Sydney Harbour Catchment Water Quality Improvement Plan

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Abstract

Greater Sydney Local Land Services (GS LLS) is using an integrated hydrological and ecological modelling approach to develop the Sydney Harbour Catchment Water Quality Improvement Plan (SHCWQIP). The objectives of the project are to achieve an improvement in the water quality and ecological integrity of Sydney Harbour and its catchment; to engage key land managers and other stakeholders in the project design and process; and encourage ownership of the outcomes.

The process includes the characterisation of land and its use within the catchment draining to Sydney Harbour. Intensive water quality monitoring has been undertaken to assist the development and validation of catchment pollutant export models (CPEM) to simulate and quantify the mobilisation and transport of stormwater. A high resolution 3-dimensional hydrodynamic model of the Harbour and its tributaries was developed and integrated with the CPEMs for the development of water quality models that simulate and predict the transport and fate of pollutants and phytoplankton under varying climate and land use management scenarios. Probabilistic higher order ecological response models were developed to predict the influence of management strategies on the ecology of the Harbour.

Integration of the above models into a Decision Support System (DSS) was done to investigate the impact of different management strategies on water quality and Harbour ecology. Output from the DSS includes catchment loads, median estuary water quality concentrations, costs of management actions and likelihoods various of ecological condition impacts in the freshwater and estuarine systems.

The project has secured funding partnerships with the majority of the local governments within the Sydney Harbour Catchment, as well as Sydney Water, Roads Maritime Services, Office of Environment and Heritage (OEH), Harbour City Ferries and the Sydney

Institute or Marine Sciences (SIMS). The SHCWQIP project is nearing completion and a draft Plan will be available for review by the end of 2014.

Introduction

Sydney Harbour, together with its foreshores, headlands and tributaries is the city's largest and most accessible open space and natural area. It is Sydney's best loved urban space; a national icon; a busy transport corridor; an economic powerhouse for industry, commerce, trade and tourism; and much more. The Harbour embodies the nature of Australia. It remains a place of unmatched Aboriginal significance. It is a direct and accessible symbol of Eora cultures. It contains the most significant surviving evidence of colonial settlement and is now a powerful symbol of a multicultural Australia.

Sydney Harbour and its catchment have natural resource assets of national significance and as identified within the *Environment Protection and Biodiversity Conservation Act* (1999), these assets include: 3 threatened ecological communities; 62 threatened species; 29 migratory species; and 48 marine protected species.

Sydney Harbour is a special type of estuary classified as a drowned river valley (Roy *et al*., 2001). It contains a wide variety of habitats that support an incredible diversity of organisms. According to a recently published literature review of the Harbour undertaken by the Sydney Institute for Marine Sciences (Hedge *et al.* 2014):

> *There are more fish species in Sydney Harbour (586) than for the entire coast of the United Kingdom.*

However, all is not right with Sydney Harbour. The sediments still carry the toxic legacy of years of industrial discharges. Testing of fish and crustaceans revealed high levels of dioxins that resulted in a complete ban on all commercial fishing in Sydney Harbour in January 2006 (DPI 2012). Whilst recreational fishing has not been banned, fishers have been advised that no fish or crustaceans caught west of the Sydney Harbour Bridge should be eaten and for fish caught east of the bridge generally no more than 150 grams per month should be consumed (DPI 2012). Whilst changes in legislation have made it illegal to purposely dump toxic waste in Sydney Harbour, thousands of tons of toxic pollutants still enter the Harbour each year through the stormwater system and sewage overflows.

Stormwater is a toxic cocktail that contains everything from heavy metals (such as copper, zinc and lead) to viral pathogens (Freewater, 2004). Many of these chemicals will never break down or take decades to do so. Birch *et al.* (2010) estimate that stormwater contributes an average of 475 t total nitrogen (TN), 63.5 t total phosphorus (TP) and 343,000 t total suspended solids (TSS) to Sydney Harbour each year. These volumes may triple in a very wet year. Stormwater pollution is now the major threat to the ecological integrity of Sydney Harbour.

The SHCWQIP is the first environmental management plan to encompass the whole of Sydney Harbour's catchment as well as the waterways and will provide the first coordinated management framework for the 25 local councils, 11 state government agencies and 2 federal government agencies who have a stake in improving the future health of Sydney Harbour and its catchments.

The SHCWQIP project is by its nature highly complex and includes several detailed modelling projects. Each of these sub projects have produced detailed reports. Whilst this paper reports on some of that work, readers are directed to the detailed reports for further information.

Methods

The project uses an integrated modeling approach, first coined as *Hydro-ecology* (Freewater, 2003) but advanced considerably since its conception in the 1990s (Freewater, 2004a, 2004b, 2005, 2007; Freewater, *et al*., 2006, 2012; Taylor *et al.,* 2007 Platell & Freewater, 2009; Freewater & Kelly, 2012). This approach is used to understand how catchment land management, estuarine hydrodynamics and ecology interact. This approach is outlined in Figure 1, however, the details have been omitted for clarity. Such detail includes the data compilation study and software review that was completed prior to any modelling. A communication strategy and a business plan were also developed to communicate the project to potential partners.

The integrated modeling process for Sydney Harbour is complex but, put simply, it involves the following key stages of development:

1. The characterisation of land and its use within the entire catchment draining to Sydney Harbour.
2. Intensive water quality monitoring and the collection and analysis of historic water quality data.
3. The development and calibration of catchment pollutant export models (CPEMs) to simulate and quantify the mobilisation and transport of stormwater borne pollutants and sewage network discharges and overflows to receiving waters under varying climate conditions.
4. The development and calibration of high resolution 3-dimensional hydrodynamic models of the Harbour and its tributaries that simulate tidal flows and processes of advection and dispersion.
5. Integration of pollutant export models with hydrodynamic models for the development of water quality models that simulate and predict the transport and fate of pollutants under varying climate and land use management scenarios. These *deterministic* models also simulate the ecological response of phytoplankton to climate and land use management scenarios (Sydney Harbour Ecological Response Models (SHERM)). Box-model versions were also developed for use in the Decision Support System (DSS).
6. Development of probabilistic Bayesian Network (BN) higher order ecological response models (ERMs) to predict the influence or impact of land use management strategies on the ecology of the Harbour.
7. Integration of all of the above models (using metamodels of the more complex models where necessary) into DSS to investigate different combinations of land use and stormwater management strategies on water quality and ecological processes within Sydney Harbour. Predicted output from the DSS is provided in terms of catchment loads, receiving water quality concentrations, costs of catchment management actions and ecological condition probability distributions together with simple graphics, maps and other data accessible to all levels of understanding, thus providing an even playing field for assisting with community education and decision-making processes.

8. The application of the DSS with local and state government funding partners and stakeholders to develop agreed water quality targets for the Harbour and its tributaries; and to develop and list specific actions that these partners will undertake to achieve these targets.

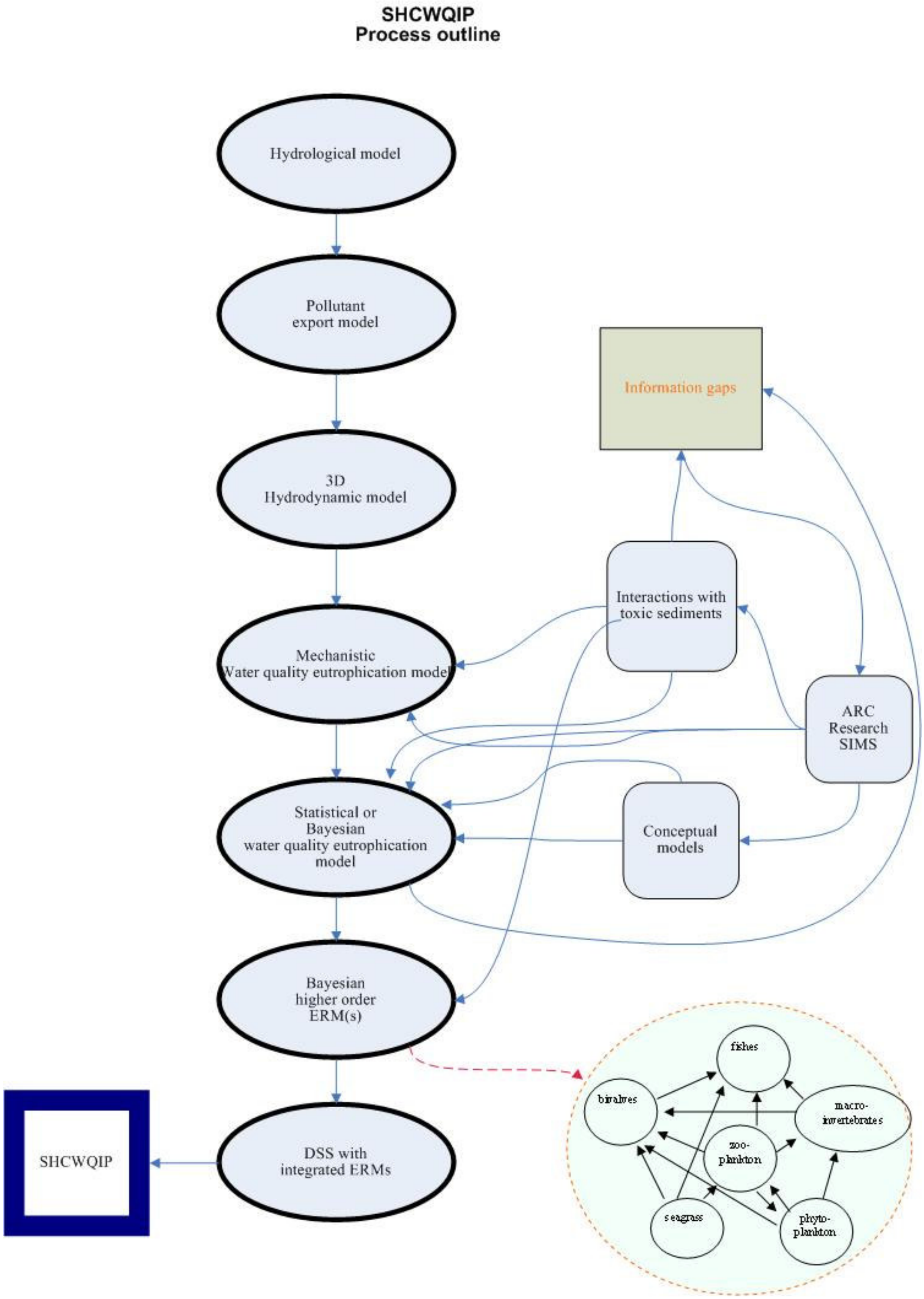


Figure 1 SHCWQIP integrated modelling process

Before any hydrological modelling was completed a process of catchment delineation was undertaken. Using the *ESRI* Geographical Information System (GIS), the greater Sydney Harbour catchment was divided into more than 2,500 sub-catchments. Sydney Harbour itself was divided into four major sections: Parramatta River, Lane Cove River, Middle Harbour and Port Jackson. Whilst LiDAR data existed for the shoreline, it had to be corrected to accurately describe foreshore slopes and the heights of seawalls. This process involved physical surveys and digitising data into GIS spatial layers.

