In partnership with:

Greater Sydney Local Land Services
Office of Environment and Heritage
Sydney Institute of Marine Sciences
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Sydney Harbour Estuary Processes Study

Greater Sydney Harbour Coastal Management Program
Stage 2 Detailed Studies of Vulnerabilities and Opportunities

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[GS-1551-24]

EXECUTIVE SUMMARY

This report represents the culmination of seven years of collaborated research into Sydney Harbour that began with the development of the Sydney Harbour Catchment Water Quality Improvement Plan. The report contributes to Stage 2 of the coastal management program (*Detailed Studies of Vulnerabilities and Opportunities*) to fill gaps in current knowledge about the coastal management issues affecting Sydney Harbour. The information provided by these studies is to support decision-making and assist communities to understand these coastal management issues. This will enable actions to be developed to address those issues including current and future risks, as well as to promote public access, use and enjoyment of the Harbour and support the continued prosperity of the NSW economy.

The improved knowledge generated by these studies will help support the identification, evaluation and selection of appropriate management actions required to address management issues in an integrated and strategic manner during Stage 3. This includes actions to support ecologically sustainable development, manage and reduce risks from coastal hazards, promote public access, improve community awareness and understanding, and support the well-being of the local community and coastal ecosystems. These studies will build on the history of Sydney Harbour including biophysical, demographic, infrastructure and economic changes, and how community aspirations have changed over time. It includes an assessment of threats and opportunities that concentrates primarily on threats to environmental assets and represents a preliminary analysis of the sorts of considerations that may need to be taken into account when considering future management initiatives for Australia's most iconic waterway.

Very high threats to environmental values were considered likely to result from the full range of climate change stressors, from habitat damage caused by anchoring and mooring, from increased inputs of nutrients and sediments from the surrounding and largely urbanised subcatchments, from toxic pollutants (including legacy pollutants in sediments) and from some aspects of fishing (notably illegal fishing and the discarding of unwanted catch). Many of these activities are likely to also impinge on social and economic values, because Sydneysiders consider the ecological health and aesthetic nature of the Harbour as fundamental to the appreciation and enjoyment of the Harbour and its surrounding foreshore, by residents and visitors alike.

Opportunities to address these very high threats, and many of the lesser threats also identified, will require a carefully considered and coordinated response from all those responsible for managing various aspects of the Harbour and its surrounding catchment. Some of those opportunities have been scoped out in this report, but they are intended to be indicative rather than exhaustive. They are provided to inform Stage 3 of the Greater Sydney Harbour Coastal Management Program process.

Six Spined Leatherjacket (*Meuschenia freycineti*) at Bare Island

Glossary of Acronyms

ARI	Average Recurrence Interval
BMA	Benthic Micro-Algae
CALD	Culturally and Linguistically Diverse
CAPER DSS	Catchment Planning and Estuary Response Decision Support System
CPEM	Catchment Pollutant Export Model
DPI	Department of Primary Industries
DSS	Decision Support System
EFM	Environmentally Friendly Mooring
EPA	Environmental Protection Authority
GS LLS	Greater Sydney Local Land Services
GTP	Gross Pollutant Trap
ISQG-H	Interim Sediment Quality Guideline-High
LGA	Local Government Authority
MEMA	Marine Estate Management Authority
MPA	Marine Protected Area
N	Nitrogen
NIS	Non-Indigenous Species
OC	Organic Carbon
OEH	NSW Office of Environment and Heritage
OM	Organic Matter
P	Phosphorous
PAH	Polycyclic Aromatic Hydrocarbon
PEM	Pollutant Export Model
POP	Persistent Organic Pollutant
PPCP	Pharmaceuticals and Personal Care Products
RFH	Recreational Fishing Haven
RMS	NSW Roads and Maritime Services
SHERM	Sydney Harbour Ecological Response Model
SHEPS	Sydney Harbour Estuary Processes Study
SHCWQIP	Sydney Harbour Catchment Water Quality Improvement Plan
SIMS	Sydney Institute of Marine Science
SMCMA	Sydney Metropolitan Catchment Management Authority
TBT	Tributyltin
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorous
TSS	Total Suspended Solids
WSUD	Water Sensitive Urban Design

Anemone Hermit Crab (*Dardanus pedunculatus*)

Foreword

The Sydney Harbour Estuary Processes Study (SHEPS) was developed to provide detailed studies of physical, ecological and biogeochemical processes of the Harbour. The study area encompasses the entire estuary and its drainage catchment with linkages to the Tasman Sea. It comprises the tidal waterway, foreshore and adjacent land of Sydney Harbour, including the entrance area and tidal tributaries covering the whole region of Sydney Harbour and associated tributaries and catchments. These studies aim to fill gaps in current knowledge about the coastal management issues affecting the Harbour and contributes to Stage 2 of the new coastal management program process.

> *The information provided by these studies is to support council decision-making and assist communities to understand these coastal management issues. This will enable actions to be developed to address those issues including current and future risk from coastal hazards, as well as to promote public access, use and enjoyment of the coast and support the continued prosperity of the NSW economy.*
>
> *The improved knowledge generated by these studies will help support the identification, evaluation and selection of appropriate management actions required to address coastal management issues in an integrated and strategic manner during Stage 3.*
> *(OEH, 2015).*

This project was only possible because of the collaborative funding partnerships that the then Sydney Metropolitan Catchment Management Authority (now Greater Sydney Local Land Services (GS LLS)) established to develop the Sydney Harbour Catchment Water Quality Improvement Plan (Freewater and Kelly, 2015). Partners included the 16 local government authorities that were within the Sydney Harbour catchment (i.e. Auburn, Ashfield, City of Sydney, Blacktown, Parramatta, Holroyd, Strathfield, Canada Bay, Ryde, Ku-ring-gai, Manly, Lane Cove, Woollahra, Leichhardt, Marrickville and Burwood); the NSW Office of Environment and Heritage (OEH); Sydney Water; and NSW Roads and Maritime Services and Sydney Institute for Marine Sciences (SIMS). These partnerships continued under the leadership of GS LLS. SIMS has either provided or contributed to all of the ecological research and reviews.

Sydney Pygmy Pipehorse (*Idiotropiscis lumnitzeri*)

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1 INTRODUCTION

1.1 Background

The Sydney Harbour Estuary Processes Study (SHEPS) is the result of seven years of collaborative research led by the Greater Sydney Local Land Services (GS LLS). Collaborative partners included the Sydney Institute of Marine Sciences (SIMS), NSW Office of Environment and Heritage (OEH), NSW Roads and Maritime Services (RMS), Sydney Water, 11 local government authorities (i.e. Inner West, City of Sydney, Blacktown, Parramatta, Strathfield, Canada Bay, Ryde, Ku-ring-gai, Northern Beaches, Lane Cove and Woollahra).

In 2015 the GS LLS finalised the Sydney Harbour Catchment Water Quality Improvement Plan (SHCWQIP). Development of the SHCWQIP (Freewater and Kelly, 2015) included the integration of various hydrological, catchment and ecological models. These models were used to develop a Decision Support System, which was used to set water quality targets and provide a tool to test various water quality management strategies.

SIMS were engaged to collect and analyse water quality data for the calibration of the SHCWQIP models. In 2013 the then Sydney Metropolitan Catchment Management Authority (now GS LLS) successfully partnered with SIMS to be awarded an Australian Research Council Industry Grant. The study was titled: **Testing the waters: impacts of contaminants on ecosystem structure and function in urban waterways.** The aim of the study was to determine how nutrients and contaminants interact to affect Sydney Harbour. Publications arising from this research, together with other publications and projects commissioned by GS LLS are included in this Report.

At the conclusion of the SHCWQIP, GS LLS had not expended its entire budget. A key action listed within the SHCWQIP was to develop a coordinated management program for Sydney Harbour:

> ***Action 46 – All of government:*** *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.*
>
> *A collaborative approach to the management of Sydney Harbour will achieve the best possible results in supporting coordinated action to improve water quality in Sydney Harbour. The governance structure for such an Urban Water Management Program should be developed collaboratively by Local and State governments and the priorities should include:*

- *Developing trust and relationships between organisations to enhance collaboration on water quality and other environmental management issues.*
- *Undertaking catchment wide education programs such as:*
    - *Connection between what goes in the drain and water quality in the Harbour.*
    - *Impacts of littering*
    - *Education for developers on potential benefits of WSUD in their developments including higher land values around wetlands and desirable green features. Provide information on types of WSUD options that might provide amenity benefits in development as well as improve water quality*
    - *Building capacity to implement, design and maintain WSUD and other environmental works such as habitat friendly seawalls within Councils.*
- *Reviewing legislation and regulatory impediments to water quality improvements in the catchment and Harbour.*
- *Joint monitoring activities and scientific investigations.*
- *Collation of monitoring data and activities to make this accessible to the public such as production of a report card or provision of real time stormwater monitoring data on a website.*
- *Developing a shared long-term vision and action towards this by members.*
- *Development of a whole of catchment, whole of government management plan for Sydney Harbour, its tributaries and its catchment.*

GS LLS realised that the development of the SHCWQIP had produced a considerable volume of research that could inform a Sydney Harbour Estuary Management Plan. After consultation with the collaborative funding partners, the decision to proceed with the Sydney Harbour Estuary Processes Study was made. The SHEPS was begun in 2015 and was designed to address step 3 of the, then, NSW Estuary Management Manual (NSW Government, 1992), which recommended an eight-step process to develop and implement an Estuary Management Plan:

1. form an Estuary Management Committee;
2. assemble existing data (data compilation study);
3. **undertake an Estuary Processes Study**;
4. undertake an Estuary Management Study;
5. prepare a draft Estuary Management Plan;
6. review Estuary Management Plan;
7. adopt and implement the Estuary Management Plan; and
8. monitor and review the management process as necessary.

The NSW Government has since reformed the estuary and coastal management process. The elements of the reform are new legislation - *the Coastal Management Act 2016* – a new coastal management manual and a Coastal Management State Environmental Planning Policy (SEPP) with related maps. The NSW coastal management manual sets out a staged process for developing a Coastal Management Program (CMP). It is structured in five stages as shown in Figure 1.1.

Figure 1.1 Five stage process for developing a coastal management program

Coastal management programs (CMPs) will replace coastal zone management plans (CZMPs). They will be prepared by councils in consultation with their communities and relevant government authorities, and in accordance with the new coastal management manual. The purpose of a CMP is to set the long-term strategy for the coordinated management of land within the coastal zone, and give effect to the management objectives for the four coastal management areas, namely:

- **Coastal wetlands and littoral rainforest areas** - Protect and enhance the resilience of natural values, processes and functions of wetlands and littoral rainforests.
- **Coastal vulnerability areas** - Mitigate current and future risks associated with coastal hazards, giving priority to natural foreshore defences and avoiding management impacts on biological diversity, ecosystem integrity, natural processes, public access, use and amenity, social and cultural values, and on adjoining land resources and assets.

- **Coastal environmental areas** (including coastal lakes, lagoons, estuaries headlands and rock platforms, and relevant buffer areas) - Protect, enhance and improve the resilience of health and the natural and social values of coastal waterways, headlands and rock platforms.
- **Coastal use areas** - Protect and enhance the scenic, social and cultural values of the coast and accommodate both urban and natural stretches of the coastline.

Councils must also identify priority objectives for their coastal management areas. When identifying objectives for a CMP that includes one or more coastal management area, councils must be consistent with the objectives for coastal management areas as required by the Coastal Management Act and Coastal Management SEPP. The objectives must also align with the objectives identified by the local community in developing the Community Strategic Plan.

There will be a strong emphasis on the implementation of CMPs. The *Coastal Management Act 2016* achieves this by requiring CMPs to be given effect within the local government Integrated Planning and Reporting (IP&R) framework. The *Coastal Management Act 2016* also includes performance auditing powers to ensure that CMPs are effectively implemented.

1.2 Scope of the Study

The main objectives of the SHEPS were:

a) To identify and document the physical, ecological and biogeochemical processes of the estuary (i.e. hydrodynamic and sedimentary processes, including tidal behaviour, freshwater inputs, water balance, mixing, exchange with the Tasman Sea, sediment types and sediment movement) and interactions among and between these processes (e.g. establishment of the water quality parameters of importance to the health of the estuary, mixing and flushing of pollutants) through investigation, data collection and comprehensive analysis.
b) To identify and document the ecological processes of the Estuary and related processes covering flora and fauna, species composition and distribution; habitat composition and distribution; the productivity and health of the ecosystems; the range and sensitivity of habitats to environmental disturbance; and rare and endangered species.
c) To define a baseline condition of the Estuary (water quality, habitats, species, etc.) and interactions on which management decisions can be made.

The SHEPS objectives have been expanded to align with stage 2 of the new coastal management manual. A Stage 1 Scoping Study (Sydney Harbour Coastal Management Program Scoping Study) has also since been developed (BMT WBM, 2017). SHEPS 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). This Report includes an assessment of the values, threats and opportunities for Sydney Harbour.

The project has used the Hydro-Ecology integrated modeling paradigm (Freewater, 2003, 2004a, 2004b, 2005, 2007). This paradigm is based on the premise that hydrological processes control life and so, ecological processes cannot be understood without an holistic understanding of the ecosystem's hydrology. Integrated modelling is used to understand how catchment characteristics and land management, hydrological processes (including estuarine hydrodynamics) and estuarine ecological processes interact. Briefly, the Hydro-Ecology approach involves 3 key stages:

1. characterising the catchment in terms of land-use and modelling rainfall and runoff with associated predicted pollutant loads
2. modelling estuarine hydrodynamics, pollutant and sediment transport and deposition
3. modelling ecological responses, larval dynamics and conceptualising the impacts of anthropogenic activities

2 CATCHMENT

2.1 General Physiography

Sydney Harbour is a *drowned valley* type estuary (Roy, 1981) comprised of three valley systems: Middle Harbour, Lane Cove River and Parramatta River. The fluvial systems forming the valleys eroded down into bedrock (Hawkesbury Sandstone) and the valleys have been infilled to a significant degree in the late Quaternary; the thickness of sediments is about 80 m at the entrance and averages about 20 to 30 m over much of Port Jackson. Inside the entrance there is a flood tidal delta which was at a depth of 6 m below the surface, but this was dredged to a depth of 13m between 1869 and 1924. That little maintenance dredging has been required since the channel was dredged attests to minimal sand input to the entrance from the adjacent shelf.

The seabed of Port Jackson comprises several deep "holes", rocky islands, shoals and basins separated by sills. The deepest hole is 46m in depth, located upstream from the Sydney Harbour Bridge. Typical holes are about 35 m in depth, located on the landward edge of steep sided tidal delta sands; a sill only about 3m in depth occurs over the Middle Harbour tidal delta located near Clontarf (refer nautical chart AUS 200). The entrance to Port Jackson is about 1.5 km in width and 20 m in depth; this morphology contrasts with Botany Bay and Jervis Bay in which the deepest part of the embayment is at the entrance. Such a pattern indicates Port Jackson is at a comparably less mature stage of infilling and estuary evolution (Roy, 1984b).

2.2 Geology and geomorphology

The broad geological formations found in metropolitan Sydney are illustrated in figure 2.1. The primary geological units recognised are Quaternary sands and alluvium, Tertiary sand and alluvium, Jurassic basalt and Triassic Wianamatta, Hawkesbury and Narrabeen shales and sandstones (OEH, 2013). Rocks formed during depositional phases in the Triassic period (250-205 million years ago) are the most extensive in the Sydney area. During this period the coarse-grained sands that characterise the sandstone plateaus of the north and south of the study area were laid down. In the middle Triassic fine-grained material was deposited across what are now the Cumberland Plain and the north shore. These are areas of shale and siltstone. Jurassic-aged (207-150 million years ago) igneous material was laid down during a period of increased volcanism and residual basalt material remains at isolated sites today. The Tertiary period (65-7 million years ago) formed another depositional phase, and being younger, formed a thin, layer on top of the Triassic rocks in local areas such as northern Holsworthy. The deposited sediments were a mix of sand, gravel and clay. The most recent depositional phases have occurred during the Quaternary period (5.3 million years ago to the present day). Deposition has occurred at estuaries, on flats and banks adjoining rivers and streams, and near the coastline where the oceans and wind have laid down material that defines today's coastal sand dune systems (OEH, 2013).

Basalt

There are only a few examples of past volcanic activity in the study area. These are isolated sites known as diatremes or volcanic 'necks' or 'vents' which are pipe-like intrusions through rock. They form where hot molten rock reached the surface by penetrating the sandstone strata. The molten rock cooled, forming a basaltic rock which eroded to form a fertile clay soil. Such formations are found at Prospect Hill near Parramatta, Campbells Crater, Oxford Falls and Browns Field on the Hornsby plateau. The latter form an oval-shaped depression surrounded by sandstone bedrock and the former is a residual basalt peak. Dykes are expose vertical sheets of igneous material that have oozed through rock layers and been exposed through erosion. The largest occurs at West Head in Ku-ring-gai Chase National Park (NP), while smaller examples are exposed at sea cliffs on Kurnell headland and in Royal NP (OEH, 2013).

Quaternary Sand

The major sand dune systems visible today were formed during the Quaternary period. These dunes arose from either marine or wind-blown deposits. Older dunes formed during the Pleistocene (between

2 million and 12,000 years ago) have been exposed to longer periods of weathering and leaching. These dunes support highly podsolised and infertile soils. In the Sydney metropolitan area these old dunes are wind-blown deposits found above sandstone headlands at North Head, Maroubra, La Perouse, Kurnell and Bundeena. They include the North Head and Woy Woy soil landscapes. Younger dunes formed from marine deposits during the Holocene (12,000 years ago to current) are more fertile, as they still retain mineral enrichment in the soil. These are found on the Kurnell isthmus and Newport areas (OEH, 2013).

Quaternary Alluvium

Alluvial deposits also formed along low-lying areas and drainage channels during the Quaternary period. During this time sea levels rose by about 60 metres and formed the major estuaries and Harbours of Sydney today. These alluvial soils may be variable in composition depending on whether the river has eroded sandstone- or shale-dominated catchments. Alluvial soils include higher levels of sand in the alluvium, whereas flats along Cabramatta Creek retain a greater component of silts and clays. Invariably this influences the water-retaining capacity of the soil, particularly after inundation. The floristic composition of plant communities that grow on them differ as a result (OEH, 2013).

Tertiary Sands and Clays

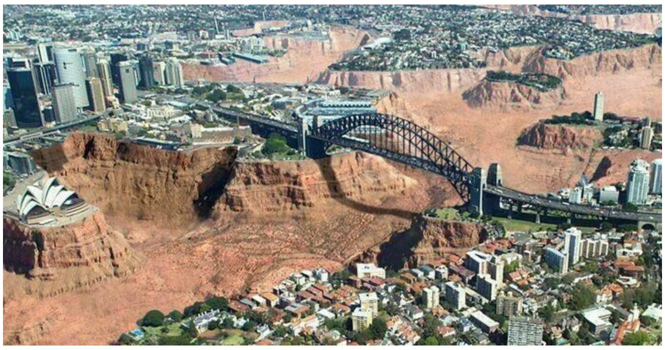
Older Tertiary-aged alluvial deposits are found on the top of the major Triassic depositions in small localised areas. These are defined by the Berkshire Park and Birrong soil landscapes. These soils are typically a mix of gravels, clay and sand. Most are heavily eroded and the depth of material can vary over short distances, as can the composition of the material. The most extensive areas that support native vegetation occur near Holsworthy in the south-west of the study area (OEH, 2013).

Wianamatta Shale

Soils derived from the Wianamatta group formation are associated with the landscapes of the Cumberland Plain. The Wianamatta group comprises two types of shale known as the Bringelly shales and the Ashfield shales. These are separated by a band of sandstone known as the Minchinbury sandstone. The Bringelly shales are mostly deep clay loams that form the gently undulating topography of the western boundary of the study area and beyond. These soils are most prominent in the north shore and inner west of Sydney. They also form a rim around the perimeter of the deeper Bringelly shales of the Cumberland Plain and mark the intergrades between the deep shales and the Hawkesbury sandstone bedrocks (OEH, 2013).

Mittagong Formation

The youngest of the sandstone series is the Mittagong formation (Herbert 1980). This stratum lies above the Hawkesbury formation and consists of an interbanding zone of quartz sandstone and fine-grained shale. It is represented by the Lucas Heights soil landscape (Hazelton and Tille 1990). It is characterised by broad flat ridges rather than the narrow rocky ridgelines of the Hawkesbury formation. It is extensive on the western Woronora Plateau, but is also found patchily throughout the Hornsby plateau. Soils vary from deep clay loams to skeletal sandy rocky podsols (OEH, 2013).



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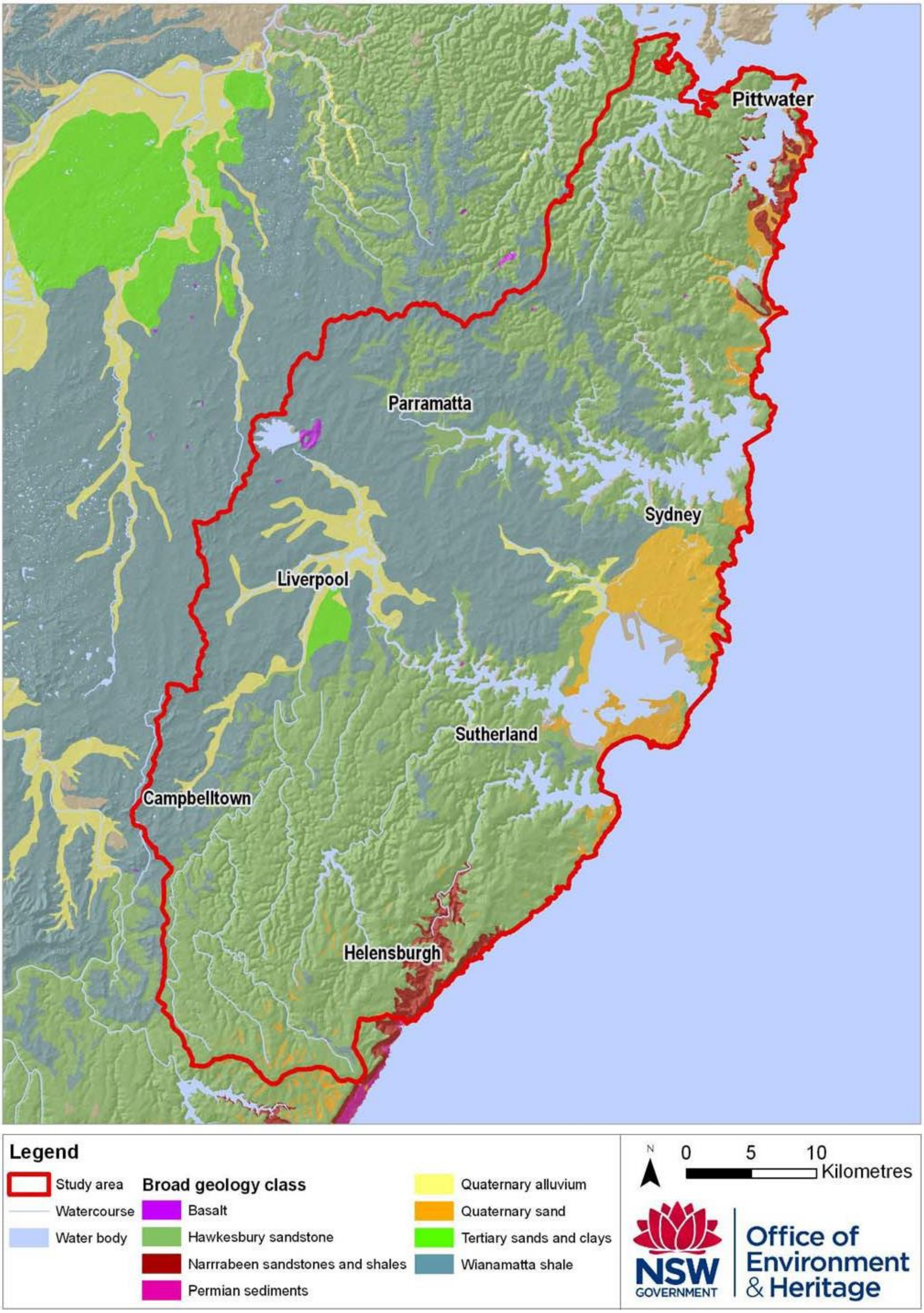


Figure 2.1 Broad geology of metropolitan Sydney (OEH, 2013)

Hawkesbury Formation

The Hawkesbury geological formation extends across the Woronora and Hornsby plateaus and is typified by skeletal rocky soils that comprise very infertile siliceous material. Common across both plateaus are mantles of laterite, known as ironstone, perched above the sandstone. These are rust- or coffee- coloured gravels and rocks of varying thickness. At the deepest sites, such as hill crests, the ironstone may erode to form a clay-like material, but mixes with the underlying quartz sands, again producing a soil of shale and sandstone elements. Ironstone mantles are rarely mapped in the study area but have an important role in determining the distribution of some vegetation communities. The Hawkesbury formation also includes local shale lenses within or above the bedrock which can produce a soil comprising both shale and sandstone elements (OEH, 2013).

Narrabeen Group Formation

The oldest of the sedimentary rocks in the Sydney metropolitan area are those in the Narrabeen group formation. These are layers of sandstone and shale which outcrop in deeply dissected gullies and escarpments in the north and south of the study area. The Narrabeen group has horizontal layers that mix moderately fertile fine-grained chocolate shale and lithic sandstone. They form a clay loam soil with greater moisture-holding capacity than the sandy soils associated with Hawkesbury sandstone. As the Narrabeen strata lies beneath the lithic Hawkesbury sandstone it may share soil properties as eroding cliff lines from above heap colluvial material on steep escarpment slopes. This is noticeable on the escarpment of the lower Hawkesbury River and the Hacking River valley (OEH, 2013).

2.3 Climate

Sydney has a temperate climate characterised by warm summers and cool to mild winters. Temperatures are milder closer to the coast, with a greater range experienced in the western plains of the study area. Mean monthly temperatures for January are 25.9 degrees Celsius at Sydney and 28.1 degrees Celsius at Parramatta, while mean monthly temperatures in July are 7.8 degrees Celsius for Sydney and 4.6 degrees Celsius at Parramatta.

Rainfall patterns follow a similar east-west gradient. Mean annual rainfall is highest closest to the coast with highest rainfall received in the Hacking River valley near the Illawarra Escarpment (above 1500 millimetres per annum) and the north shore around Turramurra where rainfall exceeds 1400 millimetres per annum (OEH, 2013). Figure 2.2 illustrates average rainfalls across metropolitan Sydney.

Sydney generally has 103.9 clear days annually, with the monthly percent possible sunshine ranging from 53% in January to 72% in August. Sydney's heat is predominantly dry in spring, but usually humid in the summertime, especially late summer – however, when temperatures soar over 35 °C, the humidity is generally low as such high temperatures are brought by searing winds from the Australian desert. In some hot summer days, low pressure troughs would increase humidity and southerly busters would decrease temperatures by late afternoon or early evening. In late autumn and winter, east coast lows can bring large amounts of rainfall.

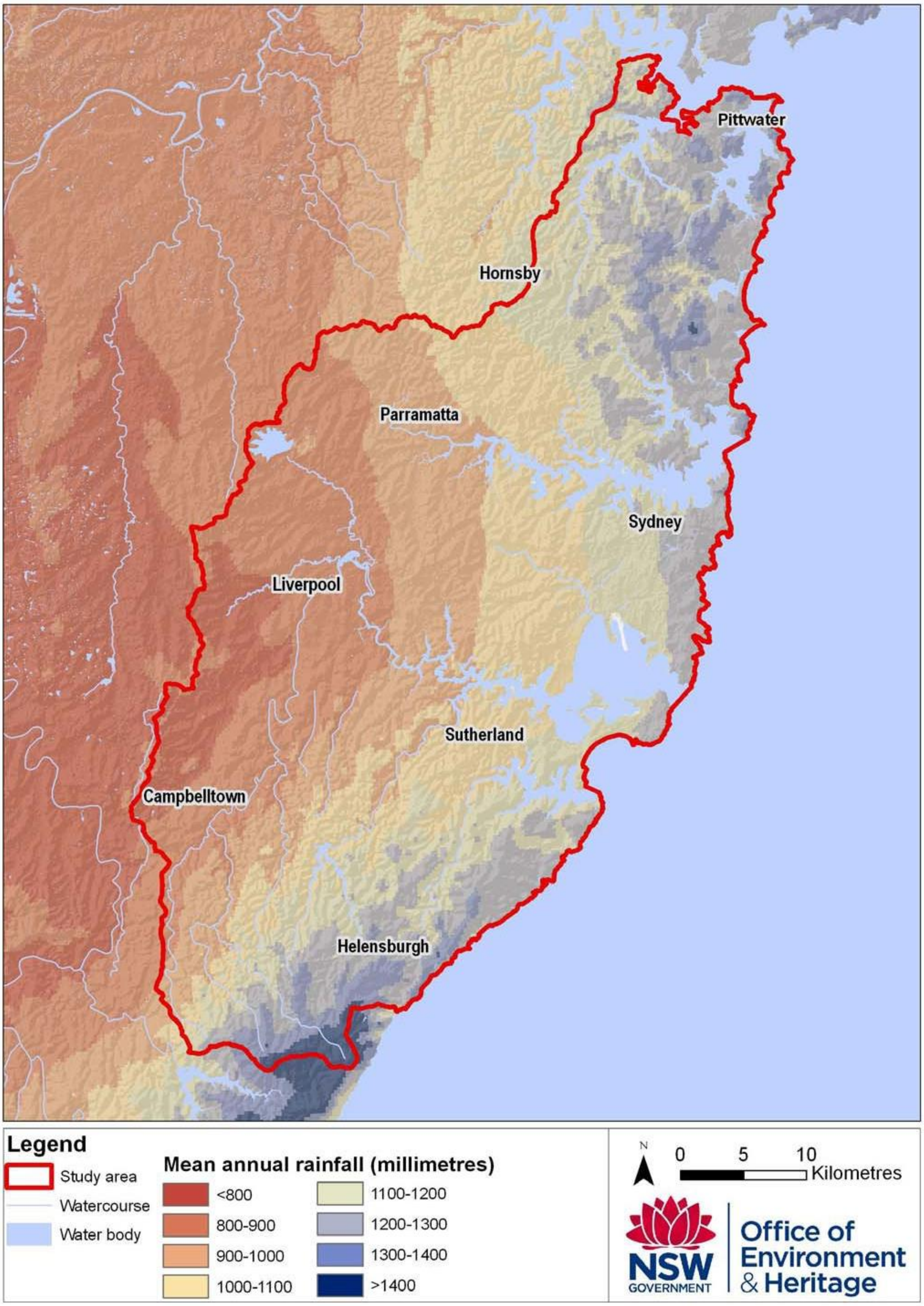


Figure 2.2 Average rainfall across metropolitan Sydney

Sydney experiences an urban heat island effect, making certain parts of the city more vulnerable to extreme heat, particularly the west. Efforts have been introduced to investigate and mitigate this heat effect, including increasing shade from tree canopies, adding rooftop gardens to high rise structures and changing pavement colour. The El Niño Southern Oscillation plays an important role in determining Sydney's weather patterns: drought and bushfire on the one hand, and storms and flooding on the other. Sydney is prone to heat waves and drought, which have become more common in recent years.

2.4 Catchments

Sydney Harbour catchment covers an area of 484 km^2 and has been divided into 4 catchment areas for this Report:

- the Parramatta River catchment
- the Lane Cove River catchment
- the Middle Harbour catchment, and
- the remaining foreshore areas draining into Port Jackson.

2.4.1 The Parramatta River catchment

The Parramatta River catchment covers approximately 250 km^2. The river is the main tributary to Sydney Harbour and is tidal to the Charles St weir. The catchment has been heavily developed and has a long history of industrialization. Relatively little vegetation is left in the catchment with small isolated patches scattered throughout the catchment but predominantly in the northern part and along creek lines.

The Parramatta River catchment was the earliest developed sub-catchment, and is now comprised of industry, residential and business zoning. The lower reaches of the Parramatta River are some of the most polluted areas of Sydney Harbour. This is mainly due to sediment contamination resulting from a long history of heavy industry situated adjacent to the waterway.

There are 34 tributary creeks draining to Parramatta River:

- Domain Creek
- Hunts Creek
- Darling Mills Creek
- Bellamys Creek
- Blue Gum Creek
- Bell Bird Creek
- Hawthorne Canal
- Iron Cove Creek
- Powells Creek
- Tarban Creek
- Glades Creek
- Grove Creek
- Excelsior Creek
- Saw Mill Creek
- Christmas Bush Creek
- Stevenson Creek
- Rifle Range Creek
- Northmead Gully Creek
- Charity Creek
- Archer Creek
- Haslams Creek
- Duck River
- Duck Creek
- Abecketts Creek
- Finlaysons Creek
- Coopers Creek
- Pendle Creek
- Girraween Creek
- Blacktown Creek
- Toongabbie Creek.
- Clay Cliff Creek
- Subiaco Creek
- The Ponds Creek
- Vineyard Creek.

2.4.2 The Lane Cove River Catchment

The Lane Cove River catchment covers approximately 95 km^2. The river is a northern tributary to the Sydney Harbour located on the northern side of Parramatta River joining between Clarkes Point, Woolwich and Greenwich Point, Greenwich and is tidal downstream from the weir near Fullers Bridge. 'The estuary is characterised by an open mouth with semi-enclosed bays with shallow or submerged deltas and on-going sediment infilling in some areas' (Gondwana Consulting, 2011).

Lane Cove River is a sparsely developed catchment in comparison to that of Parramatta River and Port Jackson. The catchment is relatively young and largely devoid of heavy industry, mainly comprised of business and residential.

Lane Cove River has a total of 29 tributary creeks:

- Coups Creek
- Scout Creek
- Camp Creek
- Byles Creek
- Devlins Creek
- Terrys Creek
- Mars Creek
- Shrimptons Creek
- Congham Creek
- Quarry Creek
- Rudder Creek
- Blackbutt Creek
- Amaroo Gully Creek
- Falls Creek
- Links Creek
- Little Blue Gum Creek
- Sugar Bag Creek
- Blue Gum Creek
- Swaines Creek
- Porters Creek
- Pages Creek
- Martins Creek
- Kittys Creek
- Strangers Creek
- Buffalo Creek
- Brickmakers Creek
- Tannery Creek
- Tambourine Creek
- Gore Creek.

2.4.3 The Middle Harbour Catchment

The Middle Harbour catchment covers approximately 100 km^2. The river is a northern tributary arm to Sydney Harbour and an inlet of the Tasman Sea located north of the Sydney central business district between Grotto Point near Clontarf and Middle Head. Middle Harbour has its main source in the upper reaches of Garigal National Park where it forms Middle Harbour Creek and flows southeast to become Middle Harbour at Bungaroo. Bushland covers one-quarter of the catchment mostly in Garigal National Park (22 km^2).

The shore of Middle Harbour is mostly rugged, forested or barren with few flat land areas so the area was almost entirely neglected for the first two centuries of European settlement in Sydney. Land use in the catchment is mainly residential with a population of approximately 200,000 people. There is also some industrial and commercial land use. Middle Harbour has a sparsely developed catchment in comparison to the other catchments. Furthermore, development is relatively young and largely devoid of heavy industry, predominantly featuring business and residential zoning. Middle Harbour has a total of 17 tributary creeks:

- Fireclay Gully Creek
- Bare Creek
- Frenchs Creek
- Carroll Creek
- High Ridge Gully Creek
- Rock Creek
- Stony Creek
- Gordon Creek
- Middle Harbour Creek
- Moores Creek
- Bates Creek
- Scotts Creek
- Camp Creek
- Sugarloaf Creek
- Sailors Bay Creek
- Flat Rock Creek
- Willoughby Creek.

