Water Quality Improvement Plan to Estuary Processes Study – Recycling the Science for Sydney Harbour

[1]P Freewater, [2]P Scanes, [3]E Johnston, [4]A Ferguson, [5]M Sun & [6]K Dafforn
[1]Greater Sydney Local Land Services
[2,4]Office of Environment and Heritage
[3,5,6]Sydney Institute of Marine Sciences

Greater Sydney Local Land Services (GS LSS) completed the Sydney Harbour Catchment Water Quality Improvement Plan (SHCWQIP) in June 2015. High resolution hydrological and ecological models of Sydney Harbour and its catchments were created to support the Plan's development. The Plan was also supported with ecological research undertaken in partnership with the NSW Office of Environment and Heritage (OEH) and the Sydney Institute of Marine Sciences (SIMS). GS LLS is now recycling these models and research outcomes to develop the Sydney Harbour Estuary Processes Study (SHEPS), which will provide the scientific basis to develop the first ever whole of catchment, whole of government, Sydney Harbour Estuary Management Plan.

SHEPS development includes further 3D modelling of hydrological processes to investigate larval recruitment and transport into the Harbour; the resuspension, transport and accumulation of sediment contaminants; examine targeted measures to improve stormwater and sewer overflow impacts; the impact of vessel traffic on hydrodynamics and sediment transport process; and tsunami hazard. This work will be synthesised with other work undertaken in partnership with OEH and SIMS so as to develop the SHEPS in line with the government's new *Marine Estate Management Act 2014*, which indicates that management of the marine estate should be based on an assessment of threat and risk to community benefits.

The principle objectives of the SHEPS are to:

1. create a conceptual process model of the Harbour that makes explicit the links between ecological processes and the social, economic and environmental benefits arising from the Harbour;

2. provide a synthesis of existing information through additional modelling to clarify the impacts of pollutants on fundamental ecological processes;

3. develop a spatially explicit ecosystem response model framework for Sydney Harbour that allows ongoing scenario testing, and can be readily updated to incorporate new understanding of pressure-stressor-impact relationships derived from other studies; and

4. prepare the SHEPS in such a way as to provide the scientific basis to develop the management options for consideration in the subsequent Sydney Harbour Estuary Management Study and Management Plan.

Introduction

The Sydney Harbour Catchment Water Quality Improvement Plan (WQIP) is the first environmental management plan to encompass the whole of Sydney Harbour's catchment as well as the waterways and provides 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.

Greater Sydney Local Land Services (GS LLS), together with its local and state government partners, used an integrated hydrological and ecological modelling approach to develop the WQIP. The objectives of the project were 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 included 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 and associated pollutants. A high resolution 3-dimensional hydrodynamic model of the Harbour and its tributaries was developed and integrated with the CPEM 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 these models into a Decision Support System (DSS) was done to investigate the impact of different management strategies on water quality and Harbour ecology. Figure 1 provides a schematic of the DSS framework. The Sydney Harbour DSS incorporates the following components:

- 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 water sensitive urban design (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.

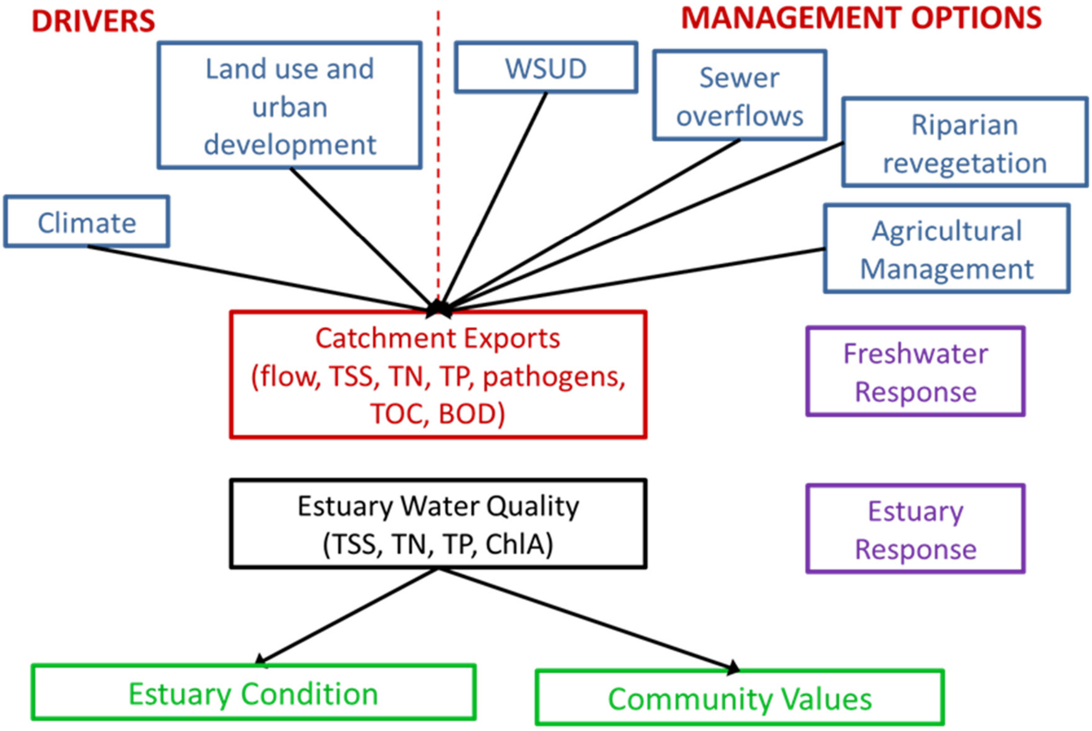

Figure 1 Framework for the integrated model on which the Sydney Harbour DSS is built

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. The DSS integrates management actions, land use and climate, catchment water quality, receiving water quality and management costs to:

- Allow the examination and prioritization of catchment management scenarios that could be implemented to protect water quality in Sydney Harbour and its tributaries;
- Provide a tool that can be used by local councils and catchment managers to facilitate the testing of local scale catchment management scenarios and prioritise local water quality improvement interventions; and
- Evaluate costs.

The main objective of the resulting Water Quality Improvement Plan is to identify threats to water quality in the Harbour and its tributaries and to set targets for pollutant load reductions (in terms of total nitrogen, total phosphorus, suspended sediment and pathogens) required to protect the condition and values of the Sydney Harbour, its tributaries, estuaries and waterways. In addition, it is expected that the Plan will be a tool for raising awareness and promoting behaviour changes amongst individuals and organisations. It is anticipated that the Plan will find an audience amongst Local, State and Federal Government agencies as well as with interested individuals, community groups and organisations.

The WQIP is designed to give focus and direction to water quality policy development and on-ground implementation throughout the Sydney Harbour catchment. It will help guide more localised or sub-catchment planning and policy development by local councils and regional groups of councils. It should also help guide regional planning policies such as the Sydney Metro Strategy and its sub-regional strategies and the Marine Estate Management Strategy being developed and implemented by the NSW Government.

