INTEGRATED HYDROLOGICAL AND ECOLOGICAL MODELLING TO DEVELOP THE SYDNEY HARBOUR CATCHMENT WATER QUALITY IMPROVEMENT PLAN

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Abstract

The Sydney Metropolitan CMA is leading a project to develop the Sydney Harbour Catchment Water Quality Improvement Plan (SHCWQIP). The development of the Plan will involve several steps and will involve partnership support from the local councils and government agencies which manage land draining to Sydney Harbour. The major steps involve the integration of various catchment models, pollutant export models, 3D hydrodynamic model, water quality and ecological deterministic and probabilistic models, incorporated into a Decision Support System (DSS) that will inform the SHCWQIP.

The overarching objective is to put in place a process to improve the ecological health of Sydney Harbour as a lasting legacy for generations to come. The DSS will be capable of simulating water quality and ecological responses to a wide variety of land-use management scenarios, including but not limited to planning instruments, stormwater management and WSUD. The DSS will be used in consultation with land managers to set water quality targets within the SHCWQIP.

Deterministic Ecological Response Models (ERMs) will simulate water quality and phytoplankton dynamics in the Harbour and will be integrated with probabilistic ERMs. The probabilistic ERMs, imbedded in the DSS, will use Bayesian belief systems, which don’t require precise system quantification and have much faster processing speeds. These will be developed for both freshwater and estuarine systems. Probabilistic ERMs can consider higher order ecological phenomena such as phytoplankton-zooplankton dynamics, seagrass dynamics, ecotoxicology, biodiversity, etc.

Whilst some data already exists, much more data is required to populate, calibrate and test the models. Some of these data are being sourced through partnerships with the Sydney Institute for Marine Sciences (SIMS) and Sydney Water.

Introduction

Sydney Harbour and its waterways still carry the toxic legacy of years of industrial abuse. Although the dumping of toxic waste has been banned since the 1970s, the bulk of these toxins will persist in the sediments for many years to come.

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 toxins still enter the Harbour each year through the stormwater system. Stormwater is a toxic cocktail that contains everything from heavy metals (such as copper 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.

After a large storm millions of litres of stormwater flow into the harbour and form a discrete layer above the saltwater; a process referred to as stratification. This stormwater plume may be up to two metres deep. Eventually, as the rain stops, the plume weakens, mixes with the saline harbour water, and the suspended sediments begin to settle on the bottom of the harbour. These sediments are generally associated with heavy metals and various other pollutants that bind or absorb to the surface of the sediment.

Whilst various organisations have installed stormwater quality improvement devises around the catchment, there is currently no coordinated, catchment-wide plan with sufficient technical detail to guide the improvement of water quality from catchments draining to Sydney Harbour. Urbanisation of these catchments has impacted upon all aspects of the hydrological cycle with significant detrimental impacts on water quality.

The Sydney Harbour Catchment Water Quality Improvement Plan (SHCWQIP) encompasses the whole catchment as well as the Harbour and will provide a coordinated management framework for the 25 local councils, 11 state government agencies and 2 Commonwealth government agencies who have a stake in improving the future health of Sydney Harbour and its catchments.

Sydney Harbour Catchment Water Quality Improvement Plan

The Sydney Metropolitan Catchment Management Authority (SMCMA) is coordinating the development of the Sydney Harbour Catchment Water Quality Improvement Plan (SHCWQIP). The objectives of the SHCWQIP are to develop a Water Quality Improvement Plan that will achieve an improvement in the water quality of Sydney Harbour, its tributaries and its catchments; and to engage key land managers and other stakeholders in the project design and process, and encourage ownership of the outcomes.

The development of a catchment-wide SHCWQIP with the key stakeholders allows a coordinated approach as well as a transparent and open discussion of the water quality improvements needed to protect the environmental values of Sydney Harbour and tributaries. The development of the SHCWQIP will require a number of studies over a three to four year period.

Modelling to support development of the Plan

The project uses an integrated modelling approach 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. The SMCMA also developed a communication strategy for the project and a business plan to help potential partners understand the project.

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.

The *XP Rafts* software was used to build hydrologic models, which describe patterns of rainfall and runoff. Hydrologic models are simplified, conceptual representations of a part of the hydrologic cycle. They are primarily used for hydrological prediction and for understanding hydrological processes. The *Rafts* models represent the physical processes observed in the real world, with representations of surface runoff, subsurface flow, evapotranspiration, and channel flow.

