# The Hunter River Estuary Water Quality Model

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**Abstract**
This paper presents a detailed hydrodynamic and water quality model to simulate ecological processes in the Hunter River estuary. Following an extensive 3-year multi-disciplinary field campaign, the model was developed to assess total catchment management options. The model outcomes are linked to existing water sharing plans, pollution reduction plans and coastal reforms underway in NSW.

Initially a detailed scoping study was undertaken to determine the values and requirements of the key stakeholders across the catchment. Data gaps were subsequently prioritised, and an inter-agency modelling oversight committee was formed to ensure that the modelling tools would be accepted across the region. Following these developmental stages, a field program was initiated which included: estuary wide flow gauging and water quality assessments, microbial linkages, ecotoxicological assessments, sedimentation dynamics, DNA sequencing, qPCR analyses, catchment hydrological flux measurements, nutrient mesocosm experiments, bathymetry surveys and the development of crop irrigation modules.

The field data analyses resulted in a conceptual model of the eco-hydraulics of the estuary. A robust numerical model was formulated through an extensive process of external peer review. A source model was selected that ensured the broadest flexibility and ongoing usage rates. A multi-disciplinary approach was undertaken to ensure the model represents a wide range of estuarine processes. The final model is currently undergoing additional peer review, calibration/validation and simulation testing.

*Keywords:* estuarine hydrodynamics, coastal management, water quality, wastewater treatment.

## 1. Introduction

The Hunter River Valley is located 130 km north of Sydney. It is one of the largest coastal catchments in NSW with an area of 21,500 km$^2$. The Hunter River Estuary is approximately 65 kilometres from Newcastle Harbour to Oakhampton and includes the lower Williams River to Seaham and the Paterson River to Gostwyck (Figure 1).

The Hunter River Estuary is subject to ongoing developmental pressures that require systematic and robust decision making. To this aim, an estuary wide scoping study was undertaken to determine the 'state of the science' for modelling and data in the Hunter River estuary. The outcomes of this study highlighted:

- There were significant data gaps or outdated data across the Hunter River, especially pertaining to bathymetry data;
- Twelve (12) numerical models were previously developed for the Hunter River estuary, however, each model was purpose built and was not designed to assess the broader hydrodynamic and water quality dynamics of the estuary;
- Significant knowledge gaps were apparent in the Hunter River estuary that limited the development of a robust conceptual model; and,
- Significant developmental, climate change, environmental, and planning pressures are emergent? across the estuary.

Based on the outcomes of this scoping study, it was determined that a purpose built, estuary wide hydrodynamic model, with capacity for detailed water quality assessments, was required. The model was to be developed through a consultative process with multiple targeted field campaigns. The obtained data was then analysed to develop a comprehensive conceptual model of the site which, via extensive peer review, was used to build a scientifically defendable numerical model of the estuary.

An overarching independent committee, The Hunter River Estuary Hydrodynamic Modelling Platform Committee, was formed to oversee the hydrodynamic model construction process and ensure the widespread, robust application of the approach. To encourage industry wide uptake, creative commons licencing protocols have been adopted that allows the field data, modelling platform and related files to be freely shared for all future proponents. Users can choose to use the available baseline data to construct an alternative hydrodynamic model or to use the existing calibrated and peer reviewed model for simulations.

The overarching purpose of the data gathering, hydrodynamic model construction and sharing protocols is to:

- Reduce duplicity and resource wastage in the creation of additional modelling packages;
- Ensure confidence in decision making (i.e. reduce uncertainty) via the use of a peer review, independently constructed, robust model;
- Freely share the most up-to-date data files with regular file updates achieved via a creative commons licencing format;
- Encourage the study of important water quality processes with additional modules developed, as needed.


**Figure 1.** Study site location.

This paper outlines the development of the hydrodynamic and water quality models for the Hunter River estuary as per the recommendations of [1]. It is our understanding that this approach to hydrodynamic modelling – to create a regulator approved hydrodynamic model and data platform freely shared to improve decision making – is the first of its kind in Australia and potentially worldwide. As such, this paper highlights the model development process and the aims to collaboratively share the data as it is developed. It is worth noting that the overall development, simulation testing and data sharing protocols are currently in development.