Components of the SHCWQIP have been guided by an Advisory Panel made up of experts from state government, local government and from academia. On advice from this panel, ecological response modelling was being done as a pilot study to test the suitability of the *Delft3D* modelling system and the Bayesian Network (BN) approach. The pilot study, focusing on the Parramatta River catchment and tributaries, was completed in 2013 and relevant stakeholders were trained to use the resulting DSS. The pilot was considered a success and the decision was made to continue with the rest of the Harbour with only some minor changes to the methods, including the removal of the *Rafts* models. The *Source* models were modified to assume the required hydrological functions, without the additional post-processing problems that were encountered when integrating data exported from the *Rafts* to the *Source* models (Catchment Research, 2014).

Source simulates current and potential future catchment characteristics to evaluate impacts of land use and/or the implementation of best management practices. The *Source* or Catchment Pollutant Export Model (CPEM) provides catchment flows and pollutant loads for the *Delft3D-WAQ* (Sydney Harbour Ecological Response Models (SHERM)). Modelling is run to estimate pollutant loads from the current land use pattern (eg. TSS, TP, TN and *Enterococci*). The implications of increased area or intensity of urban development, or changes in rainfall regimes associated within climate change, or implementation of 'best practice' stormwater controls, can then be estimated through repeated modelling with modified catchment or rainfall parameters respectively.

An existing *Delft3D* 2D hydrodynamic model was refined (eg. much higher grid resolution) and extended to include high resolution bathymetry data collected from upstream of Parramatta River to the Port Jackson entrance, the whole of the Lane Cove River and Middle Harbour (Cardno and Baird, 2014a). This model, which simulates water levels, currents, temperature and salinity, was calibrated with available water level and current/discharge data (Cardno and Baird, 2014a). Another change was the integration of algorithms developed by the NSW Office of Environment and Heritage (OEH). These algorithms were considered appropriate for modelling microbenthic-phytoplankton nutrient dynamics and were provided by Dr Peter Scanes (a member of the expert panel) and his estuary management team for incorporation into the water quality and phytoplankton models (*Delft3D-WAQ*). The water quality model (*Delft3D-WAQ*) utilised result files from the hydrodynamic model to represent volume fluxes within the model domain. Two water quality models, one a box model of only 32 regions, the other a more detailed model, were applied in this investigation. The box model was developed as a highly efficient (fast computational times) model that could undertake simulations relatively quickly. The study team developed 2D and 3D versions of the *Delft3D-WAQ* model, which formed the basis of the SHERM. The transport-dispersion processes of the *Delft3D-WAQ* module were calibrated to the calibrated *Delft3D-FLOW* model results through comparison of salinity distribution between the two models. The SHERM was designed to simulate a range of water quality and biological processes (Cardno and Baird, 2014b).

Water quality processes represented in the SHERM include:

- Physical processes
    - Temperature
    - Salinity
    - Dissolved oxygen and re-aeration
- Nutrients
    - Nitrogen
    - NH_4, NO_x and two organic fractions (fast and slow decay fractions)
    - Nitrification and de-nitrification
    - Decomposition of organic nitrogen into soluble fractions
    - Sediment and water column exchange
    - Zero-and-first order nitrogen flux (release) from sediments
- Phosphorus
    - PO_4 (absorbed and soluble) and two organic fractions (fast and slow decay fractions)
    - Decomposition of organic phosphorus into soluble fractions
    - Sediment and water column exchange
    - Zero-and-first order phosphorus flux (release) from sediments
- Carbon
    - Two organic fractions (fast and slow decay fractions)
- Algal processes
    - Primary production
    - Respiration
    - Mortality including grazing
    - Separation into green and diatom species with the option to further increase the number of species including benthic algae.
- Biological Contaminants
    - *E.coli*
    - Total coliforms
    - Faecal coliforms

The transport fluxes from the *Delft3D-FLOW* model were processed and aggregated initially onto a coarse grid (the box model) that was used for the initial calibration of the SHERM model (Cardno and Baird*,* 2014b). Calibration was initially undertaken in a sequence of steps that can be summarised as follows:

1. Calibration of transport and dispersion characteristics.
2. Calibration of the biological contaminant process and concentrations.
3. Calibration of total nutrient balance (i.e. TN, TP, TOC).
4. Calibration of nutrient cycle to represent dissolved inorganic nutrient concentrations accurately within the model.
5. Calibration of the primary production including algal processes and dissolved oxygen levels.

Following the completion of the calibration and validation of the SHERM, the model system was applied to the simulation of four selected 1-year scenarios. The 1-year scenarios involved the simulation of different rainfall conditions (i.e. wet, dry and average) as well as two different catchment inflow scenarios for the average year (Cardno and Baird*,* 2014b).

The 3D hydrodynamic box models were prepared by aggregation of the full model hydrodynamics so that, for example, Iron Cove became one box and the tidal exchange and catchment flows described bulk flows – maintaining mass conservation. Other examples were the Parramatta River above Silverwater Road and Homebush Bay (including Powells and Haslam's Creeks). The box model version of the SHERM has been applied to undertake a conservative tracer assessment of the contribution of the discharges within each of the 32 cells in the 3D box model to the overall catchment nutrient load into the harbour. The DSS requires tracer simulations to define the contribution of each catchment zone in the harbour to the total harbour wide load. To ensure consistency between the SHERM and the DSS, the catchment inflows into the harbour have been characterised by the cell of the box model they discharge into (Cardno and Baird*,* 2014b).

The DSS builds on two previously developed DSS, the *CLAM tool* (a Bayesian Network based system) and *CAPER*. These decision support systems have mostly been developed and advanced by Dr Rebecca Kelly (nee Letcher) who has applied them to the Tamar Estuary, Darwin Harbour, Botany Bay and other important Australian waterways (Letcher *et al.,* 2006a, 2006b, 2007; Kelly *et al.,* 2012). The BN capacity was incorporated to develop this new DSS that provides both the detailed spatially explicit scenario input and outputs of *CAPER* and the flexibility of the *CLAM* approach to incorporate a wide range of social and ecological impacts using limited information (Freewater and Kelly, 2012).

This new DSS allows for:

- Evaluation of ecological responses of the estuary to changes in management options and land use;
- Detailed spatial representation of management options, catchment and estuary water quality and ecological impacts; and
- Probability distribution of impacts on any social or ecological indicator of interest for lumped spatial areas, including those where only limited data, such as expert opinion or workshop output, is available.

To model the effects of land use and climate on catchment pollutant load exports, a metamodel of the *Source* (CPEM) model was produced (Freewater and Kelly, 2012). This metamodel uses a smaller set of subcatchments to provide a compromise between ease of use by DSS end users and sufficient detail to provide outputs for key locations and subcatchments. This phase also included refinement of *MUSIC* modelling used to capture the impacts of WSUD options on catchment loads. While it is possible to include the impacts of WSUD in the *Source Catchments* model, the most accurate and flexible way of doing this relies on using pollutant load reductions calculated by the *MUSIC* model (in the same way the DSS uses these modelled reductions).

Pollutants able to be modelled in the DSS are limited to those produced by the CPEM and the sewer overflow data. To model the impacts of changes in catchment loads on estuary water quality and ecological condition a metamodel of the SHERM was developed. Scenario levers to be included in the DSS include changes in land use (including urban development and redevelopment), WSUD, changes to sewer overflow and riparian rehabilitation. Other scenario options, such as rural residential and agricultural lands management may also be considered.

An important phase in the development of the DSS was the scoping phase. This phase was used to actively engage potential end-users and key stakeholders. It was aimed at scoping their needs and preferences for such a tool as well as informing their expectations of the final product. Key information sought through the scoping phase included:

- Scenario options including management actions, climate scenarios and potential development options of interest to key stakeholders;
- Pollutants of interest and impacts of concern on ecological health and socioeconomic values (such as recreation and amenity);
- Requirements for specific subcatchments and estuary zones to be reported against in the interface to enable reporting and to facilitate the use of the DSS for planning and management purposes;
- Preferences for data display and output, including likelihood of exceedance, graphs, maps, relative changes; and
- Drivers, processes and impact nodes and their linkages for the Bayesian Network component of the integrated model.

These stakeholders were consulted again through a series of workshops to:

- Identify values, issues and impacts of concern to be considered in developing the Plan; and
- Specify scenarios to be considered in developing the WQIP:
  - Future threats and pressures on water quality
  - Potential management actions to improve water quality

There were also a series of community forums:

- To educate the community about the WQIP and what it will do; and
- To seek community input on scenarios and management actions to be considered by the Plan.

Results

The CPEM now simulates all Sydney Harbour Catchments in one model domain, including the Middle harbour and Port Jackson subcatchments. The model also simulates all model processes directly in the Source Catchments framework (version 3.5.0) and simulates on a 30 minute time step (Catchment Research, 2014). The key purposes of this model are to provide:

- Subdaily flow and pollutant load time series for all inflow locations to Sydney Harbour for use in receiving water modelling; and
- Subcatchment and land use based mean annual flow and pollutant load estimations for use in the Sydney Harbour DSS and associated WQIP.

The catchment area draining to the Sydney Harbour is approximately 484 km^2 which has been broken into 550 subcatchments, connected via a node link network (Figure 2). The model includes the facility to incorporate modelled sewer overflow time series for approximately 553 sewer overflow locations within the model domain. In addition to these features, the model simulates the rainfall runoff process using 30 minute rainfall data from 23 rain gauge locations and the *Simhyd* rainfall-runoff model for land use based subcatchment flows. The Event Mean Concentration/ Dry Weather Concentration model has been used for water quality constituent generation (Catchment Research, 2014).

The subcatchment and associated node-link maps were agglomerated to one map for the entire Sydney Harbour catchment, resulting in approximately 1900 subcatchments. These subcatchments were then accumulated to reduce the overall model size and enable the entire catchment to be constructed in 1 model domain with a model time period of > 10 years (Catchment Research, 2014). In addition to the existing subcatchment maps provided by GS LLS, a Local Government Area (LGA) map was obtained. This map was used in the subcatchment accumulation process to split subcatchments along LGA lines (Figure 3). Subcatchments were accumulated based on the following general rules:

- At least one subcatchment draining to each major bay;
- All Subcatchments less than 5 ha were considered for amalgamation; and
- Subcatchments were amalgamated to align with gauging locations and water quality sampling points.