The *Rafts* models were then integrated into pollutant export models, using the *Source* software to simulate pollutant export from each subcatchment (figure 1). *Source* simulates current and potential future catchment characteristics to evaluate impacts of land use and/or the implementation of best management practices. 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.

These models were then integrated into a hydrodynamic model of the estuary. The *Delft 3D* hydrodynamic modelling software was used because of its flexible curvi-linear grid system and because an existing model of Sydney Harbour had already been developed and was available to use with this software. The SMCMA has had the hydrodynamic grid refined and extended up into the freshwater reaches of the Upper Parramatta River.

Components of the SHCWQIP are being 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 is being done as a pilot study to test the suitability of the *Delft 3D* modelling system and the Bayesian Network approach. The pilot study will focus on the Parramatta River. If the models can be demonstrated to be reliable, then they will be used for the rest of the Harbour and its waterways.

An advantage of the *Delft 3D* system is that it comes with a specific module for modelling water quality that can be applied to phytoplankton dynamics in the estuary. This is the water quality eutrophication model referred to in figure 1. The model is calibrated using water quality data collected during intensive sampling programs in the Harbour; from winter and summer phytoplankton species identification and cell count studies; and solar radiation data collected by the SMCMA. A metamodel of this mechanistic Ecological Response Model (ERM) is then integrated with probabilistic ERMs and implemented within the Decision Support System (DSS).

Ecological Response Models (ERMs)

ERMs are used to represent the behaviours of complex systems by applying our understanding of physical, chemical and biological processes, to predict ecological changes in waterway characteristics under changing environmental conditions and changing catchment land uses. They summarise known information and processes and help with predictions or explanations of system response. Models can range in complexity from a conceptual level to numerical models that are solved through computer applications. The mechanistic *Delft 3D* water quality eutrophication model is at the very complex end of this range. The probabilistic ERM proposed for the SHCWQIP sits about halfway along this range. It uses a Bayesian network approach to model ecological phenomena.

Bayesian networks (BNs) (also referred to as Bayesian decision networks or Bayesian belief networks) represent one branch of Bayesian modelling. They are graphical models used to establish the causal relationships between key factors and final outcomes (cause-effect relationships). The quantitative relationships between variables in the models are expressed probabilistically. BNs work by examining the conditional dependence between variables. Model parameters can be updated using Bayes's theorem. Being probabilistic, the models readily incorporate small data sets or highly variable or vague information, with uncertainties being reflected in model outputs. BNs are particularly useful in modelling ecological processes as often only scant data is available, and relationships are highly variable.