2.4.4 Foreshore areas draining to Port Jackson

Port Jackson is a Harbour that ‘comprises of all the waters within an imaginary line joining North Head and South Head. Within this Harbour lie North Harbour, Middle Harbour and Sydney Harbour (Geographical names board of New South Wales, Reference no. 47142). For the purposes of this study the ‘rest of Port Jackson’ refers to the Harbour components described above but excludes Middle Harbour. Despite making up almost 70% of the Sydney Harbour volume, Port Jackson has the smallest catchment, with only 55.7 km^2 of catchment. Subsequently only 6 tributary creeks feed the waterway. The catchment however, is highly developed, with a large impervious fraction resulting in high runoff volumes per unit of land in comparison to the other sub-catchments:

- Rush Cutters Creek
- Double Bay Creek
- Whites Creek
- Orphan School Creek
- Johnstons Creek
- Sirius Creek.

These foreshore catchment areas flowing to Port Jackson cover approximately 39 km^2. The Harbour is semi diurnal tide dominated and stretches 19 km from the most easterly point at the Tasman Sea at the entrance at North and South Heads to the most westerly point where Lane Cove and Parramatta Rivers enter the port.

The Harbour is heavily embayed. The bays on the southern side of the Harbour tend to be wide and rounded, whereas bays on the south side are generally narrow inlets. There are many recreational and bushland areas including the Sydney Harbour National Park scattered throughout the mainland and many of the bays have beaches. The major central business district of Sydney (1,687 m^2) begins at Circular Quay, which started as a small bay on the south side that overtime has become a rectangular quay due to the reclaiming of land. The northern side of the Harbour is mainly used for residential purposes.

2.5 Catchment land use

Table 2.1 and Figure 2.3 summarise the relative land use areas of the major subcatchments in the Sydney Harbour catchment. Figure 2.3 shows that the catchment is heavily urbanized with 80% of the catchment covered by urban land use types. The majority of the catchment is residential (47%), 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.

Table 2.1 Relative land use areas of the Sydney Harbour subcatchments

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%

Sewer overflows are also a substantial issue in the catchment. Figure 2.4 shows the sewer overflow points in the catchment. Sewer overflows can be caused by illegal connections of stormwater into the sewer system and incursion of stormwater and rainfall into sewer pipes due to cracks in the pipe network. These overflows generally operate during high flow events and discharge a mix of stormwater and untreated sewage.

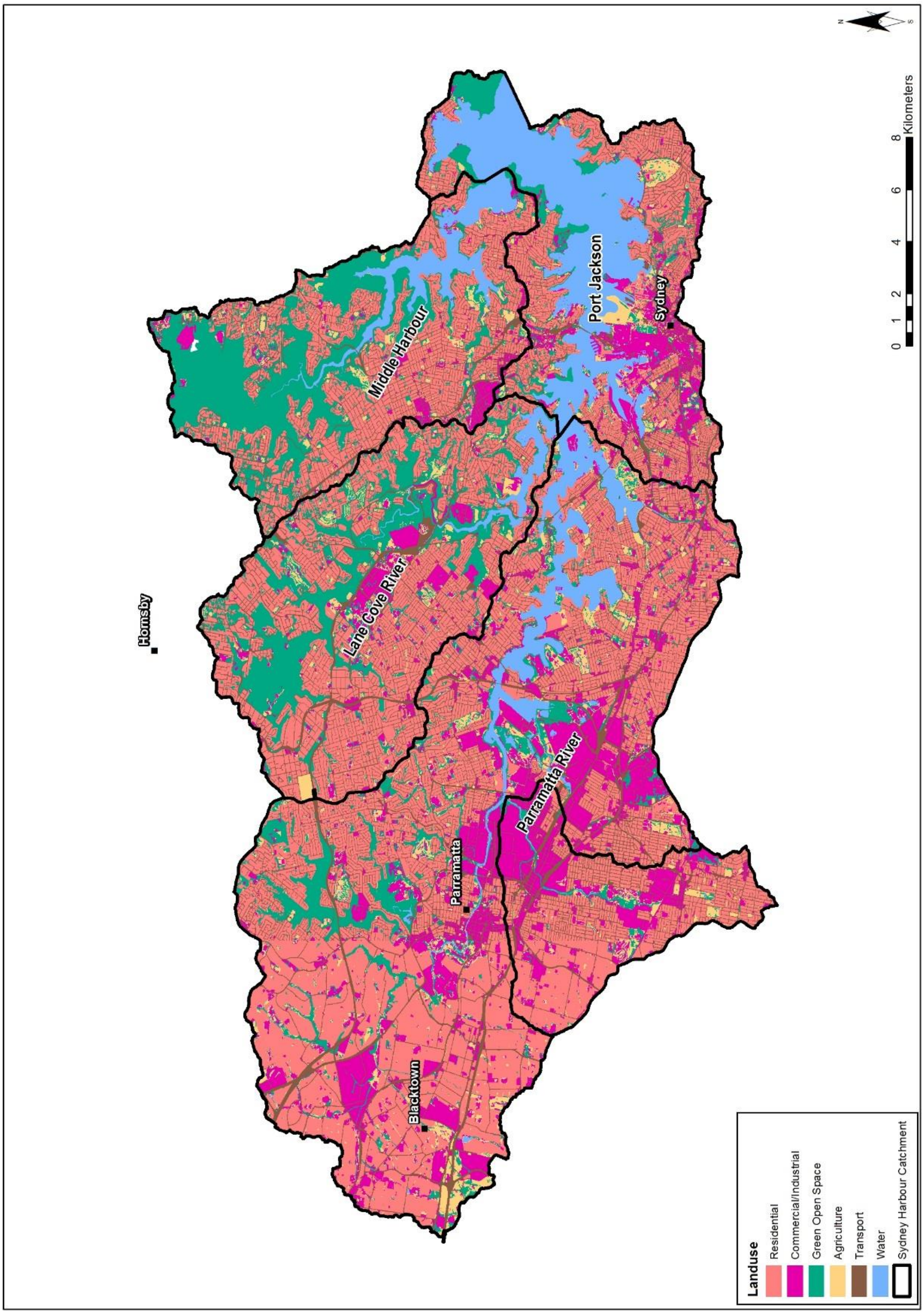


Figure 2.3 Land use in the Sydney Harbour catchment

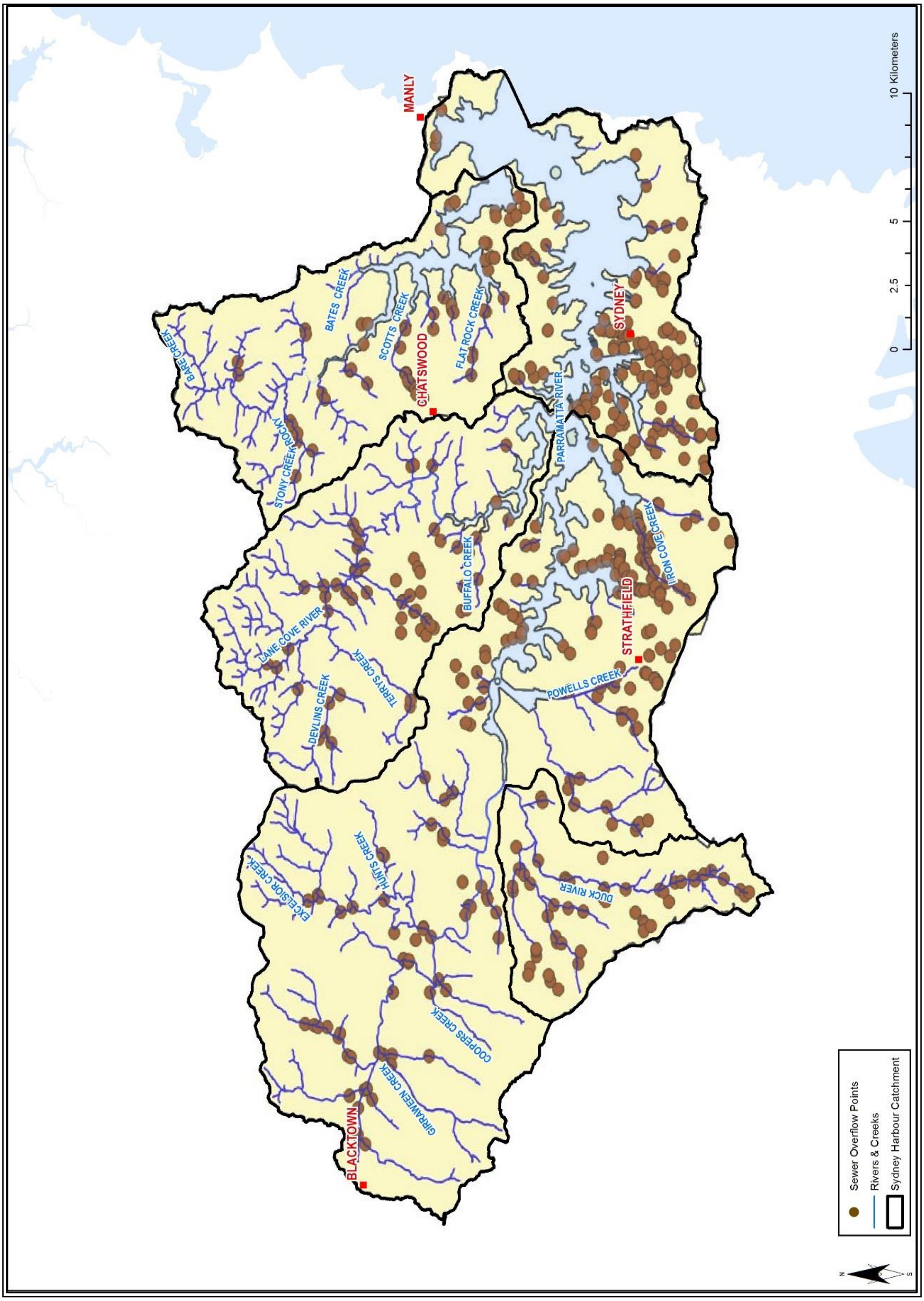


Figure 2.4 **Sewer overflow points in the Sydney Harbour catchment**

2.6 Past and current actions

Past actions in and around the Harbour have played a significant role in the condition of the estuaries and waterways today, particularly with regard to industrial pollution and toxic sediments, and the constructions of barriers including seawalls and weirs.

Up until the 1970's industrial waste was dumped into the Parramatta River. This has resulted in the southern central embayments being heavily contaminated with a range of heavy metals and chemicals. The northern embayments are not as affected because lack of access to the northern shore delayed industrialisation and development of these areas. Homebush Bay, Iron Cove and the area around Breakfast Point are the most contaminated areas. There are numerous fishing bans in the Parramatta River due to contamination particularly around Homebush Bay where there is a complete fishing ban. Stakeholders acknowledged that heavy industry in the past around Darling Harbour had also contaminated sediments and suggested that they would value sediments being cleaned up enough so fish could be eaten.

In tidal sections below Fullers Bridge (Lane Cove catchment), industrial waste was released into the Lane Cove estuary up until the early 1990's. Toxic chemicals from tanneries were released into the Burns Bay catchment from the 1880's to 1970 and effluent from the corn starch factory near Epping Road was disposed directly into the estuary until 1991. There is also potential for leachate to enter the estuary from landfills at Buffalo Creek (operated 1950's – 1972), Magdala Road (operated 1959-1972) and Stony Creek (operated 1954-1980). Dredging of the middle section of the Lane Cove River estuary took place in the late 1950's to 1974; however, there has been concern that this inhibited tidal flushing of the estuary.

In Middle Harbour, sedimentation is present in the north and south arms of Sandy Loaf Bay where Flat Rock Creek discharges into Long Bay and Sandy Bay, Clontarf. This area was last dredged in 1988. Since this time the sediment is visible at low tide for 50 metres from the rock walls which has restricted boating and recreational fishing in the area (Reocities, accessed 2014).

Since European settlement there has been significant alteration to the Harbour shore line. In 1978 Pitblado (1978; in Hedge *et al.*, 2014a) estimated that about 24% (or 77 km) of shoreline had been removed due to reclamation, while more recently Hedge *et al.* (2013) suggest that more than 50% of the intertidal shoreline is made up of artificial breakwalls. Others reported that about 22% of the estuary (50km^2) had been reclaimed for industry, residential and recreational purposes (Birch, 2007; Birch *et al.*, 2009 in Hedge *et al.*, 2014a).

In the 1930's a weir was constructed above the tidal range across the river at Fullers Bridge in the Lane Cove catchment. This prevented tidal ingress upstream of the weir and caused significant changes to the physical processes and natural ecosystems by creating a low energy freshwater sedimentary environment behind the weir. Although the Lane Cove estuary has undergone significant environmental change since European settlement, extensive rocky shoreline sections remain as open space or narrow areas of natural (or modified) bushland between low to moderate density urban development. Larger areas of bushland surrounding the river's edge are near Riverview and Lane Cove West. In the middle to northern reaches (Fig Tree Bridge to Fullers Weir) approximately 80% of the main arm of both sides of the river is covered with bands of riparian vegetation that extends greater than 20 metres from the shoreline.

The hydrodynamics of Sydney Harbour play an important role in the state of its water quality. Rainfall in Sydney is characterised by dry conditions with infrequent high rainfall events (>50 mm rainfall) (Hedge *et al.*, 2013). Stormwater is therefore mainly generated under high rainfall events with the volume of stormwater under dry, intermediate and high rainfall conditions 10, 30 and 60% respectively (Birch and Rochford, 2010; Lee *et al.*, 2011 in Hedge *et al.*, 2014a). The Harbour is well flushed near the entrance but poorly flushed in the upper reaches. Water residence time varies from 0-20 days in the main body of water, to up to 130 days in the top of Parramatta River (Roughan *et al.,* unpublished in Hedge *et al.*, 2014a). Therefore, during high rainfall and consequential stormwater events, pollutants that are discharged near to the outlet can be flushed to the ocean, but otherwise they will linger within the estuaries.

While many swimming baths in Middle Harbour often comply with water quality guidelines, *faecal coliform* and *Enterococci* compliances are considerably varied. There are also several stormwater overflows throughout the catchment that contribute pollution to Middle Harbour. Contaminants include suspended solids, nutrients (phosphorus and nitrogen), hydrocarbons, herbicides and pesticides from houses, gardens, roads and industrial areas.

In Port Jackson, industrialisation in the Sydney area has caused marine pollution and anthropogenic sediment to be deposited into the Harbour. There are several sewer overflow points and stormwater drain discharges throughout the region, thus water quality compliance is varied across the Port Jackson region. *Faecal coliform* and *Enterococci* densities tend to increase with increasing rainfall.

2.6 Vegetation

This section of the Report documents the Harbour's Littoral Rainforest, foreshore and intertidal vegetation.

2.6.1 Littoral Rainforest

Littoral Rainforest is an endangered ecological community (EEC) listed under the Australian Government's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) and the NSW Threatened Species Conservation Act 1995. The ecological community provides habitat for over 70 threatened plants and animals and it provides an important buffer to coastal erosion and wind damage. An ecological community is an assemblage of species which can include flora, fauna and other living organisms that occur together in a particular area. They are generally recognized by the trees, shrubs and groundcover plants that live there.

Littoral Rainforest is a closed forest ecological community recognised by its close proximity to the ocean (generally <2km) and closed canopy (i.e. ~70% of the sky obscured by tree leaves and limbs). Vegetation structure can range from low thickets in wind exposed environments to tall forest in more protected sites. The plant species in this ecological community are predominantly rainforest species with moist, evergreen, leathery leaves (eg. *Acmena smithii*, lilly pilly – figure 2.5) and vines may be a major component of the canopy. Whilst dominated by rainforest species, scattered individuals of sclerophyllous (hardleaved) plants, such as Smooth-barked Apple (*Angophora costata*), Coastal Banksia (*Banksia integrifolia*), Bangalay (*Eucalyptus botryoides*) and Forest Red Gum (*E. tereticornis*) may also be present.

The height of the canopy plants varies depending on the degree of exposure and can range from one to 25 metres. Emergent trees may be present above the canopy, for example species from the genera Araucaria (Bunya and Hoop pines in the northern bioregions only), Banksia or Eucalyptus. The ground layer of the vegetation typically is sparse. Plants with drought tolerant and succulent features are generally more common in littoral rainforest than in more inland rainforest types. Trunks often host lichens (but rarely mosses) and canopy stem sizes tend to be smaller compared to that in more inland rainforest. Ground ferns and epiphytes are lower in diversity in littoral rainforests compared to many other rainforest types. Feather palms, fan palms and large leaved epiphytes are generally rare.

Figure 2.5 ***Acmena smithii,*** **lilly pilly**

Littoral Rainforests have important cultural significance to Indigenous people. They are rich sites for hunting and gathering due to the provision of foods, fibers and medicines. Their location by the sea also made them ideal for meeting and camping (DEE, 2016). Fruits found in Littoral Rainforest in the Sydney Basin region include lilly pilly (*Syzygium smithii*) and wild grapes (*Cissus hypoglauca*) (Isaacs, 2002). The cabbage-tree palm (*Livistona australis*) was also important and rhizomes from common bracken (*Pteridium esculentus*) were beaten into a paste, roasted and eaten. New Zealand spinach (*Tetragonia tetragonioides*) was an important green vegetable and flowers of Callistemon species were sucked for nectar (Isaacs, 2002).

Rainforest plants were also harvested for medicinal purposes. For example; heated leaves from the peanut tree (*Sterculia quadrifida*) was used for stingray and stonefish stings; swelling and diarrhoea were treated with the leaves of the sandpaper fig (*Ficus opposita*); bark from the cocky apple (*Planchonia careya*) was used to treat wounds; coughs were treated with native sarsaparilla (*Smilax glyciphylla*); rheumatism and sprains were treated with stinging nettle (*Urtica incise*); stomach ailments, muscular pains and toothaches were treated red ash (*Alphitonia excelsa*) (Low, 1990) and the seeds of the buttercup orchid (*Cymbidium madidum*) were said to confer sterility (Isaacs, 2002).

Gathering of fruit in Littoral Rainforest habitats was also accompanied by hunting of a variety of mammals and birds that were attracted to the fruiting plants, as well as hunting of snakes which were drawn in by the high abundances of mammals and birds (Isaacs, 2002). Numerous grubs, snails and other invertebrate taxa were also harvested.

The main threats to littoral rainforest are clearing and land development. Developments nearby or upstream that change drainage patterns also impact on the EEC. Other impacts include those resulting from climate change, such increased storm activity and intensity, changes to fire regimes and species composition.

An interactive map of the NSW Coastal Management SEPP areas, that includes littoral rainforest of Sydney is available on the OEH website at:

http://webmap.environment.nsw.gov.au/PlanningHtml5Viewer/?viewer=SEPP_CoastalManagement

An extract showing the littoral rainforest mapped for Sydney Harbour is provided in Figure 2.6.

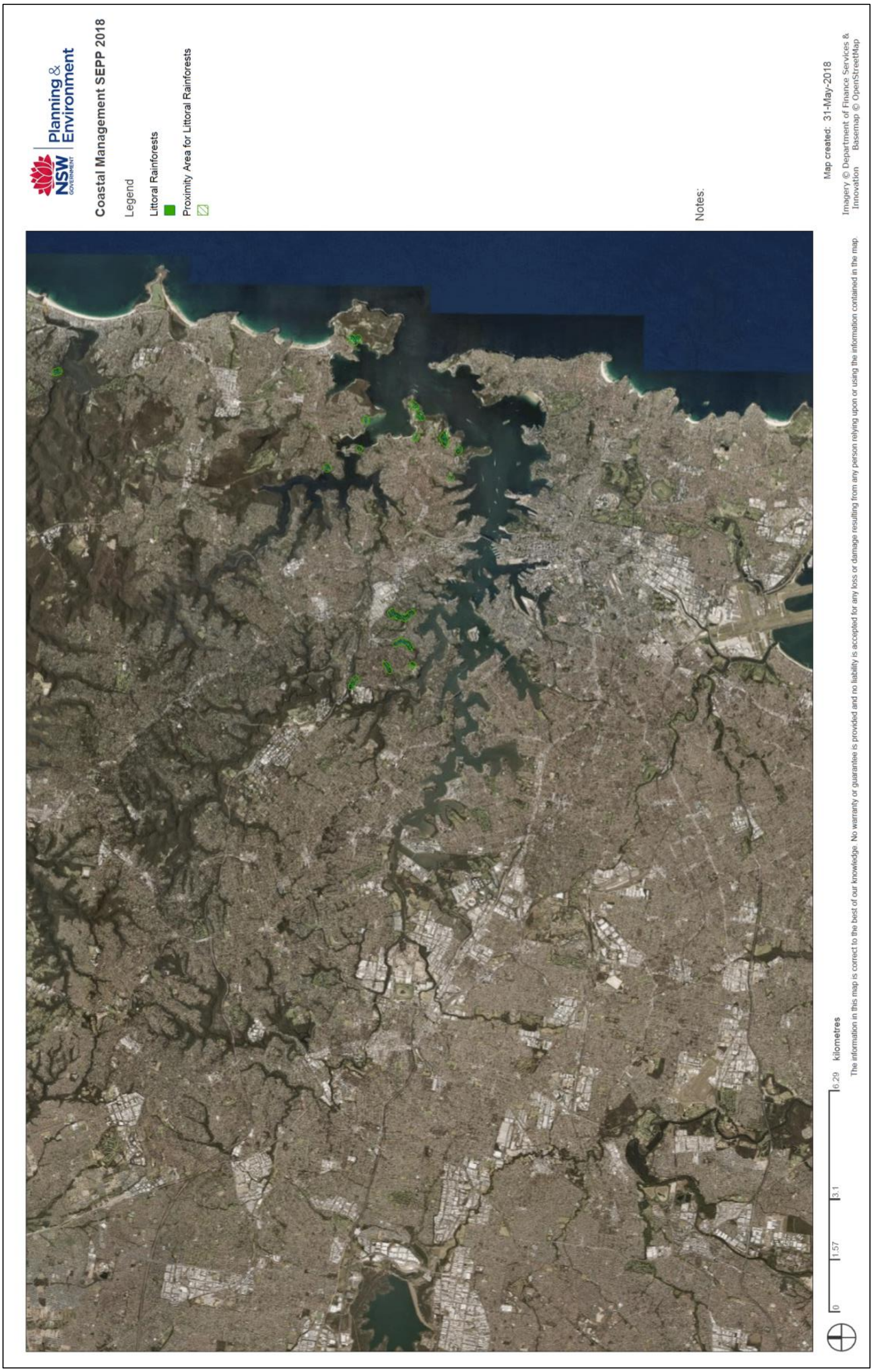


Figure 2.6 **CM SEPP littoral rainforest and proximity area**

2.6.2 Foreshore and Estuarine Vegetation

Saltmarsh and Mangroves

Macrophytes are terrestrial plants adapted to living on the edge of saltwater or in shallow water. Several seagrass species have been reported in Sydney Harbour (Hedge *et al.,* 2014a). The population of strapweed seagrass, *Posidonia australis*, has undergone such a significant decline in its distribution in Sydney Harbour that it was recently listed as an endangered population under the *Fisheries Management Act 1994*. There are at least six species of mangroves in NSW, of which the two most common occur in Sydney Harbour; the grey mangrove and the river mangrove. Mangroves are protected from 'harm' under the Fisheries Management Act 1994. Nineteen saltmarsh species are found within Sydney Harbour. One of these (*Wilsonia backhousei*) is listed as vulnerable under the *Threatened Species Conservation Act 1995*.

Coastal (intertidal) saltmarsh has been defined as an intertidal plant community complex dominated by herbs and low shrubs (Adam, 1995). Saltmarshes generally occur between average high water of spring and neap tides (Morrisey, 1995). For the most part there is a clear structural distinction between saltmarsh and mangrove, which is defined as an intertidal community dominated by trees (Adam, 1995). Saltmarsh provides habitat for numerous organisms of both terrestrial and marine origin and are potentially important for commercially and recreationally significant fishes (Adam, 1995).

Patterns of 'zonation' have been described by Morrisey (1995) for NSW saltmarshes. Morrisey (1995) suggests that *Sarcocornia quinquiflora* occupy the lowest point in this zonation, where the saltmarsh meets the mangroves. Morrisey (1995) suggests that the grass *Sporobulus virginicus* is often found here but can also occur higher on the shore, however, the upper marsh is generally colonised by sedges and rushes, dominated by Juncus and other plants. Morrisey (1995) suggests that within this broad-scale pattern of zonation there is small-scale patchiness and the saltmarsh appears as a mosaic of patches of different assemblages.

Coastal wetlands are popularly identified as important habitats for birds (Adam, 1995). The number of species breeding in saltmarshes is small but upper marsh vegetation provides nest sites for some species (for example the white-fronted chat *Ephthianura albifrons*). A large part of the population of one of the rarest species in Australia, the orange-bellied parrot (*Neophema chrysogaster*), overwinters on saltmarshes in Victoria where it feeds on the seeds of chenopods (Adam, 1995). Migratory waders feed largely on invertebrates in intertidal sand and mudflats but saltmarshes may provide secure high tide roosts. Conservation of waders is a matter for international concern and the Commonwealth is signatory to three agreements (the Ramsar Convention, the Japan-Australia Migratory Birds Agreement and the China-Australia Migratory Birds Agreement) which impose obligations to protect habitats utilised by migratory waders (Adam, 1995).

Research has outlined the presence of trophodynamic relationships between saltmarsh-derived crab zoeae, small itinerant fish (specifically the glassfish *Ambassis jacksoniensis*) and larger commercially important species of fish in estuaries of the eastern coast of Australia (Mazumder *et al*., 2006; Hollingsworth and Connolly, 2006; Platell and Freewater, 2009). Moreover, the endangered ecological community 'Coastal Saltmarsh' has been shown to play an important role in the ecological functioning of estuaries (Freewater and Gladstone, 2011).

In settled areas saltmarshes have been reclaimed for port, industrial and housing development, road construction, parks and sports fields. In more recent decades saltmarshes at sites well removed from existing urban centres have been threatened by developments for recreation and tourism (marinas, resorts and canal estates). Construction of solar salt production ponds in Western Australia has also resulted in some loss of saltmarsh. Some reclamation for agriculture (mainly pasture) has occurred but this has probably involved much smaller areas than have been lost from freshwater wetlands on coastal floodplains. Compared with the total extent of the habitat losses are likely to have been small, but they are concentrated in the south-east of the continent where the initial total area was small and where biodiversity is highest. The losses are therefore likely to be significant both nationally in terms of effects on biodiversity and regionally in terms of loss of habitat functions. Nevertheless, it is difficult to predict the specific impacts of losses in view of the paucity of quantitative information on ecosystem functions.

A much larger area of saltmarsh than has been lost from reclamation has been damaged by various forms of habitat degradation. Adjacent to settlements many saltmarshes are subject to illegal rubbish dumping and to disturbance through the construction and maintenance of easements for pipelines and powerlines. Vehicular use alters the microtopography and drainage, leading to changes in vegetation. Even if access is prevented (an impossibility in most instances) recovery may take many years (Freewater and Gladstone, 2011). Trampling may cause long term damage to vegetation, in particular where succulent species predominate. Stormwater drains frequently discharge into saltmarshes. Apart from introducing gross pollutants, nutrients and weed propagules, freshwater discharge can cause local erosion and, through altering the salinity regime, promote the spread of fresh or brackish water species such as *Phragmites australis* and Typha species at the expense of more salt tolerant species. Saltmarshes are depositional sinks and pollutants from both terrestrial and marine sources may accumulate in them. Sewage discharge and runoff from agricultural catchments may promote algal productivity in estuaries, and the accumulation of decaying masses of algae on saltmarsh may cause damage to the underlying vegetation. Oil spills close to sea ports have affected some marshes but these impacts have been inadequately studied (Freewater and Gladstone, 2011).

The harsh physio-chemical environment of saltmarshes could be assumed to provide protection against invasion by exotic species. Nevertheless, a number of significant invasive weeds threaten the natural biodiversity and community structure of saltmarshes, including the cord grass *Spartina anglica*, pampas grass *Cortaderia selloana* and the rush, *Juncus acutus*.

As a consequence of global warming, associated with the 'Greenhouse effect', sea level may rise. Intertidal wetlands have adjusted to previous sea level fluctuations but the consequences of a rise in the near future may be different from those of the past. If the sea level were to rise, a regression of the seaward boundary of intertidal wetlands would occur (Freewater and Gladstone, 2011). Where topography and other circumstances permit, this regression would be accompanied by an extension landward. However, in much of south-eastern and south-western Australia alienation of the hinterland for a variety of usages would mean severe limits on opportunities for landward movement and sea level rise would be accompanied by net loss of habitat. In the case of saltmarsh this loss would be exacerbated by the landward expansion of mangroves into former saltmarsh.

The majority of saltmarsh is outside formal reserves. Protection from development can be conferred through planning, and increased public concern for wetland protection (particularly for coastal wetlands) has meant that planning authorities have, over the past decade, taken an increasingly sympathetic view towards saltmarsh protection (Freewater and Gladstone, 2011).

Large scale maps of saltmarsh in Sydney Harbour, produced in the early 1980s and the mid 2000s, were based on air photo interpretation with follow-up field checks to determine the ability of air photos to detect small patches of coastal saltmarsh (Williams *et al*., 2011). The ground-truthing revealed another 609 patches not seen on the air photos. It also meant that many small patches, obscured in the air photos by mangrove canopy were resolved and joined to reveal larger patches of saltmarsh. Whilst this work seemed to indicate an increase in the total area of existing saltmarsh, they also may be areas of saltmarsh that have been recently invaded by mangroves and may result in the loss of the saltmarsh species at these sites (Williams *et al*., 2011).

According to Williams *et al*. (2011), the pedestrian survey located 757 saltmarsh patches (70% of these were less than 100 m^2 in area) with a total area of 37.3 ha. Williams *et al*. (2011) indicate that Parramatta River, relative to the Lane Cove River, Middle Harbour Creek and Sydney Harbour, supports the most numerous and extensive patches: 461 patches (61% by number), 29 ha (78% by area). Most of the patches of saltmarsh (60%), as well as most of their area (76%), are located in the most upstream Riverine Channel geomorphic zone of the Parramatta River, followed by downstream zones Fluvial Delta and Central Mud Basin. The fewest patches (14) and smallest area (0.04 ha) were in the Marine Tidal Delta. Williams *et al*. (2011) found the *conservation sensitive* species as well as some of the weed species also appeared to be restricted to the upper and middle parts of the estuary.

In 2007, The Sydney Metropolitan Catchment Management Authority (SMCMA) led a project understand the type and condition of vegetation in the Harbour waters and on the foreshore lands and its value to the ecosystems and biodiversity - *Sydney Harbour Foreshore & Estuarine Vegetation*

Mapping: Assessment, Planning and Management report (SMCMA, 2008). The aim was to develop appropriate management actions for the different stakeholders. It is emphasized that these data sets are now 10 years old and some changes in vegetation are expected. However, the changes are not likely to be significant.

The estuarine components of this project covered all estuarine areas of Sydney Harbour, Parramatta River and tributaries. This included the area from North Head to South Head, including upstream to the natural tidal limits of Middle Harbour (St. Ives and Davidson) to the weir on Lane Cove River; the eastern-most weir at Parramatta; and to Granville at Duck River and Duck Creek.

The foreshore components of this project included, as a minimum, the foreshore land from Mean High Water Mark (MHWM) to 40 m landward. In some instances, the mapping was extended upslope beyond 40 m to a maximum of 200 m, where contiguous vegetation was present. The shoreline of the study area is a little over 360 km in length.

Threats to vegetation are listed in table 2.2.

Management options listed were based on a series of guiding principles to maintain areas of high conversation value and to protect and enhance areas of habitats that were considered poor or average condition. These principles included:

- Avoid separation of high conservation value lands and provide more connectivity between vegetation areas
- Reduce the amount of edges of habitats areas by consolidate development and conservation area boundaries
- Minimise risks to biodiversity and habitats and rehabilitate native vegetation communities
- Reduce the indirect impacts of surrounding land use such as impacts on water quality.

Management actions were then separated into 4 categories:

1. **Strategic Planning** – through development applications and proposals, consideration is given to threatened species and biodiversity. Assessment of each application on case by case basis has a cumulative adverse impact on the amount of vegetation remaining or impacts from development, such as change in water quality. Several strategic planning mechanisms such as the standard Local Environment Plan (LEP) provide a set of rules each development application must adhere to. This in turn ensures consistency in the decision making of the applications.

2. **Land and Water Management** – Local Government has an important role in managing lands through land use planning, education and providing resources. Through this management, Council can proactively protect specific native vegetation areas, like saltmarsh. Other Council operations such as maintenance of foreshore lands can directly affect the land and water quality too that has direct impact on the foreshore vegetation.

3. **Education –** by undertaking education and awareness campaigns, decisions can be made on behaviour that directly impacts and influences biodiversity and vegetation. Over time this will have significant impact in increasing the understanding and skills of foreshore vegetation.

4. **Resources –** these are the factors that are needed to implement to the management options. It can include funding, materials, info and staff. The management options listed below aim to make the most of these resources to make a positive change.

Examples of management actions are listed in table 2.3.

Table 2.2 Threats to Vegetation

	Saltmarsh	Seagrass	Fauna	Mangrove	Terrestrial Foreshore vegetation
Increased flooding from sea level rise	✓	✓	✓	✓	✓
Stormwater channel structures		✓	✓		
Decrease in water quality from stormwater runoff	✓	✓	✓	✓	✓
Unmanaged Access - Trampling from foreshore walking tracks	✓		✓	✓	✓
Rubbish Dumping	✓	✓	✓	✓	✓
Litter	✓		✓		
Fire Damage			✓		✓
Invasion by weeds and migration of weeds with changing climates.	✓		✓		✓
Urban and dry land salinity					
Acid Sulphate Soils					
Soil Disturbance					
Anchour and Outboard motors damaging seagrass beds		✓	✓		
Structures shading seagrass		✓	✓		
Illegal clearing of vegetation for recreation and views			✓	✓	✓
Location to recreation activities	✓		✓		✓
Recreational vehicles	✓	✓		✓	✓
Incursion of Mangrove and other species		✓			
Land clearing, fragmentation and degradation.	✓		✓		✓
Changes to natural flow regime	✓	✓	✓		

Table 2.3 Management examples

Management Type	**Topic**	**Example Actions**
Strategic Planning	Land Zoning in Local Environmental Plans	Councils review and propose amendments to zoning and special provisions (e.g. approval for clearing of native vegetation) of foreshore areas containing native vegetation remnants and estuarine vegetation. NSW Department of Planning & Environment has approval function to amend the zoning. Provisions are already set / developed for in biodiversity management.
	Waterways and Riparian Zones	Additional zoning through the Sydney Regional Environmental Plan (and Councils LEP) for riparian vegetation and the

		waterways. These zonings would aim to prevent development that would have an adverse impact on the natural waterways.
	Environmental Protection Overlays	Additional requirements for preventing adverse impacts to biodiversity from development. These requirements are specific to certain areas as specified in the Local Environment Plan (LEP) and shown on associated maps.
	Other	Water Sensitive Urban Design – treatment of stormwater and runoff within the whole Sydney Harbour catchment, prior to entering rivers or watercourses to ensure water quality is maintained for biodiversity.
Water and Land Management	Community Land	Using the vegetation mapping, plant relevant local species in regeneration projects.
	Prepare Plans of Management	Prepare a generic plan of management for all council reserves. These plans of management should identify and propose suitable management options to biodiversity and habitat function in the area.
	Manage fire for the protection of life, property and biodiversity	Identify and locate fire sensitive species of flora and fauna (eg. rainforest gullies) and develop management recommendations.
	Improve water quality and habitat for aquatic biodiversity for the wellbeing of many different plants and animals.	Retain natural drainage systems and prioritise the rehabilitation of concrete lined stormwater channels to a more natural condition to provide space for biodiversity.
	Weed Management - compete with native species and are often unsuitable habitat or food for native animals.	Conduct inspections to identify the presence of noxious weeds within foreshore lands and issue notices for weed control
	Feral Animals - potential contributor to extinction of some native animals	Liaise with animal ethics organisations to identify best practice/most effective control methods
	Council Operations to protect and enhance biodiversity values on council foreshore lands	No mow zones or designated access points.
Education	Community Awareness – raising awareness about importance of biodiversity.	Communicate the link between everyday activities such as land clearing and pollution and the effect this has on threatened species and their habitat.

