy, and Food SDGs. *SAIS Review of International Affairs* **34** (2), 37–50. http://doi.org/10.1353/sais.2014.0022.

WHO/UNICEF 2015 Progress on sanitation and drinking water - 2015 update and MDG assessment. WHO New York, NY, USA http://www.wssinfo.org/fileadmin/user_upload/resources/JMP-Update-report-2015_English.pdf (accessed 30 Sep 2015).

Willetts, J. R., Carrard, N. R., Retamal, M. L., Nam N. D. G, Paddon, M., Thuy, D. X., Trung, N. H. & Mitchell, C. A. 2010 *Selecting sanitation options: a case study of south Can Tho-technical report. Cost effectiveness and Sustainability of Sanitation Options: A Case Study of South Can Tho* – Technical Report, Institute for Sustainable Futures, University of Technology, Sydney, pp. 50.

3.4 Critical reflections on the published review

Considering the published review in the context of the whole inquiry, I identify two critical reflections that informed subsequent parts of this inquiry. The first relates to the review's application of the planetary boundaries framework as a heuristic for assessing WASH literature. The planetary boundaries framework had a rapid rise to prominence, informing SDG policy dialogues (Griggs et al., 2013; Hajer et al., 2015; Pisano & Berger, 2013) and attaining >3,500 citations in scientific literature in the decade since its publication (Downing et al., 2019). In sustainability literature, the planetary boundaries concept has become a reference point – it is the rationale for action and a means for determining which issues warrant focus. Reviews of how the planetary boundaries concept has been applied point to limitations, such as insufficient integration of social dimensions (Downing et al., 2019; Drees et al., 2021) and challenges applying the boundaries at different scales (Bunsen et al., 2021; Montoya et al., 2018).

My application of the planetary boundaries framework – to assess the presence or absence of relevant ideas in WASH discourse – can be similarly critiqued as lacking nuanced discussion of social, and local, dimensions. While acknowledging this critique, I maintain the usefulness of applying the framework as a heuristic to identify issues warranting greater WASH sector focus, which was a novel approach for considering WASH-sustainability interconnections. Nevertheless, the planetary boundaries framework was not an appropriate lens for subsequent analyses in the inquiry or its synthesis given their focus on national and local scales (in studies 2 and 3 respectively) and intent to identify ways for WASH professionals to meaningfully connect sustainability and social imperatives.

A second and related reflection is whether insights from sustainability transformations scholarship may have driven the literature review in different directions. In the 5 years since the review was published my interest in sustainability transformations scholarship has expanded as the field has grown (as described in section 1.3). In the published review I drew on transition studies and the multi-level perspective to identify co-evolution and 'tipping innovation's cascade' as strategies for supporting a scale-up of sanitation reuse from niche to regime

levels. These ideas remain relevant, though imply stepwise rather than transformative changes. Insights from sustainability transformations may have prompted equal focus on 'deeper' leverage points related to purpose and mindsets (Abson et al., 2017; Waddock et al., 2020) as discussed in section 7.2, and on more nuanced conceptions of scaling up such as those described by Lam et al. (2020) as discussed in sections 7.3 and 7.9.

3.5 Approach to reviewing more recent WASH discourse

To update the review of WASH discourse and sustainability, I undertook a critical review of literature published between 2017–2021. A critical review (as described by Grant & Booth, 2009) analyses the conceptual contributions of different literature sources, taking stock and evaluating how a body of work engages with the research topic. In this case, I reviewed literature to assess how themes and future directions identified in the original review were reflected, developed and/or contradicted in more recent work. Academic literature was identified through searches of SCOPUS and Google Scholar using the same search strings as the original systematic review plus terms related to themes and future directions. I also reviewed non-academic literature from key WASH sector organisations such as UNICEF and the World Health Organization (WHO) – adopting a pragmatic approach to ensure the inclusion of relevant grey literature while not repeating a systematic search process. Titles and abstracts were scanned for relevance, with the most relevant documents reviewed in full for thematic insights and overall framing of sustainability. Documents were reviewed and tagged in Mendeley with insights captured in Airtable, using the software's database functionality to identify and analyse themes across sources.

Insights presented in this section draw from the critical review as well as targeted literature reviews completed for each of the inquiry's subsequent studies. Study 2 reviewed literature at the intersection of water service delivery and groundwater resource management, as presented in publication 2 (Chapter 4). Literature pertaining to sanitation-related reuse was reviewed for study 3 (publication 3, Chapter 5), including a focus on system costs and their distribution. Sustainability transformations literature reviewed for study 4 (publication 4, Chapter 6) informed

the analysis of WASH discourse as reflecting an instrumental conception of sustainability, rather than one which highlights the interdependence of people and earth system resources (discussed in section 3.8).

3.6 How have the published review's themes and future directions been addressed in more recent literature?

Table 4 documents how themes identified in the systematic literature review have since been reflected, developed, or contradicted in more recent work. The updated review identified a key shift in WASH engagement with climate change. This theme is flagged in the table and elaborated in section 3.7.

Table 4 Exploring how recent literature has addressed themes and future directions

Themes and future directions from 2017 review	Insights from more recent literature
THEMES	
Theme 1: Development and environment in tension	The perceived tension between development and environment was not a theme in 2017–2021 literature, with increasing acknowledgement of the importance of environmental sustainability considerations in WASH. Since publication of the original review, the integrated agenda of the SDGs is more widely reflected in WASH literature (e.g. Dwipayanti et al., 2017; Herrera, 2019; MacDonald et al., 2017; Roy & Pramanick, 2019; Workman et al., 2021). However, limitations are recognised, for example Herrera (2019) notes the integration of broader sustainability considerations in WASH metrics but questions the practical relevance of integrative approaches given local governance challenges. Further, although environmental considerations are no longer presented as 'too hard' or 'not urgent' (as described in the original review), an instrumental perspective dominates in which sustainability must be address in order to achieve (and not undermine) human development outcomes (discussed in section 3.8).
Theme 2: Water security as a bridge between WASH and environmental sustainability	Water security remains a topic of interest in the WASH sector. Publication 2 (Chapter 4) reviewed literature at the intersection of groundwater resource considerations and water service delivery, identifying the emergence of water resource considerations in WASH sector frameworks. Research on household water security (or insecurity) has elaborated the connections between household water services and social, institutional, resource and climate considerations (Achore et al., 2020; Dickin et al., 2021; Mukherjee et al., 2020; Wutich et al., 2017). A body of literature offers assessments of water security

Themes and future directions from 2017 review	Insights from more recent literature
	with reference to similarly diverse ecological and social drivers, with a particular focus on water security for cities and urban areas (e.g. Fallon & Neville, 2021; Groot & Mustafa, 2019; Khan et al., 2020; Lorenzo & Kinzig, 2019). Institutional literature leverages the sense of urgency connoted by concepts of water security and scarcity to advocate for political commitment, finance and private sector innovation towards water secure WASH (e.g. UNICEF, 2021a). The original review interpreted sectoral interest in water security as promising for WASH-sustainability integration, and recent literature elaborates both conceptual and practical considerations. However gaps persist, for example a review of water security frameworks found limited attention given to sanitation despite sanitation being a critical element of water security (Paudel et al., 2021).
Theme 3: Responding to environmental threats	The original review characterised WASH sector conceptions of climate change as constituting a “significant threat” to water and sanitation services. A key development in recent literature is a reconceptualisation of climate change from ‘threat’ to ‘operating context’ for WASH service delivery. The presentation of climate change as the context for WASH is elaborated and discussed in section 3.7 (and therefore not detailed in full here).
Theme 4: WASH as an environmental opportunity	Literature on the potential benefits of sanitation-related reuse has increased since publication of the original review, with SCOPUS identifying 300 relevant articles since 2017 (5 years) compared with 271 for the original review period of 2010–2016 (7 years). Reuse is now widely included alongside ‘or safe disposal’ in conceptualisations of the sanitation service chain (Hyun et al., 2019). Publication 3 (Chapter 5) reviewed sanitation reuse literature, including noting increasing application of circular economy language to resource-oriented sanitation (e.g. Danso et al., 2017; Mallory, Akrofi, et al., 2020; Moya et al., 2019; Schroeder et al., 2019; Sgroi et al., 2018; Willcock et al., 2021). Complementary work has linked sanitation-related reuse to planetary health (Jennifer Cole, 2018) and argued for a re-conceptualisation of sanitation as “a human-derived resource system, where people are part of the resource cycle” (Trimmer et al., 2020, p. 10446). Opportunities for sanitation-related reuse to enhance ecosystem services have also been identified (Trimmer et al., 2019; Willcock et al., 2021). Willcock et al. (2021) quantify the role of nature in treating human waste and argue for further consideration of “how engineered and natural infrastructure interact within a circular economy” (p. 192). Trimmer et al. (2019) propose a conceptual

Themes and future directions from 2017 review	Insights from more recent literature
	framework to define ways in which resource recovery from sanitation can enhance ecosystem services.
FUTURE DIRECTIONS	
Future direction 1: Do more good instead of do less harm	The idea of 'doing more good' is reflected in a recent high-profile articles linking sanitation-related reuse to ecosystem services. Trimmer et al. (2019) assert that "sanitation need not only consume: recovered resources (nutrients, organic matter and water) may enhance multiple ecosystem services, thereby expanding the value of sanitation" (p. 681). An emerging narrative that 'WASH action is climate action' also reflects 'do more good' thinking (elaborated below in section 3.7). The concept of regenerative infrastructure (linked to circular economy discourse) is increasingly appearing in academic and institutional literature spanning high- and low-income countries (e.g. Delgado et al., 2021; Koottatep et al., 2019), but is not yet common in WASH sector discourse.
Future direction 2: Maximise synergies and minimise trade-offs	Discussion of SDG synergies trade-offs is common in sustainable development literature, including multiple references to potential synergies between SDG 6 and other goals (e.g. Hopkins et al., 2021; Kroll et al., 2019; Lim et al., 2018). However, Taka et al. (2021) argue that such analyses typically focus on links between WASH, poverty and health with less focus on broader conceptions of water security that encompass both societal and ecological needs. Similarly, Cunha Libanio (2021) notes a lack of integration between WASH and 'nexus' research fields, though recent work by Srivastava et al. (2022) has begun to explore the interconnections with a focus on humanitarian settings. Synergies with climate change action are more frequently mentioned (discussed in section 3.7).
Future direction 3: Identify and address gaps	The original review identified gaps in WASH sector focus when viewed through a planetary boundaries lens including climate change mitigation, novel entities, biosphere integrity and water use efficiency. Literature exploring climate change mitigation in sanitation has increased substantially in recent years (e.g. Dickin et al., 2020; McNicol et al., 2020; Mikhael et al., 2021; Mills et al., 2020; Reid, 2020), while other areas remain understudied. In a review of social science contributions to WASH and future directions for engineering, Workman et al. (2021) argue for increased focus on "emerging concerns and contaminants" given the sector's "major influence on the realities of humanity's environmental future" (p. 412).

Themes and future directions from 2017 review	Insights from more recent literature
Future direction 4: Support a transition of the reuse agenda from niche to regime	As described above (Theme 4), literature on sanitation-related reuse has increased in recent years and was reviewed in publication 3 (Chapter 5). Despite reuse being widely regarded as beneficial, literature has dominantly focused on business models and whether or not reuse can drive investment in earlier stages of the sanitation chain (e.g. Danso et al., 2017; Mallory, Holm, et al., 2020; Otoo et al., 2018; Rao et al., 2017). Transition strategies identified in the original review – reframing reuse as necessary, co-evolution and tipping innovation's cascade – have not been explored in recent literature. This observation informed the focus for study 3 in this inquiry, which analysed costs as a basis for determining how to support resource-oriented sanitation delivered by a local government service provider.

3.7 A key shift: climate change as the operating context for WASH

WASH discourse has moved from conceptions of climate change as an environmental threat, to widespread acknowledgement of climate change as the operating context for service delivery. Since the systematic review was published in 2017, literature connecting WASH and climate change has increased and diversified. Climate change is now widely described as inevitable, having significant impacts, bringing substantial uncertainties, and something that must be considered in any WASH initiative. The two perspectives identified in the original review – 'climate proofing' and 'integrated adaptation' – have persisted, though discourse has increasingly emphasised the complexity of climate impacts on services and communities. In this section I explore how recent literature has expanded focus to (i) encompass the social as well as technical dimensions of climate change implications for WASH; (ii) address mitigation as well as adaptation in climate change responses; and (iii) frame WASH and climate action in synergistic terms, highlighting opportunities to strengthen service delivery and climate resilience in tandem.

WASH sector literature has increasingly engaged with the complex ways in which climate change influences services and communities. In 2017 (the same year the original review of WASH discourse was published) Kohlitz et al., (2017) identified a tendency for WASH responses to emphasise 'outcome vulnerability' perspectives

on climate change, focusing on vulnerabilities of the physical aspects of WASH service delivery. While noting the value of an outcome vulnerability orientation for service reliability, the authors argued for an expansion of perspective to incorporate 'context vulnerability' and 'resilience' lenses, both of which offer complementary insights into adaptive capacity within social and socio-ecological systems (Kohlitz et al., 2017). Since then, WASH studies have increasingly explored the intersection of climate change with social and governance dynamics (e.g. Abrams et al., 2021; Dickin et al., 2021; Donkor, 2020; Grasham et al., 2021).

The expansion of perspective is evident in literature designed to support WASH professionals to grapple with climate change implications for programming and service delivery. The 'how tough is WASH framework' (Howard et al., 2021) assesses community and institutional dimensions alongside infrastructure resilience. Research in Indonesia informed a framework for climate-resilient citywide inclusive sanitation that addresses planning, institutions, financing and user engagement as well as infrastructure and water cycle considerations (Willetts et al., 2022). UNICEF's strategic framework for WASH Climate Resilient Development incorporates behavioural and governance dimensions alongside 'climate smart' infrastructure and technologies (UNICEF/GWP, 2017). More generally, sanitation-focused literature has emphasised the importance of moving beyond technocratic responses to consider soft adaptation strategies such as capacity building for wastewater managers and the development of effective information systems (Dickin et al., 2020; ISF-UTS and SNV, 2019; WHO, 2019). Similar themes are evident in water-focused literature, for example, analysis of the resilience of drinking water supplies to extreme weather events found that management behaviours were critical drivers of water quality, and must be considered alongside infrastructure (Charles et al., 2022).

Complementing WASH literature on climate adaptation, an expanding body of work has explored ways in which WASH can contribute to mitigation efforts, with a particular focus on sanitation. A number of studies have noted the risk of increased emissions associated with expanding access to onsite sanitation (e.g. Dickin et al., 2020; González et al., 2019; Kulak et al., 2017; Somlai et al., 2019; Van Eekert et al., 2019), and called for prioritisation of lower emissions options such as those

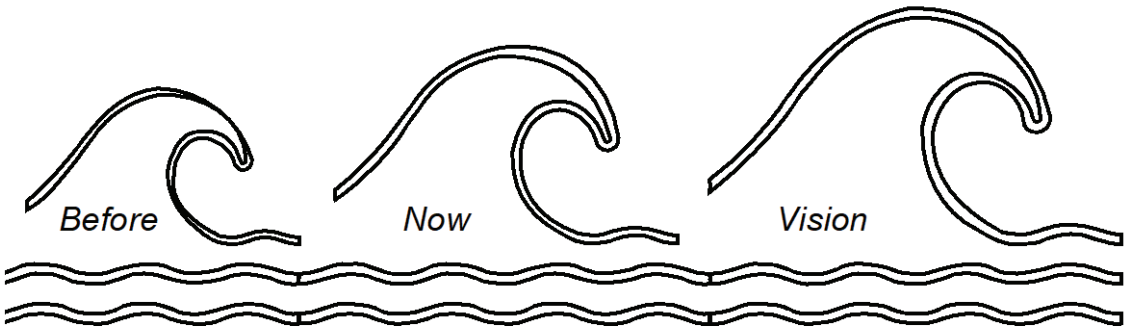
designed to recover resources (e.g. Kulak et al., 2017; McNicol et al., 2020). A lack of data on emissions associated with various sanitation options has been noted (Dickin et al., 2020), and ongoing research is attempting to address this gap, for example, the Climate and Costs in Urban Sanitation (CACTUS) research led by University of Leeds, and the Sanitation and Climate: Assessing Resilience and Emissions (SCARE) research led by University of Bristol.

Finally, an emerging narrative in WASH sector discourse is that 'WASH action is climate action', flagging opportunities to achieve synergistic outcomes for WASH and climate resilience. For example, the potential to leverage climate finance to support WASH-related climate action has been identified (e.g. Dickin et al., 2020; Mason et al., 2020; Mikhael et al., 2021; UNICEF, 2021b). Dickin et al. (2020) cite economic co-benefits and emissions reductions among the potential outcomes from complementary climate and sanitation investment. In an analysis undertaken for WaterAid, Mason et al. (2020) emphasise the importance of pursuing shared climate and WASH financing objectives: "making climate finance work for water, but also making water (and water finance) work for climate" (p. 53). The potential for resilience-focused action to drive integration in urban systems has been identified by Mikhael et al. (2021), who argue that resilience offers a frame for integration of sanitation with drainage, solid waste, energy and transport. In an advocacy document pitched at planners, policymakers, and experts in climate and WASH sectors, UNICEF (2021b) asserts the "huge potential contribution of the WASH sector to global climate goals" based on opportunities for WASH to build resilience, mitigate emissions and mobilise climate finance. These narratives demonstrate the extent to which climate change is driving greater integration of sustainability concerns in WASH, with further potential to deepen responses as discussed below (section 3.8).

3.8 An instrumental conception of sustainability, with momentum towards interdependence

In this section I discuss the evolution in WASH sector discourse in the period addressed in the published literature review and since, identifying current mainstream engagement with sustainability as reflecting an instrumental

perspective. Based on the analysis of past and current discourse, I characterise this instrumental perspective as a ‘wave’ between a historic tendency for the WASH sector to equate sustainability with functionality of infrastructure, and a future direction (the vision of this inquiry) towards conceiving sustainability in terms of interdependence between people and earth system resources. The three waves are illustrated in Figure 7 and elaborated below. While each wave is distinct there is fluidity between them. Each wave also builds on (rather than replaces) prior perspectives, indicating increasing breadth and depth of engagement with sustainability ideas.



Functionality

Sustainability conceived as functionality of a service for users, except by niche groups e.g. those advocating resource-oriented sanitation

Focused on functionality of infrastructure as critical for people to access services

Instrumentalism

Water resources and climate feature in mainstream sector discourse, paying attention to these considerations is important to ensure functionality for users

Expansion of perspective but reinforcing the status quo, focused on management of resources *for* people using services

Interdependence

WASH sector responds and contributes to systemic changes seeking a sustainable relationship between people and planet

Focused on people and resources as interdependent, equally important system components

Figure 7 The evolution of WASH sector discourse on sustainability

A tendency for WASH sector discourse to frame sustainability with reference to infrastructure functionality provided the motivation and rationale for this inquiry (as described in section 1.3). While the dominant ‘continuity of service’ definitions of sustainability implicate resources and natural systems, WASH perspectives have historically overlooked these interactions and emphasised infrastructure durability or functionality (Jiménez et al., 2017; Lockwood & Smits, 2011; Whaley & Cleaver,

2017). The functionality perspective placed infrastructure and people at the centre of thinking about sustainability, being highly focused on user experiences. Such thinking was characteristic of the Millennium Development Goal era, perpetuated by targets that emphasised household access to water and toilets without sufficient attention to water quality or management of faecal waste (Weststrate et al., 2019). While sub-groups of WASH professionals have long advocated for broader sustainability perspectives (e.g. those focused on ecological sanitation), environmental considerations were dominantly conceived as further problematising an already complex challenge (as described in publication 1). Nevertheless, it is undeniable that functional infrastructure is critical for sustainable WASH services. As such, the functionality perspective rightly persists through subsequent eras, complemented with increasingly comprehensive sectoral conceptions of sustainability.

More recent sector discourse conveys an instrumental perspective. In line with the integrated SDG agenda, recent discourse identifies water resource management and climate change as critical for WASH sustainability. The focus on water security has continued and climate change is now presented as the operating context in which WASH services are delivered. Yet the perspective is instrumentalist, whereby environmental considerations linked to water resources and climate change must be managed to facilitate continuous service delivery. The perspective is evident in many climate focused documents (e.g. Alhassan & Hadwen, 2017; Fleming et al., 2019; Howard et al., 2021). It is also apparent in sector sustainability frameworks that identify environment amongst several sustainability dimensions (e.g. Boukerrou et al., 2019; Daniel et al., 2021; Jiménez et al., 2017; UNICEF & UNDP-SIWI Water Governance Facility, 2021). Such an approach is a natural evolution for a sector focused on addressing fundamental human needs and increasingly recognising the critical role of natural systems in doing so. As such, I do not use ‘instrumental’ pejoratively, but rather to characterise a dominant perspective and highlight opportunities for deeper, more transformative, engagement with sustainability concepts.

Placing the instrumental perspective within an evolving WASH discourse, I identify an emerging ‘wave’ in which WASH perspectives on sustainability recognise the

interdependence of people and planet. The key progression of an ‘interdependent’ compared with an ‘instrumental’ perspective is the positioning of people and resources as fundamentally linked and equally important. In contrast to viewing environmental considerations as issues to manage in support of service provision, interdependence connotes the unique position of natural systems as both foundational for and fundamentally linked to WASH. In other words, environmental considerations have a different, and more central, place compared with human constructed dimensions of sustainability such as financial and institutional aspects. Such a perspective challenges, rather than reinforces, a dominant discourse in which resources are managed *for* rather than *interdependently with* people.

In WASH literature, there is momentum for evolution towards a conception of sustainability that recognises interdependence between people and earth system resources. IRC’s WASH system building blocks position water resources management as one of nine essential WASH sub-systems, and the authors identify its unique, foundational character: “Water resource management is a slightly different type of building block because it underlies the entire sector’s existence: the natural environment is the very foundation of WASH availability and sustainability” (Huston & Moriarty, 2018 p.26). However, not all models of WASH systems strengthening building blocks include this dimension (e.g. Sanitation and Water for All, 2016).

Recent work analysing the ways in which nature provides sanitation services (e.g. Masi et al., 2018; Prescott et al., 2021; Trimmer et al., 2019; Willcock et al., 2021) also presents a perspective of interdependence. In one such study, (Willcock et al., 2021) call for “a holistic understanding of the fully coupled links between sanitation and nature”. Links between WASH and environmental justice are also emerging, for example, the Lancet Commission on WASH and Health aims to “reimagine and reconstitute WASH not only as a central pillar of public health, but also as a pathway to gender equality and social and *environmental* [emphasis added] justice” (Amebelu et al., 2021). Envisioning WASH as a pathway to environmental justice implies deep engagement with the connections between WASH and natural systems, and how they are experienced inequitably by different groups.

Evolution towards a perspective of interdependence implies a more transformative approach to WASH sector sustainability in line with normative directions advocated in sustainability transformations scholarship. In the WASH sector, the term 'transformative' has been used to prompt a rethink of public health approaches in response to the WASH Benefits and SHINE trials (Pickering et al., 2019; Vila-Guilera et al., 2021) and in analysis of WASH contributions to gender equality (Macarthur et al., 2020). As sector conceptualisations of 'transformative WASH' develop there is opportunity for sustainability considerations to be central, informed by ideas of interdependence. The ways in which interdependence between people and resources can inform WASH perspectives is explored further in this inquiry's synthesis (Chapter 7).

3.9 Summary

In this chapter, I presented the inquiry's literature review in the form of a published review of WASH-sustainability discourse 2010–2016 and critical review of more recent documents. The published review identified four themes evident in WASH literature: a perceived tension between environmental sustainability and WASH development imperatives, the idea that water security is a helpful concept for bridging service delivery and sustainability, different attitudes about how best to respond to threats such as climate change, and promotion of sanitation reuse opportunities. Based on an analysis of discourse with reference to the planetary boundaries framework, the published review also proposed four future directions to guide WASH research: fostering a 'do more good' instead of 'do less harm' approach, focusing on synergies and minimising trade-offs, identifying and addressing gaps in current focus, and supporting a transition of the reuse agenda from niche to regime scale. I reflected on the review's application of the planetary boundaries framework in light of recent critiques and the inquiry's emergent sustainability transformations lens.

The updated review explored how themes and future directions from the published review have been reflected, developed, or contradicted in more recent work. A key finding was a shift in WASH discourse about climate change such that climate change is now widely acknowledged as the operating context for service delivery.

Finally, I characterised the evolution of discourse through three ‘waves’ or perspectives – moving from a focus on functionality (before), to instrumentalism (now), with an emerging discourse of interdependence (the vision). The next part of this thesis presents an orientation to Part II, introducing the inquiry’s two in-depth studies focused on groundwater reliance and resource concerns (study 2) and life-cycle costs of resource-oriented sanitation (study 3).

PART II Two studies of WASH-sustainability interactions

Two in-depth studies exploring specific areas within the WASH-sustainability nexus, informing a more grounded understanding of the conceptual and practical challenges.

Orientation to the in-depth studies: choices and rationale

Overview

Part II of this thesis presents two in-depth studies exploring dimensions of the intersection between WASH and planetary sustainability: the first focused on groundwater as a source of drinking water in Southeast Asia and Pacific countries, and the second an analysis of the life-cycle costs of a resource-oriented sanitation system in urban Sri Lanka. In this orientation I explain and justify the choice of topics for in-depth studies and articulate how they respond to the inquiry's overarching research question. Journal publications documenting the studies are presented as Chapters 4 and 5.

Topic choices: Why groundwater and resource-oriented sanitation?

The decision to focus on groundwater and resource-oriented sanitation in two in-depth studies – from a wide range of potential WASH-sustainability topics – was driven by three considerations: insights from the review of WASH discourse (publication 1, Chapter 3); my experiences and observations from pre-PhD research projects; and seeking diversity of study in terms of geography, sub-sector and sector 'lenses' (monitoring and costing). Here, I explain how these considerations informed and justified the selection of the two studies.

First, of the themes and gaps identified in the literature review, discourse on groundwater and resource-oriented sanitation raised particular sustainability questions. The theme of 'responding to threats' noted groundwater's potential as a climate-resilient water source, despite limitations in our knowledge about how climate change will affect aquifers and their already stressed state in many parts of the world. The discourse analysis highlighted a disjunct between a WASH narrative in which groundwater was positioned as a resilient resource, and water resource management perspectives on the stressed state of groundwater globally. In study 2, I sought to explore the relevance of each narrative and tensions between them by assessing the situation for ten Southeast Asia and Pacific countries. Similarly, the discourse analysis identified a gap in sector literature regarding resource-

oriented sanitation systems, contrasting pilot-scale studies with conceptual (but not well-grounded) analyses. In study 3, I sought to contribute empirical data about an operational city-scale system, exploring what it takes – from a life-cycle cost perspective – for such systems to succeed and progress regenerative approaches in line with Raworth's (2017b) doughnut concepts.

Second, my previous experiences as a WASH researcher informed in-depth study selection, most notably two formative experiences in Vietnam. While researching the extent to which piped water services were reaching poor-identified households in rural areas, I interviewed service providers focused on strategies for increasing user demand to increase revenue, which would have extracted larger volumes of water. There was no knowledge (or monitoring) of water resource considerations, or coordination with water resource management agencies, and I felt concerned by the potential cumulative impacts. This experience highlighted a need for further consideration of both household water use practices and the need for strengthened coordination between WASH and water resource professionals, which I explored in study 2.

Similarly, the focus and framing of study 3 was informed by research comparing sanitation options for an urban area. This previous research was undertaken in partnership with a Vietnamese utility and university. Utility partners emphasised the importance of cost information for informing government decision making, and the research grappled with a lack of empirical data on costs of urban sanitation service options, and particularly those involving reuse. The experience also highlighted the importance of bridging research activities with government direction-setting. The partner university was undertaking pilot studies of urine-diversion systems and constructed wetlands at the time, and there was untapped opportunity for such studies to inform government planning.

Third, a key consideration in study selection was pursuit of diversity in terms of geographic and sectoral dimensions – striking a balance between breadth and depth that is characteristic of transdisciplinary approaches and designed to address the overarching research question from multiple angles. To complement the global ‘sector’ perspective of studies 1 and 4, studies 2 and 3 contributed contextualised analyses to the inquiry. Study 2 explored groundwater reliance and resource

concerns at national scale across ten countries in Southeast Asia and Pacific regions, while study 3 featured a city-scale case study in Sri Lanka. The intention was to include a mix of cultural and biophysical contexts in which different sustainability considerations are more or less relevant, and to consider the different scales at which WASH systems and sustainability dynamics operate. Such an approach acknowledges the importance of researching across scales when undertaking change-oriented research to progress sustainability (Mauser et al., 2013).

The in-depth studies each addressed a different WASH sub-sector, with study 2 focused on water service delivery and study 3 focused on sanitation. I note that these choices exclude hygiene, which can contribute to environmental pollution (e.g. through child faeces management and the use of products containing contaminants, as described in publication 1) and generate solid waste (e.g. menstrual hygiene products, see Elledge et al., 2018). Yet a focus on water and sanitation in this inquiry was justified given the direct and profound connections between water and sanitation services and natural resource systems.

The two in-depth studies analysed WASH-sustainability dynamics with reference to two sector ‘lenses’ that drive priorities and actions: monitoring (study 2) and costs (study 3). The indicators and frames used to monitor WASH services drive action and investment (Bartram et al., 2014). Study 2 sought to highlight and address a gap in current monitoring at the global level (data collated by WHO/UNICEF through the Joint Monitoring Program), which emphasises the facility providing water rather than the resource from which it is sourced. It identified the risk that as access to ‘safer’ water services in the form of piped water increases, we are losing a global picture of implicated resources. The importance of critical perspectives on monitoring frames has been argued by Tortajada & Biswas (2018), who call for increased academic engagement with SDG 6 targets and indicators to address neglected topics including resource and environmental considerations.

WASH sector decisions and actions are also strongly driven by costs, hence the focus on costing in study 3. The relative costs of different service delivery options is a critical driver of investment towards efficient and equitable service delivery, yet the sector has suffered from a lack of information about financial considerations

(Tortajada & Biswas, 2018). In particular, a tendency to inadequately consider ongoing system costs has been linked to high rates of service failure (Daudey, 2018; Moriarty et al., 2013). In analysing the life-cycle costs of a resource-oriented sanitation system, study 3 sought to make the case for resource-oriented systems from a normative sustainability perspective, and to contribute critical data on the scale and distribution of required investments to support ongoing and equitable service delivery. The central importance of costs for the WASH sector has been affirmed by the Lancet Commission on WASH and Health, which is assessing the financial costs of achieving universal access to safely managed services as one of three priority areas for action (Amebelu et al., 2021).

How the in-depth studies addressed the overarching research question

Study 2 responded to the inquiry's overarching research question by translating insights from data into priorities for WASH professionals at national and sub-national scales (Figure 8). The publication itself articulates two research questions that explore (i) the extent of household reliance on groundwater as a source of drinking water in ten Southeast Asia and Pacific countries, and (ii) groundwater resource issues that may influence water services now and in the future. The relevance of findings for WASH professionals was explored in the publication's discussion, which considered how WASH professionals at national and sub-national scales can meaningfully engage in groundwater resource management as a foundation for universal, sustainable service delivery. In this thesis I articulate this analysis as a third research question (as described in Chapter 1 and illustrated in Figure 8), though it was implicit in the publication. The analysis applied the service delivery approach framework of three institutional levels (Moriarty et al., 2013; World Bank, 2017) as a sector-relevant heuristic to identify implications for national WASH agencies, service authorities and service providers, thereby addressing the

overarching research question's focus on WASH professionals.

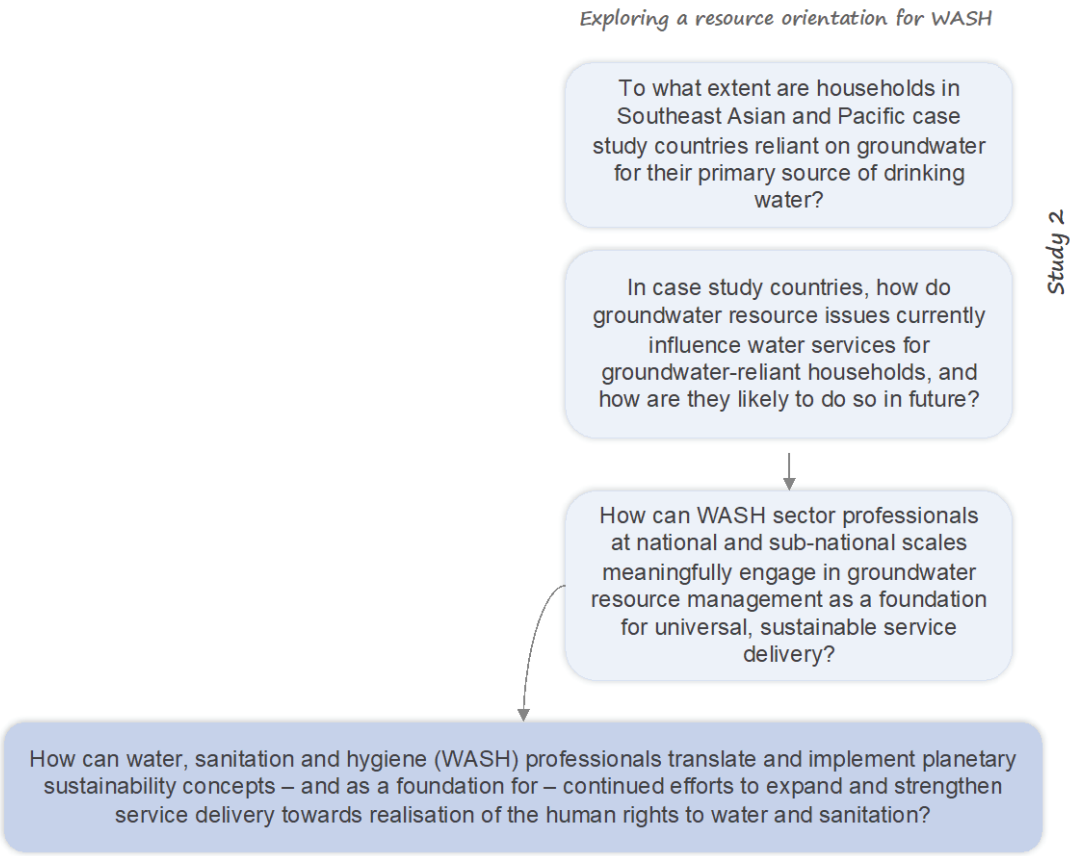


Figure 8 How study 2 research questions addressed the overarching question

Similarly, study 3 informed the inquiry's overarching research question by interpreting technical findings in their wider sectoral context (Figure 9). The importance of cost data to inform resource-oriented sanitation was argued, as was the critical need to focus on equity of access and distribution of costs. The study explored the role of local government as a resource-oriented service provider, a sector-relevant contribution given that local governments are typically responsible for service delivery where utilities do not exist. Beyond the costs and insights reported in the publication, the study explored how the case study sanitation system was established. Insights from this analysis provided further contribution to the inquiry's overarching research question. They are included with critical reflections on the publication in section 4.3 and reflected in the synthesis theme focused on purpose (section 7.4).

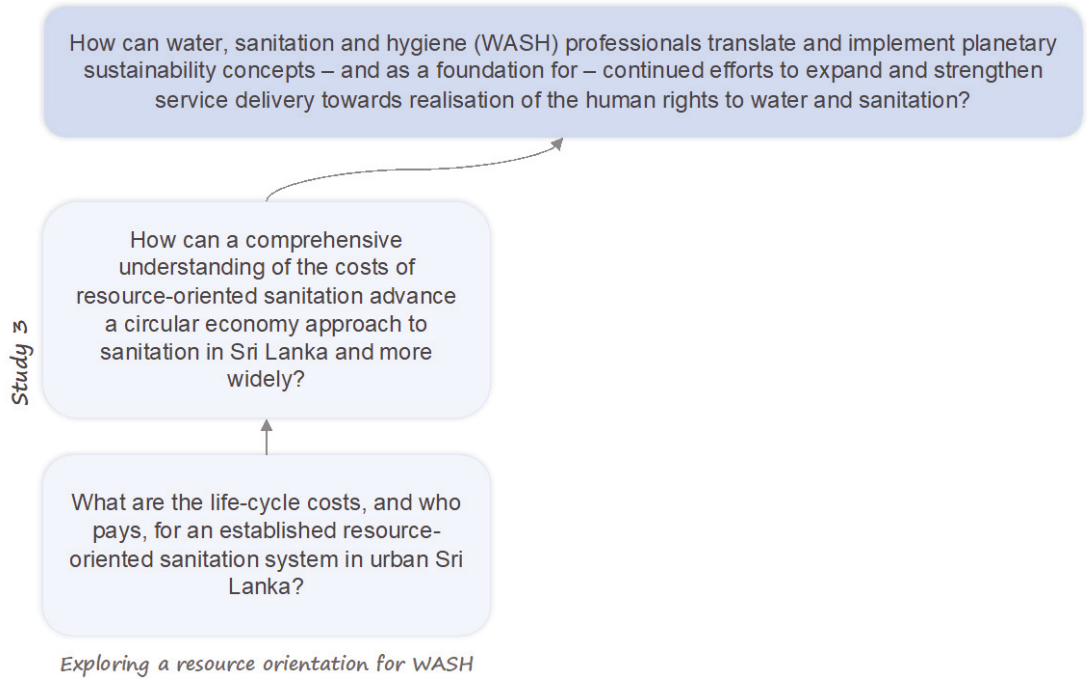


Figure 9 How study 3 research questions addressed the overarching question

4 Chapter 4 Study of groundwater reliance and resource concerns

4.1 Overview

This chapter presents the second of four publications included in this 'thesis by compilation', published in the journal *Water* in 2019. The article was the output for study 2, which analysed household reliance on groundwater as a source of drinking water in ten Southeast Asian and Pacific countries and related resource concerns. As described in the orientation to Part II of this thesis, the study responded to a gap in knowledge about the use of groundwater as a source of drinking water, and related resource concerns relevant for WASH professionals. Following presentation of the publication, I critically reflect on the study's approach to proposing WASH sector actions, explaining how these reflections informed a focus on worldviews in subsequent parts of the inquiry.

4.2 Publication 2 — Groundwater as a source of drinking water in Southeast Asia and the Pacific: A multi-country review of current reliance and resource concerns

Publication 2 is in the open access journal *Water* and is included in this thesis in its published form. The publication is available online at https://doi.org/10.3390/w11081605,

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Article

Groundwater as a Source of Drinking Water in Southeast Asia and the Pacific: A Multi-Country Review of Current Reliance and Resource Concerns

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Abstract: Groundwater is widely acknowledged to be an important source of drinking water in low-income regions, and it, therefore, plays a critical role in the realization of the human right to water. However, the proportion of households using groundwater compared with other sources is rarely quantified, with national and global datasets more focused on facilities—rather than resources—used. This is a significant gap in knowledge, particularly in light of efforts to expand water services in line with the inclusive and integrated agenda of the Sustainable Development Goals. Understanding the prevalence of groundwater reliance for drinking is critical for those involved in water services planning and management, so they can better monitor and advocate for management of water resources that supports sustainable services for households. This paper contributes data that can be used to strengthen the integration of resource considerations within water service delivery and inform the work of development partners supporting this area. We approach this issue from two perspectives. Firstly, we collate data on the proportion of households using groundwater as their primary drinking water source for 10 Southeast Asian and Pacific nations, finding an average of 66% (range of 17–93% for individual countries) of households in urban areas and 60% (range of 22–95%) of households in rural areas rely on groundwater for drinking. Together, these constitute 79% of the total population across the case study countries. Secondly, we review current and emerging groundwater resource concerns within each country, using a systems thinking approach to assess how groundwater resource issues influence household water services. Findings support the case for governments and development agencies to strengthen engagement with groundwater resource management as foundational for achieving sustainable water services for all.

Keywords: groundwater; Southeast Asia; Pacific Island Countries; water services; human right to water; water resources; sustainability; Sustainable Development Goals

1. Introduction

Around the world, groundwater makes a critical contribution to progressive realization of the human right to water. In developing country contexts—where 2.1 billion people still lack access to safely managed water and 844 million lack even basic water [1]—development of groundwater is considered a key strategy for addressing gaps in service delivery [2] and for building resilience to the impacts of climate change [2,3]. Groundwater is already the preferred source of drinking water globally [4], often considered more reliable than surface water and more accessible, given it can be directly exploited by users [5]. However, data on actual use is lacking, with knowledge gaps evident across local, regional and global scales [6].

Meanwhile, there is recognition by hydrogeology scholars that groundwater resources are under threat from overexploitation and pollution. Overexploitation is occurring in a context where

groundwater has shifted in status from "a reserve resource" used in periods of scarcity to "one that is now systematically abstracted in an uncontrolled or unregulated manner" [7]. With management and regulation yet to adequately respond in many contexts, groundwater remains poorly understood and inadequately protected [8]. The result is widespread stress on groundwater resources, with an estimated 1.7 billion people living in areas affected by overexploitation [9]. At the same time, groundwater quality is under threat from an ever-increasing list of anthropogenic pollutants [5]. With groundwater constituting 98% of the world's freshwater reserves [2], a focus on the governance of groundwater resources is essential to ensure we remain within the safe threshold of the freshwater use planetary boundary [10,11].

In this context, efforts to ensure sustainable, safe drinking water supplies must consider the relevant water resource and its management. For the global water, sanitation and hygiene (WASH) sector—comprising development organizations, researchers and government agencies responsible for service delivery—this requires a greater focus on the resources underpinning water supplies. As argued by Bradley and Bartram [12], WASH professionals need to give higher priority to water resources management, especially to groundwater management, and to consider water services and water resources management together in spite of their typical institutional separation. Recently, efforts have been made at the global level to better situate WASH services within broader water resource management (WRM), evidenced by the integration of WASH and WRM within a single Sustainable Development Goal (SDG). Guided by the SDG framework, those working on water service delivery are prompted to think about domestic water supply (target 6.1) in tandem with the quality of water resources (target 6.3), water-use efficiency (target 6.4) and water resource management (target 6.4). This promotes a broadening in WASH discourse, which has focused on the health, social and economic aspects of water services, and has placed less emphasis on their underpinning resources [13].

The neglect of resource considerations in WASH discourse reflects the fact that domestic use of groundwater is not typically considered a threat to groundwater resources, with agriculture dwarfing the domestic sector in terms of volumes extracted. Agriculture accounts for an estimated 70% of groundwater withdrawals worldwide, with the domestic sector responsible for just over 20% and industry just under 10% (based on 2010 data) [5]. However, a focus on total extractions obscures the critical link between resource management and households' access to water. Although household water use alone might not lead to overexploitation of groundwater resources, households reliant on groundwater have a central interest in its management and sustainability. Further, a global perspective on the contribution of domestic demand to total water extraction conceals local variations which can be important. For example, growing urban centers can have substantial water demand [14] and may be sites of localized groundwater stress. It is important to maintain the quality of raw water used for domestic purposes in order to protect human health and avoid expensive water treatment. Groundwater quality has a major bearing on the cost of using it for different purposes [15].

In recent years, integration of water resource considerations into WASH sector thinking is emerging in a number of evolving frameworks guiding service planning, delivery and oversight [12,16,17]. In the rural water sector, recent evolutions of the service delivery approach, which offers a widely used guiding frame for sector analysis and strengthening, include 'water resources management and security' as one of five building blocks for sustainable service delivery [18]. The inclusion of water resources within the service delivery approach framework acknowledges the growing recognition by governments of the challenges of both physical and economic water scarcity [18], and represents a notable shift compared with earlier iterations, which emphasised institutional, financial, asset management and monitoring considerations [19] but did not include resources. The service delivery approach articulates three institutional levels comprising national agencies, service authorities and service providers. Within this framing, the scope of focus on water resources considers both water availability and quality as well as institutional links between water resource managers and the service authorities and providers responsible for drinking water [18].

In metropolitan areas, there is a longer history of integrating resource considerations into the way water services are conceived and planned. Frameworks that have been applied to developing cities include Integrated Urban Water Management (IUWM) [20], sustainable urban water management (SUWM) [21], Water Sensitive Cities [22] and Nature Based Solutions [23]. Resource conservation and protection feature across 17 principles for water-wise cities developed by the International Water Association to support sustainable urban water management that links services with basins [24]. However, the extent to which these frameworks have put into practice has been variable [20,22], with particular challenges applying them in developing cities [22]. Further, Howard [25] argues that models for holistic urban water management have not adequately addressed the particularities of groundwater resource systems, despite advances in urban groundwater science, and identifies a need for involvement of all stakeholders in decision-making processes that inform groundwater governance. This includes a more proactive role for water utilities in groundwater resource management, mobilizing their technical expertise, as argued by Foster and Sage [26].

If the WASH sector is to adequately integrate resource considerations within service delivery approaches and progressive realization of the human right to water, it is essential to acquire a better understanding of which resources are used. In tracking progress towards SDG 6.1, the WHO/UNICEF Joint Monitoring Program (JMP) collates comprehensive data on facilities used by households for drinking water, including the type of resources used for water points, such as wells, springs or rainwater tanks. However, for those using piped or packaged water, the resource supplying these systems is not consistently identified in any standardized monitoring. With the increasing use of piped and packaged water [1,27], there is a growing knowledge gap about the extent to which households rely on groundwater. This is evidence of the "paucity of well-structured, globally useful, up-to-date and SDG-relevant groundwater data available", as found by Guppy et al. [4] in their analysis of the interlinkages between groundwater and the SDGs.

Addressing this gap, this paper offers an analysis of the role of groundwater in supplying drinking water services across ten Southeast Asian and Pacific Island countries. We approach the issue from two perspectives: (i) Integrating available data to calculate the proportions of households using groundwater as their primary source of drinking water, which we define as 'groundwater reliance' given the critical role of drinking water in supporting human health, and (ii) synthesising literature on the status of groundwater resources and emerging pressures, and undertaking a systems analysis of the links between resource issues and water service delivery. The intention is to contribute to WASH sector discourse and direction-setting by establishing a baseline of proportions of households using groundwater for drinking in each country, and identify the breadth of resource issues that must be considered, analyzed and planned for as part of efforts to expand, and sustain, services. In taking a multi-country approach, we sought to uncover the breadth and diversity of experiences, which can guide the scope and focus of much-needed future sub-national and local analyses.

2. Materials and Methods

This study involved the review and synthesis of secondary sources, with the investigation framed by two research questions:

(i) To what extent are households in Southeast Asian and Pacific case study countries reliant on groundwater for their primary source of drinking water?
(ii) In case study countries, how do groundwater resource issues currently influence water services for groundwater-reliant households, and how are they likely to do so in future?

Case study countries were selected to represent the diversity of countries across Southeast Asia and the Pacific, based on criteria including region (six from Southeast Asia and four from the Pacific), geography (island, coastal and land-locked nations), level of development and extent of urbanization. In selecting a diverse set of countries, the intention was to achieve breadth in the analysis of groundwater use and resource issues evident across the region, which can inform deeper contextual analyses at

national and sub-national scales in future. The countries chosen from Southeast Asia are: Cambodia, Indonesia, Lao People's Democratic Republic (PDR), Myanmar, Timor Leste and Vietnam. Those from the Pacific are: Kiribati, Papua New Guinea (PNG), Solomon Islands, Vanuatu.

2.1. Calculating Household Groundwater Reliance

To answer the first research question, data were collated from the WHO/UNICEF JMP and country sources, including utility information and sector reports. Information was sought separately for urban and rural areas because differences in their typical water supply profiles would be obscured in aggregated national datasets. The most recent complete dataset from each of the JMP country files was used to identify proportions of households using point-source groundwater, tap water or packaged water as their primary drinking water service. The study sought to identify the overall quantum of groundwater reliance, so it was concerned with identifying water source rather than whether the facilities were defined as safely managed, basic, limited or unimproved according to JMP definitions. Further, we acknowledge that a focus on primary drinking water services obscures the reality that many households use more than one water source across seasons and for different purposes [28]. However, given multiple water source use (MWSU) is an emerging area of research with limited consistent data available to date [28], our approach was to focus on the primary source of drinking water in line with the methodology used to track SDG target 6.1.

Country-specific data were used to assess the proportion of tap water and packaged water sourced from groundwater. In this analysis, both aquifer and spring sources were defined as groundwater given they are both subject to aquifer resource issues. Targeted internet searches were used to identify data on sources used for piped and packaged water. For our calculations data from online databases (e.g., utility benchmarking), peer-reviewed literature and sector reports were preferred. However, company websites and media reports were used when they were the only available sources, which was typically the case for water sources used for packaged water.

Collated data provided the basis for calculating the proportion of households using groundwater in each country. Where there was uncertainty, conservative choices were made to avoid overstating the extent of reliance. Additionally, when there was any doubt about the inclusion or exclusion of particular figures for a given country, a minimum or maximum estimate was calculated to show the range of uncertainty (these figures are shown in Supplementary Materials). Finally, initial calculations were shared with sector experts in case study countries to sense check the assumptions and logic used. The data sources and assumptions underlying the calculations for each case study country are described in full in Supplementary Materials.

In analyzing data from diverse sources, it was necessary to reconcile a mismatch in unit of analysis between drinking water and domestic water more broadly. JMP datasets focus on drinking water only (taking a user perspective), while country-specific information is typically more supplier-oriented, describing either sources of water for domestic supply generally (for both consumptive and non-consumptive purposes) or sources for supplying all users across domestic, industrial and commercial sectors. To address the potential for this mismatch to affect estimates of household groundwater reliance, we compared data on facilities used for drinking and non-drinking purposes where this information was available (e.g., in some census datasets) to assess the scale of difference.

2.2. Identifying Resource Concerns and Impacts on Household Water Supply

To identify resource concerns, we first undertook a literature review of current and emerging resource concerns. Academic and non-academic literature was identified through targeted searches in Google Scholar and Google's general search engine of 'groundwater' and the name of each case study country. Based on an initial scan of the most pertinent literature, a snowballing approach was used to identify further relevant documents. Advice on relevant documentation was also sought from sector

experts. Resource sustainability concerns identified from the document review were collated for each country and then considered across countries to build a picture of common themes and key differences.

To identify how groundwater resource concerns impact household services, we used the systems thinking technique of influence diagramming to explore the relationships between types of resource concerns and water services articulated with reference the human right to water. According to the human rights framework, water for personal and domestic uses must be available, safe, acceptable, accessible and affordable [29]. As a clear, comprehensive and globally endorsed conceptualization of household water requirements, the components of the right to water offered a helpful way of exploring the various ways resource issues can affect household water supply. We applied a systems thinking technique as a heuristic for exploring interconnections, given the value of this approach for engaging with complexity, reframing situations and enabling "thinking and acting in purposeful ways" [30]. Within systems thinking, influence diagrams are sense-making tools for exploring the multiple interconnections characteristic of complex systems [31], and represent a mental model of a problematic situation that can help identify actions to improve the situation [32]. They focus on 'influence' rather than causal relationships, and in doing so seek to identify networks of interconnection rather than root causes [31]. As part of broader systems thinking approaches, influence diagrams have been used in resource management to identify interactions between biophysical and 'soft' systems [33].

2.3. Limitations

The main limitation of this study relates to the availability and reliability of data on water resources linked to household uses. As described above, it was necessary to compile data from a wide variety of sources with sometimes inconsistent boundaries of analysis, and to make assumptions where information was not available. We addressed concerns about the validity of assumptions by triangulating from multiple information sources and seeking reviews of our draft workings from sector experts. While lack of data reliability is a limitation, it also underpins the value of the study in making a first assessment of household groundwater reliance in contexts where this information is not otherwise available at a national scale.

Across both data collection and literature review methods, the focus was primarily on English language material, which brings a risk of overlooking relevant information in other languages. While some data was sourced and translated through country contacts (for example, utility data for Vietnam and Indonesia), this was not consistently possible. In reviewing the status of groundwater resources, a focus on published English-language material also presents issues of possible bias, with a tendency in the literature to focus on locations within countries where issues have already been observed. This has the potential to obscure geographic diversity within countries, but it was a necessary trade-off in taking a multi-country perspective.