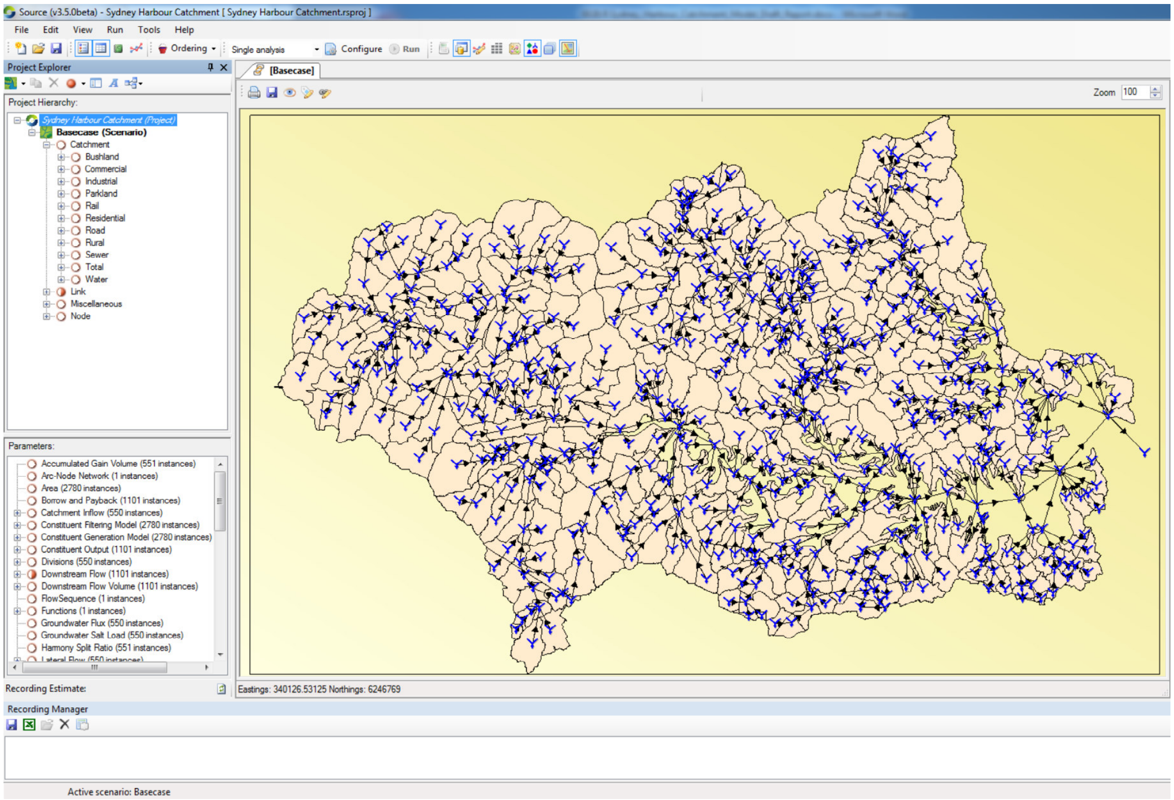


Figure 2 Catchment Pollutant Export Model

Land use in the 484 km^2 Sydney Harbour Model is broken into 10 categories (Functional Units) as described in Table 1. Land use was aggregated to a 5m grid for import to the CPEM (Figure 4). The model area attributed to sewer overflows is an artefact of the Upper Parramatta River model where sewer overflows were modelled as small land parcels (Catchment Simulation Solutions, 2011 & 2012). In the current model, sewer overflows are modelled as input time series at nodes, however the sewer overflow land use artefact in the Upper Parramatta remains (Catchment Research, 2014).

Table 1 Sydney Harbour Catchment Land Use

Land Use	Area (km2)	Area (%)
Bushland	30.25	6.25%
Parkland	67.91	14.04%
Residential	227.33	47.00%
Roads	89.47	18.50%
Railway	4.08	0.84%
Industrial	18.96	3.92%
Commercial	41.08	8.49%
Water	2.97	0.61%
Rural	1.60	0.33%
Sewer	0.04	0.01%
Total	483.7	100%

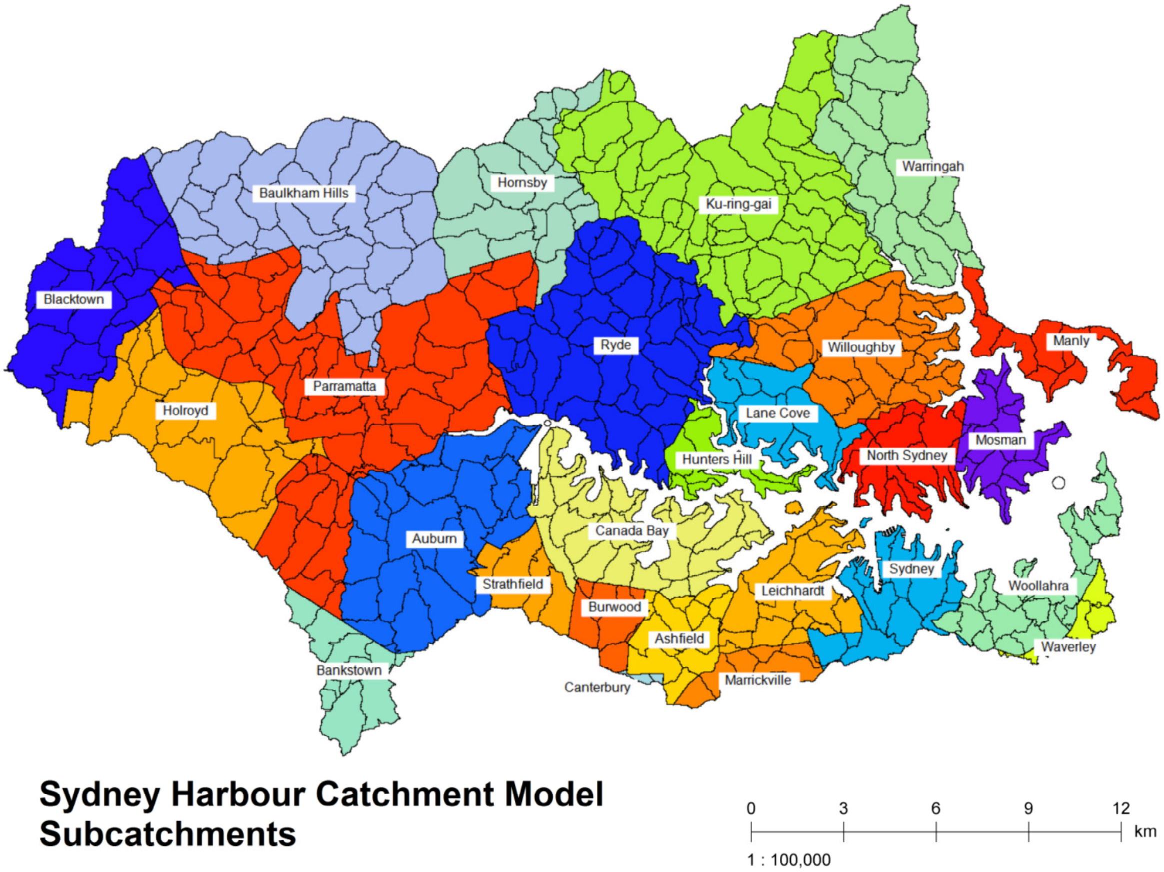


Figure 3 Sydney Harbour Subcatchment Map

Rainfall and evaporation data used in the CPEM has been sourced from GS LLS and Bureau of Meteorology (2013). The raw data used includes 30 minute time step data and pluvio data from the Bureau of Meteorology in addition to 30 minute time step data and raw data (time and number of tips) from stations collated by GS LLS. There are more rainfall gauging stations in the Sydney Harbour catchment than are practical to incorporate in the catchment model and from these gauges, a subset of 22 gauge locations has been chosen for incorporation to the model (Catchment Research, 2014). These gauges were chosen for their location within or nearby to the model domain, their length of record and completeness of record and their availability for future updating (Figure 5).

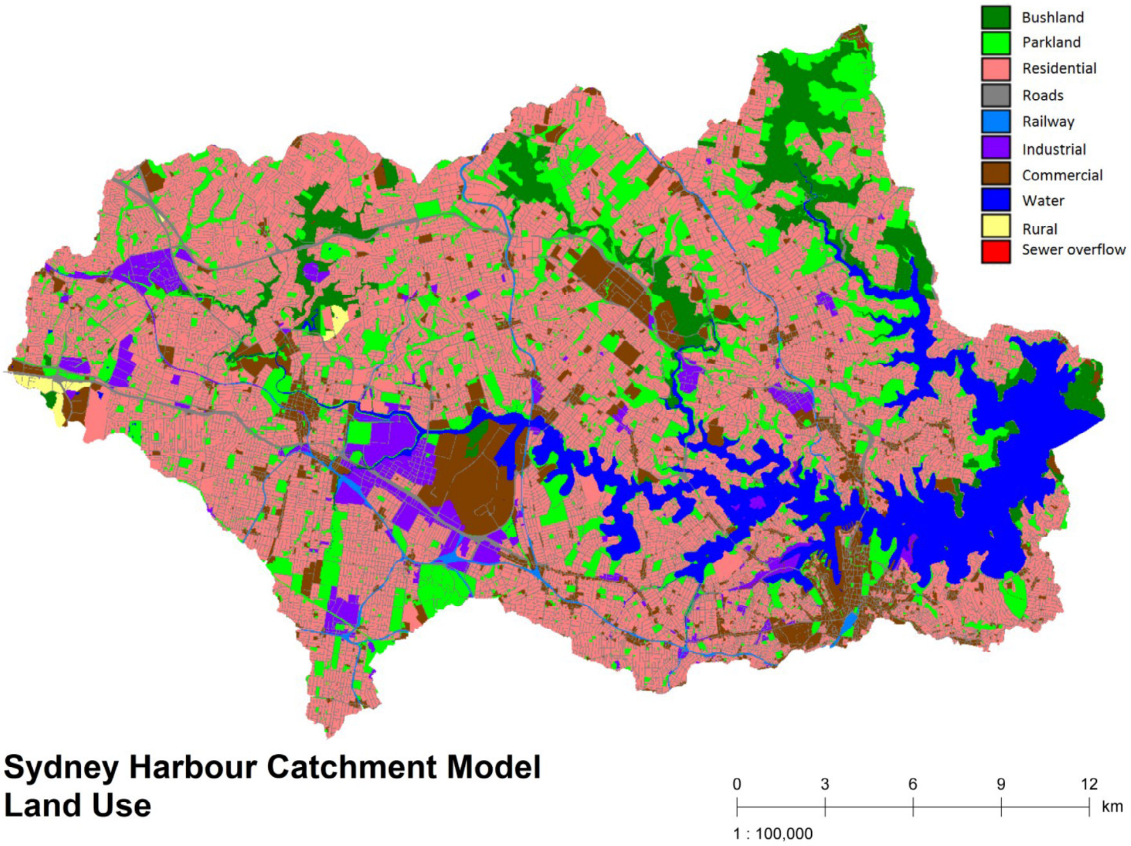


Figure 4 CPEM Land Use

Water quality data from within the model domain was obtained by contacting each LGA and requesting data for water quality constituents (Total Suspended Solids (TSS), Total Nitrogen (TN), Total Phosphorous (TP), faecal coliforms, *Enterococci*, *E.coli*, Biochemical Oxygen Demand (BOD) and Total Organic Carbon (TOC)). In addition to LGA data, water quality data from GS LLS and Sydney Water was also used (Catchment Research, 2014).