	Develop skills within the community to help conserve biodiversity in foreshore areas.	Support and develop Bushcare and Landcare groups for areas.
	Develop training and resources within Councils	Access to mapping and continuous updates on biodiversity legislation and policy changes.
	Provision of information to key people whose activities may affect vegetation	Educate builders and developers to achieve better control of sedimentation from building sites using existing Council information.
	Gather information about level of understanding to inform education programs	Conduct survey of council residents to identify knowledge about behaviour that impacts on biodiversity – eg. litter stormwater, illegal clearing etc. and feed this into education material.
Resources	Data Management Strategy	Council to develop a process for storing, handling and accessing information that is kept up-to-date and relevant.
	Partnerships	Enhance the social aspect of Bushcare activities that involve biodiversity by encouraging field days, picnics and outings for interested parties.
	Grants and Funding	Other funding could also be sought from business through various partnerships, sponsorships of various programs.

The following ***Sydney Harbour Foreshore & Estuarine Vegetation Mapping: Assessment, Planning and Management*** (SMCMA, 2008) maps are provided:

- Conservation Priorities - Figure 2.7
- Endangered Ecological Communities - Figure 2.8
- Saltmarsh Locations - Figure 2.9

Figure 2.10 Provides an extract from CM SEPP showing the coastal wetlands and proximity area mapped for Sydney Harbour.

The Sydney Coastal Council Group produced a report on threats to saltmarsh and mangroves in the Harbour (Rogers *et al.*, 2017). They describe ecosystem services provided by estuarine wetlands in the Sydney region. These services are summarised briefly below:

- *Fisheries provision*: Research at Towra Point and Homebush Bay has demonstrated the importance of intertidal mangrove and saltmarsh as a habitat for estuarine fish, including species of commercial significance (Mazumder *et al.*, 2006; Freewater *et al.,* 2007). The release of crab larvae from these wetlands into the spring tide provides an important source of nutrition for zooplanktivorous fishes (principally the Port Jackson Glassfish *Ambassis jacksoniensis*) but also juveniles of commercially important species (eg the Flat Tailed Mullet *Liza argentea*). These species, the most numerically important in the estuary, in turn serve as prey for higher order carnivores, such as the bream *Acanthropagrus australis.*

- *Biodiversity Habitat Provision*: Coastal saltmarsh is an important roosting habitat for migratory shorebirds. Migratory birds inhabiting estuaries feed on nutrient rich mudflats exposed by the low tide, but at high tide select roosting habitats providing protection from predators and, if possible, secondary feeding opportunities. A study by Lawler (1998) of 134 roosting sites found 83% to be more than 30 m distant from 5m tall trees, including mangroves. While mangroves were used as roosts by some species, these were primarily those immediately adjacent to the estuary. Spencer (2010) working in the Hunter estuary found waders preferentially using saltmarsh as a night time roost, and feeding on chironomids within saltmarsh pools to supplement their diet.

- *Carbon sequestration*: Mangroves and saltmarsh are highly effective at capturing and storing atmospheric carbon dioxide, a characteristic captured by the term “Blue Carbon”. Saintilan *et al.* (2013) demonstrated relatively high carbon stores within mangrove and saltmarsh in the Hawkesbury River to the north of the region, with higher carbon in the saltmarsh rush *Juncus kraussii* than in the succulent and grass-dominated saltmarsh communities. Kelleway *et al.* (2016) demonstrated that mangrove encroachment of saltmarsh at two locations on the Georges River (Half Moon Bay and Towra Point) over 70 years led to an increase in carbon store, primarily after 40 years. Carbon stores are lower in sandy environments characteristic of the flood-tide deltaic mouths of estuaries and higher in the riverine silts and muds of the fluvial delta and mud basin environments (Kelleway *et al.*, 2016, Saintilan *et al.*, 2013).

- *Shoreline protection*: The root systems of mangrove and saltmarsh protect estuarine shorelines in two important ways. First, they add to the cohesive strength of soils by providing a connected matrix resistant to erosion (Krauss *et al.*, 2014). Second, they promote vertical accretion of sediment, both by interrupting flow and thereby promoting soil deposition, but also more directly through root mass increase over time. In this way the presence of mangrove and saltmarsh improves the capacity of the wetland to increase elevation in relation to sea-level rise. At Homebush Bay, mangrove surface elevation gain has matched the rate of sea-level rise since 2000 (Saintilan and Rogers in prep.), though saltmarsh has been less effective in this regard.

- *Visual amenity*: Shoreline vegetation is an important component of the visual landscape of the urban estuary. Efforts to provide a more aesthetically pleasing environment in relation to concreted channels have been one driver for the reintroduction of coastal saltmarsh in such programs as the Cooks River Urban Water Initiative.

(Rogers *et al*., 2017)

According to Rogers *et al.* (2017), a comparison of historic and aerial photography has demonstrated a consistent increase in mangrove extent and subsequent saltmarsh decline. The decline has prompted the listing of Coastal Saltmarsh as an Endangered Ecological Community in three NSW Bioregions, including the Sydney Basin bioregion (Rogers *et al.,* 2017). They suggest that changes in relative sea-level are likely to have been an important driver of mangrove encroachment into saltmarsh across SE Australia and is consistent with a global trend of mangrove proliferation at poleward limits of mangrove range (Saintilan *et al.*, 2014).

Table 2.4 lists available georeferenced spatial data for Sydney Harbour.

Sporobolus virginicus

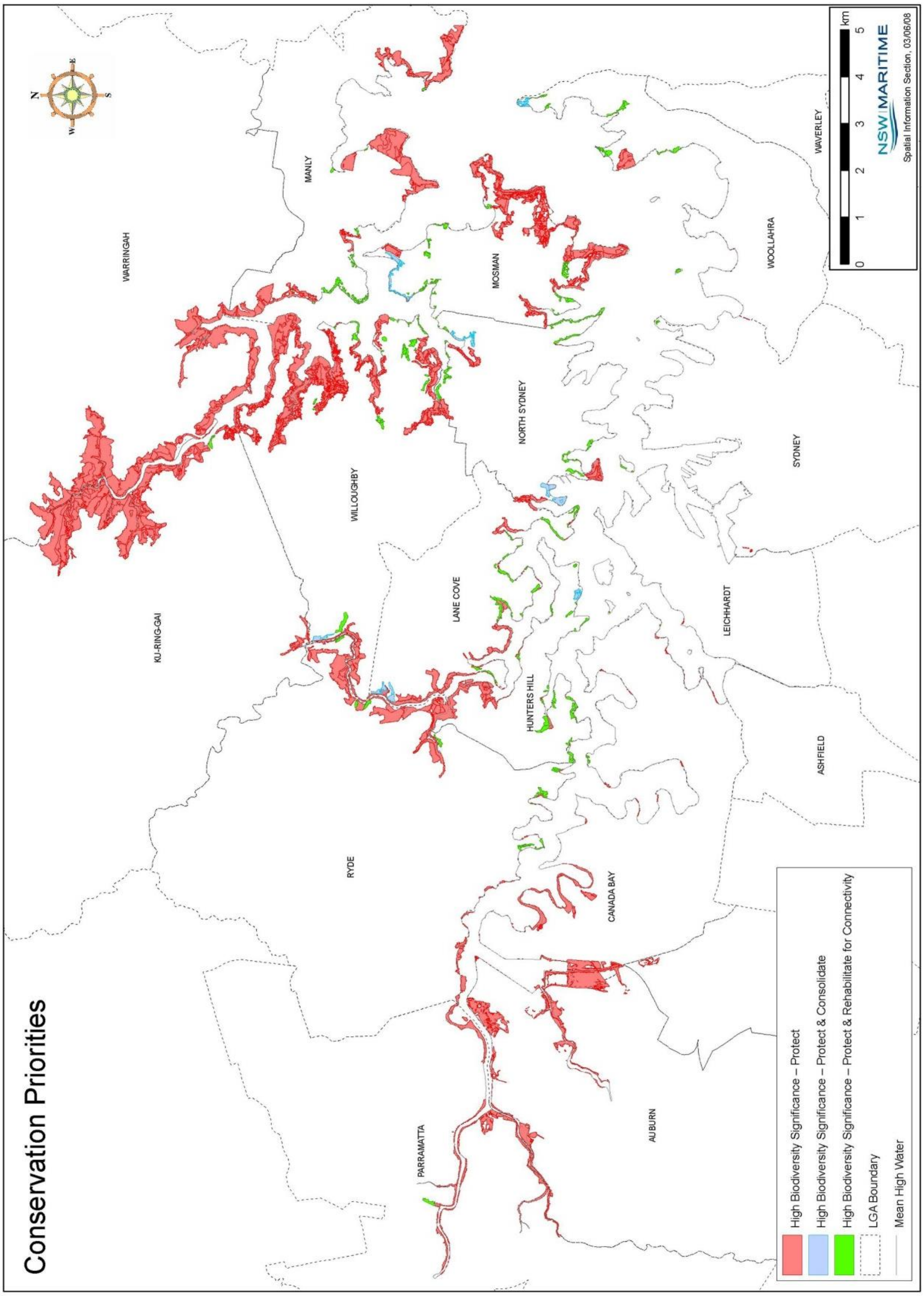


Figure 2.7 Conservation Priorities (SMCMA, 2008)

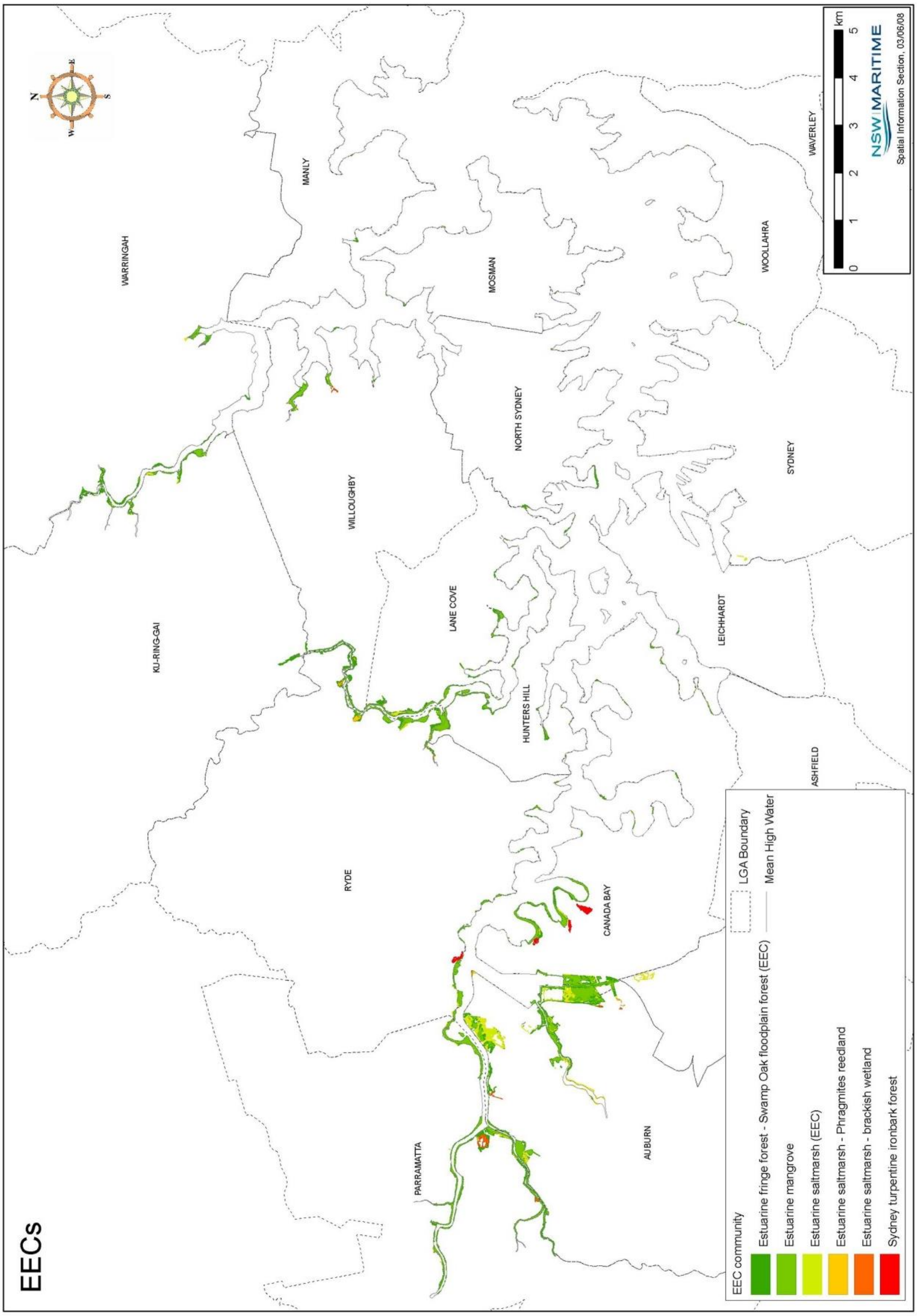


Figure 2.8 Endangered Ecological Communities (SMCMA, 2008)

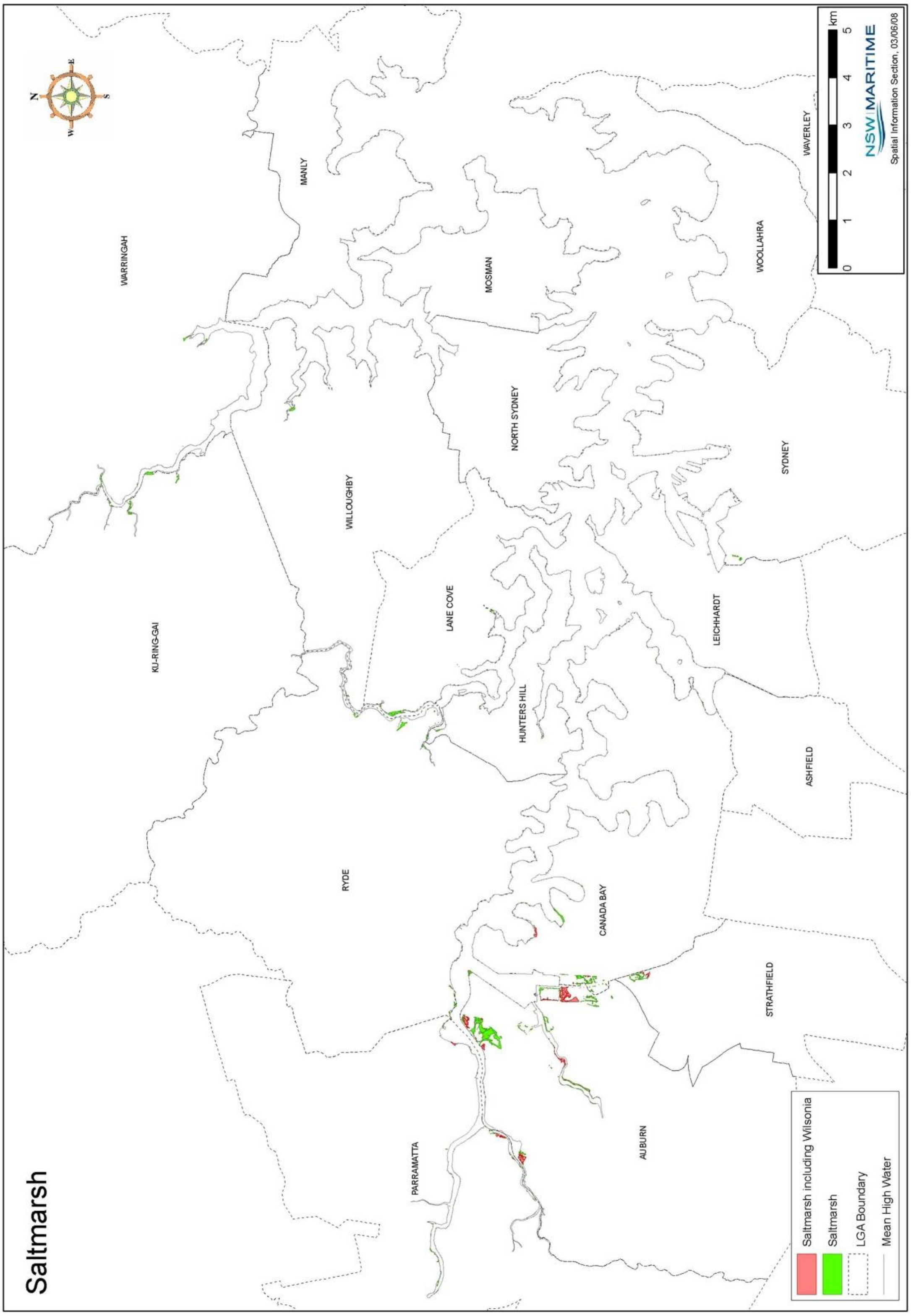


Figure 2.9 Saltmarsh Locations (SMCMA, 2008)

Figure 2.10 CM SEPP coastal wetlands and proximity area for Sydney Harbour

Table 2.4 Georeferenced spatial data for Sydney Harbour

Category	Spatial Layer	Source
PLANNNING	Standard Instrument Local Environmental Plan - Land Zoning	NSW Department of Planning and Environment
ENVIRONMENT	Estuaries (Macrophytes Details)	NSW Office of Environment and Heritage
ENVIRONMENT	Nearshore subtidal marine reef systems and soft sediment mapping, New South Wales	NSW Office of Environment and Heritage
PLANNNING	State Environmental Planning Policy no. 71 - Coastal Protection	NSW Department of Planning and Environment
ENVIRONMENT	NSW Marine Habitats 2002	NSW Office of Environment and Heritage
INFRASTUCTURE	Boat Ramps	NSW Road and Maritime Services
PHYSICAL ENVIRONMENT	Estuary Depth	NSW Office of Environment and Heritage
ENVIRONMENT	Estuary Condition Rating System	NSW Office of Environment and Heritage
PLANNNING	NSW Marine Park Boundaries 2007	NSW Office of Environment and Heritage
PHYSICAL ENVIRONMENT	Estuary Tidal Limits	NSW Office of Environment and Heritage
ENVIRONMENT	Estuary Mangrove Limits	NSW Office of Environment and Heritage
INFRASTUCTURE	Estuary Foreshore Structures	NSW Office of Environment and Heritage
INFRASTUCTURE	Boat Ramps	Roads and Maritime Services
INFRASTUCTURE	Wharf SH: public wharf, jetty, or landing	Roads and Maritime Services
INFRASTUCTURE	Marina SH: marina, boatshed or boat hire	Roads and Maritime Services
PHYSICAL ENVIRONMENT	Depth Contour SH: approximate depth contours in metres below Zero Fort Denison Tide Gauge	Roads and Maritime Services
INFRASTUCTURE	Seawall SH: top or toe of seawall (or retaining wall)	Roads and Maritime Services
INFRASTRUCTURE	NSW Bicycle Geodatabase 2014	Government Architect NSW
ENVIRONMENT	Ramsar Wetlands	Government Architect NSW
PLANNING	Recreation Trails	Government Architect NSW
PLANNING	Sydney Public Open Space	Government Architect NSW
ENVIRONMENT	National Parks and Wildlife Services (NPWS) Estate	Government Architect NSW
ENVIRONMENT	Metro Sea	Government Architect NSW
ENVIRONMENT	Metro Hydro Area	Government Architect NSW
ENVIRONMENT	Lakes	Government Architect NSW
ENVIRONMENT	Geophysical Strata Rating High Environmental Value (GSR HEV) Detailed OEH	Government Architect NSW
PLANNING	Green Grid Links	Government Architect NSW
ENVIRONMENT	GSC Strahler Watercourses	Government Architect NSW
ENVIRONMENT	Canals	Government Architect NSW
ENVIRONMENT	Biomap Cumberland Subregion Core Areas	Government Architect NSW
ENVIRONMENT	Biomap Cumberland Subregion Regional Corridors	Government Architect NSW
PLANNING	County (all LGAs in study)	Spatial Information Exchange (SIX) NSW Government

PLANNING	Easement (all LGAs in study)	Spatial Information Exchange (SIX) NSW Government
PLANNING	Federal Electoral Division (all LGAs in study)	Spatial Information Exchange (SIX) NSW Government
PLANNING	LALC (all LGAs in study)	Spatial Information Exchange (SIX) NSW Government
PLANNING	Land District (all LGAs in study)	Spatial Information Exchange (SIX) NSW Government
PLANNING	Lands Office (all LGAs in study)	Spatial Information Exchange (SIX) NSW Government
PLANNING	LLSR (all LGAs in study)	Spatial Information Exchange (SIX) NSW Government
PLANNING	LGA (all LGAs in study)	Spatial Information Exchange (SIX) NSW Government
PLANNING	Lot (all LGAs in study)	Spatial Information Exchange (SIX) NSW Government
ENVIRONMENT	NPWS Reserve (all LGAs in study)	Spatial Information Exchange (SIX) NSW Government
PLANNING	Parish (all LGAs in study)	Spatial Information Exchange (SIX) NSW Government
INFRASTRUCTURE	Railway Corridor (all LGAs in study)	Spatial Information Exchange (SIX) NSW Government
INFRASTRUCTURE	Road (all LGAs in study)	Spatial Information Exchange (SIX) NSW Government
INFRASTRUCTURE	Road Corridor (all LGAs in study)	Spatial Information Exchange (SIX) NSW Government
PLANNING	State Electoral District (all LGAs in study)	Spatial Information Exchange (SIX) NSW Government
ENVIRONMENT	State Forest (all LGAs in study)	Spatial Information Exchange (SIX) NSW Government
PLANNING	Suburb (all LGAs in study)	Spatial Information Exchange (SIX) NSW Government
ENVIRONMENT	Water Feature (all LGAs in study)	Spatial Information Exchange (SIX) NSW Government
ENVIRONMENT	Water Feature Corridor (all LGAs in study)	Spatial Information Exchange (SIX) NSW Government
ENVIRONMENT	Metropolitan Sydney Coastal Environment Area	NSW Department of Planning and Environment
ENVIRONMENT	Metropolitan Sydney Coastal Land Application	NSW Department of Planning and Environment
ENVIRONMENT	Metropolitan Sydney Coastal Use Area	NSW Department of Planning and Environment
ENVIRONMENT	Metropolitan Sydney Coastal Wetlands	NSW Department of Planning and Environment
ENVIRONMENT	Metropolitan Sydney Coastal Wetlands 100 m	NSW Department of Planning and Environment
ENVIRONMENT	Metropolitan Sydney Littoral Rainforests	NSW Department of Planning and Environment
ENVIRONMENT	Metropolitan Sydney Littoral Rainforests 100 m	NSW Department of Planning and Environment
ENVIRONMENT	Metropolitan Sydney Local Government Coastal Hazard Area	NSW Department of Planning and Environment
PLANNING	Metropolitan Sydney Regional Growth Area	NSW Department of Planning and Environment
PHYSICAL ENVIRONMENT	30 m DEM	Geoscience Australia
ENVIRONMENT	Estuarine Macrophytes	City of Parramatta Council
ENVIRONMENT	Vegetation Significance	City of Parramatta Council
ENVIRONMENT	Native Vegetation	City of Parramatta Council
ENVIRONMENT	Natural Area Survey 2010 data as supplied by consultant	North Sydney Council
ENVIRONMENT	Natural Area Survey 2010 data as supplied by consultant	North Sydney Council

PLANNING	North Sydney cadastral data as supplied by Land Registry	North Sydney Council
INFRASTUCTURE	Services	North Sydney Council
INFRASTUCTURE	Location of stormwater drains as maintained by NSC	North Sydney Council
ENVIRONMENT	Natural Area Survey 2010 data as supplied by consultant	North Sydney Council
INFRASTUCTURE	Pollution trap locations as maintained by NSC	North Sydney Council
INFRASTUCTURE	Seawall locations and maintained by NSC	North Sydney Council
ENVIRONMENT	Natural Area Survey 2010 data as supplied by consultant	North Sydney Council
PLANNING	North Sydney Local Environmental Plan 2013	North Sydney Council
ENVIRONMENT	Natural Area Survey 2010 data as supplied by consultant	North Sydney Council
ENVIRONMENT	Natural Area Survey 2010 data as supplied by consultant	North Sydney Council
PLANNING	Land zoned SP2 – Infrastructure “Car Park” from North	North Sydney Council
PLANNING	Sydney LEP 2013	North Sydney Council
PHYSICAL ENVIRONMENT	Contours 0.5 m	North Sydney Council
ENVIRONMENT	Biodiversity Hotspots	North Sydney Council
PLANNING	Council Controlled Land	North Sydney Council
PLANNING	Crown Land from Cadastre	North Sydney Council
PLANNING	Cadastre	City of Canada Bay
INFRASTUCTURE	Carparks	City of Canada Bay
ENVIRONMENT	Coastal land boundary	City of Canada Bay
PHYSICAL ENVIRONMENT	Bathymetry contours	City of Canada Bay
PLANNING	Crown land	City of Canada Bay
INFRASTUCTURE	Ferry wharves	City of Canada Bay
PLANNING	Flood planning, hazard and study areas	City of Canada Bay
PLANNING	Community and operational land	City of Canada Bay
ENVIRONMENT	LEP 2013 biodiversity	City of Canada Bay
PLANNING	LEP 2013 floor space ratio	City of Canada Bay
PLANNING	LEP 2013 heritage	City of Canada Bay
PLANNING	LEP 2013 height of buildings	City of Canada Bay
PLANNING	LEP 2013 land zone	City of Canada Bay
PLANNING	Parks management plan	City of Canada Bay
INFRASTUCTURE	Road centre line	City of Canada Bay
PLANNING	Cadastre	Municipality of Hunters Hill
PLANNING	LGA boundary	Municipality of Hunters Hill
PLANNING	Wards 2007	Municipality of Hunters Hill
PLANNING	CCD boundaries 2003, 2006	Municipality of Hunters Hill
PLANNING	Suburbs	Municipality of Hunters Hill
PHYSICAL ENVIRONMENT	Aerial photo 1999 Lands	Municipality of Hunters Hill
PHYSICAL ENVIRONMENT	Aerial photo March 2003 QAS	Municipality of Hunters Hill
PHYSICAL ENVIRONMENT	Aerial photo January 2007 SKM	Municipality of Hunters Hill
PHYSICAL ENVIRONMENT	Aerial photo January 2009 SKM	Municipality of Hunters Hill
PHYSICAL ENVIRONMENT	Aerial photo January 2011 SKM	Municipality of Hunters Hill
INFRASTUCTURE	Road polygon and centrelines	Municipality of Hunters Hill
PLANNING	LEP land zoning	Municipality of Hunters Hill
ENVIRONMENT	Conservation zones	Municipality of Hunters Hill
PLANNING	Public Reserves	Municipality of Hunters Hill
PLANNING	Bushfire Zones May 2016	Municipality of Hunters Hill

PHYSICAL ENVIRONMENT	Foreshore Building Line	Municipality of Hunters Hill
PHYSICAL ENVIRONMENT	Tidal Limit	Municipality of Hunters Hill
INFRASTUCTURE	Drainage network, easements	Municipality of Hunters Hill
INFRASTUCTURE	Walking and cycling trails	Municipality of Hunters Hill
PLANNING	Waterway leases	Municipality of Hunters Hill
INFRASTUCTURE	Public toilets	Municipality of Hunters Hill
PHYSICAL ENVIRONMENT	Contour lines - 10 m, 2 m and 1 m	Municipality of Hunters Hill
PLANNING	Road Names	Municipality of Hunters Hill
ENVIRONMENT	Acid Sulphate Soils	Municipality of Hunters Hill
ENVIRONMENT	New Conservation Area	Municipality of Hunters Hill
PLANNING	Community Groups	Municipality of Hunters Hill
PLANNING	Lots > 600 sqm	Municipality of Hunters Hill
PLANNING	Heritage and Lots 600 sqm	Municipality of Hunters Hill
PLANNING	Lots Outside Conservation	Municipality of Hunters Hill
ENVIRONMENT	River Rehabilitation Areas	Municipality of Hunters Hill
PLANNING	2008 SEPP	Municipality of Hunters Hill
ENVIRONMENT	Saltmarsh 2009 and 2010	Municipality of Hunters Hill
PLANNING	LEP 2009 various layers	Municipality of Hunters Hill
PLANNING	Significant Structures	Municipality of Hunters Hill
ENVIRONMENT	Weed Biomass 2010 and 2015	Municipality of Hunters Hill
ENVIRONMENT	Vegetation Community 2010	Municipality of Hunters Hill
ENVIRONMENT	Management Zones 2010	Municipality of Hunters Hill
ENVIRONMENT	Revegetation Zones 2010	Municipality of Hunters Hill
PLANNING	Lands Easement	Municipality of Hunters Hill
PLANNING	Crown Lands/Water/Road	Municipality of Hunters Hill
PLANNING	LEP 2010 various layers	Municipality of Hunters Hill
ENVIRONMENT	Waste Zones	Municipality of Hunters Hill
ENVIRONMENT	Sea Level Rise +2.2 m	Municipality of Hunters Hill
PLANNING	S94 Community Infrastructure	Municipality of Hunters Hill
PLANNING	Playgrounds	Municipality of Hunters Hill
ENVIRONMENT	River Corridors	Municipality of Hunters Hill
PLANNING	Riverglade Study Area	Municipality of Hunters Hill
PLANNING	LEP 2012 various layers	Municipality of Hunters Hill
ENVIRONMENT	Street Trees (circa 2000)	Municipality of Hunters Hill
ENVIRONMENT	Contaminated Land Cleanup	Municipality of Hunters Hill
PHYSICAL ENVIRONMENT	Aerial photo January 2014 SKM	Municipality of Hunters Hill
PHYSICAL ENVIRONMENT	Aerial IR January 2014 SKM	Municipality of Hunters Hill
PLANNING	Open Space 2003, 2014	Municipality of Hunters Hill
PLANNING	Bedlam Bay Zones	Municipality of Hunters Hill
ENVIRONMENT	PRC Native Habitat Fauna	Municipality of Hunters Hill
ENVIRONMENT	Weed Map 2017	Municipality of Hunters Hill
ENVIRONMENT	Coastal Land Application	Municipality of Hunters Hill
PLANNING	Bushcare sites	Inner West Council
ENVIRONMENT	Marrickville bandicoot protection zone	Inner West Council
ENVIRONMENT	Marrickville wildlife corridor	Inner West Council
ENVIRONMENT	Marrickville priority biodiversity sites	Inner West Council
ENVIRONMENT	Marrickville vegetation mapping: large trees, small trees, shrubs and grass areas	Inner West Council
ENVIRONMENT	GreenWay corridor	Inner West Council

PLANNING	WSUD - Raingardens	Inner West Council
PHYSICAL ENVIRONMENT	Marrickville subcatchments	Inner West Council
ENVIRONMENT	Contaminated sites	Inner West Council
PHYSICAL ENVIRONMENT	Contours - 2m and 10m	Inner West Council
ENVIRONMENT	Ridge drainage lines	Inner West Council
ENVIRONMENT	Water course	Inner West Council
ENVIRONMENT	DCP Flooding	Inner West Council
ENVIRONMENT	Acid Suphate soils	Inner West Council
PLANNING	LEP layers inc zoning, heritage areas and items	Inner West Council
PLANNING	Cadastre	Inner West Council
INFRASTRUCTURE	Roads (including State and Regional)	Inner West Council
INFRASTRUCTURE	Stormwater pits and pipes	Inner West Council
INFRASTRUCTURE	Sewerage pits and pipes	Inner West Council
INFRASTRUCTURE	Maritime leases	Inner West Council
PLANNING	Council land	Inner West Council
PLANNING	Council buildings	Inner West Council
PLANNING	Council car parks	Inner West Council
INFRASTRUCTURE	Ferry wharf	Inner West Council
INFRASTRUCTURE	Bus stops	Inner West Council
INFRASTRUCTURE	Bus routes	Inner West Council
INFRASTRUCTURE	Bicycle routes (inc light,heavy, mixed, shared paths)	Inner West Council
INFRASTRUCTURE	Westconnex layers	Inner West Council
PLANNING	Crown Land	Inner West Council
PLANNING	Parks	Inner West Council
PLANNING	Sports grounds	Inner West Council
PLANNING	Playgrounds	Inner West Council
INFRASTRUCTURE	Emergency services (eg police, hospital)	Inner West Council
INFRASTRUCTURE	Community facilities (eg churches, museum, libraries)	Inner West Council
INFRASTRUCTURE	Aged and child care and schools	Inner West Council
ENVIRONMENT	Coastal Inundation 1 yr	Sydney Coastal Councils Group (SCCG)
ENVIRONMENT	Coastal Inundation 1 yr 40	Sydney Coastal Councils Group (SCCG)
ENVIRONMENT	Coastal Inundation 1 yr 40 LU	Sydney Coastal Councils Group (SCCG)
ENVIRONMENT	Coastal Inundation 1 yr 90	Sydney Coastal Councils Group (SCCG)
ENVIRONMENT	Coastal Inundation 1 yr 90 LU	Sydney Coastal Councils Group (SCCG)
ENVIRONMENT	Coastal Inundation 1 yr LU	Sydney Coastal Councils Group (SCCG)
ENVIRONMENT	Coastal Inundation 100 yr	Sydney Coastal Councils Group (SCCG)
ENVIRONMENT	Coastal Inundation 100 yr 40	Sydney Coastal Councils Group (SCCG)
ENVIRONMENT	Coastal Inundation 100 yr 40 LU	Sydney Coastal Councils Group (SCCG)
ENVIRONMENT	Coastal Inundation 100 yr 90	Sydney Coastal Councils Group (SCCG)
ENVIRONMENT	Coastal Inundation 100 yr 90 LU	Sydney Coastal Councils Group (SCCG)
ENVIRONMENT	Coastal Inundation 100 yr LU	Sydney Coastal Councils Group (SCCG)

3 HYDROLOGY

3.1 General

The East Australian Current (EAC) and its eddy field off the coast of Sydney provides a nutrient deplete sub-tropical water mass (Hedge *et al.,* 2014). Current speeds offshore can be up to 1.5 ms^{-1} and water flowing past the entrance to the Harbour is continually being renewed (Hedge *et al.,* 2014a).

The balance between freshwater inflow, precipitation and evaporation modifies salinity concentrations in the estuary. The Harbour is well flushed near the entrance but poorly flushed in the upper reaches. Water residence time varies from 0-20 days in the main body of water, to up to 130 days in the top of Parramatta River (Roughan *et al.,* unpublished in Hedge *et al*., 2014a). Rainfall in the Sydney catchment is characterised by dry conditions, punctuated by infrequent, high-precipitation events (rainfall > 50 $mm.day^{-1}$). During dry-weather (rainfall < 5 $mm.day^{-1}$), the estuary is well-mixed (normal ocean salinity). A small, highly-urbanised (86%) catchment and extensive impervious surfaces result in rapid runoff during high-precipitation events (Hedge *et al.,* 2014a). Stormwater reaching the estuary under these conditions forms a buoyant layer one to two metres thick above saline estuarine waters. Pollutants that are discharged near to the outlet can be flushed to the ocean, but otherwise they will linger within the estuaries. The volume of stormwater entering Sydney Harbour under dry, intermediate and high precipitation conditions is approximately 10%, 30% and 60% of total loading respectively (Birch and Rochford, 2010 in Hedge *et al.,* 2014a).

Circulation within Sydney Harbour is dominated by the tide, with influence from prevailing winds. Tidal velocities are periodic, reversing every 6 h and vary both spatially and over a tidal period. Typically, towards the mouth of the Harbour, depth averaged tidal velocities range from 0.1 to 0.25 ms^{-1} over the spring neap cycle. Ebb flow from the Harbour during a spring tide (range 1.6 m) is strongest near the northern side of the entrance and a clockwise eddy is formed (Hedge *et al.,* 2014a).