3. Results

3.1. Households Using Groundwater in Case Study Countries

Across the ten case study countries, an average of 66% of households in urban areas and 60% in rural areas were found to be using groundwater as their primary source of drinking water. Urban areas showed lower rates of household groundwater reliance in Cambodia (17%) and PNG (25%) and higher rates in Timor-Leste (93%), Indonesia (90%), Kiribati (90%), Vanuatu (86%), Lao PDR (80%) and Myanmar (72%). In rural areas, we found lower rates of groundwater reliance in Melanesian countries of PNG (22%), Solomon Islands (28%) and Vanuatu (34%) and the highest rate of reliance in the Micronesian atoll islands of Kiribati (95%). Southeast Asian case study countries Indonesia (92%), Timor-Leste (81%) and Myanmar (78%) were also found to have high rates of rural household groundwater dependence. Findings across all case study countries are summarised in Figure 1, with data sources and assumptions underlying the calculations described in full in Supplementary Materials.

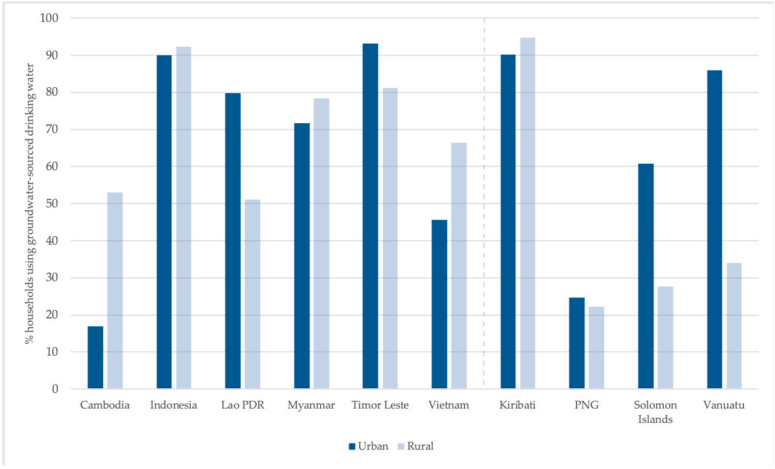

Figure 1. Proportion of households using groundwater as their primary source of drinking water in urban and rural areas across case study countries.

Groundwater-sourced drinking water is supplied to households in case study countries through a mix of point source facilities, piped systems and packaged water. The breakdown of facilities used across urban and rural areas is shown in Table 1 (with data sources and assumptions described in Supplementary Materials). Identifying the resources supplying piped and packaged water was important for urban areas, where the use of point-source groundwater is declining with the increasing use of tap and packaged water [1,27]. Case study countries where piped water in urban areas was found to be wholly or substantially drawn from groundwater included Solomon Islands, Vanuatu, Kiribati and Timor-Leste with 94%, 68%, 67% and 65% respectively of urban households using piped water drawn from groundwater sources. Countries where packaged water in urban areas was found to be wholly or substantially drawn from groundwater included Lao PDR, Indonesia and Myanmar, with 64%, 46% and 34% of households respectively using packaged water sourced from groundwater. In rural areas, point source facilities continue to be the primary form of groundwater supply across the region, and findings, therefore, reflect data on facilities used. Timor-Leste was the only country where piped groundwater (in the form of gravity-fed spring-sourced systems) formed a substantial proportion of piped supplies (38%). Smaller proportions of households using groundwater-sourced piped water were also identified in Indonesia (6%), Kiribati (6%) and Vietnam (5%). Packaged water formed part of the mix in rural Lao PDR (21%), Indonesia (16%), Vietnam (8%) and Myanmar (4%).

Table 1. Proportion of households using point-source, piped and packaged water sourced from groundwater in urban and rural areas.

	Urban % Households Using Groundwater-Sourced Drinking Water				**Rural % Households Using Groundwater-Sourced Drinking Water**			
	Point source	**Piped**	**Packaged**	**Total Urban**	**Point Source**	**Piped**	**Packaged**	**Total Rural**
Cambodia	13	4	0	**17**	50	0	0	**50**
Indonesia	38	6	46	**90**	71	6	16	**92**
Lao PDR	13	3	64	**80**	34	0	21	**55**
Myanmar	34	3	34	**72**	75	0	4	**78**
Timor Leste	28	65	0	**93**	43	38	0	**81**
Vietnam	17	17	12	**46**	53	5	8	**66**
Kiribati	23	67	0	**90**	89	6	0	**95**
PNG	5	20	0	**25**	22	0	0	**22**
Solomon Is.	3	58	0	**61**	28	0	0	**28**
Vanuatu	2	83	1	**86**	22	0	0	**22**

Moving from national proportions to identify numbers of people implicated, the analysis found that 79% of both urban and rural populations aggregated across case study countries used groundwater as their primary source of drinking water (346 of 437 million people). Figure 2 indicates the relative

numbers of people drinking groundwater in each case study country and shows the relationship between urban and rural groundwater reliance for each country. Indonesia had the highest groundwater-reliant population (more than 200 million) of the ten countries reviewed, far more than Vietnam (more than 55 million) and Myanmar (more than 40 million) in second and third place respectively. For most case study countries, rates of reliance on groundwater for drinking were reasonably comparable across urban and rural areas, with three notable exceptions: Vanuatu and the Solomon Islands, with much higher rates of urban groundwater reliance, and Cambodia where rural groundwater reliance was almost three times higher than urban. Looking at facilities used to supply groundwater, 219 million of the case study population used groundwater-based point source facilities (66 million in urban areas, 153 million in rural). Groundwater-sourced piped water supplied 25 million (14 million urban, 11 million rural) and groundwater-sourced packaged water supplied 102 million people (76 million urban, 26 million rural).

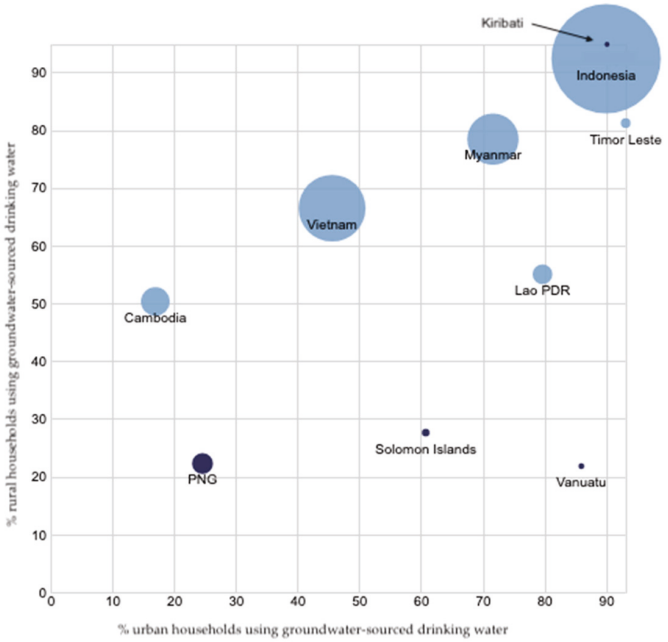

Figure 2. Proportion of urban and rural households using groundwater as their primary source of drinking water with associated relative populations across countries indicated by circle size.

3.2. Current and Emerging Groundwater Resource Concerns

Analysis of the context and concerns relating to groundwater resources in case study countries revealed a range of current and emerging issues related to both the quality and quantity of groundwater sources. Table 2 summarises issues identified in the literature for urban and rural areas in each of the ten case study countries. In urban areas, pollution from unsafe sanitation was the most commonly identified threat to groundwater quality in all case study countries. Depletion was an issue for countries with substantial urban groundwater reliance, resulting in dry season shortages in Timor-Leste, Kiribati and Myanmar and subsidence in large cities in Indonesia and Vietnam. In rural areas, hot spots were identified in Cambodia and Lao PDR where drawdown of groundwater levels was affecting accessibility for domestic supplies. Quality concerns in rural areas included saline intrusion in coastal areas (in Cambodia, Timor-Leste, Vietnam and Solomon Islands) and agriculture-related pollution (in Vietnam and Solomon Islands). Uncertainties and future pressures are also noted, with common themes across countries being: A lack of comprehensive data, increasing water demand, and resource risks related to predicted climate change impacts.

Influence diagramming based on this review of current and emerging groundwater resource concerns enabled exploration of the relationship between groundwater resource concerns and the

components of the human right to water, namely: Availability, quality, affordability, accessibility, and acceptability (Figure 3). In developing the diagram, our main interest was physical characteristics because the focus of the study is the physical aspects of resources and how they influence water services. The effects of a particular relationship depend on the situation. Therefore, the directions of the arrows in Figure 3 should not be taken as indications of positive or negative influences. Further, in line with systems thinking approaches, diagramming was undertaken to increase our understanding of system relationships rather than to reveal a 'truth' [31]. As such, for generating insights, the process of developing the diagram was as important as, or more important than, the diagram itself, which is inevitably a simplified representation of reality. Further, given the intent of this study was to explore the breadth of issues at a regional scale, the diagram represents a generalized model that can guide the scope and focus of local-scale analyses.

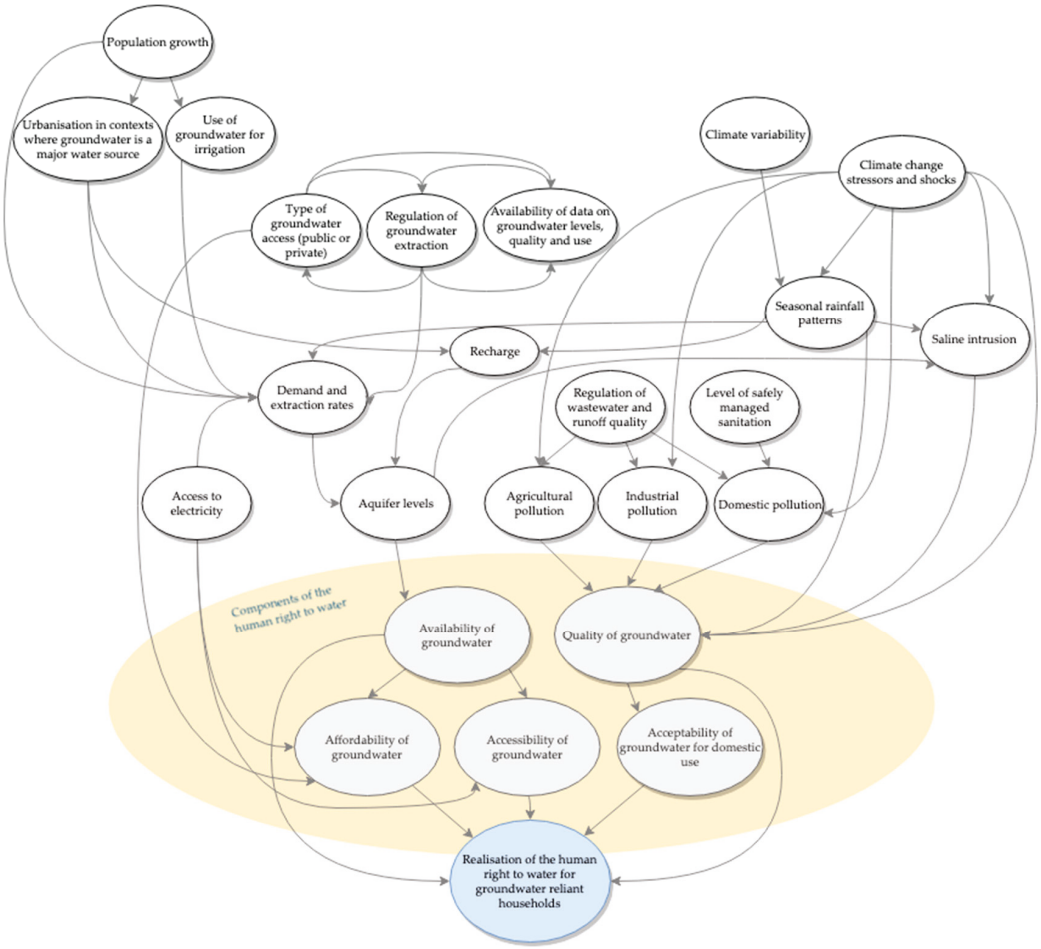

Figure 3. Influence diagram exploring how resource dynamics affect components of the human right to water for groundwater-reliant households. Arrows should be read as 'influences', rather than implying causation. Note that important factors shaping groundwater resources and their access, such as soil type and geology, are held constant, and therefore, not included in the diagram.

Table 2. Synthesis of literature on groundwater resource concerns in case study countries.

	Current Issues in Urban Areas	Current Issues in Rural Areas	Uncertainties and Future Pressures
Cambodia	Urban wastewater pollution has been identified as a threat to groundwater quality, with studies identifying bacterial contamination [34].	Rapid growth in use of groundwater for irrigation in the Mekong threatens household groundwater use [35]. Over-extraction may contribute to: Saline intrusion [36], land subsidence and exacerbation of naturally occurring arsenic contamination [35].	Comprehensive data not available but a study is underway [37]. Cambodia Wellmap database is thought to lack critical information and be out of date [34]. Threats include industrial pollution, increasing agricultural use and saline intrusion [37]. Increased use of agricultural and domestic electric pumps can increase extraction rates [35].
Indonesia	Over-extraction and pollution are impacting groundwater across urban Indonesia [38,39]. In Jakarta, observed issues include pollution from wastewater as well as flooding, subsidence and salinization in northern coastal areas [40,41]. In Yogyakarta city, leaching from on-site sanitation has caused pollution of drinking water sources [42].	Much less literature on rural groundwater, likely reflecting generally fewer resource concerns. One study in the lowlands of Sumatra found arsenic concentrations exceeding drinking water guidelines in 12 of 97 tubewells [43].	Self-supply from groundwater for domestic use is common, though is unregulated [44]. Deep groundwater resources are increasingly used in industrial and service sectors and exploited at an unsustainable rate [24].
Lao PDR	Deep wells in Vientiane found to be saline and unsuitable for domestic use [45]. Sanitation-related contamination identified, but data is sparse [46]. Beyond Vientiane, limited information on groundwater resources in urban areas.	Villages in northern Champassak province have experienced lowering of water table depths beyond the reach of average domestic wells [47].	No serious widespread issues reported, but "preventative protection" called for due to increasing demand [48]. Demand will increase due to population growth, changed agricultural practices [49] and climate change driving surface water shortages [50]. Limited data available to support sustainable management [49].
Myanmar	Yangon groundwater experiencing increasing pressure due to population growth, urbanization and land cover change. Extraction rates for domestic use alone exceed recharge [51]. The water is thought to be potable, but data to confirm quality is lacking and there are reported cases of tubewells being abandoned due to saline intrusion [51].	A study of central Myanmar's Dry Zone [52] reports the existence of hundreds of thousands of tubewells and dugwells but there is no database to support monitoring and management and there is a lack of regulation. Over-exploitation has resulted in water level drawdown and deterioration of water quality [52].	Pavelic et al. explore the potential for groundwater to support agricultural expansion in the Dry Zone, finding rates of replenishment lower than expected [53]. Rigorous assessment of groundwater interventions, and management that protects groundwater for community uses and the environment are needed. Climate change impacts are expected to include a lowering of the shallow groundwater table and saline intrusion, particularly in coastal areas [54].
Timor-Leste	Population growth and urbanization have led to dry season shortages in Dili aquifer [55]. Shallow aquifers in urban areas, which are the primary source of water for households, often receive untreated wastewater [56] and have been found to commonly contain elevated concentrations of dissolved solids and microbiological contaminants [57].	Groundwater is currently high quality, except where seawater intrusion is a problem [58], but testing has revealed bacteriological contamination of unprotected sources due to animal and domestic waste [56].	There is a lack of knowledge about groundwater sustainability, but climate change, reduced water availability and growing demand are anticipated to increase pressure on groundwater [58]. Climate change is expected to lead to saline intrusion in coastal centers [56]. There is a lack of information about the density of boreholes and volumes of water extracted in urban areas, though their use is expected to grow due to underperforming piped water services [56].

Table 2. *Cont.*

	Current Issues in Urban Areas	Current Issues in Rural Areas	Uncertainties and Future Pressures
Vietnam	Aquifers supplying Hanoi and Ho Chi Minh City are considered to be over-exploited and polluted [59,60] and in Ho Chi Minh City extraction rates are reportedly five times higher than recharge [61]. Groundwater levels in Can Tho City in the Mekong Delta are dropping by up to half a meter each year [62].	Shallow groundwater resources in the Mekong are characterized by salinization and pollution (likely due to domestic wastewater), causing increased exploitation of deeper aquifers (up to 400–50 m) [62]. Indications of contamination from pesticides: 5 of 22 groundwater samples in Mekong Delta found to contain levels exceeding European Commission recommended concentrations [63].	The impacts of climate change on groundwater are uncertain. Modeling for a coastal aquifer in central Vietnam projected a decrease in groundwater resources, contrary to assumptions that increased rain would result in increased recharge [64]. Reductions in recharge in the short, medium and longer term have also been projected in the Mekong Delta, with a resultant decline in groundwater levels and storage [65].
Kiribati	A study of the freshwater lens on Bonriki Island [66] found pumping is causing sustained contraction. Pollution of shallow freshwater lenses under human settlements is a serious concern given shallow permeable soils and short travel times to the water table, with the result that groundwater in large areas of urban Tarawa is no longer potable [67].	Studies on outer islands have found E. coli bacteria in more than 90% of sampled wells, related to proximity to toilets and other sources of contamination [68,69].	Kiribati extremely vulnerable to climate change due to its low average altitude (2 m above sea level). Quantity and quality of groundwater is likely to be affected by both variations in rainfall and sea level rise [70]. A regional vulnerability assessment of Pacific Island groundwater and future climates [71] found Kiribati is one of three countries with the greatest number of islands most vulnerable to low rainfall.
Papua New Guinea	Monitoring of groundwater very poor and little is known about the situation in many provincial towns and almost all district towns [72]. Contamination from onsite wastewater systems is a concern for urban centers where groundwater is the source of utility supplies including Lae, Kimbe and Kavieng [73].	Groundwater still considered to be the safest and most reliable source of water, and is the only reliable source on outer islands and in mainland coastal communities [74].	PNG has abundant surface water resources (hence lower household groundwater reliance) and groundwater resources have not yet been developed at scale. However, there is evidence that groundwater is increasingly being used due to its high quality and reliability [75]. Changing agricultural practices and the increasing use of artificial fertilizers, pesticides, herbicides and palm oil mill effluent (for irrigation) pose a threat to groundwater and surface water quality [73].
Solomon Islands	Poor sanitation has led to suspected cases of groundwater contamination in Honiara, and pollution is driving a shift from groundwater to rainwater [76]. Contamination of groundwater from sewage outfalls, septic tanks, unserved informal settlements and a septage disposal facility has also been reported [77].	Salinization of groundwater is increasing in coastal villages and atoll islands due to sea water intrusion during extreme weather events or as a general trend) [78]. Quality of ground-water and surface water threatened by chemicals and fertilizers used for palm oil development on Guadalcanal plains [79].	An assessment of Pacific Is. groundwater and future climates [71] found Solomon Is. to be one of three countries with the greatest number of islands most vulnerable to low rainfall, and one of three countries with the greatest number of islands most vulnerable to mean sea-level rise. As well as sea level rise, residential development and mining have been identified as future threats to groundwater quality [74].
Vanuatu	Groundwater quality in Port Vila and Luganville generally good, but poor sanitation is an acknowledged threat and groundwater levels are decreasing while pumping is increasing [78].	No concerns evident in literature, and a study across 10 islands found groundwater to be a safer source than rainwater in microbial terms [80].	A comprehensive and accurate database of the quality, quantity and location of water resources does not yet exist [81]. Increasing use of motorized pumps [80] may impact extraction volumes.

The process of developing the influence diagram generated three material insights about the groundwater resource situation and how it affects water service delivery. Firstly, data availability, regulation of groundwater extraction and type of groundwater access are highly interconnected, and therefore, warrant particular consideration. Across the case study countries, poor data was identified as a critical gap that prevents effective resource management and regulation. The type of groundwater access is pivotal in this picture, with household self-supply or service provider access and commercial access (e.g., for packaged water) presenting different challenges for monitoring and regulation compared with publicly managed systems. Secondly, influences on groundwater quality arise from domestic, agricultural, industrial and natural processes, indicating the need for a cross-sectoral approach to addressing quality concerns. Thirdly, climate-related pressures arising from natural variability and climate change emerged as being connected with many other system processes, and they, therefore, demand attention with a view to building resilience for households relying on groundwater for drinking.

4. Discussion

The two bodies of information explored in this study—household reliance on groundwater for drinking supplies and groundwater resource concerns—are both foundational for sustainable water service delivery. Bringing these analyses together, this discussion explores implications for WASH professionals across three themes of (i) data gaps and monitoring, (ii) regulatory priorities for sustainable services, and (iii) building resilience to emerging threats. Points raised in this discussion reflect an inductive analytical approach, with a focus on those insights most relevant to WASH sector scholars and practitioners. As such, the focus was on interpreting the findings to inform how water services are conceptualized, planned and managed. We also note that although pollution from unsafe sanitation emerged as a common threat to groundwater resources across case study countries, there is substantial ongoing work in the WASH sector focused on progressing safe sanitation [82,83], so we focus this discussion on other implications from the analysis. To contextualize the discussion within current WASH sector framing, where relevant, we draw on the service delivery approach framework of three institutional levels [18,19] to identify implications for national WASH agencies, service authorities and service providers.

4.1. Data Gaps and Monitoring

Situating findings from this analysis with reference to academic literature revealed limited research addressing rates of groundwater use for drinking, with available figures often presented as background information rather than empirical findings. The overall proportion of the aggregated population from case study countries found to be using groundwater for drinking (79%) is higher than figures reported in the literature, which estimate half of the global population to be reliant on groundwater for drinking [2,5,6,84]. Regional studies estimate that a third of all people in Asia rely on groundwater for drinking [85,86]. This is substantially different from the 79% found to be groundwater-reliant across case study countries in this paper. Other than the abovementioned global and regional estimates, there is limited research addressing rates of groundwater use for drinking [6]. This makes it challenging to benchmark findings and situate case study countries within a broader set, highlighting a need for further research to validate the initial estimates presented in this paper and to extend geographic reach.

In urban areas, global monitoring data indicates a trend away from the use of point source facilities to greater use of piped and packaged water [1,27], with a consequent increasing knowledge gap in standardized monitoring about which water resources are used in those cases. Foster et al. [14] estimate that more than 1.5 billion urban dwellers worldwide currently rely on groundwater, which represents more than three-quarters of the global urban population. Comparable rates of urban reliance were also identified in this study. However, systematic, comprehensive and reliable data is acknowledged to be lacking [14,87] and further work is needed to validate both total estimates of urban groundwater reliance and how these reflect diversity across and within countries. This is

important given that groundwater use in cities is forecast to increase due to the pressures of population growth, increasing per capita water use, reduced surface water security (related to climate change) and higher ambient temperatures [14]. Improving our understanding of the extent to which groundwater resources are relied upon is particularly critical for small towns and urbanizing rural centers, where authorities are faced with complex planning challenges and professionalized utilities have not yet established [88]. Studies in Africa identify a need for urban water suppliers to better coordinate with agencies responsible for groundwater resource management [89,90]. In Southeast Asian and Pacific countries, urban water service providers and authorities could similarly play a more active role in debates and planning for sustainable groundwater resource management.

For WASH sector professionals, particularly at the national level, there is a need to collate information about the groundwater resource implications of packaged water given its status as a growing source of drinking water [27] including in countries reviewed in this study (particularly in Lao PDR, Indonesia, Myanmar and Vietnam). While studies have explored the public health implications of packaged drinking water [91], its classification within global monitoring standards [27], and equity and power dynamics [92], sustainability implications have received only limited attention and focused on plastic waste [93,94] rather than on the relevant water resources. In this study, when compiling figures on groundwater use, packaged water was typically the most difficult form of use to identify and quantify. More systematic and rigorous research into the sources and distribution of packaged water is needed to track what is emerging to be an important part of the global water supply picture. Taking an equity perspective will be critical, given that the resources supplying packaged water can be distant from the locations where it is consumed, and given that the associated risks and benefits can also be widely distributed across different populations.

The use of multiple water sources for different household uses is another critical consideration for understanding groundwater use, given that drinking water is just one (albeit critical) form of household water use. Households in low and middle income countries commonly obtain water from a range of sources, as evidenced by a growing body of literature on multiple water source use (MWSU) [28,80]. In our case study countries, where data allowed, we investigated sources of water used for drinking and for other domestic purposes to assess how this might affect interpretations of groundwater use. In some cases, for example, in countries where the use of packaged water for drinking was high (Lao PDR, Myanmar, Indonesia), the volume of groundwater used was less than the volumes of other domestic sources (e.g., tap water was sourced from a mix of surface and groundwater). In other cases, we found that if we based our analysis on primary drinking sources alone, we were likely to underestimate the importance of groundwater. In rural Vanuatu, for example, a 2016 census included questions on both main and alternative drinking sources. The use of groundwater was found to be substantially greater (by a factor of three) when the use of groundwater as a secondary source was included [95]. In Lao PDR, a study of rural household groundwater use found that some households used point-source groundwater for non-drinking domestic purposes in situations where reticulated water was used for drinking [96]. In atoll islands of the Solomon Islands, an analysis of water resources management found that groundwater is used for washing but not drinking [73]. In Indonesia, anecdotal evidence suggests households use bottled water for cooking as well as drinking and piped water for washing and cleaning [97], which aligns with MWSU research indicating a positive correlation between sources of water for consumptive and non-consumptive uses [98]. In future work looking at groundwater use, it will be important to consider the MSWU picture, and build on the growing empirical research in this area.

Moving from groundwater use to resource management, a lack of sufficient data to inform appropriate groundwater management was identified across case study countries, reflecting a region-wide gap in groundwater monitoring systems and data [99]. With data and information acknowledged to be critical for effective groundwater governance [15], there is an urgent need to invest in monitoring and improve the quantity and quality of groundwater information, including through approaches such as remote sensing [99]. For the WASH sector, there is an opportunity for service

authorities and providers to play a direct role monitoring the resources on which they rely, and to proactively coordinate (for information sharing and strategy development) with agencies responsible for groundwater resource management.

4.2. Regulatory Priorities for Sustainable Services

Informed by the analysis of groundwater use, resource concerns and system interactions, we identify regulatory priorities for the WASH sector relating to self-supply situations, monitoring and management of service providers, and agricultural groundwater extraction. These respond to acknowledged data gaps (as discussed above) and interconnections between data availability, type of groundwater access (public or private) and regulation of abstraction (as identified in systems diagramming).

In the WASH sector, self-supply is seen as a viable strategy for accelerating access to safely managed water when treated, and supported, as a formal service delivery model [19,100,101]. However, risks have been identified for groundwater-sourced systems, including the potential for privately-financed wells used for both drinking and productive activities to result in a drawdown of groundwater levels [100], and the invisibility of abstraction from, and potential pollution of, aquifers [89]. Much of the documented experience with supported self-supply has focused on Africa and South Asia [102], and there is a need to explore how research to date relates to Southeast Asian and Pacific contexts. In case study countries where the proportion of households using point-source groundwater was high, studies have reported regulatory challenges because access of this type is commonly on-plot, self-financed and difficult to monitor. For example, research in Vietnam's Can Tho Province found that much more of the groundwater used by households came from private shallow tube-wells than from utility-managed groundwater plants [62]. In Indonesia's capital Jakarta, unregistered private abstraction continues apace despite the institution of regulatory approaches, such as differential tariffs over the past 20 years [40]. Self-supply is also widespread in rural Cambodia: Of more than 35,000 groundwater point sources included in the WellMap database that include ownership information, 83% are described as 'private', increasing to 91% in areas with elevated arsenic. Although self-supplied water services are (by definition) managed by individual households, responses from both national agencies and service authorities are still needed to ensure the safety and sustainability of groundwater-based self-supply systems.

Second, regulatory frameworks must evolve to ensure adequate monitoring and management of those abstracting and supplying groundwater to safeguard against unsustainable abstraction and use. One example is the case of private sector providers, which have particular incentives to maximize volumes of water sold. Small-scale private water suppliers are increasingly supported by development agencies [103] and some governments, such as in Vietnam [104] and Cambodia [105]. Research in Vietnam found private water providers in rural areas seeking to increase customer demand for water as a strategy to improve business viability, but without consideration of sustainable abstraction rates [104]. These issues are not only relevant to private providers and monitoring and regulation are critical irrespective of service delivery model. For example, a study in Indonesia's coastal city of Semarang identified a need for policy and tariff structures that promote groundwater conservation given the prevalence of community-based providers supplying artesian water (under both commercial and non-commercial models) [106]. Water service delivery agencies, particularly at the service authority level, can play a role monitoring and regulating the operations of service providers, including ensuring coordination with regulatory requirements for abstraction which may be separately governed by water resource agencies.

Third, it is important that agricultural groundwater use is regulated to ensure that domestic supplies are protected. This is evidenced by the situation in south-eastern Cambodia, where rapidly increasing abstraction for irrigation threatens to make groundwater inaccessible to standard household pumps within fifteen years [35]. A regulatory response involving the preservation of groundwater for low-volume, high-priority uses (such as domestic supply) and ensuring agricultural development is

shaped by available surface water supplies has been proposed [35]. Calls to preserve groundwater for domestic uses and replace other uses with surface water wherever possible have also been made with reference to Lao PDR [49] and Vietnam [62]. While agricultural groundwater use is not within the purview of ministries governing water services delivery, WASH agencies can proactively advocate for prioritization of domestic supplies within water allocation planning at national and sub-national scales.

4.3. Building Resilience to Emerging Threats

Groundwater threats arising from climate variability and climate change were commonly identified in the literature across reviewed countries, indicating a need to strengthen the resilience of groundwater-supplied households. Particular concerns were raised in the climate-vulnerable Pacific Islands of Kiribati and Solomon Islands [71] and coastal areas in Southeast Asia in Myanmar [54], Timor-Leste [56] and Vietnam [64,65]. Compared with other water resources, groundwater is considered less likely to be affected by climate change and it is, therefore, believed to be positioned to form the basis of adaptation programs [3]. However there remains considerable uncertainty about the actual relationship between groundwater and climate [107], and the resilience of groundwater-sourced household supplies to climate-related hazards varies depending on aquifer depth and the quality of system construction [108,109]. Further, climate-related pressures can indirectly affect groundwater, as revealed in diagramming conducted in this study. For example, a shift in demand away from climate-affected water sources to more resilient groundwater sources can ultimately influence aquifer levels. Taylor et al. [107] identify this threat of overexploitation, forecasting rises in groundwater abstraction in absolute terms and as a proportion of total water withdrawals. For WASH institutions, strategies which rely on groundwater as the basis of adaptation pathways need to be carefully considered in context, along with broader approaches to building resilience, such as being identified in both urban and rural WASH literature [110,111].

A final consideration relates to emerging contaminants and their potential to pollute groundwater sources that supply drinking water. Pollution from greywater or agricultural and industrial sectors was not a strong theme in the reviewed literature, with only three countries (Vietnam, Papua New Guinea and Solomon Islands) identifying particular areas affected by pesticide and fertilizer contamination [63,73,79]. However, this area requires attention, given monitoring systems are poorly equipped to identify the expanding range of contaminants and their impacts [5,112,113]. Global reviews have found groundwater pollution at environmentally significant concentrations from a range of pharmaceutical and personal care products (PPCPs), industrial compounds and lifestyle compounds, such as caffeine [112,113]. PPCPs have been found to be difficult to remove from groundwater, indicating a need to control their release from the source [112]. There are implications here for WASH institutions at all levels, with a need for leadership at the national level to ensure emerging contaminants are on the agenda in cross-sectoral forums and inform future service delivery frameworks governing groundwater-based systems.

5. Conclusions

This study has established a baseline of populations using groundwater for drinking in ten Southeast Asian and Pacific nations and identified the breadth of resource issues that must be considered, analyzed and planned for as part of efforts to expand and sustain water services. The results of this study confirm groundwater to be a critical source of drinking water for households in case study countries, with comparable rates of households using groundwater as their primary source of drinking water in urban (66%) and rural (60%) areas. Our findings point to higher rates of reliance than commonly reported in the literature, with 79% of the total population across case study countries found to be drinking groundwater. Our review of literature on groundwater resource concerns across case study countries found common concerns related to: Pollution from unsafe sanitation, depletion leading to dry season shortages and subsidence, and both vulnerabilities and uncertainties about future climate-related pressures and threats.

Systems diagramming provided insight on the relationships between resource concerns and household water services, which generated implications relevant to WASH institutions at national, service authority and service provider levels. These include priorities for further data collation and analysis, a need to review regulatory approaches that address different models of groundwater-based service provision (including both private and public), and considerations for strengthening the resilience of water services.

In taking a multi-country approach, this paper provides comparative data and captures the diversity of experiences, identifying resource themes and building a generalized model of system interactions. This can inform global and local action and advocacy around the risks and concerns raised, as well as inform the scope and focus of future studies within relevant countries at local scales. These can, in turn, underpin strengthened engagement in groundwater resource management by those involved in water service delivery, and ultimately strengthen the sustainability of groundwater-based water services.

Supplementary Materials: The following is available online at http://www.mdpi.com/2073-4441/11/8/1605/s1, Appendix A Data sources and assumptions for groundwater use calculations.

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References

1. WHO/UNICEF. Progress on Drinking Water, Sanitation and Hygiene: 2017 Update and SDG Baselines. 2017. Available online: https://www.who.int/mediacentre/news/releases/2017/launch-version-report-jmp-water-sanitation-hygiene.pdf (accessed on 14 December 2018).
2. Velis, M.; Conti, K.I.; Biermann, F. Groundwater and human development: Synergies and trade-offs within the context of the sustainable development goals. *Sustain. Sci.* **2017**, *12*, 1007–1017. [CrossRef]
3. Howard, G.; Calow, R.; Macdonald, A.; Bartram, J. Climate change and water and sanitation: Likely impacts and emerging trends for action. *Annu. Rev. Environ. Resour.* **2016**, *41*, 253–276. [CrossRef]
4. Guppy, L.; Uyttendaele, P.; Villholth, K.G.; Smakhtin, V. *Groundwater and Sustainable Development Goals: Analysis of Interlinkages*; UNU-INWEH Report Series, Issue 04; United Nations University Institute for Water; Environment and Health: Hamilton, ON, Canada, 2018.
5. Margat, J.; van der Gun, J. *Groundwater Around the World: A Geographic Synopsis*; CRC Press Taylor & Francis Group: Boca Raton, FL, USA, 2013; 376p.
6. Giordano, M. Global Groundwater? Issues and Solutions. *Annu. Rev. Environ. Resour.* **2009**, *34*, 153–178. [CrossRef]
7. Molle, F.; López-Gunn, E.; Van Steenbergen, F. The local and national politics of groundwater overexploitation. *Water Altern.* **2018**, *11*, 445–457.
8. Foster, S.; Chilton, J.; Nijsten, G.; Richts, A. Groundwater—A global focus on the 'local resource'. *Curr. Opin. Environ. Sustain.* **2013**, *5*, 685–695. [CrossRef]
9. Gleeson, T.; Wada, Y.; Bierkens, M.F.P.; van Beek, L.P.H. Water balance of global aquifers revealed by groundwater footprint. *Nature* **2012**, *488*, 197–200. [CrossRef] [PubMed]
10. Steffen, W.; Richardson, K.; Rockstrom, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, S.R.; de Vries, W.; de Wit, C.A.; et al. Planetary boundaries: Guiding human development on a changing planet. *Science* **2015**, *347*. [CrossRef] [PubMed]
11. Bogardi, J.J.; Fekete, B.M.; Vörösmarty, C.J. Planetary boundaries revisited: A view through the "water lens". *Curr. Opin. Environ. Sustain.* **2013**, *5*, 581–589. [CrossRef]

12. Bradley, D.D.J.; Bartram, J.K.J. Domestic water and sanitation as water security: Monitoring, concepts and strategy. *Philos. Trans. A. Math. Phys. Eng. Sci.* **2013**, *371*, 20120420. [CrossRef]
13. Carrard, N.; Willetts, J. Environmentally sustainable WASH? Current discourse, planetary boundaries and future directions. *J. Water Sanit. Hyg. Dev.* **2017**, *7*, 209–228. [CrossRef]
14. Foster, S.; Hirata, R.; Misra, S.; Garduño, H. Sustainable Groundwater Management: Contributions to Policy Promotion. In *Urban Groundwater Use Policy: Balancing Benefits and Risks in Developing Nations 2010*; The World Bank: Washinton, DC, USA, 2010; Available online: http://documents.worldbank.org/curated/en/471001468159609056/Urban-groundwater-use-policy-balancing-the-benefits-and-risks-in-developing-nations (accessed on 14 December 2018).
15. Megdal, S.B. Invisible water: The importance of good groundwater governance and management. *NPJ Clean Water* **2018**, *1*, 15. [CrossRef]
16. Hadwen, W.L.; Powell, B.; MacDonald, M.C.; Elliott, M.; Chan, T.; Gernjak, W.; Aalbersberg, W.G.L. Putting WASH in the water cycle: Climate change, water resources and the future of water, sanitation and hygiene challenges in Pacific Island Countries. *J. Water Sanit. Hyg. Dev.* **2015**, *5*, 183–191. [CrossRef]
17. UN Water/WHO Global Analysis and Assessment of Sanitation and Drinking-Water (GLAAS) 2018/2019 Informational Modules: Introduction to GLAAS. Available online: https://www.who.int/water_sanitation_health/monitoring/investments/module1-introduction-to-glaas-2018.pdf (accessed on 19 May 2019).
18. World Bank. *Sustainability Assessment of Rural Water Service Delivery Models: Findings of a Multi-Country Review*; World Bank: Washington, DC, USA, 2017.
19. Moriarty, P.; Smits, S.; Butterworth, J.; Franceys, R. Trends in rural water supply: Towards a service delivery approach. *Water Altern.* **2013**, *6*, 329–349.
20. Brikké, F.; Vairavamoorthy, K. Managing Change to Implement Integrated Urban Water Management in African Cities. *Aquat. Procedia* **2016**, *6*, 3–14. [CrossRef]
21. Barron, N.J.; Kuller, M.; Yasmin, T.; Castonguay, A.C.; Copa, V.; Duncan-Horner, E.; Gimelli, F.M.; Jamali, B.; Nielsen, J.S.; Ng, K.; et al. Towards water sensitive cities in Asia: An interdisciplinary journey. *Water Sci. Technol.* **2017**, *76*, 1150–1157. [CrossRef] [PubMed]
22. Bichai, F.; Cabrera Flamini, A. The Water-Sensitive City: Implications of an urban water management paradigm and its globalization. *Wiley Interdiscip. Rev. Water* **2018**, *5*, e1276. [CrossRef]
23. WWAP (United Nations World Water Assessment Programme)/UN-Water. *The United Nations World Water Development Report 2018: Nature-Based Solutions for Water*; UNESCO: Paris, France, 2018.
24. International Water Association. *Principles for Water Wise Cities*, 2nd ed.; International Water Association: London, UK, 2016; Available online: https://iwa-network.org/wp-content/uploads/2016/08/IWA_Brochure_Water_Wise_Cities.pdf (accessed on 19 May 2019).
25. Howard, K.W.F. Sustainable cities and the groundwater governance challenge. *Environ. Earth Sci.* **2015**, *73*, 2543–2554. [CrossRef]
26. Foster, S.; Sage, R. Groundwater science in water-utility operations: Global reflections on current status and future needs. *Hydrogeol. J.* **2017**, *25*, 1233–1236. [CrossRef]
27. Vedachalam, S.; MacDonald, L.H.; Omoluabi, E.; OlaOlorun, F.; Otupiri, E.; Schwab, K.J. The role of packaged water in meeting global targets on improved water access. *J. Water Sanit. Hyg. Dev.* **2017**, *7*, 369–377. [CrossRef]
28. Elliott, M.; Foster, T.; MacDonald, M.C.; Harris, A.R.; Schwab, K.J.; Hadwen, W.L. Addressing how multiple household water sources and uses build water resilience and support sustainable development. *NPJ Clean Water* **2019**, *2*. [CrossRef]
29. UN Special Rapporteur on the Human Right to Safe Drinking Water and Sanitation. In *Realising the Human Rights to Water and Sanitation: A Handbook by the UN Special Rapporteur*; Office of the United Nations High Commissioner for Human Rights: Geneva, Switzerland, 2014; Available online: https://www.ohchr.org/en/issues/waterandsanitation/srwater/pages/handbook.aspx (accessed on 19 May 2019).
30. Huutoniemi, K.; Willamo, R. Thinking Outward: Heuristics for Systemic Understanding of Environmental Problems. In *Transdisciplinary Sustainability Studies: A Heuristic Approach*; Huutoniemi, K., Tapio, P., Eds.; Routledge: New York, NY, USA, 2014; pp. 23–49.
31. Armson, R. *Growing wings on the way: Systems thinking for messy situations*; Triarchy Press: Devon, UK, 2011; 338p.

32. Checkland, P.; Poulter, J. Soft Systems Methodology. In *Systems Approaches to Managing Change: A Practical Guide*; Reynolds, M., Holwell, S., Eds.; Springer-Verlag: London, UK, 2010; pp. 191–242.
33. Bosch, O.J.H.; King, C.A.; Herbohn, J.L.; Russell, I.W.; Smith, C.S. Getting the big picture in natural resource management—Systems thinking as 'method' for scientists, policy makers and other stakeholders. *Syst. Res. Behav. Sci.* **2007**, *24*, 217–232. [CrossRef]
34. AEC. *Water Infrastructure Study: Rapid Assessment of Existing Groundwater Studies and Groundwater Use in Cambodia*; Advancing Engineering Consultants: Phnom Penh, Cambodia, 2016.
35. Erban, L.E.; Gorelick, S.M. Closing the irrigation deficit in Cambodia: Implications for transboundary impacts on groundwater and Mekong River flow. *J. Hydrol.* **2016**, *535*, 85–92. [CrossRef]
36. WaterAid/British Geological Survey. *Groundwater Quality: Cambodia*; British Geological Survey: London, UK, 2016; Available online: http://www.bgs.ac.uk/downloads/start.cfm?id=3346 (accessed on 16 August 2018).
37. Sophally, S. Groundwater Resources in Cambodia. Institute for Global Environmental Strategies: Japan. 2011. Available online: https://www.iges.or.jp/en/natural-resource/groundwater/PDF/activity20110602/S1-3_Mr.Sok-Sophally_GW_Cambodia.pdf (accessed on 16 August 2018).
38. Asian Development Bank. *Indonesia Country Water Assessment*; Asian Development Bank: Mandaluyong, Philippines, 2016; ISBN 978-92-9257-360-7.
39. Tirtomihardjo, H. Groundwater basins in Indonesia and their potency. In Proceedings of the Asia Pacific Water Forum (APWF) Regional Water Knowledge Hub for Groundwater Management Launch Meeting, Bankok, Thailand, 2–3 June 2011.
40. Furlong, K.; Kooy, M. Worlding water supply: Thinking beyond the network in Jakarta. *Int. J. Urban Reg. Res.* **2017**, *41*, 888–903. [CrossRef]
41. Shaad, K.; Burlando, P. Monitoring and modelling of shallow groundwater dynamics in urban context: The case study of Jakarta. *J. Hydrol.* **2018**, in press. [CrossRef]
42. Cronin, A.A.; Odagiri, M.; Arsyad, B.; Nuryetty, M.T.; Amannullah, G.; Santoso, H.; Darundiyah, K.; Nasution, N.A. Piloting water quality testing coupled with a national socioeconomic survey in Yogyakarta province, Indonesia, towards tracking of Sustainable Development Goal 6. *Int. J. Hyg. Environ. Health* **2017**, *220*, 1141–1151. [CrossRef] [PubMed]
43. Winkel, L.; Berg, M.; Stengel, C.; Rosenberg, T. Hydrogeological survey assessing arsenic and other groundwater contaminants in the lowlands of Sumatra, Indonesia. *Appl. Geochem.* **2008**, *23*, 3019–3028. [CrossRef]
44. Hadipuro, W. Indonesia's water supply regulatory framework: Between commercialisation and public service? *Water Altern.* **2010**, *3*, 475–491.
45. JICA. *The Lao People's Democratic Republic the Preparatory Survey on Vientiane Capital Water Supply Expansion Project Final Report*; Japan International Cooperation Agency (JICA): Tokyo, Japan, 2015.
46. Noda, K.; Makino, T.; Kimura, M.; Douangsavanh, S.; Keokhamphui, K.; Hamada, H.; Iida, T.; Oki, K. Domestic water availability in Vientiane, Lao PDR. *J. Agric. Meteorol.* **2017**, *73*, 45–50. [CrossRef]
47. Vote, C.; Eberbach, P.; Zeleke, K.; Inthavong, T.; Lampayan, R.; Vongthilath, S. The use of groundwater as an alternative water source for agricultural production in southern Lao PDR and the implications for policymakers. In *A Policy Dialogue on Rice Futures: Rice-Based Farming Systems Research in the Mekong Region, Phnom Penh, Cambodia, 7–9 May 2014*; ACIAR Proceeedings No. 142; Australian Centre for International Agricultural Research: Canberra, Australia, 2014; pp. 103–115.
48. Bussard, T. *SDC Guideline for Sustainable Groundwater Resource Management*; Swiss Agency for Development and Cooperation: Bern, Switzerland, 2016.
49. Viossanges, M.; Pavelic, P.; Rebelo, L.; Lacombe, G.; Sotoukee, T. Regional mapping of groundwater resources in data-scarce regions: The case of Laos. *Hydrology* **2017**, *5*, 2. [CrossRef]
50. Bai, B.; Cheng, Y.P.; Jiang, Z.C.; Zhang, C. Climate change and groundwater resources in Lao PDR. *J. Groundw. Sci. Eng.* **2017**, *5*, 53–58.
51. Khaing, K.K. Groundwater environment in Yangon, Myanmar. In *Groundwater Environment in Asian Cities: Concepts, Methods and Case Studies*; Shrestha, S., Pandey, V., Thatikonda, S., Shivakoti, B., Eds.; Butterworth-Heinemann: Oxford, UK, 2016; pp. 317–335. ISBN 9780128031667. [CrossRef]
52. Drury, L.W. *Hydrogeology of the Dry Zone—Central Myanmar*; Australian Water Partnership: Canberra, Australia, 2017; ISBN 9781921543333.

53. Pavelic, P.; Sellamuttu, S.S.; Johnston, R.; McCartney, M.; Sotoukee, T.; Balasubramanya, S.; Suhardiman, D.; Lacombe, G.; Douangsavanh, S.; Joffre, O.; et al. *Integrated Assessment of Groundwater Use for Improving Livelihoods in the Dry Zone of Myanmar*; Research Report 164; International Water Management Institute (IWMI): Colombo, Sri Lanka, 2015.
54. Zaw, T.; Than, M.M. Climate change and groundwater resources in Myanmar. *J. Groundw. Sci. Eng.* **2017**, *5*, 31–43.
55. Pinto, D.; Shrestha, S. Groundwater Environment in Dili, Timor-Leste. *Groundw. Environ. Asian Cities Concepts Methods Case Stud.* **2016**, 263–286. [CrossRef]
56. World Bank. *Timor-Leste Water Sector Assessment and Roadmap about the Water Global Practice*; World Bank: Washington, DC, USA, 2018.
57. Ximenes, M.; Duffy, B.; Faria, M.J.; Neely, K. Initial observations of water quality indicators in the unconfined shallow aquifer in Dili City, Timor-Leste: Suggestions for its management. *Environ. Earth Sci.* **2018**, *77*, 711. [CrossRef]
58. Wallace, L.; Sundaram, B.; Brodie, R.S.; Marshall, S.; Dawson, S.; Jaycock, J.; Stewart, G.; Furness, L. *Vulnerability Assessment of Timor-Leste's Groundwater Resources to Climate Change*; Geoscience Australia: Canberra, Australia, 2012; ISBN 978-1-922103-63-5.
59. Dục, L.V. Sanitation of Water Source and Treatment of Garbage and Wastes in Hanoi City. In *Statement at East Asian and Middle-South American Conference on Environmental Industry*; Ministry of Construction: Hanoi, Vietnam, 2012. Available online: https://www.mofa.go.jp/region/latin/fealac/pdfs/4-6_vietnam.pdf (accessed on 14 December 2018).
60. Leeuwen CJ, V.a.n.; Dan, N.P.; Dieperink, C. The Challenges of Water Governance in Ho Chi Minh City. *Integr. Environ. Assess. Manag.* **2015**, *12*, 345–352. [CrossRef] [PubMed]
61. Nguyen, Q.T. The main causes of land subsidence in Ho Chi Minh City. *Procedia Eng.* **2016**, *142*, 333–340. [CrossRef]
62. Wagner, F.; Tran, V.B.; Renaud, F.G. Groundwater Resources in the Mekong Delta: Availability, Utilization and Risks. In *The Mekong Delta System: Interdisciplinary Analyses of a River Delta*; Renaud, F.G., Kuenzer, C., Eds.; Springer: Dordrecht, The Netherlands, 2012; pp. 201–220. [CrossRef]
63. Chau, N.D.G.; Sebesvari, Z.; Amelung, W.; Renaud, F.G. Pesticide pollution of multiple drinking water sources in the Mekong Delta, Vietnam: Evidence from two provinces. *Environ. Sci. Pollut. Res. Int.* **2015**, 9042–9058. [CrossRef] [PubMed]
64. Tam, V.T.; Batelaan, O.; Beyen, I. Impact assessment of climate change on a coastal groundwater system, Central Vietnam. *Environ. Earth Sci.* **2016**, *75*, 1–15. [CrossRef]
65. Shrestha, S.; Bach, T.V.; Pandey, V.P. Climate change impacts on groundwater resources in Mekong Delta under representative concentration pathways (RCPs) scenarios. *Environ. Sci. Policy* **2016**, *61*, 1–13. [CrossRef]
66. Post, V.E.A.; Bosserelle, A.L.; Galvis, S.C.; Sinclair, P.J.; Werner, A.D. On the resilience of small-island freshwater lenses: Evidence of the long-term impacts of groundwater abstraction on Bonriki Island, Kiribati. *J. Hydrol.* **2018**, *564*, 133–148. [CrossRef]
67. White, I.; Falkland, T. Management of freshwater lenses on small Pacific islands. *Hydrogeol. J.* **2010**, 227–246. [CrossRef]
68. Loco, A.; Singh, A.; Mataio, M.; Bwatio, E.; Sinclair, P. *Kiriwatsan Water Resources Assessment Abaiang Island, Kiribati*; UNICEF: Suva, Fiji, 2015.
69. Loco, A.; Sinclair, P.; Singh, A.; Mataio, M. *Kiriwatsan Water Resources Assessment Maiana Island, Kiribati*; UNICEF: Suva, Fiji, 2015.
70. ISF-UTS. *Background Report on Kiribati Domestic Water Supplies and Climate Change*; Institute for Sustainable Futures: Sydney, Australia, 2015.
71. Dixon-Jain, P.; Stewart, N.G.; Al, E. *Pacific Island Groundwater and Future Climates*; Geoscience Australia: Canberra, Australia, 2014; ISBN 9781925124323.
72. Government of Papua New Guinea. *Papua New Guinea National Water, Sanitation and Hygiene Policy 2015*; Department of National Planning and Monitoring: Port Moresby, Papua New Guinea, 2015.
73. SOPAC. *Management in Pacific Island Countries National Integrated Water Resource Management*; Diagnostic Report Papua New Guinea; Pacific Islands Applied GeoScience Commission (SOPAC): Suva, Fiji, 2007.