## 2. Data Availability and Campaigns

Numerical models, by their nature, are simplifications of the reality under investigation. Acceptable performance of numerical models requires the use of robust methodologies to calibrate and validate the modelled and observed datasets. Uncertainties are intrinsic to all numerical models. Water quality models generally encompass three types of uncertainties, which include "*structural uncertainty*, *uncertainties in boundary conditions* and *uncertainty of the model parameters values"* (2).

The uncertainty of model input occurs because of changes in natural conditions, limitations of measurement, and lack of data (3). Given that it is desirable to evaluate the performance of models with respect to observed water quality data, the accuracy, frequency and relevance of the available data dictates the attainable degree of certainty in the model. The main sources of uncertainty of the boundary conditions consist of:

- Uncertainty in the magnitude of the spatial distribution of rainfall events;
- Uncertainty in the magnitude and timing of water extractions;
- Uncertainty in the WWTW discharges and concentrations;
- Uncertainty in the local catchment inflows and concentrations; and
- Uncertainty of the water quality concentration at the upstream inflow boundary and downstream open boundary.

Uncertainty are often related to the limited amount of data available. As an initial task in this study, the available data was reviewed and subject to quality assurance checks. Where significant knowledge gaps remained outstanding, field campaigns were undertaken to supplement the existing data sets. This section summarises those field campaigns, details the datasets obtained and highlights the relevance of the data gathered to the overall modelling program underway. Where relevant, ongoing field campaigns and/or remaining knowledge gaps are discussed.

For clarity, this section has been divided into the following:

- Bathymetry data;

- Boundary data
- Flow Gauging Campaigns; and,
- Water quality data.

### 2.1 Bathymetry Data

Numerous field campaigns within the Hunter River Estuary have been undertaken to collect bathymetry data. (1) highlighted that several data gaps remain, and outdated data existed. For instance, prior to this study limited bathymetry data was available for Fullerton Cove as well as a long stretch of the Patterson River from the town of Paterson to the river's tidal limit in Gostwyck.

In addition, the *Hunter River Geomorphology Study* (4) indicated that the Hunter River has a highly mobile bed, subject to regular changes in bathymetry. Field investigations conducted in 2011 and 2015 (5) have shown the bathymetry of the Williams River and Hunter River north of Maitland has changed significantly since the last major bathymetric survey in 1984. Further, previous surveys of the South Arm of the Hunter River had not surveyed a rock bar in the channel adjacent to Hexham Island, which restricts flows and significantly influences the hydrodynamics of the lower estuary. The updated bathymetry for the estuary is provided in Figure 2.

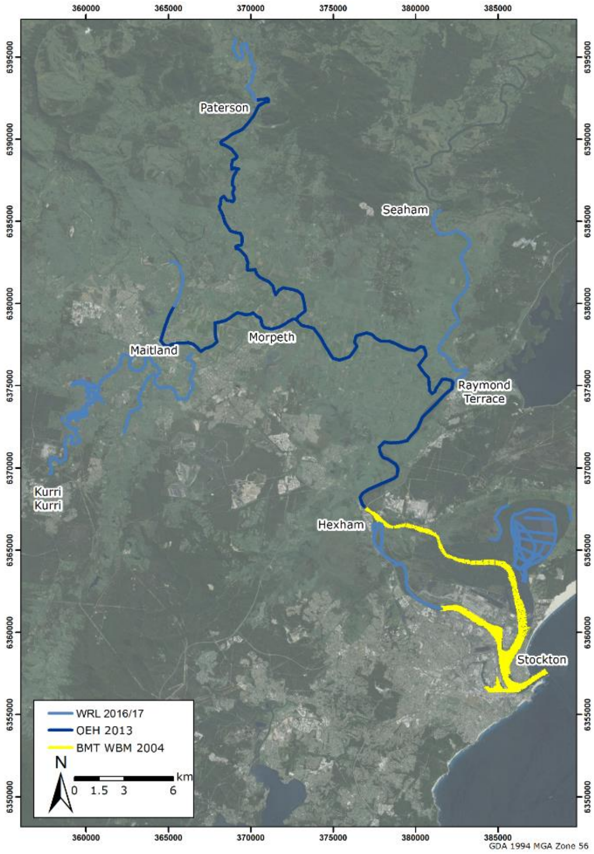


**Figure 2.** Updated bathymetry data.

### 2.2 Boundary Data

Boundary data is used to represent the connections between the Hunter River Estuary and its surrounds. Key components of this dataset include:

- River inflow;
- Rainfall and evaporation;
- Ocean levels;
- Flow extraction (for irrigation); and
- Water quality fluxes.