Discharge volumes are estimated to be up to 6000 m^3s^{-1} across the heads, at the peak of the ebb tide, with more than 4000 m^3s^{-1} coming from the main branch of Port Jackson (including the Parramatta and Lane Cove Rivers) and less than 1500 m^3s^{-1} coming from Middle Harbour. Offshore surveys reveal that even under dry conditions, tidal outflows from Sydney Harbour can extend several kilometres offshore (Hedge *et al.,* 2014a).

Residual flows can be produced by wind forcing or lateral density gradients driven by variations in temperature or salinity. Within Sydney Harbour, the tide-induced residual circulation forms many gyres at regions of complex geometry and bathymetry (Hedge *et al.,* 2014a). This interaction of the tidal current with the topography might result in retention of organisms or pollution. Circulation patterns vary depending on the wind direction, which contributes to a difference in Harbour retention and flushing. Under southerly wind forcing, flushing is a maximum near the mouth of Sydney Harbour with greater retention times under easterly and northeasterly winds. In the upper reaches of Sydney Harbour northeasterly winds result in the fastest flushing times with southerly and easterly winds having a similar impact on lower flushing, and greater retention. Water age within the Harbour was shown to vary from 0 to 20 d in the main body of the Harbour, up to 130 d in the upper reaches of the Parramatta River. Wind forcing resulted in age anomalies of 30 ±12 days depending on the prevailing direction, with the up-estuary winds increasing mixing, and hence reducing the age of the water (Hedge *et al.,* 2014a).

3.2 Catchment flows and associated pollutant input

This section is sourced from the Sydney Harbour Catchment Water Quality Improvement Plan (SHCWQIP) (Freewater and Kelly, 2015). The Plan is provided in full as Appendix A. The SHCWQIP was developed using an integrated hydrological and ecological modelling approach. The process included the characterisation of land and its use within the catchment draining to Sydney Harbour. Intensive water quality monitoring was undertaken to assist the development and validation of catchment pollutant export models (CPEMs) 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.

All models were integrated into the CAPER Decision Support System (DSS) to support the development of the SHCWQIP. 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.

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 georeferenced spatial layers.

The Sydney Harbour Catchment Model was developed to simulate stormwater runoff and associated pollutant loads for 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.

The key purposes of this model was 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 Decision Support System and associated Water Quality Improvement Plan.

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. 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.
Subcatchments (figure 3.1) 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.

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.

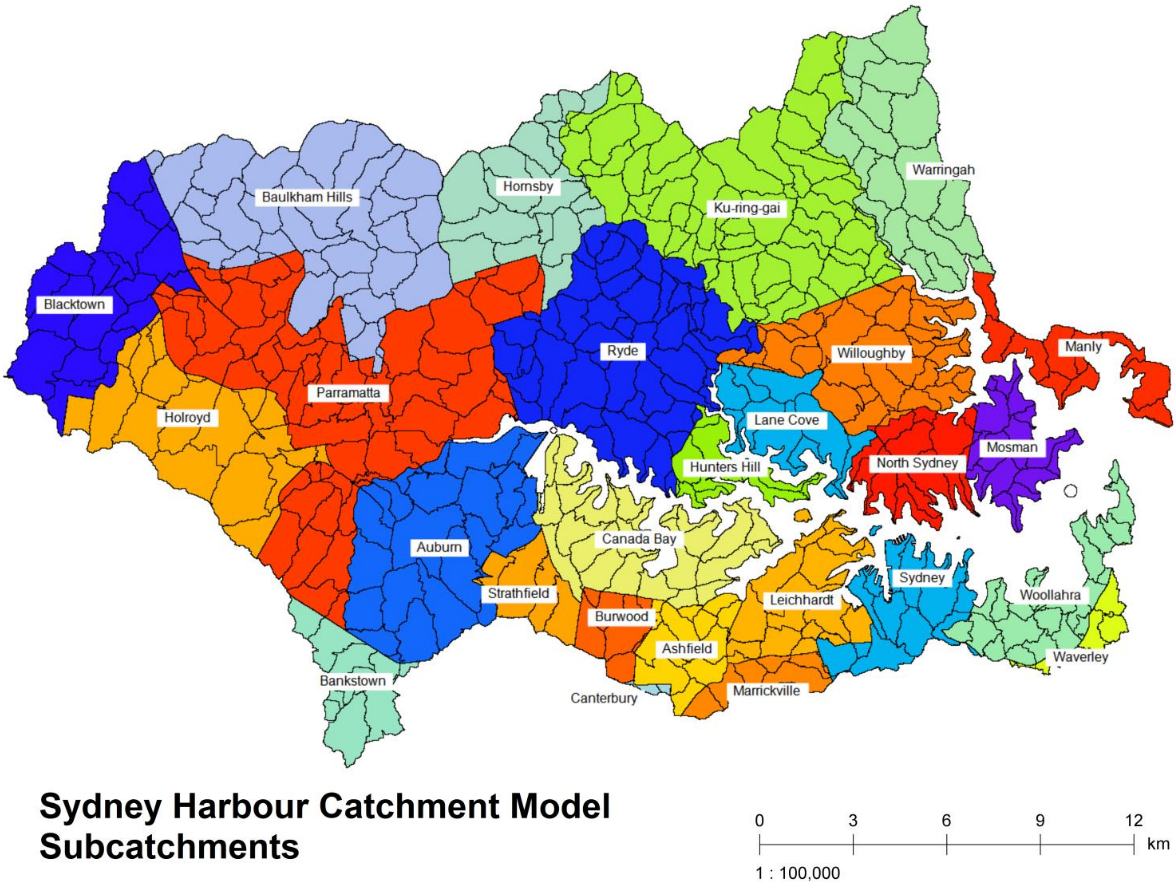


Figure 3.1 The Sydney Harbour Subcatchment Map

3.2.1 Major sources of pollutant loads

Diffuse loads versus sewer overflows

Figure 3.2 illustrates the proportion of loads derived from diffuse sources versus sewer overflows. It shows that most pathogens (93% *Enterococci* and 80% faecal coliforms) are contributed from sewer overflows. Conversely, TN, TP and TSS are clearly dominated by diffuse sources, which account for 90% of nutrient and 98% of sediment loads. The total annual average loads of these pollutants from various land uses and sewer overflows for each of the 4 subcatchment areas to Sydney Harbour are given in *Appendix B - Sydney Harbour Catchment Model*.

Figure 3.3 shows the split of contributions of each pollutant from diffuse versus sewer overflows for each of the 4 main subcatchments making up the Harbour. This Figure shows that the dominant sources of nutrients and sediments are diffuse for each of the four major subcatchments, being at least 86%, but more commonly over 90% of the pollutant source. A greater proportion of nutrients are derived from sewer overflows than diffuse sources when compared to sediments for Parramatta, Lane Cove and Middle Harbour. Sewer overflow data provided by Sydney Water for Port Jackson foreshore areas had zero flows and so no sewer overflow contribution for any pollutant. This appears to be an omission by Sydney Water and since the completion of the SCHWQIP they have offered to re-supply the data.

Sydney's sewerage system is implicated as the source of most of the pathogen concentration within the Sydney Harbour, with reports that sewerage overflows occurred more than 3000 times a year (Bickford *et al.*, 1999 in Hedge *et al.*, 2014a), although it is expected that this number would have decreased since the north-side tunnel was completed. Stakeholders are particularly worried about the *E. coli* and *Enterococci* values being too high for Harbour pools to be used with the one at Manly being given as an example. This concern is echoed by results from the Sydney Harbour CAPER DSS which show that the primary source of pathogens to the Harbour is sewer overflows. Contributions from sewer overflows ranged from 67% for Middle Harbour *E. Coli*, to 95% pollution of *Enterococci* for Parramatta. The Parramatta subcatchment has the highest percentage of sewer overflow pollution of each type of pathogen, compared to the other catchments.

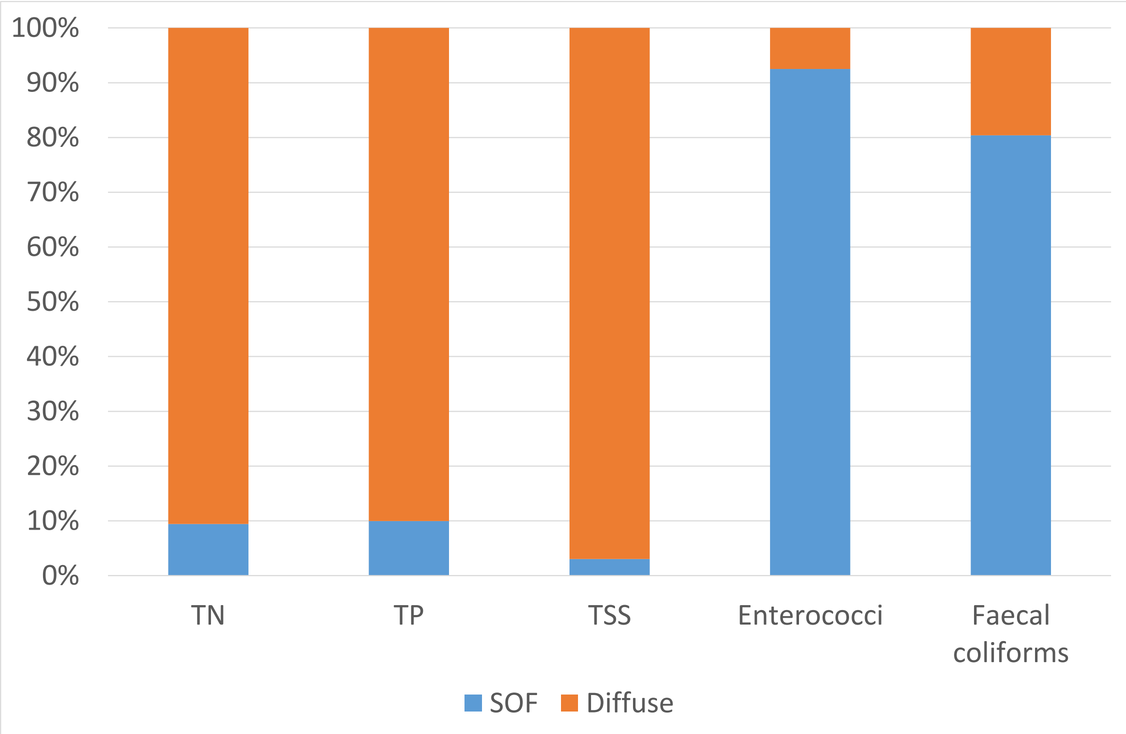


Figure 3.2. **The percentage of each water pollutant that is contributed from sewer overflows (SOF) versus diffuse sources, for the whole of the Sydney Harbour**

In Lane Cove an extensive sewer system (The Northern Suburbs Ocean Outfall Sewer (NSOOS) services) runs through the catchment, with about 120 overflow points discharging directly into the Lane Cove River and its tributaries (Rawling and Stricker, 1992 cited in Sinclair Knight Merz, 1997). As the tidal section of Lane Cove Estuary has limited exchange of riverine water, with each tide poor quality water remains in the estuary for long periods of time compared to elsewhere in Port Jackson. Thus, the export and dilution of pollutants and salinity of the water column which affects the rates of die-off of pathogens has health implications for marine life and users (EPA, 1995 cited in Sinclair Knight Merz, 1997).

The Northern Suburbs Ocean Outfall Sewer (NSOOS) crosses Middle Harbour at The Spit, between Parriwi Point and Clontarf Flat. There are main sewer overflows located at Quakers Hat Bay, near Mosman; Scotts Creek, near Castle Cove and Tunks Park, Cammeray. In high rainfall events diluted sewage is also discharged into Middle Harbour from near Roseville Bridge.

Figure 3.3 **The proportion of pollutants that is contributed from sewer overflows (sof) versus diffuse sources for the four major subcatchments in the Sydney Harbour catchment (sof data provided by Sydney Water for Port Jackson was incomplete).**

Figure 3.4 shows the percentage of the diffuse loads of each pollutant that come from various land uses in the catchment. It also shows the percentage of the catchment area under each land use. It shows clearly that the majority of the diffuse pollutant load to the Harbour is coming from residential areas. These areas correspond to 47% of the area and contribute 81% of the diffuse *E. coli, Enterococci*, and faecal coliform loads, and 51- 52% of the TN, TP and TSS. Roads contribute more substantially to nutrients and sediment but less to pathogens relative to their area compared to residential areas.

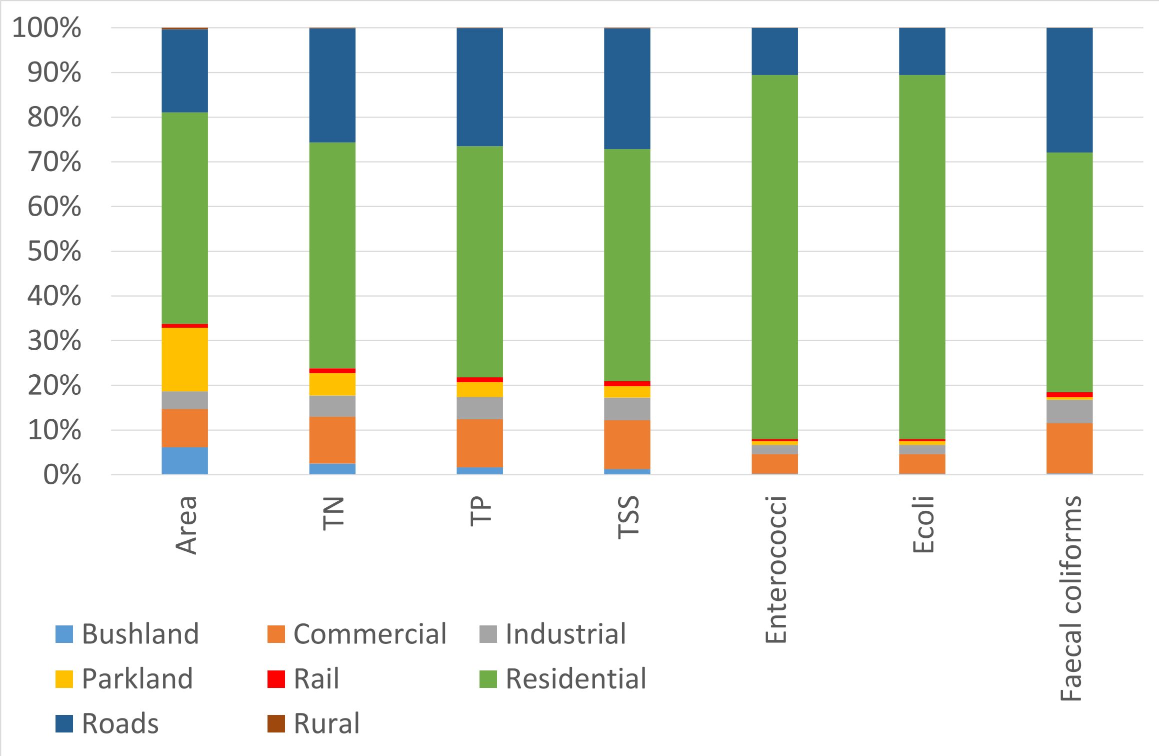


Figure 3.4 **Relative proportion of pollutant load that is coming from each land use for the whole Sydney Harbour catchment**

The land use that contributes the least pollutant loads to the Harbour is rural. Rural land contributes less than 1% of all pollutants, but it also covers less than 1% of the area. Rail areas are also very small contributors of pollutants to the Harbour, covering 1% of the catchment and contributing 0-1% of the load of any pollutant.

Figure 3.5 shows that Roads, Rail, Industrial and Commercial land uses are the worst contributors to TN, TP, TSS and faecal coliform pollutant loads by unit area. So, whilst railways contribute the second lowest absolute pollutant load to the catchment, by unit area, they are the largest contributor of 4 of the 6 pollutants shown here. Given this, it can be expected that rail areas are substantial contributors to local water quality issues. Although residential land is not the greatest contributor of TN, TP, TSS and faecal coliforms by unit area, it is still by far the greatest contributor of *Enterococci* and *E. coli*, which emphases the need to manage the impacts of runoff from residential areas on the Harbour water quality. Roads are the next greatest contributor of pathogen pollution for all subcatchments. Commercial property also contributes a substantial proportion (10-20%) of the pathogen pollution for Port Jackson, and to a lesser extent for Lane Cove and Parramatta subcatchments, although these land uses produce *Enterococci* and *E. coli* to a smaller extent compared to their relative area. The impact from industrial land use is also notable for the Parramatta catchment. Industrial and commercial areas produce above the average amount in terms of nutrients, sediments and faecal coliforms, but relatively less for *Enterococci.*

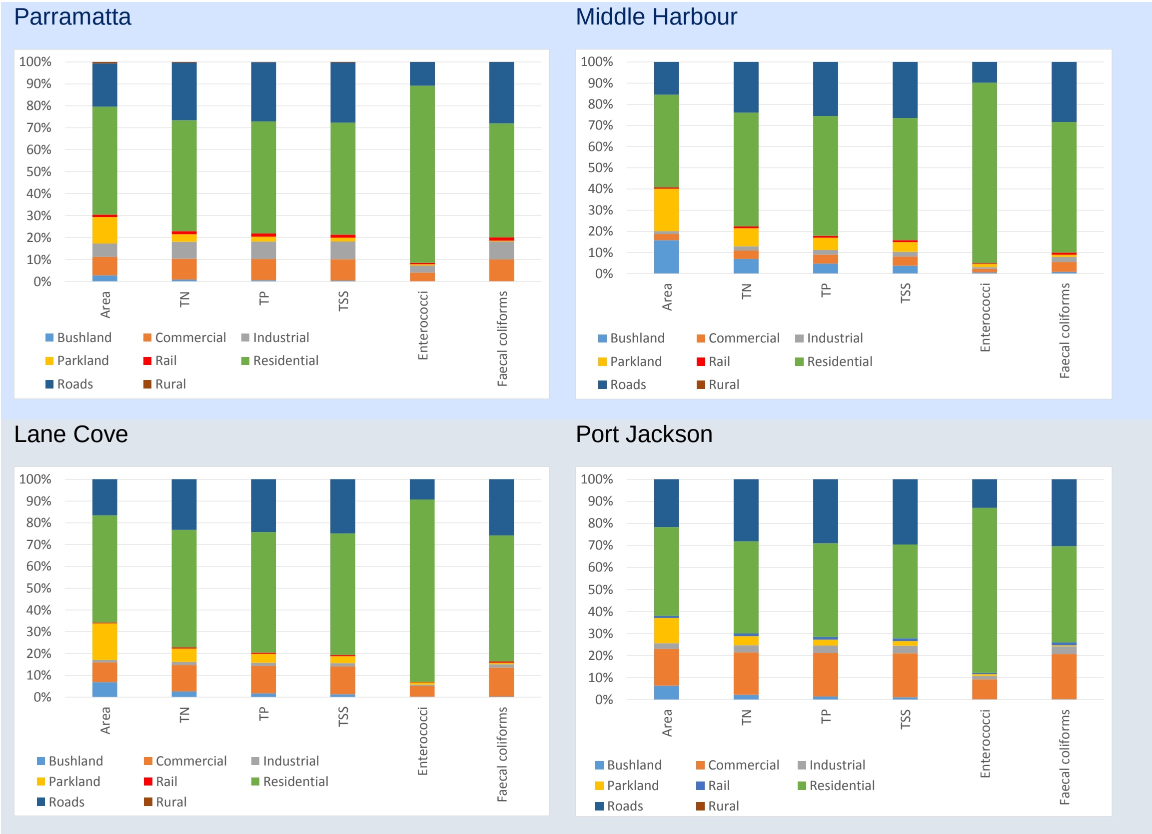
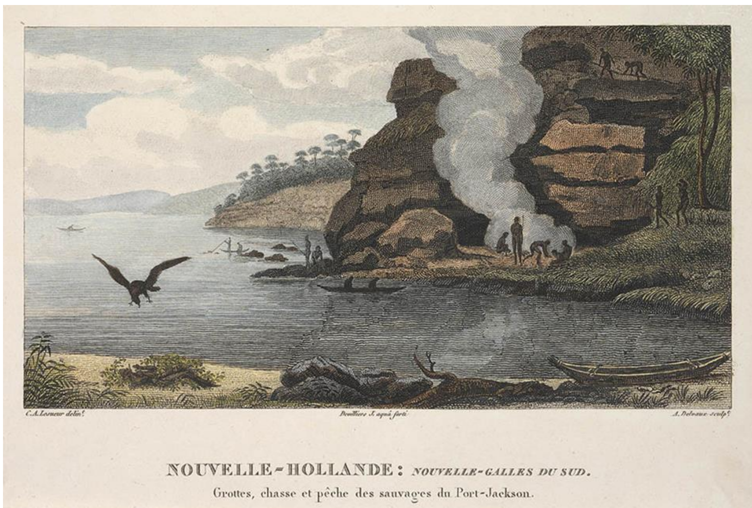


Figure 3.5 **Percentage of pollutant load coming from each land use for the four major subcatchments in the Sydney Harbour catchment**

3.2.2 Change in pollutant loads and estuary condition since European settlement

The current pollutant loads and their sources illustrate the impact of development on Sydney Harbour. This point is made even clearer when comparing the current loads with those estimated from pre-European settlement (modelled assuming bushland is the only land use in the catchment). Figure 9 shows that for the whole of Sydney Harbour the TN, TP and TSS loads are likely to have increased about 3, 5 and 6-fold, respectively compared to pre-European values. The results are very similar for each of the subcatchments, with the Parramatta subcatchment having the greatest increase in loads being about 4, 6 and 7–fold increases in TN, TP and TSS, respectively. This highlights the impact of urbanization on water quality.



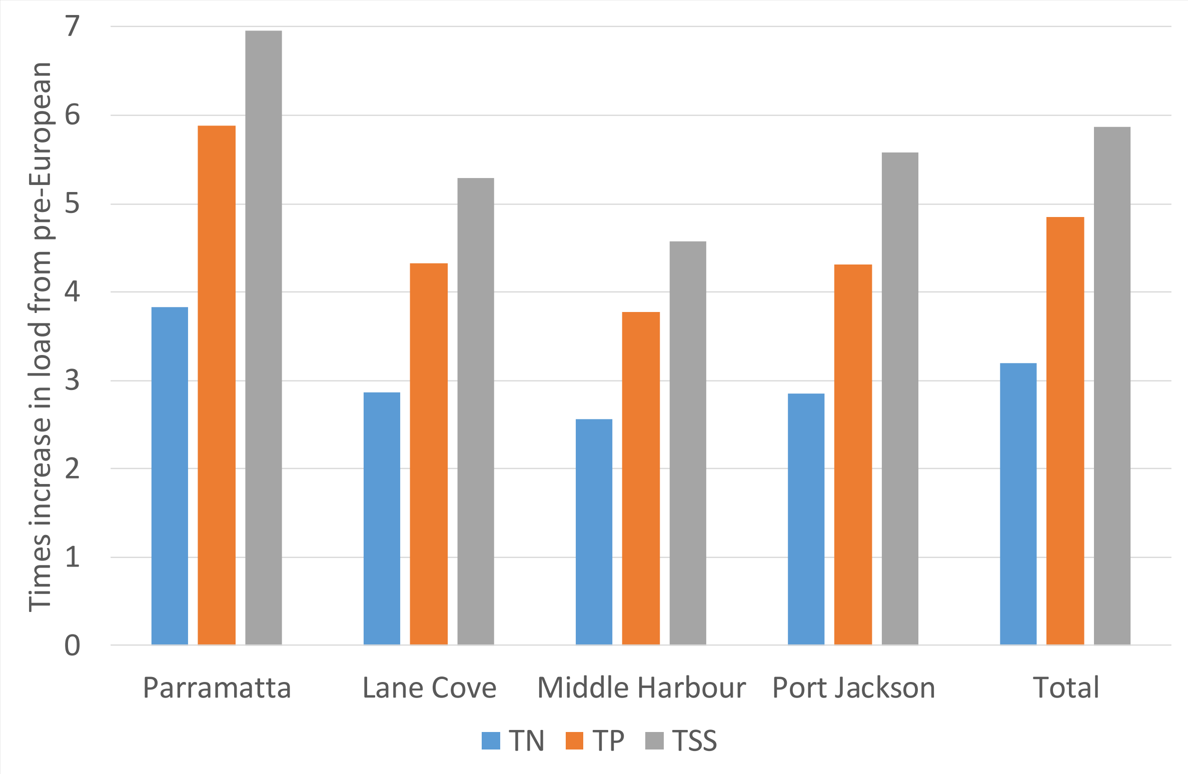


Figure 3.6 **Current nutrient and sediment loads versus estimated pre-european loads for the four major subcatchments**

The change is even more dramatic when considering pathogen loads (see Figure 3.7). Increase in the *Enterococci* loads and *faecal coliform* loads are estimated at roughly 470 and 130-fold respectively. Obviously, with the influx of a very large population and a loss of natural groundcover to filter pollutants, came the influx in pathogens which have ultimately ended up in the waterways. Again, the largest increase is in the Parramatta subcatchment where the increase in *Enterococci* and *faecal coliform* loads are more than double that of any other subcatchment, roughly 770 and 220-fold respectively. Relative increases in Port Jackson pathogens are less than elsewhere in the catchment (although still very substantial at roughly 30-fold increases) because of the lack of sewer overflows in this area, which are a large source of pathogen loads as discussed above.

Weedy Seadragon (*Phyllopteryx taeniolatus*)

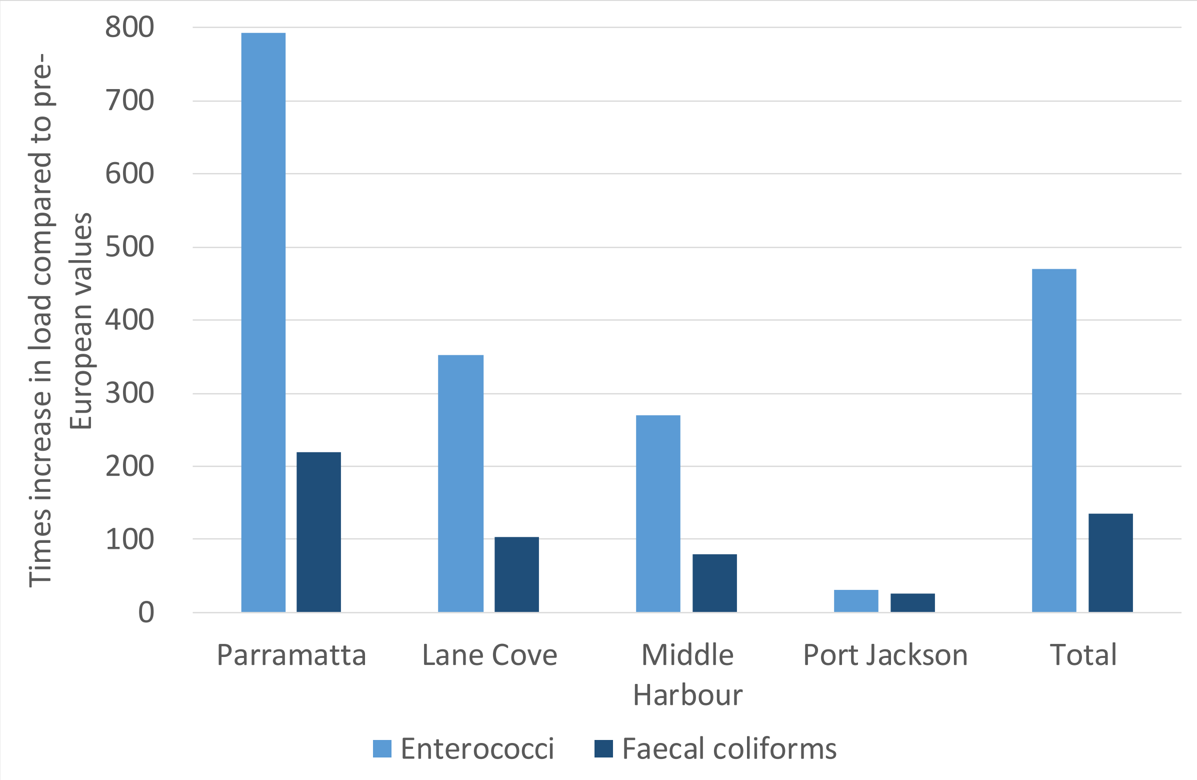
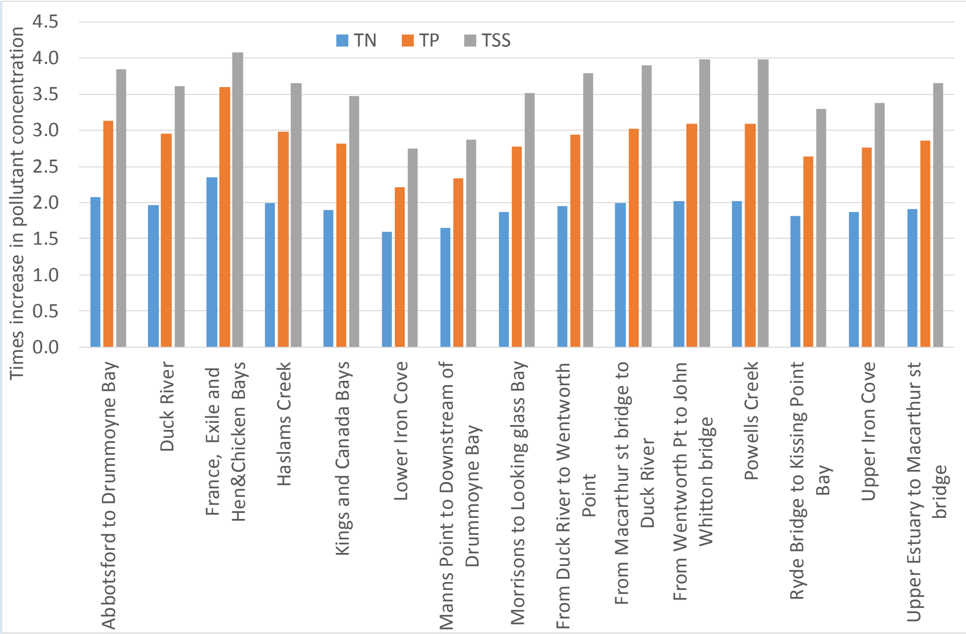


Figure 3.7 **Comparison of the current *enterococci and faecal coliform* loads and the pre-European values for the four major subcatchments**

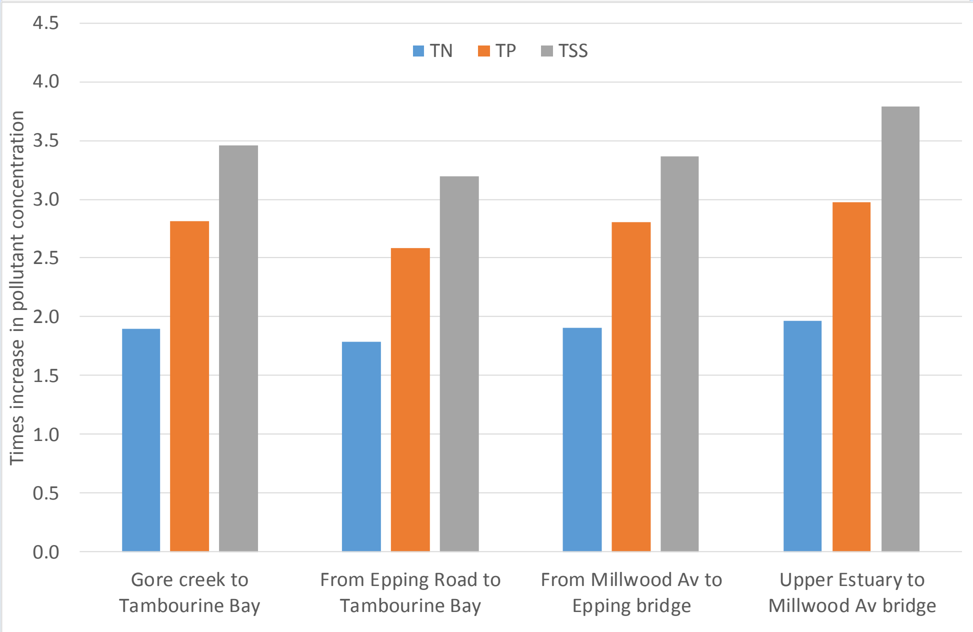
Focusing on the change in the concentration of pollutants (TN, TP TSS, *Enterococci* and *faecal coliforms*) on the subcatchment estuaries compared to pre-European values shows a similar story as the change in the loads discussed above. Figures 3.8 and 3.9 shows estimates of impact on the pollutant concentrations (TN, TP and TSS; and *Enterococci* and *faecal coliforms*) in the major estuary zones associated with the various major subcatchments since European settlement, due to the changes in loads given in Figures 9 and 10. In the Parramatta region, and for the whole of Sydney Harbour, the greatest impact on estuary condition for all pollutants were France Bay, Exile Bay and Hen and Chicken Bay with a 2.3, 3.6, 4.1, 767, and 203-fold estimated change in TN, TP, TSS, *Enterococci* and faecal coliforms. The Lower Iron Cove zone had the least change in pollutant concentration in the Parramatta Region, but it still corresponds to 1.6, 2.2, 2.7, 25 and 13-fold increases in TN, TP, TSS, *Enterococci* and *faecal coliforms*, respectively.

In the Lane Cove region there was not a lot of difference between the change in TN, TP and TSS concentrations between the major estuaries, except for change the *Enterococci* concentrations from Millwood avenue to Epping Bridge, which were over double that of any other major estuary zone in that area. These values were comparable to the Haslams Creek estuary, which had the third greatest increase in pathogen concentration of the Parramatta region estuary zones. In the Middle Harbour region, 3 of the 4 estuary zones had TN, TP and TSS values similar to that of the estuaries in Lane Cove, while the change in these pollutants for the Bantry Bay to Echo Point estuary zone more closely matched the worst estuary zone in the Parramatta region (France Exile and Han & Chicken Bays).For pathogens, Bantry Bay to Echo Point had the greatest increase in *Enterococci* of the estuary zones in the Middle Harbour, and it was the third highest increase of any estuary in the whole of Sydney Harbour. Sugar Loaf Bay to the Spit had one of the lowest changes in pathogen concentrations of any estuary in the whole of Sydney Harbour. In the remaining estuary zones of the Harbour, Rose and Double Bays had the greatest change in TN, TP and TSS from the pre-European concentrations with similar changes to three of Parramatta's top 5 estuary zones (from MacArthur St bridge to Duck River, From Wentworth Point to John Whitton bridge and Powells Creek), Upper Estuary to Millwood in the Lane Cove Region, and Bantry Bay to Echo Point in the Middle Harbour Region. Farm Cove, Sydney Cove and Neutral Bay had an extreme increase in *Enterococci* (about 400 times), with Blackwattle, Johnstons and Rozelle Bays also being high (238 times). Note that the Blackwattle Bay was noted by the stakeholders as being very dirty following rainfall events. Rose and Double Bays are estimated to have had the lowest change in pathogen concentration since European settlement, being 24 times for *Enterococci* and 19 times for faecal coliforms.