74. IGRAC. Groundwater Monitoring in Small Island Developing States in the Pacific. In Proceedings of the Workshop Summary on Advancing Groundwater Monitoring in Pacific SIDS, Suva, Fiji, 29 August–2 September 2016; International Groundwater Resources Assessment Centre (IGRAC): Delft, The Netherlands, 2016.
75. Food and Agriculture Organization of the United Nations (FAO). *AQUASTAT Survey 2011: Papua New Guinea*; FAO: Rome, Italy, 2011.
76. Quigley, N.; Beavis, S.G.; White, I. Rainwater harvesting augmentation of domestic water supply in Honiara, Solomon Islands. *Aust. J. Water Resour.* **2016**, *20*, 65–77. [CrossRef]
77. World Bank. *Urban Water Supply and Sanitation Sector Project (P165872) Project Information Document/Integrated Safeguards Data Sheet*; Report No: PIDISDSC24841; World Bank: Washington, DC, USA, 2016.
78. Food and Agriculture Organization of the United Nations (FAO). *AQUASTAT survey 2016 Solomon Islands*; FAO: Rome, Italy, 2016.
79. SOPAC. *National Integrated Water Resource Management Diagnostic Report—Solomon Islands*; Pacific Islands Applied GeoScience Commission (SOPAC): Suva, Fiji, 2007.
80. Foster, T.; Willetts, J. Multiple water source use in rural Vanuatu: Are households choosing the safest option for drinking? *Int. J. Environ. Health Res.* **2018**, *28*, 579–589. [CrossRef] [PubMed]
81. Government of Vanuatu. *Vanuatu National Water Strategy 2008–2018*; Department of Geology Mines and Water Resources: Port Vila, Vanuatu, 2008.
82. Winkler, M.; Jackson, D.; Sutherland, D.; Payden; Lim, J.U.; Srikantaiah, V.; Fuhrimann, S.; Medlicott, K. Sanitation safety planning as a tool for achieving safely managed sanitation systems and safe use of wastewater. *WHO South East Asia J. Public Heal.* **2017**, *6*, 34. [CrossRef]
83. Berendes, D.M.; Sumner, T.A.; Brown, J.M. Safely managed sanitation for all means fecal sludge management for at least 1.8 billion people in low and middle income countries. *Environ. Sci. Technol.* **2017**, *51*, 3074–3083. [CrossRef] [PubMed]
84. Fienen, M.N.; Arshad, M. The International Scale of the Groundwater Issue. In *Integrated Groundwater Management*; Jakeman, A.J., Barreteau, O., Hunt, R.J., Rinaudo, J.-D., Ross, A., Eds.; Springer: Cham, Switzerland, 2016; pp. 21–48.
85. Morris, B.L.; Lawrence, A.R.L.; Chilton, P.J.C.; Adams, B.; Calow, R.C.; Klinck, B.A. *Groundwater and Its Susceptibility to Degradation: A Global Assessment of the Problem and Options for Management*; Early Warning and Assessment Report Series, RS. 03-3; United Nations Environment Programme: Nairobi, Kenya, 2003; Volume 53, ISBN 9788578110796.
86. Shrestha, S.; Pandey, V.P. Groundwater as an Environmental Issue in Asian Cities. In *Groundwater Environment in Asian Cities: Case Studies, Concepts, and Methods*; Shrestha, S., Pandey, V.P., Thatikonda, S., Shivakoti, B.R., Eds.; Elsevier Science & Technology: Oxford, UK, 2016.
87. Foster, S. *Urban Groundwater Dependency in Tropical Africa: A Scoping Study of Pro-Poor Implications*; UPGro Working Paper; Skat Foundation: St.Gallen, Switzerland, 2017.
88. Calow, R.; MacDonald, A.; Denis Le Seve, M. The Environmental Dimensions of Universal Access to Safe Water. In *Equality in Water and Sanitation Services*; Cumming, O., Slaymaker, T., Eds.; Routledge: New York, NY, USA, 2018; pp. 95–117.
89. Grönwall, J. Self-supply and accountability: To govern or not to govern groundwater for the (peri-) urban poor in Accra, Ghana. *Environ. Earth Sci.* **2016**, *75*. [CrossRef]
90. Foster, S.; Bousquet, A.; Furey, S. Urban groundwater use in Tropical Africa—A key factor in enhancing water security? *Water Policy* **2018**, *20*, 982–994. [CrossRef]
91. Williams, A.R.; Bain, R.E.S.; Fisher, M.B.; Cronk, R.; Kelly, E.R.; Bartram, J. A systematic review and meta-analysis of fecal contamination and inadequate treatment of packaged water. *PLoS ONE* **2015**, *10*, e0140899. [CrossRef]
92. Kooy, M.; Walter, C.T. Towards a situated urban political ecology analysis of packaged drinking water supply. *Water* **2019**, *11*, 225. [CrossRef]
93. Stoler, J. Improved but unsustainable: Accounting for sachet water in post-2015 goals for global safe water. *Trop. Med. Int. Heal.* **2012**, *17*, 1506–1508. [CrossRef]
94. Wardrop, N.A.; Dzodzomenyo, M.; Aryeetey, G.; Hill, A.G.; Bain, R.E.S.; Wright, J. Estimation of packaged water consumption and associated plastic waste production from household budget surveys. *Environ. Res. Lett.* **2017**, *12*. [CrossRef]

95. VNSO. *2016 Post-TC Mini-Census Report*; Vanuatu National Statistics Office (VNSO): Port Vila, Vanuatu, 2017.
96. Vote, C.; Newby, J.; Phouyyavong, K.; Inthavong, T.; Eberbach, P. Trends and perceptions of rural household groundwater use and the implications for smallholder agriculture in rain-fed Southern Laos. *Int. J. Water Resour. Dev.* **2015**, *31*, 558–574. [CrossRef]
97. Warburton, E. Bottled Water—Big Business in Indonesia. Available online: https://blogs.ei.columbia.edu/2011/09/12/bottled-water-big-business-in-indonesia/ (accessed on 16 July 2018).
98. Elliott, M.; MacDonald, M.C.; Chan, T.; Kearton, A.; Shields, K.F.; Bartram, J.K.; Hadwen, W.L. Multiple Household water sources and their use in remote communities with evidence from Pacific Island countries. *Water Resour. Res.* **2017**, *53*, 9106–9117. [CrossRef]
99. Asian Development Bank. *Asian Water Development Outlook 2016*; Asian Development Bank: Manila, Philippines, 2016; Available online: https://www.adb.org/publications/asian-water-development-outlook-2016 (accessed on 14 December 2018).
100. Smits, S.; Sutton, S. *Self Supply: The Case for Leveraging Greater Household Investment in Water Supply*; IRC: The Hague, The Netherlands, 2012.
101. Butterworth, J.; Sutton, S.; Mekonta, L. Self-supply as a complementary water services delivery model in Ethiopia. *Water Altern.* **2013**, *6*, 405–423.
102. Olschewsk, A. Supported Self-supply—Learning from 15 years of experiences. In Proceedings of the 7th RWSN Forum "Water for Everyone", Abidjan, Côte d'Ivoire, 29 November—2 December 2016.
103. Willetts, J.; Murta, J.; Gero, A.; Carrard, N.; Harris, D. Political Economy Influences on Enterprise Engagement in Indonesia, Vietnam and Timor-Leste. In *Water, Sanitation and Hygiene Services Beyond 2015—Improving Access and Sustainability, Proceedings of the 38th WEDC International Conference, Loughborough, UK, 27–31 July 2015*; Shaw, R.J., Ed.; WEDC: Loughborough, UK, 2015.
104. Carrard, N.; Madden, B.; Chong, J.; Grant, M.; Nghiêm, T.P.; Bùi, L.H.; Hà, H.T.; Willetts, J. Are piped water services reaching poor households? Empirical evidence from rural Viet Nam. *Water Res.* **2019**, *153*, 239–250. [CrossRef]
105. Asian Development Bank. *Cambodia: Water Supply and Sanitation Sector Assessment, Strategy and Road Map*; Asian Development Bank: Manila, Philppines, 2012; ISBN 9789290925682.
106. Hadipuro, W.; Indriyanti, N.Y. Typical urban water supply provision in developing countries: A case study of Semarang City, Indonesia. *Water Policy* **2009**, *11*, 55–66. [CrossRef]
107. Taylor, R.G.; Scanlon, B.; Döll, P.; Rodell, M.; Van Beek, R.; Wada, Y.; Longuevergne, L.; Leblanc, M.; Famiglietti, J.S.; Edmunds, M.; et al. Ground water and climate change. *Nat. Clim. Chang.* **2013**, *3*, 322–329. [CrossRef]
108. Luh, J.; Royster, S.; Sebastian, D.; Ojomo, E.; Bartram, J. Expert assessment of the resilience of drinking water and sanitation systems to climate-related hazards. *Sci. Total Environ.* **2017**, *592*, 334–344. [CrossRef]
109. Foster, S.; MacDonald, A. The 'water security' dialogue: Why it needs to be better informed about groundwater. *Hydrogeol. J.* **2014**, *22*, 1489–1492. [CrossRef]
110. Johannessen, Å.; Wamsler, C. What does resilience mean for urban water services? *Ecol. Soc.* **2017**, *22*. [CrossRef]
111. Kohlitz, J.; Chong, J.; Willetts, J. Analysing the capacity to respond to climate change: A framework for community-managed water services. *Clim. Dev.* **2019**, 1–11. [CrossRef]
112. Sui, Q.; Cao, X.; Lu, S.; Zhao, W.; Qiu, Z.; Yu, G. Occurrence, sources and fate of pharmaceuticals and personal care products in the groundwater: A review. *Emerg. Contam.* **2015**, *1*, 14–24. [CrossRef]
113. Lapworth, D.J.; Baran, N.; Stuart, M.E.; Ward, R.S. Emerging organic contaminants in groundwater: A review of sources, fate and occurrence. *Environ. Pollut.* **2012**, *163*, 287–303. [CrossRef]

4.3 Critical reflections: beyond what to do, exploring how to do it

A critical reflection of the study is its focus on 'what' WASH professionals can do, rather than 'how' they might strengthen the sustainability of groundwater-based water services through collaboration. The published study identified priorities for WASH professionals at national, service authority and service delivery levels in areas of data collation, regulation, and resilience-building. Action in these areas requires collaboration between multiple WASH and water resource management actors and agencies, and integration across disciplinary perspectives. While the priorities identified in the study remain relevant, further consideration about how integration can occur is warranted, given the inherent challenges involved in bridging disciplinary epistemologies (Wickson et al., 2006).

A particular challenge in bridging epistemologies is integrating natural science perspectives, which tend to favour reductionist approaches, with those characteristic of social sciences, which tend towards contextual approaches (Mauser et al., 2013). The recommendation in the publication that WASH agencies coordinate with water resource management authorities on monitoring and the prioritisation of domestic supplies, for example, requires integration between scientific, management and service delivery orientations. Reflections regarding the importance of bridging disciplinary perspectives to support collaborative action underpinned engagement with WASH professionals' worldviews in study 4 (Chapter 6) and ideas about engagement with purpose in the inquiry's synthesis (Chapter 7). In these parts of the inquiry, I explored how transdisciplinary conceptions of purpose (after Jantsch, 1970) could inform 'how' sustainability is foregrounded in WASH by aligning everyday actions with longer-term imperatives.

4.4 Summary

This chapter presented an in-depth study on the use of groundwater as a source of drinking water in ten Southeast Asian and Pacific nations, and associated resource concerns. The analysis found that 79% of people in case study countries use groundwater as a source of drinking water, demonstrating the importance of groundwater resources for achievement of the human right to water. It identified a

breadth of groundwater resource concerns relevant for WASH professionals, and suggested implications for WASH agencies, service authorities and service providers. Priority areas for attention were identified as addressing data gaps and monitoring, strengthening regulation of self-supply and abstraction by different actors, and building resilience to emerging threats. In reflecting on the publication in the context of this thesis, I emphasised the challenges involved in bridging WASH and water resource management realms given worldview and epistemological diversity (ideas that are explored in Chapters 6 and 7). The next chapter presents the inquiry's second in-depth study – an analysis of the life-cycle costs of a resource-oriented sanitation system in urban Sri Lanka.

5 Chapter 5 Study of life-cycle costs of resource-oriented sanitation

5.1 Overview

This chapter presents the third publication included in this 'thesis by compilation'. The article, Life-cycle costs of a resource-oriented sanitation system and implications for advancing a circular economy approach to sanitation was published in the *Journal of Cleaner Production* in 2021. As described in the orientation to Part II of this thesis, the study explored in depth what it costs, and who pays, to prioritise a resource-orientation in sanitation service delivery. Following presentation of the publication, I critically reflect on the published study in light of the inquiry as a whole, identifying relevant insights regarding how the case study scheme was established, and use of the circular economy concept as a sustainability narrative.

5.2 Publication 3 — Life-cycle costs of a resource-oriented sanitation system and implications for advancing a circular economy approach to sanitation

Publication 3 is an open access article in the *Journal of Cleaner Production* and is included in this thesis in its published form. The publication is available online at https://doi.org/10.1016/j.jclepro.2021.127135.

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Life-cycle costs of a resource-oriented sanitation system and implications for advancing a circular economy approach to sanitation

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ABSTRACT

Implementing a circular economy approach to sanitation requires knowledge of the costs to construct, operate and maintain resource-oriented systems. Yet the dearth of data on costs of urban sanitation in general, and resource-oriented systems in particular, limit opportunities to progress sustainable sanitation in low- and middle-income countries. This paper contributes empirical data on the life-cycle costs of a resource-oriented sanitation system in urban Sri Lanka, addressing a gap in evidence about how much it costs, and who pays, for a system that integrates fecal sludge management with nutrient capture and reuse. Costs across the system life-cycle were analyzed according to: (i) cost type; (ii) phases of the sanitation chain; and (iii) distribution between actors. Over a 25-year lifespan, the system had an annualized cost of USD 2.8/person or USD 11/m^3 of septage treated. Revenue from co-compost sales covered reuse-related costs plus 8% of present value costs for other phases of the sanitation chain. Findings affirm both the potential for resource-oriented sanitation to generate revenue, and the need for substantial complementary investment in the overall system. The system was found to be reliant on household investment, yet financially viable from the service provider perspective with revenue from desludging services (89%) and co-compost sales (11%) that exceeded costs over the system lifespan and in most years. The analysis of total costs, financial perspectives, and reuse specifics contributes critical evidence to inform policy and planning that supports a purposeful and equitable transition towards circular economy approaches to sanitation.

1. Introduction

There is a growing body of research and practical experience exploring opportunities for beneficial reuse of human excreta. Sanitation approaches that incorporate reuse are variously framed as resource-oriented sanitation (Hashemi et al., 2018) (the term adopted in this study), regenerative sanitation (Koottatep et al., 2019), sustainable sanitation (Andersson et al., 2016), resource recovery and reuse (Rao et al., 2017) and ecological sanitation (Simha and Ganesapillai, 2017). The benefits of sanitation-related reuse are cross-sectoral and far reaching, including partially offsetting treatment costs, providing alternatives to expensive or non-local inputs (such as synthetic fertilizers) and improving access to resources for constrained populations (Trimmer et al., 2020). End products can be used as soil conditioner or fertilizer in agriculture, fuel for combustion, generation of energy through biogas, animal feed, or in building materials (Diener et al., 2014). With a focus on low- and middle-income countries where sanitation systems are rapidly developing, 'reuse over disposal' has been identified as a theme of recent environmental science literature (Hyun et al., 2019).

Increasingly, sanitation systems incorporating reuse are being positioned within the circular economy discourse (Danso et al., 2017; Mallory et al., 2020a; Moya et al., 2019; Schroeder et al., 2019; Sgroi et al., 2018). However, reflecting divergence in circular economy conceptions generally (Kirchherr et al., 2017; Merli et al., 2018), the relevance of circular economy concepts to sanitation has yet to be comprehensively defined and interrogated beyond a central reference to resource-oriented systems that facilitate beneficial reuse of human waste. Within literature focused on sanitation in low- and middle-income countries, circular economy debates are dominantly concerned with business models (Otoo et al., 2018), with a particular focus on the potential (or not)

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for revenue generation, cost recovery and incentivizing investment (Danso et al., 2017; Diener et al., 2014; Mallory et al., 2020b; Rao et al., 2017). This business model orientation is consistent with wider circular economy literature, which tends to emphasize economic aims and be less concerned with the reality that realizing a circular economy requires holistic systemic change to achieve its central aim of sustainable development (Kirchherr et al., 2017).

Nevertheless, the potential for circular economy approaches to sanitation to address both human and environmental concerns and achieve sustainable development has been recognized by the international community. Sustainable Development Goal (SDG) target 6.3 is to improve water quality by 2030, including through "halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally" (United Nations, 2015). In tandem with SDG target 6.2 — achieving sanitation and hygiene for all — these widely accepted normative directions demand that the global sanitation sector focuses on solutions that facilitate safe reuse. The relevance of circular economy concepts to this aim has been affirmed in a review identifying a strong relationship between circular economy practices and SDG 6 targets (Schroeder et al., 2019).

Prioritizing safe reuse in sanitation requires redressing a tendency for resource-oriented systems to be pilot or niche in nature, lauded through rhetoric but lacking integration within larger systems and markets (Carrard and Willetts, 2017; Schrecongost et al., 2020). There is a need for further research about, and implementation of, resource-oriented systems at city or whole-of-community scales. Implementing such systems at scale demands a shift of perspective away from 'whether' resource-oriented systems can achieve cost recovery or incentivize investment — as is reflected in literature linking circular economy ideas with sanitation to date (Mallory et al., 2020a) — towards 'how' we can properly finance and manage systems where reuse is the requisite end-point of the sanitation chain.

To normalize a resource-orientation in the planning and delivery of sanitation services, it is critical to build evidence about the full costs of such systems. Economic and financial analysis of the costs of urban sanitation generally is a growing field of research (Daudey, 2018; Mills et al., 2020). Yet substantial challenges persist related to data availability and to the quality and comprehensiveness of cost studies. Daudey (2018) suggests a particular need for contextualized studies that identify the full range of costs associated with service delivery, across a system life-cycle, taking into account all phases of the sanitation chain.

Studies that identify the distribution of costs between actors is also a gap (McConville et al., 2019). Consideration of the financial perspectives of different actors is essential for the design of cost-sharing arrangements that ensure sanitation is affordable for all and support service providers with the requisite level of public investment, given sanitation's status as a public good (Schrecongost et al., 2020). More generally, there is opportunity to move beyond a project assessment approach to costing, towards closer analysis and monitoring of the financial characteristics of sanitation systems. Analysis of the financial dynamics of different configurations is critical for addressing a history of public underinvestment in sanitation service delivery and a lack of focus on financial viability (Schrecongost et al., 2020).

The need for contextualized, comprehensive, actor-oriented cost analyses is similarly apparent for resource-oriented sanitation systems specifically. A body of studies discuss the potential for resource-oriented sanitation to improve the financial viability of sanitation chains (Andersson et al., 2017; Diener et al., 2014; Otoo et al., 2018; Rao et al., 2017), while others include reuse options in comparative analyses of sanitation system costs (Dodane et al., 2012; McConville et al., 2019; Willetts et al., 2010). However most studies to date report projected rather than observed data, with a tendency to overestimate the value of reuse-related revenue (Mallory et al., 2020b). Building empirical evidence about the total costs of resource-oriented systems over their life-cycle, and across the full sanitation chain, can reveal opportunities for system optimization, underpin system sustainability by identifying the types and timing of investments required, and provide a foundation for the design of optimal cost sharing and financing arrangements.

This study contributes an analysis of the life-cycle costs of a resource-oriented sanitation system serving an urban area of Balangoda in Sri Lanka. In Sri Lanka, reflecting the urban sanitation situation globally, there is a critical need for improved excreta management, and considerable potential for reuse. The dominant form of sanitation in Sri Lanka is onsite systems, with 86% of households using septic tanks or pits (Ministry of City Planning and Water Supply, 2018). In urban areas, disposal of septage (solids and liquids removed from on-site sanitation) is a major problem faced by local authorities (Ministry of City Planning and Water Supply, 2018). Only 2% of households in Sri Lanka are connected to sewerage systems (Government of the Democratic Socialist Republic of Sri Lanka, 2018), with the majority of septage discharged into the environment without adequate treatment (ADB et al., 2017). Government policy articulates a need for sanitation initiatives to focus on improved septage management, including through treatment for safe reuse (Government of the Democratic Socialist Republic of Sri Lanka, 2017). There is both a need and opportunity to inform operationalization of the policy, including contributing evidence on the costs of sanitation reuse systems.

The resource-oriented sanitation system presented in this paper has been operating for a decade, and therefore provides locally-grounded, broadly relevant data on the costs of sanitation systems based on onsite containment, transport, treatment and reuse. With onsite systems used by 60% of households in Central and Southern Asian cities (UNICEF and WHO, 2019) and an estimated 66% of households in low- and middle-income cities worldwide (Berendes et al., 2017), the study has substantial potential to inform the implementation of resource-orientated sanitation globally.

We preface the analysis by noting the position of the authors that we must, wherever feasible, make reuse a part of sanitation planning and financing (Carrard and Willetts, 2017), in alignment with the SDGs and principles for citywide inclusive sanitation (Lüthi et al., 2020). We view this as a normative goal rather than one requiring justification through a promising business case, in line with the circular economy imperative to pursue systemic change (Kirchherr et al., 2017) and be regenerative and distributive by design (Raworth, 2017a). As such, the aim of this study was to explore in detail the cost-profile of a sanitation system with a view to informing future planning, investments, and cost-sharing arrangements for resource-oriented sanitation in Sri Lanka and more widely.

We first describe the details of the system under consideration and approach to costing. We then present and discuss findings from the analysis across three themes: total costs of the system over its lifespan; the distribution of costs between system actors, with a particular focus on the perspective of local government as service provider; and specifics of the reuse phase of the sanitation chain, including a discussion of critical considerations regarding cost optimization and system expansion.

2. Methods

2.1. Study objectives and context

The study explored sanitation system costs, and associated financial perspectives, in the context of a broader agenda to

facilitate the application of resource-oriented sanitation systems at scale. The objective of the study was to identify the life-cycle costs of the resource-oriented sanitation system in Sri Lanka, taking into account actual incurred costs since system establishment and anticipated future required investments. Costs were analyzed by cost category, phase of the sanitation chain and from the perspectives of the main system actors. Analysis included an in-depth focus on costs associated with the reuse phase of the sanitation chain, and consideration of the role of local government as a resource-oriented service provider. The study was approved by the University of Technology Sydney Human Research Ethics Committee (Reference: ETH18-2522) and aligned with the International Water Management Institute Research Ethics Policy.

The analysis case is a fecal sludge management system in Balangoda, an urban centre in Sabaragamuwa Province of Sri Lanka with a population of approximately 30,000. Balangoda was selected for analysis due to the presence of an operational – and reportedly successful (Otoo et al., 2018; Rao et al., 2017) – example of a city-scale fecal sludge management system that incorporates reuse of treated sludge for productive agricultural use. Insights from the Balangoda case are relevant across Sri Lanka, where the 2018 National Sanitation Policy and national SDG targets to achieve safe sanitation (Ministry of City Planning and Water Supply, 2018) are driving investment in fecal sludge (as well as wastewater) treatment systems across urban centers. Results are also relevant more widely, given the prevalence of fecal sludge-based sanitation systems around the world in low- and middle-income countries.

The characteristics of the sanitation system are typical of urban contexts in Sri Lanka and other low- and middle-income countries. It comprises: household containment tanks (of various sizes and specifications); on-demand desludging by vacuum truck; transportation; and passive (gravity-based) treatment of septage at a fecal-sludge treatment plant (FSTP) comprising a receiving tank, two sedimentation tanks, an effluent treatment facility and drying beds (see supplementary material for a system diagram). The FSTP has capacity of $15m^3$/day and average actual throughput of $10–12m^3$/day. In Balangoda, dried fecal sludge is mixed with compost derived from the organic fraction of municipal solid waste to produce co-compost, which is pelletized for sale. The co-compost contains municipal solid waste compost (100 parts), dried fecal sludge (30 parts), mineral rock phosphate (10 parts) and rice husks (5 parts). The entire system is owned and operated by the local authority, Balangoda Urban Council. The fecal sludge treatment plant was constructed in 2008 at Council's already-operational municipal solid waste facility. A pilot-scale pelletizer was added to the system in 2016 by way of donation from the International Water Management Institute.

2.2. Approach to costing

The costing method was informed by a life-cycle costs approach adapted for water, sanitation and hygiene (WASH) analyses through the WASHCost initiative (Fonseca et al., 2011), and principles of integrated resource planning adapted for urban water and sanitation systems (Mitchell et al., 2007; Willetts et al., 2010). Life-cycle costing involves aggregating the full range of costs of ensuring an adequate, equitable and sustainable service to a population in a specified area (Fonseca et al., 2011). Three characteristics of the life-cycle costs approach justified its application in this analysis. First, the approach is oriented towards delivery of sanitation services rather than project evaluation. It seeks to articulate the full costs of providing a specified service (in this case sanitation incorporating reuse) such that they can be planned for, rather than informing project evaluation (Ratna Reddy et al., 2012). Second, the life-cycle cost approach uses defined and comprehensive cost categories that facilitate a systematic process of identifying all costs involved in service delivery. The use of defined cost categories – and in particular the inclusion of non-annual capital maintenance costs – makes transparent the types and timing of investments required. Third, application of life-cycle costing in the WASH sector intends to be directly useful for decision makers by improving understanding of the full costs of different sanitation systems and implications for what finance is needed, when, to ensure continued service delivery (Fonseca et al., 2011). In this study, articulating the full costs of a resource-oriented sanitation system (and zooming in on the reuse component) can inform future similar investments, including laying a foundation for system optimization and identification of potential cost efficiencies.

Integrated resource planning is a holistic approach that accounts for both material flows and financial exchanges required to achieve a defined service outcome (Beecher, 1996; Mitchell et al., 2007; Willetts et al., 2010). As such, integrated resource planning aligns well with the principles of citywide inclusive sanitation and the WASHCost life-cycle costing approach. Two principles from integrated resource planning as described by Mitchell et al. (2007) usefully informed the study. First is the explicit definition of an appropriately holistic system boundary. In this study, the system encompassed all phases of the sanitation chain (containment through to disposal/reuse) and a clear costing boundary was articulated that incorporated financial costs and benefits but excluded externalities (as discussed in section 2.4). Second, an integrated resource planning approach emphasizes the importance of applying appropriate cost perspectives. In this analysis, all financial costs and benefits were included to determine whole-of-society costs (as advocated for in both life-cycle costing and integrated resource planning approaches), with a secondary analysis exploring the distribution of costs between primary system actors.

Costs were identified for four phases of the sanitation service chain: (1) containment; (2) transportation and emptying; (3) treatment; and (4) reuse. Containment was deliberately included, in contrast to many sanitation costs analyses (Daudey, 2018), to ensure potentially substantial costs incurred by households – which are often overlooked (Danert and Hutton, 2020) – were considered and made transparent. The costing boundary was defined to incorporate all costs borne by the primary system stakeholders, namely the local authority (as the service provider) and households (as the main service users). Finance provided by the national government and the costs of a pelletizer donated by the International Water Management Institute were also included. In this system, service users include smaller commercial and some institutional premises, as well as households. For simplicity, 'households' were used as a proxy for all users, as they are the dominant group in this mix. The costing analytical boundary is shown in Fig. 1.

In defining the costing boundary, it is important to acknowledge that the resource-oriented sanitation system sits within, and is dependent on, a larger system that includes municipal solid waste management and agriculture. The wider system costs and implications for interpretation of this study are discussed further in Section 3.1.

Cost data was sourced from written records and semi-structured interviews with government officials involved in establishing and/or operating the sanitation service system. Cost categories described in the WASHCost life-cycle costing approach (Fonseca et al., 2011) were used to identify the range of relevant costs to include. For the system in question, this comprised: capital expenditure; operational expenditure; capital maintenance expenditure; and support costs. Data resolution was not sufficient to separate direct and indirect support costs as described in the WASHCost methodology, so they are included as a single category.

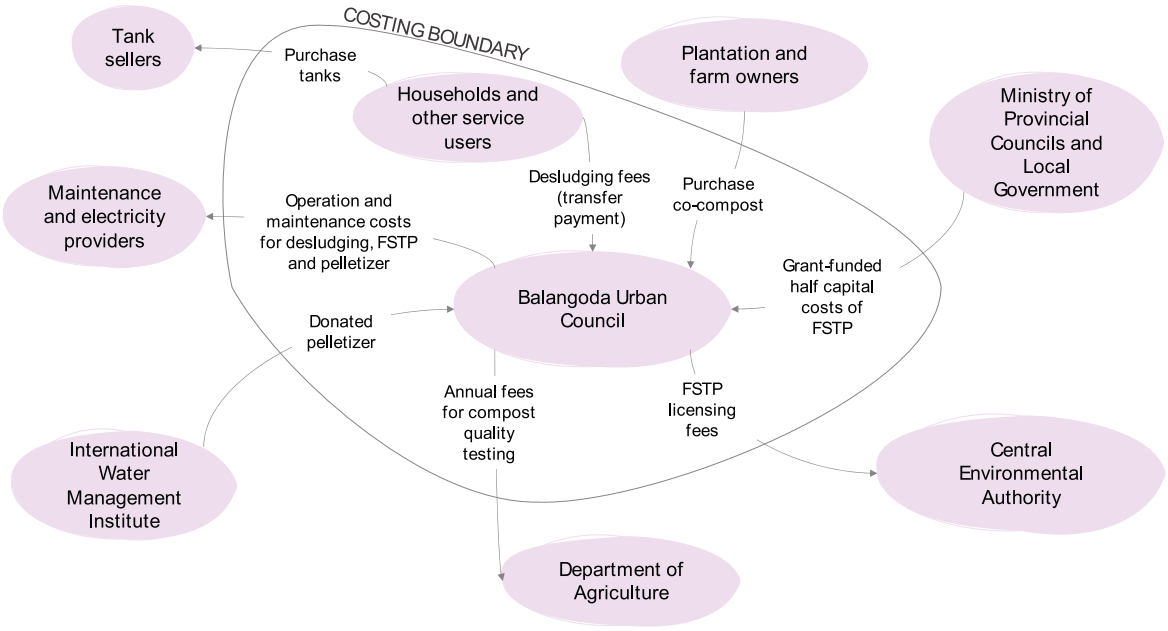

Fig. 1. Costing boundary showing financial flows included in the analysis. The direction of arrows indicates the direction of financial flows.

The cost of capital was also considered but was not relevant in this case as all finance was provided through grants or capital works budgets. Revenue associated with the sale of co-compost was included based on the median of available data (10 years) with sensitivity analysis conducted for a 95% confidence interval of the mean. Household payments for desludging services (when taking the local government perspective) were also included. Costs were apportioned to the sanitation system (from wider system costs) based on the ratio of fecal sludge included in co-compost, and the marginal difference in sale price achieved when selling the more nutrient-rich product. Cost estimates relied on a mix of actual (historic) costs reported in current values, and hypothetical costs predicting likely future investments required for the system to function as intended over time. Costs included in the analysis are described in supplementary material.

2.3. Data analysis

A spreadsheet-based model was used to calculate the net present value of life-cycle costs over a 25-year system lifespan. The analysis timeframe was defined to reflect the expected asset replacement period for household tanks and treatment components (as reported in interviews) and ensure that long-term operation and maintenance costs were included in the analysis. The net present value calculation applied a discount rate of 10%, which is the rate used by the Sri Lankan Department of National Planning. Relevant costs identified during semi-structured interviews were aggregated according to WASHCost cost categories described above. The frequency of capital maintenance costs was predicted by key informants and included in the model when incurred (rather than annualized) to show the timing of required investments. All costs were converted to 2018 US dollars by applying deflator factors (World Bank, 2019a) and a period average exchange rate of USD 1 equal to LKR 162.465 (World Bank, 2019b).

Analyzed costs were disaggregated according to cost category, phase of the sanitation chain, and cost perspectives. Costs are reported as net present value and annualized per person costs, the latter to situate costs relative to those reported in other studies. A cost per m^3 of septage treated was also calculated as a metric that reflects the cost of actual service provided: the amount of septage that is treated. Reflecting inherent uncertainties in the input data (particularly for future projections), cost findings are reported to two significant figures. Sensitivity analysis examined the impact of a lower discount rate (6%) and changes in assumptions about the population served. The cost per m^3 of septage treated provides an alternative metric given uncertainty about the population served.

3. Results and discussion

This section presents and discusses findings from the analysis including: (i) system costs across different cost categories and phases of the sanitation chain; (ii) the distribution of system costs between actors; (iii) detailed analysis of the reuse phase, including cost drivers and implications for extending the reach of resource-oriented sanitation; and (iv) areas for further research.

3.1. System costs

The sanitation system – from containment to reuse – has a total net present value of approximately USD 370,000, with an annualized per person cost of USD 2.8 (equivalent to USD 12 per household) and cost of USD 11 per m^3 of septage treated. Sensitivity analysis using a lower discount rate found a comparable annualized per person cost. System costs are shown in Table 1 and Fig. 2 by cost category and phase of the sanitation chain. Treatment costs represented the largest portion of total system costs (35%) followed closely by containment costs (33%), which were included as part of capital maintenance expenditure to reflect the staggered nature of household tank replacements over time in established urban areas. The cost of emptying and transfer constitute just over a quarter of the costs (28%), with investments required for reuse a far smaller portion (4%). Costs associated with reuse portion of the chain are net positive, with revenue from co-compost sales covering costs associated with preparing compost for sale plus 8% of the present

Table 1
Present value costs of the sanitation system by cost category and sanitation chain phase.

	Containment	Emptying & transport	Treatment	Reuse	Total costs by category
Capital costs	0	−49,000	−77,000	−4,700	−130,000
Operational costs	0	−52,000	−39,000	−7,400	−99,000
Capital maintenance costs	−140,000	−14,000	−25,000	−1,900	−180,000
Support costs	0	0	−8,400	−1,300	−9,700
Revenue	0	0	0	46,000	46,000
Total costs by phase of sanitation chain	−140,000	−120,000	−150,000	31,000	−370,000

All costs are shown in USD 2018 values to two significant figures.

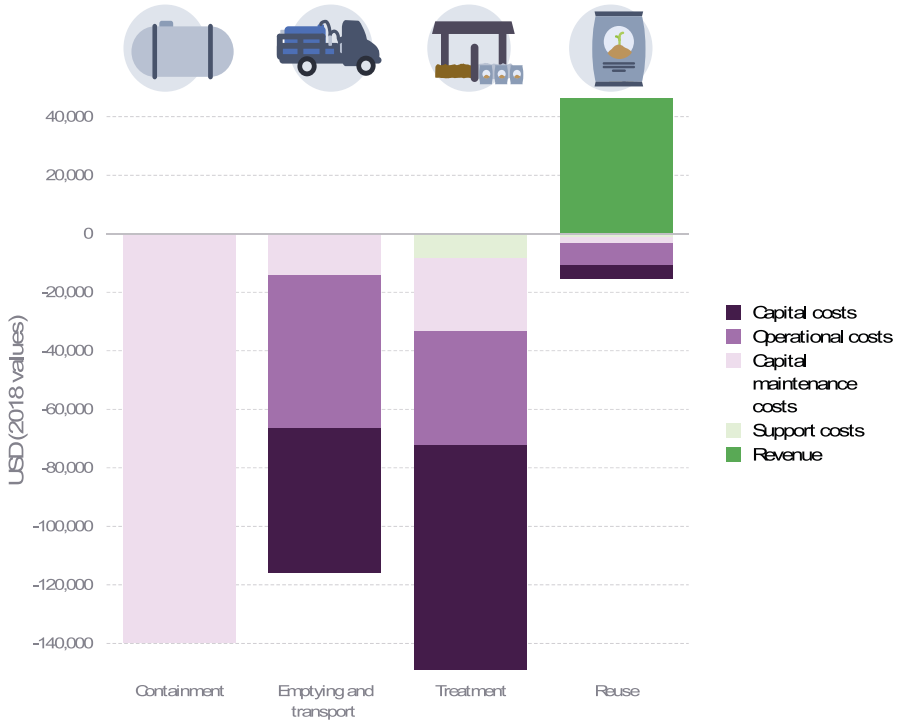

Fig. 2. System costs (NPV) across the sanitation chain shown by cost category.

value costs for other phases of the sanitation chain. Reuse costs are discussed further below in section 3.3. The summary of costs by category shows that capital maintenance costs exceed other categories due to the inclusion of household tanks, which account for 78% of all capital maintenance expenses.

The timing of costs over the system lifespan – and therefore required investments – is illustrated in Fig. 3. The system requires an annual investment of around USD 22,000, a figure which includes operational costs borne by the service provider and rolling household tank replacements. A more detailed breakdown of how costs are borne by different stakeholders is provided below in section 3.2. The higher costs incurred approximately every five years represent required capital maintenance investments in desludging trucks, the treatment facility and the compost pelletizer.

The annualized per person cost found in this study (USD 2.8/person/year) is lower than other sanitation cost analyses. Studies in Kampala, Uganda (McConville et al., 2019) and Dakar, Senegal (Dodane et al., 2012) found annualized per person operating costs for full-chain fecal sludge management systems of USD 14 and USD 11.6 respectively. A study of the costs of full-chain fecal sludge management systems globally found annualized per person costs in the range of USD 6.3–24 (Cairns-Smith et al., 2014). Costing studies of onsite systems in Dhaka, Bangladesh (Ross et al., 2016) and Johannesburg, South Africa (Manga et al., 2020) found per household annualized costs of approximately USD 100 and USD 150 respectively, pointing to higher per person costs than was found in the Balangoda analysis. It is important to note that different methodologies and included costs make direct comparison of costs across studies inappropriate, however it is clear that the Balangoda system has a relatively low per person cost.

The lower costs found in this study are explained by the sanitation system's integration within a wider municipal solid waste facility and passive treatment design. Because the FSTP was constructed on the existing municipal waste management site, capital costs did not include land or road construction. Road and facility construction costs amounting to USD 300,000 were incurred as part of compost plant establishment in 2003 (equating to approximately USD 1 million in 2018 values), financed by the Central Environmental Authority through its Pilisaru program and Provincial Council (Otoo et al., 2018). Land was provided at no cost from the Land Reform Committee (Otoo et al., 2018). The passive treatment design keeps operational costs low, requiring no electricity and few manual laborers (who also work within the wider

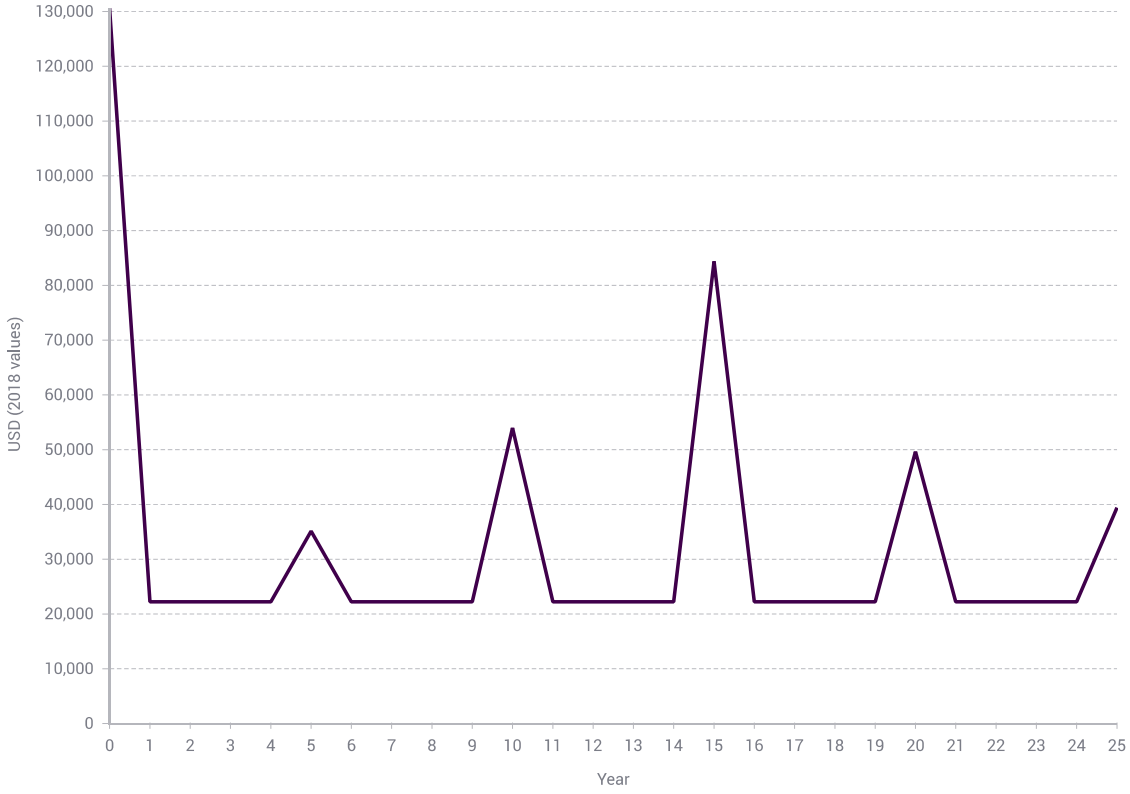

Fig. 3. System costs over time. The required annual investment in most years is USD 22,000, with higher capital maintenance investments required approximately every five years.

municipal solid waste plant). Integration of the sanitation system within an existing waste facility means Balangoda cost findings are applicable in other Sri Lankan cities, where more than 100 similar composting facilities exist. However, in interpreting their relevance to other contexts where these facilities are not common, costs of the wider system would need to be factored into analysis and planning.

It is also important to note that the per person annualized cost found for the Balangoda system is calculated from assumptions about the actual population served, size of household tanks and desludging frequency, all of which have a degree of uncertainty given the absence of validated data and anecdotally wide variation in household practices. To validate findings, calculations were repeated for a range of scenarios based on different assumptions about tank sizes and desludging frequencies, all of which resulted in a per person annualized cost of USD 2.3–2.8. The reported figure of USD 2.8 is considered the most reliable of these, being based on Council records of revenue received from desludging services and a schedule of fees charged to households and other service users. The assumptions and scenarios underpinning these calculations are further detailed in supplementary material. For future sanitation cost analyses, acknowledging a widespread lack of data on household tank sizes and desludging frequencies, we propose that reporting a metric based on the cost of actual septage treated (USD 11/m^3 treated each year in Balangoda) could be a helpful addition to reporting of per person annualized costs.

3.2. Who pays? The distribution of system costs

Exploring the financial perspectives of system actors is an essential foundation for sustainable and equitable sanitation services. Articulating who pays (and when costs are incurred) for different system components can inform equitable distribution of costs and ensure ongoing costs are planned for and adequately financed. The distribution of costs in the Balangoda case (Table 2; Table 3; Fig. 4) is typical of similar onsite sanitation systems. Insights from the analysis (discussed in turn below) relate to: the system reliance on household investment; the substantial revenue received by the local government (as service provider) from desludging fees and fertilizer sales; and a simplicity in the distribution of costs that would shift with involvement of private sector service providers.

Households bear the largest share of costs. More than three-quarters of the whole-of-life costs are borne by households, and just 23% is borne by the local authority. Household costs comprise investment in onsite containment (constituting a third of costs borne by households) and fees paid for desludging (two thirds of household costs). Fees paid for desludging were excluded from the total system costs as they represent transfer payments between households and Council from a whole-of-society perspective, but are included in the analysis of who pays given their importance for exploring the financial perspectives of system actors.

Substantial household investment is a characteristic feature of onsite sanitation systems (Daudey, 2018; Dodane et al., 2012; McConville et al., 2019; Satterthwaite et al., 2019). This has important implications for equity, with unaffordability driving unsafe practices for lower-income households (for example improper containment and insufficient frequency of desludging). In Balangoda, population calculations indicate that the Council-operated desludging service is used by approximately half the town population, raising questions as to how septage is dealt with by remaining households. Consideration of how to ensure services are affordable for all is demanded from government agencies responsible for service oversight, which may include subsidization

Table 2
Distribution of costs between actors for each phase of the sanitation chain.

	Local govt	National government	Households	Donation
Containment	0	0	−140,000	0
Emptying and transfer	250,000	0	−360,000	0
Treatment	−110,000	−37,000	0	0
Disposal/reuse	35,000	0	0	−3,600
Total	170,000	−37,000	−500,000	−3,600

Table 3
Distribution of costs between actors for each cost category.

	Local govt	National government	Households	Donation
Capital costs	−90,000	−37,000	0	−3,600
Operational costs	−41,000	0	−360,000	0
Capital maintenance costs	−99,000	0	−140,000	0
Support costs	−9,700	0	0	0
Revenue	410,000	0	0	0
Total	170,000	−37,000	−500,000	−3,600

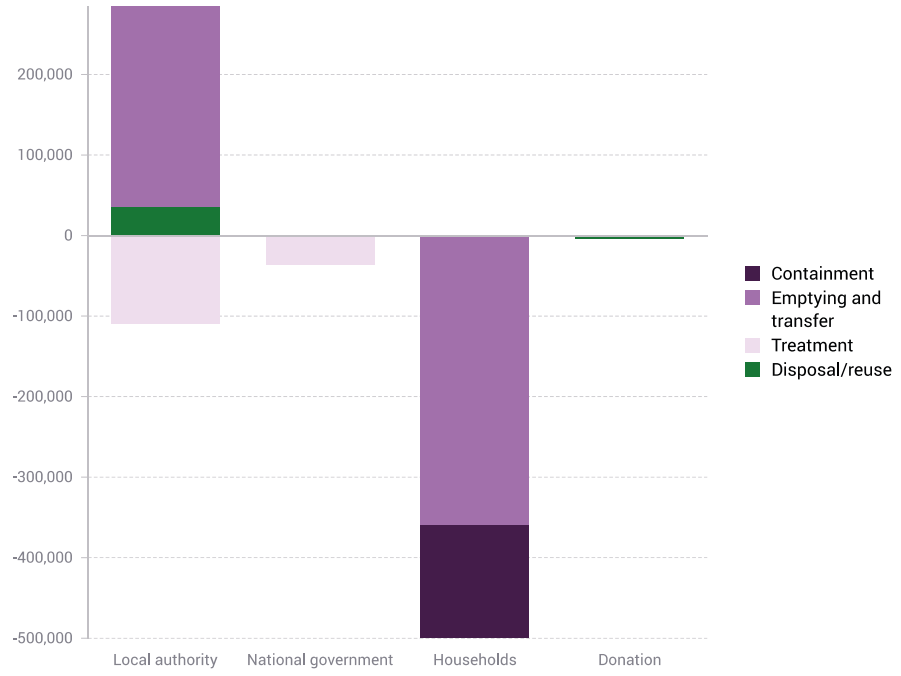

Fig. 4. Costs by actor. Households bear the greatest costs, revenue outweighs costs for the local authority as the service provider.

of onsite systems as is common for sewer systems (Gambrill et al., 2020). More generally, further research on household investment in sanitation services is warranted, given household investments are a significant, poorly understood and largely ignored part of the water and sanitation financing picture (Danert and Hutton, 2020).

The perspective of the local government service provider contrasts markedly with that of households, with revenue that exceed costs over the system lifespan and in most years of service. At the time of system establishment, local government investment was matched by a grant from the national government, which supported construction of the FSTP. On an annual basis, revenue from household payment of desludging fees plus sale of fertilizer is sufficient to cover the ongoing costs associated with desludging, treatment and reuse aside from one point in time (year 15) where forecast capital maintenance costs are more substantial and additional finance (in the order of USD 30,000) would be required. From the service provider (Council) perspective, the sanitation system therefore achieves financial viability on a user pays basis; an often-idealized though disputed approach to financing service delivery in the water and sanitation sector (Franceys et al., 2016).

However, the reality of government budgeting processes means that sanitation-related revenue is not necessarily used to cover ongoing sanitation system costs. In Balangoda, revenue from sale of co-compost is earmarked in budgeting processes for reinvestment in the waste management system (along with revenue from sale of recyclable waste) and therefore contributes to covering ongoing costs. In contrast, desludging fees received from households are directed to a common revenue pool, which is subject to annual negotiations about priority investments across a range of Council services. With revenue from desludging services constituting 89% of the modelled financial benefits, the extent to which Council can rely on sanitation-related revenue to cover ongoing system costs is

uncertain. As such, earmarking of sanitation-related revenue – for the reuse phase and more widely – is an important factor in determining how the modelled cost-profile of an urban sanitation system plays out in practice. Furthermore, in contexts with an active private desludging market (as is the case in many low- and middle-income cities including elsewhere in Sri Lanka), additional thought would be required to arrange transfer payments such that Council is able to cover whole-of-system costs, and businesses are incentivized to discharge at the FSTP.

3.3. The reuse sub-system: detailed costs and implications

In this section we present detailed findings for the reuse phase of the Balangoda system and discuss implications for investment in resource-oriented sanitation systems in Sri Lanka and more widely. Implications suggest that: (i) reuse-related revenue makes a moderate contribution to whole-of-system financial viability and other sources of finance (from households or government) are needed for the whole system to function; (ii) detailed costing of the reuse sub-system can inform optimization of its financial contribution, making apparent key cost drivers and testing assumptions about the value of different system investments; and (iii) to extend the reach of resource-oriented sanitation systems, there is a need for further analysis of pathways for system expansion.

The reuse sub-system generates a net surplus over the system lifespan and on an annual basis. Over the lifespan, present value costs of USD 15,000 and financial benefits of USD 46,000 result in a total net benefit of USD 31,000. Sensitivity analysis based on the range of recorded revenue values found a minimum net benefit of USD 30,000 and a maximum of USD 78,000, indicating our findings are conservative regarding revenue potential. The proportional distribution of present value reuse costs are shown in Fig. 5, including pelletizer purchase (23%) and replacement (13%), electrical connection (7%) and running costs (4%), phosphate valorization (15%), bags (30%) and licensing and inspection fees paid to the Central Environmental Authority (8%).

The reuse sub-system has a net benefit over the system lifespan, however revenue from reuse makes a relatively small contribution to wider system costs. On an annual basis, revenue from the sale of co-compost is sufficient to cover just under half (43%) of the annual operating and support costs for other phases of the sanitation chain. Over the system lifespan, revenue (after covering reuse-specific costs) equates to approximately 10% of present value costs of the wider system. More specifically, it represents 8% of present value costs of containment, emptying/transport and treatment and 12% if containment (household) costs are excluded.

Findings affirm that resource-oriented sanitation can generate revenue in practice, but suggest caution in asserting the potential for a resource-orientation to drive investment in sanitation services at whole-of-system scale, as has been hypothesized (Diener et al., 2014; Murray and Ray, 2010). The inability of reuse to underpin overall system profitability has been similarly identified in analyses of reuse systems in India (Center for Water and Sanitation - CEPT University, 2019) and in Haiti and Kenya (Moya et al., 2019). A review of the financial value of fecal sludge reuse from 43 studies in low- and middle-income countries also found resource recovery to have a limited role in the overall financial viability of resource-oriented sanitation systems (Mallory et al., 2020b). Further, while resource-oriented sanitation options have been found to have lower costs than traditional systems in economic cost comparisons (Hashemi and Boudaghpour, 2020; Shi et al., 2018), this does not signify potential for full financial cost recovery and specific attention on financial viability for whole-of-chain systems is required (Schrecongost et al., 2020). As such, while a resource-orientation can improve the overall financial profile of a sanitation service and partially offset required public investment, additional finance will be required to ensure the viability of earlier phases of the sanitation service chain as preconditions for a successful reuse scheme.