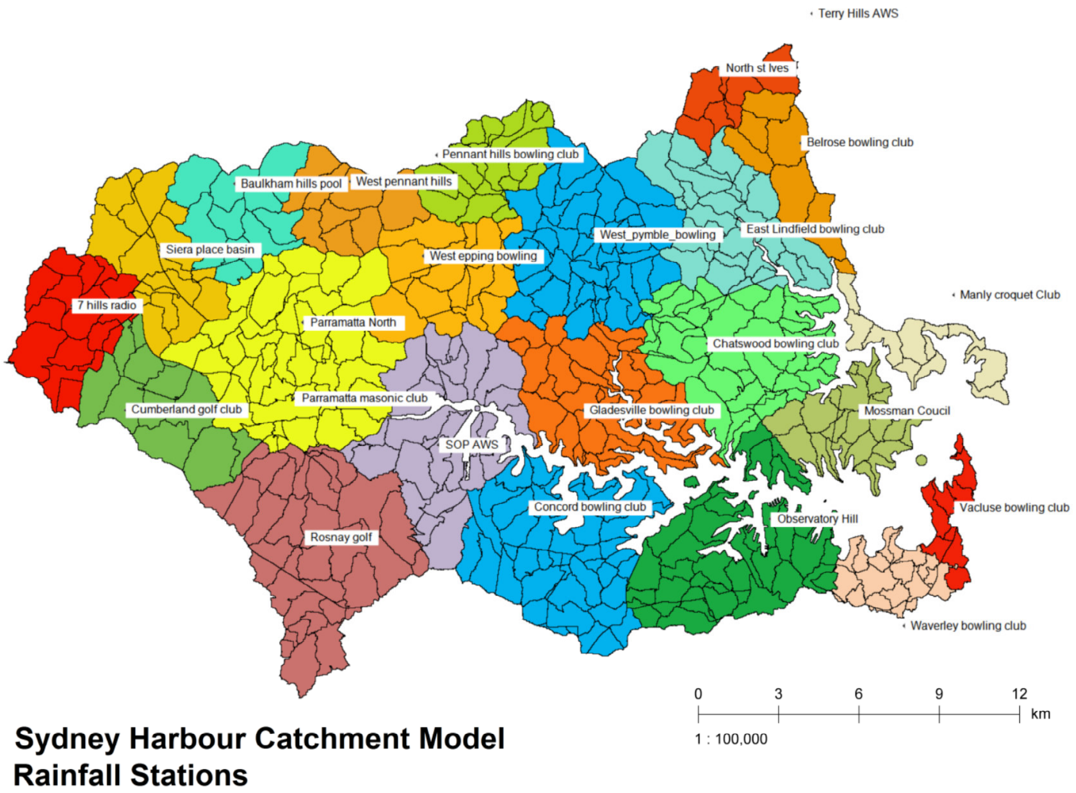


Figure 5 Rain Gauges and Subcatchment Rainfall Assignment

Water quality parameters from other Sydney Harbour catchment models (Original Upper Parramatta River model and Lower Parramatta River model) were assigned from literature values and were also partially based on those used in the Botany Bay catchment model. These land use based parameters were updated using the collated grab sample data from the entire model domain (Figure 6). Direct correlation and optimisation between modelled water quality values and recorded values is not applicable with the current 30 minute time step model. Only a small fraction (18%) of all the water quality data collated had a time stamp at which the sample was taken. Therefore there is no direct correlation between most of the water quality data and corresponding output value from the model unless the model was reverted to a daily time step. Despite this limitation, the collated water quality data has been used to generate mean and percentile values which have then been used to adjust the literature water quality values. For example (Catchment Research, 2014):

- The literature based Dry Weather Concentration (DWC) parameter for Total Nitrogen was 1.8 mg/L for residential land use:
- The 50th percentile from all 1811 water quality data points was 1.03 mg/L
- The 1.8 mg/L corresponded roughly to the 80th percentile of all monitoring data suggesting that using this value as the DWC for the main land use in the model would result in overprediction of baseflow water quality levels.
- Therefore the 50th percentile value for TN was adopted for the DWC as the model parameter.

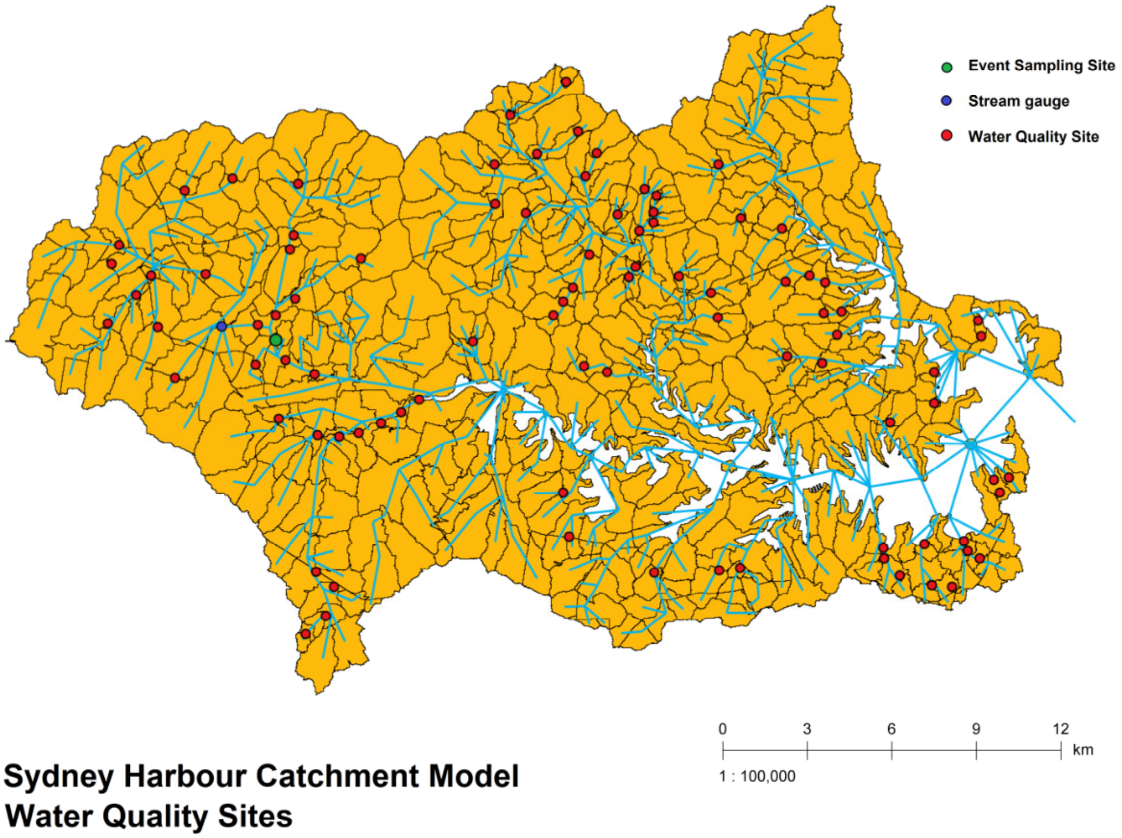


Figure 6 Sydney Harbour Water Quality Sites

Appropriate conversions were undertaken during post processing to obtain results in the correct units. The final water quality parameters used in the model are presented in Table 2 (Catchment Research, 2014).

The 553 sewer overflow locations and associated 30 minute modelled time series of these overflows for the period 1/7/2010 - 1/7/2013 were provided by Sydney Water. This number of time series is a 10 fold increase over the 48 time series included in the Upper Parramatta River model and therefore requires a different approach to incorporation into the model domain to keep model structure and size to a manageable level. The locations of the overflows are shown in Figure 7. Analysis of the sewer overflow data has been conducted as part of this investigation by looking at the number and magnitudes of overflow events. An event is a series of overflow time steps with zero flow on time steps either side of the event. In the 3 year period provided (2010-2013), 1422 events occurred across the 32 groups totalling 165 ML of sewer overflow for the entire harbour (Catchment Research, 2014). Previous Upper Parramatta sewer overflow volume for the period 2004-2008 was 2762 ML (Catchment Research, 2011). Model mass balance results for the current conditions scenario are presented in Table 3.