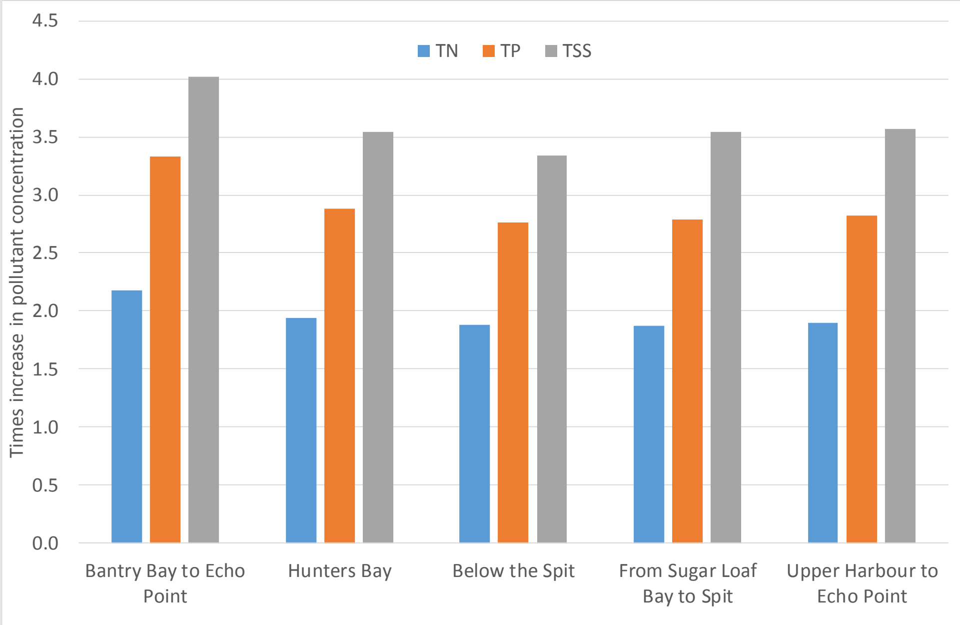
Parramatta



Lane Cove



Middle Harbour



Sydney Harbour

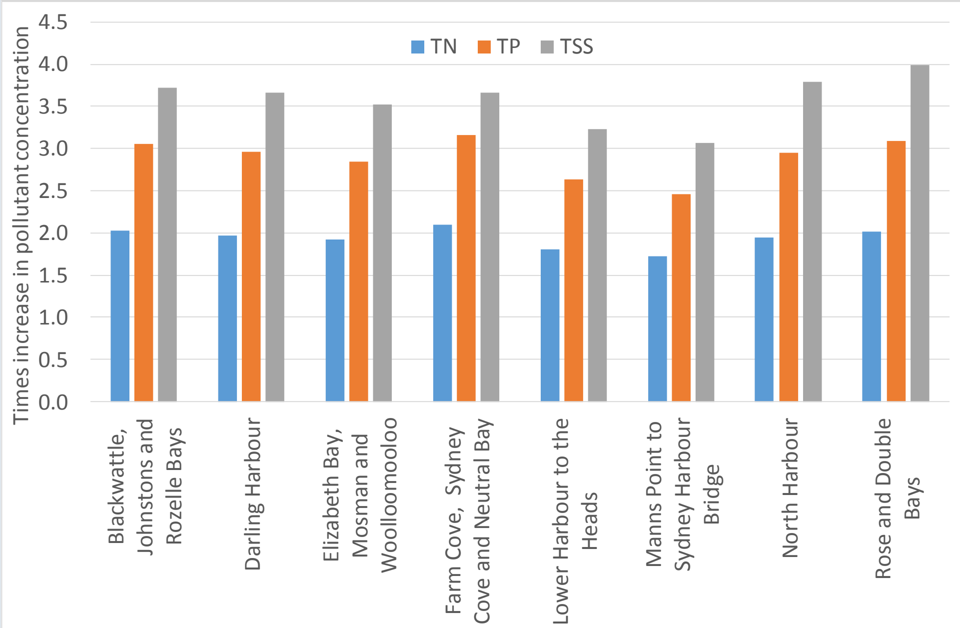
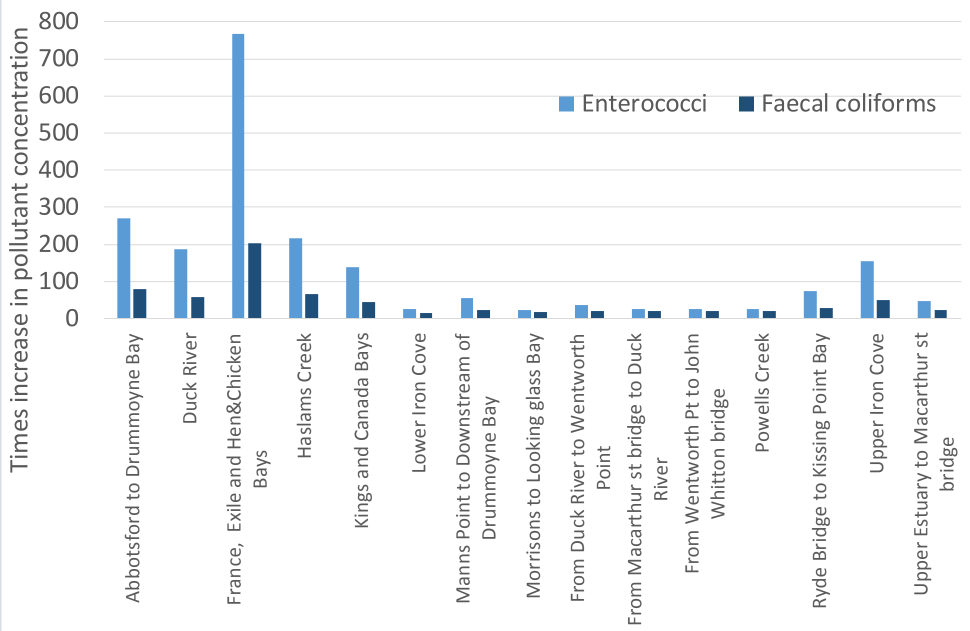
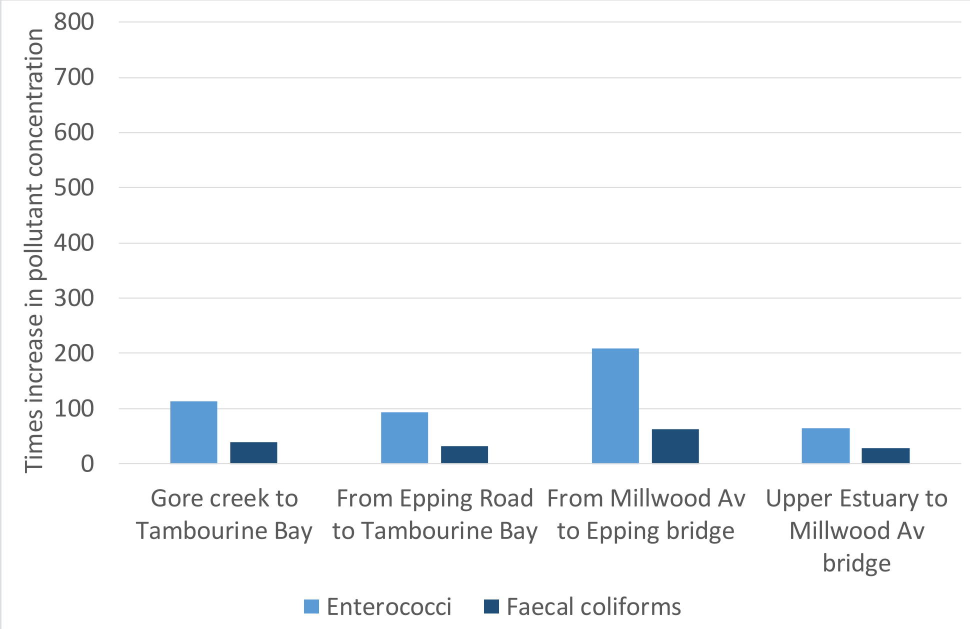


Figure 3.8 **Comparison of the current nutrient and sediment concentrations and the pre-European values for the major estuaries in the four major subcatchments.**

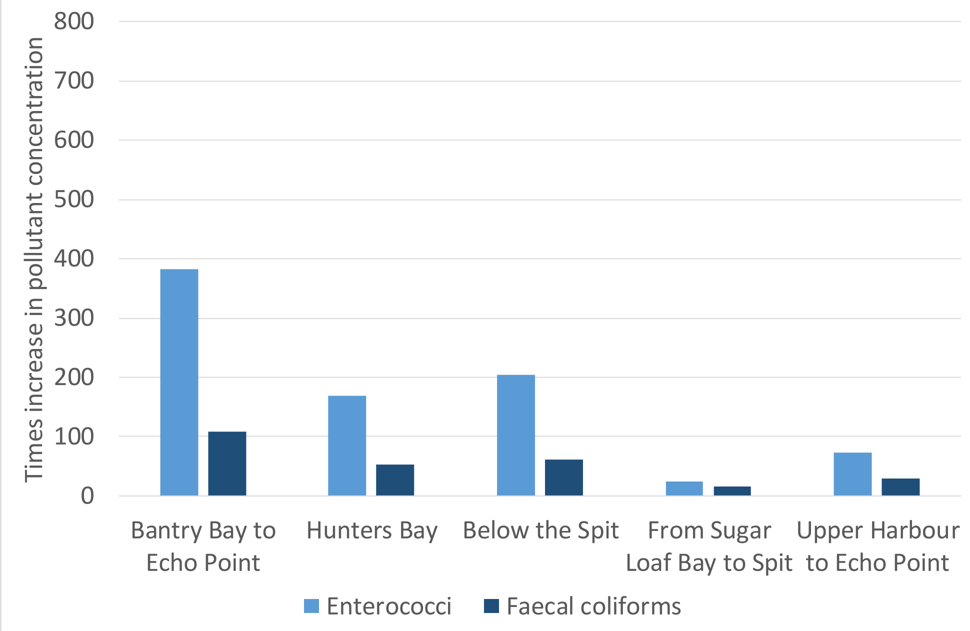
Parramatta



Lane Cove



Middle Harbour



Sydney Harbour

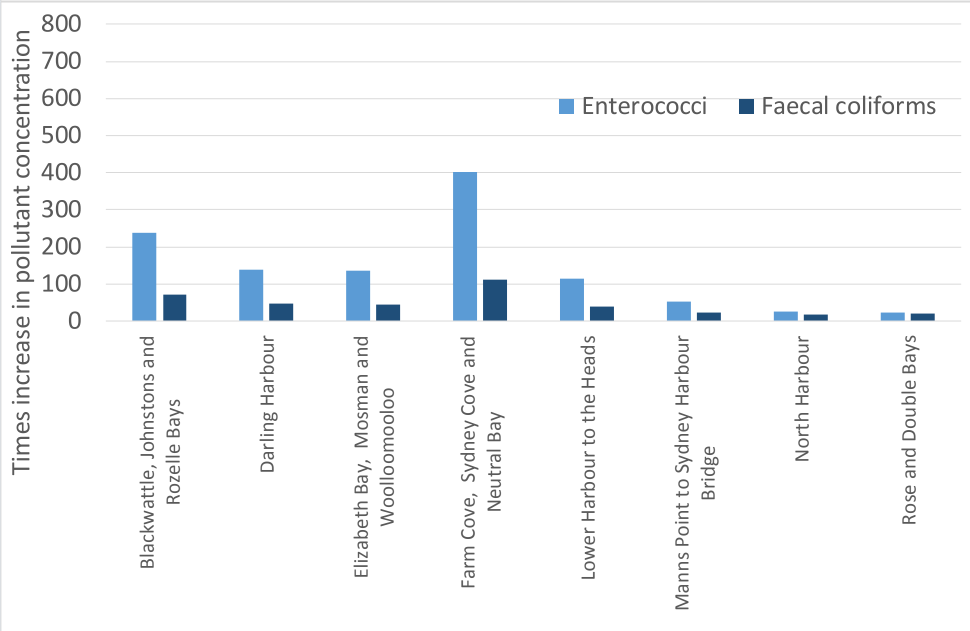


Figure 3.9 **Comparison of the current nutrient and sediment concentrations and the pre-European values for the major estuaries in the four major subcatchments.**

3.3 Hydrodynamic modelling

An integrated hydrological and ecological modelling approach (Hydro-Ecology - Freewater, 2003) was used to develop the Sydney Harbour Catchment Water Quality Improvement Plan (SHCWQIP). 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 transport of stormwater pollutants to the Parramatta River and Port Jackson. 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 weather 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.

The purpose of the hydrodynamic model was to provide spatial and temporal descriptions of tidal levels, currents and salinity used to drive a detailed water quality and ecological response model for Port Jackson and the Parramatta River termed the Sydney Harbour Ecological Response Model (SHERM). Water temperatures were adopted from monthly temperatures based on recorded data.

The model is an extension of a pre-existing Port Jackson - Parramatta River hydrodynamic model that has previously been used to successfully simulate the advection and dispersion of salinity and passive tracers (Baird, 2013), including calibration and operation of a winter period water quality (WQ) model. This winter WQ data was collected by SIMS (2012) for the SMCMA. An additional set of spring-summer WQ data was collected over the period from October to December 2012.

The 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 – Appendix C.1). 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, 2017 – Appendix C.3). 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, 2017). 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, 2017).

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, 2016).

Significant effort has been put into making the pre-existing 2D hydrodynamic model more computationally efficient without sacrificing essential flow structure resolution. The challenge consisted in locally coarsening the grid resolution (mainly along the flow and transversally where flow structure was consistent in order to conserve bathymetric gradients, horizontally and vertically) - in order to reduce the run time and minimise the impact on the calibrated model flows.

Cardno has undertaken an advanced calibration of the horizontal eddy diffusivity that greatly influences dispersion processes. Salinity gradient influences the current flows in horizontal and vertical directions and hence mixing processes. It is therefore important to use an appropriate horizontal dispersion coefficient for the model. Vertical dispersion is controlled by the layer definition and the k-e turbulence model.

The spatial recovery of salinity gradients following a period of fresh water inflows provides an opportunity to calibrate the dispersion coefficient. Figure 3.10 shows calibration time-series of salinity at various locations in Sydney Harbour comparing the depth averaged salinity of the model with the weekly measurements from SIMS from October 2012 to December 2012. The measured salinity data (top and bottom values) was averaged with an 80% weight applied to the upper reading, given that fresh water inflows would affect that area of the water column most.

The model performs well throughout this period in terms of salinity recovery (post inflow dry period) and with large inflows of fresh water from the catchment model included, as · prepared by Joel Stewart (March 2014). The catchment discharges were prepared by the study team and adjusted based on previously calibrated water quality model data (Baird Australia, 2013).

Cardno optimized the pre-existing *Delft3D* 2D hydrodynamic FLOW model by reducing the run time without compromising on the accuracy of the model. This was a key step before the conversion to a 3D model. They also setup and calibrated 3D hydrodynamic Z and sigma-layer models. Although the Z-layer model enables a better description of the vertical stratification, the sigma-layer model presents similar vertical and horizontal velocity magnitude and direction gradients. The sigma-layer model has been found to run about 5 times faster than the Z-model. The sigma-layer model (8 layers and salinity) requires 1 day of computational time for 1 day of real time. Therefore, the 3D hydrodynamic sigma-model was used to generate the hydrodynamic flow data required as input for the water quality modelling. However, the hydrodynamic sigma-model outputs were converted into equivalent Z-layer data prior to use with *Delft3D*-WAQ model because the stratification is critical to water quality processes.

Detailed 3D hydrodynamic modelling undertaken by Cardno and Baird (2017) are provided in Appendix C.3. The following section includes a summary of the following:

- Wave climate and elevated water levels at nearshore locations throughout much of the estuary
- The propagation of rare tsunami events into Port Jackson
- Impact of vessel traffic on hydrodynamics and sediment Transport
- The transport and fate characteristics of dioxin contaminated sediments in Homebush Bay

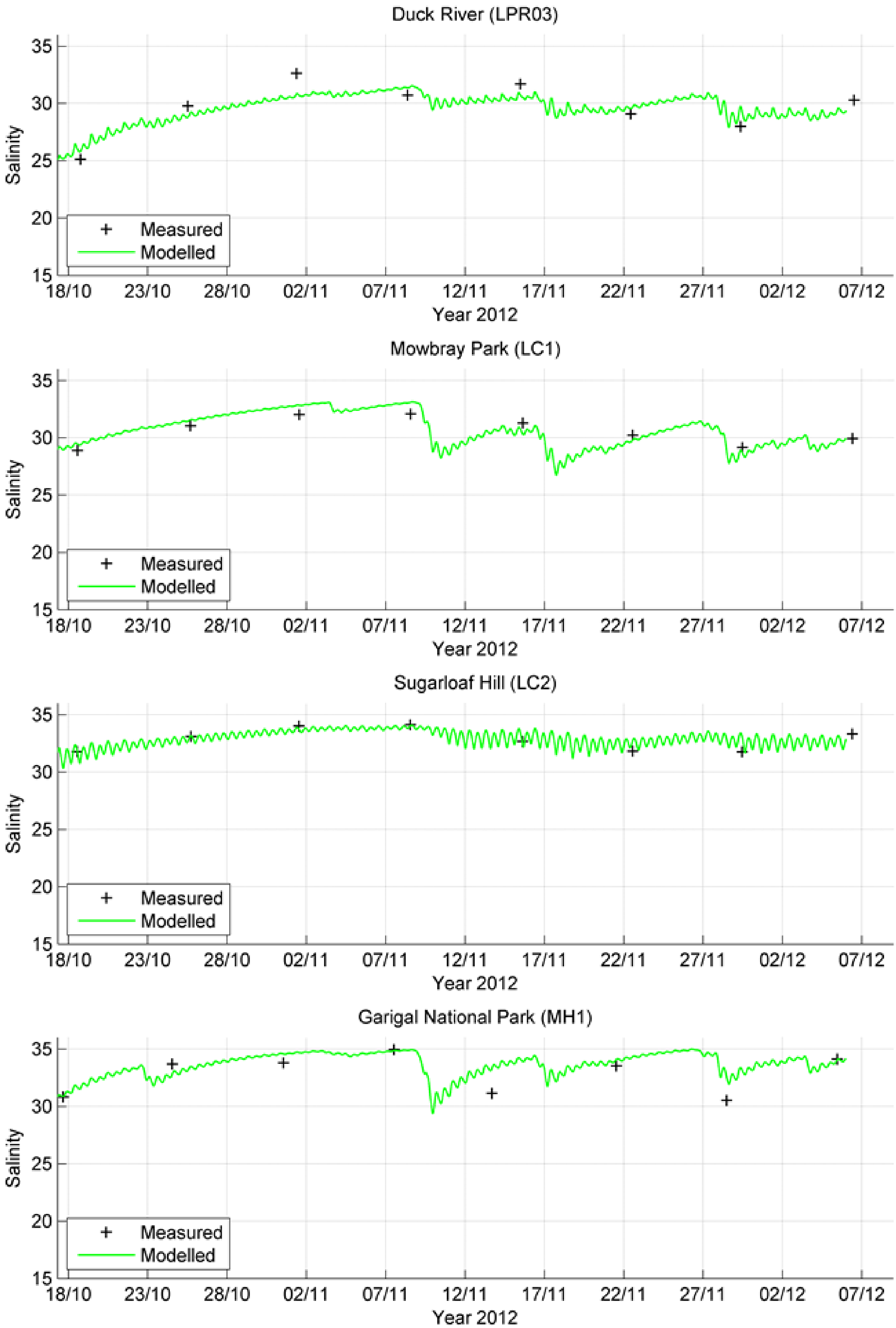


Figure 3.10 **Sydney Harbour ERM – setup and calibration of 3D model: Depth Averaged Salinity Calibration Time Series (Eddy diffusivity has been set universally at 20m^2s^{-1})**

3.3.1 Wave and Water Level Investigations

Wave data are required as one component of shoreline facilities design and estuarine levels assessment. Together with water level, these parameters are used to determine estuarine planning levels, design appropriate seawall crest levels and for assessment of inundation hazard risks. The following sections are sourced directly from Cardno and Baird (2014b). The complete report is included in Appendix C.2.

Swell Waves

Peak swell wave events were extracted from the model output time-series to estimate the 20 and 100-years ARI design swell wave heights (Hs) via an extreme value analysis (EVA). The results are detailed by location in Cardno and Baird (2014b) - Table B.1 in Appendix B. These results show that swell wave effects diminish generally in a westward direction, but that Nielsen Park, for example, is a swell affected area – caused by the form of the estuarine seabed, and known for occasional surf. Clontarf Reserve is also affected, as is Manly Cove and the Balmoral Beach area. These sites are known to have been affected by ocean waves in May 1974 or April 2015, for example. Swell penetration to Garden Island is low, but important for Defense operations. Swell penetration is very dependent on offshore wave direction.

The assumption of no penetration beyond the Harbour and Spit Bridges was validated by the model results.

Local Wind Waves

The SWAN wave model, presented in Figure 3.11, was used to develop the wind wave climate at foreshore locations within Sydney Estuary up to the Gladesville Bridge area. Virtually no swell penetrates further than the Harbour Bridge. Therefore, local sea conditions were investigated for assessment of wave conditions for the locations upstream of the bridges and some locations downstream of them, depending upon their aspect and exposure. The swell and wind wave results were then combined to prepare site specific wave conditions.

To investigate the local wind wave climate within the estuary, a full range of wind conditions was modelled:

- Wind speeds from 4 to 28 ms^{-1} – at 4 ms^{-1} intervals;
- Wind directions from all around the clock – at 11.25 degrees intervals; and
- Water level of 1.1m AHD

The influence of the local winds on the wave climate is highly spatially variable within the estuary due to the complex geometry of the various headlands and embayments. Wind direction is a key parameter affecting wave growth along the directionally variable fetches for each nearshore output location. The results of this wave modelling provided a basis for developing 59 years of time-series of wave parameters at the foreshore locations from the observed wind data time-series. This model output provided a long-term time-series of wave parameters at each of the foreshore locations in terms of Hs, Tz and direction, together with wind speed and direction.

These results were then examined to identify peak storm wave heights, which were then analyzed using the Extreme Value Type 1 distribution to estimate the 20 and 100-years ARI design sea wave heights (Hs). The local wind wave results are detailed by location in Cardno and Baird (2014b) - Table B.1 in Appendix B, together with the swell results.

Water Level

Water levels are formed from a number of increments:

- Eustatic and Tectonic Changes
- Tides
- Wind Set-up and the Inverse Barometer Effect
- Wave Set-up
- Wave Run-up

- Fresh Water Flow
- Tsunamis
- Greenhouse Effect
- Global Changes in Meteorological Conditions

Tidal planes were adopted from the 2015 Australian National Tide Tables (ANTT, 2015 in Cardno, 2017) for Fort Denison. These tidal planes, presented in Table 3.1 were considered appropriate for the study site and are relative to local lowest astronomical tide (LAT). There is some variation in phase and tidal planes throughout the estuary, but the differences do not affect this investigation materially. Tides in this location are semi-diurnal; that is, there are normally two high and two low tides each day. On rare occasions there may be only one high or low tide because the lunar tidal constituents have a period of about 25 hours. There may also be a significant diurnal difference; that is, a significant difference between successive high tides and successive low tides.

Table 3.1 Tidal Planes for Sydney (Source: ANTT, 2014)

Tidal Plane	m LAT	m AHD
Highest Astronomical Tide (HAT)	2.1	1.1
Mean High Water Springs (MHWS)	1.6	0.6
Mean High Water Neaps (MHWN)	1.4	0.4
Mean Sea Level (MSL)	1.0	0.0
Mean Low Water Neaps(MLWN)	0.6	-0.4
Mean Low Water Springs (MLWS)	0.4	-0.6
Lowest Astronomical Tide (LAT)	0.0	-1.0

Table 3.2 presents extreme water levels for typical ARIs, derived from the Fort Denison tide gauge water level records CSIRO (2012). These 'design still water levels' include projections of mean sea level rise associated with climate change for the years 2050 and 2100. Note that MSL varies from day-to-day, but this has no effect on wave conditions.

Table 3.2 Extreme Water Levels at Fort Denison in m AHD (Source: CSIRO, 2012)

ARI (Years)	Existing	2050	2100
1	1.24	1.58	2.08
50	1.42	1.75	2.25
100	1.44	1.78	2.28

Wind duration is important to the development of water level set-up. In reality, the critical wind duration that causes the maximum wind set-up at a given location would change in line with the variation of fetch lengths and depths in the individual directions. When the matter of actual wind speed and direction duration is considered this combination is unlikely to persist for more than six hours in any one combined condition. To this end, a six-hour peak wind duration was employed, which is likely to allow the maximum wind set-up to occur while also ensuring that phasing with the high tide is incorporated.

Figures 3.12 and 3.13 present a spatial representation of the maximum water level variation from wind setup within the Sydney Estuary by comparison with Fort Denison, for respectively 20 and 100-year ARI. The wind set-up can range from near zero up to 9cm in the most critical areas such as Homebush Bay and Middle Harbour. These figures also display the most influential wind direction in terms of wind set-up. Theses direction outcomes are mostly dependent on the available fetches at each location, but can be summarized by:

- Southern sector winds have more influence in the northern sections of the entrance and Port Jackson
- Western sector winds contribute to the wind set-up in southern parts of Port Jackson
- Eastern sector winds have more influence in the areas upstream of the Harbour Bridge, with a tendency to be more north-eastern due to the spatial configuration of the various bays such as Rozelle Bay, Iron Cove and Hen and Chicken Bay.

Estuary Planning Levels

The estimation of design planning levels includes many components, such as:

- Storm tide level at Fort Denison
- Wind set-up adjustment at each site
- Wave set-up at each site, a function of edge treatment and incident waves
- MSL Rise (2010, 2050 and 2100)
- Local design wave parameters
- Wave run-up, a function of edge treatment type and roughness
- Freeboard allowance

Results for each of these components are presented in Cardno and Baird (2014b) Appendix C specifically for the 20 and 100-years ARI return periods.

Storm tide level was based on extremal analysis of the long-term Fort Denison water level records. Wind set-up at each location was derived as a difference from the Fort Denison design levels, which implicitly included wind set-up effects at the Fort Denison site. This was undertaken by numerical modelling and has been presented in Cardno and Baird (2014b).

The process of wave set-up refers to the deviation of the mean water level because of wave shoaling, breaking and momentum flux conservation as waves progress shoreward across the surf zone. Goda (2000, in Cardno and Baird, 2016) provides an approximation of this set-up based on the significant wave height (Hs) or the breaking wave height (Hb) near the shoreline, whichever is smaller. The calculation of wave set-up is implicitly included in the calculation of the wave run-up heights.

In defining the planning level, these design wave heights are to be used, generally. However, consideration of possible boat waves that may approach the shore when design water levels are present needs attention.

Wave run-up calculations were developed for a range of edge treatments that may best describe those found along the Sydney estuary foreshore. They included:

- 1 in 5 rocky shore
- Vertical wall
- 1 in 10 natural slope

Calculations were undertaken for four edge treatment crest levels, being 0.5 m AHD, 1 m AHD, 1.5 m AHD and 2 m AHD, for each edge treatment type.

In defining the run-up level, three mechanisms of wave run-up were identified. They included wave run-up without overtopping of the edge treatment crest, wave run-up rising above the edge treatment crest, thereby resulting in wave overtopping, and wave overtopping when the design still water level is above the edge treatment crest; the last case not being a desirable condition.

The definition of estuarine planning levels can therefore be undertaken using the following calculation:

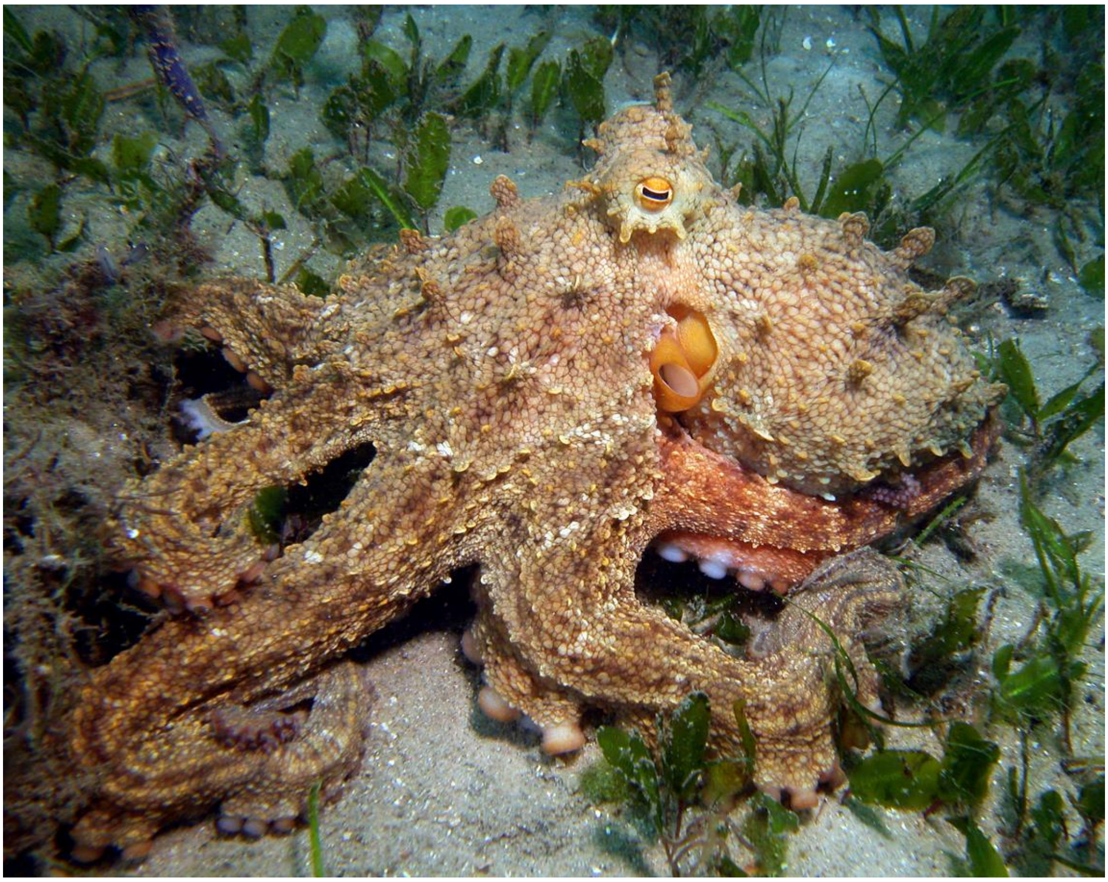
PL = DWL + WRH where:

- PL: Planning Level
- DWL: Design Water Level = Design Level at Fort Denison + Local Wind Setup (relative to Fort Denison) + 0.4 m Mean Sea Level rise – 2050.

- WRH: Wave Run-up Height - based on edge treatment type.

Both the design water level and wave run-up level are presented in Cardno and Baird (2014b) - Appendix C for the 20 and 100 - years design return periods and a freeboard of 0.3m is included.

Calculation of run-up height, to undertake the above calculations, requires use of the run-up equations presented in Cardno and Baird (2014b) - Appendix D.