The contribution of reuse-related revenue is nevertheless meaningful and warrants detailed analysis towards cost optimization. In Balangoda, costs associated with the reuse phase of the sanitation chain are driven by the decision to pelletize the co-compost, which raises questions about whether investment in pelletization is financially justified. Costs related to pelletization – including purchase of the pelletizer, an electrical connection fee, machine replacement and electricity running costs – constitute almost half of all reuse-related expenditure. In this case, pelletizer

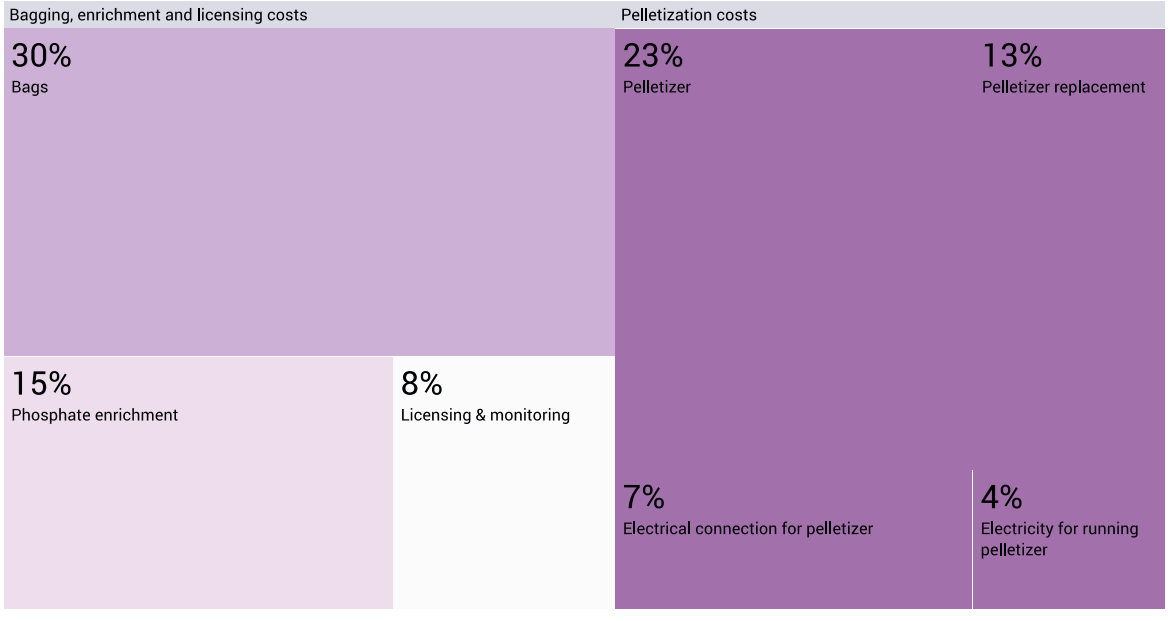

Fig. 5. Pelletizer-related costs constitute almost half of all life-cycle costs associated with the reuse sub-system.

purchase (17% of reuse costs) was externally financed in the form of a donation from the International Water Management Institute, however ongoing annual costs and future maintenance costs are borne by Balangoda Urban Council as the service provider.

The decision to pelletize co-compost was justified by Balangoda Urban Council based on two assumptions: first that a pelletized product can retail for double the price of a non-pelletized product (USD 0.12/kg instead of USD 0.06/kg); and second that pelletization increases demand for the product in a market accustomed to applying pelletized commercial fertilizer. Pelletization has also been identified as a strategy to address perceived cultural barriers associated with handling and using a compost containing dried fecal sludge (Otoo et al., 2018). There is mixed evidence from literature about the validity of these assumptions. Pelletization is claimed to command higher prices, improve usability, achieve a steadier rate of nutrient release compared with traditional powdered fertilizers, and enable access to new markets (including through reducing transport costs and improved product desirability) (Moya et al., 2019; Nikiema et al., 2013; Otoo et al., 2018). Yet consumer willingness to pay is uncertain. A study in Kampala, Uganda found that while farmers prefer a pelletized product, the modelled cost of pelletization exceeded farmer willingness to pay for this attribute (Danso et al., 2017). A study in the Sri Lankan district of Nuwara Eliya found higher willingness to pay for fecal sludge-fortified compost in powdered, rather than pelletized, form (Waidyarathne et al., 2018), though willingness to pay relative to costs was not considered in this case. Further empirical evidence, in the form of future sale records and pelletizer-related costs (including validation of modelled future costs), is required to assess whether pelletization is a cost-effective investment in the Balangoda system and for resource-oriented sanitation systems more widely.

More generally, further research on the relative costs and marketability of different end-use products across contexts is needed to inform the technical, institutional and financial design of resource-oriented sanitation systems at scale. In a review of the market potential of multiple fecal sludge-derived end-use products in Ghana, Senegal and Uganda, Diener et al. (2014) found the use of sludge as soil conditioner to be less profitable than other options, though they noted the challenges of calculating cost recovery given limited empirical evidence. Mallory et al. (2020b) also identified the dominance of theoretical studies and limited evidence on markets for a range of reuse products. Murray and Ray (2010) argue for a "back-end user" focus to ensure the outputs of sanitation systems meet the specific needs of end-users (as customers). This "designing for reuse" approach (Murray and Ray, 2010) requires consideration of commercial fertilizer markets if the planned product is intended to reduce the extent of reliance on chemical fertilizers. In Balangoda, government subsidies for chemical fertilizers place co-compost in a competitive market (Otoo et al., 2018), a consideration which has driven valorization of the co-compost with the addition of 7% mineral rock phosphate. In other locations, calls have been made to 'level the playing field' between sanitation-based fertilizers and the wider market, for example by providing incentives for use of organic fertilizers (Moya et al., 2019). Ultimately, both market analysis and policy interventions are required to optimize the nutrient reuse and financial contributions of resource-oriented sanitation systems in different contexts.

Finally, analysis of the Balangoda system highlights priorities for research and practical action towards a stronger resource-orientation within efforts to advance citywide inclusive sanitation. A critical question for Balangoda, and onsite sanitation service systems more generally, is how to ensure services reach all. At present, analysis suggests that although the Balangoda sanitation service is theoretically available for all residents to make use of, in practice it serves approximately half the population. There may be options for increasing customer desludging demand towards achievement of citywide service delivery, for example through the institution of scheduled desludging as has been successfully piloted in other locations (ISF-UTS & SNV, 2019; Mehta et al., 2019). Prospective analysis of the potential costs required to increase rates of desludging, expand FSTP production and optimize reuse-related revenue is critical to inform future investment strategies. As part of this analysis, it will be important to explore the relative merits of maintaining Council monopoly or facilitating private sector provision of desludging services. In undertaking similar analyses more generally, it is important to acknowledge a tendency in fecal sludge reuse studies to overstate projected revenue (Mallory et al., 2020b). This study – building on a decade of empirical data – is well-placed to inform robust analysis of future scenarios and cost-sharing arrangements that ensure resource-oriented sanitation services are financially viable and affordable for all.

3.4. Limitations and future research

A limitation of this study is its focus on financial costs and exclusion of social and environmental externalities. Relevant externalities include greenhouse gas emissions incurred or avoided due to fecal sludge transport and treatment, the expected health benefits associated with safe sanitation service provision, and environmental benefits linked to safer management of fecal sludge. The decision to exclude externalities was made in the knowledge that the economic benefits of fecal sludge management are already well documented (Balasubramanya et al., 2017), and are challenging to comprehensively monetize for particular contexts. We therefore chose to focus on the actual financial flows within the Balangoda system for reasons of scope. Nevertheless, further analysis of the health and environmental benefits of safely managed fecal sludge in Balangoda would add value to the findings of this study.

The study would ideally also be complemented by assessment of opportunities to optimize the case study sanitation system beyond those identified in this study as relevant to the reuse phase. Optimization could include cost efficiencies in specific phases of the sanitation chain, or system re-configuration (for example exploring different technological options) to maximize financial and wider reuse benefits. Considering the system with reference to principles of regenerative sanitation (Koottatep et al., 2019) could identify future improvements. Analysis of system efficacy would also be of value given rapid scale-up of FSTPs and an associated need for evidence about their functioning (Klinger et al., 2019). Additionally, the necessity of drawing a manageable system boundary for analysis means that important aspects of demand (agricultural markets for the co-compost) and supply (producers of system components) were excluded, and future research could inform strategies to reduce input costs and increase demand for the end product.

A final area for future research relates to innovative financing and the equitable distribution of costs and benefits associated with resource-oriented sanitation systems. A focus on equity is critical to ensure resource-oriented systems align with the imperative to address deep inequalities within and between countries (Raworth, 2017a, 2017b) as we grapple with global sustainability challenges (Raworth, 2017b). There is scope to explore different models of cost sharing between government agencies, service providers (whether government or privately owned) and households. Cost sharing arrangements will ideally encourage widespread use of sanitation services and facilitate system viability over the long term. This includes ensuring affordability for households and incentivizing proper tank installation and emptying. It also includes incentivizing (and regulating) appropriate emptying in situations with an active

private desludging market. Exploration of innovative financing opportunities for resource-oriented systems is a priority, including strategies to enable the public investment required to ensure system viability and affordability.

4. Conclusion

The merits of resource-oriented sanitation are well established and far reaching. This analysis contributes empirical data on the life-cycle costs of an established, successful resource-oriented system in Balangoda, Sri Lanka. Findings affirm both the potential for resource-oriented sanitation to generate revenue, and the need for substantial complementary investment to ensure whole-of-system financial viability. Analysis of financial perspectives revealed system reliance on household investment (as is common in places with dominantly onsite systems) and a promising business case for the local government service provider – though this derives primarily from a monopoly on desludging services rather than sale of co-compost and is subject to budget prioritization processes. Costs of the reuse phase indicate potential for optimization, informed by critical questioning of assumptions regarding system investments and exploring pathways for system expansion.

The findings of this analysis can inform efforts to advance the implementation of resource-oriented systems in cities where onsite sanitation is common, as is the case across low- and middle-income countries. The global sanitation community is striving to achieve the Sustainable Development Goals and citywide inclusive sanitation in a context of increasing environmental pressures. Building evidence about the costs of resource-oriented sanitation systems in practice can inform greater ambition and practical action towards more widespread implementation and optimization of circular economy approaches to sanitation.

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CRediT authorship contribution statement

Naomi Carrard: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Project administration, Funding acquisition. **Nilanthi Jayathilake:** Investigation, Validation, Writing – review & editing. **Juliet Willetts:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.127135.

References

ADB, JICA, World Bank, 2017. Towards Sustainable Water and Sanitation Services in Sri Lanka: beyond Sustainable Development Goals to Supporting the National Economic Vision.

Andersson, K., Dickin, S., Rosemarin, A., 2016. Towards "sustainable" sanitation: challenges and opportunities in urban areas. Sustainability 8, 1289. https://doi.org/10.3390/su8121289.

Andersson, K., Otoo, M., Nolasco, M., 2017. Innovative sanitation approaches to address multiple development challenges. Water Sci. Technol. https://doi.org/10.2166/wst.2017.600 wst2017600.

Balasubramanya, S., Evans, B., Hardy, R., Ahmed, R., Habib, A., Asad, N.S.M., Rahman, M., Hasan, M., Dey, D., Fletcher, L., Camargo-Valero, M.A., Rao, K.C., Fernando, S., 2017. Towards sustainable sanitation management: establishing the costs and willingness to pay for emptying and transporting sludge in rural districts with high rates of access to latrines. PLoS One 12, 1–20. https://doi.org/10.1371/journal.pone.0171735.

Beecher, J., 1996. Avoided cost: an essential concept for integrated resource planning. Water Res. Educ. 104, 28–35.

Berendes, D.M., Sumner, T.A., Brown, J.M., 2017. Safely managed sanitation for all means fecal sludge management for at least 1.8 Billion people in low and middle income countries. Environ. Sci. Technol. 51, 3074–3083. https://doi.org/10.1021/acs.est.6b06019.

Cairns-Smith, S., Hill, H., Nazarenko, E., 2014. Urban Sanitation: Why a Portfolio of Solutions Is Needed. Bost. Consult. Group, Boston, USA, pp. 1–30. https://doi.org/10.1109/ISIEA.2010.5679450.

Carrard, N., Willetts, J., 2017. Environmentally sustainable WASH? Current discourse, planetary boundaries and future directions. J. Water, Sanit. Hyg. Dev. 7, 1–21. https://doi.org/10.2166/washdev.2017.130.

Center for Water and Sanitation - CEPT University, 2019. Policy brief: financing and business models for faecal sludge and septage treatment for urban India. https://pas.org.in/Portal/document/UrbanSanitation/uploads/Policy brief - Financing and business models FSSM_22.7.2019.pdf. (Accessed 11 November 2019).

Danert, K., Hutton, G., 2020. Shining the spotlight on household investments for water, sanitation and hygiene (WASH): let us talk about HI and the three 'T's. J. Water, Sanit. Hyg. Dev. 64, 2230–2238. https://doi.org/10.2166/washdev.2020.139.

Danso, G.K., Otoo, M., Ekere, W., Ddungu, S., Madurangi, G., 2017. Market feasibility of faecal sludge and municipal solid waste-based compost as measured by farmers' willingness-to-pay for product attributes: evidence from Kampala, Uganda. Resources 6, 31. https://doi.org/10.3390/resources6030031.

Daudey, L., 2018. The cost of urban sanitation solutions: a literature review. J. Water, Sanit. Hyg. Dev. 8, 176–195. https://doi.org/10.2166/washdev.2017.058.

Diener, S., Semiyaga, S., Niwagaba, C.B., Muspratt, A.M., Gning, J.B., Mbéguéré, M., Ennin, J.E., Zurbrugg, C., Strande, L., Mbeguere, M., Ennin, J.E., Zurbrugg, C., Strande, L., 2014. A value proposition: resource recovery from faecal sludge - can it be the driver for improved sanitation? Resour. Conserv. Recycl. 88, 32–38. https://doi.org/10.1016/j.resconrec.2014.04.005.

Dodane, P.H., Mbéguéré, M., Sow, O., Strande, L., 2012. Capital and operating costs of full-scale fecal sludge management and wastewater treatment systems in Dakar, Senegal. Environ. Sci. Technol. 46, 3705–3711. https://doi.org/10.1021/es2045234.

Fonseca, C., Franceys, R., Batchelor, C., Mcintyre, P., Klutse, A., Komives, K., Moriarty, P., Naafs, A., Nyarko, K., Pezon, C., Potter, A., Reddy, V.R., Snehalatha, M., 2011. Life-Cycle Costs Approach: Costing Sustainable Services. IRC - International Water and Sanitation Center.

Franceys, R., Cavill, S., Trevett, A., 2016. Who really pays? A critical overview of the practicalities of funding universal access. Waterlines 35, 78–93.

Gambrill, M., Gilsdorf, R.J., Kotwal, N., 2020. Citywide inclusive sanitation—business as unusual: shifting the paradigm by shifting minds. Front. Environ. Sci. 7, 1–10. https://doi.org/10.3389/fenvs.2019.00201.

Government of the Democratic Socialist Republic of Sri Lanka, 2018. Sri Lanka Voluntary National Review on the Status of Implementing Sustainable Development Goals.

Government of the Democratic Socialist Republic of Sri Lanka, 2017. National Policy on Sanitation in Sri Lanka.

Hashemi, S., Boudaghpour, S., 2020. Economic analysis and probability of benefit of implementing onsite septic tank and resource-oriented sanitation systems in Seoul, South Korea. Environ. Technol. Innov. 18, 100762 https://doi.org/10.1016/j.eti.2020.100762.

Hashemi, S., Han, M., Namkung, E., 2018. Fate of fecal indicators in resource-oriented sanitation systems using nitrifying bio-treatment. Int. J. Environ. Res. Publ. Health 15. https://doi.org/10.3390/ijerph15010164.

Hyun, C., Burt, Z., Crider, Y., Nelson, K.L., Prasad, C.S.S., Rayasam, S.D.G., Tarpeh, W., Ray, I., 2019. Sanitation for Low-Income Regions : A Cross-Disciplinary Review.
ISF-UTS & SNV, 2019. Scheduled Emptying Services as an Entry Point for Change.
Kirchherr, J, Reike, D, Hekkert, M, 2017. Conceptualizing the circular economy: An analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.
Klinger, M., Gueye, A., Sherpa, A.M., Strande, L., 2019. Scoping Study: Faecal Sludge Treatment Plants in South-Asia and Sub-saharan Africa.
Koottatep, T., Cookey, P.E., Polprasert, C., 2019. Regenerative Sanitation: A New Paradigm for Sanitation 4.0, Regenerative Sanitation: A New Paradigm for Sanitation 4.0. https://doi.org/10.2166/9781780409689.
Lüthi, C., Willetts, J., Hoffmann, S., 2020. Editorial: City-Wide Sanitation: The Urban Sustainability Challenge. Front. Environ. Sci. 8, 1–4. https://doi.org/10.3389/fenvs.2020.585418.
Mallory, A., Akrofi, D., Dizon, J., Mohanty, S., Parker, A., Rey Vicario, D., Prasad, S., Welvita, I., Brewer, T., Mekala, S., Bundhoo, D., Lynch, K., Mishra, P., Willcock, S., Hutchings, P., 2020a. Evaluating the circular economy for sanitation: findings from a multi-case approach. Sci. Total Environ. 744 https://doi.org/10.1016/j.scitotenv.2020.140871.
Mallory, A., Holm, R., Parker, A., 2020b. A review of the financial value of faecal sludge reuse in low-income countries. Sustainability 12, 1–13. https://doi.org/10.3390/su12208334.
Manga, M., Bartram, J., Evans, B.E., 2020. Economic cost analysis of low-cost sanitation technology options in informal settlement areas (case study: soweto, Johannesburg). Int. J. Hyg Environ. Health 223, 289–298. https://doi.org/10.1016/j.ijheh.2019.06.012.
McConville, J.R., Kvarnström, E., Maiteki, J.M., Niwagaba, C.B., 2019. Infrastructure investments and operating costs for fecal sludge and sewage treatment systems in Kampala, Uganda. Urban Water J. 16, 584–593. https://doi.org/10.1080/1573062X.2019.1700290.
Mehta, M., Mehta, D., Yadav, U., 2019. Citywide inclusive sanitation through scheduled desludging services: emerging experience from India. Front. Environ. Sci. 7, 1–10. https://doi.org/10.3389/fenvs.2019.00188.
Merli, R., Preziosi, M., Acampora, A., 2018. How do scholars approach the circular economy? A systematicliterature review. J. Clean. Prod. 178, 703–722.
Mills, F., Willetts, J., Evans, B., Carrard, N., Kohlitz, J., 2020. Costs , Climate and Contamination : Three Drivers for Citywide Sanitation Investment Decisions, 8, pp. 1–14. https://doi.org/10.3389/fenvs.2020.00130.
Ministry of City Planning and Water Supply, 2018. SACOSAN Sri Lanka Country Paper.
Mitchell, C.A., Fane, S., Willetts, J., Plant, R.A.J., Kazaglis, A., 2007. Costing for Sustainable Outcomes in Urban Water Systems: A Guidebook.
Moya, B., Sakrabani, R., Parker, A., 2019. Realizing the circular economy for sanitation: assessing enabling conditions and barriers to the commercialization of human excreta derived fertilizer in Haiti and Kenya. Sustainability 11, 3154. https://doi.org/10.3390/su11113154.
Murray, A., Ray, I., 2010. Commentary: back-end users: the unrecognized stakeholders in demand-driven sanitation. J. Plann. Educ. Res. 30, 94–102. https://doi.org/10.1177/0739456X10369800.
Nikiema, J., Cofie, O., Impraim, R., Adamtey, N., 2013. Processing of fecal sludge to fertilizer pellets using a low-cost technology in Ghana. Environ. Pollut. 2, 70–87. https://doi.org/10.5539/ep.v2n4p70.
Otoo, M., Rao, K.C., Hope, L., Atukorala, I., 2018. Resource Recovery from Waste: Business Models for Energy, Nutrient and Water Reuse in Low- and Middle-Income Countries, Resource Recovery from Waste: Business Models for Energy, Nutrient and Water Reuse in Low- and Middle-Income Countries. Routledge.
Rao, K.C.k., Otoo, M., Drechsel, P., Hanjra, M.A., 2017. Resource recovery and reuse as an incentive for a more viable sanitation service chain. Water Altern 10, 493–512.
Ratna Reddy, V., Jayakumar, N., Venkataswamy, M., Snehalatha, M., Batchelor, C., 2012. Life-cycle costs approach (LCCA) for sustainable water service delivery: a study in rural Andhra Pradesh, India. J. Water, Sanit. Hyg. Dev. 2, 279–290. https://doi.org/10.2166/washdev.2012.062.
Raworth, K., 2017a. Doughnut Economics: Seven Ways to Think like a 21st-Ccentury Economist. Cornerstone, London, UK.
Raworth, K., 2017b. A Doughnut for the Anthropocene: humanity's compass in the 21st century. Lancet Planet. Heal. 1, e48–e49. https://doi.org/10.1016/s2542-5196(17)30028-1.
Ross, I., Scott, R., Blackett, I., Hawkins, P., 2016. Tools and Guidelines: Fecal Sludge Management: Diagnostics for Service Delivery in Urban Areas 66.
Satterthwaite, D., Beard, V.A., Mitlin, D., Du, J., 2019. Untreated and Unsafe: Solving the Urban Sanitation Crisis in the Global South.
Schrecongost, A., Pedi, D., Rosenboom, J.W., Shrestha, R., Ban, R., 2020. Citywide Inclusive Sanitation: a public service approach for reaching the urban sanitation SDGs. Front. Environ. Sci. 8, 19. https://doi.org/10.3389/FENVS.2020.00019.
Schroeder, P., Anggraeni, K., Weber, U., 2019. The relevance of circular economy practices to the sustainable development goals. J. Ind. Ecol. 23, 77–95. https://doi.org/10.1111/jiec.12732.
Sgroi, M., Vagliasindi, F.G.A., Roccaro, P., 2018. Feasibility, sustainability and circular economy concepts in water reuse. Curr. Opin. Environ. Sci. Heal. 2, 20–25. https://doi.org/10.1016/j.coesh.2018.01.004.
Shi, Y., Zhou, L., Xu, Y., Zhou, H., Shi, L., 2018. Life cycle cost and environmental assessment for resource-oriented toilet systems. J. Clean. Prod. 196, 1188–1197. https://doi.org/10.1016/j.jclepro.2018.06.129.
Simha, P., Ganesapillai, M., 2017. Ecological Sanitation and nutrient recovery from human urine: how far have we come? A review. Sustain. Environ. Res. 27, 107–116. https://doi.org/10.1016/j.serj.2016.12.001.
Trimmer, J.T., Miller, D.C., Byrne, D.M., Lohman, H.A.C., Banadda, N., Baylis, K., Cook, S.M., Cusick, R.D., Jjuuko, F., Margenot, A.J., Zerai, A., Guest, J.S., 2020. Re-envisioning sanitation as a human-derived resource system. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.0c03318.
UNICEF, WHO, 2019. Progress on Household Drinking Water, Sanitation and Hygiene 2000-2017. Special focus on inequalities, Progress on Drinking Water, Sanitation and Hygiene 2000-2017.
United Nations, 2015. Transforming Our World: the 2030 Agenda for Sustainable Development. https://doi.org/10.1007/s13398-014-0173-7.2. https://sustainabledevelopment.un.org/content/documents/7891Transforming%20Our%20World. pdf.
Waidyarathne, R.G.I.C., Edirisinge, J.C., Otoo, M., Weerakkody, W.J.S.K., 2018. An Inquiry into Farmer Perception on " Fortified Compost .", 17th Agric. Res. Symp, pp. 430–434.
Willetts, J., Carrard, N., Retamal, M., Mitchell, C., Trung, N.H., Nam, N.D.G., Paddon, M., 2010. Cost-effectiveness Analysis as a Methodology to Compare Sanitation Options in Peri-Urban Can Tho, Vietnam. IRC WASH Cost Symp.
World Bank, 2019a. World Bank data - GDP deflator - Sri Lanka. https://data.worldbank.org/indicator/NY.GDP.DEFL.ZS?end=2018&locations=LK&start=1995. (Accessed 25 October 2019).
World Bank, 2019b. World Bank Data - official exchange rate (LCU per US$, period average) - Sri Lanka 2018. https://data.worldbank.org/indicator/PA.NUS.FCRF?end=2018&locations=LK&start=20. (Accessed 11 May 2019).

5.3 Critical reflections: the importance of enablers and narratives

In making necessary choices about the scope and focus of the journal article, two aspects of the study not elaborated in the publication warrant mention here as they informed the inquiry's overall findings. The first relates to how the resource-oriented sanitation system was established, with key enablers being the vision and hard work of a champion, and the availability of public finance. The scheme was conceived and driven by Council's Public Health Inspector. The Inspector saw a need for improved faecal sludge management, an opportunity to add value to the established composting system, and a vision of positively contributing to sanitation, food security, and environmental health in the Balangoda jurisdiction. To progress from idea to implementation, the Inspector secured support and drew in resources in the form of expertise and finance from his professional networks, including a grant from the Ministry of Provincial Councils, Local Government and Sport. The scheme's establishment demonstrates what can happen when an individual WASH professional takes a purposive approach, acting and influencing in line with their vision to achieve sustainability outcomes – reflections that informed a focus on purpose in publication 4 (Chapter 6) and the synthesis (Chapter 7).

Second, the journal article positioned the analysis within circular economy discourse, though with limited critical discussion of definitions, debates and how application of circular economy concepts may inform WASH sector sustainability transformations. Literature on circular economy concepts has rapidly increased over the past decade, with varying levels of connection to sustainability and sustainable development ideas and limited focus on social and institutional dimensions (Nikolaou et al., 2021). In the study, I sought to draw out certain institutional (local government service delivery) and social (equitable distribution of costs) implications of cost findings to highlight their importance. Yet I did not explore how locating a resource-oriented sanitation study within circular economy discourse economy serves as a "sustainability narrative" that shapes pathways of change in socio-technical and social-ecological systems (D'Amato, 2021). Reflections on the potential for circular economy concepts to shape WASH pathways informed the inquiry's insights regarding reframing sector perspectives, which are elaborated in the synthesis (Chapter 7).

5.4 Summary

This chapter presented an in-depth study on the life-cycle costs of a resource-oriented sanitation system in urban Sri Lanka. For the analysed system, revenue from co-compost sales covered reuse-related costs plus 8% of present value costs for other phases of the sanitation chain. The system was financially viable from the local government service provider perspective, though reliant on household investment. In addition to contributing empirical data on urban sanitation costs, the analysis refined a replicable methodology for assessing costs and their distribution. It presented cost analysis as foundational for achieving the normative aim of advancing resource-oriented sanitation, and aligned this aim with wider circular economy imperatives. Reflecting on the publication in the context of this thesis, I described enablers of the case study system that informed a focus on purposive approaches in subsequent phases of research. I also identified how conceptions of circular economy as a sustainability narrative informed the inquiry's synthesis theme of reframing WASH sector perspectives towards a deeper resource-orientation. The next part of this thesis presents an orientation to Part III, introducing the knowledge co-production process undertaken with WASH professionals and articulating its contribution to the overarching research question.

PART III Collaboration and implications

Presenting the process and outcomes of a knowledge co-production process with WASH professionals designed to explore insights from previous studies and seek mutual learning, then synthesising learning to identify meta-level implications for WASH sector sustainability transformations.

Orientation to the co-production study and synthesis

Overview

Part III of this thesis presents the inquiry's fourth and final study, which involved a knowledge co-production process with WASH professionals (Chapter 6). It then concludes the thesis with a synthesis (Chapter 7), which draws together insights from across the studies to identify three themes for WASH sustainability transformations. This orientation explains and justifies the decision to include a knowledge co-production process in the inquiry with reference to its transdisciplinary approach and normative sustainability orientation. I explain how the co-production process connected findings from previous studies to address the inquiry's overarching research question.

Why is knowledge co-production a precursor to the inquiry's synthesis?

The decision to include a knowledge co-production process in the inquiry was driven by two considerations: the emphasis in transdisciplinary approaches on integrating multiple knowledge types through collaboration, and recent scholarship on the potential for knowledge co-production processes to shape and drive sustainability transformations. Here, I explain how each of these considerations informed the decision to include a co-production process as a precursor, and critical bridge towards, the inquiry's synthesis.

First, as described in Chapter 2 (section 2.2), a key feature of transdisciplinary research is meaningful collaboration between researchers and other stakeholders to bring together scientific, practical, local and personal knowledge. While acknowledging tensions between transdisciplinary ideals and the individual nature of doctoral inquiry (as discussed in section 2.7), I sought to include an explicitly collaborative process. Such a process enabled me to explore the resonance and relevance of findings from prior studies with a range of WASH professionals, and generate mutual learning about possible connections between research insights and pathways for action. The co-production process was enormously beneficial for my personal learning and the overall inquiry as elaborated in publication 4 (Chapter

6) where I reflect on researcher power in co-production, and Chapter 7 where I explain how the co-production process informed synthesised insights relevant for WASH professionals.

Second, the decision to include a knowledge co-production process was driven by recent scholarship positioning knowledge co-production as a method for both shaping and driving sustainability transformations. Literature advocating the potential of knowledge co-production to progress sustainability transformations is reviewed in publication 4 (Chapter 6), including assertions that co-production can reconfigure knowledge generation (in line with transdisciplinary principles) and support the collective progression of ideals. Informed by this scholarship, I included a co-production process in this inquiry with an aspiration to both inform research insights and inspire participant WASH professionals towards action in positive directions.

Addressing the overarching research question through co-production and synthesis

Study 4 responded to the inquiry's overarching research question by engaging WASH professionals in deliberation about the relevance and usefulness of planetary sustainability ideas for their work. In the journal article detailing the study, I articulated two study-specific questions. The first explored how WASH sector co-production can generate new knowledge, shared understandings and new competencies relevant to WASH-sustainability intersections (using the framework developed by Schneider et al., 2019). The second added a loop of reflection about how co-production worked as a tool for sectoral sustainability transformation. As such, while the first question directly addressed the overarching question, the second extended insights from the inquiry to consider the practical, nuanced application of co-production as an approach for progressing sustainability transformations through and beyond the inquiry (as shown in Figure 10). While the second question looked beyond the overarching research question, it did shape relevant ideas about reflexive research practice elaborated in the synthesis (Chapter 7).

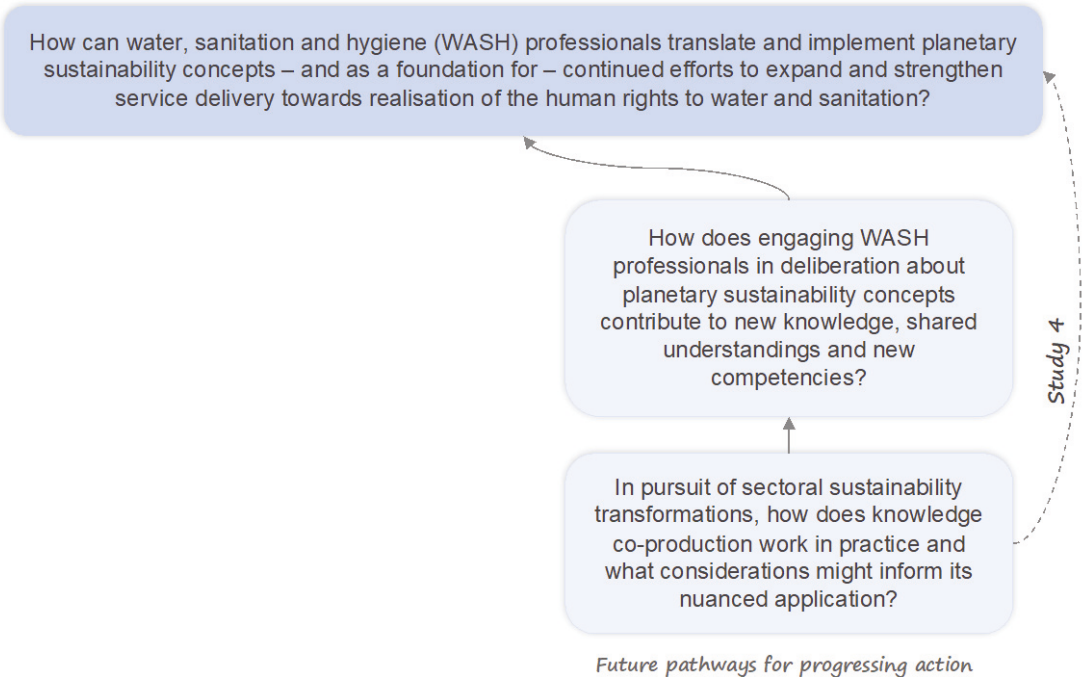

Figure 10 How study 4 research questions addressed the overarching question

The inquiry's synthesis, like study 4, directly addresses the overarching research question. The actor-orientation of the overarching question informed the sensemaking process, in which I reflected on the meaning of each study for WASH professional practice. I applied the circles of control-influence-concern as a heuristic tool (as described in section 7.2), articulating how synthesised themes relate to different groups of WASH professionals and considering my potential to influence change. In doing so, my response to the overarching research question reflects the dual intent of the inquiry to contribute knowledge and seek improvement in the situation.

6 Chapter 6 Knowledge co-production for WASH sustainability

6.1 Overview

This chapter presents the fourth publication included in this 'thesis by compilation'. The publication presents the rationale, approach, findings and critical analysis for study 4: a process of knowledge co-production with WASH professionals focused on strengthening sectoral engagement with sustainability imperatives. Following presentation of the publication, I critically reflect on the study in light of recent scholarship analysing pathways from co-production to sustainability transformations.

6.2 Publication 4 — Placing sustainability at the centre of water, sanitation and hygiene: knowledge co-production for sectoral transformation

Publication 4 is an open access article in *Current Research in Environmental Sustainability* and is included in this thesis in its published form. The publication is available online at https://doi.org/10.1016/j.crsust.2022.100154, and forms part of the journal's special issue focused on stakeholder engagement and co-production in transdisciplinary research.

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Placing sustainability at the centre of water, sanitation and hygiene: Knowledge co-production for sectoral transformation

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ABSTRACT

Efforts to expand the delivery of water, sanitation and hygiene (WASH) services are occurring in the context of increasing pressures on the environmental and resource systems on which WASH services depend. As such, it is imperative to explore how sustainability considerations can be made central to WASH initiatives in ways that strengthen both service delivery and environmental systems. This article contributes insights from a transdisciplinary knowledge co-production process designed to bridge conceptual and practical priorities in a sectoral context – the WASH sector – with the intent to inform transformations at multiple levels from local practice through to global discourse. The co-production process was held online with a select group of WASH professionals from 10 countries. The design involved three components: engaging with worldviews and sustainability concepts; discussing the practical relevance of featured research studies in participant's professional roles; and co-creating ideas about desirable futures and transformation pathways. Findings from the process relate to its method, outcomes and implications for future knowledge co-production across four themes: (i) fostering self-reflection and engaging with purpose; (ii) considering sustainability across scales and contexts; (iii) generating ideas for individual and sectoral action; and (iv) reflecting on researcher power and considerations for future co-production processes. The case demonstrates the potential for co-production in a sectoral context to foster generative self-reflection, shared understandings and practical ideas for action towards sustainability transformations. Methodological insights suggest that future knowledge co-production proponents could beneficially emphasize purpose, work across scales and contexts, and take a reflexive approach to power.

1. Introduction

Universal access to safe water, sanitation and hygiene (WASH) services is foundational for human flourishing. Addressing the substantial challenge of expanding access is the 'WASH sector', a global community of diverse professionals. The sector's efforts are focused primarily on low- and middle-income countries, where 2 billion people live without safely managed water services and 3.6 billion without safely managed sanitation services (UN-Water, 2021). As such, the sector is influenced by the history and dynamics of development aid and associated power dynamics (Hargrove, 2019). A wide range of public and private institutions engage in WASH activities at global, national and local levels, with professionals spanning technical, social and regulatory roles. Multiple public agencies are implicated in WASH, including those with remits relevant to public works, health, education, environment and resource management.

WASH is both a public health and environmental concern, yet focus on 'sustainability' as an environmental rather than service continuity consideration is relatively recent in mainstream sector discourse (Hargrove, 2019; Carrard and Willetts, 2017). Normative directions for the WASH sector are described in Sustainable Development Goal (SDG) 6 (Ensure access to water and sanitation for all) (United Nations, 2015) and the human rights to water and sanitation (United Nations, 2010). Both articulate visions for an equitable and sustainable global community in alignment with sustainability transformation agendas (Scoones et al., 2020), particularly when SDG 6 is viewed as intended within the integrated, interconnected SDG framework (Nilsson et al., 2016; Cerf, 2019). To progress and deepen WASH sector engagement with sustainability, there is opportunity to explore how the WASH sector can foreground planetary sustainability imperatives within and through its ongoing work.

Knowledge co-production is a potentially powerful method for exploring how the WASH sector can strengthen its focus on planetary sustainability. Knowledge co-production – defined as a way to produce

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science that is iterative, collaborative, inclusive of different knowledge types and (increasingly) normative in intent (Wyborn et al., 2019; Norström et al., 2020) – is well suited to a sector characterized by disciplinary and institutional diversity. As both a means to reconfigure knowledge production and a strategy for collective progression of ideals (Schuttenberg and Guth, 2015), co-production promises an integrated vision of research and action that can address societal challenges and move us towards preferred futures. Co-production as a method has been traced to disciplinary traditions in public administration, science and technology studies, and sustainability science (Miller and Wyborn, 2020). In this article, while acknowledging the influence of multiple disciplinary bodies of work, we primarily draw on conceptions of co-production articulated in sustainability science in which, in line with our investigation, co-production is focused on generation of knowledge (or a reimagined 'science') in pursuit of sustainable futures (Miller and Wyborn, 2020). As such, our use of the terms 'knowledge co-production' and 'co-production' (for brevity) should be viewed as interchangeable and reflective of sustainability science conceptions.

Interest in knowledge co-production has increased markedly in recent years, with literature spanning its potential, performance and pitfalls. The potential of co-production stems from its importance for reshaping conceptions of earth system governance (Miller and Wyborn, 2020) and its emergence as the 'gold standard' of engaged science (Lemos et al., 2018). Co-production is conceived as a multi-purpose method: for legitimating research outcomes, driving the implementation of knowledge in society, and/or bringing diverse perspectives and knowledge types to bear in the design of problem-solutions (Wyborn et al., 2019; Norström et al., 2020; Chambers et al., 2021). In global sustainability research, knowledge co-production is a key step in scientific integration, a means for science and society to engage in dialogue that produces rigorous, relevant research (Mauser et al., 2013; Schneider et al., 2021).

With the proliferation of knowledge co-production examples, the performance of co-production as a tool for achieving sustainability outcomes has emerged as a critical area for further research. Co-production has been credited with achieving sustainability outcomes across a wide range of sustainable development themes (Lemos et al., 2018; Chambers et al., 2021; Jagannathan et al., 2020; Pohl et al., 2010). However, reported outcomes do not yet attest to the transformative potential of co-production claimed by its proponents (Jagannathan et al., 2020; Oliver et al., 2019). To address the risk that co-production becomes an end in itself rather than a means for effective engagement (Lemos et al., 2018), there is opportunity to strengthen the evidence base about co-production's achievements and potential. Articulating theories of change about the ways in which co-production can drive transformative change is one means by which to define and assess complex impact pathways (Schuttenberg and Guth, 2015; Oberlack et al., 2019; Schneider et al., 2019). One such an approach has been described by Schneider et al. (2019) who identify three generic mechanisms through which knowledge co-production can lead to impact, namely knowledge generation, social learning and enhancing leadership competencies.

Recent literature also highlights potential pitfalls associated with knowledge co-production and its role in sustainability transformations. Co-production – particularly when normatively framed – has been critiqued as tending towards apolitical conceptions of engagement and knowledge (Wyborn et al., 2019; Jagannathan et al., 2020; Turnhout et al., 2020; Fritz and Binder, 2020). Questions of power are particularly pertinent when co-production occurs in contexts characterized by deep historical asymmetries, such as is the case with South-North collaboration (Vincent et al., 2020). While there is a growing body of work emphasizing the importance of power in shaping co-production and its outcomes, a tendency to suggest 'balancing' strategies (Norström et al., 2020; Vincent et al., 2020) could be matched by relational approaches advocating for more nuanced and reflexive perspectives (Fritz and Binder, 2020). Beyond power analysis, relational approaches have been advocated as a means to develop more situated, diverse knowledge production processes in sustainability science (West et al., 2020), and to challenge dominant linear conceptions in which knowledge production is followed by action (West et al., 2019). Such linear conceptions are evident in many 'project' models of co-production, driven by research funding paradigms and a policy-relevant focus on impact pathways (Chambers et al., 2021).

As scholarship and practice on co-production has diversified and evolved, co-production researchers have synthesized insights from multiple processes to offer heuristics and principles for future processes. Four principles for high quality co-production have been proposed by Norström et al. (2020), namely that co-production for sustainability should be context-based, pluralistic, goal-oriented and interactive. The authors expound the principles to inform both design and assessment of co-production. They situate the principles within a call for co-production to engage with deep drivers of current unsustainable trajectories and attend to the values, politics and power inherent in transformative change (Norström et al., 2020). As such, the usefulness of the principles is in their nuanced application across the diverse realms in which co-production occurs.

Complementing a principled approach to co-production design, Chambers et al. (2021) offer a heuristic for identifying benefits and trade-offs associated with different approaches. The analysis identifies six distinct modes of co-production based on analysis of the ways in which co-production processes engage with purpose, power, politics and pathways to impact (Chambers et al., 2021). A key outcome of the analysis is the articulation of trade-offs associated with different design choices, for example knowledge-focused processes were more likely to influence policy compared with relational approaches, but had less potential to inspire collective action (Chambers et al., 2021). Whether, and how, co-production can be designed to achieve both actionable knowledge and transformation of norms and structures – characterized as pragmatic scope 1 and transformative scope 2 outcomes by Jagannathan et al. (2020) – is an important question for future endeavors.

Drawing on the history and trajectory of co-production in transdisciplinary sustainability research, the study presented in this article explores how co-production can contribute to sustainability transformations in the WASH sector. A sectoral focus is novel in knowledge co-production scholarship, with examples tending to focus on specific place- or issue-based questions (Chambers et al., 2021; Jagannathan et al., 2020; Schneider et al., 2019). In this case, we draw on co-production techniques to consider how they might inform a foregrounding of sustainability within a broad professional community. The co-production process involved a diverse group of professionals deliberating the relevance and usefulness of planetary sustainability concepts for WASH. Insights from the process relate to its method, outcomes and implications for future co-production. We first describe the research aims, context and co-production design. We then present and discuss findings from the analysis across four themes: fostering self-reflection and engaging with purpose; considering sustainability across scales and contexts; generating ideas for individual and sectoral action; and reflecting on power and considerations for future co-production processes.

2. Materials and methods

2.1. Aims and scope

The knowledge co-production process sought to engage selected WASH professionals in reflection and deliberation about sectoral engagement with planetary sustainability concepts, with a view to inspiring sustainability-oriented action. Two research questions guided the inquiry:

1. How does engaging WASH professionals in deliberation about planetary sustainability concepts contribute to new knowledge, shared understandings and new competencies?
2. In pursuit of sectoral sustainability transformations, how does knowledge co-production work in practice and what considerations might inform its nuanced application?

This first question explores WASH sector co-production with reference to three generic mechanisms of impact generation associated with transdisciplinary knowledge co-production proposed by Schneider et al. (2019). In Schneider et al.'s theory of change, new knowledge, shared understandings and new competencies are direct activities and outcomes of co-production processes that can drive longer term sustainability transformations by contributing respectively to knowledge promotion, social learning and competence building for reflective leadership (Schneider et al., 2019).

The second research question seeks deeper reflection about how we conceive and design co-production processes when viewed from the WASH sector perspective. In seeking deeper reflection, the intent is to interrogate our assumptions about how co-production should occur and how it might contribute to sustainability transformations. In responding to this question, we situate WASH co-production process reflections within recent literature on principles and critical considerations for co-production in transdisciplinary sustainability research. As such, evidence underpinning the analysis includes both outputs from the knowledge co-production process with WASH professionals, alongside applications and adaptations of insights from literature on knowledge co-production as a strategy for progressing sustainability transformations generally.

2.2. Positioning co-production within doctoral research

The process was undertaken as the culmination of the lead author's transdisciplinary doctoral research exploring the potential for greater WASH sector focus on global sustainability imperatives. [First author] was therefore the facilitator for the co-production process. The doctoral research built on a 10-year career in applied WASH research, responding to a gap in sector discourse and action about sustainability. Three studies completed in earlier stages of the doctoral research provided input content for group reflection. They included: (i) a systematic review of WASH sector sustainability discourse and the potential for planetary boundary ideas to inform future directions (Carrard and Willetts, 2017); (ii) analysis of reliance on groundwater as a source of drinking water and emerging resource issues in ten Southeast Asia and Pacific countries (Carrard et al., 2019); and (iii) analysis of the life-cycle costs of a resource-oriented sanitation system in urban Sri Lanka and implications for advancing a circular economy approach to sanitation (Carrard et al., 2021). The co-production process sought both engagement with research findings and the collaborative development of pathways for action that may inspire long-term sectoral transformation.

The co-production process, and wider doctoral research, built from the lead and co-authors' established careers as transdisciplinary WASH sector researchers. The co-production process featured in this article is not the only, but rather the most recent, of the authors' co-production practices, and generated insights therefore draw on a longer history of transdisciplinary WASH research. In situating the contribution as transdisciplinary, we adopt a conception of co-production as tantamount to transdisciplinary research that is purpose-driven, problem-focused, collaborative, transcends disciplinary boundaries and involves representatives from public, private and civil society realms (Pohl et al., 2021). We also note the authors' position as white women living in a high-income country, operating within the asymmetric power structures characteristic of international development research and seeking to reflexively approach applied research in pursuit of a just and sustainable world.

2.3. Design and analysis

Design of the co-production process sought to prioritize voices and experiences from low- and middle-income countries, and to maximize the diversity of WASH domains and contexts represented within a small group size that enabled inclusive discussion. The decision to prioritize low- and middle-income country participants was in effort to counter the historic dominance of high-income country voices in sector leadership (Worsham et al., 2021). The process was run online with a total of 14 participants across two sequential Zoom videoconferencing forums with the same agenda (nine in the first session, five in the second). The aim was to recruit 12–16 participants in total, such that each session would have a sufficiently small group to enable inclusive, open and meaningful engagement and exchange. Participants were recruited purposively through professional networks: the focus was on those with an expressed interest in the nexus of WASH and sustainability. In targeting participants with interest in the topic, the intent was to capitalize and build on existing knowledge and motivation to act. Participant recruitment also sought diversity in gender, age, level of professional experience, country of origin and aspect of WASH sector focus.

The final cohort included 6 women and 9 men from 10 countries. Of the 14 participants, 11 identified as nationals of low- and middle-income countries, with 8 living in their country of origin. Participants held roles as government officials and policy advisors, researchers, private sector consultants, an international organization advisor and civil society representatives. A number held multiple positions, for example working in both research and consulting roles. Participants had disciplinary backgrounds in engineering, earth system science, social science, and policy and planning. Both water and sanitation expertise were represented across urban and rural contexts. The cohort broadly reflected a mix of skills and roles typical of the WASH sector, with a notable exception that no participants identified as public health experts or having roles focused on hygiene (including for example handwashing or menstrual health). Further, no participants identified as having specialist skills in gender equality, disability, and social inclusion, which are critical considerations for the pursuit of universal, equitable WASH services (Cumming and Slaymaker, 2018; Workman et al., 2021). Limitations related to group representativeness are discussed in Section 2.4.

Prior to the online forums, participants were invited to complete the Worldviews Test based on Hedlund-de Witt's Integrative Worldviews Framework (Hedlund-de Witt, 2012). The Integrative Worldviews Framework extends previous measures of environmental values, moving beyond a tendency to focus on binary constructions towards recognition of the human potential for cognitive integration (Hedlund-de Witt, 2012). Questions in the Worldviews Test explore perceptions of reality, knowledge, values, identity and society (Worldviews Test, n.d.). In requesting prior completion of the Worldviews Test, the intent was to orient participants towards open, inclusive, reflexive discussion (Hedlund-de Witt, 2014). As such, the identified mix of worldviews was not given emphasis during forum discussions, with participants instead invited to firstly reflect on what completion of the Worldview test brought up for them, and secondly to be mindful of the importance of diverse worldviews and value systems in shaping a knowledge co-production process.

Each forum ran for 2.5 h with a three-phase agenda. The first phase involved orientation to the purpose and format of the forum, introduction of framing sustainability concepts and a reflection on the Worldviews Test. The idea of a 'safe and just space for humanity' between planetary boundaries and social foundations (Rockström et al., 2009; Steffen et al., 2015; Raworth, 2017) was introduced to frame WASH-sustainability conversations. Participants were invited to share their thoughts about the experience of taking the Worldviews Test and reflect on how different values and worldviews might inform the content and outcomes of group activities focused on WASH and sustainability.

In the second phase, the facilitator shared brief (3 min) pre-recorded videos about research studies (described in 2.2). Videos told the story of

each study according to a central idea (framed as a future direction or call to action), justification of its relevance to WASH professionals, and selected details of research findings and analytical insights. Participants were then prompted to share responses using the interactive presentation platform Mentimeter or directly in discussion. Prompts invited responses regarding how the content made participants feel (emotional reaction), what it made them think about (relevance to their own experiences), and what it inspired them to do (how they might act in their work). The decision to share research through video storytelling sought to leverage the power of stories as mechanisms for scientific communication and sustainability transformations (Veland et al., 2018; Riedy, 2021). Prompting for feelings sought to link emotional responses (which are foundational for motivation (Riechers et al., 2019)) with reflections on relevance and ideas to inspire action – the ultimate goal of co-production.

The third phase involved a futures-oriented co-creation activity using an adapted form of the Three Horizons framework. The Three Horizons framework is a foresight tool that supports groups to grapple with complex challenges and generate agency in designing viable pathways towards a preferred future (Sharpe et al., 2016; Sharpe, 2013). The tool identifies three horizons: the first representing the current (unsustainable) system; the third the emerging and preferred successor to the current system; and the second the domain of innovations and disruptions that can either perpetuate the existing unsustainable system or be harnessed to achieve the preferred future.

In the forum, the Three Horizons framework was adapted for online, condensed application, using a collaborative whiteboard (Miro) to co-create ideas about each horizon. The activity was scoped to focus on the intended outcome of the forum, which was to prompt a shift in WASH sector activities towards greater focus on sustainability. As such the preferred, viable future was articulated as *a future where water and sanitation professionals pursue the human rights to water and sanitation for all in ways that contribute to (and don't undermine) planetary sustainability*. Participants were invited to continue adding content to the collaborative whiteboard after the forum, allowing time for ideas to emerge beyond the actual time-limited events.

Inductive analysis of forum data identified insights about co-production outcomes (research question 1) and process (research question 2). Data included audio recordings of discussions and outputs from interactive platforms (Mentimeter, Miro whiteboard and Zoom chat). Codes were developed with reference to three relevant frameworks. The first group of codes identified outcomes of the WASH forums linked to Schneider et al.'s (Schneider et al., 2019) mechanisms for impact generation, with a particular focus on the direct activities and outcomes of (i) new knowledge, (ii) shared understandings and (iii) new competencies. To elicit process reflections, a second group of codes drew on Norström et al. (2020) principles that knowledge co-production should be: (i) context-based; (ii) pluralistic; (iii) goal-oriented; and (iv) interactive. A third group of codes sought complementary insights by exploring data through the lens of leverage points for sustainability transformations (Waddock et al., 2020). A list of codes used is provided in Appendix A.

Analysis of forum data was iterative, informed by thematic analysis of knowledge co-production literature and prior doctoral research on WASH discourse (Carrard and Willetts, 2017). The iterative analysis was a deliberate strategy to ensure validity of findings given the small-scale nature of the engagement process and intent to derive general insights relevant to either or both co-production as a method, and strategies for strengthening WASH sector engagement with sustainability imperatives. Strategies to ensure validity (drawing on the framework and definitions of Creswell and Miller (2000)) included peer debriefing between the lead and co-authors to challenge assumptions and interpretations, and researcher reflexivity (elaborated in Section 3.4). The research was approved by the University of Technology Sydney Human Research Ethics Committee (Reference: ETH21-5896).

2.4. Limitations

The co-production process involved a single point of interaction with each group of participants, which is a limitation given the co-production ideal of long-term iterative engagement (Chambers et al., 2021; Jagannathan et al., 2020). The decision to proceed with a single point of engagement was made to ensure timely completion of the research project and minimize participant inconvenience, however opportunities to reflect and revisit discussion points were foregone due to this choice. As one mitigating strategy, engagement before and after the event was encouraged by setting up message groups, email threads and an open collaborative whiteboard. Further, while the short-form nature of the co-production process did not allow for collaborative framing of the design and discussion topics, the researchers' long-term transdisciplinary research in the sector provided a strong foundation for appropriate pitching of content and activities. The limitations and value of short-form co-production are discussed further in Section 3.5.

A further limitation relates to overall representativeness. Representativeness is an important principle, but it is unachievable in small group settings, given the diversity and breadth of the WASH sector. Our objective was rather to ensure indicativeness through diversity in dimensions relevant to the sector and the questions at hand (see Section 2.3). We recognize that alternatively constituted cohorts would have shaped discussions in different ways. The validity of our findings comes from their generality, that is we do not seek to provide definitive insight into the ways in which WASH professionals engage with sustainability concepts. Instead, in keeping with our process and data, our findings are general, and relate to knowledge co-production as a research method and approach to create change.