Table 2 Model Water Quality Parameters

	Biochemical Oxygen Demand		Faecal coliforms		Total Nitrogen		Total Organic Carbon		Total Phosphorous		Total Suspended Solids		*Enterococci*		*E.coli*	
	mg/L		CFU/100 mL		mg/L		mg/L		mg/L		mg/L		CFU/100 mL		CFU/100 mL	
	EMC	DWC	EMC	DWC	EMC	DWC	EMC	DWC	EMC	DWC	EMC	DWC	EMC	DWC	EMC	DWC
Bushland	6.2	0.1	600	100	1.3	1.03	8	8	0.1	0.07	60	8	120	20	120	20
Commercial	5.5	0.1	10000	300	2.8	1.03	33	8	0.33	0.07	204	8	1000	260	1000	260
Industrial	5.5	0.1	10000	300	2.8	1.03	33	8	0.33	0.07	204	8	1000	260	1000	260
Parkland	6.2	0.1	600	100	1.3	1.03	8	8	0.1	0.07	60	8	120	260	120	260
Railway	5.5	0.1	10000	100	2.8	1.03	33	8	0.33	0.07	204	8	1000	260	1000	260
Residential	10.1	0.1	10000	300	2.8	1.03	19	8	0.33	0.07	204	8	4000	260	4000	260
Roadway	5.5	0.1	10000	300	2.8	1.03	33	8	0.33	0.07	204	8	1000	70	1000	70
Rural	6.2	0.1	600	100	2.8	1.03	8	8	0.1	0.07	204	8	120	20	120	20

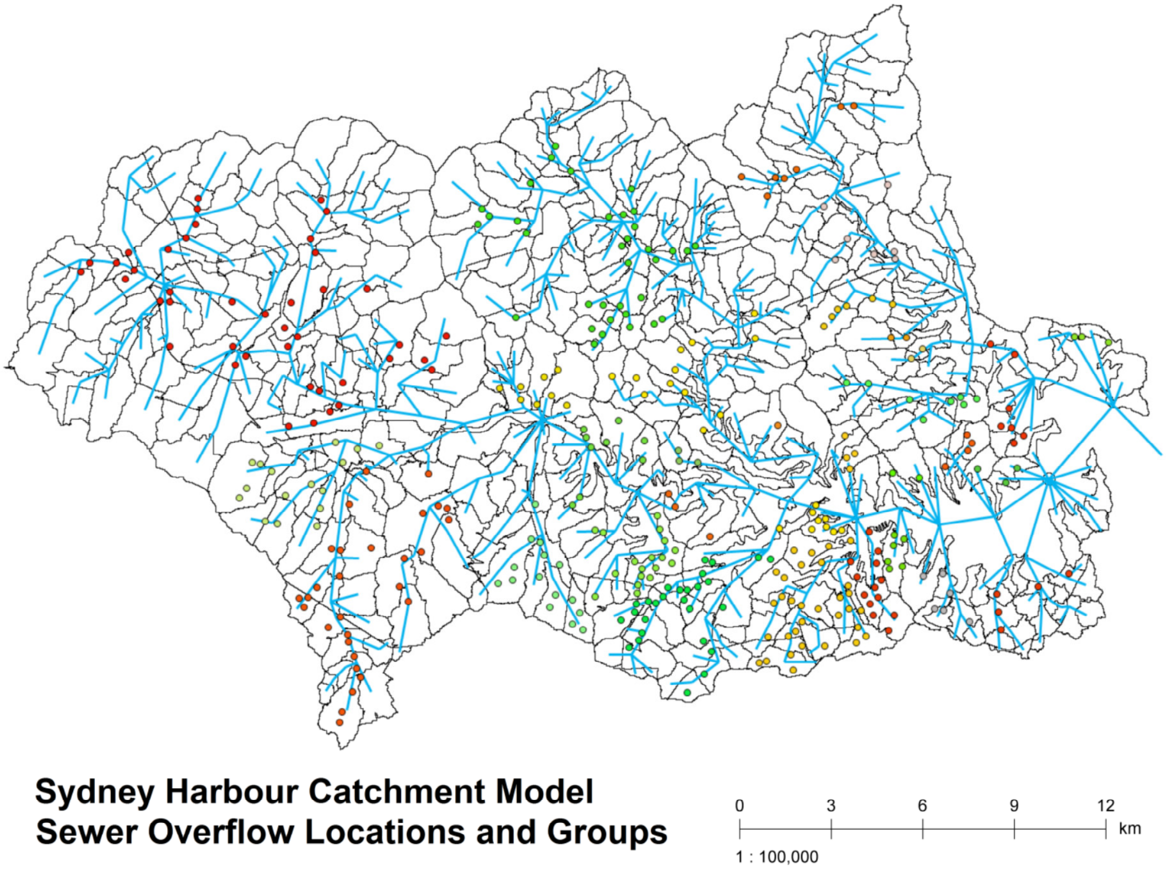


Figure 7 Sydney Harbour Sewer Overflow Locations

Table 3 Total flow and pollutant export mass balance (2010-2013)

Mass Balance	Diffuse Catchment loads	Sewer overflow load	Total Load	Sewer overflow contribution (%)
ML	902163.2	165.0	902328.2	0.02%
BOD (t)	6137	3.30	6140.4	0.05%
TSS (t)	107466	32.99	107499.2	0.03%
TN (t)	1723.9	1.67	1725.6	0.10%
TP (t)	181.4	0.20	181.6	0.11%
TOC (t)	15941	2.84	15943.8	0.02%
Enterococci (CFU)	1.68E+16	4.12E+14	1.72E+16	2.39%
E.coli (cfu)	1.68E+16	1.65E+15	1.85E+16	8.94%
Faecal coliforms (CFU)	4.95E+16	2.06E+15	5.16E+16	4.00%
BOD (mg/L)	6.80	20.0	6.8	
TSS (mg/L)	119.12	200.0	119.1	
TN (mg/L)	1.91	10.1	1.9	
TP(mg/L)	0.20	1.2	0.2	
TOC (mg/L)	17.67	17.2	17.7	
Enterococci (CFU /100ml)	1864	250000	1909	
E.coli (CFU /100ml)	1864	1000000	2046	
Faecal coliforms (CFU /100ml)	5489	1250000	5717	

The results of the mass balance show that over the 3 year model period (2010-2013) approximately 0.02% of the flow in Sydney Harbour may have been attributed to sewer overflows.

- Approximately 0.1% of total catchment nutrient load may be a result of sewer overflows; and
- Approximately 9% of *E.coli* and 4% of faecal coliform loads and 2% of *Enterococci* may be a result of sewer overflows.

Model results for diffuse loads from the entire 13.5 year model time series are presented in Table 4 and monthly totals for the entire period are shown in Figure 8.

Table 4 Total flow and pollutant export mass balance (2000- 2013)

mass Balance	Total Diffuse Catchment loads	Mean Annual Load	Mean concentration
ML	3287870	243546	
TSS (t)	394219	29201	119.9
TN (t)	6286	466	1.91
TP (t)	664	49	0.20
Faecal coliforms (CFU)	1.8E+17	1.3484E+16	5536
E.coli (CFU)	6.2E+16	4.5705E+15	1877
Enterococci (CFU)	6.2E+16	4.5705E+15	1877
TOC (t)	58752	4352	17.87
BOD (t)	23120	1713	7.03

The CPEM, *Delft3D* hydrodynamic model and SHERM systems have all been calibrated using data available for each model system. The CPEM was used to provide catchment flows and pollutant loads for the SHERM. The *Delft3D* hydrodynamic model provides advective forcing conditions for the SHERM and can also provide 3D salinity and temperature inputs (if required). These models have relatively high spatial and temporal resolution requiring considerable model resources should they be run in a single model domain (Cardno and Baird*,* 2014a).

The *Delft3D* 2D hydrodynamic *FLOW* model was optimised, reducing the run time without compromising the accuracy of the model. The 3D hydrodynamic Z and sigma-layer models were then set up and calibrated. The sigma-layer runs approximately five times faster than the Z model. The sigma-layer model (8 layers and salinity) requires one day of computational time for 1 day of real time. Figure 9 shows the model extent. For computational efficiency, the hydrodynamic model has been constructed as a series of nine individual domains; which are processed in parallel. Figures 10a and 10b show the calibration results that compare the measured flow discharge with the pre and post-optimisation model results. This figure shows that the pre and the post-optimisation models both perform very well when compared to the measured cross-sections. Figure 11 is a map of the depth-averaged horizontal velocity (from the Z model) that covers the complete extent of the model near the time of peak ebb flow with no catchment flows (Cardno and Baird*,* 2014b).

The water quality model component of the SHERM is capable of modelling the water quality processes in 2D or 3D, and also at high horizontal resolution or a 32-element box model of Sydney Harbour. The Delft3D Water Quality suite utilises the outputs from the calibrated hydrodynamic model to describe transport fluxes between grid cell or box elements and then a numerical scheme is adopted to solve the process equations for selected water quality processes and the net transport-dispersions. Figures 12a and 12b present time series of key water quality indicators from the 3D model calibration simulation for one of eleven sites. The time series have been presented as depth-averaged data and model results (Cardno and Baird*,* 2014b). The parameters presented in time series are:

- Salinity;
- Dissolved oxygen;
- Chlorophyll-*a;*
- Silica;
- Total nitrogen and phosphorus;
- Nitrate (NO_x) and ammonium (NH_4); and
- Dissolved inorganic phosphorus (DIP).

Comparison of the modelled results and depth-averaged measurements indicates that the SHERM is simulating water quality processes reasonably well (Figure 12).

A major innovation of this project is the inclusion of Bayesian network (BN) functionality in the DSS. The BN incorporates impacts on ecological condition and socioeconomic values such as recreation and amenity that are less certain and rely on a mix of quantitative and qualitative information. This information includes survey information, monitoring data, expert and key stakeholder opinion, and literature values. The first step in developing the BN is development of a conceptual framework linking changes in catchment and estuary water quality to ecological condition and socioeconomic values (Freewater and Kelly, 2012). Conceptual frameworks were developed for both freshwater and estuarine reaches of the Harbour (Figures 13a & 13b). Data sources and uncertainty are documented in the DSS interface.