Everyone's actions have the potential to contribute to water quality issues. Choices that households, businesses, developers, Local and State governments make will all have an effect on the levels of nutrients, sediments and pathogens exported from the catchment into the tributaries, estuaries and Harbour. To be effective, the Plan needs to be owned and implemented by all levels of government as well as by individuals and organisations. The Plan provides direction on how each of these groups could act to implement its recommendations.

The Plan has been written to reduce future pollutant loads to the Harbour, its tributaries and estuaries. It also provides some future direction into how to manage specific pollution problems arising from past activities, for example issues with toxic sediments derived from past industrial activities in the catchment. It has been developed to be consistent with the risk framework being designed and implemented for management of the Marine Estate by the Marine Estate Management Authority (MEMA).

The Plan proposes load and condition targets for Sydney Harbour and its catchment. Management actions to achieve these targets and address other threats are proposed and rated for their relative importance based on the risk level of the threat they address as well as their relative contribution to resolving the threat. Among the recommendations is the need for a whole of government approach to set up and adequately fund a program or initiative to coordinate management actions in the Sydney Harbour catchment and assist MEMA in the management of threats to the Harbour. This high priority action should facilitate collaboration between Local Government, State Government, Sydney Water and key business interests. This priority includes the development of whole of catchment, whole of government Management Plan for Sydney Harbour.

It was recognised that much of the work required to inform a Sydney Harbour Estuary (Coastal Zone) Management Plan was completed for the development of the WQIP. Thus the research, data compilation and modelling is being recycled and built upon to develop the first ever whole of catchment Sydney Harbour Estuary Processes Study (SHEPS). Importantly, the SHEPS is again being developed in collaboration with local and state government stakeholders and it will align with the new *Marine Estate Management Act 2014*, which indicates that management of the marine estate should be based on an assessment of threat and risk to community benefits.

Community benefits derive from environmental, social and economic factors. In order to properly assess threats, it is necessary to properly understand the interrelationship between the outcomes of the impacts of environmental stressors with social and economic values and benefits.

Recent work that provides a sound basis for this synthesis step includes:

1. A report that identifies and synthesises existing biophysical understanding of the harbour has recently been published and a further two reports have identified the data available regarding social and economic assessments of the harbour (SIMS)

2. A study of social values for the NSW Marine Estate has identified a suite of values and benefits arising from the Sydney region (MEMA)

3. The Sydney Harbour Ecological Response Model (SHERM) provides pollutant inputs, hydrodynamic modelling and a preliminary assessment of algal growth potential (GS LLS)

4. Research into influences of catchment inputs on estuary ecosystem response and construction of models to highlight most cost-effective areas for management intervention (NSW Northern Rivers, Logan River Qld, Lake Macquarie, Tuggerah Lakes) (OEH)

5. Ongoing SIMS research into social values of users of Sydney Harbour, spatially explicit quantification of human use of the harbour and patterns of marine debris & microplastics.

6. Ongoing research within the Sydney harbour ARC Linkage “Testing the Waters” is revealing the influences that contaminants have on basic ecological processes (SIMS and OEH), including:

    a. Effects of interactions between organic pollutants and heavy metals on sediment metabolism, nutrient flux, microbial assemblages, macroinvertebrates

    b. Effects of flushing rate and proximity to stormwater drains on sediment nutrient flux and metabolism, microbial assemblages

The aim of this project is three-fold:

1. creation of a conceptual process model of the harbour that makes explicit the links between ecological processes and the social, economic and environmental benefits arising from the harbour.

2. synthesis of existing information through additional modelling to clarify the impacts of pollutants (in both sediment and water column) on fundamental ecological processes

3. the development of a spatially explicit ecosystem response model framework for Sydney Harbour that:

    a) allows ongoing scenario testing, and
    b) can be readily updated to incorporate new understanding of pressure-stressor-impact relationships derived from any future studies.

This study would then identify the threats to such benefits (using causal mechanisms) - through their potential impact on ecological processes. An ecological process model for the harbour will be created that explicitly identifies the social, economic and ecological benefits of the harbour and stressors that threaten these benefits.

Methods

Development of preliminary conceptual model

A conceptual model of the system based on expert opinion and management concerns will be developed. The conceptual model will represent the main drivers of ecosystem function within clearly delineated functional zones, and include all major biotopes and biota. Broadly, this model should attempt to describe the linkages between pressures, stressors, and biological responses within the system.

All the existing material on physical and ecological processes within the Harbour and the external and internal drivers of those processes will be collated. This model will expand on models that currently underpin the WQIP such as those created for the CAPER DSS that predominantly consider land-based threats to water quality. The model will include (but not be limited to) consideration of hydrological processes, sedimentation and resuspension, habitat availability, food webs, primary productivity and nutrient cycling. Natural and anthropogenic drivers of these processes will be identified including: fresh water flow, climate variables, pH, sediment movement, erosion and resuspension, biota removal (e.g. recreational fishing) contamination, litter, organic enrichment, non-indigenous species and bacteria/pathogens. Further hydrological modelling (based on existing Delft3D model system) will be done to support conceptual model development:

- Wave and Water Level Modelling – These investigations are to address sea and swell, depending upon location, noting that swell is of importance as far as Nielsen Park and Manly Cove. Water levels are to be based on Fort Denison records and regional variations arising from the prevailing winds and hydrodynamic changes. A bath-tub approach will not be applied. Appropriate sea level rises are to be included and recommendations made in terms of wave run-up levels for a range of edge treatments. Although block-by-block results are not required, sufficient spatial detail is required for other qualified consultants to prepare that information. A range of average recurrence intervals (ARI) is to be investigated – 50, 100 and 200-years.

- Tsunami Hazard – Existing model systems (and results based on Delf3D) are to be used to describe the tsunami run-up hazard and navigation hazards in selected port areas. The results will be presented for a range of ARI in terms of water levels and current speeds on a harbour-wide scale.

- Vessel Traffic Impacts on Sediment Transport – The high usage of Sydney harbour by commercial and recreational boats on sediment transport processes has been examined in previous studies. A desk-top study considering a range of vessels will be undertaking to develop a conceptual model to describe potential effects from boating traffic on estuarine processes within the harbour. A study framework will be prepared to examine the effect of vessel traffic in a quantitative manner.

- Contaminated Sediment Transport and Accumulation – Historical discharge of contaminants have caused contaminated fine sediment accumulations, notably in the Homebush Bay area. Professor Gavin Birch (UNSW) will work with the Delft3D modelers to undertake investigative sediment transport modelling in order describe future movements of contaminated sediments and time scales of concentration changes. This investigation will be based on the Delft3D system that can handle cohesive, non-cohesive and mixed sediment conditions. Modelling will address sediment re-suspension and transport in order to describe changes in existing areas of high contaminant concentration and also the effects of vessels (see above) and catchment inflows using selected examples. The aim is to describe the long term likely fate of contaminated sediments.