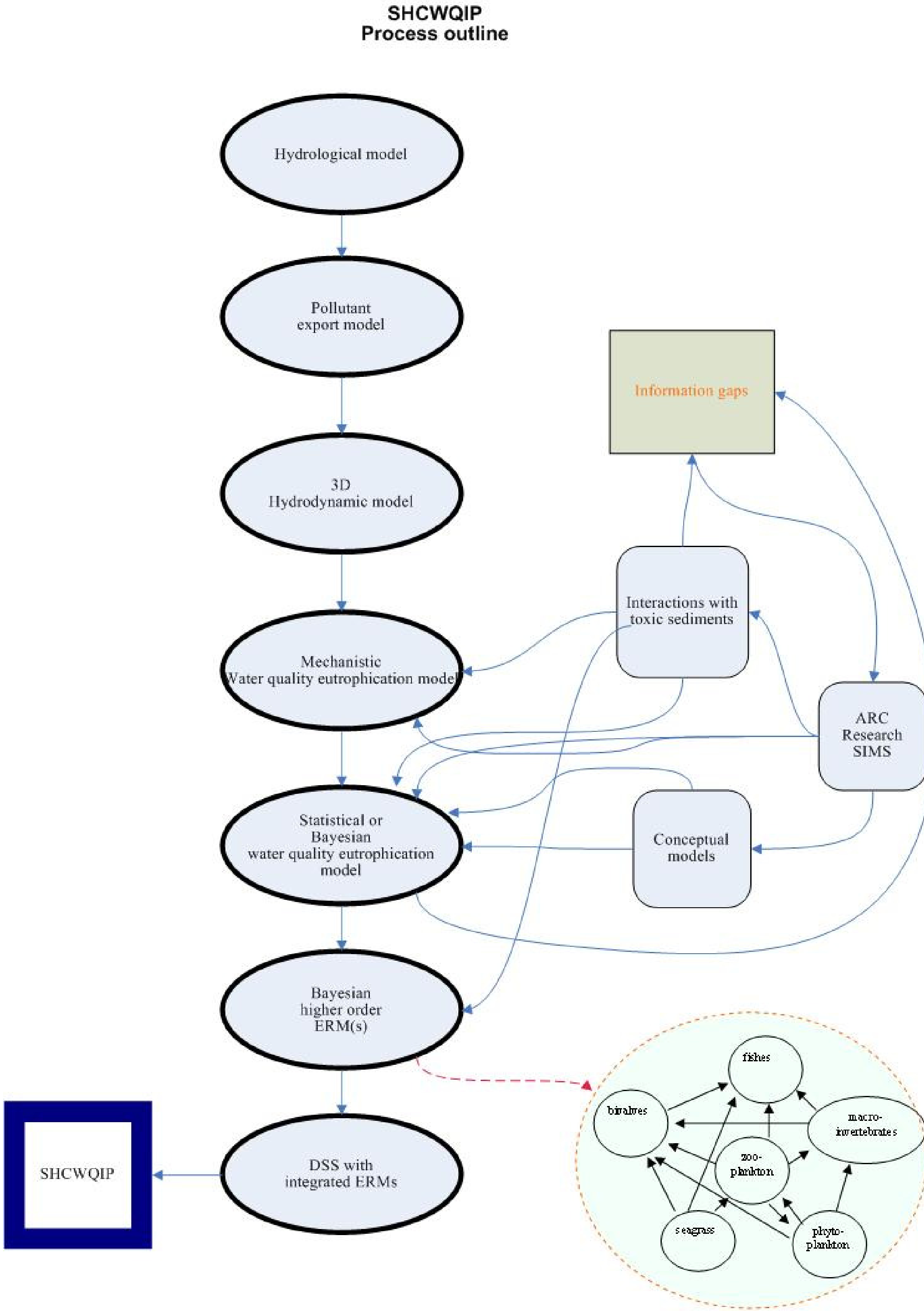

Figure 1 SHCWQIP integrated modelling process

A Bayesian decision network is made up of a collection of nodes that represent important environmental variables. Arrows represent the causal relationships between the nodes (variables). Bayesian networks use the network structure to calculate the probability certain events will occur, and how these probabilities will change given subsequent observations or a set of external (management) interventions. A prior probability represents the likelihood that an input parameter will be in a particular state. The *conditional probability* calculates the likelihood of the state of a variable given the states of input variables affecting it. And the *posterior probability* is the likelihood that a variable will be in a particular state, given the input variables, the conditional probabilities, and the rules governing how the probabilities combine.

The Decision Support System (DSS)

The Decision Support System builds on two previously developed DSS, the CLAM tool (a Bayesian Network based system) and CAPER, to create a 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. This new DSS would allow 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 (where detailed modelling is available); 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.

The concept is to use CAPER as the basic structure and interface of the DSS and to integrate with this the BN functionality of CLAM for social and ecological impacts. The CAPER interface would also require modification to allow investigation of BN impacts (using concepts previously applied in CLAM).

The CAPER DSS was designed to:

- Integrate information from catchment water quality models, receiving water quality models, MUSIC modelling, literature and expert opinion;
- Provide information on the costs and benefits associated with different management options;
- Allow the trade-offs associated with different *land use and land management* options in the catchment to be assessed;
- Be accessible to non-technical users (ie people without any modelling skills or background) and stakeholders; and
- Provide a memory of project methods and outputs and make models more accessible to stakeholders, managers and policy makers.

The CAPER DSS delivers on these needs by using a generic modelling platform and an easy-to-use interface shell that can be rapidly tailored to meet the needs of new applications. The system has been designed to include 'soft' data such as text descriptions, photos and maps. It contains a significant amount of contextual information and provides internal documentation of assumptions and models used in each application to make these available to people without significant modelling skills. It has previously been applied to the Great Lakes in NSW, Botany Bay and Darwin Harbour.

The CAPER DSS integrates:

- A Pollutant Export Model (eg. Source Catchments model)
- An estuary Receiving Water Quality Model (eg Delft 3D WAQ)
- Ecological impacts (eg. seagrass in Great lakes, seagrass, macroinvertebrates in Darwin Harbour)
- Water Sensitive Urban Design effects and costs (MUSIC) (eg. Great lakes, Botany Bay, Darwin Harbour)
- Sewage Treatment Plant and point source management (eg. STPs in Darwin Harbour)
- Other management actions (eg. riparian corridors, agricultural management)

The CAPER DSS framework is flexible enough to be reused to include almost any management option affecting catchment water quality or point source inputs to the estuary.