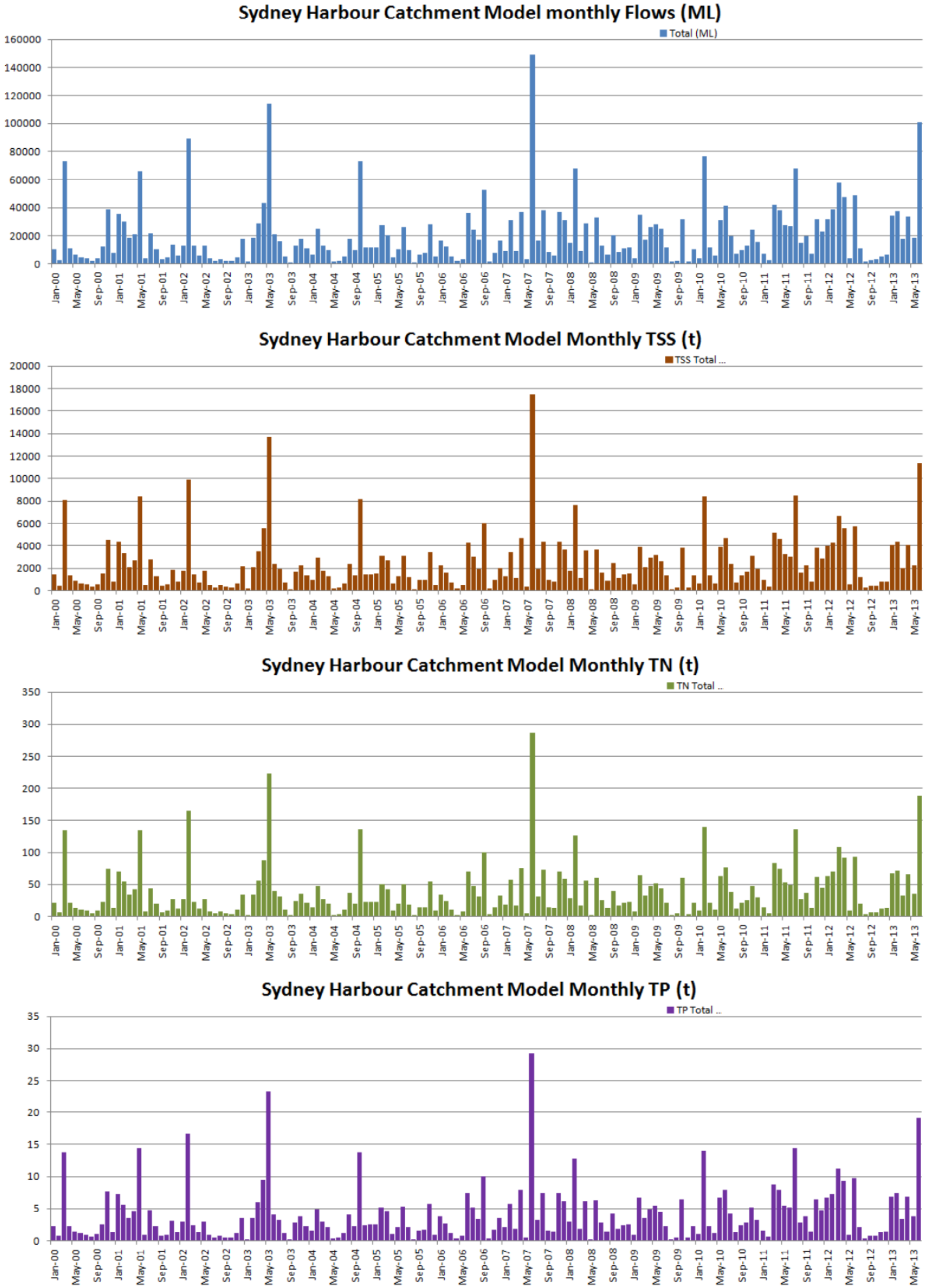


Figure 8 Sydney Harbour Monthly Flows and Loads

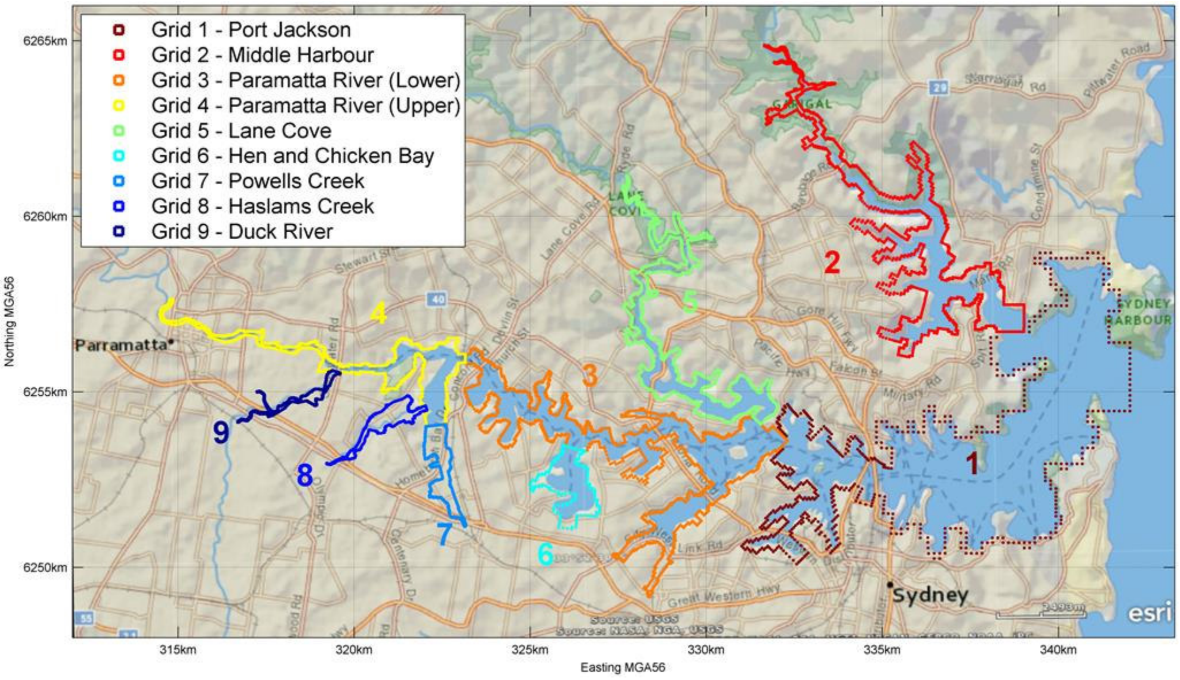
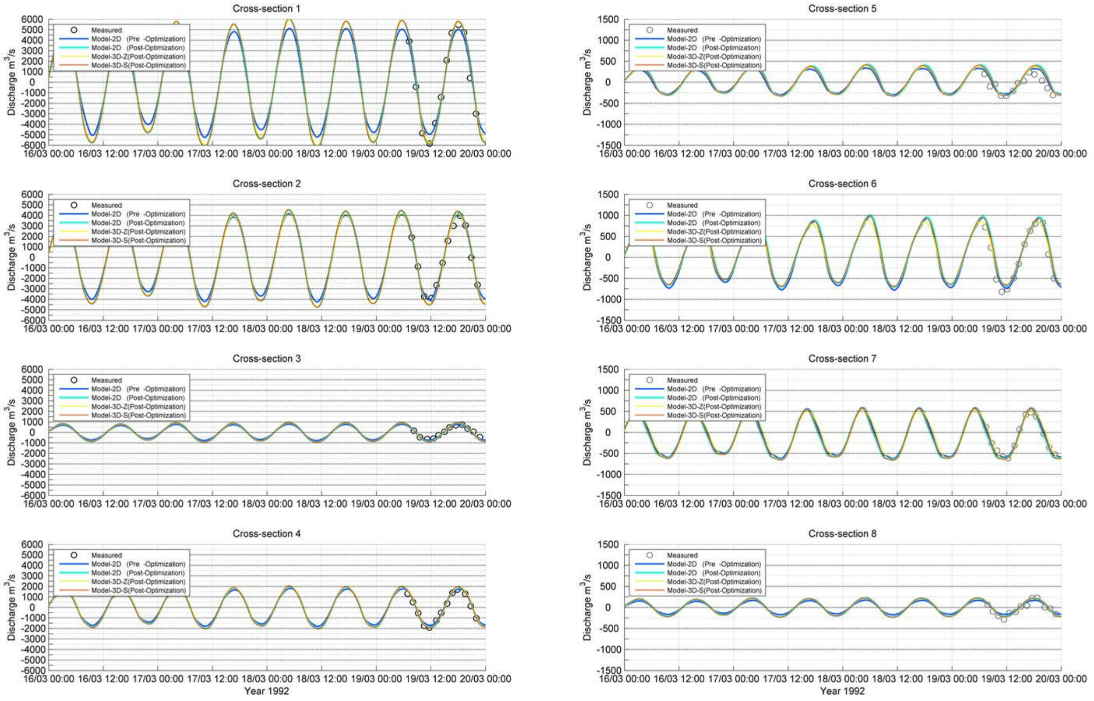


Figure 9 Hydrodynamic Model Extent and Domain Decomposition



a b

Figure 10 Hydrodynamic Model Discharge Calibration Time Series
(a) Cross Section 1-4 (b) Cross Section 5-8

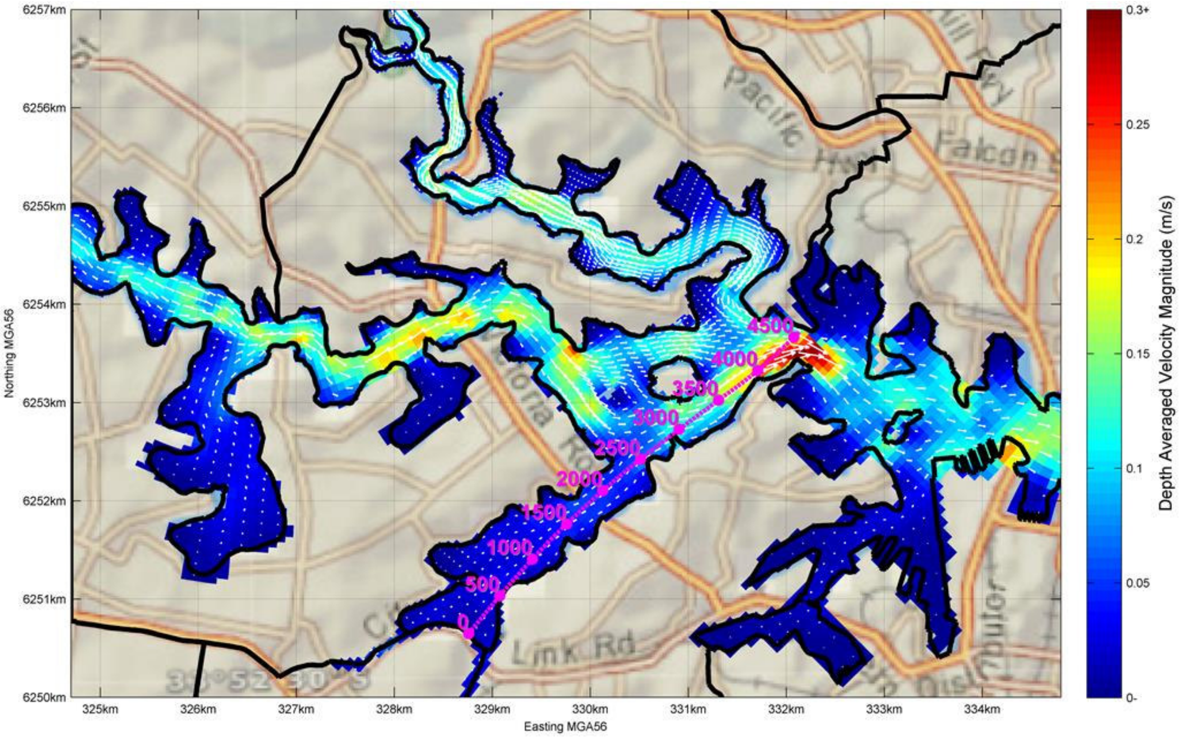


Figure 11 Hydrodynamic Model Depth Averaged Velocity Map and Transect Location Z-model (3D)

Results provided in the DSS interface include:

- Catchment loads by subcatchment and/or LGA:
  - Tables of data, maps, graphs
  - TN, TP, TSS, Flow, *E.coli, Enterococci*, faecal coliforms, BOD, TOC, Cost; totals, percent change from base case and per ha
  - Climate change options
- Sewer overflows in tables for:
  - TN, TP, TSS, Flow, *E.coli*, *Enterococci*, faecal coliforms, BOD, TOC
- Estuary impacts
  - Chl-*a*, TN, TP, TSS (or as allowed for by SHERM)
  - By estuary zone
    - As coloured map
    - As a summary table of fixed percentiles
    - As a probability of being within different community value and estuary condition thresholds (eg. using cut-off values developed by Peter Scanes and Geoff Coade)