Previous modelling of the Hunter River Estuary highlighted critical data gaps in the boundary data (1 and 4). This included major uncertainties with external boundaries and concerns related to the tidal pool extractions. The field campaign undertaken for this study aimed to supplement existing data, filling knowledge gaps based on a priority ranking. The following sections outline data which will be used in the development of boundary conditions for the subsequent modelling of the Hunter River Estuary.

The Hunter River Estuary has three main tributaries:

- Hunter River;
- Paterson River; and
- Williams River.

The flow from these rivers at the tidal limit (**Error! Reference source not found.**) has been used as boundary data. Available boundary datasets are comprised of a combination of historical measured data and modelled data. Historical flow data from the Hunter and Paterson Rivers is available for model calibration and verification. Boundary data predicted using DPI Water's Integrated Quantity and Quality Model (IQQM) of the catchments is available for future model scenarios for these same catchments. The Hunter Water Corporation operates a detailed hydrological model of the Williams River which was available to this study.

The downstream boundary of the Hunter River Estuary is located at the Hunter River ocean entrance at Newcastle. At this location both water level and salinity are applied as boundary conditions for the model. Water levels at this location are calculated using a tide level generation tool based on tidal constituent analysis for both historical and future scenarios. Tidal flows into and out of the Hunter River Estuary are calculated by the model based on an applied ocean level time series.

Previous modelling of the Hunter River Estuary has not included water extractions from the estuary tidal pool for irrigation of farmland adjacent to the tidal pool. To date, this has been difficult to calculate as there was limited information on the number, location and volume allocation of irrigation licences.

As such, the rate and timing of water extraction for irrigation is largely unknown. For this study, sufficient information was obtained to develop a preliminary irrigation extraction routine based on a soil moisture budget, annual allocations and crop model. Details on the routine are provided in [6].

## 2.3 Flow gauging campaigns

(1) noted the lack of historical local catchment runoff data as a major deficiency in the data set available to support estuarine water quality modelling. For this study, flow data gauging was completed at four (4) locations within the Hunter River Estuary at key locations over a tidal cycle on multiple occasions. These measurements examined the passage of the water through the estuary as the tide fluctuated.

To understand the dynamics of flow mixing in the estuary, it is important that the tidal fluctuations and salinity diffusion throughout the whole estuary is modelled accurately. Varying salinity and water levels throughout the estuary are related to the boundary condition of these parameters at the ocean. By measuring both parameters at multiple locations over extended temporal periods, the model could be calibrated and then validated to ensure that it adequately represents the mixing and exchange of river and ocean sourced flows.

To understand local catchment fluxes at a representative catchment, Anvil Creek, in the Black Creek catchment was gauged under various flow events. This gauging site was selected as it is located upstream of the Branxton WWTW, meaning that any flows or water quality parameters measured at this location are directly related to the catchment properties and not influenced by the introduction of effluent from the treatment works. Analysis of the water quality flux from this catchment assisted in parameterising the catchment runoff modelling of other local catchments as limited historical measurements was available.

## 2.4 Water Quality Data

Extensive water quality monitoring and analysis has been conducted to understand the ecological and biogeochemical functioning of the Hunter River Estuary. This data supports the numerical modelling tasks by providing a detailed understanding of nutrient and ecological processes. Water quality measurements were obtained throughout the Hunter River Estuary and included the following:

- A long-term water quality sampling program;
- Continuous water quality sampling over a tidal cycle;
- Water quality profile measurements;
- Microbial community field surveys;
- Whole Effluent Toxicity (WET) testing;
- Zooplankton laboratory analysis; and
- Nutrient amendment experiments.

Monitoring has been conducted at three different temporal scales. The long-term monthly monitoring program was conducted by DPI Water/UTS. To validate this data set and characterise the variation at different temporal scales, additional intensive monitoring has been conducted twice weekly and over a tidal cycle.