The latest version of the DSS has been developed to allow users to design scenarios and view results on the basis of subcatchment boundaries or local government areas (LGAs). Results provided in the current interface are:

- Catchment outputs by subcatchment and/or LGA:
    - Tables of data, maps, graphs (Figure 2)
    - TN, TP, TSS, Flow, Cost; totals and per ha
    - Climate change options
- Estuary impacts
    - Chl-A, TN, TP, TSS (or as allowed for by RWQM)
    - 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)

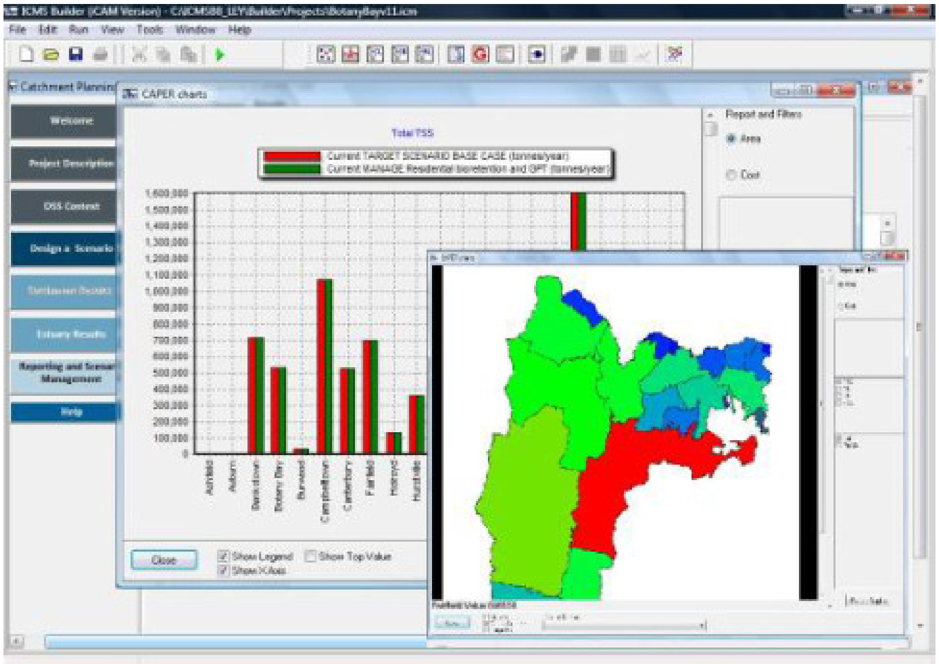

Figure 2 Example output displays for the Catchment Results in the Botany Bay CAPER DSS

Data can also be exported from the DSS to Excel for use outside the system.

Scenarios able to be considered by the CAPER DSS include:

- Land use change such as redevelopment and intensification, greenfield development
- Water Sensitive Urban Design (WSUD) such as bioretention, buffers, GPT, vegetated swales, wetlands
- STP modification such as improved treatment to remove nutrients
- Land management change such as riparian corridors, changes in fertiliser use in agricultural areas
- Climate change – typically 2030, 2070 scenarios.

The Coastal Lakes Assessment and Management (CLAM) tool is a separate DSS to the CAPER system. It uses a Bayesian Network (BN) approach as the basis of an integrated model which can include social, economic and biophysical processes and impacts. In the past it has been used extensively as an ecological response modelling approach in numerous lakes and estuaries in NSW. BNs are able to utilize any mix of qualitative and quantitative information in their design and construction. The CLAM tool is very flexible. It is essentially a broad based, holistic approach that can be applied to any system or range of management decisions. By using a BN approach, CLAM automatically produces outputs on the likelihood of impacts. The major limitation of the CLAM tool has been its inability to allow flexible representation of spatially specific management options and impacts.

Figure 3 shows a typical conceptual framework underlying a CLAM application. The conceptual frameworks used for CLAM tend to be very specific to the case study, and are developed using feedback from key stakeholders and other experts.