A final limitation is that the process was run in English, which precluded the inclusion of non-English speakers. Given ongoing knowledge decolonization debates in the sector, and the fact this emerged as a theme for action (see Section 3.3), developing mechanisms to enable multi-lingual processes will be important for future co-production events.

3. Results and discussion

In this section we present and discuss results across four themes: (i) fostering self-reflection and engaging with purpose; (ii) considering sustainability across scales and contexts; (iii) generating ideas for individual and sectoral action; and (iv) reflecting on researcher power and considerations for future co-production processes. The four themes integrate data from the WASH sustainability forums with insights from knowledge co-production literature, and the authors' WASH sector perspective. We conclude by synthesizing findings across the lenses of our analysis and considering the limitations and value of short-form co-production.

3.1. Fostering self-reflection and engaging with purpose

The WASH sustainability forums fostered participant self-reflection and engagement with value-based ideals about future directions. Prior completion of the Worldviews Test (Hedlund-de Witt, 2012) was a novel and useful exercise for participants, enhancing self-reflection and an openness to plural perspectives. Participants appreciated the opportunity for self-reflection, sharing that the test "helped me to understand myself" or "helped me to know myself a little more". The test facilitated an expansion of thinking beyond daily activities into a more reflective mode, moving towards reflexivity by exploring ways of thinking, assumptions and underlying values (Bradbury and Divecha, 2020). One participant reflected that "questions do not relate to my daily activities, so it was interesting to explore myself", while another shared her experience of a different way of thinking: "at the beginning I felt that my thoughts were short-circuiting because it is the first time that I have questioned myself in that way to identify what my worldview is".

Presentation of the group results also elicited reflections about the importance of listening to plural perspectives informed by different values. As one participant expressed, the experience prompted thoughts about "the need to listen more and pay attention to what's happening in other parts of the world…the need to seek to understand other worldviews because they are equally valid just as much as any other".

While participants expressed primarily positive reactions to completion of the Worldviews test, they shared concerns relating to its (perceived) dichotomous presentation of science and faith and its appropriateness across diverse cultural contexts. Two participants expressed discomfort with questions about the relative importance of science and spirituality in driving personal perspectives. They had trouble choosing between science-oriented and faith-oriented responses, with one emphasizing the need to respect diverse ways of thinking across cultures and spiritual orientations:

> *"For many professional people, science only should become the answer to everything. However, I believe…in the different cultures around the world…all of them should be respected…the most important [aspect] for me is respect of thinking, especially…thinking of the spiritual word that everyone believes in."*

The appropriateness of the test for diverse cultural contexts was also questioned by participants, particularly with reference to conceptions of tradition and modernity.

> *"I don't know if it takes into consideration the cultural diversity that we all come from, something that is…modern in one part of the world can be considered very traditional in other parts of the world."*

Despite these concerns, participant completion of the Worldviews Test was an effective mechanism for establishing an open, reflective tone. Concerns expressed by participants augmented its value as a reflective exercise, validating the decision to focus on the personal experience of test taking rather than group results. The discussions conveyed interest in, and a safe space for, self-reflection – a foundational skill for competency in reflective leadership (Schneider et al., 2019). Creating space for discussion about worldviews also provided opportunity for the facilitator to share her own epistemic values and motivation for convening the events, fostering reflexivity about facilitator power in shaping co-production processes (discussed further in Section 3.4).

In addition to establishing a safe space for open discussion, reflecting on worldviews, along with introduction of big picture sustainability concepts, oriented participants towards engagement with purpose. The concept of purpose underpinning forum design drew from the foundational transdisciplinary work of Jantsch (1970), in which purpose denotes value-based ideals about human survival in dynamically changing environments. The emphasis on purpose was designed to complement linear conceptions of change implied in goal-oriented co-production processes in which participants agree to a measure of success and "meaningful milestones (that is, stepping-stone goals) to achieve and monitor progress" (Norström et al., 2020). While the complexity of social change and its causal pathways is widely acknowledged in co-production literature (Norström et al., 2020; Jagannathan et al., 2020; Oberlack et al., 2019), linear assumptions about knowledge-action pathways persist (West et al., 2019). In the WASH forums, creating space to reflect on deeply held values enabled consideration about the alignment of goal-oriented actions with purposive imperatives. As one forum participant expressed: "[I'm] thinking about what my life goal is, where I'm going and what my priority is".

Consideration of the ways in which engaging purpose can inform deeper reflection is particularly pertinent when thinking from a WASH sectoral perspective. The WASH sector is strongly driven by goals and targets articulated in SDG 6 (Ensure access to water and sanitation for all) and the human rights to water and sanitation. While WASH sector goals are shaped by purposive thinking, they risk losing criticality after their adoption if purpose is not continuously re-considered. A failure to continually reflect on purpose in tandem with the pursuit of goals can result in perverse outcomes, such as occurred when the Millennium Development Goal precursor to SDG6 drove marked efforts to expand sanitation to access in households, with no commensurate focus on safe management of the generated waste (Herrera, 2019; Tortajada and Biswas, 2018) – a critical aspect of WASH for achieving desired public health outcomes.

Discussions in the WASH sustainability forums responded to both sector goals (SDG6 and its targets) and broader purpose (placing the goals within the wider vision of a safe and just space for humanity), yet it was the purposive lens that most effectively elicited reflective contributions. The vision of a safe and just space for humanity (Rockström et al., 2009; Steffen et al., 2015; Raworth, 2017) prompted participants to expand or deepen their thinking about what 'sustainability' means for them. For example, as one participant shared:

> *This concept of planetary boundaries and sustainability boundaries, and this doughnut diagram…it's a fairly new concept to me to think about it this way. When we think about sustainability…I never really think about it in such big picture, you know, pushing planetary boundaries. I don't go to that level.*

Others were prompted to reflect on human-nature relations, conveying either a perspective of inter-connectedness: "it makes me think about sustainability…the need to imagine ourselves as connected to nature" or reflecting a conception of utility and stewardship towards nature: "natural resources are a gift in our lives, and we should…do our activities trying to replenish after taking advantage of them". Human-nature connectedness has been identified as a "realm of deep leverage" for sustainability transformations (Abson et al., 2017; Riechers et al., 2021). When seeking to lay foundations for broad and deep change – such as when focusing on sector-wide engagement with sustainability – experiences from the forums therefore suggest value in emphasizing purpose alongside goal-oriented thinking.

Emphasizing purpose in the WASH sustainability forums was particularly valuable given the short-form nature of the process. A pragmatic balancing of goal-oriented discussion and action identification (see Section 3.3), with deeper questioning of purpose, created space for relevance to emerge from the process rather than be predefined. Klenk and Meehan argue for this kind of emergent relevance in transdisciplinary research, suggesting that shifting our collaborative frames from notions of "engagement" to "encounters" between researchers and stakeholders can helpfully re-orient attention towards more responsive, open forms of relevance (Klenk and Meehan, 2017). *Re*-conceiving co-production as shaped by purposeful encounters asserts the value of each encounter for shifting conversations towards ideals, even in cases when long term engagement is not feasible. A purposeful approach to co-production encounters also allows for the characteristic messiness of knowledge production and use (Arnott and Lemos, 2021), while maintaining focus on what is ultimately important.

3.2. Considering sustainability across scales and contexts

The cross-context and cross-scale nature of discussions in the WASH sustainability forums is a second theme, with results indicating value in processes that link big picture ideas to diverse local realities. The value of discussions that cross scales and contexts is a particularly relevant finding for sectoral rather than project-focused co-production, given the intent to inform transformations at multiple levels from local practice through to global discourse. Consideration of changes across places and scales is both necessary for a sector such as WASH, which seeks to reconcile universal aims with local realities, and aligned with breadth and depth of transformation required to address sustainability challenges (Linnér and Wibeck, 2019).

In the forums, participants both asserted the importance of place-based context *and* moved fluidly in their reflections between global

(sector-wide) issues and local realities. Initially, when discussing future directions for WASH informed by planetary boundaries, participants demonstrated a preference to prioritize local perspectives and skepticism about the meaning of global concepts for local contexts. As one participant expressed, "national and local context and culture is very important in putting forward these future directions". As discussions progressed, participants began sharing their perspectives on how the ideas under discussion manifested in their local areas, and what that might mean for their professional practice. One participant spoke about government leadership and the opportunities and risks presented by digitalization in the management and monitoring of water and sanitation services. Another linked sustainability concepts to the need to focus on women's empowerment and leadership development. Ultimately, encouraging reflections that span places and issues brought to light interconnections that may have been lost with a narrower focus.

Moving from the conceptual to empirical, engagement with WASH-sustainability studies focused on groundwater reliance and resource-oriented sanitation provided space for participants to reflect on the relevance of each for their own context, and draw on their contextualized experiences to enrich shared understandings about sector-wide challenges. Responding to the groundwater study, one participant shared an expansion of focus: "I'm intrigued because as a water practitioner…of course the focus has always been piped water to households and it's quite intriguing to learn that it's also important to focus on the water source". The groundwater study elicited reflections about the cultural significance of wells in some contexts, the potential for groundwater depletion to cause conflict in areas with large refugee populations, the relative costs of different water sources, the ways in which access to water resources drive inequalities, groundwater pollution from heavy metals, climate change impacts and data (un)availability. Discussions about resource-oriented sanitation spanned reflections on how policy frameworks can drive technological innovation, the importance of mindset change for achieving circular economy visions, the affordability of alternative sanitation models, and the distribution of responsibilities between citizens and state. The breadth of ideas discussed spanned environmental, social, technical and governance considerations, each grounded with contextualized examples.

The importance of context in shaping co-production activities and outcomes is self-evident and rightly reflected in co-production literature (Norström et al., 2020). Yet while a broad conception of context as "not synonymous with local" is presented (Norström et al., 2020), in practice co-production literature is dominated by local examples (Wyborn et al., 2019; Schneider et al., 2021; Moallemi et al., 2020). When seeking sectoral transformation, equal focus is warranted on the ways in which the local connects to the global in mutually informative ways. An explicit focus on identifying interconnections encourages a systemic perspective that can generate potentially catalytic ideas and actions across places and scales. As such, sectoral co-production can benefit from the more general call for exploration of how co-production can work across scales with globally powerful actors (Chambers et al., 2021; Schneider et al., 2021).

3.3. Generating ideas for action: Individual intentions and sectoral priorities

A third theme is the generation of ideas for action, which encompassed both individual intentions and identifying sectoral priorities. Action towards sustainability is a core objective of co-production (Norström et al., 2020; Miller and Wyborn, 2020) and the generation of action ideas is therefore an important area of analysis. It is important to note that the focus here is on *ideas* for action rather than action itself, given the pathways from intention to action would take more time and likely require further engagement to both bolster intentions and measure outcomes. Nevertheless, two forms of action ideas emerged from the forums that warrant critical reflection: actions that can be taken within each participant's individual realm of influence; and priorities for sector-wide focus.

Individual ideas for action were generated during both discussions about presented research studies and the Three Horizons visioning activity. When prompted 'what are you inspired you to do in your work?', participants shared ideas for actions in policy, education, technology and community engagement. For example, one participant shared a motivation to train university students in resource-oriented sanitation, while another was inspired to advocate for groundwater policy formulation in their jurisdiction. Participants also expressed a general intent to include a stronger sustainability orientation in their work, for example to "think more on sustainable and circular solution", "think of complex interconnected issues of resources, access, governance" and to "go beyond the technical responsibilities of building… infrastructure, to foresee consequences for the inappropriate use of natural resources or polluting them".

The individual action ideas constitute seeds of transformation knowledge – knowledge about how to make change from the current to preferred situations (Schneider et al., 2019). However, action ideas expressed at the individual level do not equate to the impact pathway of shared understandings leading to coordinated, joint action in project framed co-production processes (Schneider et al., 2019). The focus on individual actions can be attributed to the single round of engagement, the diversity of participant interests and locations, and prompts linking discussion content to participants' own work. Yet ideas were shaped by group discussion about common interests informed by diverse experiences and plural perspectives, so are reflective of the ideal of co-production in which interaction is foundational for learning and action (Norström et al., 2020). The expression of meaningful action ideas relevant to participants' own work indicates that in addition to driving joint action, co-production may forge a path to impact through 'enabling' transformation approaches in which "individually smaller actions…over time…shift system states in ways which may be unexpected but which reflect the values and visions of mobilized agents" (Scoones et al., 2020). Further exploring, and finding ways to measure, these kinds of changes is an important area of future focus.

Beyond individual intentions, sectoral transformation knowledge was generated through the Three Horizons visioning activity, with two themes emerging: the importance of building networks to drive collective action for sustainability; and the imperative to decolonize development knowledge. When asked about future directions and actions following the visioning activity, participants shared their intentions to "connect with more networks", "build even more than before strategic alliances", "look for innovative partnerships", "build more bridges" and "build solidarities". One participant focused particularly on fostering collective action with young people, harnessing their local knowledge and making use of the connective potential of open-source technologies to co-develop strategies that address local sustainability concerns. The focus on building networks and solidarities suggests participant intent to further explore sustainability-WASH connections by moving towards collective action in their own contexts, in ways that strengthen their diverse individual intentions.

A second action theme identified through the Three Horizon discussions concerned the redressing of power imbalances in knowledge contributing to WASH sector priorities and plans. When reflecting on horizon three – trends taking us in the direction of our preferred future – participants highlighted that "decolonization debates [are] driving different voices in the conversations". One participant reflected on the influence of established power structures in shaping decision-making:

> *Historical models…pertain not only to technology of centralized supply or centralized management of wastewater, but there are also historical models of power sharing. There are also historical models of decision-making processes, which obviously the people in power have interesting continuing status quo and any change in that.*

Participants asserted the importance of valuing 'community'

knowledge to address inequities, for example the "incorporation of traditional knowledge to ensure local communities have a greater voice". Others spoke more generally about changes in education curricula stressing diversity of voices, and "a change in perception about knowledge and knowledge creation [such that] traditional knowledge from Global South will be central moving ahead". The emergence of knowledge decolonization as a theme relevant to WASH-sustainability visions reflects wider sector discourse highlighting and challenging the dominance of Global North voices in shaping conversations (Worsham et al., 2021; Luseka, 2020; Kapur, 2020). As sustainability conversations continue across the sector, a power-reflexive approach will be essential to address critical questions about whose voices carry influence (discussed further in Section 3.4).

3.4. Researcher power and considerations for future co-production processes

In this final section we build on the action-theme of addressing WASH sector power imbalances by considering researcher power, and how researcher-reflexive approaches might inform future co-production activities. We reflexively acknowledge the extent of researcher influence over the WASH sustainability forums and discuss the tensions and trade-offs associated with alternative strategies. In doing so, we acknowledge the facilitator's position of privilege as a high-income country researcher working within South-North research collaborations.

In these WASH sustainability forums, the lead researcher determined who to invite, the agenda, and how participation was managed. A targeted set of actors were invited – WASH professionals primarily from low- and middle-income countries with an interest in sustainability – to the exclusion of others. While the inclusion criteria were justified with reference to the aims and ethical considerations of the research, it is important to consider the extent to which this decision shaped the process. Equally, in framing the topic and using previous work as input knowledge for reflection, the facilitator scoped which sustainability and WASH issues (from a potential plethora) were given focus. While participant reflections and discussion could in theory have diverged to a wider set of issues, they tended to stay close to the topics on the agenda, reflecting the truism that 'the questions you ask determine the answers you get'. This was the case despite the participants being professionals with capacity to critically challenge how discussions were framed.

Power is increasingly acknowledged as important in co-production (Wyborn et al., 2019; Norström et al., 2020; Schuttenberg and Guth, 2015; Chambers et al., 2021; Vincent et al., 2020). Yet to date, power has dominantly been conceived as something to be identified and ameliorated, such that imbalances do not lessen the quality of engagement and its outcomes (Norström et al., 2020; Vincent et al., 2020; Bréthaut et al., 2019). A more reflexive approach to power in transdisciplinary research has been advocated by Fritz and Binder (2020) who draw on theories of power as relational, and participation as constructed by societal contexts, to elucidate the ways in which power shapes transdisciplinary research. In this model three types of power are at play in transdisciplinary research: instrumental power in which one actor influences another; structural power, which describes the conditions (both material and structural) influencing actors' decision-making; and discursive power in which subtle forms of influence – through values, norms and ideas (such as sustainability) – influence an agenda or process (Fritz and Binder, 2020). Researchers, funding bodies and practitioners exercise these three types of power in different ways, with researchers having substantial instrumental and discursive power in their choice of who to include, setting the agenda, and dictating the rules of engagement (Fritz and Binder, 2020).

For future co-production processes seeking sustainability transformations, recognition of the multiple ways in which researcher-facilitator power manifests demands reflexively sitting with, rather than trying to solve, power dynamics. In other words, it means challenging the tendency for researchers to consider themselves as neutral or objective facilitators whose role is "identifying positions of power…and developing ameliorative strategies" (Norström et al., 2020). A researcher-reflexive approach is needed (Fritz and Binder, 2020) in which the aim is to recognize and be explicit about the profound ways in which researcher power shapes process, and in doing so to consider "the possibility of moving from power over to power with" (Bradbury and Divecha, 2020). This is particularly true for processes involving collaborations between Global South and Global North researchers and participants, which are shaped by historical and perpetuating power imbalances.

In seeking sectoral transformations for sustainability, a researcher-reflexive approach could pursue different strategies for co-production. One strategy is to cede researcher power in determining the agenda and mode of engagement within a process, taking a purposive approach but leaving space for participants to determine what is worthy of discussion and how those discussions should happen (though it is important to acknowledge that this initial process is in itself shaped by the researcher). An open, purposive approach is more likely to achieve a sought-after feature of co-production: the recognition and valuing of diverse knowledge types (Norström et al., 2020; Blythe et al., 2018) that researchers may not have allowed space for given assumptions they bring to the agenda and process design. This plurality is particularly important in the pursuit of sustainability transformations given a dominance of positivist epistemologies in environmental sustainability discourse (Blythe et al., 2018), a feature also characteristic of the WASH sector given the importance of engineering and public health disciplines in expanding WASH services.

A second strategy is one of open acknowledgement, rather than ceding, of researchers' instrumental power. It is not always appropriate to redistribute or balance power, for example participants may not want the responsibility of shaping a process and taking on decision making roles (Turnhout et al., 2020), particularly if their participation is not remunerated or in situations where participation fatigue is a risk (Lemos et al., 2018). Yet power must be acknowledged and addressed if co-production is to fulfil its aim to contribute to sustainability transformations that do not inadvertently reinforce existing unequal power relations (Turnhout et al., 2020). For researchers, investing in the development of reflexive skills that enable responsiveness to positionality will support co-production processes in which friction can be productive, and relevance (and therefore impact) can be emergent (Klenk and Meehan, 2017).

3.5. Synthesis of findings and reflections on the value of short-form co-production

In this final section, we synthesize insights from previous themes with reference to the analysis frames that informed their development, namely Schneider et al.'s generic mechanisms of impact generation (Schneider et al., 2019), and Norström et al.'s principles for co-production in sustainability research (Norström et al., 2020). Reflecting on the cross-theme synthesis, we conclude by considering the limitations and value of short-form co-production processes when working in a sectoral context.

Exploring outcomes with reference to Schneider et al. (2019) theory of change for co-production identified ways in which the process generated (i) new knowledge, (ii) shared understandings and (iii) new competences – the direct activities and outcomes of co-production that can lead to impact. Systems and target knowledge were developed through cross-scale and cross-context discussions, as well as purposive reflections that prompted critical consideration of goals. The seeds of transformation knowledge were identified in visioning and action-oriented discussions, generating individual action-intentions and priority sectoral themes of knowledge decolonization and building solidarities for collective action. The focus on collective action arose from activities designed to build shared understandings of sector challenges and future possibilities, which emphasized joint learning and the need

for deliberation about values and how they drive actions. Finally, new experiences of self-reflection, in particular reflection about worldviews, provided an initial step towards development of reflective leadership skills, though building such experiences into competencies would require long-term personal development beyond a single co-production event.

Analyzing the process through the lens of principles for co-production in sustainability research (Norström et al., 2020) identified three considerations for the nuanced application of co-production ideals, particularly when working towards sectoral change. First, a goal-orientation can be enriched by an emphasis on purpose, such that goals are critically questioned and shared visions that transcend goals can emerge. Second, to complement the dominance of locally situated co-production examples, there is scope to consider how future co-production can work across scales and contexts to foster system-wide perspectives. Finally, a reflexive focus on researcher power is essential for co-production to engage meaningfully with the ways in which power shapes the plurality and interactivity of co-coproduction processes.

The short-form nature of the WASH co-production process was a limitation given the strong emphasis placed on long-term engagement in co-production scholarship, yet there was demonstrable richness in the conversations that suggests value in co-production even when long-term engagement is not feasible. Short-form engagement is certainly constrained in its capacity to achieve and demonstrate impact, and claiming impact from the WASH sustainability forums is unrealistic. Similarly, multiple points of interaction would be required to cement trusting relationships, bridge different levels of expertise across relevant concepts, and allow for iterative building of knowledge over time. Nevertheless, the data shows there was depth of engagement in the WASH forums that attests to the value of short-form co-production if well designed and facilitated, and the process generated potentially catalytic ideas for action. Three design features underpinned the richness of WASH forum discussions: working from values to connect with deep motivations for change; using engaging narratives to incorporate research insights and elicit reflections on their relevance for each participant; and including visioning to foster imagination about possible preferred futures and pathways that move us towards them. While longer-term engagement would strengthen WASH forum outcomes, findings demonstrate the value of well-designed co-production of shorter duration when timelines and funding models preclude more established approaches.

4. Conclusion

In the context of global environmental challenges, it is imperative to consider how different actors and groups can contribute to sustainability transformations. As a sector united by human rights ideals and shaped by resource management realities, the WASH sector is well-placed to contribute novel thinking and practices towards sustainable futures. Knowledge co-production – with its potential to both diversify and integrate knowledge and action – offers a mechanism for progressing WASH sustainability discourse, as the co-production case profiled in this article demonstrates. The co-production process, although short in duration, generated rich discussions that fostered self-awareness and connected deeply held values with sustainability imperatives and ideas for practical action. The process articulated priority themes for strengthening the sector's focus on sustainability: solidarity building for collective action; and knowledge decolonization. Progressing these themes through further engagement and action, including during future sector co-production processes, will be important.

The co-production experience also highlighted considerations for the nuanced application of co-production principles, particularly the opportunity to enrich a goal-orientation by emphasizing purpose, to explore how co-production can work across scales and contexts, and to strive for power-aware processes by strengthening and enacting researcher reflexivity. The findings of this analysis can inform future co-production activities, particularly those seeking to generate knowledge and catalyze action in a sectoral context. The findings also show the value of short-form co-production when the ideal of longer-term engagement is not feasible. Well-designed processes can engage, inspire, and offer a strong foundation for further research and action.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crsust.2022.100154.

References

Abson, D.J., Fischer, J., Leventon, J., Newig, J., Schomerus, T., Vilsmaier, U., von Wehrden, H., Abernethy, P., Ives, C.D., Jager, N.W., et al., 2017. Leverage points for sustainability transformation. Ambio 46, 30–39.
Arnott, J.C., Lemos, M.C., 2021. Understanding knowledge use for sustainability. Environ. Sci. Pol. 120, 222–230.
Blythe, J., Silver, J., Evans, L., Armitage, D., Bennett, N.J., Moore, M.L., Morrison, T.H., Brown, K., 2018. The dark side of transformation: latent risks in contemporary sustainability discourse. Antipode 50, 1206–1223.
Bradbury, H., Divecha, S., 2020. Action methods for faster transformation: relationality in action. Action Res. 18, 273–281.
Bréthaut, C., Gallagher, L., Dalton, J., Allouche, J., 2019. Power dynamics and integration in the water-energy-food nexus: learning lessons for transdisciplinary research in Cambodia. Environ. Sci. Pol. 94, 153–162.
Carrard, N., Willetts, J., 2017. Environmentally sustainable WASH? Current discourse, planetary boundaries and future directions. J. Water Sanit. Hyg. Dev. 7, 209–228.
Carrard, N., Foster, T., Willetts, J., 2019. Groundwater as a source of drinking water in Southeast Asia and the Pacific: a multi-country review of current reliance and resource concerns. Water (Switzerland) 11.
Carrard, N., Jayathilake, N., Willetts, J., 2021. Life-cycle costs of a resource-oriented sanitation system and implications for advancing a circular economy approach to sanitation. J. Clean. Prod. 307, 127135.
Cerf, M.E., 2019. Sustainable development goal integration, interdependence, and implementation: the environment–economic–health nexus and universal health coverage. Glob. Challenge. 3, 1900021.
Chambers, J.M., Wyborn, C., Ryan, M.E., Reid, R.S., Riechers, M., Serban, A., Bennett, N. J., Cvitanovic, C., Fernández-Giménez, M.E., Galvin, K.A., et al., 2021. Six modes of co-production for sustainability. Nat. Sustain. 49.
Creswell, J.W., Miller, D.L., 2000. Determining validity in qualitative inquiry. Theory Pract. 39, 124–130.
Cumming, O., Slaymaker, T., 2018. Equality in Water and Sanitation Services. Routledge.
Fritz, L., Binder, C.R., 2020. Whose knowledge, whose values? An empirical analysis of power in transdisciplinary sustainability research. Eur. J. Futur. Res. 8.
Hargrove, A., 2019. Global aid in the water sector: a descriptive analysis of international development effectiveness. Int. J. Soc. Sci. Stud. 7, 19.
Hedlund-de Witt, A., 2012. Exploring worldviews and their relationships to sustainable lifestyles: towards a new conceptual and methodological approach. Ecol. Econ. 84, 74–83.
Hedlund-de Witt, A., 2014. Rethinking sustainable development: considering how different worldviews envision "development" and "quality of life.". Sustain 6, 8310–8328.
Herrera, V., 2019. Reconciling global aspirations and local realities: challenges facing the sustainable development goals for water and sanitation. World Dev. 118, 106–117.
Jagannathan, K., Arnott, J.C., Wyborn, C., Klenk, N., Mach, K.J., Moss, R.H., Sjostrom, K. D., 2020. Great expectations? Reconciling the aspiration, outcome, and possibility of co-production. Curr. Opin. Environ. Sustain. 42, 22–29.
Jantsch, E., 1970. Inter- and transdisciplinary university: a systems approach to education and innovation. High. Educ. 1, 403–428.
Kapur, D., 2020. Decolonisation of WASH Knowledge: Addressing Institutional Bias. IRC WASH Blog. https://www.ircwash.org/blog/decolonisation-wash-knowledge-addressing-institutional-bias. accessed 27 September 2021.

Klenk, N.L., Meehan, K., 2017. Transdisciplinary sustainability research beyond engagement models: toward adventures in relevance. Environ. Sci. Pol. 78, 27–35.
Lemos, M.C., Arnott, J.C., Ardoin, N.M., Baja, K., Bednarek, A.T., Dewulf, A., Fieseler, C., Goodrich, K.A., Jagannathan, K., Klenk, N., et al., 2018. To co-produce or not to co-produce. Nat. Sustain. 1, 722–724.
Linnér, B.-O., Wibeck, V., 2019. Sustainability Transformations: Agents and Drivers across Societies. Cambridge University Press.
Luseka, E., 2020. Initiating de-colonisation of WASH sector knowledge. Medium. https://medium.com/@euphresia_luseka/initiating-de-colonization-of-wash-sector-knowledge-c8ad0a9f8d6 (accessed 27 September 2021).
Mauser, W., Klepper, G., Rice, M., Schmalzbauer, B.S., Hackmann, H., Leemans, R., Moore, H., 2013. Transdisciplinary global change research: the co-creation of knowledge for sustainability. Curr. Opin. Environ. Sustain. 5, 420–431.
Miller, C.A., Wyborn, C., 2020. Co-production in global sustainability: histories and theories. Environ. Sci. Pol. 113, 88–95.
Moallemi, E.A., Malekpour, S., Hadjikakou, M., Raven, R., Szetey, K., Ningrum, D., Dhiaulhaq, A., Bryan, B.A., 2020. Achieving the sustainable development goals requires transdisciplinary innovation at the local scale. One Earth 3, 300–313.
Nilsson, M., Griggs, D., Visbeck, M., 2016. Map the interactions between sustainable development goals. Nature 1534, 320–322.
Norström, A.V., Cvitanovic, C., Löf, M.F., West, S., Wyborn, C., Balvanera, P., Bednarek, A.T., Bennett, E.M., Biggs, R., de Bremond, A., et al., 2020. Principles for knowledge co-production in sustainability research. Nat. Sustain. 3.
Oberlack, C., Breu, T., Giger, M., Harari, N., Herweg, K., Mathez-Stiefel, S.-L., Messerli, P., Moser, S., Ott, C., Providoli, I., et al., 2019. Theories of change in sustainability science: understanding how change happens. Gaia 28, 106–111.
Oliver, K., Kothari, A., Mays, N., 2019. The dark side of coproduction: do the costs outweigh the benefits for health research? Heal. Res. Policy Syst. 17, 1–10.
Pohl, C., Rist, S., Zimmermann, A., Fry, P., Gurung, G.S., Schneider, F., Speranza, C.I., Kiteme, B., Boillat, S., Serrano, E., et al., 2010. Researchers' roles in knowledge co-production: experience from sustainability research in Kenya, Switzerland, Bolivia and Nepal. Sci. Public Policy 37, 267–281.
Pohl, C., Klein, J.T., Hoffmann, S., Mitchell, C., Fam, D., 2021. Conceptualising transdisciplinary integration as a multidimensional interactive process. Environ. Sci. Pol. 118, 18–26.
Raworth, K., 2017. A doughnut for the Anthropocene: humanity's compass in the 21st century. Lancet Planet. Heal. 1, e48–e49.
Riechers, M., Henkel, W., Engbers, M., Fischer, J., 2019. Stories of favourite places in public spaces: emotional responses to landscape change. Sustain 11.
Riechers, M., Balázsi, Á., García-Llorente, M., Loos, J., 2021. Human-nature connectedness as leverage point. Ecosyst. People 17, 215–221.
Riedy, C., 2021. Discursive entrepreneurship: ethical meaning-making as a transformative practice for sustainable futures. Sustain. Sci. https://doi.org/10.1007/s11625-021-00978-z.
Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H.J., et al., 2009. A safe operating space for humanity. Nature 461, 472–475.
Schneider, F., Giger, M., Harari, N., Moser, S., Oberlack, C., Providoli, I., Schmid, L., Tribaldos, T., Zimmermann, A., 2019. Transdisciplinary co-production of knowledge and sustainability transformations: three generic mechanisms of impact generation. Environ. Sci. Pol. 102, 26–35.
Schneider, F., Tribaldos, T., Adler, C., Biggs, R.O., De, Bremond A., Buser, T., Krug, C., Loutre, M., Paulavets, K., Moore, S., et al., 2021. Co-production of knowledge and sustainability transformations: a strategic compass for global research networks. https://doi.org/10.1016/j.cosust.2021.04.007.
Schuttenberg, H.Z., Guth, H.K., 2015. Seeking our shared wisdom: a framework for understanding knowledge coproduction and coproductive capacities. Ecol. Soc. 20.
Scoones, I., Stirling, A., Abrol, D., Atela, J., Charli-Joseph, L., Eakin, H., Ely, A., Olsson, P., Pereira, L., Priya, R., et al., 2020. Transformations to sustainability: combining structural, systemic and enabling approaches. Curr. Opin. Environ. Sustain. 42, 65–75.
Sharpe, B., 2013. Three Horizons: The Patterning of Hope.
Sharpe, B., Hodgson, A., Leicester, G., Lyon, A., Fazey, I., 2016. Three horizons: a pathways practice for transformation. Ecol. Soc. 21.
Steffen, W., Richardson, K., Rockstrom, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., et al., 2015. Planetary boundaries: Guiding human development on a changing planet. Science (80-) 347, 1259855-.
Tortajada, C., Biswas, A.K., 2018. Achieving universal access to clean water and sanitation in an era of water scarcity: strengthening contributions from academia. Curr. Opin. Environ. Sustain. 34, 21–25.
Turnhout, E., Metze, T., Wyborn, C., Klenk, N., Louder, E., 2020. The politics of co-production: participation, power, and transformation. Curr. Opin. Environ. Sustain. 42, 15–21.
United Nations, 2010. General Assembly Resolution 64/292, UN doc. A/Res/64/292.
United Nations, 2015. General Assembly Resolution 70/1, UN doc. A/Res/70/1.
UN-Water, 2021. Summary Progress Update 2021 - SDG 6 - Water and Sanitation for All.
Veland, S., Scoville-Simonds, M., Gram-Hanssen, I., Schorre, A.K., El Khoury, A., Nordbø, M.J., Lynch, A.H., Hochachka, G., Bjørkan, M., 2018. Narrative matters for sustainability: the transformative role of storytelling in realizing 1.5°C futures. Curr. Opin. Environ. Sustain. 31, 41–47.
Vincent, K., Carter, S., Steynor, A., Visman, E., Wågsæther, K.L., 2020. Addressing power imbalances in co-production. Nat. Clim. Chang. 10, 877–878.
Waddock, S., Waddell, S., Goldstein, B., Linner, B., Schäpke, N., Vogel, C., 2020. Transformation: How to spur radical change. In: Our Future on Earth Report. Edited by Scrutton A. Future Earth.
West, S., van Kerkhoff, L., Wagenaar, H., 2019. Beyond "linking knowledge and action": towards a practice-based approach to transdisciplinary sustainability interventions. Policy Stud. 40, 534–555.
West, S., Haider, L.J., Stålhammar, S., Woroniecki, S., 2020. A relational turn for sustainability science? Relational thinking, leverage points and transformations. Ecosyst. People 16, 304–325.
Workman, C.L., Cairns, M.R., De Los Reyes, F.L., Verbyla, M.E., 2021. Global water, sanitation, and hygiene approaches: anthropological contributions and future directions for engineering. Environ. Eng. Sci. 38, 402–417.
Worldviews Test. https://wvtest.com/ last accessed 06/01/2022.
Worsham, K., Sylvester, R., Hales, G., McWilliams, K., Luseka, E., 2021. Leadership for SDG 6.2: is diversity missing? Environ. Health Insights 15.
Wyborn, C., Datta, A., Montana, J., Ryan, M., Leith, P., Chaffin, B., Miller, C., Van Kerkhoff, L., 2019. Co-producing sustainability: reordering the governance of science, policy, and practice. Annu. Rev. Environ. Resour. 44, 319–346.

6.3 Critical reflections: the WASH-sustainability forums and pathways to sustainability transformations

While the co-production study generated valuable discussions and ideas, the extent to which a single process may inform and catalyse sustainability transformations for participants and the sector more widely is necessarily limited. As such, while claiming impact from the process is unrealistic (as argued in the publication), further reflection on the connections between this inquiry's co-production activities and sustainability transformations is warranted. Scholarship on co-production and its role in sustainability transformations is relatively nascent and continuing to develop, and literature published since my publication's submission offers a novel lens through which to reflect on this inquiry's co-production process. In particular, Chambers et al. (2022) introduce the concept of "co-productive agility" as a skillset for navigating the space between goal-oriented co-production activities and process-focused sustainability transformation ideas. The authors define co-productive agility as "an emergent feature vital for turning tensions into transformations" (p. 2). They identify four pathways for co-productive agility that can nurture shifts in perspectives and foster transformative actions over time: (i) elevating marginalised agendas, (ii) questioning dominant agendas, (iii) navigating conflicting agendas, (iv) exploring diverse agendas (Chambers et al., 2022).

Considering the co-production study with reference to Chambers et al.'s (2022) four pathways highlighted strengths and limitations of the WASH-sustainability co-production process. A strength was its emphasis on 'questioning dominant agendas' by taking a learning-orientation approach, acknowledging values and questioning established sector approaches. In particular, the WASH-sustainability forums mirrored examples included in Chambers et al.'s (2022) analysis that "sought to foster awareness of framing choices by focusing participants on a higher common purpose" (p. 11). It also demonstrated a characteristic limitation of this collaborative pathway, in which initiatives emphasising knowledge production and learning can fail to institutionalise collaborations for transformation (Chambers et al., 2022). While the WASH-sustainability forums identified collective action towards

sustainability as a sector priority, the extent to which the process led to actual network building was limited.

The WASH-sustainability forums were less strongly aligned with Chambers et al.'s (2022) other three collaborative pathways of elevating marginalised agendas, navigating conflicting agendas and exploring diverse agendas. While certain features did reflect defining characteristics of each pathway, limitations are evident. For example, the intentional prioritisation of voices from low- and middle-income countries sought to address aid sector power dichotomies, but participation was still limited to English-speakers with ability to join an online event. Similarly, the focus on reflection and reflexivity accords with characteristics of the 'navigating conflicting agendas' pathway, however the forums did not explicitly create space for raising, sitting with and navigating conflicting agendas.

Many of these limitations could have been addressed if the co-production process occurred over a longer period. The single point of interaction was identified as a limitation and discussed in the publication. Given additional time and resources, I would ideally have run the co-production process over a longer period with a series of interactions to enable stronger relationship building, more thorough engagement with content, and deeper reflection.

Reflections on both the limitations and strengths of the co-production process provided a critical bridge between the substantive findings of in-depth studies and the conceptual orientation of the inquiry's synthesis. Inspired and informed by the richness of co-production conversations, themes identified in the synthesis emphasise frames and processes that can drive sectoral sustainability transformations rather than a particular agenda for change. A processual focus aligns with relational approaches to sustainability (West et al., 2020) and seeks to address Chambers et al. 's (2022) critique that "research and practice may spend too much time debating which agenda for change is best, and too little time considering how to facilitate better interactions among different agendas" (p. 13). Ultimately, the co-production process catalysed my thinking about how to drive and shape sustainability transformations in WASH, as described in the inquiry's synthesis and conclusion (Chapter 7).

6.4 Summary

This chapter presented a knowledge co-production process undertaken with WASH professionals to inform sectoral sustainability transformations. The analysis contributed both new knowledge on WASH-sustainability priorities and methodological insights on transdisciplinary knowledge co-production. Priority themes for progressing WASH sustainability were identified by the group as network building and knowledge decolonisation. Methodological insights asserted that knowledge co-production processes could beneficially emphasise purpose, work across scales and contexts, and take a reflexive approach to power. Reflecting on the publication, I explored strengths and limitations of the co-production process through the lens of 'co-productive agility', which informed the inquiry's synthesis. In the next and final chapter of this thesis, I synthesise insights across the inquiry to identify three meta-level themes, before articulating the inquiry's contributions and identifying areas for future research.

7 Chapter 7 Synthesis and conclusion

7.1 Overview

The final chapter of this thesis responds to the overarching research question, synthesising insights from each of the included studies to identify three meta-level themes relevant to strengthening WASH sector engagement with planetary sustainability imperatives: (i) *reframing* sector perspectives towards a deeper resource-orientation, such that resources are considered to be as central as people when defining issues and responses; (ii) *reimagining* purpose to foreground longer-term goals and imperatives, such that they inform WASH professionals' everyday actions; and (iii) *reflexively researching*, exploring how researchers can ethically shape WASH discourse in line with the ideals of sustainability transformations. I first describe the process of sensemaking across the four included studies, before articulating the three themes – reframing, reimagining and reflexively researching – as a synthesis of the inquiry's contribution to knowledge. The contribution is presented in terms of both new knowledge and the problem-solving intent of the inquiry, with themes mapped to realms of control, influence and concern that shape my ability to create change (as introduced in section 1.2.3). The final section of this chapter summarises the contributions of the inquiry to transdisciplinary outcome spaces of knowledge, learning and situational change, and identifies directions for future research.

7.2 Weaving the studies together: three emergent themes

The three themes explored in this synthesis – reframing, reimagining, and reflexively researching – arose from a process of sensemaking across the four included studies. Sensemaking applied an actor-oriented lens and two heuristics to identify meta-level insights that respond to the inquiry's overarching research question, which asked:

How can water, sanitation and hygiene (WASH) professionals translate and implement planetary sustainability concepts within – and as a foundation for – continued efforts to expand and strengthen service delivery towards realisation of the human rights to water and sanitation?

As described in section 1.5, this overarching question is informed by sub-questions associated with the included studies that speak to WASH sector action towards stronger integration of sustainability concepts. As such, the question focuses on the actors implicated in the inquiry – WASH professionals – identifying ways in which sustainability concepts can be made meaningful for, and inform action by, WASH professionals. The identified themes therefore represent both research findings and directions for WASH professional action.

The actor-orientation of the overarching question shaped an iterative process of sensemaking within and across studies. In each study, I questioned the relevance and meaning of findings for WASH professionals and articulated implications for researchers and knowledge leaders (studies 1 and 4), water service authorities and service providers (study 2) and urban sanitation planners and managers (study 3). Insights from studies 1–3 informed the design of the knowledge co-production process in study 4, which offered opportunity to engage with WASH professionals, reflect on their reception, and identify priority themes for WASH sector transformation.

Finally, I applied two analytical lenses as a heuristic technique to make sense of insights across the four studies, namely, leverage points for sustainability transformations (Abson et al., 2017; Meadows, 2008; Waddock et al., 2020), and the idea that we each operate within circles of control, influence and concern (adapted from S. R. Covey, 1989). Each of these two lenses and their application in sensemaking is described in turn below. Figure 11 illustrates the process of weaving together insights from each of the studies, informed by the analytical lenses, to identify the three themes for WASH sustainability transformations.

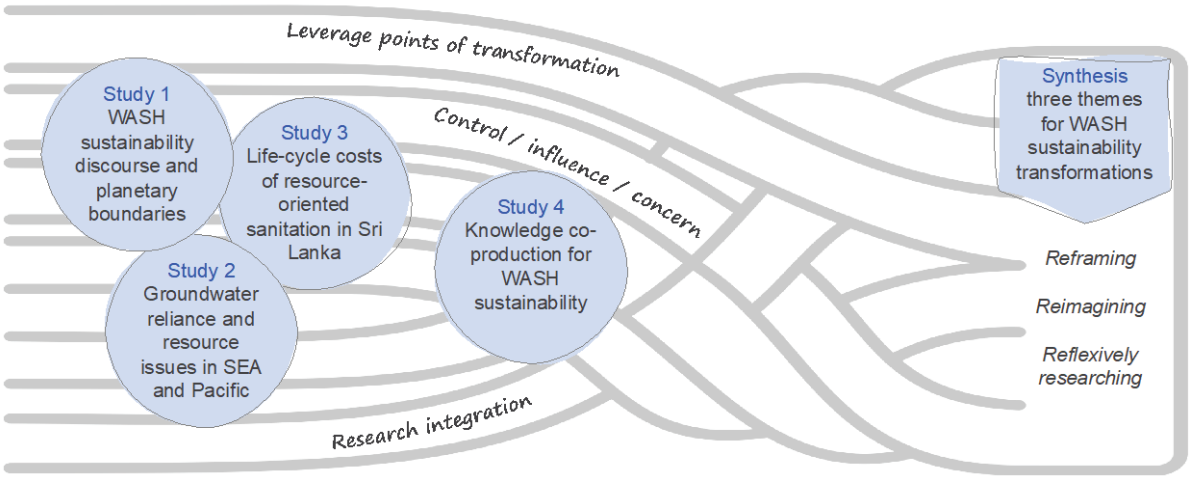

Figure 11 Weaving the studies together to identify three emergent themes

In applying a leverage points lens to sensemaking, I drew on work from systems thinking (Meadows, 2008) that has been applied to sustainability transformations (Abson et al., 2017; Waddock et al., 2020). Meadows' (2008) foundational work proposed twelve places to intervene in complex and dynamic systems to achieve positive change. I considered how each of the studies might inform action at the 'deeper' leverage points (based on Meadows' original hierarchy), characterised by Abson et al. (2017) as those influencing the intent of a system by addressing "underpinning values, goals, and world views of actors that shape the emergent direction to which a system is oriented" (p. 32). I also considered how the studies might inform actions relevant to the leverage points framework adapted by Waddock et al. (2020), which identifies '5Ps' for driving transformation: perspectives; purposes; power relations; performance metrics; and practices, policies and processes (collectively termed 'system operation'). Ultimately, applying a leverage points lens to sensemaking influenced the level at which synthesised themes sit. Rather than focusing on specific policy or practice implications, themes address 'system intent' levers related to perspectives (reframing), purposes (reimagining) and power relations (reflexively researching).

Applying the lens of control-influence-concern (after S. Covey, 1998; S. R. Covey, 1989) complemented the leverage points perspective by situating myself as a researcher with reference to the inquiry's themes, and in doing so, grounding their potential to generate change in line with the inquiry's normative intent. In other

words, I sought to explicitly consider how emergent themes might inform future researcher actions towards WASH sector sustainability transformations. The third theme – reflexively researching – arose from this process. The themes of reimagining and reframing map to realms of influence and concern respectively, as illustrated in Figure 12 and discussed in sections 7.3 and 7.4.

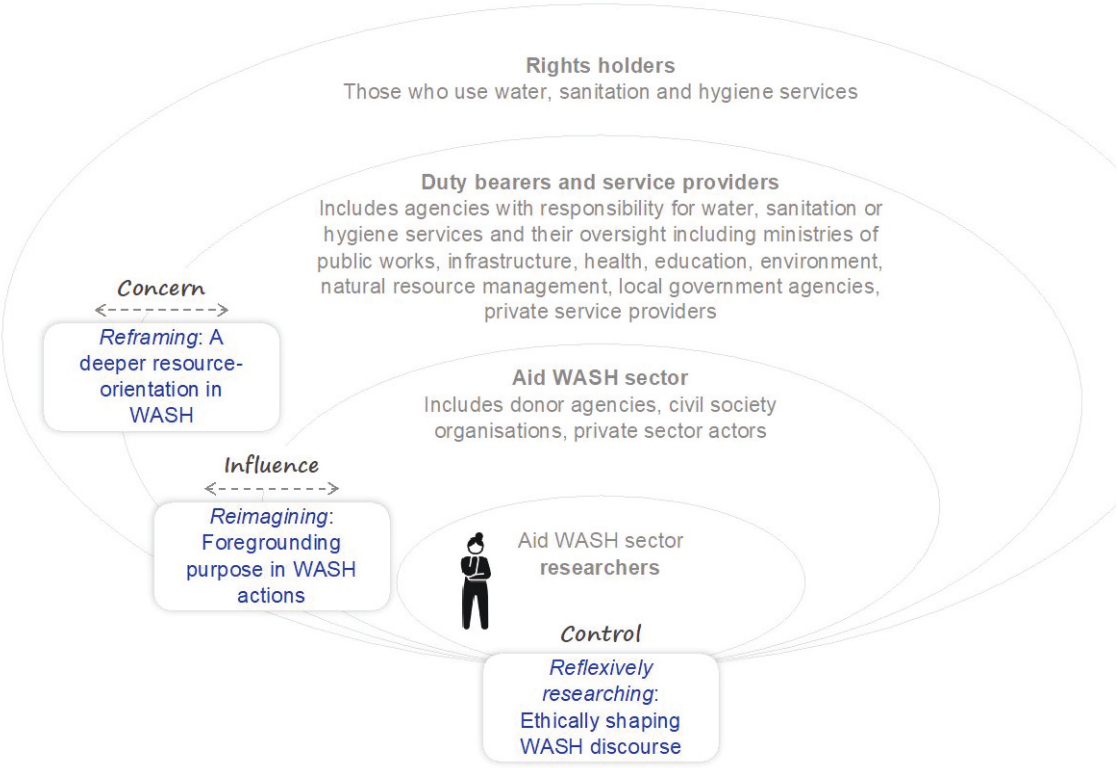

Figure 12 The three themes mapped to realms of control, influence and concern

In the subsequent sections I present each of the three themes that respond to the inquiry's overarching research question. Within each I first define the theme, then demonstrate how it emerged from (and is reflected in) each of the included studies. Drawing on conceptual frames and literature that guided the inquiry, I discuss implications of the theme for connecting WASH practice with sustainability transformations, then locate each theme with reference to my realms of concern, influence and control.

7.3 Reframing: a deeper resource-orientation in WASH

The first theme is about reframing WASH problems and responses such that resources, and the natural systems in which they are situated, are considered interdependently with people. A deeper resource-orientation in WASH means that resources, as well as people, are considered from the outset in any problem framing, service delivery approach or monitoring initiative. In identifying a role for reframing in WASH, I draw from social learning conceptions in which reframing refers to "the emergence of new, shared perceptions on the issues faced by a relatively heterogeneous group exploring a mutually perceived but somewhat ill-defined challenge" (Sol et al., 2013, p. 37). This definition, while originally used in the context of regional development in the Netherlands, is apt for the WASH sector given its heterogeneity and collective pursuit of a complex challenge. I also draw from discussions about the role of framing in driving climate change discourse, in which frames are stories that drive a particular train of thought (Nisbet, 2009), and involve the "strategic selection (conscious or not) of language features for a particular purpose" (Fløttum & Gjerstad, 2017, p. 2). For WASH professionals, developing shared frames of WASH challenges and responses as fundamentally linked to resources and the natural systems from which they arise, offers potential to shift responses towards greater alignment with sustainability imperatives.

In proposing a role for reframing to strengthen WASH sector engagement with sustainability imperatives, I note that reframing towards a stronger resource-orientation is a trend already evident in the WASH sector. This theme therefore builds on, and seeks to deepen, shifts in perspective that have emerged over past decades. As discussed in Chapter 3, sector discourse already links WASH with water security, promotes resource-oriented sanitation (including in SDG target 6.2), and increasingly situates WASH within the context of climate change. As such, I view reframing as an evolutionary trend that seeks to 'scale deep' – to shift WASH sector values, mindsets and culture beyond instrumental conceptions of sustainability towards a more implicit resource-orientation that speaks to the interdependence of people and resources. The idea of 'scaling deep' draws from discussions about amplifying sustainability transformations, where scaling deep "aims to change people's values, norms, and beliefs…by fostering new mind-sets,

changing perceptions, and introducing new ways of relating and knowing as well as new value systems" (Lam et al., 2020, p. 16.). In 'scaling deep', reframing also seeks to increasingly align WASH perspectives with relational approaches in sustainability science, which seek to move beyond dualistic thinking about 'social' and 'ecological' systems towards conceptions that recognise the inextricable connections between human and nature (West et al., 2020).

The idea that reframing can support WASH sector professionals to achieve a deeper resource-orientation is both evident within, and emergent from, the four studies included in the inquiry. Study 1 (WASH discourse and planetary boundaries) identified strengths and gaps in WASH sector engagement with sustainability imperatives by applying the frame of planetary boundary thinking, which represented a novel analytical lens compared with more commonly used WASH frames of reference such as SDGs and human rights criteria. The updated discourse analysis characterised an evolution in WASH sector thinking (section 3.8) about sustainability from functionality (past), to instrumentalism (present), to interdependence of people and resources (future). Articulating this evolution is a propositional reframing that speaks directly to this theme, demonstrating strategic selection of language to inspire particular trains of thought.

Responding to the identified need for greater focus on resources, studies 2 and 3 explored how a resource-orientation might inform WASH engagement with resource considerations for a regional-scale groundwater analysis (study 2) and a city-scale sanitation case study (study 3). The central idea of study 2 was that the WASH sector has a critical interest in groundwater resource sustainability, opportunity to better monitor the use of groundwater resources for drinking water services, and a responsibility to proactively engage in groundwater resource management. In study 3, I argued that financial analysis of resource-oriented sanitation should move away from comparative performance against traditional systems, towards clarifying actual costs and considerations that might inform investment in viable, equitable resource-oriented systems. Both studies engaged in reframing by departing from common ways of considering WASH questions, challenging the sector's focus on facilities (rather than resources) in study 2 and the

tendency for other reuse costing studies to consider ‘whether’ rather than ‘how’ to implement resource-oriented sanitation at scale in study 3.

Engagement with WASH professionals in study 4 demonstrated the potential of reframing to prompt new ways of thinking about WASH professional practice. In sharing findings from studies 2 and 3 according to their central ‘reframed’ idea, I engaged in an intentional process of articulating the meaning of detailed studies for wider sectoral relevance. As described in Chapter 6, responses from participants illustrated how reframing can shift perspectives, exemplified by a water practitioner expanding focus to think about both household water facilities and water sources (an idea that he found “intriguing” as a water practitioner). Similarly, discussions about resource-oriented sanitation addressed the importance of mindset change for achieving circular economy visions, with a ‘how’ (rather than ‘whether’) mindset generating alternative ideas about policy directions and government actions. Discussions illustrated the power of frames – the strategic selection of stories – to drive particular trains of thought.