- Larvae Transport – It will be necessary to expand the existing hydrodynamic model further offshore and to the north and south because most of the current interest in larvae is near the harbour entrance. This model expansion will include tidal and large scale coastal currents. An algorithm will be developed to represent the ultimate locations of larval releases and present the results in terms of density of larval arrival. A particle tracking system within Delft3D will be used and the method will be sufficiently flexible to allow for bottom and near surface larval transport description. Professor David Booth (UTS, Sydney) will work with the Delft3D modelers for this task.

- Stormwater & Sewer Overflow Improvements - Biological contaminants continue to be observed in particular locations in high concentrations, notably after wet weather events. The Delft3D model system will be used to examine potential contaminant reduction with further selected improvements in sewer overflows.

Development of Ecosystem Response Model (ERM)

OEH has an existing framework for modelling impacts of contaminants on riverine ecosystems, its acronym is DEFIRE. This framework, in part, explicitly deals with ecological processes that are mediated by sediment processes. It allows us to examine the control of a wide range of physical and biological factors on ecological processes, and in particular will utilise the data from the experimental studies of effects of contaminants.

The DEFIRE approach is a hybrid empirical / mechanistic ecosystem response model framework that allows more realistic representation of the linkages between sediment and water column processes than is possible with off-the-shelf model packages. Steps in model development include:

1. Discretisation of the system into a box framework consistent with the conceptual model developed in PART 1. Box boundaries take into consideration ecological and biogeochemical functional zones, hydrodynamic characteristics, and management considerations (e.g. the resolution of boxes should be sufficient to isolate the impacts of point sources and sub-catchments).

2. Create bathymetric grid at desired resolution. This layer allows for the spatially explicit representation of bed stress, resuspension/deposition, and benthic light climate in the model (this Step will utilise data from existing models)

3. Catchment inputs (freshwater discharge and nutrient loadings), exchange flows between box boundaries, and bed stress values imported from catchment, hydrodynamic, and wind/wave models. This Step will utilise data from existing models.

4. Customisation of model algorithms to incorporate:

   a) key features of the system identified in the conceptual model, and
   b) the results of experimental studies.

Model scenarios are best run for extended time periods (decades) to allow simulation of important climatic cycles (e.g. ENSO). Management scenarios can be run to quantify the spatial and temporal impacts of specific proposals or load increases. Model outputs can be viewed in multiple ways (spatial and temporal) to facilitate better understanding of the interactions between climatic variability, natural and anthropogenic pressures, and ecosystem function.

Tipping points in the relationship between anthropogenic pressures and (indicators of) ecosystem health can be identified by the model, thereby providing site specific management advice on appropriate threshold values for load regulation and ecosystem health assessment (e.g. monitoring guidelines).

The scope will be limited to developing the ERM framework as described above, with a particular focus on including a comprehensive representation of stormwater impacts on ecosystem function. This will be based on incorporating the results of the stormwater impact assessment study ("Testing the Waters"). This is considered to be the first stage in the development of a comprehensive ERM for Sydney Harbour, thereby paving the way for further model development based on future studies into pressure-stressor-impact relationships in the harbour.

Refinement of conceptual model and incorporation of socio-economic elements

The ERM will be used to explore spatial and temporal dynamics of stressor-impact relationships in order to refine the scope of the conceptual model. Consideration of temporal variability will be made such that variation in the relevant processes and their drivers can be described. This information will be used to create a conceptual model of how the environmental social and economic benefits of the harbour are underpinned by estuary processes. Environmental, economic and social benefits will be explicitly mapped to the processes that support them and the threats to those processes will be identified. Initial risk rankings will be made for each threat, in relation to each benefit, within each sub-catchment.

Results

Conceptual model of present-day Sydney Harbour

The ecological status of Sydney Harbour has been degraded over time by a variety of anthropogenic activities (Table 1). Recent reports on the status of Sydney Harbour by Hedge *et al*. (2014a) and Freewater and Kelly (2015) summarise the complexity of threats the estuary is facing. These threats interact directly or indirectly with ecosystem processes, *i.e*. the rates of biogeochemical transformation in the system that maintain the conditions necessary for higher functions, to determine overall ecosystem function. We present a conceptual model of Sydney Harbour that outlines how anthropogenic threats are most likely to be impacting ecosystem processes under the contexts of differing geomorphology, hydrology and biology along the estuary. In a series of layers, two frameworks distinguish important differences in ecosystem processes between well-flushed channels (Figure 2) and high-retention embayments (Figure 3) of the estuary. A greater understanding of threats to ecosystem processes will aid in the development of effective management strategies for both existing and future threats in the estuary (Birch *et al.* 2010).

Table 1 The evolution of Sydney Harbour

Holocene	**Pre-European settlement**
	Traditional land care practises of the Aboriginal people
	Heavily forested catchment
	Oligotrophic, low-turbidity waters
	Records suggest the estuary supported a relatively small fishery, but significant shellfish biomass
	Expansive seagrass and wetland habitat
1788 - 1800	**Early European occupation**
	Clearing of land for agriculture
	Expansion of settlement to fertile soils in the upper estuary (Ashfield Shale)
	Significant loss of catchment topsoil
	Increased sedimentation (8 to 27mm y-1) and turbidity beginning to impact intertidal and seagrass communities, increasing areas of aphotic sediments
1800-1854	**Early industrial revolution**
	Heavy industries established in embayments along the waterfront on the south side of the lower estuary (tanneries, metal foundries)
	Industry expanded and moved to upper estuary tributaries in 1848 (metal working and engineering, building materials, automobiles, electrical products, oil refineries, abattoirs)
	Open sewage system discharged mixtures of inorganic (industrial process and urban effluents) and nutrient-bearing organic substrates (animal and human waste) directly into the estuary
	Considerable pollution issues in lower estuary by 1948, which expanded into the upper estuary with mobilisation of industry
1860	**Industrial revolution builds momentum with technological advancement**
	Industry and urbanisation spread rapidly and replaced agriculture as the prominent land use
	Pollution issues continued to spread in the upper estuary
1898	**Three coastal outfalls constructed**
	Raw sewage and industrial effluent discharged into surf zone
	Pollution issues significantly impacted offshore ecosystems
Post WWII	**Heavy industries replaced by light industry and increasing urbanisation**
	Significant reclamation activity
	Decreased metal, organochlorine compounds (DDT, dioxins, agent orange, pesticides, furans), polycyclic aromatic hydrocarbons and polychlorinated biphenyl influx into the estuary
	Loss of intertidal and shallow subtidal habitat with reclamation and foreshore hardening
	Contaminant-laden leachate released from reclaimed lands after rainfall
	Changes to upper estuary hydrology, reducing tidal flushing
1972	**Clean Waterways Act**
	Improved control of environmental discharges
	Reduced waste generation as industry forced to discharge waste into the sewerage system
	Triggered the start of sediment remediative actions in areas of significant contamination
1990	**Deep ocean sewage outfalls**