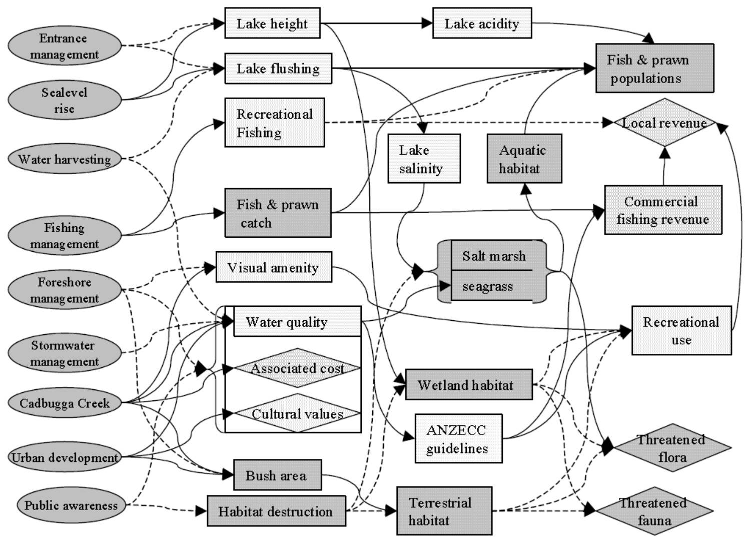

Figure 3 **A typical CLAM conceptual framework showing the integrated model structure (Coila Lake CLAM) including Ecological Response components**

An important phase in the development of the DSS is the scoping phase. This phase is used to actively engage potential end-users and key stakeholders. It is 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 includes:

- 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.

Key stakeholder feedback was sought through a scoping workshop and questionnaire. An additional workshop will be held later in the project to refine the conceptual framework for the BN and seek information to populate the BN model. Literature and data review also form an important part of this phase.

A draft framework for the integrated model is shown in Figure 4. This framework will be refined during the project to incorporate scenario options, processes and values identified during the project.

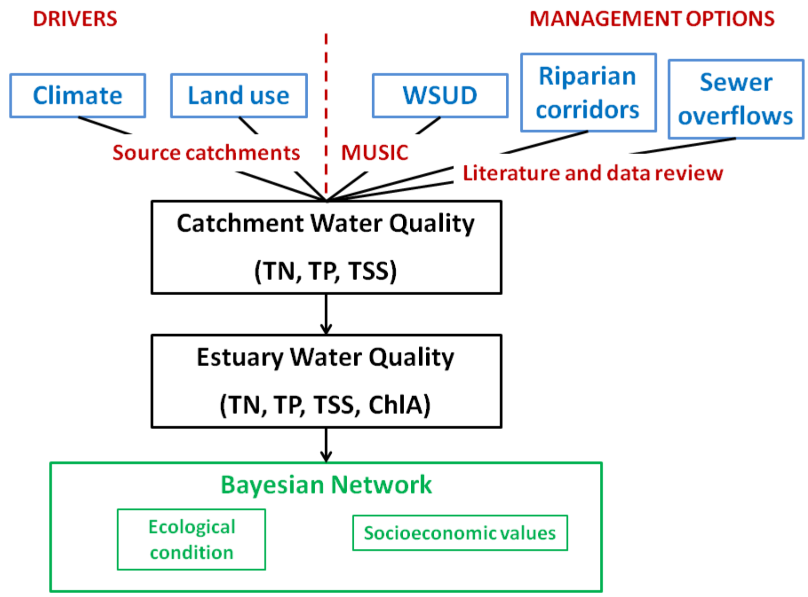

Figure 4 Draft conceptual framework for the integrated model including the ecological response model

In order to adapt the CAPER DSS to include elements of the CLAM approach and to address stakeholder preferences expressed during the scoping phase some recoding of the integrated model and interface code are required. This phase will involve development of design specifications for the interface and for the ERM detailing specific changes required to meet these needs.

To model the effects of land use and climate on catchment pollutant load exports, a metamodel of the Source Catchments model will be produced. The technique for developing such a metamodel was first developed for the Botany Bay CAPER DSS and has since been applied to the Darwin Harbour CAPER DSS. This metamodel typically uses a smaller set of subcatchments than the original Source Catchments model to provide a compromise between ease of use by DSS end users and sufficient detail to provide outputs for key locations and subcatchments. Stakeholder requirements uncovered during the scoping phase are used to inform the development of this subcatchment map. Feedback from the client and potentially key stakeholders will be used to refine the subcatchment boundaries before these are used to develop the catchment water quality metamodel. Past experience in Botany Bay has shown that this model can reproduce annual pollutant loads to within 1% of the Source Catchments model, making this a highly robust approach to capturing pollutant inputs to the estuary system.

This phase will also include refinement of MUSIC modelling used to capture the impacts of WSUD options on catchment loads. This work will build on previous analyses undertaken for the Botany Bay CAPER DSS. MUSIC is the industry standard approach to considering the impact of WSUD options. 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 will be limited to those produced by the Source Catchments model and the sewer overflow data. A typical Source Catchments model simulates catchment loads of TN, TP and TSS. It will also be possible to model pathogens, such as *Enterococci*, using the Source Catchments model. Impacts of scenarios relating to land use change such as development, and management options such as WSUD, on pathogens will be included in the DSS.