As well as obtaining water quality data for use in model validation and calibration, in depth measurements of the water quality of the Hunter River Estuary system were undertaken to understand the ecosystem's health and behaviour in response to wastewater inputs. These measurements include microbial community surveys, WET testing, and nutrient amendment experiments. The major water quality campaigns included:

- Microbial community sampling was undertaken to understand the ecological implications of wastewater in the estuary. This sampling targeted pelagic communities to understand the biological change of organisms and the health of the microbial community in terms of their ability to cycle nutrients and organic matter. This study also focussed on identifying pathogens in the estuary that would be harmful to humans and genes associated with antibiotic resistance.
- WET testing has been undertaken to enhance the understanding of toxicity in the Hunter River Estuary. This testing is designed to highlight the effects of wastewater in both inhibiting and stimulating the growth of microalgae and microbial species. This leads to a better understanding of the effect of nutrients on important biogeochemical processes. Testing was conducted on a community level to enhance the understanding of field toxicity on a more practical scale. At the community level, the abundance of genes associated with nutrient cycling, antibiotic resistance and the identification of pathogens was also analysed in the freshwater tests.

- As part of a five (5) year water quality program in the Hunter River Estuary, UTS had undertaken approximately 600 zooplankton samples. These samples were analysed to determine the effect of flow, nutrients and salinity on the organisms in the system. Zooplankton abundance (ind/m$^3$) were available for three species, namely, Copepods, Nauplii and Rotifers. For the modelling process, Copepods was categorised as Macro-Zooplankton while Nauplii and Rotifers were categorised as Micro-Zooplankton.
- Seasonal nutrient amendment experiments were conducted to provide an understanding of phytoplankton responses to potential changes in nutrient inputs to the estuary. The change in phytoplankton biomass and community composition in response to nutrient additions can demonstrate which nutrients may be limiting algal growth and this can inform on the risk of excessive algal growth or blooms and potentially determine tipping points (nutrient concentrations and stoichiometry) when these may occur. The experiments are useful in testing hypothesis related to algae growth developed from the long-term water quality study, in an environment where other factors such as light and grazing are controlled. The experiments were conducted adjacent to selected WWTW outfalls in the Hunter River Estuary and its tributaries to provide insight to potential ecological responses to changes in WWTW nutrient loads associated with future management scenarios.
- Long-term water quality sampling occurred over two (2) separate campaigns: monthly sampling, from April 2010 to March 2015, and twice weekly sampling from November 2016 to March 2017. During the water quality monitoring campaign, a full range of nutrient and physiochemical sampling was conducted including total nitrogen (TN), total phosphorus (TP), filtered reactive phosphorus (FRP), silica (Si), nitrate and nitrite (NOx), ammonium ($NH_4$), dissolved organic nitrogen (DON), dissolved total nitrogen (DTN), dissolved total phosphorus (DTP), dissolved organic carbon (DOC), total organic carbon (TOC), temperature, conductivity, dissolved oxygen (DO), turbidity, pH, and secchi depth. Biological samples were taken for: bacterial abundance, biomass, chlorophyll-a, phytoplankton and zooplankton.

## 3. Model Design and Methodology

This section provides a summary of the numerical models and modelling methodology adopted for the development of the Hunter River Estuary Hydrodynamic and Water Quality Model. The model consists of four main components, including:

- **Local Catchment** Hydrological Model (AWBM): this model predicts runoff from floodplain sub catchments based on catchment rainfall distribution;
- **Crop Model:** this model estimates the irrigation demand based on rainfall, crop type, irrigation area and water extraction licence share component and simulates flow extractions from the tidal pool;
- **Hydrodynamic Model (RMA-2):** this model computes the estuary hydrodynamics and considers transport and mixing of flows in the tidal pool including the influence of the ocean tide, catchment flows and irrigation extractions through the modelled waterway domain;
- **Water Quality Model (RMA-11):** this model computes water quality concentrations throughout the model domain as influenced by the tidal pool hydrodynamics.

The hydrological and crop models were developed to provide boundary conditions for the hydrodynamic model, which was in turn used to drive the water quality model (Figure 3).