The idea of reframing towards a stronger resource-orientation aligns with, and draws inspiration from, conceptual frames applied across this inquiry including sustainability transformations, circular economy concepts and systems thinking. Reframing has been discussed in the context of sustainability transformations as a means to open up possibilities for change by influencing the dominant discourse driving sustainability challenges (B.-O. Linnér & Wibeck, 2019; Riedy, 2021; Waddock, 2020). The concept of a circular economy is in itself an example of reframing production models, from cradle-to-grave towards regenerative, circular ideals (McDonough & Braungart, 2010; Waddock, 2020). The term is increasingly used in the WASH sector (including in this inquiry) to align previously niche ideas about ecological sanitation with global trends evident in the wider water sector and more broadly (e.g. Danso et al., 2017; Mallory, Akrofi, et al., 2020; Moya et al., 2019; Schroeder et al., 2019; Sgroi et al., 2018).

Systems thinking both supports a focus on reframing and offers entry points for doing so, with efforts to ‘scale deep’ ultimately seeking transformation in the mindsets that shape system paradigms. Evolution in system goals and shifting mindsets are two of Meadows’ most effective leverage points for intervening in a

system (Meadows, 2008). For WASH systems, reframing towards a stronger focus on resources prompts consideration of how a resource-orientation might inform post-SDG targets (influencing system goals). And collaborative goal setting processes – which inevitably frame discussions in ways that can drive mindsets in specific directions – can be shaped with a resource-orientation in mind (influencing the mindset or paradigm out of which the system arises). At national and program scales, the current WASH sector emphasis on systems strengthening (Valcourt et al., 2020) offers an entry point for reframing building blocks to emphasise interdependence between people and resources.

The idea of reframing WASH problems and responses to embed a resource-orientation relates to my realm of concern (as illustrated in Figure 12). Reframing reflects an ultimate vision for how sector actors conceive challenges in ways that shift priorities and prompt novel approaches. Reframing requires deep and wide changes across the sector that cannot be quickly enacted within dominant ways of working. As Sol et al. (2013) argue, reframing is akin to double-loop learning (after Argyris & Schön, 1978) in requiring "radical changes in underlying beliefs and values" and implying "social action, social reflection, social analysis and social planning" (p. 37). As such, reframing at the sector level demands engagement with different ways of thinking about, and prioritising, resources as critical for both WASH and a sustainable human-nature relationship. Such engagement with different ways of thinking is explored in the second theme, focused on connecting WASH professionals with purpose.

7.4 Reimagining: connecting WASH action with purpose

The second theme considers how WASH professionals – including those in the aid WASH sector as well as duty bearers and service providers – can engage with purpose to foster critical reflection and encourage alignment of everyday actions with longer-term goals and imperatives. The conception of purpose draws from Jantsch's (1970) foundational transdisciplinary work in which purpose denotes value-based ideals about human survival in changing environments (also discussed in publication 4). I term this theme 'reimagining' to evoke the deeper thought and creativity prompted by engagement with purpose, considering how everyday

actions might connect to bigger questions and motivations. For WASH professionals, engaging with purpose means thinking beyond the specific goals, targets and metrics that drive action, considering the integration of these drivers with value-based pursuits of a sustainable, equitable world. A purposeful approach also implies cultivating a positive vision of the future, harnessing the constructive power of hopeful, inspiring narratives for shaping long-term change (B.-O. Linnér & Wibeck, 2019).

The potential for engagement with purpose to facilitate the translation and implementation of sustainability concepts in WASH was addressed implicitly in study 1, evidenced in the case example featured in study 3, and explored directly in study 4. Study 1 defined a societal purpose as living within the doughnut, with planetary boundaries and social foundations together offering an aspirational 'space' in which humans and nature can coexist and thrive. As argued in publication 1 (Chapter 3), the planetary boundaries and doughnut concepts demand a purposive 'do more good' approach, in contrast to sustainability endeavours based on limits to growth and minimising externalities. In articulating the relevance of the planetary boundary framework for the WASH sector, and identifying future directions for the WASH sector informed by planetary boundary thinking, study 1 demonstrated how such thinking can shape action. In doing so, however, the future directions were pitched to researchers and knowledge leaders, acknowledging the gap between idealised concepts and their practical application. While researchers are WASH professionals with a clear role to play in driving sector priorities and actions, sector change demands a wider focus, which I sought to explore in subsequent studies.

Study 3 profiled an urban sanitation system in which purpose and action were connected to drive a circular economy approach. The case study – a city-scale faecal sludge management system that incorporates reuse of treated sludge for productive agricultural use – was conceived and championed by the local government Public Health Inspector before the SDG targets and national policy directives encouraged resource-oriented sanitation (as described in section 5.3). At the time, there was no clear financial case supporting this kind of investment, but rather an opportunity shaped by the Inspector's environmental values and capacity

to engage the requisite buy-in, technical skills and financial support. As such, the example illustrates what can happen when a WASH professional engages with purpose then acts in line with their ideals. Yet it is crucial to acknowledge the challenges involved in overriding norms, given the ability of individuals to influence actions in line with purpose is highly contextual, shaped by structures, agency and perceived legitimacy (Nentwich et al., 2015). As such, the potential for engagement with purpose to shape a stronger sustainability orientation in WASH requires further empirical exploration – a reflection that shaped a focus on purpose in study 4.

Study 4 sought to centre ideas of purpose in knowledge co-production and gauge WASH professional responses. Strategies for connecting with purpose included completion of the Worldviews Test and introduction to planetary boundaries, the doughnut and sustainability transformations concepts. These strategies elicited reflective contributions about human-nature connections and shaped ideas for action, as described in publication 4 (Chapter 6). In publication 4, I also argued that engagement with purpose is particularly constructive for the WASH sector given its focus on the goals and targets of SDG 6, with purpose offering a frame of reference for more critical pursuit of goals. However, while study 4 demonstrated benefits from intentionally connecting WASH professionals with purpose, the small-scale nature of the engagement means that findings are illustrative and further research is needed to explore the wider relevance of such an approach.

Further exploration of the potential, and pathways, for reimagining purpose to strengthen alignment of everyday actions with longer-term imperatives can usefully apply insights from futures thinking and transdisciplinary integration. Futures scholarship offers a spectrum of approaches for engaging with the future, ranging from those that seek to reduce uncertainty (such as modelling) to those that embrace uncertainty through creativity and imagination (Wyborn et al., 2021). In WASH, there is scope to complement established sector processes of modelling and planning that seek to create certainty from a rational basis (Abeysuriya et al., 2019), with creative methods that imagine possible pathways to purposively conceived futures. Both approaches are important for developing the “future consciousness” (Sharpe et al., 2016) of WASH professionals, with processes that foster imagination, creativity and embrace emergence necessary to move beyond

incremental or marginal change (Sharpe et al., 2016). Embracing uncertainty may be uncomfortable for those with positivist epistemological leanings and is not well supported by prevailing institutional structures (Bengston, 2019; Wyborn et al., 2021). Yet for WASH professionals, processes that leverage the power of imagination to facilitation action and change may generate novel insights about our sector and its relationship to sustainability transformations.

Ideas about integration can also inform strategies for leveraging purpose in WASH professional practice, by encouraging focus on ultimate 'integrated' goals and forging common ground across epistemological divides. The importance of integration for achieving the Agenda 2030 vision for people, planet and prosperity is well recognised (Cerf, 2019; Nilsson et al., 2016). This vision offers a framework for critical reflection about the alignment of WASH actions (in pursuit of SDG 6 targets) with the wider integrated SDG vision. Yet *how* to think and act in integrated ways remains challenging, and is a topic of considerable debate and complexity in both sustainability and adult learning literature (Kallio, 2011; Rogers et al., 2013; Ross, 2020). While acknowledging this complexity, a key step is bridging disciplinary perspectives across both theory and practice. This form of integration is described by Wickson et al. (2006) as a key challenge of transdisciplinarity, best addressed by looking for "coherence, correspondences and 'ridges' across the differences" (Wickson et al., 2006, p. 1053). In WASH, disciplinary diversity is characteristic (as described in section 1.2) yet rarely discussed. There is opportunity for WASH professionals to converse openly about how perspectives drive priorities and responses, exploring how divergent perspectives can be beneficially integrated in pursuit of shared purpose.

The idea of connecting WASH professionals with purpose as a strategy to creatively bridge sustainability imperatives and practical realities relates to my realm of influence (Figure 12), exercised through collaboration. Collaboratively engaging with purpose includes situating research aims in their wider context, considering the multiple ways in which problems (and responses) can be defined (reframing ideas), and seeking to make explicit the values driving collective choices. Examples from this inquiry demonstrate the potential for engaging with purpose to foreground longer-term imperatives for WASH professionals in ways

that might generate ‘transformative spaces’. Transformative spaces are defined by Pereira et al. (2018) “as ‘safe enough’ collaborative environments where experimentation with new configurations of social-ecological systems, crucial for transformation, can occur” (p. 33). For the WASH sector, such spaces must be designed with reference to ethical considerations associated with South-North collaborations (Pereira et al., 2020), a question I explore in the third theme focused on reflexively researching.

7.5 Reflexively researching: ethically shaping WASH discourse

The third theme considers the role of researchers in normative, and aspiringly transformative, processes of sectoral change. Informed by my constructivist and pragmatic epistemological orientation (as described in section 1.4), I see a reflexive approach to research as an ethical imperative, particularly given the historic and persisting power asymmetries that characterise development research and South-North partnerships. My conception of reflexivity aligns with that of Bradbury and Divecha (2020), who differentiate reflexivity from reflection: “Reflexivity is a more ambitious and challenging process of thinking about your own way of thinking, assumptions, and underlying patterns of values and world views” (p. 277). Articulating my plural epistemological perspective forms part of my reflexive practice, as does a continual practice of questioning how my values and assumptions inform my research from problem framing through to engagement with multiple scholarly and practitioner audiences.

In this theme I connect reflexive, normative research to the first two themes of reframing and reimagining and the idea of ‘discursive entrepreneurship’ defined by Riedy (2021) as “the practice of creating, performing and transforming memes, stories, narratives and discourses to promote a desired structure of the discursive landscape” (p. 7). I see normative research as a means through which to shape discourse, and concur with Riedy’s (2021) emphasis on ethics when engaging in intentional meaning-making towards sustainability transformations. In articulating this theme, I reflect on how the idea emerged from this inquiry then explore the opportunities and ethical imperatives of research as a means to shape discourse within the WASH sector.

In the inquiry, study 1 established a foundation for the theme of reflexively researching. In reviewing WASH discourse (as one of many possible literature review approaches), I recognised the role that discourse plays in constructing our realities (see Chapter 3). Analysing WASH discourse with reference to the planetary boundaries framework identified the ways in which mainstream discourse mapped – or didn't map – to key earth system processes underpinning global sustainability. In articulating consequent WASH priorities, I engaged in a process of framing future research directions using memes (such as 'doing more good' and seeking 'win-wins') and stories (scaling up reuse from niche to regime scale) to inspire action in particular directions. Similarly, studies 2 (groundwater reliance and resource concerns) and 3 (life-cycle costs of resource-oriented sanitation) represent examples of discursive entrepreneurship with their deliberate reframing of commonly accepted WASH sector questions. At the time of writing each publication my discursive entrepreneurship was unconscious. In hindsight, reflecting on the process as a deliberate act highlights the importance of undertaking normative research reflexively, and ethically.

The fourth study (co-production for WASH sustainability) engaged in more direct meaning-making with WASH professionals and considered the importance of reflexivity when facilitating knowledge co-production. As discussed in the reframing and reimagining themes (sections 7.3 and 7.4), I presented findings from studies 2 and 3 according to the central 'reframed' idea and introduced sustainability transformations as relevant to the WASH sector. Intentional choices about what to emphasise and how to share prior study insights shaped the co-production process, as discussed in publication 4 with reference to researcher-facilitator power (see Chapter 6). The discussion of a reflexive approach to researcher power is particularly important in the context of WASH sector knowledge decolonisation – a theme of the co-production process – with normative research at high risk of perpetuating colonial power asymmetries if such dynamics are not subject to reflection, and reflexivity.

A key implication arising from this theme for WASH sector researchers is that through the practice of research we inevitably engage in meaning-making that shapes sector discourse in particular directions. There is both opportunity and an

ethical imperative to build collective consciousness about the ways in which research framings and processes influence discourse given that all research activities – ranging from technical analyses through to social inquiry – engage in framing and meaning-making (Fritz & Binder, 2020; Leventon et al., 2021). Exploring the ways in which discursive entrepreneurship can feature in and alongside the robust scientific research that underpins sector directions will be important to align WASH agendas with sustainability transformations.

In highlighting this direction, I note a shift in my transdisciplinary research from alignment with the problem-solving discourse (as described in section 2.4) towards integration of problem solving with the discourse of transgression. As flagged in section 2.5, my increasing alignment with the transdisciplinary discourse of transgression is an emergent outcome of this inquiry, as I integrate problem solving with aspirations “to critique, reimagine, and reformulate the status quo” (Thompson Klein, 2015, p. 14). For the WASH sector, I see shaping discourse as a means to interrogate and reimagine commonly accepted ways of working, to inform collective consideration of our sector’s place and role in sustainability transformations.

The theme of reflexively researching relates to the circle of control (Figure 12). While the circle of control is commonly conceived individually, here I frame it collectively with reference to the WASH research community of practice within which I work. As such, I use the plural pronoun ‘we’ to represent WASH researchers who individually and collectively control our own activities, given the intent of this theme to identify and grapple with researcher roles in shaping sustainability transformations. Reflexivity is core to this process, and has been identified as critical for sustainability transformations work across transdisciplinary (Sellberg et al., 2021) and systems (Leventon et al., 2021) approaches. From a foundation of reflexive practice, we (WASH researchers) have opportunity to shape discourse from two angles. First, by bringing a sustainability transformations perspective to the design and implementation of collaborative research activities, drawing on ideas such as reframing and reimagining to critically question and constructively inform WASH engagement with sustainability imperatives. Second, to do so ethically and with a view to addressing the power imbalances characteristic of WASH and other development sectors.

I identify three specific strategies for researchers to enact these intentions. First, through close collaboration between Southern and Northern researchers and practitioners, with a view to building WASH sector sustainability-oriented discourse coalitions (after Riedy, 2020) that reframe towards a resource-orientation (see section 7.3) and inspire positive narratives. Second, researchers can undertake collaborative knowledge production in ways that maintain focus on our shared purpose of human survival in changing environments, but with flexible agendas – focusing less on pre-determined outcomes and more on processes and interactions that create space for iterative dialogue and the emergence of shared ideas for action (drawing on Chambers et al.'s 2022 conception of 'co-productive agility' – also see section 6.3). Third, we can advocate for research funders and institutions to support deeply collaborative transdisciplinary research, challenging the discursive power of funding bodies and researchers that shapes research framings and norms (after Fritz & Binder 2020 – also see publication 4).

7.6 Integrating and applying the themes

The three themes presented here are discrete, however there are complementarities and I conceive them as an integrated and mutually reinforcing set. For example, reframing can shape discourse in its strategic selection of frames to drive thoughts and actions in particular directions. Similarly, reframing relies on processes of reimagining to open possible alternative ways of conceiving and approaching situations that align with value-based ideals. And in turn, articulating value-based ideals that underpin conceptions of purpose requires a new degree of reflexivity.

As a set, the themes serve three aims. First, they respond to the overarching research question by articulating implications of the inquiry for diverse WASH professionals. Themes of reframing and reimagining are applicable to a wide range of professionals, for example, program teams who select problem-framings and design solutions, or policymakers who articulate WASH sector objectives at national or sub-national scales. Reflexively researching as a mechanism for shaping discourse is specifically applied to researchers as one subset of WASH professionals engaging in collaborative meaning-making, though the benefits of

reflexive, ethical approaches are equally relevant for a wider set of sector professionals. Second, the themes offer a meta-level framework within which to locate more specific activities that connect WASH professional practice with sustainability transformations. Finally, the themes offer signposts and principles to guide transdisciplinary research practice beyond this inquiry, as articulated in reflections about realms of concern, influence and control. Considered together, the themes suggest pathways for research practice (reflexively researching) that may influence sectoral priorities (reimagining) towards a longer-term collective reframing in which resources and their natural systems are conceived as deeply embedded with WASH and therefore a core part of WASH professional responsibility and practice.

7.7 Critiques and unresolved tensions

While the three themes in this synthesis address the inquiry's overarching research question and provide signposts for future research practice, there are inevitable gaps and tensions. In this section I apply a critical lens to synthesised themes informed by sustainability transformations literature, identifying four unresolved tensions in moving from research findings to achieve the inquiry's normative intent to inform practical, ethical and transformative sectoral action. The four tensions are bridging conceptual ideals and imperatives with practical action at local scales, applying insights pitched to a global sector across diverse contexts, grappling with power and politics in sustainability transformations, and questioning whether an anthropocentric planetary boundary lens is sufficient to drive the changes necessary for planetary sustainability and human survival. In this section I engage with each of these areas, identifying implications for interpreting and applying insights from this inquiry. Below (section 7.9), I articulate how these considerations inform areas for further research.

Moving from thematic insights to practical action is challenging. While the three themes emerged from and were reflected in studies across this inquiry, which grounds them to an extent, they sit at a conceptual level and are yet to be applied at local scales. There is a need for continued iteration between the local and global views necessary to address global challenges through grounded responses at

multiple ‘local’ scales. Publication 4 (Chapter 6) asserted the value of processes that apply big picture ideas to diverse local realities. Conversely (and complementarily), Balvanera et al. (2017) assert the value of place-based research for informing global sustainability initiatives. In synthesising insights from this inquiry I sought to balance conceptual coherence with practical relevance, but efforts to bridge sustainability transformations concepts and practice are challenging (Salomaa & Juhola, 2020) and further place-based research is needed to explore whether themes will be meaningful for localised change processes.

Similar challenges exist when considering the applicability of themes across diverse social, cultural and political contexts. The importance of contextualising normative interventions is widely acknowledged across WASH, sustainability transformations and transdisciplinarity literature (e.g. Klein, 2021; B. O. Linnér & Wibeck, 2021; Workman et al., 2021). The three themes articulated in this synthesis have yet to be tested for broad contextual relevance, and there is substantial further work to do considering how to translate and implement ideas in ways that are context-specific and responsive, for a range of places and situations. Context will always drive the application and usefulness of presented themes, and moving fluidly between contextual applications is both imperative and inherently challenging.

Questions of power are also unresolved, yet will drive the ways in which themes are interpreted and applied. Seeking to strengthen WASH sector engagement with sustainability imperatives is highly political, given that sustainable development and transformation discourses themselves arise from historical power asymmetries (Blythe et al., 2018; B. O. Linnér & Wibeck, 2021). Themes of reframing and reimagining risk depoliticising sustainability transformations by focusing on shared purpose rather than the profoundly political nature of grappling with conflicting views and designing future pathways. In advocating for purposeful approaches, I see opportunity to build collective visions while creating space for plural, inclusive transformation pathways. However, risks include the co-option of agendas by powerful interests and further exclusion of already marginalised groups (Bennett et al., 2019; Blythe et al., 2018). Further consideration of strategies for decolonising

sustainability transformations (Gram-Hanssen et al., 2021) and pursuing just transformations (Bennett et al., 2019) is needed.

A final tension in this inquiry is its embeddedness within anthropocentric perspectives on global sustainability. The planetary boundaries framework – which shaped this inquiry – has been critiqued as "dangerously anthropocentric" in its suggestion that staying within the boundaries is sufficient to guide a 'sustainable' relationship between humans and the biosphere (Kopnina, 2016). The theme of reframing towards a deeper resource-orientation exemplifies an anthropocentric perspective, with the term 'resources' implying nature's availability for human exploitation. My choice of language was deliberate given the role of natural systems in upstream (e.g. water supply) and downstream (e.g. wastewater discharge) WASH activities and my intention to offer insights that resonate with WASH professionals. Yet such framings implicitly elevate human needs over the intrinsic values of nature. I justify the approach with reference to my pragmatic epistemological orientation, which underpins the use of approaches and framings most likely to achieve normative research aims, in this case seeking relevance for WASH professionals. I also assert the resonance of anthropocentric perspectives with the notion of the Anthropocene – the description of the current human-dominated geological epoch (Crutzen, 2002) and a concept that has captured the scientific and societal imagination (Bai et al., 2016; Brondizio et al., 2016). Nevertheless, whether anthropocentric perspectives can ever drive the deep transformations required to protect the biosphere is questionable (Adelman, 2018).

7.8 Contributions of the inquiry: transdisciplinary outcomes

This chapter has so far presented three themes as a synthesis of the inquiry's contribution to knowledge, articulating how each theme emerged from the included studies and considering how themes might progress the problem-solving intent of the inquiry in future work. Complementing the thematic presentation, in this section I reflect on the original contribution of the thesis as a transdisciplinary inquiry with reference to three transdisciplinary outcome spaces (from Mitchell et al., 2015) of contributing to knowledge stocks and flows, mutual and transformational learning, and improving the situation.

Firstly, the inquiry contributed to the stocks and flows of scholarly knowledge by publishing four open access journal articles. Publishing throughout the inquiry ensured emerging insights were widely available to researchers and practitioners. Interest in the earlier publications as evidenced by citations (noted in Table 2, section 1.6) attests to their value as knowledge contributions within WASH scholarship. Insights from the inquiry were also shared in a mix of academic and practice-oriented forums, most notably the WASH Futures conference (2018), the International Conference on Sustainable Development (2021) and during the WASH sustainability co-production events central to study 4.

As is characteristic of transdisciplinary research, the contributions to knowledge span multiple levels and topic areas. Study 1 contributed novel insights about the relevance of sustainability concepts for WASH. Study 2 quantified the extent of household reliance on groundwater as a source of drinking water in ten countries, contributing evidence in support of an oft-cited but not well defined claim about groundwater's importance in safe drinking water initiatives. In highlighting resource concerns, study 2 also contributed knowledge about the fundamental importance of linking WASH and water resource initiatives. Study 3 contributed empirical data on the life-cycle costs of resource-orientation sanitation, addressing a substantial gap in knowledge about urban sanitation services in general, and resource-oriented systems in particular. Methodological and meta-level contributions arise from study 4 and this synthesis, both of which situate insights from across the studies with reference to transdisciplinary knowledge co-production processes (study 4) and themes for leveraging sustainability transformations in and through WASH professional practice. These contributions are also detailed in Table 2 (section 1.6).

Secondly, the inquiry contributed to mutual learning through stakeholder-engaged research in study 3 and the knowledge co-production process central to study 4. Close collaboration with International Water Management Institute colleagues, and meaningful dialogue with Sri Lankan government representatives, supported mutual learning about how to define 'the problem' being explored – a process that informed the focus on life-cycle costs and their distribution rather than infrastructure options assessment. Mutual learning was enriched by the diverse disciplinary, cultural and professional perspectives of those involved, which included social

scientists, engineers and public health experts from multiple continents working across research, policy and service delivery roles. Learning was deepened by my immersion in the research context, which enabled me to form strong connections with collaborators. Strong connections provided a foundation for safe yet mutually challenging dialogues, which prompted moments of cognitive dissonance that drive transformational learning (Mitchell et al., 2015; Taylor, 1998).

The co-production design contributed to learning outcomes for me (as researcher-facilitator) and for participants by emphasising interaction and reflection, creating space for emergent insights within a broadly defined agenda to strengthen WASH sector engagement with sustainability concepts. As discussed in publication 4, findings indicated joint learning by participants, though longer engagement and follow up would be required to determine the nature and transformational potential of such learning. Learning outcomes for me were more directly transformational, informing the insights articulated in publication 4 and this synthesis, particularly those focused on researcher reflexivity and the complexity of grappling with power when undertaking purposive transdisciplinary research towards sustainable futures. Ultimately, this learning deepened my transdisciplinary 'way of being' (after Gibbs & Beavis, 2020; Rigolot, 2020), developing my capacity to "see a problem from many perspectives and…seek to resolve it within and outside the constraints that it presents" (Gibbs & Beavis, 2020, p. 3).

Finally, the inquiry has contributed practical and conceptual insights that are well-placed to improve the situation by placing sustainability at the centre of WASH, though claiming actual change is unrealistic given the scale and timeframe of doctoral research. Nevertheless, interest in the research and feedback received from influential WASH professionals during the timeframe of this doctorate suggests potential for future impact. Government officials from the WASH sectors in Vietnam, Cambodia and Indonesia have engaged with the research and asserted its relevance to their current initiatives, requesting input on policy and research directions. A specific request from Vietnam's Institute for Water Resources Economics and Management sought advice regarding proposed analysis of circular economy options (Đinh Văn Đạo, personal communication, December 10, 2021). The Bill and Melinda Gates Foundation, a globally influential donor, commended

study 3's decoupling of cost distribution models with hardware options and requested a policy brief based on the study to share with consultants and utility staff (A. Schrecongost, personal communication, June 4, 2021). WaterAid Australia's Chief Executive valued the strategic perspective of study 1 as a compass for future sector directions (R. Wheen, personal communication, March 8, 2018). I have engaged with WASH researchers with common sustainability interests (e.g. at Stockholm Environment Institute and the International Water Management Institute) throughout the inquiry, building mutually beneficial connections that strengthen the contributions of WASH research to our shared goals. Through my ongoing work as a WASH researcher, I intend to continue engaging with these actors to ensure that insights from this inquiry ultimately contribute to change.

7.9 Future research

The breadth, ambition and transdisciplinary nature of this inquiry means that areas for future research are many and varied. Here I identify recommendations for further research arising from two perspectives – one from the lens of sustainability transformations, and the other based on WASH sector trends and opportunities.

From a sustainability transformations lens – and taking into account the pace and scale of change necessary to realise sustainable futures – further research is warranted on 'amplification' frameworks and their relationship to ideas of 'scaling' commonly discussed in the WASH sector. The idea of 'scaling deep' referred to in the theme of reframing (section 7.3) sits within a typology of processes for scaling initiatives by amplifying within (stabilising, speeding up), amplifying out (growing, replicating, transferring, spreading) and amplifying beyond (scaling up, scaling deep) (Lam et al., 2020). The relevance of these processes for WASH-sustainability initiatives, and how they could work together, warrant further investigation and may prompt the sector to move beyond a tendency to focus on strategies for replication as is typical of development interventions (Woltering et al., 2019). In particular, given the importance of achieving deep and rapid change to support sustainability transformations, research on how the WASH sector might 'speed up' and 'scale deep' its sustainability efforts would both support sectoral

transformations and address a wider gap in literature identified by Lam et al. (2020). Efforts to ‘speed up’ may benefit from reflection about COVID-19 responses, which have demonstrated our collective capacity to act quickly in response to urgent drivers. Across amplification initiatives, a critical question will be how to monitor and evaluate these processes, given the importance of ensuring effectiveness and demonstrating why such initiatives warrant investment.

From a WASH perspective, future research could build on and further develop insights from this inquiry by investigating how they might inform four current WASH sector interests. First, the relevance of reflexivity for decolonising WASH knowledge warrants consideration, including strategies for promulgating more reflexive research and practice across the sector. Second, applying a sustainability transformation lens to systems strengthening approaches in WASH could generate practical insights about specific, contextualised levers and pathways for strengthening sustainability in programs, policies, and national systems. Third, there are clear synergies between this inquiry and emerging WASH conversations about planetary health, and further consideration of the strengths and limitations of a planetary health perspective for driving sectoral transformations could generate additional insights that particularly resonate for WASH professionals with public health perspectives. Finally, acknowledging that any choices in policy, programming and research imply investment of limited financial resources, further research is needed to explore how financing mechanisms can best support sustainability, while also achieving human rights.

7.10 Concluding remarks

The intent of this inquiry was to strengthen the WASH sector’s response and contribution to planetary sustainability, by exploring how to translate and implement sustainability concepts to sectoral research and practice. Four studies contributed insights relevant to WASH professional practice, drawing on analysis of discourse, groundwater, costs, and knowledge co-production to identify priorities and practical strategies. The inquiry’s synthesis identified three meta-level themes that can drive and shape pathways for sectoral sustainability transformations: reframing sector perspectives towards a deeper resource-orientation; reimagining purpose to

foreground longer-term goals and imperatives, such that they inform WASH professionals' everyday actions; and reflexively researching as a means to ethically shape WASH discourse.

The broad scope and normative intent of the inquiry demanded a transdisciplinary approach, and this approach has proved fruitful in generating insights that transcend disciplinary perspectives and integrate diverse knowledge types. Bridging the transdisciplinary discourses of problem solving and transgression, the inquiry generated both solution-oriented insights and process-oriented themes and directions. The latter reflect a relational response to the inquiry's central research question, and offer a compass for future critiquing and reimagining of WASH in line with the ideals of sustainability transformations.

References

Abeysuriya, K., Willetts, J., Carrard, N., & Kome, A. (2019). City Sanitation planning through a political economy lens. *Water Alternatives*, *12*(3), 907–929.

Abrams, A. L., Carden, K., Teta, C., & Wågsæther, K. (2021). *Water, Sanitation, and Hygiene Vulnerability among Rural Areas and Small Towns in South Africa: Exploring the Role of Climate Change, Marginalization, and Inequality*.

Abson, D. J., Fischer, J., Leventon, J., Newig, J., Schomerus, T., Vilsmaier, U., von Wehrden, H., Abernethy, P., Ives, C. D., Jager, N. W., & Lang, D. J. (2017). Leverage points for sustainability transformation. *Ambio*, *46*(1), 30–39. https://doi.org/10.1007/s13280-016-0800-y

Achore, M., Bisung, E., & Kuusaana, E. D. (2020). Coping with water insecurity at the household level: A synthesis of qualitative evidence. *International Journal of Hygiene and Environmental Health*, *230*(April), 113598. https://doi.org/10.1016/j.ijheh.2020.113598

Adelman, S. (2018). The Sustainable Development Goals, anthropocentrism and neoliberalism. In D. French & L. J. Kotzé (Eds.), *Sustainable Development Goals: Law, Theory and Implementation* (pp. 15–40). Edward Elgar Publishing. https://doi.org/10.4337/9781786438768.00008

Alhassan, S., & Hadwen, W. L. (2017). Challenges and opportunities for mainstreaming climate change adaptation into WaSH development planning in Ghana. *International Journal of Environmental Research and Public Health*, *14*(7). https://doi.org/10.3390/ijerph14070749

Amebelu, A., Ban, R., Bhagwan, J., brown, J., Chilengi, R., Chandler, C., Colford, J. M., Cumming, O., Curtis, V., Evans, B. E., Freeman, M. C., Guiteras, R., Howard, G., Humphrey, J., Kang, G., Kulabako, R., Lanata, C. F., Montgomery, M. A., Pickering, A. J., … Wolf, J. (2021). The Lancet Commission on water, sanitation and hygiene, and health. *The Lancet*, *398*(10310), 1469–1470. https://doi.org/10.1016/S0140-6736(21)02005-5

Argyris, C., & Schön, D. A. (1978). *Organizational Learning: A Theory of Action Perspective*. Addison-Wesley Pub. Co.

Bai, X., van der Leeuw, S., O'Brien, K., Berkhout, F., Biermann, F., Brondizio, E. S., Cudennec, C., Dearing, J., Duraiappah, A., Glaser, M., Revkin, A., Steffen, W., & Syvitski, J. (2016). Plausible and desirable futures in the Anthropocene: A new research agenda. *Global Environmental Change*, *39*, 351–362. https://doi.org/10.1016/j.gloenvcha.2015.09.017

Balvanera, P., Calderón-Contreras, R., Castro, A. J., Felipe-Lucia, M. R., Geijzendorffer, I. R., Jacobs, S., Martín-López, B., Arbieu, U., Speranza, C. I., Locatelli, B., Harguindeguy, N. P., Mercado, I. R., Spierenburg, M. J., Vallet, A., Lynes, L., & Gillson, L. (2017). Interconnected place-based social–ecological research can inform global sustainability. *Current Opinion in Environmental Sustainability*, *29*, 1–7. https://doi.org/10.1016/j.cosust.2017.09.005

Bammer, G., O'Rourke, M., O'Connell, D., Neuhauser, L., Midgley, G., Klein, J. T., Grigg, N. J., Gadlin, H., Elsum, I. R., Bursztyn, M., Fulton, E. A., Pohl, C., Smithson, M., Vilsmaier, U., Bergmann, M., Jaeger, J., Merkx, F., Vienni Baptista, B., Burgman, M. A., … Richardson, G. P. (2020). Expertise in research integration and implementation for tackling complex problems: when is it needed, where can it be found and how can it be strengthened? *Palgrave Communications*, *6*(1). https://doi.org/10.1057/s41599-019-0380-0

Bartram, J., Brocklehurst, C., Fisher, M. B., Luyendijk, R., Hossain, R., Wardlaw, T., & Gordon, B. (2014). Global monitoring of water supply and sanitation: History, methods and future challenges. *International Journal of Environmental Research and Public Health*, *11*(8), 8137–8165. https://doi.org/10.3390/ijerph110808137

Belcher, B. M., Rasmussen, K. E., Kemshaw, M. R., & Zornes, D. A. (2016). Defining and assessing research quality in a transdisciplinary context. *Research Evaluation*, *25*(1), 1–17. https://doi.org/10.1093/reseval/rvv025

Bengston, D. N. (2019). Futures Research Methods and Applications in Natural Resources. *Society and Natural Resources*, *32*(10), 1099–1113. https://doi.org/10.1080/08941920.2018.1547852

Bennett, N. J., Blythe, J., Cisneros-Montemayor, A. M., Singh, G. G., & Sumaila, U. R. (2019). Just transformations to sustainability. *Sustainability (Switzerland)*, *11*(14), 1–18. https://doi.org/10.3390/su11143881

Blythe, J., Silver, J., Evans, L., Armitage, D., Bennett, N. J., Moore, M. L., Morrison, T. H., & Brown, K. (2018). The Dark Side of Transformation: Latent Risks in Contemporary Sustainability Discourse. *Antipode*, *50*(5), 1206–1223. https://doi.org/10.1111/anti.12405

Boukerrou, L., Ouedraogo, F. R., & Kabore, J. S. (2019). Sustainability of water investments in West Africa. *WIT Transactions on Ecology and the Environment*, *239*, 211–222. https://doi.org/10.2495/WS190191

Boyer, E. L. (1997). *Scholarship reconsidered: priorities of the professoriate*. Jossey-Bass Publishers.

Bradbury, H., & Divecha, S. (2020). Action methods for faster transformation: Relationality in action. *Action Research*, *18*(3), 273–281. https://doi.org/10.1177/1476750320936493

Bradley, D. D. J., & Bartram, J. K. J. (2013). Domestic water and sanitation as water security: monitoring, concepts and strategy. *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences*, *371*(2002), 20120420. https://doi.org/10.1098/rsta.2012.0420

Brondizio, E. S., O'Brien, K., Bai, X., Biermann, F., Steffen, W., Berkhout, F., Cudennec, C., Lemos, M. C., Wolfe, A., Palma-Oliveira, J., & Chen, C. T. A. (2016). Re-conceptualizing the Anthropocene: A call for collaboration. *Global Environmental Change*, *39*, 318–327. https://doi.org/10.1016/j.gloenvcha.2016.02.006

Bunsen, J., Berger, M., & Finkbeiner, M. (2021). Planetary boundaries for water – A review. *Ecological Indicators*, *121*, 107022. https://doi.org/10.1016/j.ecolind.2020.107022

Cairncross, S., Bartram, J., Cumming, O., & Brocklehurst, C. (2010). Hygiene, sanitation, and water: What needs to be done? *PLoS Medicine*, *7*(11), 1–7. https://doi.org/10.1371/journal.pmed.1000365

Carew, A. L., & Wickson, F. (2010). The TD Wheel: A heuristic to shape, support and evaluate transdisciplinary research. *Futures*, *42*(10), 1146–1155. https://doi.org/10.1016/j.futures.2010.04.025

Carrard, N., MacArthur, J., Leahy, C., Soeters, S., & Willetts, J. (2022). The water, sanitation and hygiene gender equality measure (WASH-GEM): Conceptual foundations and domains of change. *Women's Studies International Forum*, *91*, 102563. https://doi.org/10.1016/j.wsif.2022.102563

Cerf, M. E. (2019). Sustainable Development Goal Integration, Interdependence, and Implementation: the Environment–Economic–Health Nexus and Universal Health Coverage. *Global Challenges*, *3*(9), 1900021. https://doi.org/10.1002/gch2.201900021

Chambers, J. M., Wyborn, C., Klenk, N. L., Ryan, M., Serban, A., Bennett, N. J., Brennan, R., Charli-Joseph, L., Fernández-Giménez, M. E., Galvin, K. A., Goldstein, B. E., Haller, T., Hill, R., Munera, C., Nel, J. L., Österblom, H., Reid, R. S., Riechers, M., Spierenburg, M., … Rondeau, R. (2022). Co-productive agility and four collaborative pathways to sustainability transformations. *Global Environmental Change*, *72*, 102422. https://doi.org/10.1016/j.gloenvcha.2021.102422

Chambers, J. M., Wyborn, C., Ryan, M. E., Reid, R. S., Riechers, M., Serban, A., Bennett, N. J., Cvitanovic, C., Fernández-Giménez, M. E., Galvin, K. A., Goldstein, B. E., Klenk, N. L., Tengö, M., Brennan, R., Cockburn, J. J., Hill, R., Munera, C., Nel, J. L., Österblom, H., … Pickering, T. (2021). Six modes of co-production for sustainability. *Nature Sustainability*, *49*(1). https://doi.org/10.1038/s41893-021-00755-x

Charles, K. J., Howard, G., Villalobos Prats, E., Gruber, J., Alam, S., Alamgir, A. S. M., Baidya, M., Flora, M. S., Haque, F., Hassan, S. M. Q., Islam, S., Lazaro, A., Lwetoijera, D. W., Mahmud, S. G., Mahmud, Z. H., Matwewe, F., Pasa, K., Rahman, M., Reza, A. A. S., … Campbell-Lendrum, D. (2022). Infrastructure alone cannot ensure resilience to weather events in drinking water supplies. *Science of the Total Environment*, *813*(xxxx), 151876. https://doi.org/10.1016/j.scitotenv.2021.151876

Cole, J. (2019). Key Concepts in Planetary Health. In Jennifer Cole, A. Foster, A. Farlow, H. Bartlett, K. Zywert, & T. Harris (Eds.), *Planetary Health : Human Health in an Era of Global Environmental Change* (pp. 9–22). CAB International. https://doi.org/10.1079/9781789241655.0009

Cole, Jennifer. (2018). *Sanitation in the Context of Planetary Health: Opportunities and Challenges Report from the Secretariat of the Rockefeller Foundation Economic Council on Planetary Health* (Issue July). www.planetaryhealth.ox.ac.uk/publications/

Covey, S. (1998). *The 7 Habits of Highly Effective Teens*. Touchstone Books.

Covey, S. R. (1989). *The 7 Habits of Highly Effective People: Powerful Lessons in Personal Change*. Simon and Schuster.

Crotty, M. (1998). *The Foundations of Social Research: Meaning and Perspective in the Research Process*. Taylor & Francis Group.

Crutzen, P. J. (2002). Geology of mankind - Crutzen - Nature. *Nature*, *415*(January), 2002.

Cunha Libanio, P. A. (2021). WASH services and human development: a tangible nexus for achieving water-related SDGs. *International Journal of River Basin Management*, *0*(0), 1–10. https://doi.org/10.1080/15715124.2021.1909603

D'Amato, D. (2021). Sustainability Narratives as Transformative Solution Pathways: Zooming in on the Circular Economy. *Circular Economy and Sustainability*, *1*(1), 231–242. https://doi.org/10.1007/s43615-021-00008-1

Daniel, D., Djohan, D., & Nastiti, A. (2021). Interaction of factors influencing the sustainability of water, sanitation, and hygiene (Wash) services in rural indonesia: Evidence from small surveys of wash-related stakeholders in indonesia. *Water (Switzerland)*, *13*(3), 1–11. https://doi.org/10.3390/w13030314

Danso, G. K., Otoo, M., Ekere, W., Ddungu, S., & Madurangi, G. (2017). Market feasibility of faecal sludge and municipal solid waste-based compost as measured by farmers' willingness-to-pay for product attributes: Evidence from Kampala, Uganda. *Resources*, *6*(3), 31. https://doi.org/10.3390/resources6030031

Daryanani, A. (2012). Report: Waterlines 30th anniversary celebration event. *Waterlines*, *31*(1/2).

Daudey, L. (2018). The cost of urban sanitation solutions: a literature review. *Journal of Water Sanitation and Hygiene for Development*, *8*(2), 176–195. https://doi.org/10.2166/washdev.2017.058

Delgado, A., Rodriguez, D. J., Amadei, C. A., & Makino, M. (2021). *Water in Circular Economy and Resilience (WICER)*.

Dickin, S., Bayoumi, M., Giné, R., Andersson, K., & Jiménez, A. (2020). Sustainable sanitation and gaps in global climate policy and financing. *Npj Clean Water*, *3*(1). https://doi.org/10.1038/s41545-020-0072-8

Dickin, S., Segnestam, L., & Dakouré, M. S. (2021). *Women's vulnerability to climate-related risks to household water security in Centre-East, Burkina Faso*. https://doi.org/10.1080/17565529.2020.1790335

Donkor, F. K. (2020). Adaptive Water, Sanitation and Hygiene Management: Resilient Governance Systems. In W. Leal Filho, A. M. Azul, L. Brandli, A. Lange Salvia, & T. Wall (Eds.), *Clean Water and Sanitation* (pp. 1–12). Springer International Publishing. https://doi.org/10.1007/978-3-319-70061-8_190-1

Downing, A. S., Bhowmik, A., Collste, D., Cornell, S. E., Donges, J., Fetzer, I., Häyhä, T., Hinton, J., Lade, S., & Mooij, W. M. (2019). Matching scope, purpose and uses of planetary boundaries science. *Environmental Research Letters*, *14*(7), 073005. https://doi.org/10.1088/1748-9326/ab22c9

Drees, L., Luetkemeier, R., & Kerber, H. (2021). Necessary or oversimplification? On the strengths and limitations of current assessments to integrate social dimensions in planetary boundaries. *Ecological Indicators*, *129*(December 2020), 108009. https://doi.org/10.1016/j.ecolind.2021.108009

Dwipayanti, N. M. U., Phung, T. D., Rutherford, S., & Chu, C. (2017). Towards sustained sanitation services: A review of existing frameworks and an alternative framework combining ecological and sanitation life stage approaches. *Journal of Water Sanitation and Hygiene for Development*, *7*(1), 25–42. https://doi.org/10.2166/washdev.2017.086

Elledge, M. F., Muralidharan, A., Parker, A., Ravndal, K. T., Siddiqui, M., Toolaram, A. P., & Woodward, K. P. (2018). Menstrual hygiene management and waste disposal in low and middle income countries—a review of the literature. *International Journal of Environmental Research and Public Health*, *15*(11). https://doi.org/10.3390/ijerph15112562

Fallon, C., & Neville, G. (2021). Socio-political processes must be emphasised alongside climate change and urbanisation as key drivers of urban water insecurity. *Water Policy*, *23*, 36–57. https://doi.org/10.2166/wp.2020.333

Fleming, L., Anthonj, C., Thakkar, M. B., Tikoisuva, W. M., Manga, M., Howard, G., Shields, K. F., Kelly, E., Overmars, M., & Bartram, J. (2019). Urban and rural sanitation in the Solomon Islands: How resilient are these to extreme weather events? *Science of the Total Environment*, *683*, 331–340. https://doi.org/10.1016/j.scitotenv.2019.05.253

Fløttum, K., & Gjerstad, Ø. (2017). Narratives in climate change discourse. *Wiley Interdisciplinary Reviews: Climate Change*, *8*(1), 1–15. https://doi.org/10.1002/wcc.429

Fritz, L., & Binder, C. R. (2020). Whose knowledge, whose values? An empirical analysis of power in transdisciplinary sustainability research. *European Journal of Futures Research*, *8*(1). https://doi.org/10.1186/s40309-020-0161-4

Gibbs, P., & Beavis, A. (2020). *Contemporary Thinking on Transdisciplinary Knowledge: What Those Who Know, Know*. Springer International Publishing.

González, I. N., Cisneros, B. J., Hernández, N. A., & Rojas, R. M. (2019). Adaptation and mitigation synergies to improve sanitation: A case study in Morelos, Mexico. *Journal of Water and Climate Change*, *10*(3), 671–686. https://doi.org/10.2166/wcc.2018.121

Gram-Hanssen, I., Schafenacker, N., & Bentz, J. (2021). Decolonizing transformations through 'right relations.' *Sustainability Science*, *0123456789*. https://doi.org/10.1007/s11625-021-00960-9

Grant, M. J., & Booth, A. (2009). A typology of reviews: An analysis of 14 review types and associated methodologies. *Health Information and Libraries Journal*, *26*(2), 91–108. https://doi.org/10.1111/j.1471-1842.2009.00848.x

Grasham, C. F., Calow, R., Casey, V., Charles, K. J., de Wit, S., Dyer, E., Fullwood-Thomas, J., Hirons, M., Hope, R., Hoque, S. F., Jepson, W., Korzenevica, M., Murphy, R., Plastow, J., Ross, I., Ruiz-Apilánez, I., Schipper, E. L. F., Trevor, J., Walmsley, N., & Zaidi, H. (2021). Engaging with the politics of climate resilience towards clean water and sanitation for all. *Npj Clean Water*, *4*(1). https://doi.org/10.1038/s41545-021-00133-2

Griggs, D., Stafford-Smith, M., Gaffney, O., Rockström, J., Ohman, M. C., Shyamsundar, P., Steffen, W., Glaser, G., Kanie, N., & Noble, I. (2013). Sustainable development goals for people and planet. *Nature*, *495*(7441), 305–307. https://doi.org/10.1038/495305a

Groot, R., & Mustafa, M. (2019). *Achieving water security in peri-urban Yangon : exploring the local governance processes*. *21*, 980–998. https://doi.org/10.2166/wp.2019.058

Hadwen, W. L., Powell, B., MacDonald, M. C., Elliott, M., Chan, T., Gernjak, W., & Aalbersberg, W. G. L. (2015). Putting WASH in the water cycle: climate change, water resources and the future of water, sanitation and hygiene challenges in Pacific Island Countries. *Journal of Water, Sanitation and Hygiene for Development*, *5*(2), 183–191. https://doi.org/10.2166/washdev.2015.133

Hajer, M., Nilsson, M., Raworth, K., Bakker, P., Berkhout, F., de Boer, Y., Rockström, J., Ludwig, K., & Kok, M. (2015). Beyond cockpit-ism: Four insights to enhance the transformative potential of the sustainable development goals. *Sustainability (Switzerland)*, *7*(2), 1651–1660. https://doi.org/10.3390/su7021651

Haque, S. S., & Freeman, M. C. (2021). The Applications of Implementation Science in Water, Sanitation, and Hygiene (WASH) Research and Practice. *Environmental Health Perspectives*, *129*(8), 89001. https://doi.org/10.1289/EHP10060

Hargrove, A. (2019). Global Aid in the Water Sector: A Descriptive Analysis of International Development Effectiveness. *International Journal of Social Science Studies*, *7*(2), 19. https://doi.org/10.11114/ijsss.v7i2.3874

Harzing, A. W., & Alakangas, S. (2016). Google Scholar, Scopus and the Web of Science: a longitudinal and cross-disciplinary comparison. *Scientometrics*, *106*(2), 787–804. https://doi.org/10.1007/s11192-015-1798-9

Hernandez-Aguilar, C. (2018). Transdisciplinary Methodological Option for Initial Research Process: Training of Researchers. *Transdisciplinary Journal of Engineering & Science*, *9*, 157–181. https://doi.org/10.22545/2018/00108

Hernandez-Aguilar, C., Dominguez-Pacheco, A., Martínez-Ortiz, E. J., Ivanov, R., López Bonilla, J. L., Cruz-Orea, A., & Ordonez-Miranda, J. (2020). Evolution and characteristics of the transdisciplinary perspective in research: a literature review. In *Transdisciplinary Journal of Engineering & Science* (Vol. 11). https://doi.org/10.22545/2020/00140

Herrera, V. (2019). Reconciling global aspirations and local realities: Challenges facing the Sustainable Development Goals for water and sanitation. *World Development*, *118*, 106–117. https://doi.org/10.1016/j.worlddev.2019.02.009

Hopkins, S. R., Sokolow, S. H., Buck, J. C., De Leo, G. A., Jones, I. J., Kwong, L. H., LeBoa, C., Lund, A. J., MacDonald, A. J., Nova, N., Olson, S. H., Peel, A. J., Wood, C. L., & Lafferty, K. D. (2021). How to identify win–win interventions that benefit human health and conservation. *Nature Sustainability*, *4*(4), 298–304. https://doi.org/10.1038/s41893-020-00640-z

Howard, G., Nijhawan, A., Flint, A., Baidya, M., Pregnolato, M., Ghimire, A., Poudel, M., Lo, E., Sharma, S., Mengustu, B., Ayele, D. M., Geremew, A., & Wondim, T. (2021). The how tough is WASH framework for assessing the climate resilience of water and sanitation. *Npj Clean Water*, *4*(1). https://doi.org/10.1038/s41545-021-00130-5

Huston, A., & Moriarty, P. (2018). *Understanding the WASH system and its building blocks*. https://www.ircwash.org/sites/default/files/084-201813wp_buildingblocksdef_newweb.pdf%0Ahttps://www.ircwash.org/resources/understanding-wash-system-and-its-building-blocks

Hutton, G., & Chase, C. (2016). The Knowledge Base for Achieving the Sustainable Development Goal Targets on Water Supply, Sanitation and Hygiene. *International Journal of Environmental Research and Public Health*, *13*(6), 536. https://doi.org/10.3390/ijerph13060536

Huutoniemi, K. (2014). Introduction: Sustainability, transdisciplinarity and the complexity of knowing. In K. Huutoniemi & P. Tapio (Eds.), *Transdisciplinary Sustainability Studies: A Heuristic Approach* (pp. 1–20). Routledge. https://doi.org/10.4324/9780203734834-8

Hyun, C., Burt, Z., Crider, Y., Nelson, K. L., Prasad, C. S. S., Rayasam, S. D. G., Tarpeh, W., & Ray, I. (2019). *Sanitation for Low-Income Regions : A Cross-Disciplinary Review*.

ISF-UTS and SNV. (2019). *Considering climate change in urban sanitation: conceptual approaches and practical implications*. www.snv.org

IWA. (2016). *Water utility pathways in a circular economy*. International Water Association.

IWA. (2022). *International Water Association Specialist Groups*. https://iwa-network.org/iwa-specialist-groups/, accessed 17/03/2022

Jagannathan, K., Arnott, J. C., Wyborn, C., Klenk, N., Mach, K. J., Moss, R. H., & Sjostrom, K. D. (2020). Great expectations? Reconciling the aspiration, outcome, and possibility of co-production. *Current Opinion in Environmental Sustainability*, *42*, 22–29. https://doi.org/10.1016/j.cosust.2019.11.010

Jahn, T., Bergmann, M., & Keil, F. (2012). Transdisciplinarity: Between mainstreaming and marginalization. *Ecological Economics*, *79*, 1–10. https://doi.org/10.1016/j.ecolecon.2012.04.017

Jantsch, E. (1970). Inter- and Transdisciplinary University: A Systems Approach to Education and Innovation. *Higher Education*, *1*(1), 403–428. https://doi.org/https://doi.org/10.1007/BF01956879

Jiménez, A., Jawara, D., LeDeunff, H., Naylor, K. A., & Scharp, C. (2017). Sustainability in practice: Experiences from rural water and sanitation services in West Africa. *Sustainability (Switzerland)*, *9*(3). https://doi.org/10.3390/su9030403

Johnson, R. B., & Onwuegbuzie, A. J. (2004). Mixed Methods Research: A Research Paradigm Whose Time Has Come. *Educational Researcher*, *33*(7), 14–26. https://doi.org/10.3102/0013189X033007014

Kaguima, E. N. (2013). An assessment of the WEDC conference papers and their contribution to the WASH knowledge base. *36th WEDC International Conference: Delivering Water, Sanitation and Hygiene Services in an Uncertain Environment*, 1–6.