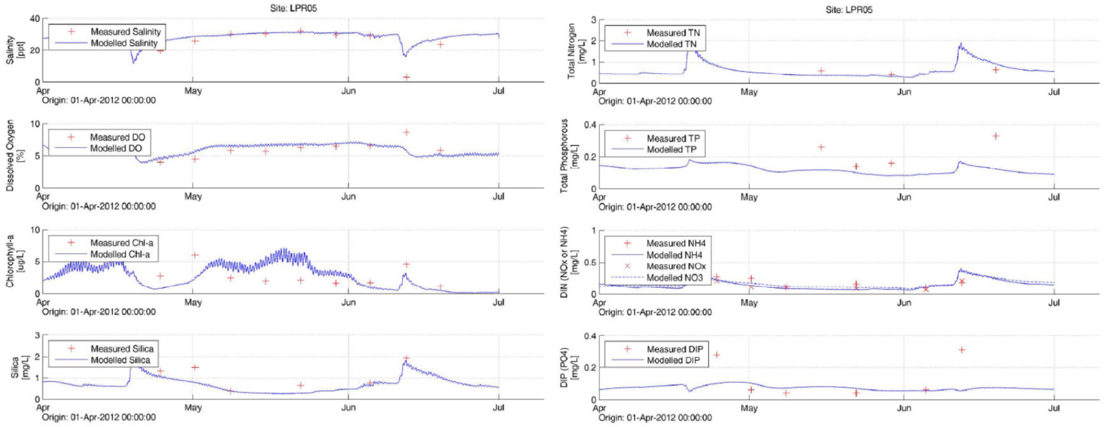


Figure 12 Water Quality Parameter Time Series 3D Box Model: Apr-Jun 2012

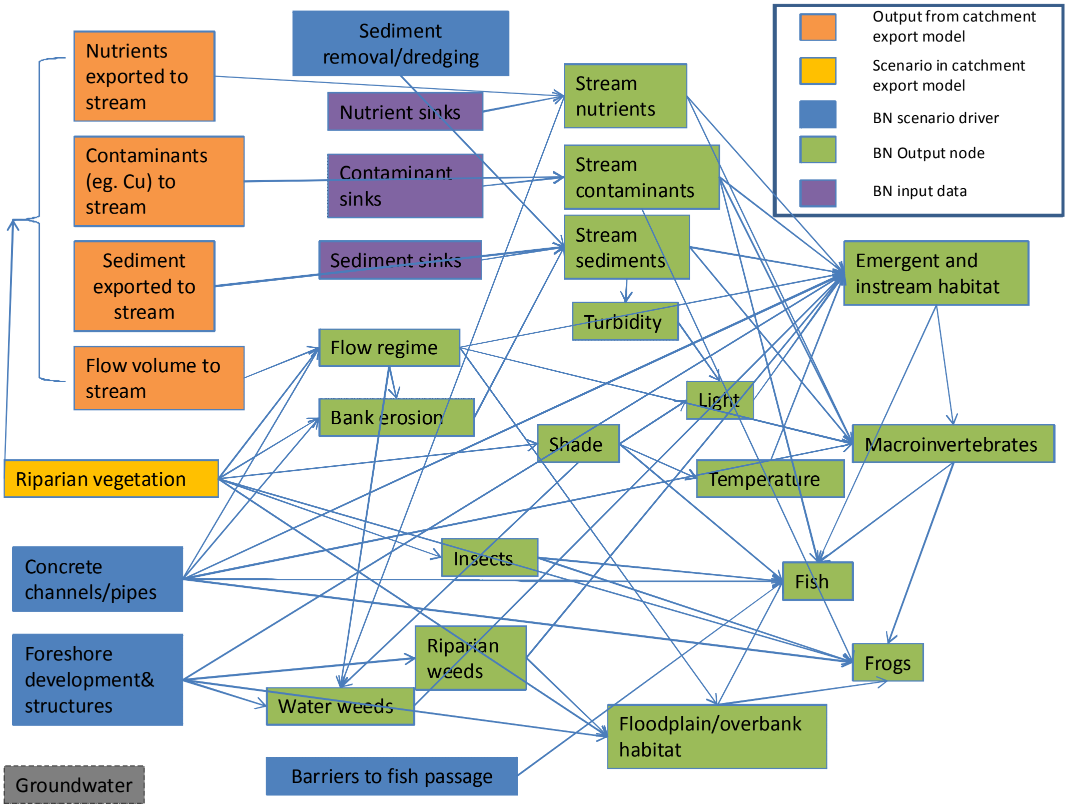


Figure 13a Freshwater conceptual framework for BN model

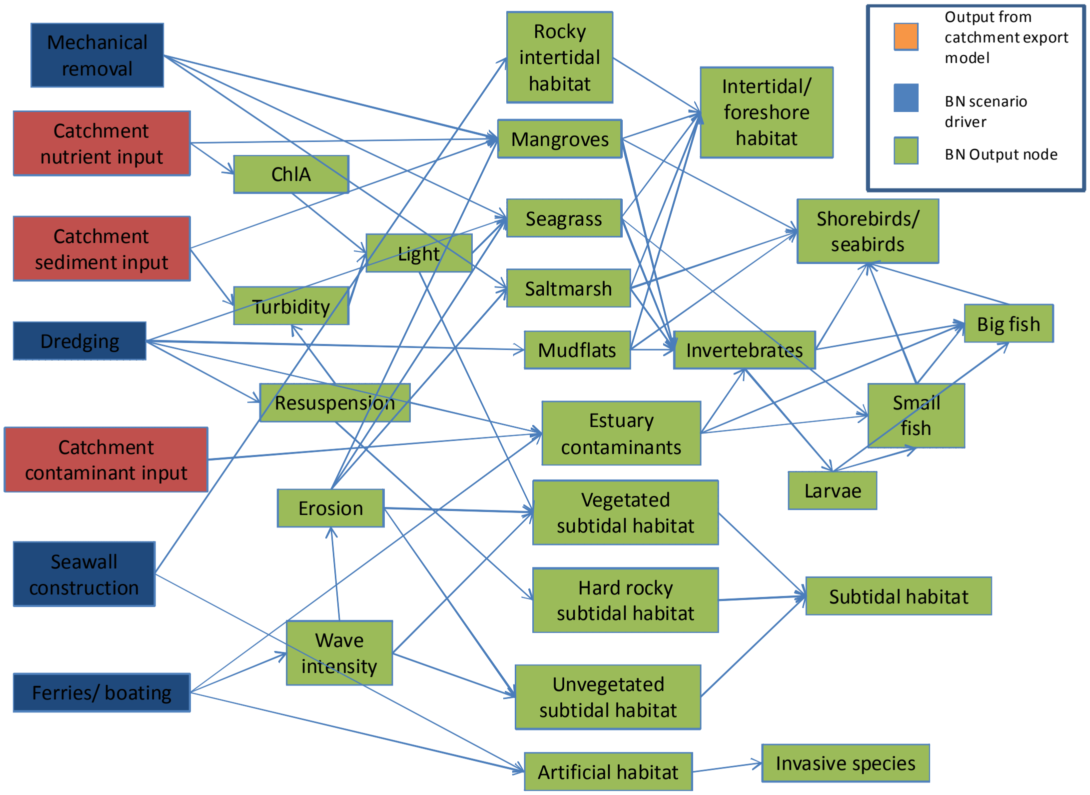


Figure 12b Estuarine conceptual framework for BN model

Discussion

The Sydney Harbour DSS is built on an integrated model (as shown in Figure 14) that incorporates:

- A metamodel of the *Source Catchments* model which uses a modelling scale consisting of intersections of subcatchments and LGAs to allow scenarios to be created, and results viewed, on either basis. This model outputs flow, TSS, TN, TP, *E.coli*, *Enterococci*, Faecal coliforms, total organic carbon and biological oxygen demand for each of the subcatchment LGA combinations.
- A metamodel of the *MUSIC* model to allow various WSUD treatment train options to be investigated.
- An empirical model of riparian vegetation and its impacts on pollutant export based on the scientific literature.
- An empirical model of sewer overflows based on data provided by Sydney Water.
- A metamodel of the *Delft3D* receiving water quality model, estimating the impacts of changes in pollutant loads to the estuary on estuary water quality using a tracer approach to produce map based spatial impacts.
- Two Bayesian Network models capturing the impact of changes in water quality on freshwater and estuarine system condition.

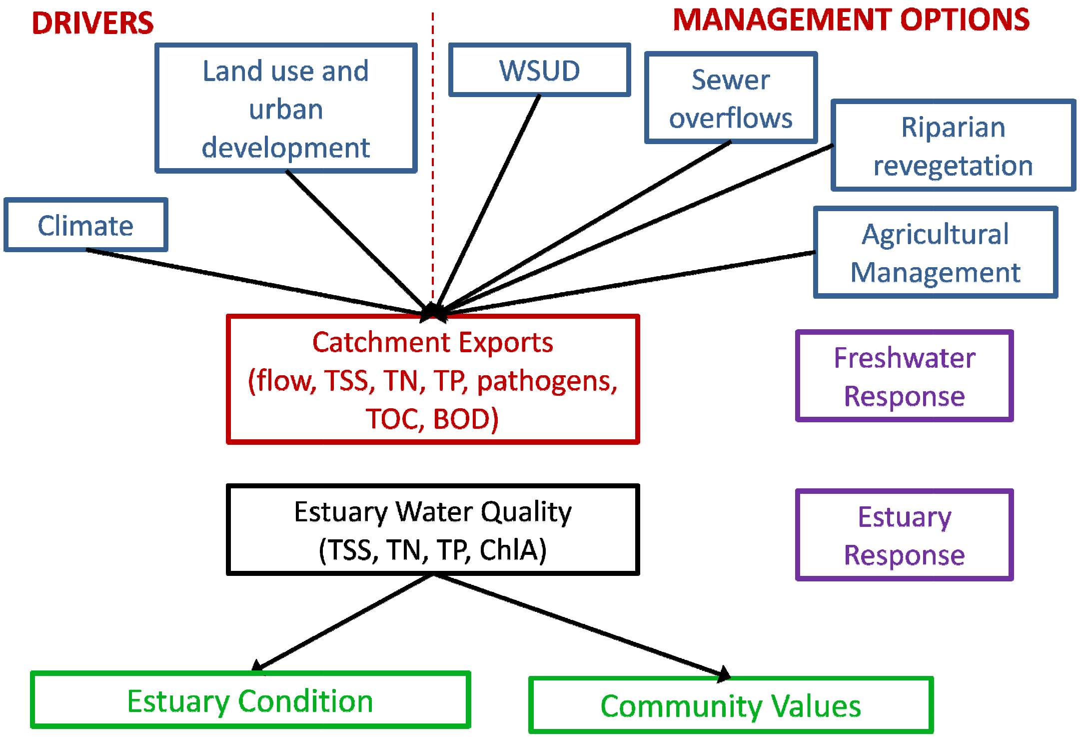


Figure 14 **Framework for the integrated model on which the Sydney Harbour DSS is built**

The DSS includes both the integrated model and quantitative data used to drive it (hard data sources), as well as a set of soft data. This includes project descriptions, reports detailing calibration and validation of the underlying model components, limitations and assumptions behind the DSS, maps and photos. These are provided to allow end users to navigate in a simple way through project history, assumptions and limitations and to gain understanding of the system required to interpret scenario results.