To model the impacts of changes in catchment loads on estuary water quality and ecological condition a metamodel of the Receiving Water Quality Model (RWQM) will be developed. It is proposed that this metamodel will use a similar tracer approach as previously developed for the Great Lakes application of the CAPER DSS. This approach is currently being implemented for development of the Darwin Harbour CAPER DSS. This will require multiple runs of the RWQM to be undertaken for major diffuse and point source inputs to the estuary. Several additional runs are also required to allow for testing of the metamodel so that uncertainties in results induced by the metamodelling approach can be assessed. At a minimum, a base case land use and climate scenario option, a decrease in pollutants and increase in pollutant load scenario will be required to adequately test the model. This will allow the distributional effects over time on estuary water quality and ecological condition to be assessed, and will provide likelihoods of outcomes required for the BN component of the model.

Scenario levers to be included in the DSS are expected to 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. Literature and data reviews will be conducted to enable these scenario options to be incorporated in the DSS. Some recoding of the DSS integrated model is expected to be required to incorporate scenario options.

A major innovation of this project is the inclusion of BN functionality currently available in the CLAM tool. It is expected that this BN functionality in addition to the RWQM metamodel will be used to create the ecological response model. The BN will incorporate 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 may include 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. Preliminary conceptual frameworks have been developed for both freshwater and estuarine reaches of Parramatta River (Figures 6-7) based on outcomes of the scoping phase. Recoding of the interface and integrated model will be required to incorporate the BN functionality into the DSS. The final conceptual framework will then be input to the DSS and data imported to populate the BN. Data sources and uncertainty will be documented in the DSS interface.

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 generally 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.

Parramatta River Pilot Project and Project Progress

The Pilot DSS will require testing to ensure the integrated model and interface are working as required. The Advisory Panel and project partners need to be confident in the quality and reliability of the input and output data, as well as the assumptions that the DSS makes. If it passes these tests the DSS will be expanded to incorporate the entire Sydney Harbour catchment and waterways.