Sydney Octopus (*Octopus tetricus*) at Manly

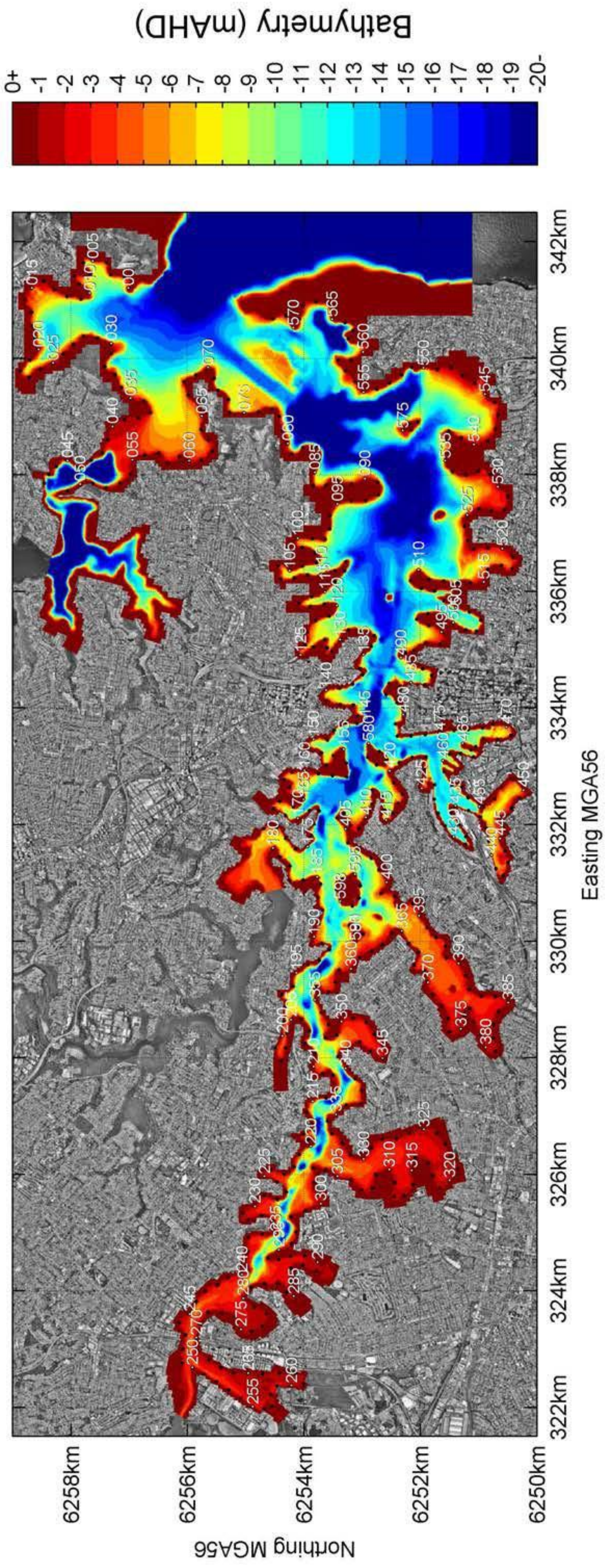


Figure 3.11 **Swan Model Bathymetry (Cardno and Baird 2014b)**

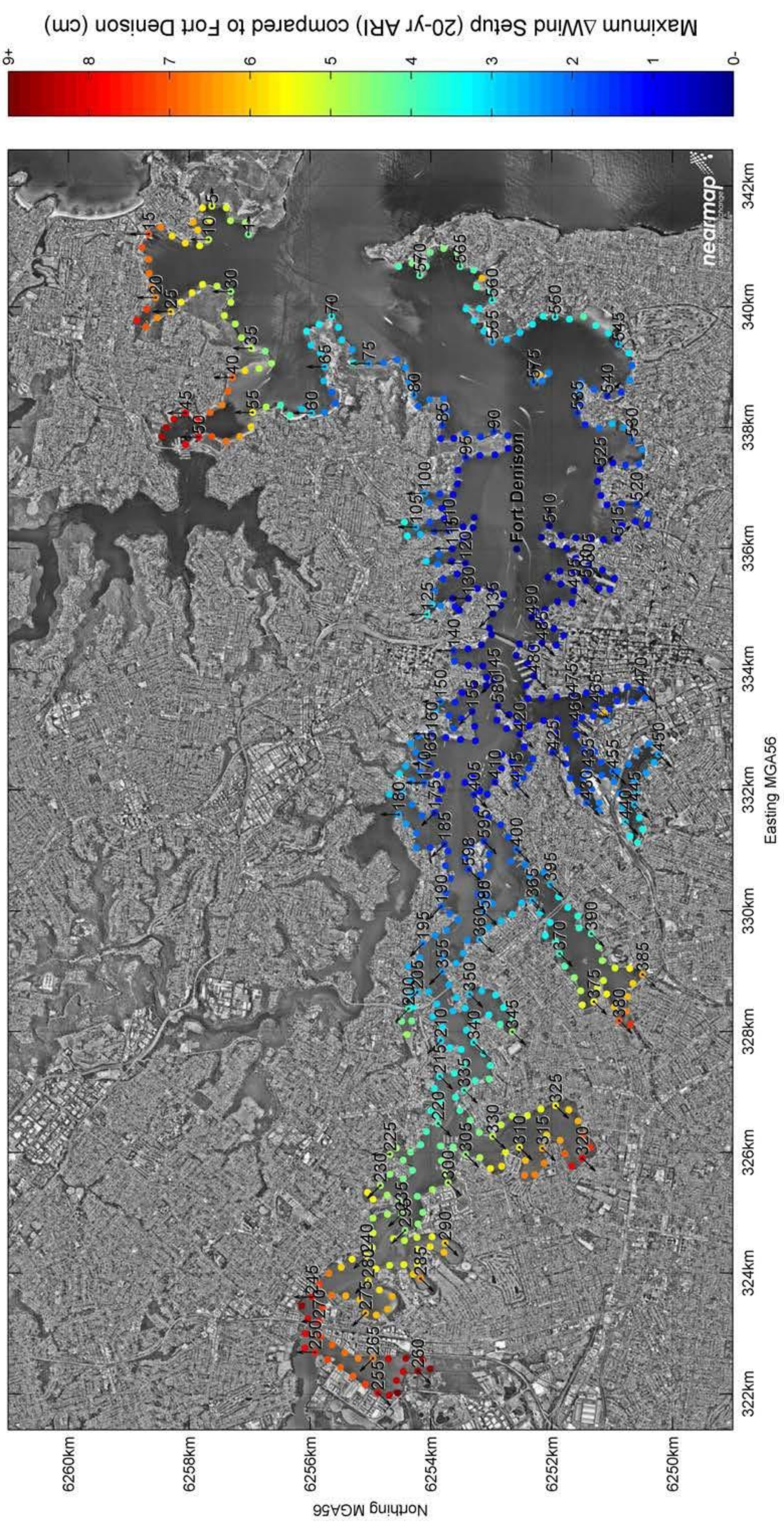


Figure 3.12 Map of Maximum Wind Setup - 20–Year ARI (Cardno and Baird, 2014b)

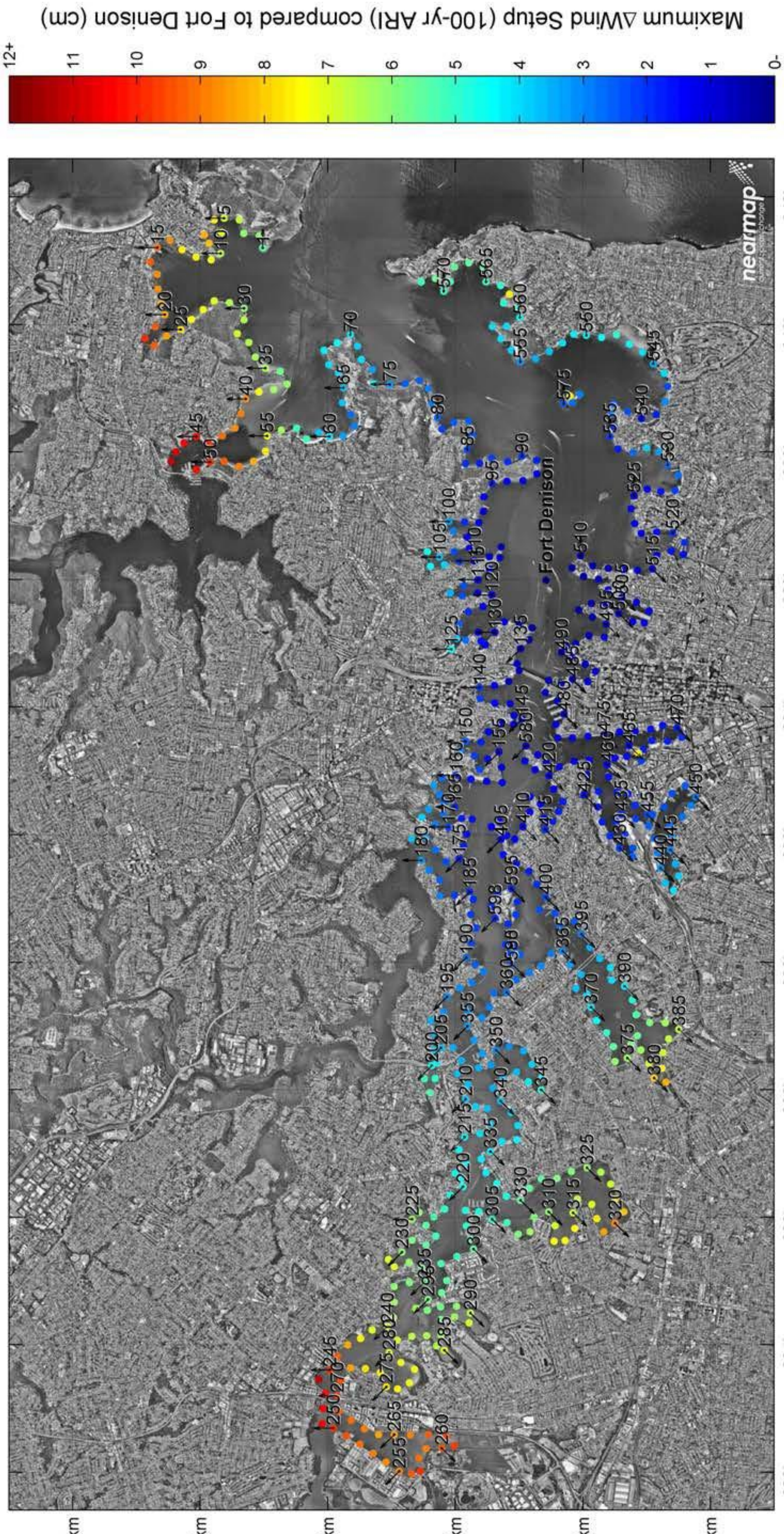


Figure 3.13 **Map of Maximum Wind Setup - 100–Year ARI (Cardno and Baird, 2014b)**

3.3.2 Tsunami Hazard

To investigate and quantify the potential tsunami hazard within Sydney Harbour, an approach was adopted whereby hydrodynamic modelling was conducted for a range of recurrence interval tsunami events from a range of tsunamigenic sources, Cardno (2013). This work was undertaken for NSW Office of Environment and Heritage (OEH) and State Emergency Services (SES).

Hydrodynamic modelling was conducted for tsunami of the following recurrence intervals – 200-years ARI and 2000-years ARI. For each recurrence interval hydrodynamic modelling was undertaken for tsunami originating from a range of critical source zones (sub-duction zones), listed in Table 3.3 and depicted in Figure 3.14.

Table 3.3 Critical Source Zones (Subduction Zones)

ARI (years)	Puysegur	New Hebrides	Subduction Zone Kermadec	Tonga	South Chile
200	X	X	X	X	**X**
2000	**X**	**X**	**X**	-	-

The subduction zones listed above were identified through interrogation of Geosciences Australia's (GA) Tsu- DAT database. Tsu-DAT provides a tool for access to GA's database of numerical modelling results of thousands of individual synthetic tsunami events and provides a summary, in terms of both probability and average recurrence interval (ARI), of the likelihood of a given tsunami height occurring at a given offshore location (at the 100m depth contour). Further information regarding the selection of critical tsunami subduction zones is provided in Cardno (2013).

In order to assess the tsunami hazard inside Sydney Harbour, Cardno utilised their calibrated and validation hydrodynamic tsunami model established as part of the NSW Tsunami Inundation and Risk Assessment study (Cardno, 2013), wherein further details on model set-up are provided.

An envelope approach was adopted whereby for each grid point the highest water levels and current speeds for each ARI were extracted from the results of the tsunami model simulation that were undertaken for each of the ARIs and source zones listed in Table 3.3. The governing water level and current speed for each grid point was then calculated by taking the maximum over the results from the different source zones as well as tide levels, where applicable (simulations for the 200- and 2,000-year ARI cases were undertaken at HAT only and MSL and HAT, respectively).

Results showed that for both the 200- and 2,000-years ARI cases the maximum water levels occur in the Manly/Jilling Cove area as well as, to a lesser extent, the Balmoral Beach area (Hunters Bay). Figures 3.15 and 3.16 describe the spatial variation in maximum tsunami run-up levels for the 200 and 2,000-years ARI cases, respectively. Table 3.4 presents example high water levels at selected locations.

Southern Calmari Squid (*Sepioteuthis australis*)

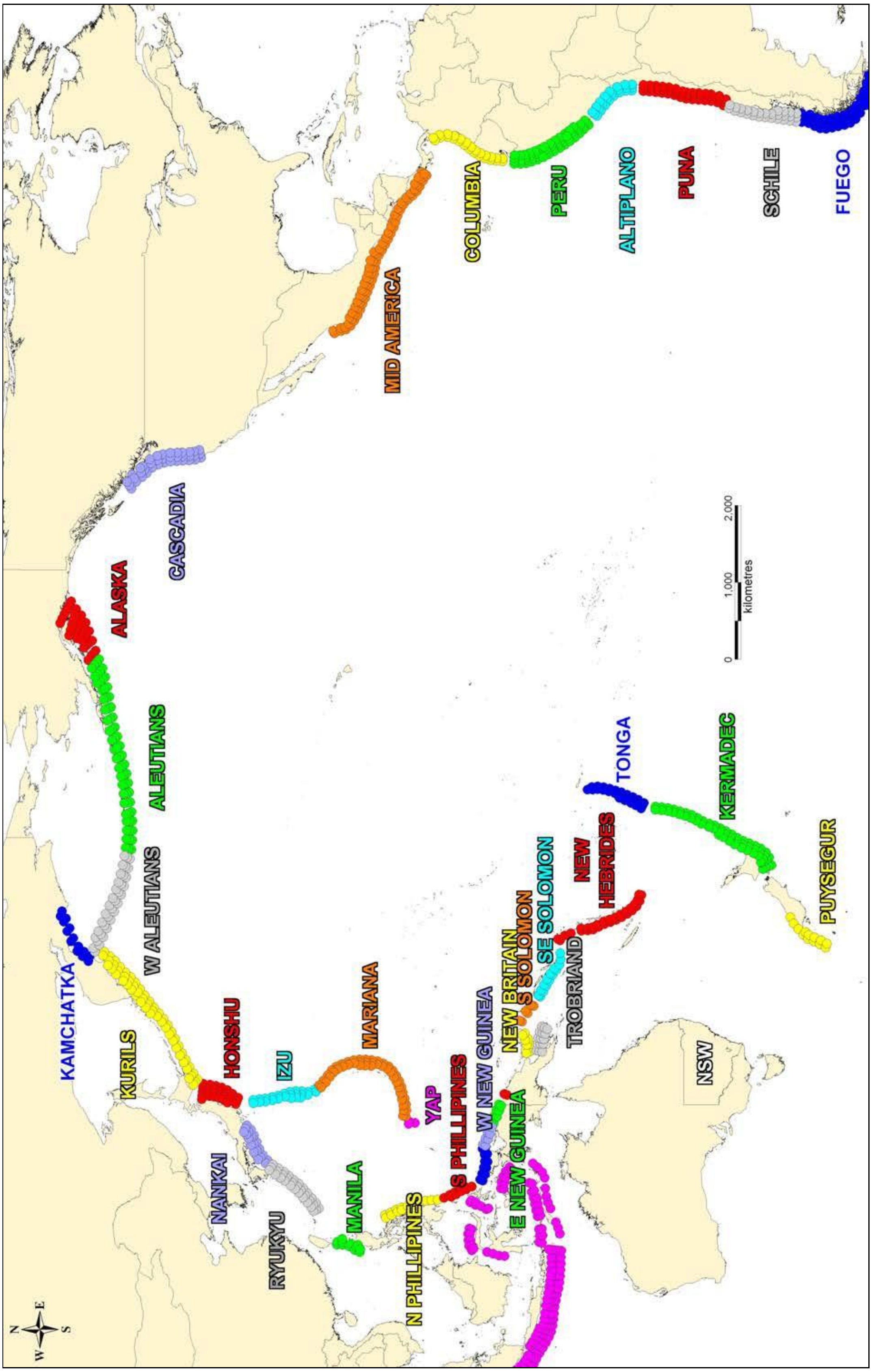


Figure 3.14 **Tsunami subduction zones (Cardno and Baird, 2016)**

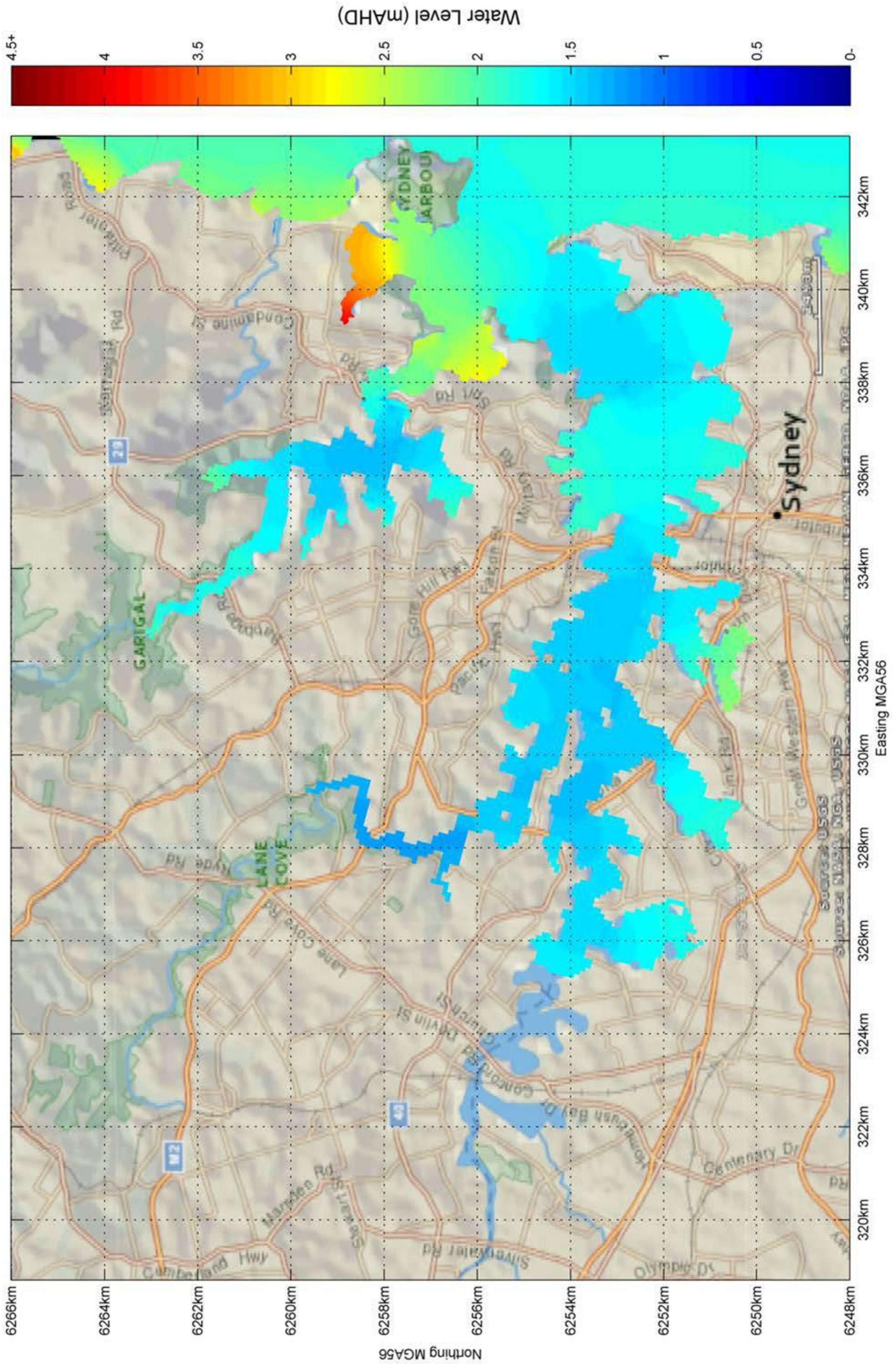


Figure 3.15 Tsunami – Maximum Water Level 200–Year ARI (Cardno and Baird, 2014b)

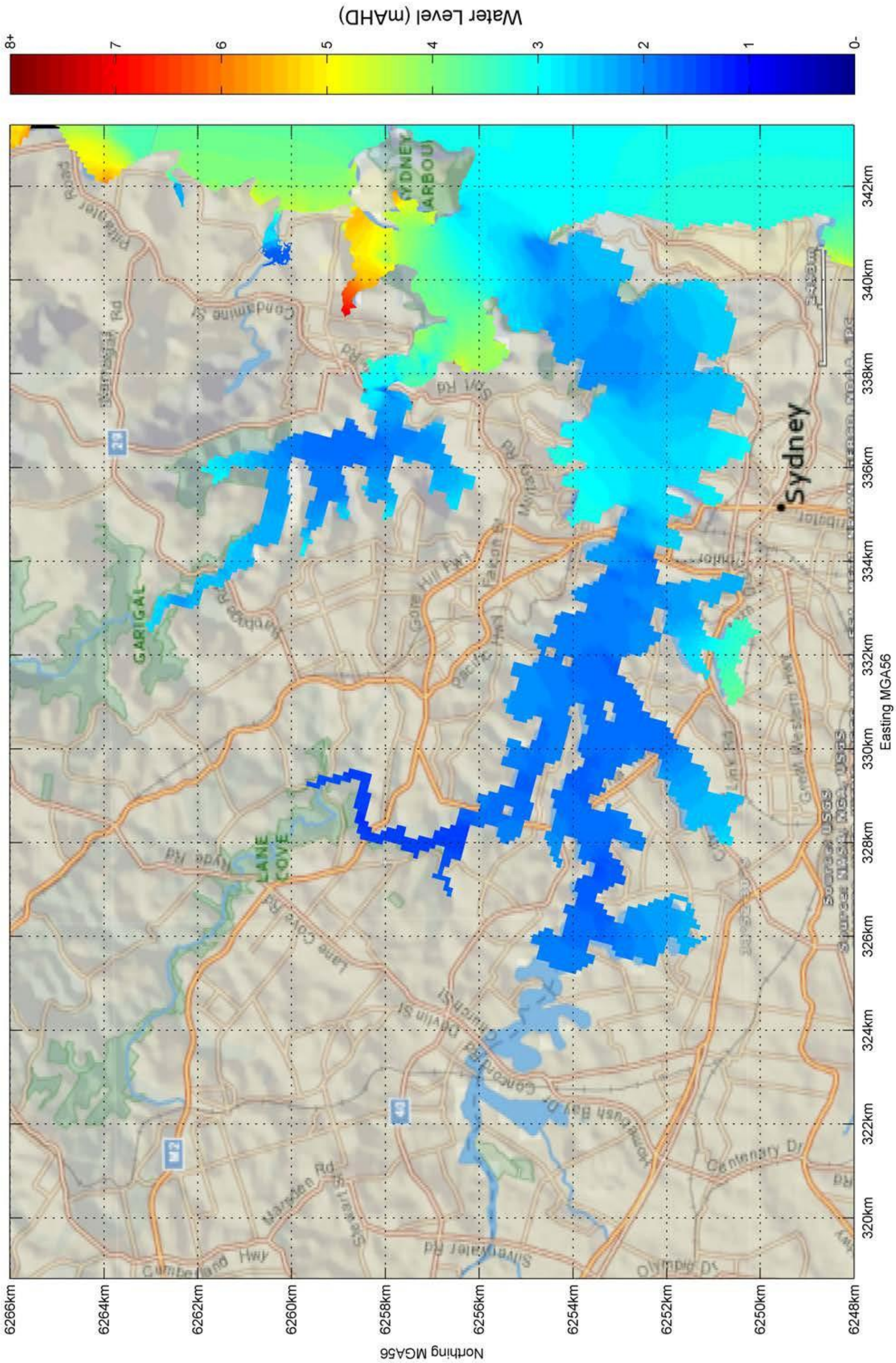


Figure 3.16 Tsunami – Maximum Water Level 2000–Year ARI (Cardno and Baird, 2014b)

Table 3.4 Peak Tsunami Water Levels (m AHD) for Selected Locations (Cardno and Baird, 2016)

Location	200-Years ARI	2,000-Years ARI
Balls Bay Wharf	1.5	**2.0**
Woolloomooloo Bay	1.8	**2.8**
Chowder Bay RAN Wharf	1.5	**2.2**
Manly Ferry Wharf	3.1	**5.3**
Watsons Bay Ferry Wharf	1.7	**2.4**
Circular Quay	**1.6**	**2.5**

Maximum current speeds were determined in a manner similar to that adopted for water levels, with the highest currents predominantly occurring in the regions of Middle Harbour and around Spit Bridge for the 200-years ARI case, and Middle Harbour and the Manly Cove/North Harbour area for the 2,000-years ARI case. Table 3.5 presents example results for selected locations at the 200 and 2,000-years ARI.

Table 3.5 Peak Tsunami Current Speeds (m/s) for Selected Locations (Cardno and Baird, 2016)

Location	200-Years ARI	2,000-Years ARI
Balls Bay Wharf	0.28	**0.58**
Woolloomooloo Bay	0.15	**0.41**
Chowder Bay RAN Wharf	0.48	**1.16**
Manly Ferry Wharf	0.29	**1.46**
Watsons Bay Ferry Wharf	0.27	**0.62**
Circular Quay	**0.19**	**0.49**

3.3.3 Vessel Traffic Effects on Scour & Sediment Transport

This issue is addressed in two ways. The first is the effect of vessel traffic on shoreline stability and the second addresses the effects on seabed ecological conditions and the relative effects of seabed disturbance by vessels and wind waves.

Shoreline Effects

Bank erosion is an issue throughout the Harbour. This is due to a range of factors, including:

- Undermining due to boat wash,
- Ageing infrastructure, the sandstone seawalls in particular,
- High rates of usage of foreshore open space,
- Erosion adjacent to stormwater outlets,
- Coastal processes (such as wind waves), or
- Dredging of navigation channels.

Bank erosion may have flow-on effects on many other features of the estuary and may pose a risk to public safety. he key issues relating to the declining condition of seawalls along the Parramatta River estuary are public safety risk, loss of foreshore amenity, property impacts, the loss of significant heritage items and environmental degradation. The failure to undertake works to mitigate and remediate foreshore erosion stems primarily from a lack of funding, although it is noted that some Councils indicated that they were unsure as to which agency was responsible for maintaining seawalls. However, It is understood that Councils are generally responsible for public infrastructure above the MHWM, while infrastructure below the MHWM is owned by the Crown.

WP Geomarine (1998) prepared an appraisal of damage to seawalls along the Parramatta River and determined that damage to seawalls has been the result of undercutting of the banks as the channel has deepened (or been deepened) and moved closer to the shoreline and/or the wave climate has been altered due to the presence and operations of the RiverCat ferries. This was said to have affected both natural and artificial shorelines. A key issue raised in the WP Geomarine (1998) report is that the audits conducted up to that date have only assessed visible damage and that the extent of damage may in fact be greater than indicated (i.e. below low tide level).

Webb, McKeown and Associates (1997) conducted an audit of seawalls along the Parramatta River estuary, except for those contained within the Leichhardt LGA. That study identified many foreshore treatments, including natural beaches or rocky shores and vegetated shores. The foreshore was divided into zones and a condition ranking (very good to very poor) was applied to each zone. Mangroves and beaches were also ranked by condition relating to the impacts of erosion. The audit also identified the type, cause and implications of each type of defect or failure and different zones were allocated a priority for repair, for which a remediation option was recommended.

Webb, McKeown and Associates' (1997) key findings were as follows:

- Seawalls in exposed locations were subject to boat waves and were in significantly poorer conditions than seawalls elsewhere in the estuary.
- The movement of tides also resulted in the loss of seawall backfill, although primarily in embayments or where stormwater pipes pass through the seawall.
- Mangroves were beneficial in preventing foreshore erosion via dissipation of wave energy and by encouraging siltation.
- Sections of river bank not protected by a seawall were subject to slumping, primarily due to boat wakes, but also due to tidal cycles (wetting and drying) and wave attack. This was particularly problematic adjacent to seawalls or where mangroves are absent.

However, it is noted that this report was prepared over 15 years ago and may not represent an accurate record of the condition of the estuary foreshores at the present time. For example, during the course of consultation with the foreshore councils, a number of locations affected by seawall collapse were identified:

- Portion of the seawall along the Silverwater stretch of Duck River recently collapsed and was replaced (pers. comm., G. Stamatakos, AMC, 2 April 2008).
- There is currently seawall construction being undertaken in Sheppards Bay, along Parsonage Street near the Ryde Bridge (pers. comm., J. Pucci, CoR, 3 March 2008).
- Seawall collapses have occurred at Werrell Reserve in Abbotsford and near the wharf at Chiswick. These areas were repaired in 2007.

It is understood that NSW Maritime has in place a program to monitor the condition of foreshore infrastructure, including seawalls, which led to the development of the *Parramatta River Long-term Shoreline Monitoring Study*. It is understood that boat wash from the RiverCat and Harbour ferries has been implicated in shoreline erosion along the estuary (Webb, McKeown and Associates, 2007).

Upper Parramatta River Estuary

Undermining of the river banks due to wash from the RiverCat ferries is particularly evident along the stretch of the main estuary upstream of Duck River. The subsequent collapse of the banks is leading to the undermining of mangroves in this location.

Although observed throughout the study area, it is particularly noted that the Upper Parramatta River Estuary was primarily affected by erosion where the banks have previously been inadequately stabilised with *ad hoc* materials.

PCC (2003) provide a list of previous seawall audits for the Parramatta River. However, one of the reports referenced, the 1998 Parramatta River Seawall Damage Appraisal and Addendum, was not available at the time of preparation of this report. The highest risk area within the Parramatta LGA was identified as being a 150m extent of seawall at Queens Park Wharf (PCC, 2003).

AWACS (1989) undertook an assessment of foreshore conditions on both sides of the river for the reach of estuary between Silverwater Bridge and Homebush Bay, also including Homebush Bay. Several sections were identified as being seawalls subject to slumping (AWACS, 1989). However, it is anticipated that these findings may now be dated and that more up to date information is required.

Sydney Olympic Park Authority (SOPA) has also prepared seawall audits and management plans for the reach of foreshore adjacent to Millennium Parklands (Webb, McKeown and Associates, 2007).

Mid Parramatta River Estuary

It is understood that City of Canada Bay Council holds an extensive photo-archive from 1984 of the foreshore from Hen and Chicken Bay to the western boundary of that LGA. This archive is held in both hard copy and electronic formats, and the photographs have been annotated and are referenced to a map. This material was prepared by the former Concord Council (now amalgamated into the City of Canada Bay). Anecdotal evidence suggests that there have been no significant changes in the seawalls along the City of Canada Bay Council foreshore since audit undertaken in 1999.

Seabed Re-Suspension by Boat Traffic

Bishop (2003) undertook extensive boat wash investigations within the Parramatta River. Her investigations provided little evidence of a deleterious effect of regulated boat traffic causing wash on the estuarine benthic organisms. However, she cites other studies that report that wind waves are important for assemblages in sedimentary habitats. However, she did find that there were differences in assemblages of macrobenthic infauna between sites affected by and not affected by boat wash. Neither was there evidence that mangrove pneumatophores appear to be effective in reducing the effect of wash on infauna.

Hughes (2006, in Cardno and Baird, 2016) undertook field observations to investigate the impact of boat traffic on re-suspension of bed sediments. The study utilised the deployment of a benthic instrument array measuring tidal water level, current speed and direction, and turbidity at several heights above the bed over a semi-diurnal tidal cycle (~12 hours) during a period of spring tides. There were deployments located near Mortlake on the Parramatta River which consisted of burst-sampling tidal currents and turbidity for 10 minutes at 5 Hz once every hour.

The study showed that while wind waves and conventional boat wakes were incapable of influencing the lower water column at either deployment site, RiverCat wakes, being long waves, can cause near-bed oscillatory flows and re-suspending bed sediment. RiverCat wakes increased near-bed turbidity by up to a factor 20 above values existing immediately prior to arrival of the wake. The magnitude of sediment resuspension in relation to RiverCat wakes was highly variable with no obvious pattern. In almost all cases, however, the re-suspension was limited to less than 0.5m above the bed.

3.3.4 Dioxin Contaminated Sediments

The dioxins found in Homebush Bay include the most toxic known to science (2, 3, 7, 8-TCDD). These dioxins cause cancer, severe birth defects, inability to maintain pregnancy, decreased fertility, reduced sperm counts, endometriosis, diabetes, learning disabilities, immune system suppression, lung problems, skin disorders, lowered testosterone levels and much more. Other toxic contaminants found at the site include, tar, tar oil, naphthalene, polycyclic aromatic hydrocarbons, pyridine, creosote oils, phenol and derivatives, mononitrobenzene, aniline, various chlorinated phenols, chlorinated benzenes, trichloranisole, bispenol-A, solvents and furans.

The primary mechanism for the spread of sediments from Homebush Bay throughout Sydney Harbour is resuspension by wave-induced currents and subsequent entrainment and transport in the tidal flow. A series of scenario-based nearfield and farfield numerical modelling exercises were used to investigate these processes. A high-resolution 3D model calibrated for tide, fluvial, and wind-wave forcing was used. The coupled sediment transport model was calibrated to achieve reported surface Total Suspended Sediment values in resuspension events.

The results indicate that the highest volumes of dioxin are transported out of Homebush Bay during strong southerly wind events associated with high ebb tidal currents. Several potential ‘hot spots’ of contaminant accumulation were identified from the model results, and dioxin-contaminated sediments will likely continue to spread throughout Sydney Harbour during high wind events. Further, potential resuspension from secondary deposition sites requires investigation with further modelling. Historical discharges of contaminants from industrial sources have caused the accumulation of contaminated fine sediments in the Sydney estuary. The toxicity from accumulated dioxins, in the Homebush Bay area, are responsible for the permanent bans placed on fishing and trawling in the Sydney estuary from February 2006 (Birch *et al.,* 2007). Further, water based activities such as swimming and diving are discouraged west of the Sydney Harbour Bridge due to water quality concerns.

The aim of this study was to gain insight into the potential long-term fate of contaminated sediments from preliminary numerical modelling exercises focused on re-suspension and transport of contaminated sediments in and near Homebush Bay. Greater Sydney Local Lands Service had an interest in understanding the migration and potential fate of these contaminated sediments and time scales of concentration changes, with a goal of understanding if or when the Sydney estuary may be reopened for fishing or if future spreading of the contaminated sediment may lead to additional areas of concern. The development of the Delft3D hydrodynamic model of the Sydney estuary in previous projects provided a platform for the investigation of these issues. Sediment transport modelling exercises reported in this section address sediment re-suspension and transport processes to describe potential changes in existing areas of high contaminant concentration and also the effects of vessels (see above).

Over 35 years, Sydney University has undertaken a comprehensive research program on the chemistry and nature of contaminated sediments in the Sydney estuary, led primarily by Professor Gavin Birch. Data from these research efforts have kindly been made available by him for the investigations and modelling.

Homebush Bay is a shallow bay extending off the southern side of the Parramatta River channel, approximately 20 km upstream of Sydney Heads (Figure 3.17). The bay is less than 2 m deep on its eastern side, and up to 5 m deep in the channel along the western bank, with a northeast-southwest alignment. Powells Creek and Haslams Creek are the tributaries feeding the bay from the southeast and southwest, respectively. These creeks drain highly urbanised catchments and the Sydney Olympic Park site.

The foreshore of Homebush Bay was lined with industrial factories through much of the 20th century, with the main contributor to dioxin contamination being the Union Carbide/Lednez site on the Rhodes Peninsula which undertook chemical production from 1928 until 1985.

The foreshore of the bay has become populated in recent years with the expansion of high density residential development on the Rhodes Peninsula on the eastern side of the bay and Wentworth Point on the western side of the bay.

Nature of Sediments

The fine silts within Homebush Bay have likely been deposited in low tidal current conditions and redistributed by north-easterly winds (PWD, 1986), while the sandy fractions at the mouth of the bay originate from the main Parramatta River. The sandy fractions at the creek mouths are likely deposited in flood events. PWD (1986). found the surface tidal currents in Homebush Bay to be in the order of 0.05 ms^{-1} in low wind conditions. The tidal range in Homebush Bay is similar to the oceanic tidal range, typically about 1.5m, indeed it has been found to amplify by 0.1 m compared to the tidal range at Fort Dennison with an approximate 1.5 hours time lag (PWD, 1986). The peak discharge was found to be in the order of 56 m^3s^{-1}.

Irvine (1980) identified that the shallow bays of the Sydney estuary, including Homebush Bay, are predominantly composed of sandy muds, which are deposited and redistributed by tidal and flood flows. In a site-specific study, PWD (1986) discriminated further by morphology, and described the sedimentology of the surface layer on the bed of Homebush Bay as close to 100% fines (silts and clays) from cores taken in the bay channel and fines mixed with up to 68% sand and shell at the mouths of the creeks. Sandy fractions are also located at the mouth of the bay. The readily resuspended surface layer is up to 0.03 m thick (Irvine 1980, Taylor and Birch 2000).

Sources of Contaminated Sediments

The level of dioxin contamination in the Sydney estuary is the highest in Australia and one of the highest in the world (Birch *et al.,* 2007). Dioxins were manufactured on the Rhodes Peninsula at the former Union Carbide site on the eastern shore of Homebush Bay for 59 years (Birch *et al.,* 2007). Polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (referred to here as ‘dioxins’) tends to bio-accumulate and is toxic to humans (Birch *et al*., 2007). Dioxins break down very slowly once bound to sediment (the half-life may exceed 50 years – US EPA Technical Factsheet on Dioxin). The use of contaminated fill to reclaim parts of the bay led to the contamination of Homebush Bay sediments. Since contaminated sediments containing dioxins have a single point source in the Sydney estuary, deduced from the singular chemical signature (Birch *et al.*, 2007), their presence in other parts of the estuary indicates the potential for their transport. Dioxins have been observed to have dispersed 4-5 km upstream and up to 12 km downstream to the central Harbour by 2007 (Birch *et al*., 2007).

Union Carbide factory at Rhodes adjacent to Homebush Bay in the 1960s

Figure 3.17 Site map of Homebush Bay (Cardno and Baird, 2017)

The following extract from Birch *et al.* (2007), summarises the previous studies of dioxin in Homebush Bay:

> Dioxin and other contaminants in the sediments of Homebush Bay in central Port Jackson were first investigated in the late 1980s. Johnstone Environmental Technology (JET) (JET, 1987) sampled and analysed sediment from five locations for dioxins and organochlorine pesticides. JET subsequently undertook sampling at a further 160 locations and at multiple depths in the bay in the period 1987– 1990. As a result of these studies a total fin fishing ban was placed on Homebush Bay by the State Pollution Control Commission in 1989. This was extended to a commercial fishing ban in the upper third of the estuary in 1990. Paramatrix and AWT Ensight (1996) undertook a limited sediment and fish tissue sampling program to validate and better understand the findings of previous studies.
>
> EVS environmental consultants (EVS, 1998) undertook a systematic sediment sampling investigation, based on three-point composite samples taken from 56 gridded cells across the bay to develop a risk- based remediation plan for the bay. URS Australian Pty. Ltd. (URS, 2002) undertook more detailed sampling and analysis of discrete samples from 144 locations within the previously defined EVS grid cells. The latter study was undertaken to support an Environmental Impact Statement then in preparation for the remediation of the bay (Parsons Brinkerhoff, 2002). Studies undertaken by the New South Wales (NSW) Food Authority resulted in temporary three-month bans on fin fishing in December 2005 and for prawn trawling in Januar, 2006. Permanent fish and prawn trawling bans were ordered in February 2006 for the entire Harbour due to dioxin tissue concentrations.