	Sewage dispersed 4km offshore in 80 m of water
	Helped to manage water and beach quality, which have seen significant improvement
	However, a legacy of industrial and urban pollution (toxicants and organic material) remains in the sediments, which may still be released
	Dredging activity ceased in Parramatta River in 1992 to limit release of legacy contaminants
	Commercial fishing and prawn trawling banned in 2006 due to bioaccumulation of legacy contaminants in harvested seafood
	Community structural shifts are reported between sites of differing contamination: decreasing community diversity in rocky reef and soft sediment habitats, e.g. kelp forests shifting to be dominated by weedy algal species, seagrass communities decreasing in size and increasingly dominated by *Caulerpa* species, which may cause sediment anoxia
Modern state	**Stormwater and sewage inputs remain a threat to ecosystem function**
	Stormwater quality improvement devices fitted at many stormwater outlets in the harbour
	Catchment users have been encouraged to install stormwater retention tanks to reduce environmental flows
	Permeable road pavements are increasingly used with subterranean drainage and a bioretention system
	Even with no rain, certain canals discharge millions of litres of untreated water a day
	Biological oxygen demand and nutrients remain elevated in the upper estuary
	Further management is necessary as the frequency and intensity of storms is predicted to increase, and chemical signatures of 'emerging contaminants' in untreated sewage are still detected in the water during dry periods

Background setting of Sydney Harbour

The iconic drowned river valley system of Sydney Harbour carves 30 km west to east, through Ashfield Shale in the elevated upper estuary transitioning to underlying Hawkesbury Sandstone in the lower estuary towards the heads. In an international setting, Sydney Harbour represents a condensed estuarine system with a strong marine influence due to the relatively dry Australian climate and small catchment size (480 km^2) (McLoughlin 2000, Birch 2007). Freshwater input is limited under dry weather conditions (<0.1 m^3/s) (Birch and Rochford 2010), and tidal turbulence ensures in a well-mixed estuary with a limited salinity range of 35 in the lower estuary to 27 in the upper estuary (Lee *et al*. 2011). The main freshwater influence occurs in the estuary following low to moderate rainfall events (5–50 mm day^{-1}), when freshwater circulates within the estuary transporting allochthonous materials within the system (Birch et al. 2010). Salinity drops significantly (20 in the upper estuary). Following high rainfall events (>50 mm day^{-1} for at least two days), stratification occurs along the estuary and a near freshwater plume carrying terrestrial inputs forms in the top 1-2 m. The majority of these inputs are transported offshore before mixing occurs (Birch and Taylor 1999, Birch 2007). This strong stratification is characteristic of Sydney Harbour and rarely occurs in larger, less marine-influenced estuaries (Birch 2007). Fortunately, stratification acts to limit the influence of terrestrial inputs following high rainfall events, as the quality and quantity of these inputs are the most significant factors influencing ecosystem processes in the present setting of Sydney Harbour.