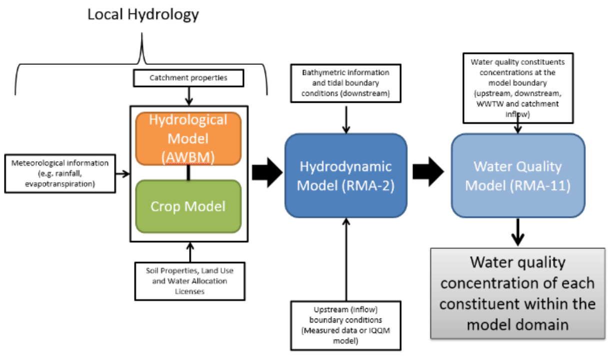


**Figure 3.** Numerical Model Configuration

The numerical models used for this study cover different areas of the Hunter Valley and were prepared using different time-steps. The model domain and time-steps used in the model are:

- **Local Catchment Hydrological Model (AWBM):** The AWBM was used to calculate runoff for the local catchment area (i.e. catchment area surrounding the Hydrodynamic and Water Quality Model). The AWBM catchment runoff model covering an area of approximately 1,300km$^2$ was run on a daily time-step.
- **Crop Model:** The crop model calculates the extraction volume corresponding licenced irrigators in the tidal pool servicing an area of approximately 80 km$^2$ within the Hunter River local catchment. This model was run on a daily time-step.
- **Hydrodynamic and Water Quality:** The RMA model domain covers an area of more than 60 km$^2$ encompassing the river estuary. The hydrodynamic and water quality model were operated on a 15-minute time-step. While the hydrodynamic data were saved every 15 minutes, the water quality data were saved every 4 hours.

WWTW outflow were made available from January 2009 to July 2018 by Hunter Water. To generate a WWTW timeseries outside this period, a flow model using Machine Learning technics was developed based on rainfall and temperature.

A water quality model was used to simulate the water quality regimes within the Hunter River Estuary. This was undertaken using RMA-11 and the hydrodynamic results predicted by RMA-2. RMA-11 is a finite element water quality model for simulation of estuaries, bays, lakes, rivers and coastal regions. Constituents represented within RMA-11 include temperature, salinity, dissolved oxygen, the nitrogen cycle (including particulate and dissolved organic nitrogen, ammonia, nitrite and nitrate), the phosphorus cycle (including particulate and dissolved organic phosphorus and phosphates), the carbon cycle (including particulate and dissolved organic carbon and total inorganic carbon) algae/micro- and macro-zooplankton and coliforms. The major interactions cycles between the nutrient related constituents within RMA-11 is shown in **Error! Reference source not found.** 4. A total of 19 constituents in the water column and 13 constituents at the bed were modelled. The complete list of constituents included in the model are summarised in **Error! Reference source not found.**1.

The local catchments runoff concentrations were based on 7 Fletcher et al. (2004) and 8 Duncan (2006). These documents reviewed literature for storm water quality originating from a number of different land use types to provide guidance on the ranges of contaminant concentrations typically found in Australian stormwater runoff. The lower, upped and median values of water quality for coliforms, total nitrogen, total phosphorus for wet weather (Event Mean Concentrations) were validated against locally derived catchment runoff data discussed above.

**Table 1.** Model Constituents

| Constituent | Water Column | Bed |
|---|---|---|
| Particulate Organic Nitrogen | ✓ | ✓ |
| Dissolved Organic Nitrogen | ✓ | ✓ |
| Ammonium | ✓ | ✓ |
| Nitrite | ✓ | ✓ |
| Nitrate | ✓ | ✓ |
| Particulate Organic Phosphorus | ✓ | ✓ |
| Dissolved Organic Phosphorus | ✓ | ✓ |
| Phosphate | ✓ | ✓ |
| Particulate Inorganic Phosphorus | ✓ | ✓ |
| Particulate Organic Carbon | ✓ | ✓ |
| Dissolved Organic Carbon | ✓ | ✓ |
| Total Inorganic Carbon | ✓ | ✓ |
| Dissolved Oxygen | ✓ | |
| Temperature | ✓ | |
| Salinity | ✓ | |
| Macro-Zooplankton | ✓ | |
| Micro-Zooplankton | ✓ | |
| Algae | ✓ | ✓ |
| Coliform | ✓ | |