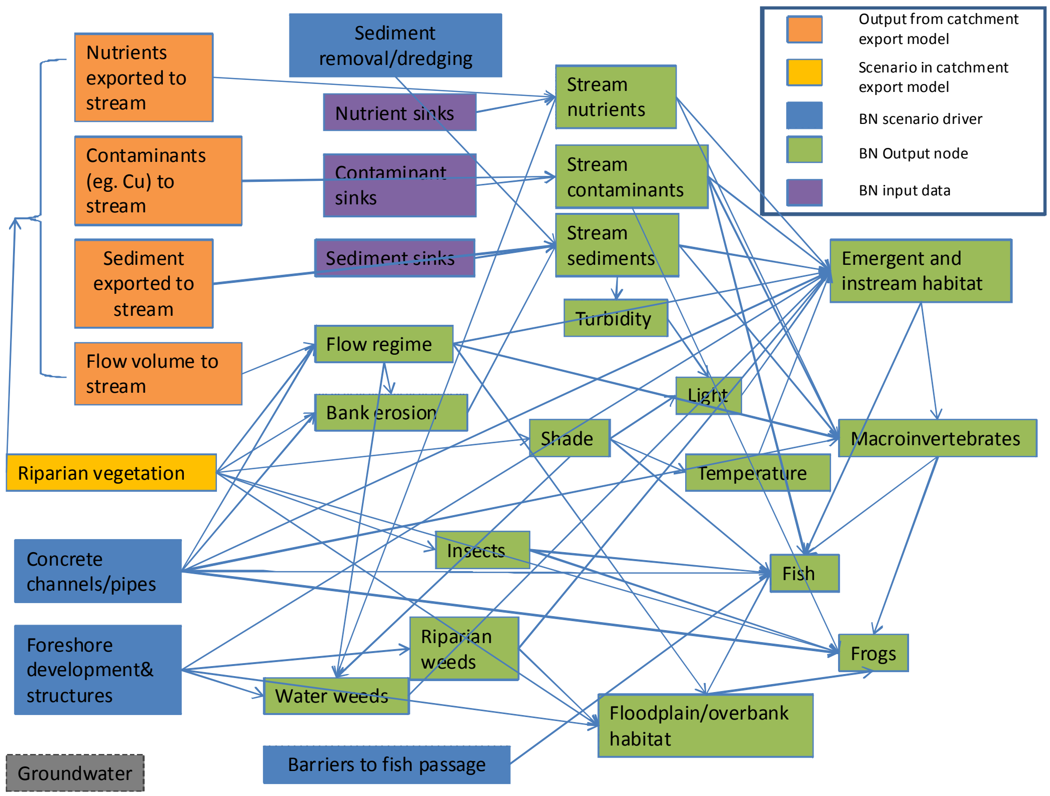

Figure 6 Freshwater conceptual framework for BN model of Parramatta River

To be of value, potential end users for the DSS need to be identified and engaged throughout the project. Training materials including a User Guide, model documentation, tutorials and presentations will be developed to allow end users to develop the skills required to develop scenarios, run the DSS and analyse results. Experience shows that most end users are able to develop the necessary skills through attendance at a one day workshop. It is proposed that one or more workshops be held to provide training for the DSS. Feedback on the intention to use the DSS will also be sought during these workshops to allow evaluation of project outcomes. Training materials will be developed in such a way as to be used in a workshop setting or to be downloaded and used in self-guided training. Ongoing phone and email support will be provided to end users as required.

There are 25 local councils within the Sydney Harbour catchment and each of these are potential end users of the DSS (Figure 8). A major challenge faced by many of these Councils, and other managers of aquatic resources, is the need to make decisions for situations where there is considerable uncertainty in understanding how the system works and how particular management actions will influence the system. It is rare to have well understood cause-effect relationships between the threats and the ecosystem. For these reasons a DSS with imbedded Bayesian capacity is an ideal decision support tool to aid in the management of estuarine ecosystems such as Sydney Harbour.

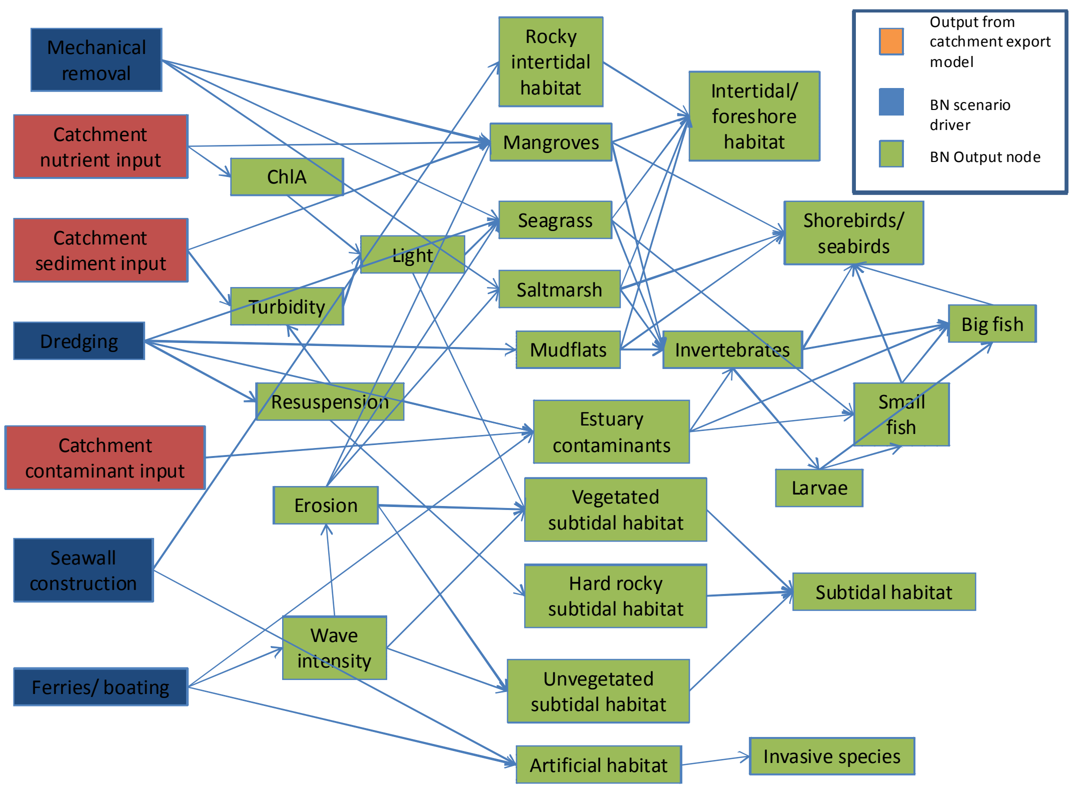

Figure 7 Estuarine conceptual framework for BN model of Parramatta River

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 will offer the following benefits to local councils and other stakeholders:

- Access to a Pollutant Export Model (PEM) 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 PEM 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 councillors 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 PEM to verify actions.
    - For which training, a copy of the DSS and user manual will be provided to all funding partners.