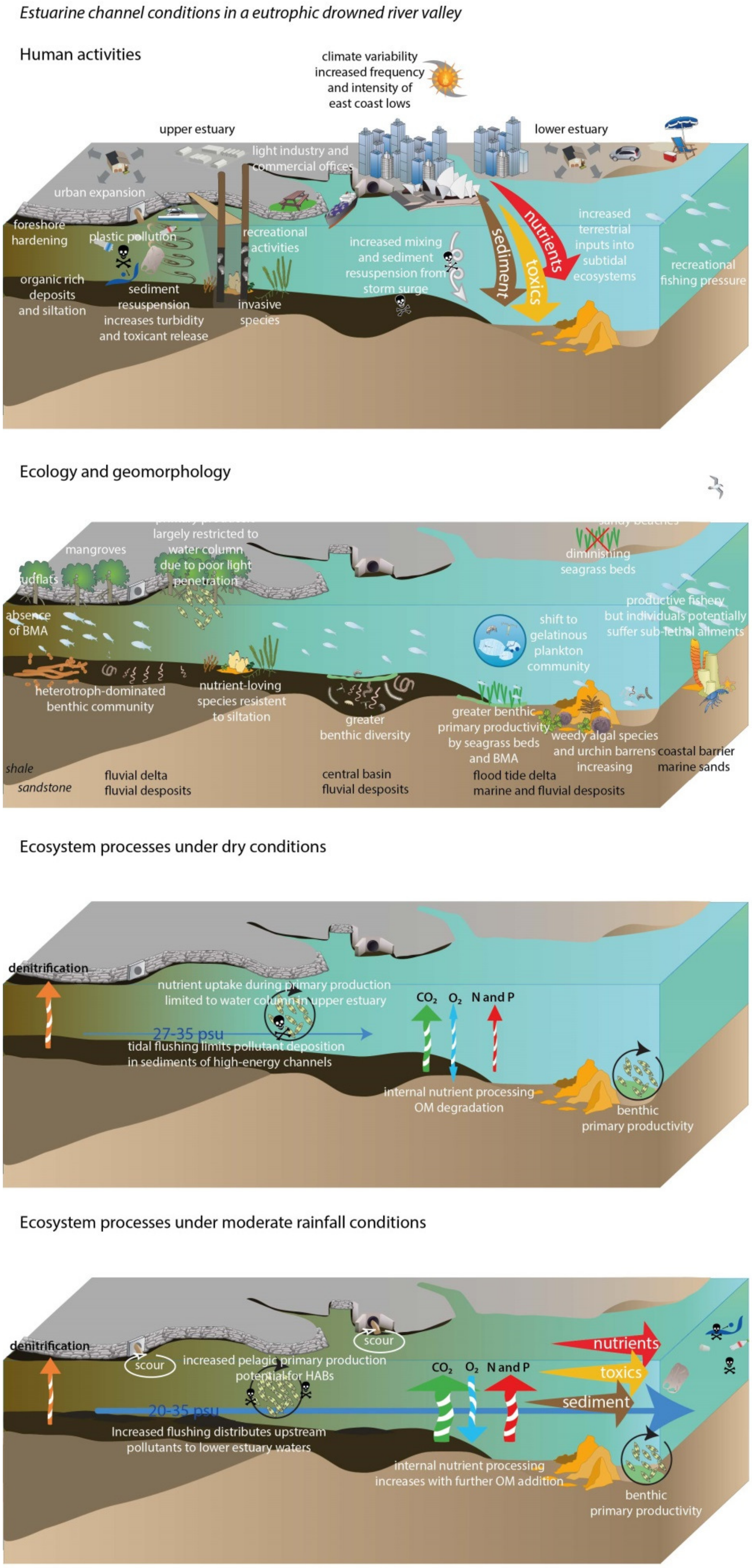

Figure 2 Estuarine channel conditions in eutrophic Sydney Harbour

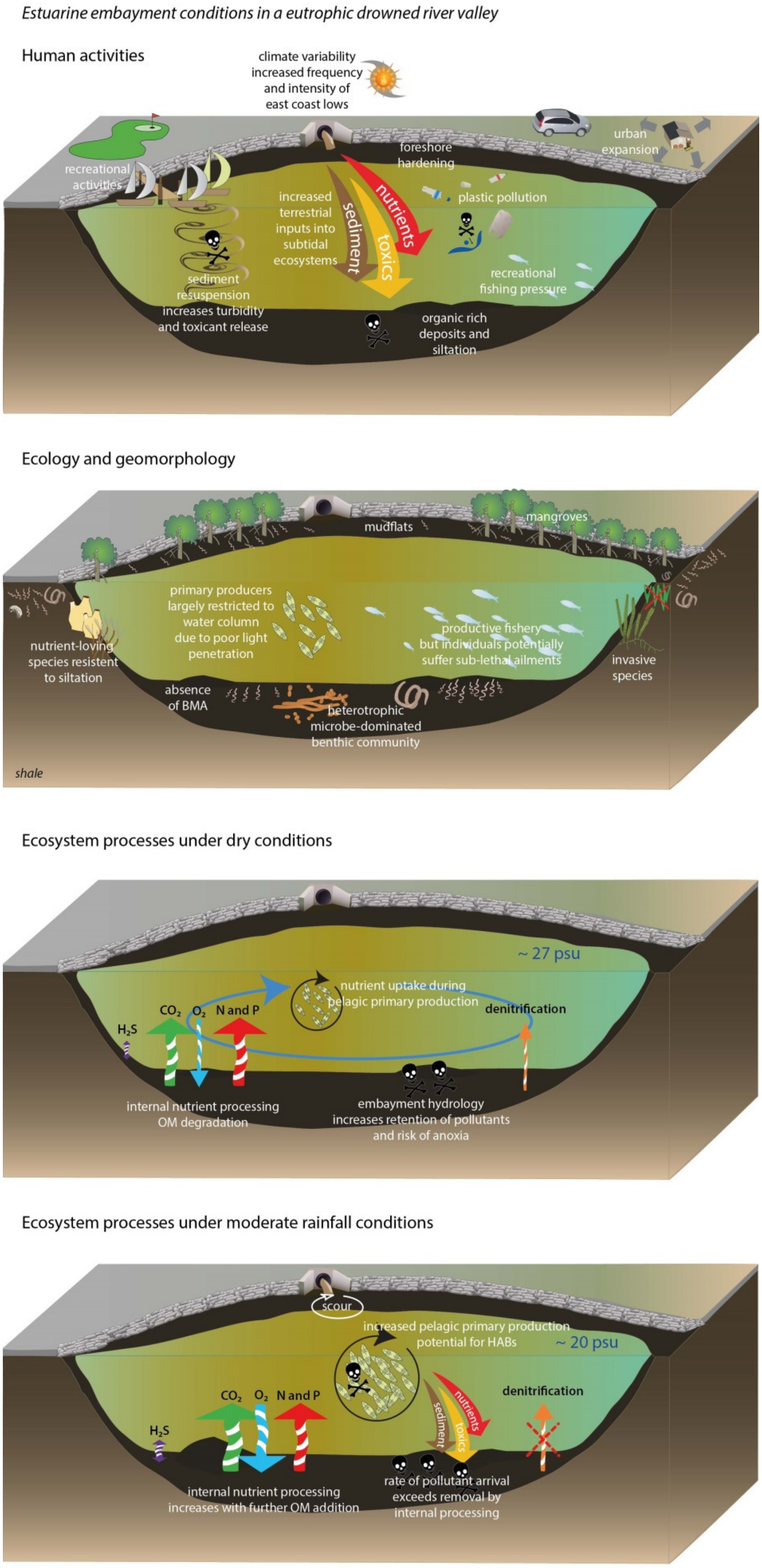

Figure 3 **Estuarine embayment conditions in eutrophic Sydney Harbour**

Anthropogenic threats in the estuary

Urban expansion over the last 220 years has transformed a once heavily forested catchment into an expanding concrete jungle (Hoskins 2009), resulting in an organically-enriched estuary with turbid waters, anoxic and aphotic sediments, and significantly reduced areas of highly productive wetland, intertidal mudflat, seagrass communities that are natural barriers to terrestrial pollutant export (Kelleway *et al.* 2007). Today, eighty-six per cent of the Sydney Harbour catchment is urbanised or industrialised (Birch 2007). Land-use is dominated by low to medium density residential housing (Birch 2007), with the extent of other landuses (e.g. commercial and light industrial centres, parklands) differing between the four sub-catchments of the estuary (Freewater and Kelly 2015) (Table 2).

Table 2. Relative land use areas of the major subcatchments in the Sydney Harbour catchment. The catchment is heavily urbanized with 80% of the catchment covered by urban land use types. The majority of the catchment is residential, with roads (19%) and parklands (14%) the next largest land uses. Rural land use (0%) and Rail (1%) are the smallest areas of land use type (reproduced from Freewater and Kelly 2015).

Subcatchment	Bushland	Commercial	Industrial	Parkland	Rail	Residential	Roads	Rural
Parramatta	3%	8%	6%	12%	1%	49%	20%	1%
Lane Cove	7%	9%	1%	17%	0%	49%	17%	0%
Middle Harbour	16%	3%	1%	20%	1%	44%	15%	0%
Port Jackson	6%	17%	3%	11%	1%	40%	22%	0%
Total	6%	9%	4%	14%	1%	47%	19%	0%

Poor waste management practices pre-1972 has left a legacy of industrial contamination in the estuary, concentrated in the off-channel embayments along the estuary's southern shore. Some of the world's highest reported concentrations of metals, organochlorine compounds (e.g. pesticide dichlordiphenyltrichloroethane (DDT) and its metabolites) and polycyclic aromatic hydrocarbons (PAHs) are reported in subsurface sediments of Sydney Harbour (Birch and Taylor 2002, Taylor *et al.* 2004). However, elevated concentrations of toxicants including metals and organochlorine compounds continue to be found in the surficial fluvial sediments of inflowing waterways. This highlights stormwater runoff, from road surfaces, urban areas and contaminated sites, as an ongoing source of toxicants for the estuary (Birch and Taylor 1999, 2002, Birch and Taylor 2004, Birch *et al.* 2009).

In addition to toxicants, stormwater is also the largest source of nutrients (990 kg km^{-2} year^{-1} of total nitrogen and 132 kg km^{-2} year^{-1} of total phosphorus) and sediment loads (715 t km^{-2} year^{-1} of total suspended solids) in the estuary (Birch *et al*. 2010, Freewater and Kelly 2015). Sewer overflows and licensed discharges represent another significant source of nutrients, as well as pathogens, pharmaceuticals and other 'emerging toxicants' of biological concern (Birch *et al*. 2015, Freewater and Kelly 2015). Sewer overflows occur in both dry and wet weather conditions due to pipe blockages and breakages, or infiltration of stormwater and illegal connections that exceed the system's capacity (Hedge *et al.* 2014a).