With all of the knowledge gained though the modelling studies, DSS development and stakeholder consultation, the SHCWQIP can be formulated to provide a long-term strategic direction for the improvement of water quality in the Sydney Harbour catchment. A major objective of the SHCWQIP will be to set targets for pollutant load reductions (in terms of total nitrogen (TN), total phosphors (TP) and total suspended solids (TSS)) required to improve and protect the ecological integrity of Sydney Harbour and its waterways. These targets will be set in consultation with all Council and State Government stakeholders. The project provides the following benefits to local councils and other stakeholders:

- Access to a CPEM for subcatchments to decide what works could be done to achieve subcatchment benefits. This PEM provides total annual loads and generation rates (kgs) per hectare.
- An Ecological Response Model illustrating the overall impact on the estuary and assisting councils and other stakeholders to see how they will be benefitting/how they can benefit the estuary.
- The science behind the CPEM and ERM would assist grant submissions for water quality improvement works or as part of s94 plans or similar contributory plans.
- Build council capacity to undertake modelling runs.

- A DSS that:
  - Can be used to consider impacts of changes in land use and management of stormwater pollutants for each council area.
  - Is useful to illustrate issues to councilors and senior managers to encourage budgetary allocation.
  - Along with the PEM be used to determine impacts of large developments and identify contributions towards local water quality improvements.
  - Can provide results which can be used to illustrate problems/issues to the community.
  - Provides estimates of the costs of management actions.
  - Which can be used to develop Stormwater Management Plans (SMP) or where an SMP has already been developed, can be used along with the CPEM to verify actions.
  - For which training, a copy of the DSS and user manual will be provided to all funding partners.

The development of the various models is also highly valuable to ecological research. The SHCWQIP Advisory Panel, which includes representatives from SIMS and OEH, has identified information gaps requiring further research. In particular, as there are significant volumes of contaminated sediments in Sydney Harbour, just as in many other urbanised and industrialised harbours, it is important to determine how these toxins influence nutrient cycling. GS LLS, OEH and SIMS are seeking to address this globally important research question and knowledge gap through an ARC Linkage Grant funded study of Sydney Harbour currently underway (GS LLS is the major industry partner). GS LLS, OEH and SIMS have also been working cooperatively on various other related projects, including the installation of real-time water quality monitoring systems around the Harbour. GS LLS is also working cooperatively with Sydney University and Harbour City Ferries to install these systems of Sydney Ferries. The first of these is installed on the Narrabeen. Data are processed and calibrated by an on-board computer and sent live to the internet as the ferry travels to and from Manly and Circular Quay. Data, which includes phytoplankton biomass, is available live and free of charge to the research community and the general public. The data is required to continually update and calibrate the models and to test the success of future management actions. The data will also be used by IMOS, which is an international organisation that uses "ships of opportunity" to monitor water quality globally. The phytoplankton data may also be used by the CSIRO to calibrate their remote sensing program.

It is anticipated that the final Sydney Harbour Catchment Water Quality Improvement Plan will be available in February 2015. The final stages are now under way and include:

- Collaborative development of Plan recommendations using the results of scenario analysis conducted using the Sydney Harbour *CAPER* DSS.
- Analysis of current catchment loads and receiving water condition.
- Development of load and condition targets.
- Development of monitoring and modelling strategies for Sydney Harbour as part of the Plan.
- Development of a MER plan to measure the success of the Sydney Harbour WQIP at achieving targets.
- Peer review of SHCWQIP
- Public exhibition for community consultation

References

Birch, G. F., Cruickshank, B and Davis, B (2010) Modelling nutrient loads to Sydney estuary (Australia) Environ Monit Assess (2010) 167:333–348

Bureau of Meteorology. (2013). http://www.bom.gov.au

Catchment Simulations Solutions (2011). Upper Parramatta River Catchment: Source Catchments Model. Prepared for the Sydney Metropolitan Catchment Management Authority. Revision 2.

Catchment Simulations Solutions (2012). Lower Parramatta River Catchment: Source Catchments Model. Prepared for the Sydney Metropolitan Catchment Management Authority. Revision 2.

Catchment Research (2014) Development of the Sydney Harbour Catchment Model. Prepared for Greater Sydney Local Land Services.

Hedge L.H., Johnston E.L., Ahyong S.T., Birch G.F., Booth D.J., Creese R.G., Doblin M.A., Figueira W.F., Gribben P.E., Hutchings P.A., Mayer Pinto M, Marzinelli E.M., Pritchard T.R., Roughan M., Steinberg P.D., 2014, Sydney Harbour: A systematic review of the science, Sydney Institute of Marine Science, Sydney, Australia.

DPI (2012) http://www.dpi.nsw.gov.au/fisheries/recreational/info/sydney-closure accessed 24 October 2012

Freewater, P. (2003). Hydro-Ecology - A Framework for Estuarine Research. NSW Coastal Conference proceedings, pp 72-80.

Freewater, P. (2004a). Hydro-Ecology: A Framework for Estuarine Research and Management. Doctoral Thesis (Science). University of Technology, Sydney

Freewater, P. (2004b). An holistic approach for linking coastal ecosystem processes to assess the impact of urban encroachment on estuarine ecology. Coastal Zone Asia Pacific Conference proceedings, pp 255-260.

Freewater, P. (2005). Hydro-Ecology - Mating Engineers and Ecologists. NSW Coastal Conference proceedings.

Freewater, P., Gladstone, W. & Suthers, I. (2006). Hydro-Ecology: An holistic, multidisciplinary approach to address "natural variability" in estuarine ecosystems for catchment management. Australian Marine Sciences Association 44th Annual Conference proceedings, p 47.

Freewater, P., Platell, M., Gladstone, W., van Ormondt, M. Taylor, D. R., & Garber, S. (2007). Dynamics of saltmarsh-mangrove complexes and their importance to estuarine food webs. NSW Coastal Conference proceedings.

Freewater, P. (2007). Management of an Estuary Processes Study. Masters Thesis (Environmental Engineering). University of Newcastle.

Freewater, P. & Kelly, R. 2012. Integrated hydrological and ecological modelling to develop the Sydney Harbour Catchment Water Quality Improvement Plan. NSW Coastal Conference proceedings.

Kelly, R; Dahlenburg, J; Catchment Research, J and Weber, T. (2102) Water quality planning with the Botany Bay CAPER DSS. In: WSUD 2012: Water sensitive urban design; Building the water sensitive community; 7th international conference on water sensitive urban design, 21 - 23 February 2012, Melbourne Cricket Ground. Barton, A.C.T.: Engineers Australia, 2012: 268-275

Letcher, R. A., Croke, B. F. W., Jakeman, A. J., and Merritt, W. S. (2006a). An integrated modelling toolbox for water resources assessment and management in highland catchments: model description. *Agricultural Systems*, 89:106-131.

Letcher, R. A., Croke, B. F. W., Merritt, W. S., and Jakeman, A. J. (2006b). An integrated modelling toolbox for water resources assessment and management in highland catchments: sensitivity analysis and testing. *Agricultural Systems*, 89:132-164.

Letcher, R. A., Croke, B. F. W., and Jakeman, A. J. (2007). Integrated Assessment modelling for water resource allocation and management - a generalised

Platell, E. & Freewater, P. (2009). Importance of saltmarsh to fish species of a large south-eastern Australian estuary during a spring tide cycle. Marine and Freshwater Research 60: pp 1-6

Roy, P., Williams, R., Jones, A., Yassini, I., Gibbs, P., Coates, B., West, R., Scanes, P., Hudson, J., Nichol, S. (2001) Structure And Function Of South-East Australian Estuaries Estuarine, Coastal And Shelf Science 53: 351-384

Taylor, D. R., Garber, S., Maratea, E. R., Freewater, & Brydon, N. (2007). Application of Bayesian Decision Support Tools in Coastal Management - Case Studies from the Gosford Area. NSW Coastal Conference proceedings.

Cardno and Baird (2014a) Sydney Harbour ERM – Setup and Calibration of 3D Model of Port Jackson and the Parramatta River. Prepared for Greater Sydney Local Land Services.

Cardno and Baird (2014b) Sydney Harbour Ecological Response Model. Prepared for Greater Sydney Local Land Services.

Williams, B. J., Freewater, P. & Thyer, M. (2005). Managing estuaries using Bayesian networks. American Society of Limnology and Oceanography conference proceedings, pp 16-45

List of Acronyms

BN - Bayesian network
BOD - Biochemical Oxygen Demand
BOM - Bureau of Meteorology
CAPER - Catchment Planning and Estuary Response
cfu – colony forming units
Chl-*a* – Chlorophyll *a*
CLAM – Coastal Lake Assessment and Management
CPEM - Catchment Pollutant Export Models
DIP - Dissolved Inorganic Phosphorus
DO – Dissolved Oxygen
DPI – Department of Primary Industries
DSS - Decision Support System
DWC - Dry Weather Concentration
ERM - Ecological Response Model
GIS - Geographical Information System
GS LLS – Greater Sydney Local Land Services
LGA - Local Government Area
LiDAR - Light Detection and Ranging
MUSIC – Model for Urban Stormwater Improvement
NH_4 - ammonium
NO_x - mono-nitrogen oxides
OEH - Office of Environment and Heritage
RWQM – Receiving Water Quality Model
s94 – Section 94
SHCWQIP - Sydney Harbour Catchment Water Quality Improvement Plan
SHERM - Sydney Harbour Ecological Response Model
SIMS - Sydney Institute of Marine Sciences
SMP – Stormwater Management Plan
TN - Total Nitrogen
TOC – Total Organic Carbon
TP - Total Phosphorus
TSS - Total Suspended Solids
WSUD – Water Sensitive Urban Design