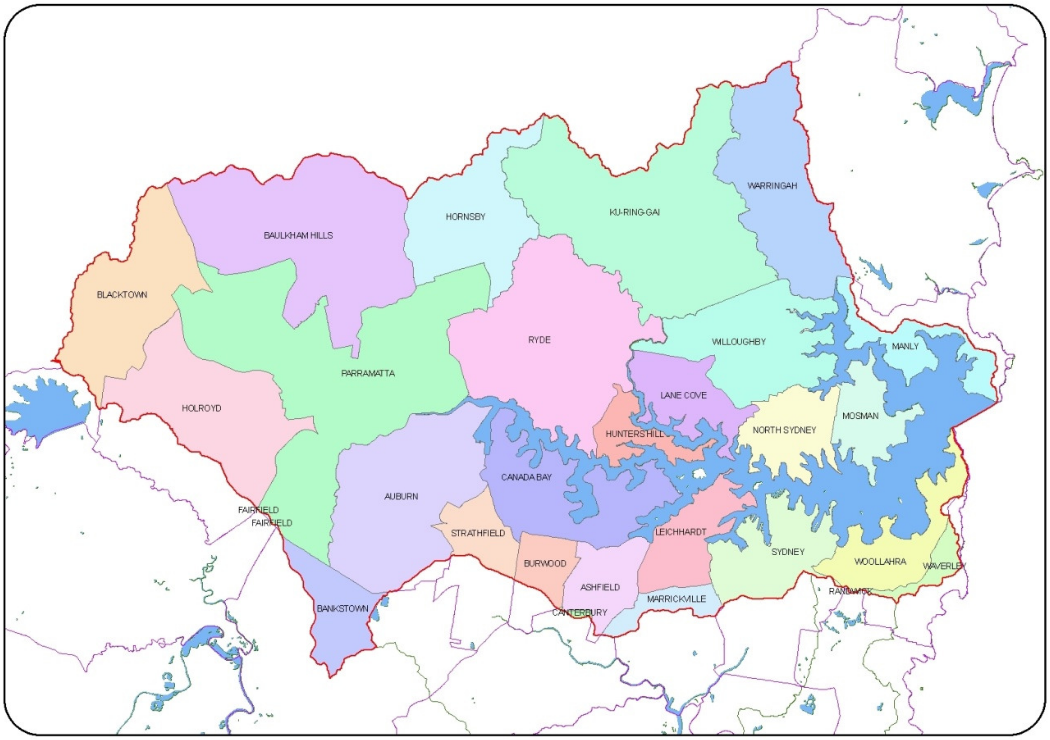

Figure 7 The 25 local councils within the Sydney Harbour catchment

The SHCWQIP will provide major stakeholder input into the strategic management of Sydney Harbour and catchments. It will provide a valuable reference in planning policies, budget proposals and external funding applications. It will allow councils to see how they fit into the bigger picture and how they can participate in regional planning.

For these funding partners, the SHCWQIP project represents excellent value for money, as they provide only a small contribution per year, compared with the total cost of the project. The process of developing the integrated models, DSS and SHCWQIP, allows practitioners to share experiences, ideas and knowledge. The process also provides an opportunity for council officers and other partners to identify other benefits that can be extracted from the project and used for other council or agency requirements (eg. contributions towards climate change modelling, cost benefit analyses of sewage infrastructure investment, etc.).

The development of the various models is also highly valuable to ecological research. The Sydney Institute of Marine Sciences (SIMS) recognise this value and are assisting the project with the provision of additional research and data. Expert scientific advice from the SHCWQIP Advisory Panel has indicated that there are information gaps requiring research within the planned ERMs. 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. This is a globally important research question and knowledge gap that SIMS is seeking to address in a major study of Sydney Harbour.

The SHCWQIP project has been underway for almost two years and much of the work has been completed already. All hydrological catchment models have been built and all pollutant export models have either been built or are nearing completion. The hydrodynamic model has been refined for Parramatta River and some of the water quality receiving model runs have been done. The conceptual frameworks for BN models of Parramatta River have been developed and construction of the pilot DSS is well underway. It is anticipated that this pilot will be ready to begin the trial testing of various management scenarios in December 2012.

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