Direct human interaction with the estuarine environment through commercial and recreational activities present further threats to ecosystem processes. Shipping activities increase sediment resuspension, remobilizing sediment-bound toxicants into the water column for transport within the estuary (Hedge *et al*. 2009). Reclamation of more than 50% of the natural shoreline has changed local hydrology, destroyed productive intertidal communities, and increased the mobilization of toxicants in contaminated landfill sites (Birch *et al*. 2009). Plastic macrodebris present a suffocation and entanglement threat to marine organisms.

Linking threats to changes in ecosystem processes

Toxicants and nutrient pollutants undergo complex interactions in the environment, which limits our understanding of the ecological ramifications facing systems with multiple stressors. The two types of pollutants also differ in the biological responses they induce. In this conceptual model, we attempt to disentangle the complex interactions occurring between different pollutants. We generalise that nutrient pollutants determine the dominant biogeochemical pathways (ecosystem processes) for nutrient cycling, while both nutrients and toxicants act to determine ecosystem process rates, with toxicants exerting a negative direction of influence on the activity of toxicant-sensitive enzymes (ecosystem processes). This reduces the diversity of enzyme activity in the system, which may impair higher-level ecosystem functions that rely on linkages between individual enzymes within a functional pathway (Islam and Tanaka 2004).

Biological responses to toxicants (e.g. metals, organochlorine compounds, PAHs, PCBs, pharmaceuticals, plastics, nanoparticles) are exclusively negative. They are most commonly reported in ecosystem studies using community-level metrics such as decreased biodiversity and changes in community structure (lethal responses) (Johnston and Roberts 2009). However, these do not provide adequate insight on how toxicants influence ecosystem processes as responses also include sublethal impacts to physiology and behavior. Responses depending on the unique physical and chemical properties of each toxicant compound, which can change under different environmental conditions. In addition to biodiversity loss, current knowledge suggests that toxicants generally act to decrease metabolism, enzyme activity including specific pathways for nutrient cycling, primary production (Johnston *et al.* 2015) and to a lesser extent carbon cycling (Islam and Tanaka 2004). The suite of endocrine disrupting toxicants, such as common drugs and household chemicals, have been associated with sub-lethal effects like reproductive failure (Snyder *et al.* 2003, Alquezar *et al*. 2006, Booth and Skene 2006). Microplastics found in both vertebrate and invertebrate guts act to increase exposure to hydrophobic surface-bound toxicants (do Sul and Costa 2014). Many toxicants bioaccumulate and biomagnify in the food chain in exposed algae, invertebrates and vertebrates throughout the harbour although concentrations remain elevated surrounding toxicant sources. This likely reduces overall ecosystem productivity and nutrient cycling rates, while posing a direct health risk to humans who consume contaminated seafood (Roach and Runcie 1998, Alquezar *et al*. 2006, Roberts *et al.* 2008, Birch and Richards 2013). As toxicant responses extend beyond the nutrient cycling impacts associated with nutrient pollution, the full range of toxicant impacts is beyond the scope of this model to encapsulate (Islam and Tanaka 2004).

Concurrently, nutrient pollution (including eutrophication, sewage, hydrocarbons, or mixtures of nutrients and other contaminants) has been found to be associated with increased community diversity in marine ecosystems (Johnston and Roberts 2009). In a global context, the nitrogen discharge received in Sydney Harbour is considered moderate and phosphorus discharge below average (Birch *et al.* 2010). Given the estuary's oligotrophic presettlement state, nutrient pollution appears to act to ameliorate some of the negative impacts that toxicants alone would have on species richness by providing more heterogeneous access to nutrients and food sources throughout the system. As such, Sydney Harbour still supports relatively diverse communities in a global context, particularly in the well-flushed lower estuary (Booth 2010).

However, aside from a positive influence to biodiversity, nutrient pollution also incurs negative responses. Increased nutrient levels are still seen to disproportionately favour opportunistic or nutrient-loving species, e.g. weedy algal species such as *Caulerpa taxifolia*, which may disadvantage native species despite increasing biodiversity (Creese and Wales 2009, Johnston and Roberts 2009, McKinley and Johnston 2010, Dafforn *et al.* 2014). Also, increases in biodiversity due to nutrient pollution are limited by the impacts of eutrophication. Nutrient pollution, in the forms of organic material and dissolved nutrients largely surrounding stormwater outlets, increase biological oxygen demand (BOD) and sulphide production in poorly-flushed aquatic systems like off-channel embayments. Such conditions limit biodiversity, favouring microbial degradation of excess organic inputs that sustain additional positive benthic fluxes of C, N, P and sulphide. Of note, increased sulphide production associated with eutrophic conditions can facilitate the precipitation of toxicants such as metals, again acting to ameliorate toxicant impacts by reducing bioavailable concentrations in the water column and biotic uptake (Lithner *et al.* 2000). However, low oxygen conditions increase P mobility into the water column, further exacerbating the eutrophic conditions in the surrounding areas (Correll 1998). Primary production becomes limited to the pelagic realm as light is limited at the benthos, preventing beneficial ecosystem processes such as oxygenation and sediment stabilisation that are provided by primary producers from reaching the benthos. Under these conditions, nitrogen removal is dominantly achieved through ecosystem processes in the ammonification pathway, as nitrifying and denitrifying organisms that transform excess nitrogen into harmless dinitrogen gas are commonly outcompeted by ammonifiers in eutrophic systems (Hulth *et al.* 2005). Unfortunately, eutrophic systems are associated with increased production of greenhouse gases (methane and nitrous oxide) (Seitzinger and Kroeze 1998, Burgin and Hamilton 2007).

The dominant threats to ecosystem processes arise from pollutants that interfere with the natural biogeochemical and biological functions of both pelagic and benthic systems in the estuary. The combined effects of eutrophication and toxicant stress are largely concentrated to low-energy muddy embayments. Heads of embayments and main channels in the estuary receive sufficient tidal flushing that resupplies oxygen and limits the accumulation of waste products and toxicants that decrease enzyme activity.

If future terrestrial inputs of nutrients and toxicants are well managed, further impacts to internal ecosystem processes can be minimized to protect the natural value of the estuary, estimated at $150 million/year in ecosystem services, as well as the significant social (recreational fishing, swimming, boating and aesthetics) and economic (fishing and tourism) benefits Sydney enjoys (Hedge *et al.* 2014b).

Ecological Response Model (ERM)

The Sydney Harbour ERM is being developed as an adaptive framework that incorporates existing data layers, hydrodynamic model outputs, and ongoing research results. As such, the ERM will provide a comprehensive library of existing environmental information about the biogeochemistry and ecology of the harbour. In particular, the ERM will include a realistic coupling of pelagic and benthic processes, recognising the emerging knowledge about interactions between light, nutrients, organic carbon and contaminants.

Two levels of spatial resolution are incorporated in the ERM:

1) a coarse scale box model consisting of a 15 box main channel array coupled to 25 embayment boxes; and

2) a fine scale (50m mesh) model which can be directly coupled to the Delft3D hydrodynamic model.