Remediation efforts were made in 2004 to reduce the dioxin concentrations in localised areas of Homebush Bay (Birch *et al.*, 2015) prior to redevelopment of the surrounding land areas. A site on the eastern bank of the bay was ordered to be remediated by the Department of Environment and Conservation to a depth of 1m within an area 300 m long and 100 m wide and replaced with clean soil and sediment (Birch *et al.*, 2015). The majority of the bay was left un-remediated and supports the largest remaining stands of mangroves in the estuary (Rogers *et al*. 2005, in Cardno and Baird, 2014a). The following extract from Birch *et al*. (2007) describes the remediation efforts:

> The remediation of dioxin contamination in soils on the Rhodes Peninsula and in sediments of Homebush Bay is being undertaken by Thiess Services, an Australian remediation contractor using both direct and indirect thermal desorption plants supplied and operated by the Environmental Chemical Corporation, California, USA. The scope of the remediation will include excavation of approximately 450,000 m^3 of fill and treatment of up to 200,000 m^3 of soil on the Rhodes Peninsula (Lednez and Allied Feeds sites) and excavation and treatment of approximately 27,000 m^3 and 10,000 m^3 of sediment, respectively from Homebush Bay. Only the most contaminated portion of the bay along the eastern shore will be remediated by removing the upper 0.5 m of sediment and by replacing it with clean fill.
>
> Ongoing monitoring will be required to determine if the ban on fin fishing and prawn trawling in place for the whole of Port Jackson, can be lifted in the future. Monitoring will also be required to demonstrate that recontamination of the clean fill does not occur by remobilization of contaminated sediment from other parts of Homebush Bay.

The conflicting information over the remediation depth (1 m or 0.5 m) is noted and a final design of the remediation has not been found. There has been limited investigation of the post-remediation state of Homebush Bay. Birch *et al.* (2015) found that remediated parts of Homebush Bay were re-contaminated with lead and zinc, and attributed this recontamination to re-suspension, transport and deposition of contaminated sediments from elsewhere in the bay to the remediation site. Prof Birch noted that the unconsolidated sediment overlying the clean fill emplaced at the remediation site was approximately 100mm thick 18 months after the remediation, indicating that the sediment in Homebush Bay is readily resuspended and transported within the bay.

Process Understanding

The concentration of dioxin in the Sydney estuary is a result of two processes that work simultaneously and in opposite directions, namely relaxation and re-mobilisation. Dioxin-enriched particles become remobilised and are transported through the estuary, whereas dioxin-poor sediments are introduced by fluvial processes over time. The fluvial sediments tend to reduce dioxin concentrations in surficial sediment i.e., relaxation, whereas re-mobilisation and deposition of dioxin-bound particles tend to increase surficial sediment concentrations elsewhere. It is the relative importance of these two processes which will define the ultimate dioxin concentration of surficial sediment in any location (pers. comm. Prof G. Birch).

The primary mechanism for the spread of dioxin-contaminated sediments from Homebush Bay through the Sydney estuary system is re-suspension of bed sediments and their subsequent entrainment and transport in the tidal flow. Re-suspension of bed sediments occurs when the bottom shear stress exceeds the sediment cohesion. The main processes influencing sediment transport and deposition within Homebush Bay are:

- Tidal oscillations
- Wind driven wave-induced currents
- Flood currents, and
- Anthropogenic (vessel movements).

Re-suspension of fine sediments does not generally occur in the shallow bays of the Sydney estuary under typical tidal currents (Irvine, 1980; Taylor, 2000), and instead are observed to be resuspended during high wind events as wind energy is transferred to the bed via wave-induced currents and cause exceedance of the critical shear stress threshold for erosion. Once these sediments are suspended in the water column, they can be transported through the Sydney estuary by tidal currents. Settling occurs relatively quickly on cessation of high wind conditions.

The Sydney estuary is relatively well mixed under ambient conditions with low freshwater discharges at all discharge locations (Birch and Taylor, 2004). Stratification occurs typically in high precipitation events, during which the freshwater runoff sits as a buoyant layer in the water column and flows over the more saline tidal flow (Taylor, 2000). This freshwater flow may provide a conduit for contaminated sediments to spread throughout the Sydney estuary when high wind and high precipitation events coincide in stormy conditions.

Spread of Dioxin Contamination from Homebush Bay within the Sydney Harbour estuary

This study established a calibrated hydrodynamic-wave-sediment transport model of the Sydney Estuary, with parameter values determined based on past studies and sensitivity testing. This model has subsequently been applied in a scenario-based approach to investigate the re-suspension and transport of dioxin- contaminated sediments from Homebush Bay throughout the Sydney Estuary under a number of environmental conditions. Details of the methods and results are provided in Appendix C.3 and in Cardno and Baird, (2017).

The model results show the potential for mobilisation and redistribution of dioxin-contaminated sediments from Homebush Bay throughout the Sydney Estuary under high wind conditions. The mechanism for sediment transport is re-suspension due to wind-wave current induced bed shear stress, and subsequent transport via tidal currents. The magnitude of the tidal currents is important in determining the contaminated sediment load exiting Homebush Bay and its subsequent deposition throughout the Sydney Estuary. The rate of resuspension and transport of dioxin-contaminated sediments within and beyond Homebush Bay is highly non-linear and complex and is based on the environmental conditions, including the wind speed, direction, event duration, tidal flow direction and magnitude, and likely changes in bathymetry. A limited number of scenarios has been investigated here, aiming to identify the most likely environmental conditions for dioxin transport. It was found that an extreme wind event from the south associated with a high tidal range promotes the greatest dioxin transport out of Homebush Bay.

The general spatial distribution of dioxin-contaminated sediments in the model results accord well with measured results of dioxin contamination in Homebush Bay and the wider Sydney Estuary. In Homebush Bay, the re-deposition of dioxin-contaminated sediment in remediated areas on the eastern foreshore has been noted (Professor Birch, pers. com.). The modelling results also indicate that for major embayments, for example, Hen and Chicken Bay and Iron Cove, the accumulation of dioxin-contaminated sediments is higher near the entrance to the main Sydney Harbour channel, and decreases upstream in the embayment towards the catchment outlets. The modelling results indicate that, following completion of the Homebush Bay remediation work in 2011, the dioxin transport out of the bay during episodic re-suspension events may have been reduced by approximately 50% based on the results of the pre- and post-remediation scenario modelling.

A complete reconstruction of the spread of dioxin throughout the Sydney Estuary is not possible because the past distribution of dioxin contamination within Homebush Bay, particularly within the timeframe of its active production, is unknown. An understanding of the future spread of dioxin-contaminated sediments throughout the Sydney Estuary would require a baseline measurement study, quantifying the present day distribution of dioxin. This distribution of contamination could be used as the initial condition for a series of model simulations of event scenarios representing future environmental conditions in the Sydney Estuary based on climatological analysis of long term wind and rainfall data. The integration of model results over a series of such events would give an indication of the possible extent and concentration of dioxin contamination over a planning timeframe.

Sydney Harbour has a high volume of vessel traffic generated by commercial, recreational and ferry vessels that transit along the Harbour, up to Parramatta Weir. This vessel traffic has the potential to generate waves and in the Parramatta River in particular high speed passenger ferries (RiverCats) have caused significant erosion and seawall stability issues at particular locations.

Homebush Bay itself has low vessel traffic compared to many areas of the Harbour and the high-speed RiverCats do not transit inside Homebush Bay. Most recreational craft that enter Homebush Bay are unlikely to generate waves of more than 0.1 m within 50 m of the vessel with associated wave periods of 2 to 3 seconds. In comparison, the wind wave events, which occur two to three times per year for several hours (each event), generate wind waves of 0.2 to 0.3 m (Hs) with wave periods of approximately 2 seconds. The small vessel waves within Homebush Bay have only a fraction of the sediment transport potential of strong winds and large tides and therefore vessel waves within Homebush Bay are a minor source of sediment re-suspension.

It is possible that in some areas of the Parramatta River, where suspended sediments from Homebush Bay may settle post-event, that vessel waves may re-suspend material and impact on the ultimate fate of contaminated sediments. However, investigations into sediment re-suspension from the longer period RiverCat wake which identified that re-suspension from RiverCats was limited to within 0.5 m of the seabed, and normally only occurred during the leading wave of a set of waves generated by the moving vessel. Based on that assessment, it is likely that vessel generated waves have only minor, localised impacts on the transport and ultimate fate of contaminated sediments in the Parramatta River.

Conclusions

The Sydney Harbour Estuary Processes Study has considered the ongoing movement of fine sediments, including potentially contaminated sediments, from Homebush Bay. A specially configured Delft3D model with high vertical and horizontal grid resolution was applied to examine the potential for resuspension of fine sediments, including dioxins in Homebush Bay and the short-term fate of the sediments and dioxin. High winds and flood events in combination with normal tides have the potential to resuspend and then transport the sediments outside Homebush Bay. Modelling of the potential spread of dioxin mobilised by high winds and flood conditions on an event basis showed the redistribution of contaminants to surrounding bays with hotspots including the northern Parramatta River bank opposite Homebush Bay (Meadowbank), Brays Bay (Rhodes) and Majors Bay (Concord). Figure 3.18 presents an example of the event-based deposition of dioxin contaminated sediment in the Parramatta River following a resuspension event in Homebush Bay.

Although the modelling was only event based over a period of days, transport of dioxin was modelled at very small concentrations to occur upstream to Parramatta Charles St Weir, and downstream to at least Glebe Island. The event modelling results also indicate that for major embayment's, for example Hen & Chicken Bay and Iron Cove Bay, the accumulation of potentially dioxin-contaminated sediments from Homebush is higher near the entrance to the main Sydney Harbour channel, and decreases upstream in the embayment towards the catchment outlets. This is consistent with the conceptual model of dioxin contamination in Sydney Harbour (figure 3.19) presented Birch (2006).

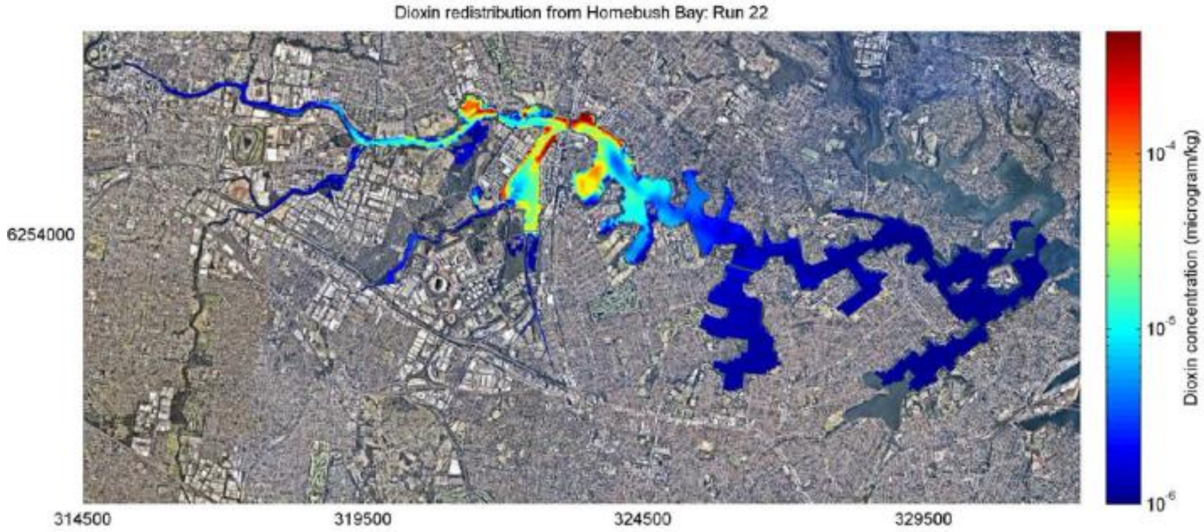


Figure 3.18 **Example of modelled fate of dioxin contaminated sediment resuspended from Homebush Bay.**

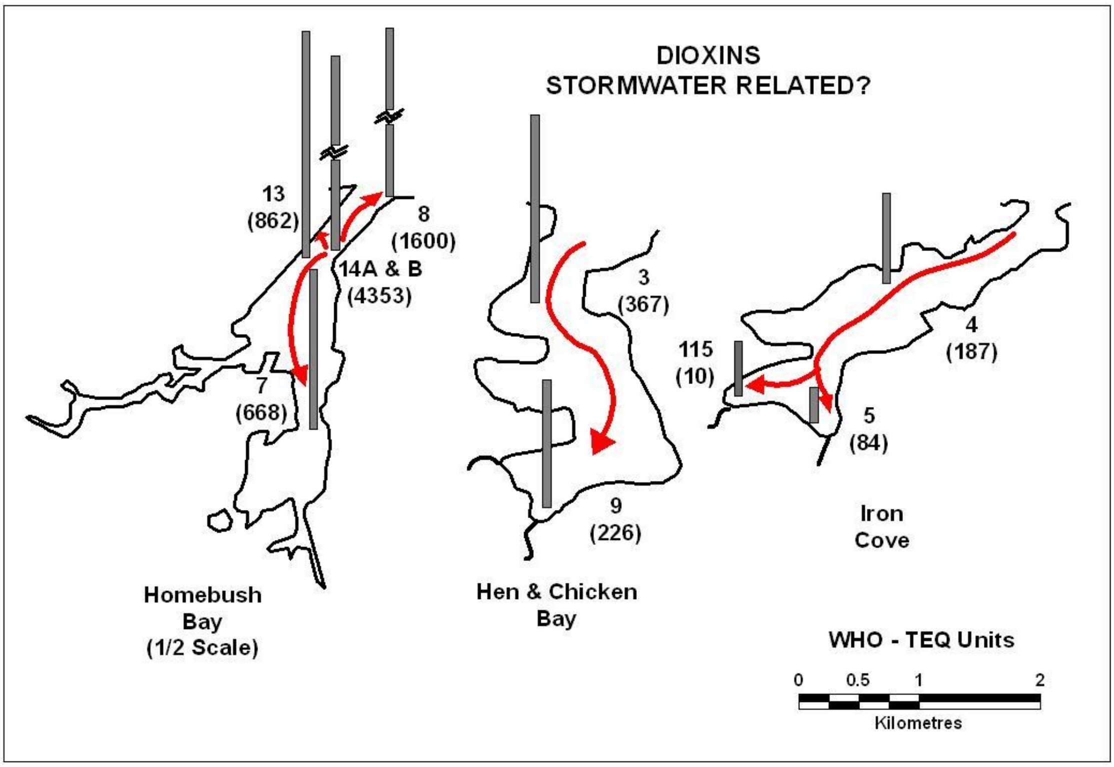


Figure 3.19 **Schematic diagram representing the distribution and concentration of dioxin in some of the bays of Sydney Estuary (Birch 2006).**

Population growth in Western Sydney, particularly along the Parramatta River is resulting in growing interest to use the river for swimming. Recent sediment sampling undertaken to assess potential swimming sites in the Parramatta River have supported the understanding that subtidal sediments are still very high in dioxins (Geochemical and EnRisks, 2017). The sum of PCDD/Fs in subtidal sediment varied from 11,700 to 160,000 pg/g. Concentrations of Total PCDD/F in subtidal sediment varied from 26.1 to 415 pg TEQ/g. The sum of dioxin-like PCBs in subtidal sediment varied from 1.35 to 18.59 ng/g. The dioxin-like PCBs in subtidal sediment varied from 0.00091 to 0.0056 ng TEQ/g.

A recent Environmental Impact Statement prepared for the NSW government (EnRiskS, 2017) states:

1) Average concentrations of dioxin-like compounds in sediments (surface and all sediments) in Homebush Bay are 810-999 pg TEQ/g.
2) The concentrations in the Parramatta River are similar/slightly lower than those in Homebush Bay but are really within the normal variability that would be expected for measurement of chemical concentrations in sediments.
3) The results for the dioxin-like compounds show not only that there is not much difference inside and outside of Homebush Bay.
4) 450 tonnes of sediment per year leaves Homebush Bay due to natural tidal processes each year.
5) Concentrations of dioxin-like compounds in the suspended particulate matter are even more consistent than those in the sediment samples.
6) There is not much difference between the suspended particulate matter results at Wentworth Point and those in the reference locations nor between the suspended particulate matter and the sediments.

Roach *et al*. (2018) collected sediment samples from 25 sites in Sydney Harbour to determine the distribution and sources of seven polychlorinated dibenzo-p-dioxins (PCDDs), 10 polychlorinated dibenzofurans (PCDFs), 12 dioxin-like polychlorinated biphenyls (PCBs) and 33 polybrominated diphenyl ethers (PBDEs). They found that the concentrations of ΣPCDDs ranged from 480-260,000 pg g-1 dry weight and were predominantly composed of OCDD (93-99%) and 1,2,3,4,6,7,8-HpCDD (1-6%). The concentrations of ΣPCDFs ranged from 7.9-4600 pg g-1 dry weight and were dominated by two congeners: OCDF (60-77%) and 1,2,3,4,6,7,8-HpCDF (17-26%). The concentrations of ΣPCBs ranged between 300–15300 pg g-1 dry weight and were dominated by five congeners: PCB-118 (48-63%), -105 (14-23%), -156 (6-22%), -167 (3-8%) and -77 (1-6%). The concentrations of total TEQ-WHO05DFP for PCDD/Fs and DL-PCBs ranged from 1.5 to 613 pg g-1 dry weight. The concentrations of ΣPBDEs ranged between 460–87200 pg g-1 dry weight and were dominated by BDE-209 (found in deca-BDE), which contributed, on average, approximately 90% of the Σ PBDEs. A former manufacturing site for Agent Orange exists in an embayment of Sydney Harbour – Homebush Bay – a likely significant source for dioxins. Generalised additive modelling (GAM) and PCA/RDA analysis confirmed that Homebush Bay (zone 5) was indeed the most significant source of PCDD/Fs.

The Estuary Processes Study modelling (Cardno and Baird, 2016) found that the main mechanism of contaminant mobilisation was resuspension by wave-induced currents during high wind events, especially a southerly wind event which aligns with the fetch of Homebush Bay. However, this key mechanism of mobilisation was not included in the process modelling undertaken for the Wentworth Point Marina Risk Assessment (EnRiskS, 2017), and this omission is a key limitation of that study.

The potential accumulation hotspots modelled in the Sydney Harbour Estuary Processes Study coincide with some of the potential swimming locations identified in the Sydney estuary (Figure 1 of Geochemical and EnRisks 2017), including Brays Bay, Meadowbank and Kissing Point. The order of magnitude of the concentration of dioxins exported from Homebush Bay in the modelling accord with the field measurements in that report and with the Birch (2006) assessments of dioxin concentrations and distribution at selected sites in the Parramatta River. Considering that the modelling for the Sydney Harbour Estuary Processes Study was only event based, the transport and fate results from the model show agreement with the contaminants that have accumulated in the Harbour over many years of resuspension events. Although the modelling did not investigate resuspension of contaminants deposited outside of Homebush Bay, it is likely that contaminants that have spread to bays further afield over time including Hen and Chicken Bay (Quarantine Reserve and Bayview Park) and Duck Creek (Silverwater Park) where measured concentrations of dioxin have been identified, continue to episodically resuspend and move throughout the Parramatta River and further afield in Sydney Harbour. The investigations completed in the Estuary Processes Study and the data presented in Geochemical Assessments and EnRisks (2017) support that further analysis, modelling and data is required to understand the current distribution of contaminated sediments in the Parramatta River and the ongoing fate of those sediments into the future.

3.3.5 Larval Transport

The two last weeks of January 2012 (following 24 hours of model warm-up) were modelled to describe the hydrodynamic conditions during a typical spring-neap cycle at the entrance and within eastern Sydney Harbour.

The modelled flows were then extracted to calculate a total of 168,500 larval tracks by releasing 500 larvae at random locations within the spawning polygon every hour of the spring-neap cycle (337 time steps) to cover all the different tidal regimes. Each larva was tracked for up to 5 days. The larvae could become trapped within these 5 days by reaching a water depth shallower than 3 m. It is most likely that 5 days after release, the larvae will end up beyond the offshore model boundary, hence do not require tracking anymore.

An additional random horizontal dispersion component was calculated and added to the tidal currents at each computational track time-step (five minute intervals) by using a dispersion coefficient of 2 m^2/s. This coefficient was selected by comparing the transport from the tidal currents and the dispersion. Without the dispersion effect, the larvae tend to follow the main flows and never approach the shallow waters. Even if the average contribution of the dispersion in the larval transport is smaller than the contribution of the tidal currents, it is still a key factor for the trapping of the larvae.

Figure 3.20 shows the release of 500 larvae (in green) within the spawning location between the Heads on the 16/01/2012 at 1pm around high tide. The additional items on the figure are:

- Light grey points represent the complete tracks with a point every 5 minutes for each larva during a period of 5 days
- Light grey circles represent the trapped locations
- Dark grey circles show the locations of the larvae after 5 days when they were not trapped after 5 days.

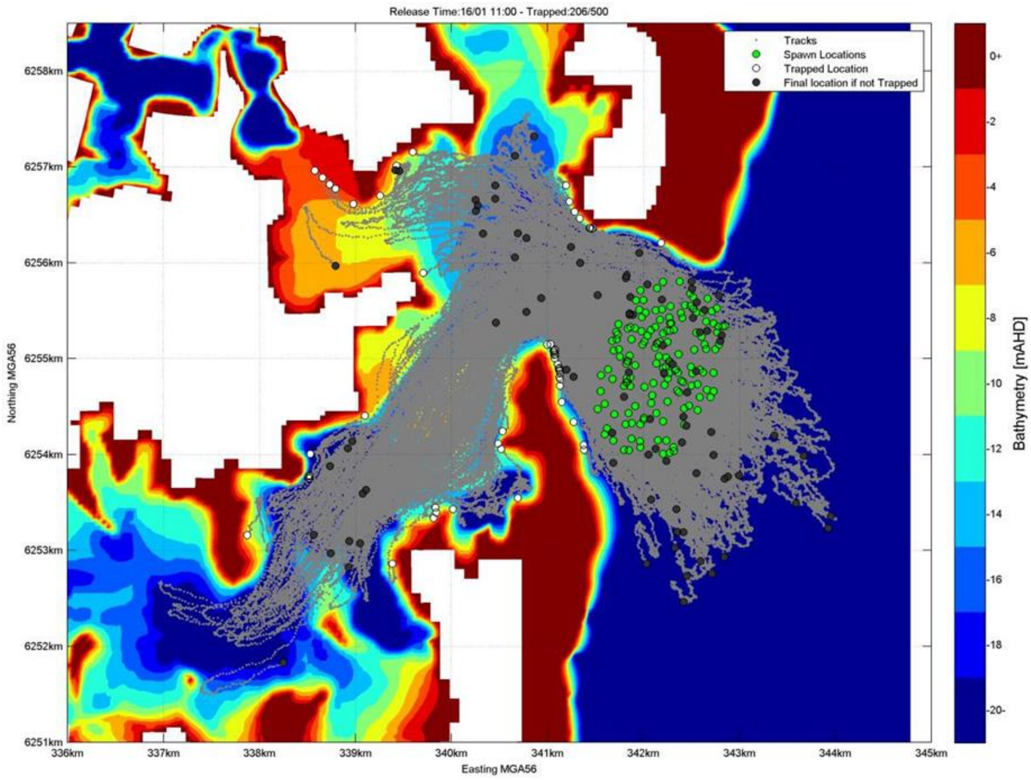


Figure 3.20 **Map of Larval Tracks Spawn Time 16/01/2012 13:00 (after Cardno and Baird, 2017)**

Figure 3.21 was generated by combining the trapped larvae results from 337 different spawning times covering the complete spring-neap cycle (Figure 3.20 shows the results from only one of these spawning times). This figure shows that overall 33% of the 168500 larvae released in the Port Jackson entrance area were trapped in various locations within the Harbour entrance. The numbers displayed on the map represent how many larvae became trapped in the location out of the 168500 released larvae. These numbers can also be interpreted in terms of percentage ratio of trapped vs released. Some hot spots were identified such as North and South Heads, Middle Harbour entrance along Balgowlah Heights but also within Port Jackson up to Taronga zoo headland. The modelling suggests that although the larvae were able to travel upstream as far as the Harbour Bridge and beyond the Spit Bridge in Middle Harbour, these events occur only rarely and most of the larvae trapped within the very dynamic sections of the estuary never end up approaching some shallow depths.

The modelling was used to assist an honours study (Burton, 2016). The study concluded that patterns of settlement of three tropical fish families in outer Sydney Harbour were not closely related to surface currents or amount of preferred habitat. The Spit Bridge butterflyfish hotspot was enigmatic, over 4 km from the Harbour mouth, but with considerably higher recruitment than at other sites. The sites that were closer to the mouth of the Harbour, which were predicted to attract the most migrants, did not reflect the same number in sites further upstream. Sites in the northern half of the Harbour had higher numbers of settlement than any site in the south side, despite tides flowing into and out of the Harbour in a southerly direction bias. The study indicates that patterns of settlement cannot be predicted from tidal flows alone. Further investigations into mechanisms of settlement, growth and persistence of these species are required to account for observed patterns of distribution and abundance.

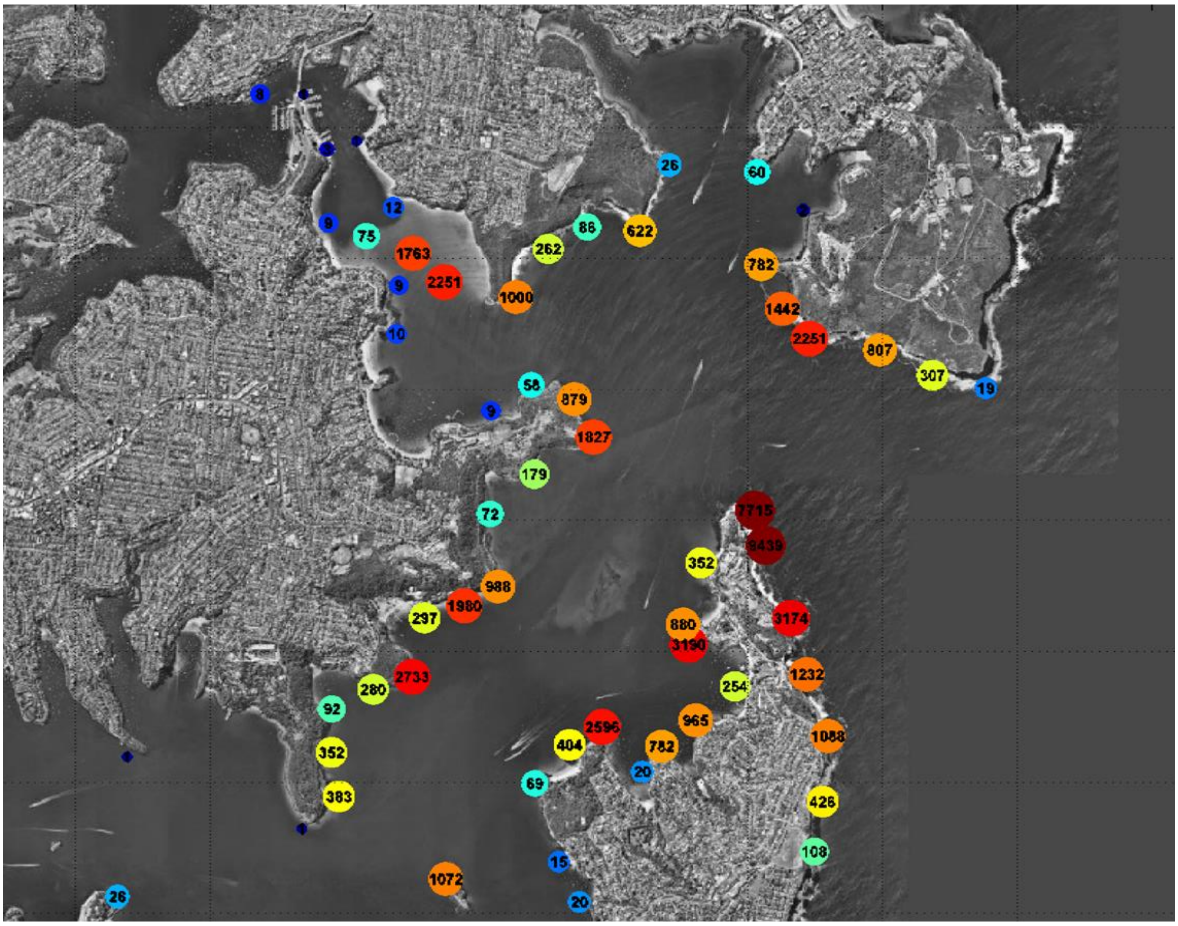


Figure 3.21 **Map of Estimated Probability of Trapped Larval Locations - Full Tidal Cycle - No Wind (after Cardno and Baird, 2017)**

3.3.6 Stormwater and Sewer Overflow Modelling

Bacterial contamination events within Sydney Harbour arising from catchment inflows and sewer overflows are major causes of reduced water quality that is observed in large sections of Sydney Harbour, particularly following rainfall events. The annual State of the Beaches report (OEH, 2015) identifies sites, particularly in Parramatta River, Lane Cove River and Middle Harbour, where water quality ratings have been assessed as poor and bad as a result of elevated enterococci concentrations, particularly following rainfall events. However, it was OEH (2015) and data collected for the GSLLS (SIMS, 2012) that indicated that there are locations in the Harbour where base flow microbial *Enterococci* loads result in water quality that is unsuitable for recreational secondary contact.

The following *enterococci* concentration scale is adopted for the NSW Beachwatch program and is derived from the microbial assessment categories used in the National Health & Medical Research Council (NHMRC) 2008 guidelines. The ratings and assessment for microbial contamination in the Beachwatch program are:

- < 41 cfu/100 ml: Good
- 41-200 cfu/100 ml: Fair
- 201-500 cfu/100 ml: Poor
- 500 cfu/100 ml: Bad

Water quality data collected for the GS LLS (SIMS, 2012) and modelling undertaken during the development of the SHERM (Cardno and Baird, 2015) highlighted that *Enterococci* concentrations could become elevated above 500 cfu/100 ml even after relatively small rainfall events totaling 10 mm in 24 hours.

The investigations into microbial contamination comprised two main tasks. The first was to revisit the water quality data set collected for the GSLLS between October and December 2012 to examine periods of time over the sampling campaign when elevated *Enterococci* concentrations were recorded in the Harbour. A number of highly elevated enterococci samples with concentrations exceeding 500 cfu/100ml were recorded in Port Jackson (between the Harbour Bridge and Rose Bay) and in Middle Harbour on 29th November 2012. The calibration of the SHERM model was reviewed for that specific event based on the catchment and sewer overflow loads that were provided from the Sydney Harbour catchment model (Catchment Research Pty Ltd, 2014).

Re-analysis of the water quality data reported in SIMS (2012) identified that in late November 2012, high *Enterococci* concentrations were observed in the Harbour, particularly between the Harbour Bridge and Rushcutters Bay, and also Middle Harbour. The elevated *Enterococci* concentrations were measured on 29 November 2012 and there was 10 mm of rainfall across the Sydney Harbour catchment in the 24-hours to 9 am on 28 November 2015.

The source data for *enterococci* loads into the Harbour included catchment and Sewer Overflow (SOFs) sourced loads from a Sydney Harbour catchment pollutant model (Catchment Research Pty Ltd, 2014). *Enterococci* and *faecal coliforms* were modelled using the high-resolution 3D SHERM Water Quality model, which provides 20 m to 50 m grid resolution throughout the whole of Sydney Harbour (Cardno and Baird, 2017) and 8-vertical layers. The transport and dispersion of the SHERM-Water Quality model has been previously calibrated using Harbour-wide salinity recovery data – see Cardno and Baird (2017).

Figure 3.22 presents a plan view of modelled surface *Enterococci* at 14:00 29 November 2012 as a smoothed surface plot, and measured enterococci from samples collected on 29 November 2012 as coloured circles. It should be noted that the vertical scale for *Enterococci* concentration in Figure 3.21 is presented on a log10 colour scale.

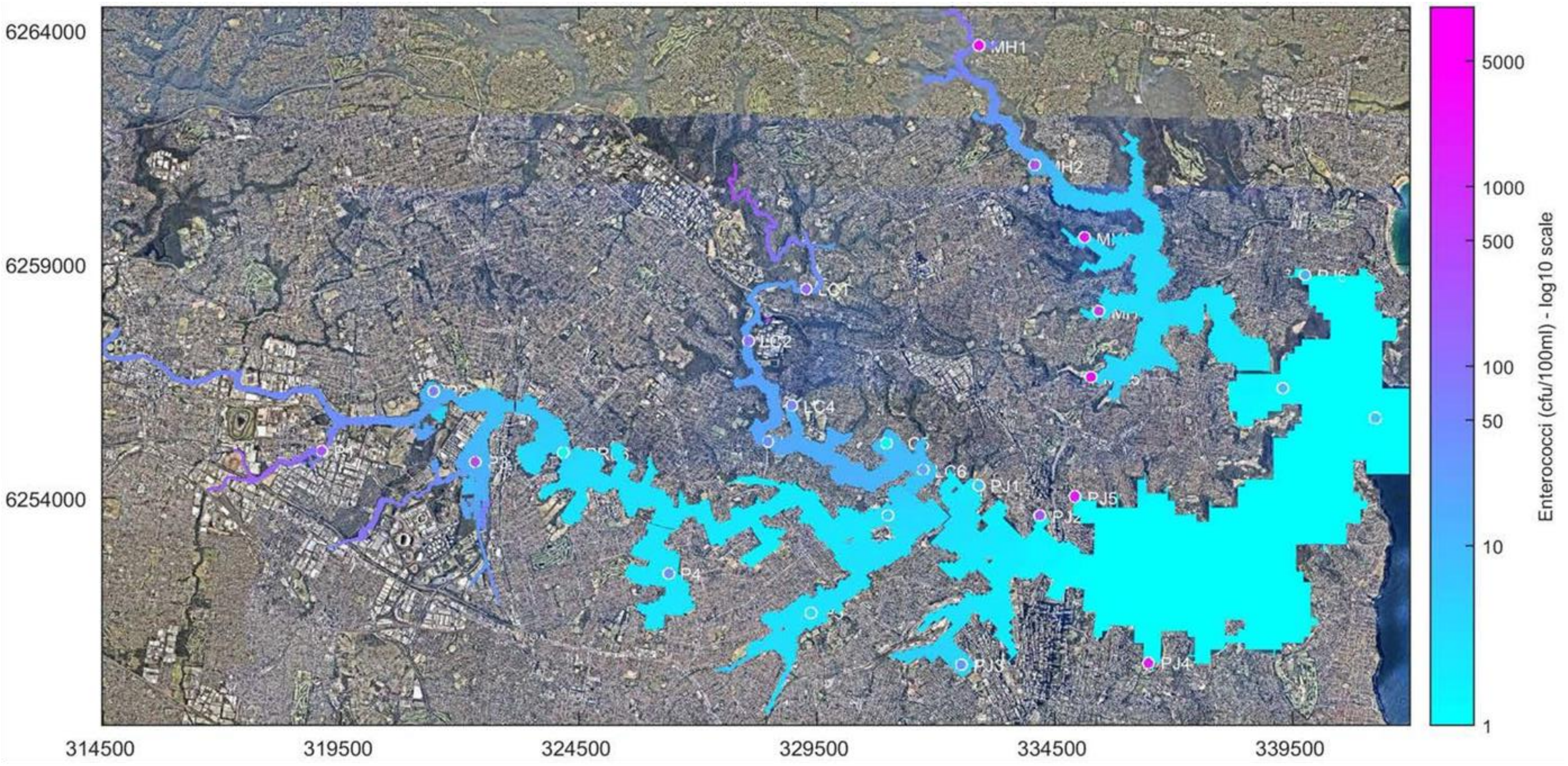


Figure 3.22 **Map of Surface *Enterococci* Concentration Modelled (patch) vs Measured (dots) 29/11/2012 (Cardno and Baird 2017)**

Figure 3.22 indicates from the data and model results that throughout the Harbour *Enterococci* concentrations were elevated above 50 cfu/100ml. Overall, in the Parramatta River (upstream of Cockatoo Island) and the Lane Cove River, whilst there is variance between the model results and measured data, the model and measurements are in a similar order of magnitude. Downstream of Cockatoo Island, and particularly between the Harbour Bridge and Rushcutters Bay (represented by sampling sites PJ2, PJ5 and PJ4), modelled *Enterococci* concentrations are two orders of magnitude lower than the measured data. Similarly, modelled *Enterococci* concentrations in Middle Harbour are significantly lower than measured. The observation of high *Enterococci* concentrations in Middle Harbour from the SIMS (2012) data set is consistent with the longer-term data collected in the Beachwatch program (see OEH, 2015).