Kallio, E. (2011). Integrative thinking is the key: An evaluation of current research into the development of adult thinking. *Theory & Psychology*, *21*(6), 785–801. https://doi.org/10.1177/0959354310388344

Kaushik, V., & Walsh, C. A. (2019). Pragmatism as a research paradigm and its implications for Social Work research. *Social Sciences*, *8*(9), 1–17.

Khan, S., Guan, Y., & Khan, F. (2020). A Comprehensive Index for Measuring Water Security in an Urbanizing World: The Case of Pakistan's Capital. *Water*, *12*(166).

Klein, J. T. (2021). Beyond Interdisciplinarity. In *Beyond Interdisciplinarity* (pp. 1–12). https://doi.org/10.1093/oso/9780197571149.001.0001

Klenk, N. L., & Meehan, K. (2017). Transdisciplinary sustainability research beyond engagement models: Toward adventures in relevance. *Environmental Science and Policy*, *78*(September), 27–35. https://doi.org/10.1016/j.envsci.2017.09.006

Kohlitz, J. P., Chong, J., & Willetts, J. (2017). Climate change vulnerability and resilience of water, sanitation, and hygiene services: A theoretical perspective. *Journal of Water Sanitation and Hygiene for Development*, *7*(2), 181–195. https://doi.org/10.2166/washdev.2017.134

Koottatep, T., Cookey, P. E., & Polprasert, C. (2019). Regenerative Sanitation: A New Paradigm For Sanitation 4.0. In *Regenerative Sanitation: A New Paradigm For Sanitation 4.0*. https://doi.org/10.2166/9781780409689

Kopnina, H. (2016). The victims of unsustainability: A challenge to sustainable development goals. *International Journal of Sustainable Development and World Ecology*, *23*(2), 113–121. https://doi.org/10.1080/13504509.2015.1111269

Kroll, C., Warchold, A., & Pradhan, P. (2019). Sustainable Development Goals (SDGs): Are we successful in turning trade-offs into synergies? *Palgrave Communications*, *5*(1), 1–11. https://doi.org/10.1057/s41599-019-0335-5

Kulak, M., Shah, N., Sawant, N., Unger, N., & King, H. (2017). Technology choices in scaling up sanitation can significantly affect greenhouse gas emissions and the fertiliser gap in India. *Journal of Water Sanitation and Hygiene for Development*, *7*(3), 466–476. https://doi.org/10.2166/washdev.2017.005

Lam, D. P. M., Martín-López, B., Wiek, A., Bennett, E. M., Frantzeskaki, N., Horcea-Milcu, A. I., & Lang, D. J. (2020). Scaling the impact of sustainability initiatives: a typology of amplification processes. *Urban Transformations*, *2*(1). https://doi.org/10.1186/s42854-020-00007-9

Lazurko, A., Alamenciak, T., Hill, L. S., Muhl, E.-K., Osei, A. K., Pomezanski, D., Schang, K., & Sharmin, D. F. (2020). What Will a PhD Look Like in the Future? Perspectives on Emerging Trends in Sustainability Doctoral Programs in a Time of Disruption. *World Futures Review*, *12*(4), 369–384. https://doi.org/10.1177/1946756720976710

Leventon, J., Abson, D. J., & Lang, D. J. (2021). Leverage points for sustainability transformations: nine guiding questions for sustainability science and practice. *Sustainability Science*, *16*(3), 721–726. https://doi.org/10.1007/s11625-021-00961-8

Lim, M. M. L., Søgaard Jørgensen, P., & Wyborn, C. A. (2018). Reframing the sustainable development goals to achieve sustainable development in the anthropocene—a systems approach. *Ecology and Society*, *23*(3). https://doi.org/10.5751/ES-10182-230322

Linnér, B.-O., & Wibeck, V. (2019). *Sustainability Transformations: Agents and Drivers across Societies*. Cambridge University Press. https://doi.org/DOI: 10.1017/9781108766975

Linnér, B. O., & Wibeck, V. (2021). Drivers of sustainability transformations: leverage points, contexts and conjunctures. *Sustainability Science*, *16*(3), 889–900. https://doi.org/10.1007/s11625-021-00957-4

Lockwood, H., & Smits, S. (2011). Supporting Rural Water Supply: Moving towards a Service Delivery Approach. In *Program*. Practical Action Publishing, IRC International Water and Sanitation Centre and Aguaconsult, 2011.

Lorenzo, T. E., & Kinzig, A. P. (2019). Double Exposures: Future Water Security across Urban Southeast Asia. *Water (Switzerland)*, *12*(116). https://doi.org/doi:10.3390/w12010116

Macarthur, J., Carrard, N., & Willetts, J. (2020). Wash and gender: A critical review of the literature and implications for gender-transformative wash research. *Journal of Water Sanitation and Hygiene for Development*, *10*(4), 818–827. https://doi.org/10.2166/washdev.2020.232

MacDonald, M. C., Chan, T., Elliott, M., Kearton, A., Shields, K. F., Barrington, D. J., Souter, R. T., Powell, B. R., Bartram, J., & Hadwen, W. L. (2017). Temporal and thematic trends in water, sanitation and hygiene (WASH) research in pacific island Countries: A systematic review. *Journal of Water Sanitation and Hygiene for Development*, *7*(3), 352–368. https://doi.org/10.2166/washdev.2017.021

Mallory, A., Akrofi, D., Dizon, J., Mohanty, S., Parker, A., Rey Vicario, D., Prasad, S., Welvita, I., Brewer, T., Mekala, S., Bundhoo, D., Lynch, K., Mishra, P., Willcock, S., & Hutchings, P. (2020). Evaluating the circular economy for sanitation: Findings from a multi-case approach. *Science of the Total Environment*, *744*. https://doi.org/10.1016/j.scitotenv.2020.140871

Mallory, A., Holm, R., & Parker, A. (2020). A Review of the Financial Value of Faecal Sludge Reuse in Low-Income Countries. *Sustainability*, *12*(8334), 1–13. https://doi.org/10.3390/su12208334

Marshall, F., Dolley, J., & Priya, R. (2018). Transdisciplinary research as transformative space making for sustainability: Enhancing propoor transformative agency in Periurban contexts. *Ecology and Society*, *23*(3). https://doi.org/10.5751/ES-10249-230308

Masi, F., Rizzo, A., & Regelsberger, M. (2018). The role of constructed wetlands in a new circular economy, resource oriented, and ecosystem services paradigm. *Journal of Environmental Management*, *216*, 275–284. https://doi.org/10.1016/j.jenvman.2017.11.086

Mason, N., Pickard, S., Watson, C., Klanten, B., & Calow, R. (2020). *Just add water : a landscape analysis of climate finance for water* (Issue October). https://washmatters.wateraid.org/sites/g/files/jkxoof256/files/just-add-water-a-landscape-analysis-of-climate-finance-for-water.pdf

Mauser, W., Klepper, G., Rice, M., Schmalzbauer, B. S., Hackmann, H., Leemans, R., & Moore, H. (2013). Transdisciplinary global change research: The co-creation of knowledge for sustainability. *Current Opinion in Environmental Sustainability*, *5*(3–4), 420–431. https://doi.org/10.1016/j.cosust.2013.07.001

McDonough, W., & Braungart, M. (2010). *Cradle to Cradle: Remaking the Way We Make Things*. Farrar, Straus and Giroux.

McNicol, G., Jeliazovski, J., François, J. J., Kramer, S., & Ryals, R. (2020). Climate change mitigation potential in sanitation via off-site composting of human waste. *Nature Climate Change*, *10*(6), 545–549. https://doi.org/10.1038/s41558-020-0782-4

Meadows, D. (2008). *Thinking in Systems: A Primer*. Chelsea Green Publishing Company.

Mikhael, G., Hyde-Smith, L., Twyman, B., Trancón, D. S., Jabagi, E., & Bamford, E. (2021). *Climate Resilient Urban Sanitation: Accelerating the Convergence of Sanitation and Climate Action*. GIZ and Resilient Cities Network.

Miller, T. R., Baird, T. D., Littlefield, C. M., Kofinas, G., Chapin, F. S., & Redman, C. L. (2008). Epistemological pluralism: Reorganizing interdisciplinary research. *Ecology and Society*, *13*(2). https://doi.org/10.5751/ES-02671-130246

Mills, F., Willetts, J., Evans, B., Carrard, N., & Kohlitz, J. (2020). *Costs , Climate and Contamination : Three Drivers for Citywide Sanitation Investment Decisions*. *8*(August), 1–14. https://doi.org/10.3389/fenvs.2020.00130

Mitchell, C., Cordell, D., & Fam, D. (2015). Beginning at the end: The outcome spaces framework to guide purposive transdisciplinary research. *Futures*, *65*, 86–96. https://doi.org/10.1016/j.futures.2014.10.007

Mitchell, C., & Willetts, J. (2009). *Zen and the Art of Postgraduate Studies: Quality criteria for inter- and trans-disciplinary doctoral research outcomes* (Issue January 2009).

Mobjörk, M. (2010). Consulting versus participatory transdisciplinarity: A refined classification of transdisciplinary research. *Futures*, *42*(8), 866–873. https://doi.org/10.1016/j.futures.2010.03.003

Montoya, J. M., Donohue, I., & Pimm, S. L. (2018). Planetary Boundaries for Biodiversity: Implausible Science, Pernicious Policies. In *Trends in Ecology and Evolution* (Vol. 33, Issue 2, pp. 71–73). https://doi.org/10.1016/j.tree.2017.10.004

Moriarty, P., Smits, S., Butterworth, J., & Franceys, R. (2013). Trends in rural water supply: Towards a service delivery approach. *Water Alternatives*, *6*(3), 329–349.

Moya, B., Sakrabani, R., & Parker, A. (2019). Realizing the Circular Economy for Sanitation: Assessing Enabling Conditions and Barriers to the Commercialization of Human Excreta Derived Fertilizer in Haiti and Kenya. *Sustainability*, *11*(11), 3154. https://doi.org/10.3390/su11113154

Mukherjee, S., Sundberg, T., & Schütt, B. (2020). Assessment of Water Security in Socially Excluded Water , Sanitation and Hygiene. *Water*, *2030*.

Nentwich, J. C., Ozbilgin, M. F., & Tatli, A. (2015). Change agency as performance and embeddedness: Exploring the possibilities and limits of Butler and Bourdieu. *Culture and Organization*, *21*(3), 235–250. https://doi.org/10.1080/14759551.2013.851080

Nicolescu, B. (2008). *Transdisciplinarity: theory and practice*. Hampton Press.

Nicolescu, B. (2014). Methodology of transdisciplinarity. *World Futures*, *70*(3–4), 186–199. https://doi.org/10.1080/02604027.2014.934631

Nikolaou, I. E., Jones, N., & Stefanakis, A. (2021). Circular Economy and Sustainability: the Past, the Present and the Future Directions. *Circular Economy and Sustainability*, *1*(2), 783–783. https://doi.org/10.1007/s43615-021-00054-9

Nilsson, M., Griggs, D., & Visbeck, M. (2016). Map the interactions between Sustainable Development Goals. *Nature*, *1534*, 320–322.

Nisbet, M. (2009). Communicating climate change: Why frames matter for public engagement. *Environment*, *51*(2), 12–23. https://doi.org/10.3200/ENVT.51.2.12-23

Otoo, M., Rao, K. C., Hope, L., & Atukorala, I. (2018). Resource Recovery from Waste: Business Models for Energy, Nutrient and Water Reuse in Low- and Middle-income Countries. In M. Otoo & P. Drechsel (Eds.), *Resource Recovery from Waste: Business Models for Energy, Nutrient and Water Reuse in Low- and Middle-income Countries*. Routledge. http://www.iwmi.cgiar.org/Publications/Books/PDF/resource-recovery-from-waste.pdf

Patterson, J., Schulz, K., Vervoort, J., van der Hel, S., Widerberg, O., Adler, C., Hurlbert, M., Anderton, K., Sethi, M., & Barau, A. (2017). Exploring the governance and politics of transformations towards sustainability. *Environmental Innovation and Societal Transitions*, *24*, 1–16. https://doi.org/10.1016/j.eist.2016.09.001

Paudel, S., Kumar, P., Dasgupta, R., Johnson, B. A., Avtar, R., Shaw, R., Mishra, B. K., & Kanbara, S. (2021). *Nexus between Water Security Framework and Public Health : A Comprehensive Scientific Review*. 1–15.

Pereira, L., Frantzeskaki, N., Hebinck, A., Charli-Joseph, L., Drimie, S., Dyer, M., Eakin, H., Galafassi, D., Karpouzoglou, T., Marshall, F., Moore, M. L., Olsson, P., Siqueiros-García, J. M., van Zwanenberg, P., & Vervoort, J. M. (2020). Transformative spaces in the making: key lessons from nine cases in the Global South. *Sustainability Science*, *15*(1), 161–178. https://doi.org/10.1007/s11625-019-00749-x

Pereira, L. M., Karpouzoglou, T., Frantzeskaki, N., & Olsson, P. (2018). Designing transformative spaces for sustainability in social-ecological systems. *Ecology and Society*, *23*(4). https://doi.org/10.5751/ES-10607-230432

Pickering, A. J., Null, C., Winch, P. J., Mangwadu, G., Arnold, B. F., Prendergast, A. J., Njenga, S. M., Rahman, M., Ntozini, R., Benjamin-Chung, J., Stewart, C. P., Huda, T. M. N., Moulton, L. H., Colford, J. M., Luby, S. P., & Humphrey, J. H. (2019). The WASH Benefits and SHINE trials: interpretation of WASH intervention effects on linear growth and diarrhoea. *The Lancet Global Health*, *7*(8), e1139–e1146. https://doi.org/10.1016/S2214-109X(19)30268-2

Pisano, U., & Berger, G. (2013). Planetary Boundaries for SD. From an internationsal perspective to national applications. ESDN Quarterly Report N°30. *European Sustainable Development Network*, *October*.

Pohl, C. (2010). From Transdisciplinarity to Transdisciplinary Research. *Transdiciplinary Journal of Engineering & Science*, *1*, 65–73. https://doi.org/10.22545/2010/0006

Pohl, C., Klein, J. T., Hoffmann, S., Mitchell, C., & Fam, D. (2021). Conceptualising transdisciplinary integration as a multidimensional interactive process. *Environmental Science and Policy*, *118*, 18–26. https://doi.org/10.1016/j.envsci.2020.12.005

Popa, F., Guillermin, M., & Dedeurwaerdere, T. (2015). A pragmatist approach to transdisciplinarity in sustainability research: From complex systems theory to reflexive science. *Futures*, *65*, 45–56. https://doi.org/10.1016/j.futures.2014.02.002

Prescott, M. F., Dobbie, M. F., & Ramirez-Lovering, D. (2021). Green infrastructure for sanitation in settlements in the global south: A narrative review of socio-technical systems. *Sustainability (Switzerland)*, *13*(4), 1–20. https://doi.org/10.3390/su13042071

Pugel, K., Javernick-Will, A., Peabody, S., Nyaga, C., Mussa, M., Mekonta, L., Dimtse, D., Watsisi, M., Buhungiro, E., Mulatu, T., Annis, J., Jordan, E., Sandifer, E., & Linden, K. (2022). Pathways for collaboratively strengthening water and sanitation systems. *Science of the Total Environment*, *802*, 149854. https://doi.org/10.1016/j.scitotenv.2021.149854

Rao, K. C. k., Otoo, M., Drechsel, P., & Hanjra, M. A. (2017). Resource recovery and reuse as an incentive for a more viable sanitation service chain. *Water Alternatives*, *10*(2), 493–512.

Raworth, K. (2013). Defining a safe and just space for humanity. In *State of the World 2013: Is Sustainability Still Possible?* (pp. 28–38). Island Press/Center for Resource Economics. https://doi.org/10.5822/978-1-61091-458-1_3

Raworth, K. (2017a). A Doughnut for the Anthropocene: humanity's compass in the 21st century. *The Lancet Planetary Health*, *1*(2), e48–e49. https://doi.org/10.1016/s2542-5196(17)30028-1

Raworth, K. (2017b). *Doughnut economics: Seven Ways to Think Like a 21st-Century Economist*. Cornerstone.

Ray, I., & Smith, K. R. (2021). Towards safe drinking water and clean cooking for all. *The Lancet Global Health*, *9*(3), e361–e365. https://doi.org/10.1016/S2214-109X(20)30476-9

Reid, M. (2020). Where mitigation and migration meet. *Nature Climate Change*, *10*(6), 493–494. https://doi.org/10.1038/s41558-020-0796-y

Riedy, C. (2020). Discourse coalitions for sustainability transformations: Common ground and conflict beyond neoliberalism. *Current Opinion in Environmental Sustainability*, *45*, 100–112. https://doi.org/10.1016/j.cosust.2020.09.014

Riedy, C. (2021). Discursive entrepreneurship: ethical meaning-making as a transformative practice for sustainable futures. *Sustainability Science*, *0123456789*. https://doi.org/10.1007/s11625-021-00978-z

Rigolot, C. (2020). Transdisciplinarity as a discipline and a way of being: complementarities and creative tensions. *Humanities and Social Sciences Communications*, *7*(1), 1–5. https://doi.org/10.1057/s41599-020-00598-5

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., De Wit, C. A., Hughes, T., Van Der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., … Foley, J. A. (2009). A safe operating space for humanity. *Nature*, *461*(7263), 472–475. https://doi.org/10.1038/461472a

Rogers, K. H., Luton, R., Biggs, H., Biggs, R. O., Blignaut, S., Choles, A. G., Palmer, C. G., & Tangwe, P. (2013). Fostering complexity thinking in action research for change in social- ecological systems. *Ecology and Society*, *18*(2). https://doi.org/10.5751/ES-05330-180231

Rosenqvist, T., Mitchell, C., & Willetts, J. (2016). A short history of how we think and talk about sanitation services and why it matters. *Journal of Water Sanitation and Hygiene for Development*, *6*(1). http://washdev.iwaponline.com/content/early/2016/02/15/washdev.2016.118.abstract

Ross, K. (2020). *Transforming the ways we create change: experiencing and cultivating transformative sustainability learning* [University of Technology Sydney]. http://hdl.handle.net/10453/149105

Roy, A., & Pramanick, K. (2019). Analysing progress of sustainable development goal 6 in India: Past, present, and future. *Journal of Environmental Management*, *232*, 1049–1065. https://doi.org/10.1016/j.jenvman.2018.11.060

Salomaa, A., & Juhola, S. (2020). How to assess sustainability transformations: A review. *Global Sustainability*, *3*(May). https://doi.org/10.1017/sus.2020.17

Sanitation and Water for All. (2016). *2016 SWA Meeting of Ministers of Water, Sanitation and Hygiene*.

Schmidt, L., Falk, T., Siegmund-Schultze, M., & Spangenberg, J. H. (2020). The Objectives of Stakeholder Involvement in Transdisciplinary Research. A Conceptual Framework for a Reflective and Reflexive Practise. *Ecological Economics*, *176*(May), 106751. https://doi.org/10.1016/j.ecolecon.2020.106751

Schneider, F., Giger, M., Harari, N., Moser, S., Oberlack, C., Providoli, I., Schmid, L., Tribaldos, T., & Zimmermann, A. (2019). Transdisciplinary co-production of knowledge and sustainability transformations: Three generic mechanisms of impact generation. *Environmental Science and Policy*, *102*(August), 26–35. https://doi.org/10.1016/j.envsci.2019.08.017

Schroeder, P., Anggraeni, K., & Weber, U. (2019). The Relevance of Circular Economy Practices to the Sustainable Development Goals. *Journal of Industrial Ecology*, *23*(1), 77–95. https://doi.org/10.1111/jiec.12732

Sellberg, M. M., Cockburn, J., Holden, P. B., & Lam, D. P. M. (2021). Towards a caring transdisciplinary research practice: navigating science, society and self. *Ecosystems and People*, *17*(1), 292–305. https://doi.org/10.1080/26395916.2021.1931452

Sgroi, M., Vagliasindi, F. G. A., & Roccaro, P. (2018). Feasibility, sustainability and circular economy concepts in water reuse. *Current Opinion in Environmental Science & Health*, *2*, 20–25. https://doi.org/10.1016/j.coesh.2018.01.004

Sharpe, B., Hodgson, A., Leicester, G., Lyon, A., & Fazey, I. (2016). Three horizons: A pathways practice for transformation. *Ecology and Society*, *21*(2). https://doi.org/10.5751/ES-08388-210247

SIWI. (2022). *Stockholm International Water Institute: Improving Water Governance*. https://siwi.org/what-we-do/improving-water-governance/, accessed 17/03/2022

Sol, J., Beers, P. J., & Wals, A. E. J. (2013). Social learning in regional innovation networks: Trust, commitment and reframing as emergent properties of interaction. *Journal of Cleaner Production*, *49*, 35–43. https://doi.org/10.1016/j.jclepro.2012.07.041

Somlai, C., Knappe, J., & Gill, L. (2019). Spatial and temporal variation of CO2 and CH4 emissions from a septic tank soakaway. *Science of the Total Environment*, *679*, 185–195. https://doi.org/10.1016/j.scitotenv.2019.04.449

Srivastava, S., Allouche, J., Price, R., & Nelis, T. (2022). *Bringing WASH into the Water–Energy–Food Nexus in Humanitarian Settings* (Vol. 2022, Issue 563). https://doi.org/10.19088/IDS.2022.006

Steffen, W., Richardson, K., Rockstrom, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. a., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sorlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223), 1259855-. https://doi.org/10.1126/science.1259855

Taka, M., Ahopelto, L., Fallon, A., & Kinnunen, P. (2021). The potential of water security in leveraging Agenda 2030. *One Earth*, *4*(2), 258–268. https://doi.org/10.1016/j.oneear.2021.01.007

Taylor, E. W. (1998). The theory and practice of transformative learning: A critical review. In *ERIC Clearinghouse on Adult, Career, and Vocational Education* (Issue 374). https://pdfs.semanticscholar.org/9ebf/010948e2f7527e4b12af385c71e12d4956fc.pdf

Thompson Klein, J. (2015). Discourses of transdisciplinarity: Looking back to the future. *Futures*, *63*, 68–74. https://doi.org/10.1016/j.futures.2015.01.003

Thompson Klein, J. (2017). Transdisciplinarity and sustainability: patterns of definition. In D. Fam, J. Palmer, C. Riedy, & C. Mitchell (Eds.), *Transdisciplinary research and practice for sustainability outcomes*. Routledge. https://www.routledge.com/Transdisciplinary-Research-and-Practice-for-Sustainability-Outcomes/Fam-Palmer-Riedy-Mitchell/p/book/9781138119703

Tortajada, C., & Biswas, A. K. (2018). Achieving universal access to clean water and sanitation in an era of water scarcity: strengthening contributions from academia. *Current Opinion in Environmental Sustainability*, *34*, 21–25. https://doi.org/10.1016/j.cosust.2018.08.001

Trimmer, J. T., Miller, D. C., Byrne, D. M., Lohman, H. A. C., Banadda, N., Baylis, K., Cook, S. M., Cusick, R. D., Jjuuko, F., Margenot, A. J., Zerai, A., & Guest, J. S. (2020). Re-Envisioning Sanitation As a Human-Derived Resource System. *Environmental Science & Technology*, *54*, 10446–10459. https://doi.org/10.1021/acs.est.0c03318

Trimmer, J. T., Miller, D. C., & Guest, J. S. (2019). Resource recovery from sanitation to enhance ecosystem services. *Nature Sustainability*, *2*(8), 681–690. https://doi.org/10.1038/s41893-019-0313-3

UN-Water. (2021). *Summary Progress Update 2021 - SDG 6 - water and sanitation for all*. https://www.unwater.org/new-data-on-global-progress-towards-ensuring-water-and-sanitation-for-all-by-2030/

UNICEF/GWP. (2017). *WASH Climate Resilient Development: Strategic Framework*.

UNICEF. (2021a). *Reimagining WASH: Water Security for All*. https://doi.org/10.1201/9780203878057.pt2

UNICEF. (2021b). *Why Water, Sanitation and Hygiene Must be Top of Your Climate Agenda*.

UNICEF, & UNDP-SIWI Water Governance Facility. (2021). *Sustainability Check Tool: Guidance for designing and implementing Sector-Wide Sustainability Checks in WASH*.

General Assembly resolution 64/292, UN doc. A/Res/64/292, (2010).

General Assembly resolution 70/1, UN doc. A/Res/70/1, (2015).

United Nations. (2015). Transforming our world: The 2030 agenda for sustainable development - A/RES/70/1. In *https://sustainabledevelopment.un.org/content/documents/7891Transforming%20Our%20World. pdf*. https://doi.org/10.1007/s13398-014-0173-7.2

United Nations Sustainable Development Group. (2019). *United Nations Sustainable Development Cooperation Framework*.

Valcourt, N., Javernick-will, A., Walters, J., & Linden, K. (2020). System approaches to water, sanitation, and hygiene: A systematic literature review. *International Journal of Environmental Research and Public Health*, *17*(3). https://doi.org/10.3390/ijerph17030702

Van Eekert, M. H. A., Gibson, W. T., Torondel, B., Abilahi, F., Liseki, B., Schuman, E., Sumpter, C., & Ensink, J. H. J. (2019). Anaerobic digestion is the dominant pathway for pit latrine decomposition and is limited by intrinsic factors. *Water Science and Technology*, *79*(12), 2242–2250. https://doi.org/10.2166/wst.2019.220

Vila-Guilera, J., Parikh, P., Chaturvedi, H., Ciric, L., & Lakhanpaul, M. (2021). Towards transformative WASH: an integrated case study exploring environmental, sociocultural, economic and institutional risk factors contributing to infant enteric infections in rural tribal India. *BMC Public Health*, *21*(1), 1–15. https://doi.org/10.1186/s12889-021-11353-z

Waddock, S. (2020). Reframing and transforming economics around life. *Sustainability (Switzerland)*, *12*(18), 1–16. https://doi.org/10.3390/su12187553

Waddock, S., Waddell, S., Goldstein, B., Linner, B., Schäpke, N., & Vogel, C. (2020). Transformation: How to Spur Radical Change. In A. Scrutton (Ed.), *Our Future on Earth Report*. Future Earth.

West, S., Haider, L. J., Stålhammar, S., & Woroniecki, S. (2020). A relational turn for sustainability science? Relational thinking, leverage points and transformations. *Ecosystems and People*, *16*(1), 304–325. https://doi.org/10.1080/26395916.2020.1814417

Weststrate, J., Dijkstra, G., Eshuis, J., Gianoli, A., & Rusca, M. (2019). The Sustainable Development Goal on Water and Sanitation: Learning from the Millennium Development Goals. *Social Indicators Research*, *143*(2), 795–810. https://doi.org/10.1007/s11205-018-1965-5

Whaley, L., & Cleaver, F. (2017). Can 'functionality' save the community management model of rural water supply? *Water Resources and Rural Development*, *9*(July 2016), 56–66. https://doi.org/10.1016/j.wrr.2017.04.001

WHO. (2018). Guidelines on sanitation and health. In *World Health Organization*. http://www.who.int/water_sanitation_health/publications/guidelines-on-sanitation-and-health/en/

WHO. (2019). *Climate, Sanitation and Health* (Issue July).

Wickson, F., Carew, A. L., & Russell, A. W. (2006). Transdisciplinary research: characteristics, quandaries and quality. *Futures*, *38*(9), 1046–1059. https://doi.org/10.1016/j.futures.2006.02.011

Willcock, S., Parker, A., Wilson, C., Brewer, T., Bundhoo, D., Cooper, S., Lynch, K., Mekala, S., Mishra, P. P., Rey, D., Welivita, I., Venkatesh, K., & Hutchings, P. (2021). Nature provides valuable sanitation services. *One Earth*, *4*(2), 192–201. https://doi.org/10.1016/j.oneear.2021.01.003

Willetts, J., & Mitchell, C. (2017). Assessing transdisciplinary doctoral research: quality criteria and implications for the examination process. In D. Fam, J. Palmer, C. Riedy, & C. Mitchell (Eds.), *Transdisciplinary research and practice for sustainability outcomes*. Routledge.

Willetts, J., Priadi, C., Ombasta, O., Wulandari, D., Imtiyaz, I., Sudhiastiningsih, N. N. S. N., Kohlitz, J., & Mills, F. (2022). Co-developing evidence-informed adaptation actions for resilient citywide sanitation: Local government response to climate change in Indonesia. *Environment and Planning B: Urban Analytics and City Science*, *49*(4).

Woltering, L., Fehlenberg, K., Gerard, B., Ubels, J., & Cooley, L. (2019). Scaling – from "reaching many" to sustainable systems change at scale: A critical shift in mindset. *Agricultural Systems*, *176*(December 2018). https://doi.org/10.1016/j.agsy.2019.102652

Workman, C. L., Cairns, M. R., De Los Reyes, F. L., & Verbyla, M. E. (2021). Global Water, Sanitation, and Hygiene Approaches: Anthropological Contributions and Future Directions for Engineering. *Environmental Engineering Science*, *38*(5), 402–417. https://doi.org/10.1089/ees.2020.0321

World Bank. (2017). *Sustainability Assessment of Rural Water Service Delivery Models Findings of a Multi-Country Review* (Issue August).

Worsham, K., Sylvester, R., Hales, G., McWilliams, K., & Luseka, E. (2021). Leadership for SDG 6.2: Is Diversity Missing? *Environmental Health Insights*, *15*. https://doi.org/10.1177/11786302211031846

Wutich, A., Budds, J., Eichelberger, L., Geere, J., M. Harris, L., A. Horney, J., Jepson, W., Norman, E., O'Reilly, K., Pearson, A. L., H. Shah, S., Shinn, J., Simpson, K., Staddon, C., Stoler, J., Teodoro, M. P., & L. Young, S. (2017). Advancing methods for research on household water insecurity: Studying entitlements and capabilities, socio-cultural dynamics, and political processes, institutions and governance. *Water Security*, *2*, 1–10. https://doi.org/10.1016/j.wasec.2017.09.001

Wyborn, C., Datta, A., Montana, J., Ryan, M., Leith, P., Chaffin, B., Miller, C., & Van Kerkhoff, L. (2019). Co-Producing Sustainability: Reordering the Governance of Science, Policy, and Practice. *Annual Review of Environment and Resources*, *44*, 319–346, https://doi.org/10.1146/annurev-environ-101718-033103

Wyborn, C., Louder, E., Harfoot, M., & Hill, S. (2021). Engaging with the science and politics of biodiversity futures: A literature review. *Environmental Conservation*, *48*(1), 8–15. https://doi.org/10.1017/S037689292000048X

Appendix A

Supplementary material associated with publication 1

SUPPLEMENTARY MATERIAL
Appendix 1 Coded literature

Abdo, J. 2015 *Sustainable Development of Domestic Water Supply in Emerging Megacities: the Case of the City of Guadalajara, Mexico*. PhD Thesis. Faculty of Environmental Sciences and Process Engineering, Brandenburg University of Technology in Cottbus. Retrieved from https://opus4.kobv.de/opus4-btu/files/3607/Gomez_Jauregui_Abdo.pdf

Abdulaziz, W. M. 2013 *WaterAid, Climate Change and the Road to the UN Conference on Climate Change (COP21)*. WaterAid, London, UK.

Abraham, B., Kakumbi, G. M., Alam, M. & von Muench, E. 2011 Alternative solutions for challenging environments: a look at UNICEF-assisted ecosan projects worldwide. In: *The Future of Water, Sanitation and Hygiene: Innovation, Adaptation and Engagement in a Changing World, 35th WEDC International Conference*, Loughborough, UK, July 6–8, 2011.

Anand, P. B. 2012 *Climate Change and Water: Impacts to Human Health and Consumption*. Asia Pacific Human Development report Background paper series 2012/15. UNDP, New York, USA.

Andersson, M. 2014 *Assessing the cultural potential of ecological sanitation in improving waste management and food security in the Taita Hills, Kenya*. PhD Thesis. Retrieved from https://helda.helsinki.fi/handle/10138/136373

Andrew, S. & Prachi, S. 2012 *Infrastructure Services post 2015, report of the Overseas Development Institute (2012)*. Overseas Development Institute, London, UK.

Anon 2012 *Regional Processes of the Americas Harmonizing Water and Energy Position Paper targets 5.1 and 5.2*. 2012 VI World Water Forum, France.

Anon 2013 *EA and EMF for RWSS sector in 28 Districts of Eastern Uttar Pradesh*. State Water and Sanitation Mission, Final report. Mott Macdonald, UK.

Arafat, I. & Rahman, Z. 2010 Ecosanitation: Importance and experience from Bangladesh. In: *Proceedings Regional Conference on Appropriate Water Supply, Sanitation and Hygiene (WASH) Solutions for Informal Settlements and Marginalized Communities, Kathmandu, Nepal*, May 19–21, 2010.

Baskovich, M. R. 2010. *Promoting Sanitation Markets at the Bottom of the Pyramid in Peru: A Win-Win Scenario for Government, the Private Sector, and Communities*. IFC Smart Lessons Brief. World Bank, Washington, DC.

Bassan, M., Mbeguere, M., Tchonda, T., Zabsonre, F. & Strande, L. 2013 Integrated faecal sludge management scheme for the cities of Burkina Faso. *J. Water Sanit. Hyg. Dev.* **3** (2), 216–221.

Bassi, A. M., Tan, Z. & Goss, S. 2010 An integrated assessment of investments to improve global water sustainability. *Water* **2** (4), 726–741.

Batchelor, C., Smits, S. & James, A. J. 2011 *Adaptation of WASH Services Delivery to Climate Change and Other Sources of Risk and Uncertainty* (Thematic Overview Paper 24). The Hague: IRC International Water and Sanitation Centre. Available from: http://www.irc.nl/top24 (accessed 25 May 2016).

Berger, M. & Finkbeiner, M. 2010. Water footprinting: How to address water use in life cycle assessment? *Sustainability* **2** (4), 919–944.

Boarnet, M. G. & Boarnet, M. G. 2008. Transportation infrastructure and sustainable development. *Access* **569**, 27–33. Retrieved from www.uctc.net/scripts/access.pl?33/Access 33 - 05 - New Planning Approaches.pdf

Bohara, R. C. 2015 *Sustainability of Rainwater Harvesting System for the Domestic Needs (A Case Study of Daugha VDC, Gulmi, Nepal).* Doctoral dissertation, Pokhara University.

BPD Water and Sanitation 2011 *Improving Partnership Governance in Water Services. Poverty Responsive PPPs For Water Services Theme: Water Resource Protection*. BPD Water and Sanitation, London.

BRAC 2015 *Water, Sanitation and Hygiene: Nine years of scale and innovation in Bangladesh*. BRAC. Programme report 2006-2015, Mohakhali, Dhaka.

Bradley, D. J. & Bartram, J. K. 2013 Domestic water and sanitation as water security: monitoring, concepts and strategy. *Philos. Trans. A Math. Phys. Eng. Sci.* **371**(2002), 20120420.

Bunclark, L., Carter, R., Casey, V., Day, St J. & Guthrie, D. 2011 *Managing Water Locally*. The Institution of Civil Engineers, Oxfam GB, WaterAid, England, pp. 96.

Butterworth, J. & Guendel, S. 2011. *WASH & Climate Change Adaptation Training Module: Facilitators Guide*. A training module prepared by the IRC International Water and Sanitation Centre for UNICEF and the National Water Resources Institute, Kaduna.

Calow, R., Bonsor, H., Jones, L., Meally, S. O., Macdonald, A. & Kaur, N. 2011 *Climate Change, Water Resources and WASH: A Scoping Study* (Working Paper 337). Overseas Development Institute, London, 69 pp.

CAP-NET 2010 *Groundwater Management in IWRM. Training Manual*. Rio de Janeiro, Brazil.

Carter, R. C. 2010 Editorial. *Waterlines* **29** (3), 179–180.

Chadha, D. 2015 Universalization of sanitary napkin use is not Menstrual Hygiene Management. *38th WEDC International Conference*, Loughborough, UK, 2015.

Cheng, S., Li, Z., Mang, H.-P., Liu, X. & Yin, F. 2014 Prefabricated biogas reactor-based systems for community wastewater and organic waste treatment in developing regions. *J. Water Sanit. Hyg. Dev.* **4** (1), 153–158.

Cheng, S., Li, Z., Shih, J., Du, X. & Xing, J. 2011. A field study on acceptability of 4-in-1 biogas systems in Liaoning Province, China. *Energy Procedia* **5**, 1382–1387.

Chiappe, F., Mujica, A., Ross, I. & Savage, M. 2015 *Climate Finance and Water Security: Inception Report*. Oxford Policy Management, Oxford, UK.

Chiluwe, Q. W. & Nkhata, B. 2014 Analysis of water governance in Malawi: towards a favourable enabling environment? *J. Water Sanit. Hyg. Dev.* **4** (2), 313–323.

Coral, N. (n.d.). *Developing and Assessing an Integrated, Sustainable and Participatory Programme to Enhance RWH Capacity in Igoko, Tanzania*. Poster. Imperial College London.

Corcoran, E., Nellemann, C., Baker, E., Bos, R., Osborn, D. & Savelli, H. (eds). 2010 *Sick Water? The Central Role of Wastewater Management in Sustainable Development: A Rapid Response Assessment*. UNEPUN-HABITAT, GRID-Arendal, Norway.

Cruz-diloné, P. 2014 *A Methodological Framework for Evaluating the Environmental Performance of Large-Scale Sanitation Systems in Developing Countries A Methodological Framework for Evaluating the Environmental Performance of Large-Scale Sanitation Systems in Developing Count*. Thesis, Sustainable Engineering (MS). Rochester University of Technology, Rochester, UK.

DBU 2015 *Terra Preta Sanitation 1 Background, Principles and Innovations*. Deutsche Bundesstiftung Umwelt, Germany.

Dean, J. M. E., Deare, F., Kydd, K., Ward-Robinson, J. & Hunter, P. R. 2012 Rainwater harvesting in rural Trinidad; a cross sectional, observational study. *J. Water Sanit. Hyg. Dev.* **2** (4), 241–249.

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) 2014 *Scarcity Amidst Plenty: Water in North East India*. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), Germany. Available from: https://www.giz.de/en/downloads/giz2014-en-scarcity-amidst-plenty-water-india.pdf

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) 2012 *Good Governance in the Kenyan Water Sector*. Deutsche Gesellschaft für Internationale Zusammenarbeit. Germany.

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) 2015 *Water For All*. Deutsche Gesellschaft für Internationale Zusammenarbeit, Germany.

Diener, S., Semiyaga, S., Niwagaba, C. B., Muspratt, A. M., Gning, J. B., Mbéguéré, M., Ennin, J. E., Zurbrugg, C. & Strande, L. 2014 A value proposition: Resource recovery from

faecal sludge - Can it be the driver for improved sanitation? *Resour. Conserv. Recycl.* **88** (2014), 32–38.

Djonputro, E. R., Blackett, I., Rosenboom, J.-W. & Weitz, A. 2010 Understanding sanitation options in challenging environments. *Waterlines* **29** (3), 187–203.

Doczi, J. 2013 *Climate Risk Management Tools for the Water, Sanitation and Hygiene Sector*. Overseas Development Institute, London, pp. 60.

Doczi, J., Dorr, T., Mason, N. & Scott, A. 2013 *The Post-2015 Delivery of Universal and Sustainable Access to Infrastructure Services*. ODI Working Paper. Overseas Development Institute, London, pp. 67.

Dora, C., Haines, A., Balbus, J., Fletcher, E. & Adair-Rohani, H. 2015. Indicators linking health and sustainability in the post-2015 development agenda. *Lancet* **385**(9965), 380–391.

Edmond, J., Sorto, C., Davidson, S., Sauer, J., Warner, D., Dettman, M. & Platt, J. 2013 *Freshwater Conservation and WASH Integration Guidelines: A Framework for Implementation in sub-Saharan Africa*. Africa Biodiversity Collaborative Group, Conservation International, and The Nature Conservancy, Washington, DC, USA.

Fakkaew, K., Koottatep, T., Pussayanavin, T. & Polprasert, C. 2015 Hydrochar production by hydrothermal carbonization of faecal sludge. *J. Water Sanit. Hyg. Dev.* **5** (3), 439–447.

Frenoux, C. & Tsitsikalis, A. 2015. Domestic private fecal sludge emptying services in Cambodia: between market efficiency and regulation needs for sustainable management. *J. Water Sanit. Hyg. Dev.* **5** (1), 143–155.

Fuhrmeister, E. R., Schwab, K. J. & Julian, T. R. 2015 Estimates of nitrogen, phosphorus, biochemical oxygen demand, and fecal coliforms entering the environment due to inadequate sanitation treatment technologies in 108 low and middle income countries. *Environ. Sci. Technol.* **49** (19), 11604–11.

Fulazzaky, M. 2014 Challenges of integrated water resources management in Indonesia. *Water* **6** (7), 2000–2020.

Garduño, H., Romani, S., Sengupta, B., Tuinhof, A. & Davis, R. 2011 *India Groundwater Governance, A Case Study*. Water Partnership Program, World Bank, Washington, DC, USA.

George, A., Morgan, T., Bhushan, J. & Gamez, M. 2014 Sustainable water and sanitation services for all in a fast changing world, addressing food security , WASH and climate vulnerability: The WaterAid-CARE partnership in Timor-Leste. Briefing Paper 2073. *37th WEDC International Conference*, Hanoi, Vietnam.

GIZ & ICLEI 2014 *Operationalizing the Urban NEXUS: towards resource efficient and integrated cities and metropolitan regions*, GIZ Eschborn. Available from:

www.iclei.org/fileadmin/PUBLICATIONS/Papers/Urban_NEXUS_Publication_ICLEI-GIZ_2014_web.pdf

Global Water Partnership 2011 *Towards Integrated Urban Water Management*. Perspectives Paper. Stockholm, Sweden.

Gnadlinger, J. 2014 How can rainwater harvesting contribute to living with droughts and climate change in semi-arid Brazil? *Waterlines* **33** (2), 146–153. Retrieved from 10.3362/1756-3488.2014.015

Govender, S. 2009 Innovative use of technology and management for sustainable development of water infrastructure in under-serviced regions. *3rd Central European Conference in Regional Science – CERS*, 2009, 275–288.

Graham, J. P. & Polizzotto, M. L. 2013. Pit latrines and their impacts on groundwater quality: A systematic review. *Environ. Health Perspect.* **121** (5), 521–530.

Gunawardana, I. P. P. & Galagedara, L. W. 2013 A new approach to measure sanitation performance. *J. Water Sanit. Hyg. Dev.* **3** (2), 269–282.

Hanjra, M. A., Blackwell, J., Carr, G., Zhang, F. & Jackson, T. M. 2012 Wastewater irrigation and environmental health: Implications for water governance and public policy. *Int. J. Hyg. Environ. Health* **215** (3), 255–269.

Heath, T. 2011 *Climate Proofing Water and Sanitation Services and Applying Integrated Water Resource Management in Slums*. MSc Thesis, Cranfield University, Cranfield, UK.

Heath, T. T., Parker, A. H. & Weatherhead, E. K. 2012. Testing a rapid climate change adaptation assessment for water and sanitation providers in informal settlements in three cities in sub-Saharan Africa. *Environ. Urban.* **24** (2), 619–637.

Hendriksen, A., Tukahirwa, J., Oosterveer, P. J. M. & Mol, A. P. J. 2012 Participatory decision making for sanitation improvements in unplanned urban settlements in East Africa. *J. Environ. Dev.* **21**, 98–119.

Hezri, A. A. 2013 Broadening the environmental dimension in the post-2015 development agenda. *IDS Bulletin* **44** (5–6), 81–88.

Hjalmarsdottir, E. H. 2012 Solar powered pumping technologies in rural water supply: Case study from Kunene region, Namibia. *Waterlines* **31** (3), 197–214.

IRC 2013 *Greywater Reuse Interventions : Keyhole and Vertical Gardens*. Case Studies of multiple use of water in Ethiopia. International Water and Sanitation Centre, The Netherlands.

Iribarnegaray, M. A., Copa, F. R., D'Andrea, M. G., Arredondo, M. F., Cabral, J. D., Correa, J. J., Liberal, V. I. & Seghezzo, L. 2012 A comprehensive index to assess the sustainability of water and sanitation management systems. *J. Water Sanit. Hyg. Dev.* **2** (3), 205–222.

Jägerskog, A., Clausen, T. J., Lexén, K. & Holmgren, T. (eds) 2013 *Cooperation for a Water Wise World – Partnerships for Sustainable Development*. Report Nr. 32. SIWI, Stockholm.

Jansz, S. 2011 *A Study into Rural Water Supply Sustainability in Niassa Province, Mozambique*. Water Aid.

Joint Development Partner Report 2011 *Natural resources management. Vietnam Development Report 2011*. Joint Development Partner Report to the Vietnam consultative group meeting, Hanoi, December, 7–8, 2010.

Juma, L. 2014 *Wastewater Management: A Case of Reducing Wastewater Release into Environment in Mathare North, Nairobi County*. A research project submitted to Kenyatta University department of environmental planning and management in partial fulfilment of degree in environmental planning and management, Kenyatta University.

Juwana, I., Perera, B. J. C. & Muttil, N. 2010 A water sustainability index for West Java. Part 1: developing the conceptual framework. *Water Sci. Technol.* **62** (7), 1629–1640.

Kamuteera, E. 2011 Promoting ecological sanitation: sharing NKKD WATSAN experiences. In: *35th WEDC International Conference*, Loughborough, UK, pp. 1–4.

Katukiza, A. Y., Ronteltap, M., Niwagaba, C. B., Foppen, J. W. A., Kansiime, F. & Lens, P. N. L. 2012 Sustainable sanitation technology options for urban slums. *Biotechnol. Adv.* **30** (5), 964–978.

Kearns, J. P., Knappe, D. R. U. & Summers, R. S. 2014 Synthetic organic water contaminants in developing communities: an overlooked challenge addressed by adsorption with locally generated char. *J. Water Sanit. Hyg. Dev.* **4** (3), 422–436.

Keatman, T. 2009 *Multi Stakeholder Partnerships and Urban Policy in Latin America and the Caribbean Initial Literature Review Summary*. BPD Water and Sanitation, London, UK.

Keatman, T. 2012 *The Silent Partner: The Role of the Environment in Multi-stakeholder Partnerships for Urban and Peri-urban Water and Sanitation Supply*. Building Partnerships for Development in Water & Sanitation, London, UK, pp. 104.

Kennedy-Walker, R., Evans, B., Amezaga, J. & Paterson, C. 2014. Challenges for the future of urban sanitation planning: critical analysis of John Kalbermatten's influence. *J. Water Sanit. Hyg. Dev.* **4** (1), 1–14.

Koné, D. 2010 Making urban excreta and wastewater management contribute to cities' economic development: A paradigm shift. *Water Pol.* **12** (4), 602–610.

Koop, S. H. & van Leeuwen, C. J. 2015. Assessment of the sustainability of water resources management: A critical review of the City Blueprint approach. *Water Resour. Manage.* **29** (15), 5649–5670.

Kosassi-Komlan, E., Dooley, T. Norman, G. (track leads) 2014 WASH Sustainability Forum, initial Concepts. *2014 WASH Sustainability Forum*, June 30–July 1, 2014, Amsterdam, Netherlands.

Kvarnstrom, E., McConville, J., Bracken, P., Johansson, M. & Fogde, M. 2011 The sanitation ladder – a need for a revamp? *J. Water Sanit. Hyg. Dev.* **1** (1), 3–12.

Lane, J. 2012 Barriers and opportunities for sanitation and water for all, as envisaged by the New Delhi Statement. *IDS Bull.* **43** (2), 13–20.

Langergraber, G. 2013 Are constructed treatment wetlands sustainable sanitation solutions? *Water Sci. Technol.* **67** (10), 2133–2140.

Langford, M. & Winkler, I. T. 2013 *Quantifying Water and Sanitation in Development Cooperation: Power or Perversity?* Boston, Harvard School of Public Health, Boston, USA.

Larsen, T. A., Hoffmann, S., Luthi, C., Truffer, B. & Maurer, M. 2016 Emerging solutions to the water challenges of an urbanizing world. *Science* **352** (6288), 928–933.

Le Quesne, T. L., Matthews, J. H., Von der Heyden, C., Wickel, A. J., Wilby, R., Hartmann, J., Pegram, G., Kistin, E., Blate, G., de Freitas, G. K., Levine, E., Guthrie, C., McSweeney C. & Sindorf, N. 2010 *Freshwater Ecosystem Adaptation to Climate Change in Water Resources Management and Biodiversity Conservation*, Water Working Notes, Note No. 28, August 2010. Water Sector Board of the Sustainable Development Network of the World Bank Group.

Lebofa, M. & Huba, E. 2011 Biogas systems in Lesotho: an effective way to generate energy while sanitizing wastewater. *Technol. Econ. Dev. (TED)* **9**, 10–17.

Leese, M. & Meisch, S. 2015 Securitising sustainability? Questioning the "water, energy and food-security nexus." *Water Alternat.* **8** (1), 695–709.

Legrouri, B. A., Kettani, D. & Kalpakian, J. 2012 *Using Demand Side Management to Adapt to Water Scarcity and Climate Change in the Saïss Basin, Morocco*. Final report Al-Akhawayn University in Ifrane, Morocco.

Lenau, T. & Hesselberg, T. 2015 Dry sanitation concepts with inspiration from nature. *J. Water Sanit. Hyg. Dev.* **5** (2), 330–335.

Little, A. 2012 *Field Assessment Concerning Multiple Deprivations in Slums and Squatter Settlements in Kathmandu, Nepal*. PQDT – UK & Ireland. MSc Thesis, The University of Edinburgh, Edinburgh, UK.

Luckson, K. 2011 The future of water, sanitation and hygiene: innovation, adaptation and engagement in a changing world Use of stabilised soil blocks for latrine construction: experiences from Darfur, Sudan. *35th WEDC International Conference*, Loughborough, UK, 2011.

Mahmood, I. B., Li, Z., Uddin, S. M. N., Mang, H.-P. & Germer, J. 2015. Co-composting of fecal matter in Mongolia using two different technologies. *J. Water Sanit. Hyg. Dev.* **5** (1), 165–171.

Malesu, M. M., de Leeuw, J. & Oduor, A. 2014 Water harvesting experiences from the southern and eastern Africa rainwater network. *J. SE. Uni.* **30** (2), 186–191.

Marcelo, D., Mandri-Perrott, C., House, S. & Schwartz, J. Z. 2016 *An Alternative Approach to Project Selection: The Infrastructure Prioritization Framework*. World Bank PPP Group.

Marke, A. 2012 *Stimulating Green Growth through Donor – Business Partnerships in Developing Countries: Filling the Evidence Gap*. Scoping Report. Overseas Development Institute, London.

Mason, N. & Calow, R. 2012 *Water Security: From Abstract Concept to Meaningful Metrics: An Initial Overview of Options*. ODI Working Paper 357. Overseas Development Institute, London.

Mathenjwa, S., Bond, T., Ndwandwe, B., Xulu, S., Kiambi, S. L., Buckley, C. & Roma, E. 2012 Development and testing of a water-efficient laundry system in informal settlements of elrhekwini municipality, South Africa. *J. Water Sanit. Hyg. Dev.* **2** (1), 31–39.

Matuszewska, E. 2010 *The Potential Impacts of Climate Change on Water Supply in Johannesburg*. MSc Thesis Faculty of Engineering and the Built Environment, University of the Witwatersrand, South Africa.

Mehta, L. & Movik, S. 2014 *Flows and Practices: Integrated Water Resources Management (IWRM) in African Contexts*. IDS Work. Papers **2014** (438), 1–34.

Mehta, L. & Movik, S. 2014. Liquid dynamics: challenges for sustainability in the water domain. *Wiley Interdisc. Rev. Water* **1** (4), 369–384.

Mehta, M. & Mehta, D. 2013 City sanitation ladder: moving from household to citywide sanitation assessment. *J. Water Sanit. Hyg. Dev.* **3** (4), 481–488.