Both models are underpinned by the same bathymetric and sediment grids (50m X 50m resolution), which are being populated from existing available datasets. The choice of model depends on the nature of the questions being posed: broader scale assessments of the relative impacts of different sub-catchment pollutant loads over long timescales are best achieved using the computationally efficient box model; whilst the fine scale dispersion of pollutants and pathogens from a particular point source can be best assessed using discrete rainfall event simulations.

The coarse scale box model works on a daily timestep, and is configured to provide a reasonable separation of impacts from different sub-catchment inputs as estimated by the catchment export model. Net daily exchanges between the boxes due to tide and freshwater flows are derived from a metamodel analysis of flows across the box boundaries as estimated by the hydrodynamic model. The coarse scale model generates detailed material budgets for each box, allowing managers to make assessments of the relative impacts of different point and diffuse sources.

Benthic processes

The Sydney Harbour benthic environment consists of a range of shallow, euphotic sediments and deep aphotic channel sediments. As such, deposited contaminants and organic matter are subject to a wide range of light environments resulting in distinctly different biogeochemical cycling pathways. The fine scale benthic grids underpinning the ERM allow for a detailed account of the effects of light on benthic productivity and associated microbial processes, even when using the coarse scale box model. The processing of material is governed by a library of algorithms, which can be updated as new research results become available.

Benthic environments are also important reservoirs of contaminants which are subject to physical disturbance due to wind waves and boat wake. The benthic grid of the ERM allows for the physical resuspension and settling of material due to bed shear stress. The inclusion of ferry wake impacts on bed shear stress is currently under investigation.

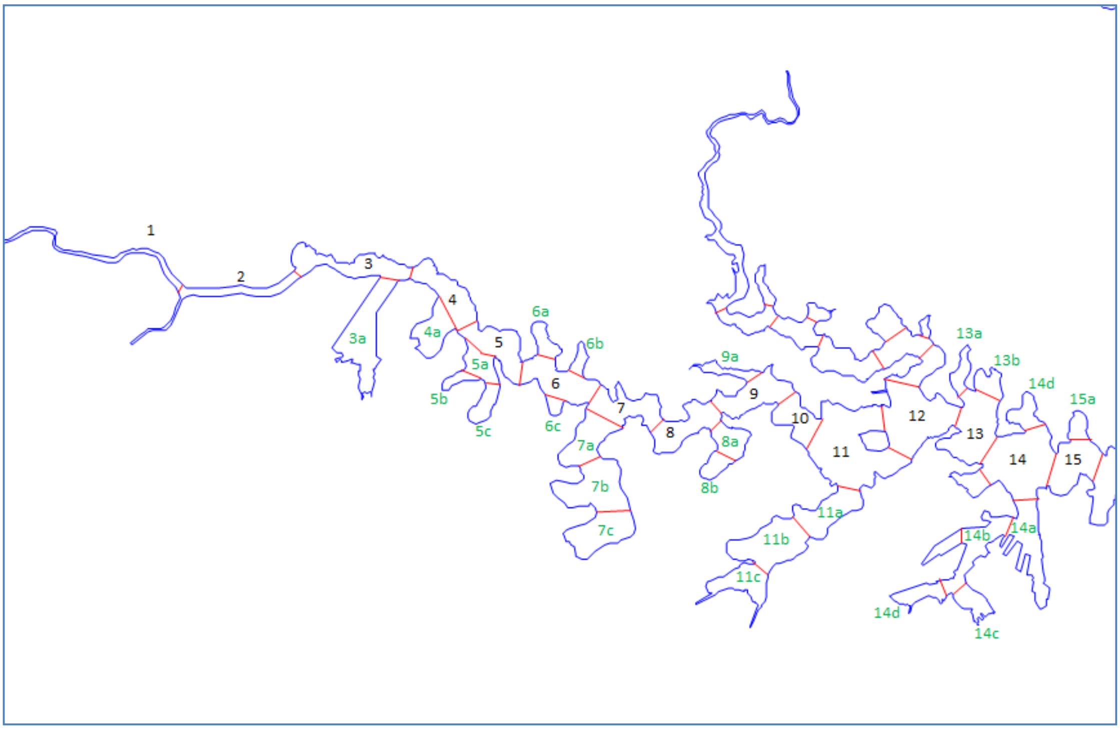

Figure 4 **ERM box layout for the Parramatta River and embayments. Main channel boxes are numbered in black and embayments in green.**

Discussion

The NSW Government's new *Marine Estate Management Act 2014* indicates that management of the marine estate should be based on an assessment of threat and risk to community benefits. Community benefits derive from environmental, social and economic factors. Therefore, in order to properly assess threats, it is necessary to properly understand the interrelationship between the outcomes of the impacts of environmental stressors with social and economic values and benefits.

In 2014 the Marine Estate Management Authority (MEMA) commissioned a community survey of approximately 1700 NSW residents to understand the environmental, social and economic values of, and benefits derived from, the NSW Marine Estate. In 2014 the Sydney Institute of Marine Sciences (SIMS) collated all available biophysical information on Sydney Harbour (Hedge *et al.* 2014a) and further reports have identified the data available regarding social and economic assessments of the Harbour. In 2015 Greater Sydney Local Services (GS LLS) completed the Sydney Harbour Catchment Water Quality Improvement Plan (Freewater and Kelly 2015). This work included the development of the Sydney Harbour Ecological Response Model (SHERM), which provides pollutant inputs, hydrodynamic modelling and a preliminary assessment of algal growth potential. This Delft3D modelling system will undergo further development to investigate larval recruitment and transport into the Harbour; the resuspension, transport and accumulation of sediment contaminants; examine targeted measures to improve stormwater and sewer overflow impacts; investigate the impact of vessel traffic on hydrodynamics and sediment transport process; and investigate the tsunami hazard. Research undertaken by the Office of Environment and Heritage (OEH), over several years and on numerous NSW estuaries, has provided considerable understanding of the influences of catchment inputs on estuary ecosystem response. OEH has used this understanding for the construction of models to highlight most cost-effective areas for management intervention. All of this work will be synthesised so as to develop the Sydney Harbour Estuary Processes Study (SHEPS) in line with MEMA's 'threat and risk assessment' paradigm.

It is anticipated that the SHEPS, when completed, will inform the development of a whole of catchment, whole of government Estuary Management Study and subsequent Management Plan for Sydney Harbour. The desire and the need for the coordinated management of Sydney Harbour have been demonstrated in the SHCWQIP (Freewater and Kelly 2015). Like the SHCWQIP, a whole of catchment Sydney Harbour Estuary Management Plan would need to be developed in line with the MEMA 'threat and risk assessment' paradigm and, most importantly, in collaboration with all government and other important stakeholder organisations.

References

Alquezar, R., S. J. Markich, and D. J. Booth. 2006. Metal accumulation in the smooth toadfish, Tetractenos glaber, in estuaries around Sydney, Australia. Environmental Pollution **142**:123-131.

Birch, G. 2007. A short geological and environmental history of the Sydney estuary, Australia. Water, Wind, Art and Debate:217-246.