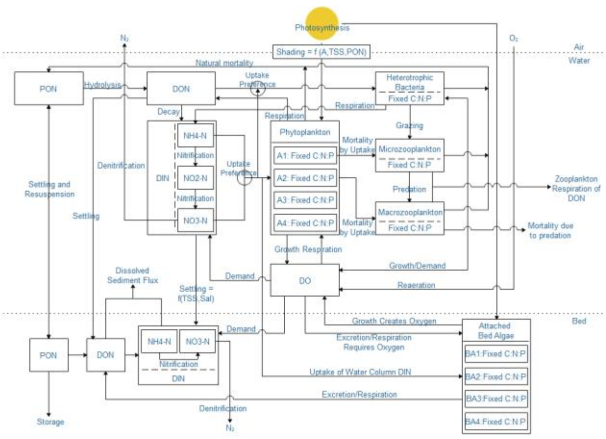

**Figure 4.** Major Nutrient Cycles within RMA-11

Freshwater inflow at the upstream boundaries account for approximately 70% of the total inflows to the model and water quality concentrations at the upstream boundaries are one of the most important input to the water quality model. Several methodologies were tested to provide water quality concentration at the upstream boundaries and implemented during the calibration process. Various model parameters were tested to match the measurements but a machine learning model was shown to provide the best prediction of water quality concentrations at the upstream boundaries based on the flow, water temperature and a seasonal indicators. Using this model to predict the concentrations at the upstream boundaries of the water quality model improved the calibration results between the water quality model prediction and measurements.

## 4. Calibration and Validation

To evaluate the performance of the numerical model, four statistical coefficients were considered, namely:

- Coefficient of Determination ($r^2$);
- Nash-Sutcliffe of efficiency (NSE);
- Percentage BIAS (% BIAS); and
- Ratio of the Root Mean Squared Error to the Standard Deviation (RMSE/STD).

The RMA-11 model was calibrated and validated against salinity measurements within the Hunter River Estuary model domain. The model was calibrated using the long-term salinity measurements collected by MHL for the period March 2010 to December 2014 at 6 locations. Model diffusion coefficients were adjusted to match the observed ranges and peaks throughout the estuary.

The model has been able to provide a reasonable prediction of the salinity compared to the measurements. The modelled salinity predictions in the lower part of the estuary have a coefficient of determination higher than 0.8 at Hexham Bridge and Raymond Terrace. In the upper part of the estuary, salinity concentrations were highly sensitive to the catchment runoff boundary conditions, extraction and the upstream inflow boundary. In general, the peaks and recovery rates are reasonably reproduced but additional good quality and long-term salinity data are recommended for future calibrations.

The RMA-11 model was also calibrated and validated against temperature measurements within the Hunter River Estuary model domain. The model was calibrated using the long-term temperature measurements collected by MHL for the period March 2013 to December 2014. Model evaporation coefficients were adjusted to match the observed ranges throughout the estuary. The agreement between measured and modelled temperature was good with seasonal variations well represented.

The RMA-11 model was calibrated and validated against water quality measurements within the Hunter River Estuary model domain. The measurements collected at Hunter River (D/S of PR Confluence), Casuarina Corner, Raymond Terrace and Kooragang Island from 2012 to 2014 were used for calibration, while the measured data from 2010 and 2011 were used for validation of the water quality constituents.

Overall the results predicted by the RMA-11 water quality model were highly sensitive to the boundary conditions at the upstream boundaries. Once the final model parameter values were established through the calibration, the model results were compared against the available for the period April 2010 – December 2014 as part of the validation process. Similar to the calibration results, the model satisfactorily captured the overall trends and patterns for water quality. The modelling exercise was able to demonstrate that the numerical model is suitable to predict water quality concentrations throughout the estuary.

## 5. Summary

The objective of this study was to build a calibrated and validated water quality model of the Hunter River Estuary to assess current and future operations/regulations within the Hunter River estuary. A water quality model (RMA-11) was upgraded and calibrated using the most accurate information available. The focus of the calibration and validation was to select model parameters and a methodology to prepare the model inputs (e.g upstream boundaries or local catchments concentrations) by testing the numerical model performance against field measurements. Further information is available upon request.

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