Melamed, C. & Ladd, P. 2013 *How to Build Sustainable Development Goals: Integrating Human Development and Environmental Sustainability in a New Global Agenda*. Overseas Development Institute, London.

Middleton, C., Allouche, J., Gyawali, D. & Allen, S. 2015 The rise and implications of the water-energy-food nexus in Southeast Asia through an environmental justice lens. *Water Alternat.* **8** (1), 627–654.

Misra, S. & Kingdom, W. 2012 *India: Improving Urban Water Supply and Sanitation Service Provision Lessons from Business Plans for Maharashtra, Rajasthan, Haryana and International Good Practices*. The World Bank and Ministry of Urban Development Government of India, India, 139 p.

Mooijman, A. 2012 *Water, Sanitation and Hygiene (WASH) in Schools*. A companion to the Child Friendly Schools Manual. UNICEF.

Moriarty, P., Batchelor, C., Laban, P. & Fahmy, H. 2010 Developing a practical approach to "light IWRM" in the Middle East. *Water Alternat.* **3** (1), 122–136.

Musiyarira, H. K. 2011 *A Context Based Planning Approach for Comparative Analysis of Centralised and Decentralised Wastewater Systems Sustainability*. Doctoral dissertation, Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg.

Muspratt, A. M., Nakato, T., Niwagaba, C., Dione, H., Kang, J., Stupin, L., Regulinski, J., Mbeguere, M. & Strande, L. 2014 Fuel potential of faecal sludge: calorific value results from Uganda, Ghana and Senegal. *J. Water Sanit. Hyg. Dev.* **4** (2), 223–230.

Nijhof, S., Jantowski, B., Meerman, R. & Schoemaker, A. 2010 Rainwater harvesting in challenging environments: Towards institutional frameworks for sustainable domestic water supply. *Waterlines* **29** (3), 209–219.

Nyambe, I. A., Mweemba, C., Tembo, J. M. & Kabika, J. 2010 *Evaluation of Ecosan Facilities in Chaisa Compound of Lusaka Lusaka Water and Sewerage Company Limited and Care International Zambia – Water and Sanitation for the Urban Poor*. Lusaka, UK.

Oageng, I. & Mmopelwa, G. P. 2014 Water consumption patterns in a rural setting in Ngamiland district, Botswana: the case of Boro village. *J. Water Sanit. Hyg. Dev.* **4** (4), 720–726.

Okem, A. E., Xulu, S., Tilley, E., Buckley, C. & Roma, E. 2013 Assessing perceptions and willingness to use urine in agriculture: a case study from rural areas of eThekwini municipality, South Africa. *J. Water Sanit. Hyg. Dev.* **3** (4), 582–591.

Omenka, E. 2010. *Improvement of Decentralised Wastewater Treatment in Asaba*. Master's Thesis, Lund University, Lund.

ONEWASH/ IRC 2015 *Sustainability of WASH services in Wukro, Tigray*. One WASH National Program Ethiopia. IRC, The Netherlands.

Pahl-Wostl, C., Gupta, J. & Bhaduri, A. 2016. Water security: a popular but contested concept. In: Pahl-Wostl, C., Gupta, J. & Bhaduri, A. (eds). *Handbook on Water Security*. Elgar, Cheltenham, UK.

Peña, H. 2011 *Social Equity and Integrated Water Resources Management*. Global Water Partnership Technical Committee. Background Paper No. 15. Global Water Partnership, Stockholm, Sweden.

Post 2015 Water Thematic Group 2012 *WASH and environmental sustainability Framing Paper: Integration for sustainable development*. UN-Water Post-2015 Water Thematic Group.

Post 2015 Water Thematic Group 2013 Post 2015. Week 4 WASH and environmental sustainability. UN-Water Post 2015 Water Thematic Group.

Post 2015 Water Thematic Group 2013 *The Post 2015 Water Thematic Consultation Report*. UN-Water.

Post 2015 Water Thematic Group 2013 *The Post-2015 Water Thematic Consultation, Synthesis Report*. Advanced Summary of Synthesis Report (Draft).

Post 2015 Water Thematic Group 2013 *Water Security & the Global Water Agenda: A UN-Water Analytical Brief*. United Nations University, Canada.

Post 2015 Water Thematic Group 2014 *A Post- 2015 Global Goal for Water. A Synthesis of key findings and recommendations from UN-Water*. UN-Water.

Post 2015 Water Thematic Group 2015 *Governing and Managing Water Resources for Sustainable Development*. The Post 2015 Water Thematic Consultation –Water Resource Management, Summary Document, UN-Water.

Poustie, M. S. & Deletic, A. 2014 Modeling integrated urban water systems in developing countries: case study of Port Vila, Vanuatu. *Ambio* **43** (8), 1093–1111.

Prahlad, I. 2015 *Environmental Sanitation Reflection from Practice. A module for Community Health Practitioners*. Sochara, Bangalore.

Rao, S. M. & Malini, R. 2015 Use of permeable reactive barrier to mitigate groundwater nitrate contamination from on-site sanitation. *J. Water Sanit. Hyg. Dev.* **5** (2), 336–340.

Rasul, G. & Sharma, B. 2016. The nexus approach to water–energy–food security: an option for adaptation to climate change. *Clim. Pol*. **16** (6), 682–702.

Ratna Reddy, V. R., Rammohan Rao, M. S. & Venkataswamy, M. 2011 “Slippage”: The bane of rural drinking water sector (a study of extent and causes in Andhra Pradesh). *J. Soc. Econ. Dev.* **13** (2), 163–188.

Ratna Reddy, V., Srinivasa Reddy, M. & Rout, S. K. 2014 Groundwater governance: A tale of three participatory models in Andhra Pradesh, India. *Water Alternat.* **7** (2), 275–297.

Rosenqvist, T., Mitchell, C. & Willetts, J. 2016. A short history of how we think and talk about sanitation services and why it matters. *J. Water Sanit. Hyg. Dev.* **6** (2), 298–312.

Savage, M., Mujica, A. & Ross, I. 2015 *Climate Finance and Water Security.* Synthesis report. Oxford Policy Management, Oxford, UK.

Schroder, J. J., Cordell, D., Smit, A. L. & Rosemarin, A. 2010 *Sustainable Use of Phosphorus*. Stockholm Environment Institute Report 357. Stockholm Environment Institute, Stockholm, Sweden.

Seck, A., Gold, M., Niang, S., Mbeguere, M., Diop, C. & Strande, L. 2015 Faecal sludge drying beds: increasing drying rates for fuel resource recovery in Sub-Saharan Africa. *J. Water Sanit. Hyg. Dev.* **5** (1), 72–80.

SEED 2010 *Formulations of an Outline Strategy for Maputo City Citywide Sanitation Planning*. Strategy, Final report. SEED, Maputo, Mozambique.

Shao, D., Yang, F., Xiao, C. & Tan, X. 2012 Evaluation of water security: an integrated approach applied in Wuhan urban agglomeration, China. *Water Sci. Technol.* **66** (1), 79–87.

Shrestha, S. Das, Rajbhandari, K., Singtan, D. B. & Mishra, S. 2011 *Rainwater Harvesting for Recharging Shallow Groundwater*. Wateraid, Nepal.

Sijbesma, C., Truong, T. X. & Devine, J. 2010 *Case Study on Sustainability of Rural Sanitation Marketing in Vietnam*. Water and Sanitation Program (WSP)/The World Bank; IRC.

Smits, S. & Sutton, S. 2012 *Self Supply: The Case for Leveraging Greater Household Investment in Water Supply*. Briefing Note. International Water and Sanitation Centre, The Netherlands.

Starkl, M., Amerasinghe, P., Essl, L., Jampani, M., Kumar, D. & Asolekar, S. R. 2013 Potential of natural treatment technologies for wastewater management in India. *J. Water Sanit. Hyg. Dev.* **3** (4), 500–511.

Suárez, F., Muñoz, J., Fernández, B., Dorsaz, J.-M., Hunter, C., Karavitis, C. & Gironás, J. 2014 Integrated water resource management and energy requirements for water supply in the Copiapó River Basin, Chile. *Water* **6** (9), 2590–2613.

SuSanA 2012 *Planning of Sustainable Sanitation for Cities*. SuSanA Fasctsheet, SuSanA.

Tayler, K. & Godfrey, S. 2011 Crossfire: Can water safety plans help in managing risk for the poor inhabitants of unplanned, pen-urban areas? *Waterlines* **30** (3), 181–188.

Tilmans, S., Diaz-Hernandez, A., Nyman, E. & Davis, J. 2014. The potential for financing small-scale wastewater treatment through resource recovery: experience from Bocas del Toro, Panama. *J. Water Sanit. Hyg. Dev.* **4** (3), 449–459.

Töykkälä, H. 2013 *Best Practices in Ecological Sanitation Projects: Case: Development Project in Zambia*. Bachelors Thesis, Häme University of Applied Sciences (HAMK), Finland.

Truyens, C., Wilmouth, R., Buckley, C., Turnberg, W. & Daniell, W. 2013 Delivering water, sanitation and hygiene services in an uncertain environment menstrual management in communal sanitation facilities: recommendations to *eThekwini Municipality 36th WEDC International Conference*, Nakuru, Kenya, 2013.

Tukic, N. & Burgess, M. 2016 China’s role in Africa's water sector: mapping the terrain. *Waterlines* **35** (1), 18–36.

Ugbenyen, A. M., Vine, N., Simonis, J. J., Basson, A. K. & Okoh, A. I. 2015 Characterization of a bioflocculant produced from the consortium of three marine bacteria of the genera Cobetia and Bacillus and its application for wastewater treatment. *J. Water Sanit. Hyg. Dev.* **5** (1), 81–88.

UN-Water 2012 *Deliverables by UN-Water for the Rio+20 United Nations Conference on Sustainable Development*. UN-Water.

UN-Water 2012 *Status Report on the Application of Integrated Approaches to Water Resources Management*. UN-Water.

UN-Water 2014 *World Water Day 2014 Advocacy Guide*. Available from: www.unwater.org/fileadmin/user_upload/worldwaterday2014/documents/WWD2014_Advocacy_Guide_WEB.pdf.

UN-Water 2015 *Water for a Sustainable World*. The United Nations World Water Development Report 2015. UN-Water.

UN-Water 2015 *A Compilation of Expert Advice on Water and Sanitation Related Indicators covering targets 6.1 to 6.6 and 11.5*. UN-Water, UN inter agency Technical Support Team.

UN-Water Decade Programme on Capacity Development (UNW-DPC) 2012 Capacity development for safe use of wastewater in agriculture. In: Ardakanian, R., Sewilam, H. & Liebe, J. (eds). *Water and the Green Economy*. UNW-DPC, Bonn, Germany.

UNICEF 2012 *WASH Staff Training Curriculum*. UNICEF.

UNICEF/NYHQ 2010 *Raising Clean Hands*. Call to Action for WASH in School Community Strategy 2010. UNICEF/NYHQ.

UNICEF/GWP 2015 *WASH Climate Resilient Development Technical Brief: Local participatory water supply and climate change risk assessment – Modified water safety plans*. UNICEF/GWP.

UNICEF/GWP 2015 *WASH Climate Resilient Development, Strategic Framework*. UNICEF/GWP.

UNICEF/GWP 2015 *WASH Climate Resilient Development: Integrating climate resilience into national WASH strategies and plans*. UNICEF/Global Water Partnerships.

Verbyla, M. E., Cairns, M. R., Gonzalez, P. A., Whiteford, L. M. & Mihelcic, J. R. 2015 Emerging challenges for pathogen control and resource recovery in natural wastewater treatment systems. Wiley Interdisciplinary Reviews: *Water* **2** (6), 701–714.

Vijayalekshmi, M., Surendran, S. K. & Mani, M. 2013 Identifying appropriate sanitation for near-coastal communities in Vizhinjam (Kerala, India) adopting the sanitation-approach framework. *Waterlines* **32** (1), 58–73. Retrieved from 10.3362/1756-3488.2013.006.

Villamayor-Tomas, S., Grundmann, P., Epstein, G., Evans, T. & Kimmich, C. 2015 The water-energy-food security nexus through the lenses of the value chain and the institutional analysis and development frameworks. *Water Alternat.* **8** (1), 735–755.

Water Research Commission 2014 *Two New Sanitation Technology Innovations from the WRC*. Technical Brief. Water Research Commission, South Africa.

WaterAid 2011 *Water Resource Management : Integrated Planning and Management at Community Level*. Training Manual. WaterAid, Nepal.

WaterAid in Nepal 2011 *Policy Guidelines – Water Resource Management*. The document can be found in the documents section of the WaterAid in Nepal country programme website– www.nepal.wateraid.org

WaterAid n.d. *Nigeria country strategy 2010–2015*. WaterAid, Nigeria.

WaterAid n.d. *Post-2015 Consultation on Environmental Sustainability*. Briefing note. WaterAid, London, UK.

WaterAid 2015 *Everyone, Everywhere: A Vision for Water, Sanitation and Hygiene Post-2015*. Water Aid, London, UK.

WHO/UNICEF 2015 *Post-2015 WASH Targets and Indicators The Post 2015 Targets*. WHO, New York, USA.

Willets, J. & Wickens, J. 2011 WASH Conference 2011: Towards sustainability in water, sanitation and hygiene. *WASH Conference 2011*: Brisbane, Australia, 11.

Willetts, J., Paddon, M., Nam, N. D. G., Trung, N. H. & Carrard, N. 2013 Sustainability assessment of sanitation options in Vietnam: planning with the future in mind. *J. Water Sanit. Hyg. Dev.* **3** (2), 262–268.

Williams, A. R. & Overbo, A. 2015. *Unsafe Return of Human Excreta to the Environment: A Literature Review*. The Water Institute at UNC, Chapel Hill, NC, USA.

World Bank 2011 *Climate Risk and Adaptation Country Profile: Costa Rica*. The World Bank Group, Washington, DC, USA.

World Bank 2011 *Vulnerability, Risk Reduction and Adaptation to Climate Change: Indonesia*. Climate Risk and Adaptation Country Profile. The World Bank Group, Washington, DC, USA.

World Bank 2012 *Strengthen Secure Sustain, Water Partnership Program 2011 Annual Report*. The World Bank, Washington, USA.

World Bank 2012 *Toward a Green, Clean, and Resilient World For All: A World Bank Group Environment Strategy 2012–2022*. The World Bank Group, Washington, DC, USA.

World Bank 2010 *Bangladesh Country Report: Environmental Strategy 2010*. The World Bank, Washington DC, USA.

World Bank/LAC 2013 *Inclusive Green Growth in Latin America and the Caribbean*. World Bank.

Zimmermann, M. 2012 Water resources management in central northern Namibia using empirically grounded modelling. *J. Water Sanit. Hyg. Dev.* **2** (2), 112.

Appendix 2 Codes used in the analysis of literature

Group	Codes
Literature type	Academic literature
	Grey literature
Sector lens	Sector lens WASH
	Sector lens Water Resource Management (WRM)
	Sector lens – other
Focus on water or sanitation	Water focus
	Sanitation focus
	Water and sanitation focus
Regional focus	Cross-regional or global
	Africa
	Middle East and North Africa
	Latin America and Caribbean
	SEA
	South Asia
	East Asia
	Pacific
	Central Asia
Focus on urban or rural	Urban focus
	Rural focus
	Urban and rural focus
	Neither urban or rural/not explicit

Topic tags	Challenging environments
	Climate change adaptation (CCA)
	Climate change tools
	Climate impacts
	Climate mitigation
	Climate resilience
	Eco-infrastructure
	Eco-technologies
	Ecological sanitation
	Ecosystem protection
	Efficiency
	Environmental governance
	Environmental harm minimisation
	Environmental health
	Environmental impact assessment
	Environmental justice
	Environmental monitoring
	Environmental risks
	Environmental tools
	Millennium Development Goals critique
	Multiple use systems
	Nexus
	Nitrogen and phosphorus
	Novel entities
	Positive contribution to environmental sustainability
	Post-2015 agenda
	Rationale for WASH
	Reducing pollution
	Reuse
	Sanitation pollution
	Sanitation pollution analysis
	Sustainability conceptions
	WASH equated with environmental sustainability
	Wastewater treatment
	Water quality
	Water recycling
	Water resource management (WRM)
	Water scarcity
	Water security
	Water source analysis
	Water source management

Appendix B

Supplementary material associated with publication 2

Appendix A: Data sources and assumptions for groundwater use calculations

Findings on the proportions of households using groundwater as their primary source of drinking water are displayed in Figures 1 and 2 for urban and rural areas respectively. Data sources underpinning calculations are detailed below for each case study country. The results of calculations are described in terms of 'best estimates' and 'minimum and maximum values'. Best estimates reflect conservative calculations to avoid overstating groundwater reliance, and minimum and maximum values are shown in this Appendix for selected cases to indicate particular uncertainties due to e.g. the existence of multiple baseline datasets.

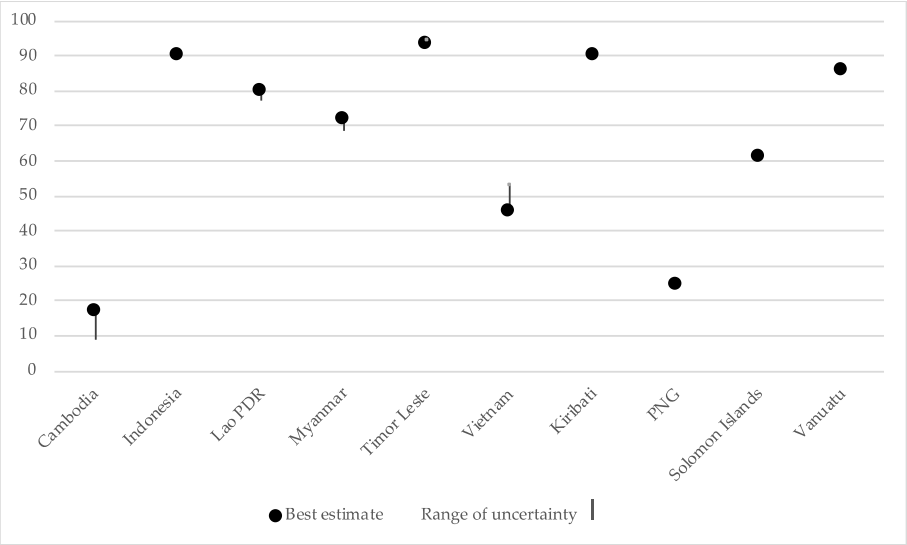

Figure 1: Proportion of urban households that are groundwater-reliant, indicating best estimates and ranges of uncertainty

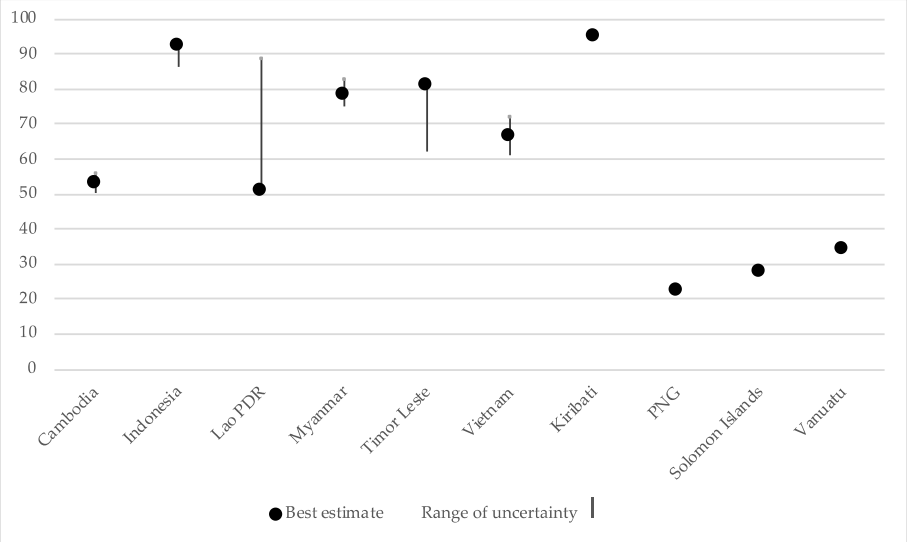

Figure 2: Proportion of rural households that are groundwater-reliant, indicating best estimates and ranges of uncertainty

Cambodia

Socio-Economic Survey (SES) 2015 data the basis for breakdown of facilities used (sourced from JMP country file). Note that SES 2015 (administered by Ministry of Planning) asked for the household's main source of drinking water for the whole year, in contrast with previous SESs which asked for the main source during wet and dry seasons separately.

Urban

Best estimate: Using SES 2015 data as basis, a calculated 17% of urban households use groundwater as their primary source of drinking water. This is based on information from a review of Cambodia's water sector [1], which identifies sources used by piped schemes in all provincial capitals (excluding Phnom Penh) and the number of households served. From this, a calculated 30% of urban households outside of Phnom Penh use tap water sourced from groundwater. Phnom Penh information was added to this, with surface water the source used by Phnom Penh Water Supply Authority (PPWA) (accessed 12 Oct 2018) which serves 96% of households in Phnom Penh (Ministry of Planning 2016). Including Phnom Penh, the calculated proportion of urban households whose tap water is sourced from groundwater is 5%.

Packaged water is excluded based on Phnom Penh Post report (accessed 12 Oct 2018) that almost all bottled water is siphoned from rivers or supplied by PPWA (which uses surface water as described above).

Minimum and maximum values: A minimum value (9%) is reported to reflect uncertainty associated with the baseline uses the same assumptions and calculations but takes NBADWQ 2015 data (assessment of urban household microbial quality of drinking water at point of consumption, sourced from JMP) as the baseline. NBADWQ has 6% of urban households using point source groundwater, 50% using tap water and 20% using packaged water (in contrast with SES 2015 respective figures of 13%, 74% and 2%).

Rural

Best estimate: Rural best estimate (53%) based on literature [2][3] noting these figures are cited as relevant for the dry season and are based on point source groundwater use only. Taken as a reasonable estimate based on similarity with SES 2015 data on point source groundwater use (50%) and expert advice that piped systems commonly use surface water.

Minimum and maximum values: Minimum and maximum values are included to provide reference points from the SES 2015 survey as complement to the best estimate figure derived from literature. Minimum value shows SES 2015 point source groundwater use (50%). Maximum value (56%) takes point source groundwater as a baseline and adds a half of the 12% tap water, indicating uncertainty given lack of available data on sources used for piped systems.

Indonesia

National socio-economic survey (SUS) 2016 data the basis for breakdown of facilities used (sourced from JMP country file).

Urban

Best estimate: calculated 90% includes point source groundwater (38%) and packaged water (46%), based on information that Danone Aqua, identified as the leading brand in a 2018 Euromonitor International market report (accessed 16 November 2018), is sourced from groundwater (company information, accessed 16 November 2018). A rapid scan of selected other brands (using a snowballing approach from media sources citing brand names) was also undertaken to verify groundwater as the typical source of packaged water. 39% of tap water included based on data that water supplied by utilities in Indonesia is 61% sourced from surface water, 16% from springs and 23% from groundwater (information based on 2016-2017 data from Perpamsi, the Association of Indonesian Water Supply Utilities). This assumes supply for different sectors (domestic, commercial, industrial) follows the same ratio as abstraction.

Rural

Best estimate: Calculation of 92% includes point source groundwater (71%) and packaged water (16%) based on information as above about the source of packaged water. 90% of tap water is also included based on information from data on sources used for piped schemes constructed under the Water and Sanitation for Low Income Communities Project (PAMSIMAS) (accessed 30 October 2018).

Minimum and maximum values: A minimum value (86%) excludes tap water to reflect that schemes built under PAMSIMAS (used as the basis for estimating the proportion of tap water sourced from groundwater) may not be representative of schemes across Indonesia.

Lao PDR

2015 census data the basis for breakdown of facilities used (sourced from JMP country file).

Urban

Best estimate: Calculated 77% includes point source groundwater (13%) and packaged water (64%) based on literature reporting that all bottled water is groundwater sourced [4]. Of households using tap water, 17% are included based on research which found that that 10 of 60 townships have groundwater-sourced piped water [4].

Minimum and maximum values: A minimum value (77%) excludes tap water given lack of information about the relative size of served populations in the 10 of 60 households using groundwater-sourced tap water [4].

Rural

Best estimate: based on literature reporting an agricultural survey [5], which identifies rural groundwater reliance as 51%. This figure is reasonably consistent with 2015 census data (55%) including those using point source groundwater and packaged water (assuming all packaged water is groundwater as described above).

Minimum and maximum values: A maximum value based on census 2015 data shows a substantial increase in proportion of households using groundwater, arising from the inclusion of 34% of households using 'other' facilities described in survey notes as 'mountain sourced' (which are assumed to be spring sourced).

Myanmar

Demographic and Health Survey (DHS) 2016 data the basis for breakdown of facilities used (sourced from JMP country file).

Urban

Best estimate: Calculated 72% includes point source groundwater (34%) and packaged water (34%) based on company information that Alpine, the brand leader in bottled water, uses groundwater and sector expert advice that packaged water is all groundwater-sourced.

Calculations for tap water are based on analysis of Myanmar's two largest cities, Yangon and Mandalay, which together represent about half of the total urban population and reflect geographic diversity, with Mandalay located in the dry zone. Yangon City Development Corporation (YCDC) supplies water to 58% of Yangon's ~4.5 million population, and as of 2014 an estimated 12.5% was sourced from groundwater [6]. Mandalay, Myanmar's second largest city, has a reticulated supply which is 90% sourced from groundwater [7] and reaches an estimated 50% of the ~1.2 million

population [8]. From these figures, the proportion of those served by tap water sourced from groundwater is calculated to be 27%.

Minimum and maximum values: A minimum value (61%) excludes tap water given lack of information about the relative size of served populations and sources of water in cities beyond Yangon and Mandalay. While we know that at least some tap water is sourced from groundwater, including the minimum value is also indicative of uncertainty related to sources of packaged water, with best estimate value based on information from one brand.

Rural

Best estimate: Calculated 78% includes point source (75%) and packaged water (4%), based on information that Alpine, the brand leader in bottled water, uses groundwater and sector expert advice that packaged water is all groundwater-sourced. Tap water is conservatively excluded given lack of data on sources used for piped systems.

Minimum and maximum values: A minimum value (75%) excludes packaged water given uncertainty beyond the leading brand. A maximum value (83%) includes half of the 7% that is tap water, reflecting that some rural piped schemes use groundwater, for example [7] describes a mix of surface and groundwater sourced piped systems in the dry zone.

Timor-Leste

Census 2010 data the basis for breakdown of facilities used (sourced from JMP country file).

Urban

Best estimate: Calculated 93% includes point source groundwater (28%) and tap water (65%) based on literature confirming that piped systems in Dili [9] and Bacau [10] use groundwater.

Minimum and maximum values: A maximum value (95%) adds packaged water. Information on the sources of packaged water was not readily available, however expert advice suggests at least one company based in Timor-Leste sources water from groundwater and much bottled water is imported from Indonesia where (as above) it is typically groundwater-sourced.

Rural

Best estimate: Calculated 81% includes point source groundwater and tap water based on advice from sector experts that villages with taps tend to be spring or aquifer sourced.

Minimum and maximum values: A minimum value (62%) includes only half the tap water, reflecting the lack of data and literature to validate expert advice and based on information that motorized pumps are used to supply water to approximately ~150,000 rural dwellers [11], which is approximately half those using tap water. Though it should be noted that this figure would exclude gravity-based spring-sourced piped systems which (according to expert advice) are common in rural areas.

Vietnam

Multiple Indicator Cluster Survey (MICS) 2014 data the basis for breakdown of facilities used (sourced from JMP country file).

Urban

Best estimate: 46% based on calculations of proportions of tap water and bottled water sourced from groundwater.

Calculation for tap water based on utility benchmarking data (accessed 2 June 2018) which has a proportional breakdown of source of water abstracted by utilities. This assumes supply for different sectors (domestic, commercial, industrial) follows the same ratio as abstraction.

Calculation for packaged water based on review of the four dominant brands of La Vie (Nestlé), Aquafina (PepsiCo), Vinh Hao (Vital), and Dasani (Coca-Cola Vietnam), which account for around 80% of sales according to a VietnamNet 2015 article. Also information from a Vietnam Investment Review 2017 article which places Aquafina market share at 40% and La Vie at 30%. Reviewed company websites or market and media reports to identify the water source for each major brand: Aquafina uses treated tap water; La Vie uses groundwater; Vital uses groundwater and Dasani uses groundwater. All sites accessed 12 Oct 2018. Tap water used for Aquafina (which has 40% market share) was conservatively assumed to be not from groundwater, though if sourced from Hanoi or Ho Chi Minh City water supplies it could be groundwater. Remaining market share assumed to use groundwater given La Vie (with 30% market share) and other market leaders use groundwater. From this analysis, a calculated total of 60% of packaged water is sourced from groundwater.

Minimum and maximum values: A maximum value (54%) includes Aquafina bottled water (from tap water) as likely originally sourced from groundwater.

Rural

Best estimate: 66% based on calculations of proportions of tap water and bottled water sourced from groundwater.

Calculation for tap water assumes 50% of tap water is sourced from groundwater. This is a conservative estimate informed by: (i) a World Bank Technical Assessment [12] focused on the northern mountainous and central highlands regions, which indicates 75% of piped schemes are groundwater or spring sourced; and (ii) research in six communes spanning three provinces in the Red River Delta and two provinces in the Mekong Delta [13,14] which found a roughly equal mix, with northern piped schemes typically sourced from surface water, and southern schemes sourced from groundwater. This calculation, while based on limited data sources, does not make a substantial difference to the overall finding given that tap water is only used by 11% of the rural population.

Calculation for packaged water uses the assumed 60% sourced from groundwater as described above for urban areas.

Minimum and maximum values: Reflecting the lack of data and related uncertainty about sources of tap water in rural areas across Vietnam, a minimum value excludes tap water and a maximum value includes an additional proportion of packaged water (in alignment with the urban calculated maximum value above).

Kiribati

Census 2010 data the basis for breakdown of facilities used (sourced from JMP country file).

Urban

Best estimate: 90% includes point-source groundwater (23%) and tap water (67%). Tap water is included based on information that the reticulated system in South Tarawa (Kiribati's only urban centre) is wholly reliant on rainfall-fed groundwater lenses [15].

Rural

Best estimate: 95% includes point source groundwater (89%) and tap water (6%). Piped water systems are mainly located on North Tarawa [16] which is reliant on shallow groundwater [17].

Papua New Guinea

Household Income and Expenditure Survey (HIS) 2010 data the basis for breakdown of facilities used (sourced from JMP country file).

Urban

Best estimate: 25% includes point source groundwater (5%) and a calculated 28% of the 71% using tap water as groundwater sourced. Calculations based on information from Water PNG (accessed 16 July 2018), a State Owned Enterprise responsible for water supply and sewerage services in urban areas, with water sources for different urban areas weighted by population.

Rural

Best estimate: 22% includes only point source groundwater use (22%). Tap water (16%) excluded based on sector expert advice that piped water in rural areas is almost exclusively from gravity fed systems, from a dammed stream.

Solomon Islands

Census 2009 data the basis for breakdown of facilities used for urban areas, and Solomon Islands Rural WASH Program data 2016 the basis for breakdown of facilities used for rural areas (sourced from JMP country file).

Urban

Best estimate: 61% includes point source groundwater (3%) plus 94% of those using tap water. Tap water calculations are based on expert advice and reports [18,19] on resources used by Solomon Water to supply Solomon Island's four largest cities (Honiara, Auki, Noro and Tulagi) with piped water. Honiara and Auki piped water supplies are sourced from groundwater, while Noro and Tulagi are sourced from surface catchments. Honiara and Auki are home to 94% of the population of these four cities (based on 2009 census data).

Rural

Best estimate: 28% includes only point source groundwater use (28%). Tap water (used by 38%) is excluded given information that most rural communities, other than those on small outlying coral atoll islands, use abundant surface water or rain water [20].

Vanuatu

Vanuatu 2016 Mini-Census data the basis for breakdown of facilities used (sourced from Vanuatu National Statistics Office). The Mini-Census was used instead of Vanuatu Demographic and Health Survey (VDHS) 2013 data (which is the most recent data included in the JMP country file) given it is more recent and involved a full population enumeration.

Urban

Best estimate: 83% includes point source groundwater (2%), tap water (83%) and packaged water (1%). Tap water included based on information that water supplied by UNELCO (concessionaire) to Port Vila is groundwater sourced, and water supplied by the Public Works Department (Ministry of Public Utilities and Infrastructure) to Luganville is spring sourced [21]. The National Water Strategy 2006-2018 [22] notes that six private suppliers also supply piped water in urban areas, and that no information is available on sources used by these operators. However, given Vanuatu's two largest urban settlements use groundwater it is assumed these providers also supply groundwater.

Packaged water included as the leading brand of bottled water, Azure Pure Water, uses groundwater (sourced from the largest aquifer on Efate island, which sits under the farm lands surrounding Bauerfield Airport).

Rural

Best estimate: 34% based on 2017 waterpoint inventory data [23] which identifies sources for community supplies. This calculation is the sum of population using groundwater as a proportion of total population.

References

1. JICA. *Survey on the water supply sector in the Kingdom of Cambodia*; Japan International Cooperation Agency (JICA): Japan, 2010.
2. AEC. Water Infrastructure Study: Rapid Assessment of Existing Groundwater Studies and Groundwater Use in Cambodia. Advancing Engineering Consultants: Phnom Penh, 2016.
3. Sophally, S. Groundwater Resources in Cambodia. Institute for Global Environmental Strategies: Japan, 2011, Available online: https://www.iges.or.jp/en/natural-resource/groundwater/PDF/activity20110602/S1-3_Mr.Sok-Sophally_GW_Cambodia.pdf (accessed on 16 August 2018).
4. Pavelic, P.; Xayviliya, O.; Ongkeo, O. Pathways for effective groundwater governance in the least-developed-country context of the Lao PDR. *Water Int.* **2014**, *39*, 469–485, doi:10.1080/02508060.2014.923971.
5. Viossanges, M.; Pavelic, P.; Rebelo, L.; Lacombe, G.; Sotoukee, T. Regional mapping of groundwater resources in data-scarce regions: the case of Laos. *Hydrology* **2017**, *5*, 1-24; doi:10.3390/hydrology5010002.
6. Khaing, K.K. Groundwater environment in Yangon , Myanmar. In *Groundwater Environment in Asian Cities: Concepts, Methods and Case Studies*; Shrestha, S.; Pandey, V.;Thatikonda, S.;Shivakoti, B. Eds.; Butterworth-Heinemann: Oxford England, 2016, pp. 317–335; ISBN 9780128031667; doi:10.1016/B978-0-12-803166-7.00012-X.
7. Drury, L. W. *Hydrogeology of the Dry Zone - Central Myanmar*; The Australian Water Partnership: Canberra, Australia, 2017; ISBN 9781921543333.
8. Frauendorfer, R. *Urban Development and Water Sector Assessment, Strategy, and Road Map*. Asian Development Bank: Phillippines, 2013; ISBN 978-92-9254-286-3.
9. Pinto, D.; Shrestha, S. Groundwater Environment in Dili, Timor-Leste. *Groundw. Environ. Asian Cities Concepts, Methods Case Stud.* **2016**, 263–286, doi:10.1016/B978-0-12-803166-7.00012-X.
10. Palmer, L. Enlivening development: Water management in post-conflict Baucau city, Timor-Leste. *Singap. J. Trop. Geogr.* **2010**, *31*, 357–370, doi:10.1111/j.1467-9493.2010.00404.x.
11. Choksey, J.; Macdonald, M. Improving Service Sustainability of Electric Pump Systems in Rural Timor-Leste. In 7 th RWSN Forum "Water for Everyone", Abidjan, Côte d'Ivoire, 29 Nov - 02 Dec 2016, 2016.
12. World Bank. Results-based Scaling up Rural Sanitation and Water Supply Program: Technical Assessment; World Bank, 2015;
13. Grant, M.; Dominish, E.; Carrard, N.; Sydney, T.; Bui, L.; Ha, H.; Noi, H.; Willetts, J. Reducing or increasing inequalities? The role of private water enterprises in rural Viet Nam. *Dev. Bull.* **2016**, *77*, 31–36, http://hdl.handle.net/10453/53595.
14. Carrard, N.; Madden, B.; Joanne Chong; Grant, M.; Nghiem, T.; Ha, L. B.; Hue, H. T. T.; Willetts, J. Are piped water services reaching poor households? Empirical evidence from rural Viet Nam. *Water Res.* **2019**, 153, 239-250.
15. World Bank Project Information Document: South Tarawa Water Supply Project, Report No: PIDISDSC21345; World Bank, 2018.
16. ISF-UTS *Kiribati water, sanitation and hygiene sector brief*; prepared for AusAID by the Institute for Sustainable Futures, University of Technology Sydney: Sydney, 2011.
17. White, I. *Tarawa Water Master Plan : 2010 - 2030*; Government of the Republic of Kiribati: Kiribati, 2010.
18. Asian Development Bank, *Proposed Loan, Grant, and Administration of Grant Solomon Islands: Urban Water Supply and Sanitation Sector Project*, Report and Recommendation of the President to the Board of Directors, 2019.
19. Heslop, E. *Social and Consumer Assessment, Honiara, Solomon Islands*; prepared for Solomon Islands Water Authority and Hunter H2O Holdings Pty Ltd., 2016.

20. SOPAC *Management in Pacific Island countries national integrated water resource management* diagnostic report Papua New Guinea; Pacific Islands Applied GeoScience Commission (SOPAC): Suva, Fiji, 2007.
21. Nath, D.; Mudaliar, M.; Ioan, C. *Water Safety Plan: Water Supply Description Assessment Vanuatu*; Pacific Islands Applied GeoScience Commission (SOPAC): Suva, Fiji, 2006.
22. Government of Vanuatu. *Vanuatu National Water Strategy 2008-2018,* Department of Geology Mines and Water Resources: Vanuatu, 2008.
23. DoWR. *Vanuatu rural water supply inventory*. Department of Water Resources (DoWR): Port Vila, 2017.

Appendix C

Supplementary material associated with publication 3

Life-cycle costs of a resource-oriented sanitation system: Empirical evidence from urban Sri Lanka – Supplementary material

Naomi Carrard,[a] Nilanthi Jayathilake,[b] Juliet Willetts[a]

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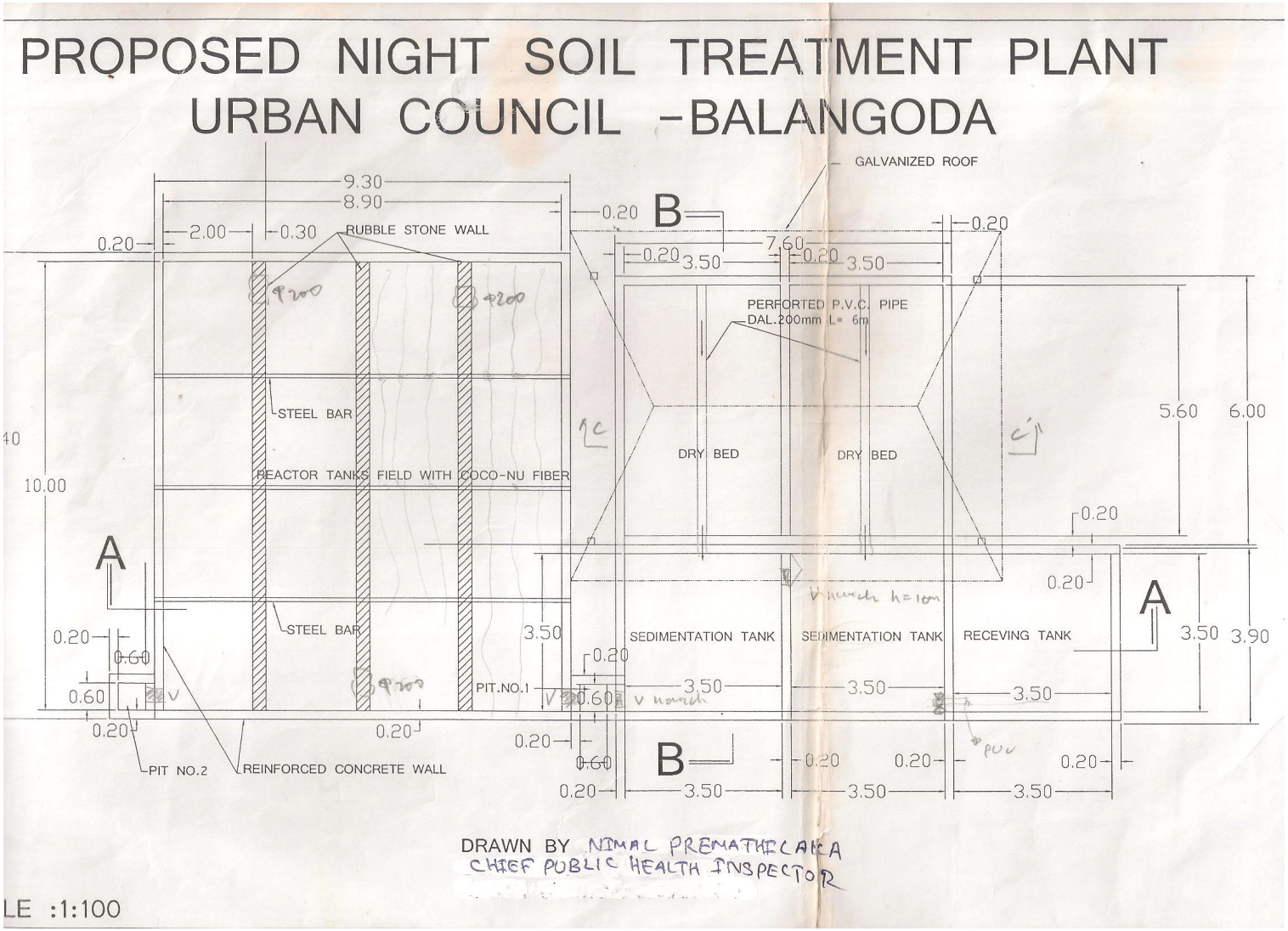
S1. The Balangoda faecal sludge treatment plant



S2. Cost data and assumptions

Table 1 details itemised system costs, replacement frequencies and allocations by stage of the sanitation chain and which actor incurs each cost. These costs were aggregated to determine the present value life-cycle cost over a 25-year system lifespan using a discount rate of 10%.

Table 1 Itemized system costs and replacement frequencies

Collated costs	LKR	Year incurred	LKR 2018 value	USD 2018 value	Frequency (years)	Chain allocation	Who pays
Capital costs							
FSTP construction Balangoda Urban Council (BUC) portion	3,300,000	2009	6,071,354	37,371	na	Treatment	BUC
FSTP construction national government portion	3,300,000	2009	6,071,354	37,371	na	Treatment	National govt
Wooden roof for sedimentation tanks	200,000	2012	260,391	1,603	na	Treatment	BUC
Steel mesh under coir mattress in drying beds	40,000	2012	52,078	321	na	Treatment	BUC
Desludging truck purchase	8,000,000	2018	8,000,000	49,243	na	Emptying and transfer	BUC
Pelletiser	494,102	2015	584,604	3,598	na	Disposal/reuse	Donation
Electrical connection fee for pelletiser	155,172	2015	183,594	1,130	na	Disposal/reuse	BUC
Operational costs							
Truck fuel, labour and maintenance	936,000	2018	936,000	5,761	1	Emptying and transfer	BUC
FSTP operation: labour, cleaning	696,000	2018	696,000	4,284	1	Treatment	BUC
Enrichment: rock phosphate	40,000	2018	40,000	246	1	Disposal/reuse	BUC
Bags (apportioned 31%)	81,502	2018	81,502	502	1	Disposal/reuse	BUC
Pelletiser running costs	10,912	2018	10,912	67	1	Disposal/reuse	BUC
Desludging fees (paid by households)	6,470,000	2018	6,470,000	39,825	1	Emptying and transfer	Households (transfer)
Capital maintenance costs							
Replace coir media in 15000L effluent treatment	1,500,000	2015	1,774,744	10,924	10	Treatment	BUC
Replace coir mattress in drying beds	1,500,000	2015	1,774,744	10,924	5	Treatment	BUC
Refreshing treatment tank - washing etc	270,000	2015	319,454	1,966	5	Treatment	BUC

Collated costs	LKR	Year incurred	LKR 2018 value	USD 2018 value	Frequency (years)	Chain allocation	Who pays
Desludging truck replacement	8,000,000	2018	8,000,000	49,243	15	Emptying and transfer	BUC
Desludging truck tank replacement	700,000	2018	700,000	4,309	10	Emptying and transfer	BUC
Pelletiser replacement	494,102	2015	584,604	3,598	10	Disposal/reuse	BUC
Septic tank replacement (annual cost for 4% of households)	2,502,680	2018	2,502,680	15,405	1	Containment	Households
Support and other costs							
Monitoring by Dept of Agriculture (apportioned 31%)	310	2018	310	2	1	Disposal/reuse	BUC
Central Environmental Authority licence and site inspection fees	22,500	2018	22,500	138	1	Disposal/reuse	BUC
Training and capacity building	150,000	2018	150,000	923	1	Treatment	BUC
Revenue							
Desludging bowser fees received	-6,470,000	2018	-6,470,000	-39,825	1	Emptying and transfer	BUC (transfer)
Sale of co-compost (apportioned 60%)	-827,555	2018	-827,555	-5,094	1	Disposal/reuse	BUC

The equivalent annualized cost was calculated as:

$$Equivalent\ annualized\ cost\ = \frac{NPV\ \times\ r}{1-(1+r)^{-n}}$$

Where r is the discount rate (10%) and n is the period of analysis in years (25).The annualized cost per person was determined by dividing the annualized system cost by the calculated number of people served by the sanitation system over its lifespan. Population calculations are described in S3.

S3. Assumptions and methods for estimating population served

Three broad approaches were used for triangulating estimates of the population served by the system over its lifespan. The first (Method 1) is based on reported population served. The second is based on sludge volumes, informed by reported volumes treated and truck trips per day (Methods 2A and 2B). The third (Method 3) is based on revenue from desludging services (documented in Council records) and fees charged to households. Method 3 was considered most reliable (being based on documented records) and therefore formed the basis of the analysis and reported findings. The different methods are presented here to show the range of possible calculations and influence of alternative assumptions on determined population, which would in turn affect the reported cost per person.

Variables

pop served	The total population served by the system (households served x average household size)
hhlds served	The number of households served by the system (ie procuring council desludging services)
hhld size	Average household size (occupancy ratio)
vol septage per day	Volume of septage treated per day (m^3)
operating days	FSTP operating days per year
tank volume	Indicative on-site sanitation tank volume (m^3), calculated as $4m^3$ based on the size specified for an average household in the Sri Lanka Standard 745 Part 2 Code of Practice for the Design and Construction of Septic Tanks and Associated Effluent Disposal Systems ($3.34m^3$) and rounded up to reflect that households are used as a proxy in this study for a mix of properties, some of which would have larger tanks
desludging frequency	Average desludging frequency, which is assumed to be 5 years based on typical tank design guidelines (note that 5 years is considered a reasonable proxy given wide variation in reported actual practices ranging from annual desludging to 10-yearly desludging, or in some cases never desludging)
trips per day	Average trips per day taken by Council-operated desludging trucks
annual revenue	Revenue per year (based on reference year 2018) that Council receives for desludging service (USD)
desludging fee	Average fee paid by a household per emptying event to use the Council desludging service (USD)

Method 1

Key driver: number of households served (10,000) as reported by Council key informants

$$pop\ served\ = hhlds\ \times\ hhld\ size$$

Result

$$ps\ = 10{,}000\ \times\ 4.2\ = 42{,}000$$

Assuming 42,000 people are served by the system, the annualised USD/person is 1.04. This is considered to be an overestimate of population served as it does not align with the most reasonable estimates for household tank sizes (based on the Sri Lanka Standard), volumes of sludge collected (based on truck sizes, likely trips per day and recorded revenue) and the volume of sludge reported to be treated at the FSTP.

Method 2A

Key driver: average volume of sludge treated each day as reported by Council key informants

$$pop\ served\ = \frac{vol\ septage\ per\ day}{average\ tank\ volume}\ \times\ operating\ days\ \times desludging\ frequency \times\ avg\ hhld\ size$$

Result

$$pop\ served\ = \frac{11}{4}\ \times\ 350\ \times\ 5\ \times\ 4.2\ = 20{,}213$$

Based on this method, the population served by the system is 20,213 people, and the annualised USD/person is 2.45 This is considered a reasonable estimate given data on the volume of sludge treated per day at the FSTP is based on site observations from operators.

Sensitivity analysis for this method, as summarized in Table 2, indicates the influence of assumptions about average tank volume and desludging frequency on findings. Assuming smaller tank volume or longer desludging frequency results in an increase in the calculated population served, with a corresponding reduction in annualised per person cost. Assuming a larger tank volume or shorter desludging

frequency results in a decrease in calculated population served and corresponding increase in annualised per person cost. All variations result in an annualised cost in the range of 1.75-3.85 USD/person.

Table 2 Sensitivity analysis of tank volumes and desludging frequencies

Average tank volume	Desludging frequency	Population served	USD/p/yr
3	5	26,950	2.10
5	5	16,170	2.80
4	2.5	10.106	3.85
4	10	40,425	1.75

Method 2B

Key driver: estimated average truck trips each day as reported by Council key informants

$$pop\ served\ = trips\ per\ day\ \times\ operating\ days\ \times\ desluding\ frequency\ \times\ avg\ hhld\ size$$

Note that one truck trip is assumed to equals one household tank emptied, with this assumption based on information about council truck volumes, average tank sizes and reported practices.

Result

$$pop\ served\ = 3\ \times\ 350\ \times\ 5\ \times\ 4.2\ = 22{,}050$$

Based on this method, the population served by the system is 22,050, and the annualised USD/person is 2.33. This is comparable to the finding from Method 2A.

Method 3

Key driver: Council desludging service revenue records

$$pop\ served = \frac{annual\ revenue}{desludging\ fee} \times desluding\ frequency \times avg\ hhld\ size$$

Result

$$pop\ served\ = \frac{39{,}825.19}{56.66} \times 5 \times 4.2 = 14{,}761$$

Assuming 14,761 people are served by the system, the annualized USD/person is 2.8. This is considered the most reliable estimate as it is based on actual records and a schedule of desludging fees (with a weighted average calculated fee of 57 USD/household based on an assumed proportion of service users located inside and outside city boundaries, of varying property types).

Sensitivity analysis for this method, as summarized in Table 3, shows the influence of lower and higher assumed average desludging fees. A lower assumed fee increases the assumed population served, with a corresponding decrease in the annualised per capita cost. Similarly, a higher assumed average fee decreases the assumed population served, with a corresponding increase in the annualised per capita cost. All variations result in an annualised cost in the range of 2.7-3.4 USD/person.

Table 3 Sensitivity analysis of desludging fees

Average desludging fee (USD)	Population served	USD/p/yr
50	16,727	2.70
60	13,939	3.10
70	11,948	3.40

Appendix D

Supplementary material associated with publication 4

Appendix A: Codes used for inductive data analysis

Process and principles	Direct activities and outcomes - towards longer term impact	Sustainability transformations leverage points
Context-based (principle 1)	**New knowledge**	**Perspectives – what is the desired mindset?**
Global v local contexts	Quality of knowledge	Mindset
Pluralistic (principle 2)	Systems knowledge	Paradigm
Participant diversity	Target knowledge	Feelings
Partiality of knowledge	Worldviews	**Purposes – what are we trying to achieve?**
Diverse ways of knowing and doing	Values	Shifting the goal
Reflexivity	Transformation knowledge	Shifting the vision
Inclusivity of discussion	Pathways to action	**Power relations – who needs to participate?**
Goal-oriented (principle 3)	Sense of agency	Participation
Diversity in vision	Integration in work	**Performance metrics – how should we measure and reward progress?**
Sense of shared vision	**Shared understandings**	Measuring progress
What success looks like	Shared understanding of knowledge	**Practices, policies, and processes – how should the system operate?**
Interactive (principle 4)	Interaction leading to learning	Future system operation
Collaboration	Joint deliberation	
Interaction between participants	Collective agency	
Success of online tools	**New competences**	
Other process feedback	Safe space	
	Self-reflection	
	Reflexivity	
	Competence building	
	Self-transformative	
	Engaging with complexity	