Birch, G., D. Drage, K. Thompson, G. Eaglesham, and J. Mueller. 2015. Emerging contaminants (pharmaceuticals, personal care products, a food additive and pesticides) in waters of Sydney estuary, Australia. Marine pollution bulletin.

Birch, G. and R. Richards. 2013. An integrated source-fate-effects model for sedimentary metals in Sydney estuary and catchment (Australia). Pages 1735-1741 *in* MODSIM2013, 20th International Congress on Modelling and Simulation.

Birch, G. and S. Taylor. 1999. Source of heavy metals in sediments of the Port Jackson estuary, Australia. Science of the Total Environment **227**:123-138.

Birch, G. and S. Taylor. 2002. Possible biological significance of contaminated sediments in Port Jackson, Sydney, Australia. Environmental monitoring and assessment **77**:179-190.

Birch, G. and S. Taylor. 2004. Sydney Harbour and catchment: contaminant status of Sydney Harbour sediments: a handbook for the public and professionals. Published by the Geological Society of Australia, Environmental, Engineering and Hydrogeology Specialist Group.

Birch, G. F., B. Cruickshank, and B. Davis. 2010. Modelling nutrient loads to Sydney estuary (Australia). Environmental monitoring and assessment **167**:333-348.

Birch, G. F., O. Murray, I. Johnson, and A. Wilson. 2009. Reclamation in Sydney estuary, 1788–2002. Australian Geographer **40**:347-368.

Birch, G. F. and L. Rochford. 2010. Stormwater metal loading to a well-mixed/stratified estuary (Sydney Estuary, Australia) and management implications. Environmental monitoring and assessment **169**:531-551.

Booth, D. J. 2010. Natural History of Sydney's Marine Fishes: where south meets north. The Natural History of Sydney, edited by D. Lunney, P. Hutchings and D. Hochuli. Royal Zoological Society of NSW, Mosman NSW:143-153.

Booth, D. J. and C. D. Skene. 2006. Rapid assessment of endocrine disruption: Vitellogenin(VTG) expression in male estuarine toadfish. Australasian Journal of Ecotoxicology **12**:3-8.

Burgin, A. J. and S. K. Hamilton. 2007. Have We Overemphasized the Role of Denitrification in Aquatic Ecosystems? A Review of Nitrate Removal Pathways. Frontiers in Ecology and the Environment **5**:89-96.

Correll, D. L. 1998. The role of phosphorus in the eutrophication of receiving waters: A review. Journal of Environmental Quality **27**:261-266.

Creese, R. and N. S. Wales. 2009. Mapping the habitats of NSW estuaries. Industry & Investment NSW.

Dafforn, K., D. Baird, A. Chariton, M. Y. Sun, M. V. Brown, S. L. Simpson, B. P. Kelaher, and E. L. Johnston. 2014. Higher, faster and stronger? The pros and cons of molecular faunal data for assessing ecosystem condition. Advances in Ecological Research **51**.

do Sul, J. A. I. and M. F. Costa. 2014. The present and future of microplastic pollution in the marine environment. Environmental Pollution **185**:352-364.

Freewater, P. and R. Kelly. 2015. Sydney Harbour Water Quality Improvement Plan. Local Land Services.

Hedge, L., N. Knott, and E. Johnston. 2009. Dredging related metal bioaccumulation in oysters. Marine pollution bulletin **58**:832-840.

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

Hedge, L. H., J. Turnbull, C. Hoisington, and E. L. Johnston. 2014b. Sydney Harbour Background Report.

Hoskins, I. 2009. Sydney Harbour: A History. UNSW Press.

Hulth, S., R. C. Aller, D. E. Canfield, T. Dalsgaard, P. Engström, F. Gilbert, K. Sundbäck, and B. Thamdrup. 2005. Nitrogen removal in marine environments: recent findings and future research challenges. Marine Chemistry **94**:125-145.

Islam, M. S. and M. Tanaka. 2004. Impacts of pollution on coastal and marine ecosystems including coastal and marine fisheries and approach for management: a review and synthesis. Marine pollution bulletin **48**:624-649.

Johnston, E. L., M. Mayer-Pinto, and T. P. Crowe. 2015. Chemical contaminant effects on marine ecosystem functioning. Journal of Applied Ecology **52**:140-149.

Johnston, E. L. and D. A. Roberts. 2009. Contaminants reduce the richness and evenness of marine communities: a review and meta-analysis. Environmental Pollution **157**:1745-1752.

Kelleway, J., R. Williams, C. Allen, N. M. Authority, and N. S. Wales. 2007. An assessment of the saltmarsh of the Parramatta River and Sydney Harbour. NSW Department Primary Industries.

Lee, S. B., G. F. Birch, and C. J. Lemckert. 2011. Field and modelling investigations of fresh-water plume behaviour in response to infrequent high-precipitation events, Sydney Estuary, Australia. Estuarine, Coastal and Shelf Science **92**:389-402.

Lithner, G., H. Borg, J. Ek, E. Fröberg, K. Holm, A.-M. Johansson, P. Kärrhage, G. Rosén, and M. Söderström. 2000. The turnover of metals in a eutrophic and an oligotrophic lake in Sweden. AMBIO: A Journal of the Human Environment **29**:217-229.

McKinley, A. and E. L. Johnston. 2010. Impacts of contaminant sources on marine fish abundance and species richness: a review and meta-analysis of evidence from the field. Marine Ecology Progress Series **420**:175-191.

McLoughlin, L. C. 2000. Shaping Sydney Harbour: sedimentation, dredging and reclamation 1788-1990s. Australian Geographer **31**:183-208.

Roach, A. and J. Runcie. 1998. Levels of selected chlorinated hydrocarbons in edible fish tissues from polluted areas in the Georges/Cooks Rivers and Sydney Harbour, New South Wales, Australia. Marine pollution bulletin **36**:323-344.

Roberts, D. A., E. L. Johnston, and A. G. Poore. 2008. Biomonitors and the assessment of ecological impacts: distribution of herbivorous epifauna in contaminated macroalgal beds. Environmental Pollution **156**:489-503.

Seitzinger, S. P. and C. Kroeze. 1998. Global distribution of nitrous oxide production and N inputs in freshwater and coastal marine ecosystems. Global Biogeochemical Cycles **12**:93-113.

Snyder, S. A., P. Westerhoff, Y. Yoon, and D. L. Sedlak. 2003. Pharmaceuticals, personal care products, and endocrine disruptors in water: implications for the water industry. Environmental Engineering Science **20**:449-469.

Taylor, S., G. Birch, and F. Links. 2004. Historical catchment changes and temporal impact on sediment of the receiving basin, Port Jackson, New South Wales. Australian Journal of Earth Sciences **51**:233-246.

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
MEMA – Marine Estate Management Authority
MUSIC – Model for Urban Stormwater Improvement
NH4 - ammonium
NOx - 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
SHEPS - Sydney Harbour Estuary Processes Study
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