Following the review of the SHERM model calibration, a major wet weather event from July 2011 that had large microbial loads from the catchment and sewer overflows was modelled to define a base case with which to assess water quality improvements that could be obtained from targeted reductions in the sewer overflow loads through targeted removal of selected sewer overflows. A total of six scenario simulations, including calibration and baseline scenarios, have been modelled.

Re-analysis of the water quality data reported in SIMS (2012) identified that in late November 2012, high *Enterococci* concentrations were observed in the Harbour, particularly between the Harbour Bridge and Rushcutters Bay, and also Middle Harbour. The elevated *Enterococci* concentrations were measured on 29 November 2012 and there was 10 mm of rainfall across the Sydney Harbour catchment in the 24-hours to 9 am on 28 November 2015.

The detailed modelling of microbial contamination from catchment and sewer overflows into Sydney Harbour have highlighted the complexity of defining the source loads into the Harbour, particularly during base flow or low rainfall events. The validation of the microbial contamination module in the SHERM using *Enterococci* data measured throughout the Harbour in November 2011 indicates that the definition of low flow *Enterococci* loads into the Harbour, particularly the Port Jackson and Middle Harbour sections, is underestimated. Key recommendations arising from the investigations presented in this report are:

1) The Office of Environment and Heritage, who administer the Beachwatch program should engage with Sydney Water to collaborate on defining data gaps.

2) Agencies should collaborate and prioritise locations in the Harbour where observed enterococci concentrations are higher than expected from the currently available source load data sets. Those locations can be targeted for further investigation, including data collection to define input loads and estuarine *Enterococci* concentrations.

3) It would be beneficial if the catchment pollutant load model and sewer overflow model data sets that are used to calculate microbial loads in the Harbour were further developed and calibrated. This task is challenging due to the complexity and age of Sydney's sewer and stormwater infrastructure.

4) Due to the proximity of the ocean entrance that promotes rapid flushing of Middle Harbour, the modelling scenarios indicate that the most significant benefit for improving recreational water quality may be achieved through targeted upgrades to the sewer system in Middle Harbour. Significant improvements in the Upper Parramatta River are also possible; however, due to the long overall flushing time downstream of Charles Street weir, the effective improvement in recreational water quality is less than could be achieved in Middle Harbour.

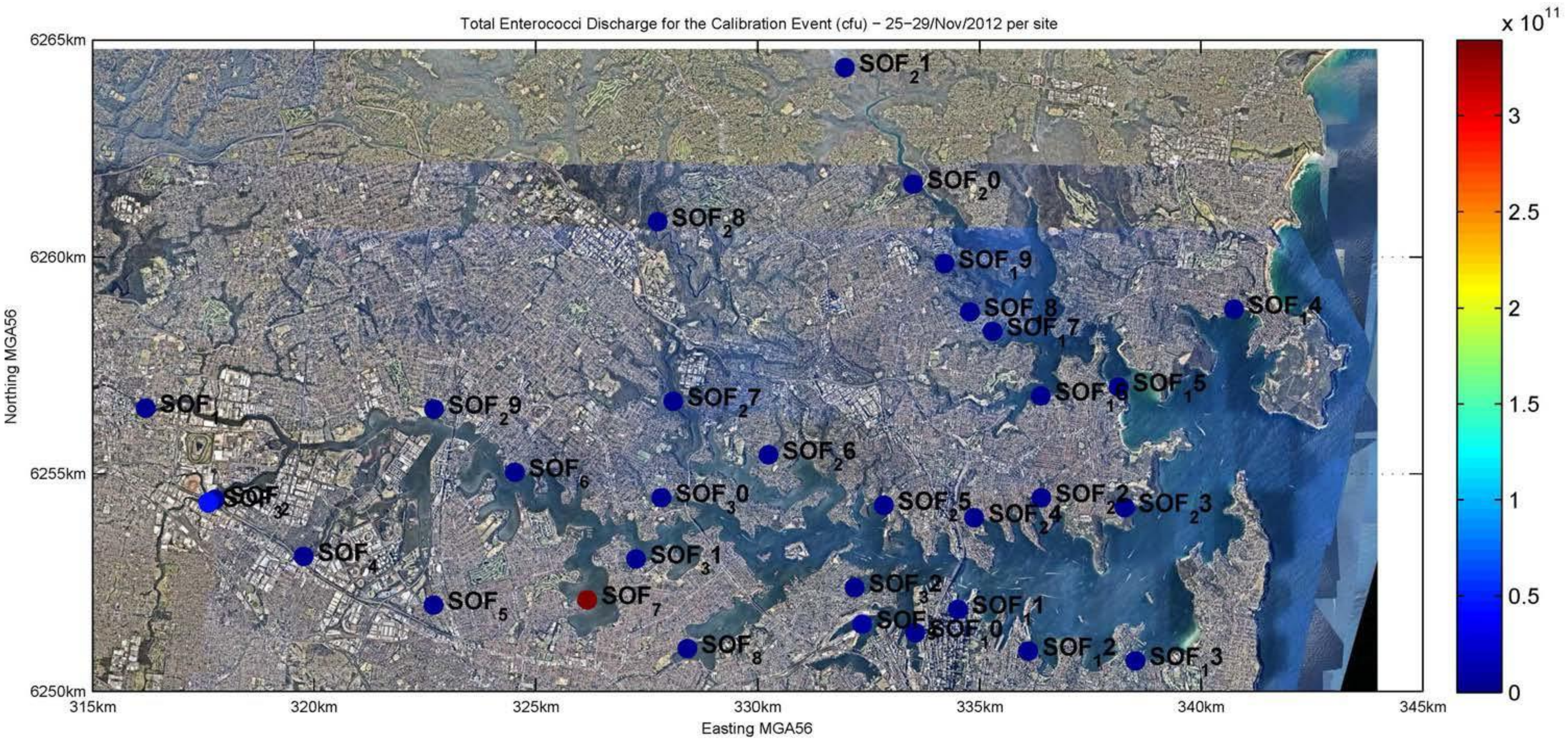


Figure 3.23 **Map of the Top 20 Modelled SOF *Enterococci* Sources 25 to 29/11/2012 (Cardno and Baird 2017)**

3.4 Stormwater – potential future loads and impacts

Sydney's population is growing faster than it did over the last 20 years. Consequently, to meet the needs of an increasing population, growth needs to be planned and managed. The NSW Government's Greater Sydney Region Plan 2018 (*A Metropolis of Three Cities*) is built on a vision of three cities where most residents live within 30 minutes of their jobs, education and health facilities, services and great places. To meet the needs of a growing and changing population the vision seeks to transform Greater Sydney into a metropolis of three cities:

- the Western Parkland City
- the Central River City
- the Eastern Harbour City

> *Green infrastructure such as urban tree canopy, green ground cover, bushland, waterways, parks and open spaces will be valued for its economic, social and environmental benefits and will help to establish the Greater Sydney Green Grid, a network of walking and cycling links that will become increasingly important in daily travel arrangements improving sustainability and the wellbeing of residents.* (GSC, 2018)

The following sections (3.4.1 – 3.4.3) are sourced directly from the Sydney Harbour Catchment Water Quality Improvement Plan (Freewater and Kelly, 2015), which is enclosed in Appendix A.

3.4.1 Worst case option

A Plan for Growing Sydney aims to fashion a more resilient city that has connected green spaces, infrastructure and housing. This includes the acceleration of urban renewal at train stations, providing homes closer to jobs, growing Sydney CBD and greater Parramatta as Sydney's second CBD, increasing productivity of Western Sydney through growth and investment, enhancing Sydney's Gateways (Port Botany, Sydney Airport and Badgerys Creek Airport) and managing long-term growth. More intensive development across the city will need to be matched with adequate investment into infrastructure and services, open spaces and renewed bushland to support healthy lifestyles of the community. For example, water management including stormwater systems and implementation of Water Sensitive Urban Design (WSUD) are essential for reducing the pressures on water quality of an increasing population and built environment. To illustrate the importance of WSUD the Sydney Harbour CAPER DSS was used to estimate potential pollutant loads for the catchment as a whole and major subcatchments of Sydney Harbour if urban density increases in the future (in line with the Plan for Growth) without implementation of WSUD techniques in infill and new developments.

Catchment Loads

Without the implementation of WSUD, increasing urban density will result in increased pollutants from areas in and around growth centers and in the overall catchment. Using the Sydney Harbour CAPER DSS, the effect of increased urban density without the use of any WSUD was investigated in relation to key pollutants (TN, TP, Total Suspended Solids (TSS), *Enterococci* and *faecal coliforms*). Figure 3.24 represents estimated increases in the key pollutants for the 4 major subcatchments of Sydney Harbour (Parramatta, Lane Cove, Middle Harbour and Port Jackson) as well as the total catchment if WSUD is not implemented in conjunction with dense urban growth in the future.

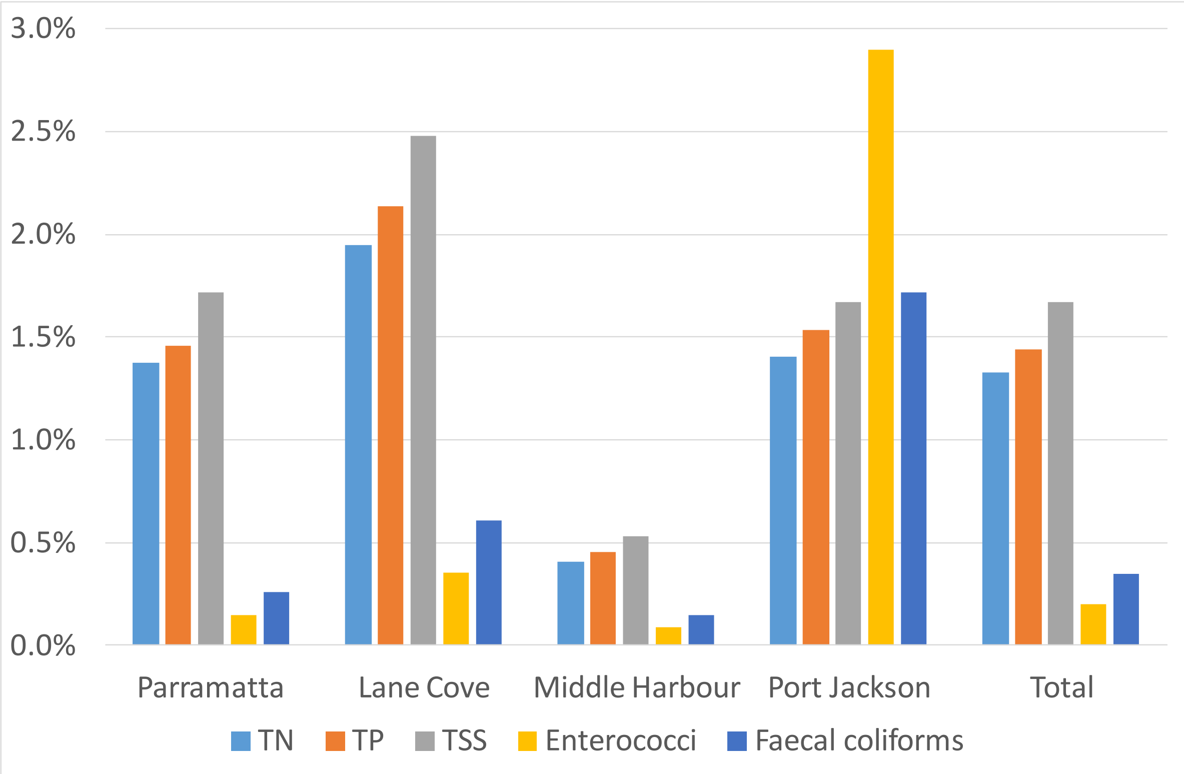


Figure 3.24 Pollutant impact on major subcatchments with increasing density of urban areas and no WSUD

With increased urban density and no WSUD, in general, all subcatchments (as well as the catchment as a whole) are expected to have the greatest load increases in TSS, TP and TN compared to *Enterococci* and *faecal coliforms* loads. Increases in TSS, TP and TN for Parramatta, Port Jackson and the catchment as a whole are estimated to be around 1.5% with increases for Lane Cove slightly higher around 2-2.5%. The lowest impact is expected in Middle Harbour due to the relatively low level of urban infill redevelopment expected in this subcatchment. TN, TP and TSS loads are estimated to increase around 0.5% with increases in *Enterococci* and *faecal coliforms* even lower. The greatest load increases of *Enterococci* and *faecal coliforms* into the system are expected to come from the Port Jackson subcatchment with an increase in *Enterococci* estimated to be nearly 3% and an increase in *faecal coliforms* around 1.5%.

Estuary condition

Increases in pollutant loads of TN, TP and TSS have also been estimated for estuary zones associated with the 4 major subcatchments (Parramatta, Lane Cove, Middle Harbour and Sydney Harbour) if urban density were to increase without the implementation of WSUD as part of developments.

Figure 3.25 illustrates the estimated increases in pollutant loads in the Parramatta estuary zones for the worst case scenario. In general most areas in the Parramatta subcatchment are estimated to have the greatest increases in TSS loads followed by TP and then TN loads. Insignificant or no increases in concentrations of all three pollutants investigated are estimated to occur in the estuary zones of France Bay, Exile Bay and Hen and Chicken Bay; Lower Iron Cove; Manns Point to Downstream of Drummoyne Bay; Morrisons Bay to Looking Glass Bay and; from Duck River to Wentworth Point. All other estuary zones are estimated to have each pollutant increase loads marginally by approximately 0.3% or above.

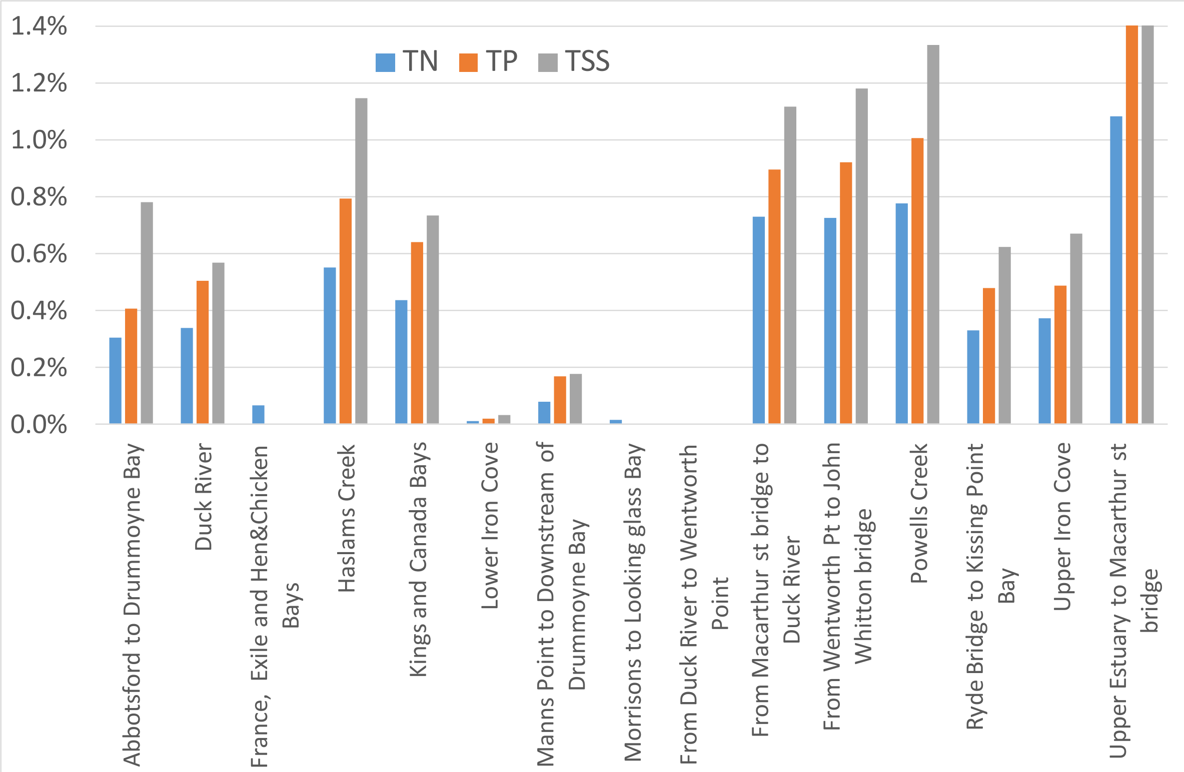


Figure 3.25 **Pollutant loads estimated for urban growth areas of Parramatta without implementing WSUD**

More specifically, the greatest increases in TSS are expected in the Upper Estuary to Macarthur Street Bridge (1.4%); Powells Creek (>1.2%); from Wentworth Point to John Whitton Bridge; Haslams Creek and; from Macarthur Street bridge to Duck River (each <1.2%). Similarly the greatest increases TP in the Parramatta subcatchment are expected in Upper Estuary to Macarthur Street Bridge (1.4%); Powells Creek (1%); from Wentworth Point to John Whitton Bridge and; from Macarthur Street Bridge to Duck River (each ~0.9%). The greatest increases expected in TN in this subcatchment are also estimated to occur in these four areas with Upper Estuary to Macarthur Street Bridge estimated to have the highest increase in loads of around 1.0% and Powells Creek; from Wentworth Point to John Whitton Bridge and; from Macarthur Street Bridge to Duck River each contributing increased TN loads of just under 0.8%.

The Lane Cove subcatchment has been divided into four main areas: Gore Creek to Tambourine Bay; from Epping Road to Tambourine Bay; from Millwood Avenue to Epping Bridge; and Upper Estuary to Millwood Avenue Bridge, for the purposes of estimating estuary zones that may experience the greatest change in pollutant concentrations if urban densities increase without the implementation of WSUD (figure 3.26).

Overall most estuary zones associated with the Lane Cove subcatchment are estimated to have the greatest increases in TSS concentration followed by TP and then TN concentrations. The greatest increase in TSS concentrations is estimated to occur in Gore Creek to Tambourine Bay (<1.0%), followed by Upper Estuary to Millwood Avenue Bridge (~0.8%). From Epping Road to Tambourine Bay and from Millwood Avenue to Epping Bridge each zone is estimated to have TSS concentration increases greater than 0.6%. In contrast, the greatest increase in TP is expected to occur in the Upper Estuary to Millwood Avenue Bridge zone (~0.6%). The other three zones are estimated to have increases of TP around 0.5% each. Increases in TN concentrations range from approximately 0.3% in the Millwood Avenue to Epping Bridge zone up to greater than 0.4% in the Upper Estuary to Millwood Avenue Bridge zone.

Five estuary zones have been considered in the Middle Harbour subcatchment in relation to increases in pollutant loads of TN, TP and TSS if urban density increases without applying WSUD (figure 3.27).

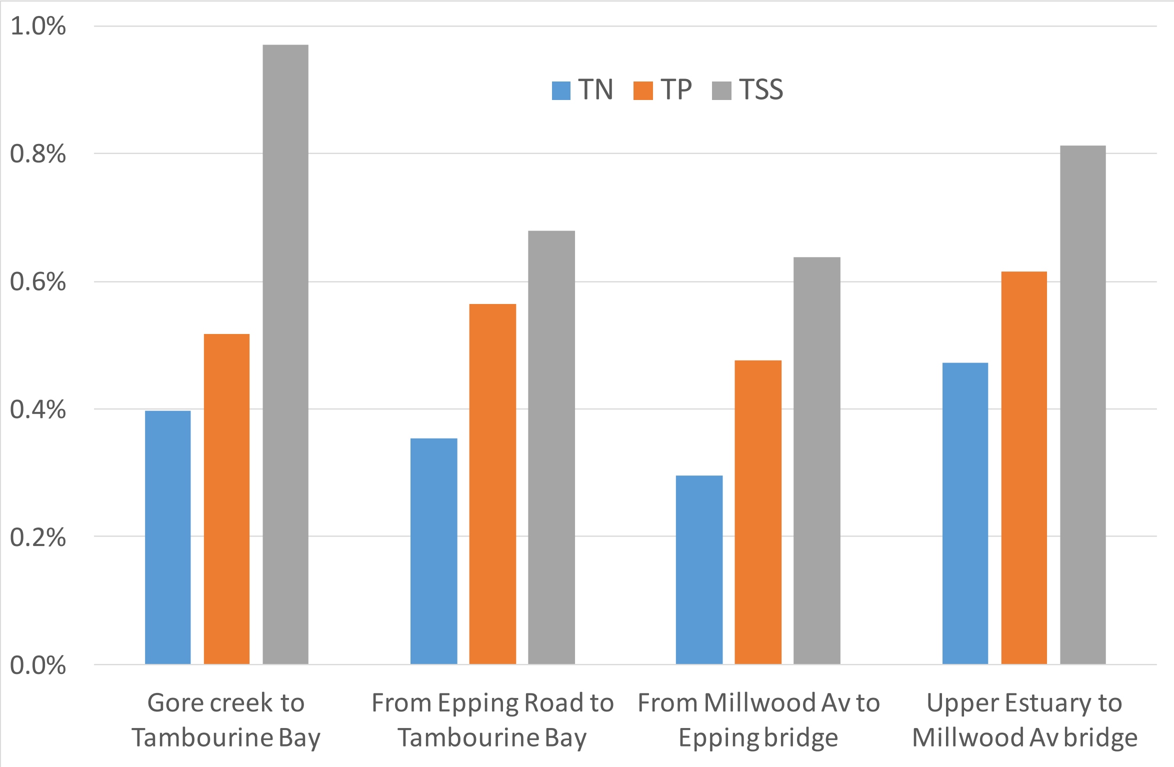


Figure 3.26 **Increases in pollutant concentrations estimated for estuary zones of Lane Cove without implementing WSUD**

As with other estuary zones the greatest increases in pollutant loads for individual areas are generally estimated to be greatest for TSS followed by TP and then TN (apart from Sugar Loaf Bay to the Spit). The estuary zones with the greatest increases estimated for all pollutants is Upper Harbour to Echo Point (TSS <1.4%; TP >1.0% and; TN~0.8%). Hunters Bay is estimated to have the second highest pollutant concentrations increases (TSS ~1.0%; TP >0.6% and; TN ~0.5%). Lower increases in TSS pollutant concentrations are expected in the Bantry Bay to Echo Point area (around 0.9%) and Below the Spit (~0.7%). For both the zones, Bantry Bay to Echo Point and Below the Spit, increases in TP concentrations are estimated to be below 0.5% each and increases in TN are estimated to be lower (<0.4% in both zones). The only zone within the Middle Harbour subcatchment with insignificant or no estimated pollutant increases with increasing urban density and no WSUD techniques applied is from Sugar Loaf Bay to the Spit.

Individual estuary zones of Sydney Harbour subcatchment have also been investigated for expected rises in pollutant loads if urban density increases without using WSUD (figure 3.28).

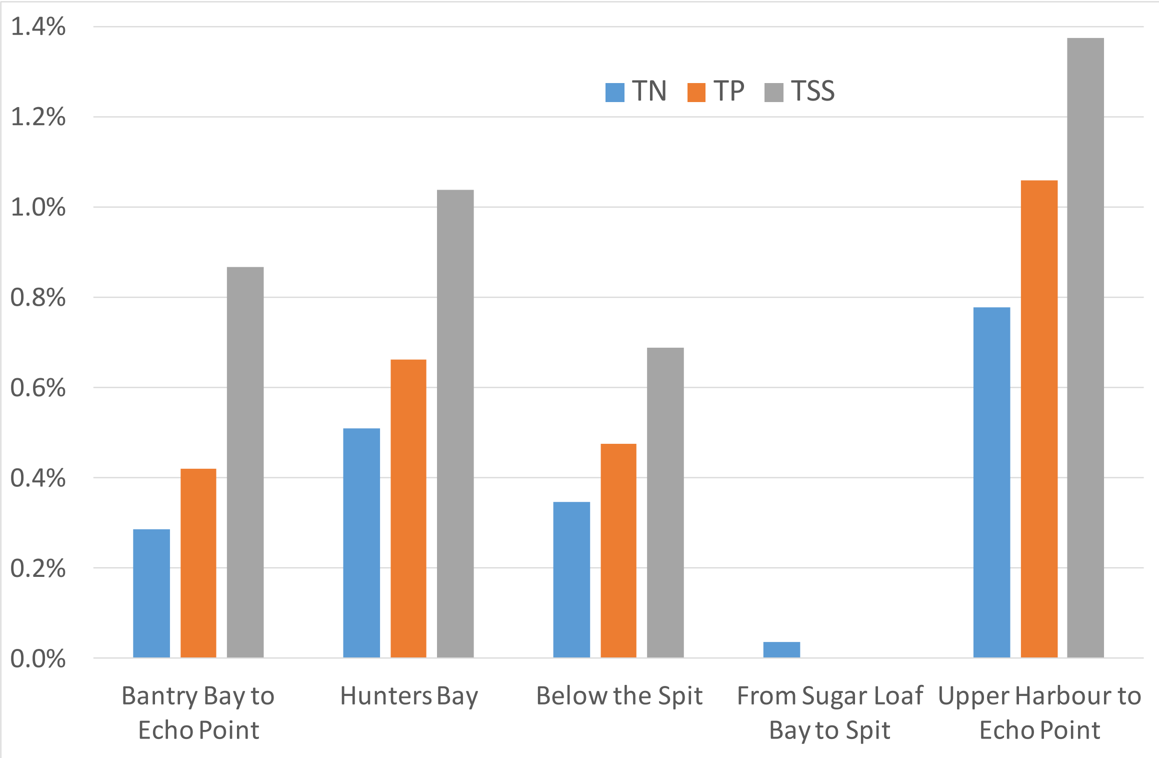


Figure 3.27 **Increases in pollutant concentrations estimated for estuary zones of Middle Harbour without implementing WSUD**

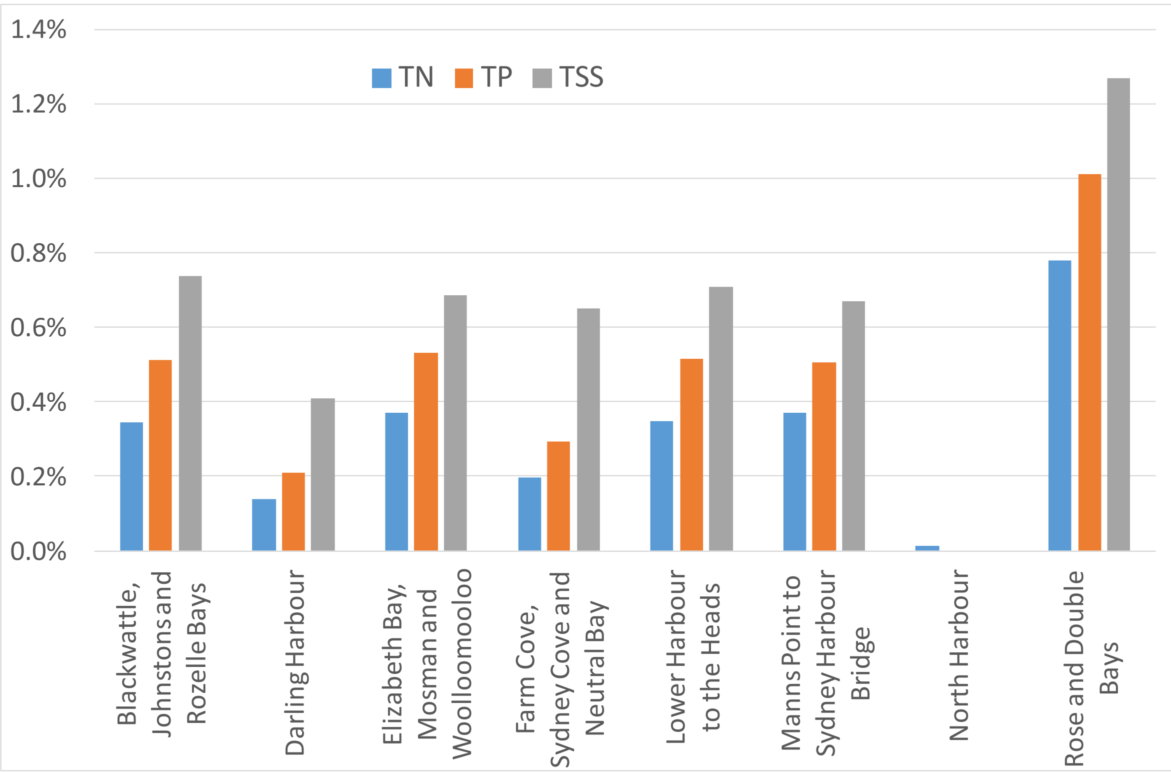


Figure 3.27 **Increases in pollutant concentrations estimated for estuary zones of Port Jackson without implementing WSUD**

Similar to the other subcatchments investigated, individual areas are generally expected to have the greatest increases in TSS concentrations followed by TP and TN. In the Sydney Harbour subcatchment, one zone, Rose Bay and Double Bay, is clearly expected to have the greatest increases in all three pollutants (TSS >1.2%; TP ~1.0%; and TN ~0.8%). In contrast, the North Harbour zone is the only place where increases in all pollutants are expected to be insignificant or have no change. For all other areas investigated, increases in pollutants are estimated to be around 0.7% for TSS (except Darling Harbour (0.4%), between ~0.2- 0.5% for TP and approximately 0.1 to <0.4% for TN.

3.4.2 Best case options

Using *A Plan for Growing Sydney* (since replaced by the Greater Sydney Region Plan 2018 (GSC, 2018)), six options were considered for the expansion of Sydney's urban density that utilises urban renewal corridors as an opportunity to implement WSUD. WSUD options developed to illustrate impacts were chosen to represent middle ground effectiveness out of available treatment trains. For example, the use of rainwater tanks, swales, GPT and bioretention in a treatment train. Four of the six scenarios investigated also consider retrofitting given percentages of existing urban areas.

The six scenarios considered using urban renewal corridors for WSUD estimated from *A Plan for Growing Sydney* are:

1. Infill redevelopment with 90% WSUD (multiple treatment trains)
2. Infill redevelopment with 70% WSUD (multiple treatment trains)
3. Infill redevelopment with 90% WSUD PLUS retrofit 10% remaining urban catchment area
4. Infill redevelopment with 70% WSUD PLUS retrofit 10% remaining urban catchment area
5. Infill redevelopment with 90% WSUD PLUS retrofit 20% remaining urban catchment area
6. Infill redevelopment with 70% WSUD PLUS retrofit 20% remaining urban catchment area

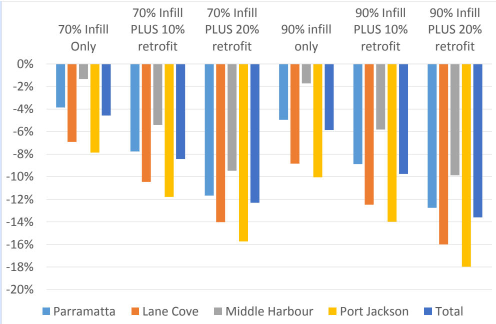
Catchment Loads

Growing urban density will result in increased pollutants in and around growth centers and in the overall catchment. Using the Sydney Harbour CAPER DSS, pollutant loads for TN, TP, TSS, *Enterococci* and *faecal coliforms* have been estimated for each major subcatchment and the catchment as a whole (total) if each of the six urban renewal scenarios were implemented.

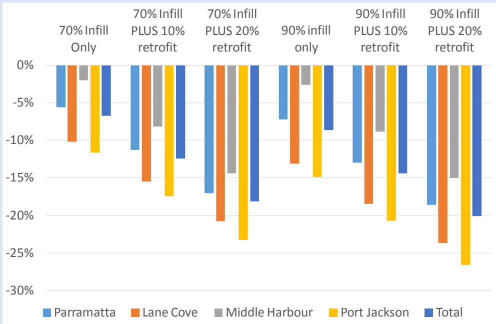
Figure 3.29 represents estimated reductions in each of the pollutants for all major subcatchments and the catchment as a whole according to each urban renewal scenario.

Sponge Garden at South Head

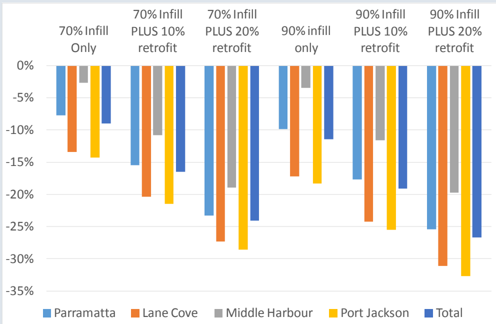
TN



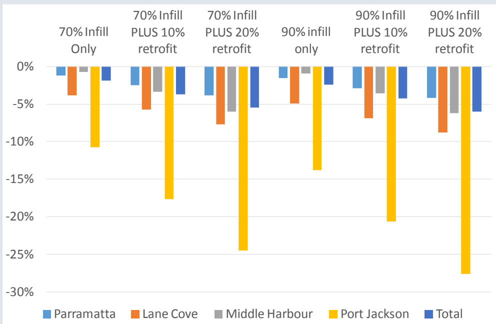
TP



TSS



Enterococci



Faecal coliforms

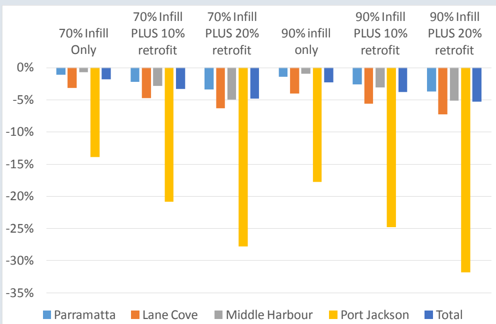


Figure 3.29 Impact of best case growth options using WSUD in infill redevelopment and retrofitting existing urban areas on pollutant loads

Figure 18 shows:

- As expected the greatest reductions in all pollutant loads throughout the subcatchments and for the catchment as a whole are expected to be achieved with infill redevelopment with 90% WSUD and retrofitting of 20% of the remaining urban catchment area with total reductions in:
    - TN ranging from approximately 10% in Middle Harbour up to 18% in Port Jackson.
    - TP ranging from 15% in Middle Harbour to 26% in Port Jackson.
    - TSS ranging from 20% in Middle Harbour to over 30% in Port Jackson.
    - *Enterococci* and *faecal coliforms* ranging from under 5% for Parramatta to over 30% for Port Jackson.
- Focusing on WSUD infill redevelopment only will address potential increases in pollutant loads expected under the 'worst case' option above and lead to slight improvements in water quality. High levels of adoption in these areas would be required to achieve this however, existing issues with water quality in Sydney Harbour would not be addressed. In order to improve water quality in Sydney Harbour, focusing on infill redevelopment alone is not the solution, some degree of retrofitting of existing areas must also be undertaken. Given physical restrictions on the extent to which infill areas are able to be treated retrofit is likely to be necessary to provide a buffer against potential increases in pollutant loads as the density of urban areas is increased.
- Some trade-off between the extents to which WSUD is focused in infill redevelopment areas versus being applied as retrofit to existing areas is possible. For example for all pollutants 70% WSUD in infill areas with 20% retrofit is similar in effectiveness (slightly more effective) than 90% infill with 10% retrofit. Given the relative expense and difficulty of retrofitting WSUD as compared to including it in redevelopments this has implications for the best strategy that can be adopted by Councils.
- When considering all six urban renewal options, there appears to be a general trend of reductions in pollutants. All options are most effective in Port Jackson, although differences between Port Jackson and Lane Cove are relatively small for nutrients and sediments. The least affected areas for nutrients and sediments are in Middle Harbour, while for pathogens the smallest impact is in Parramatta (due to the large proportion of pathogens sourced from sewer overflows in this area).

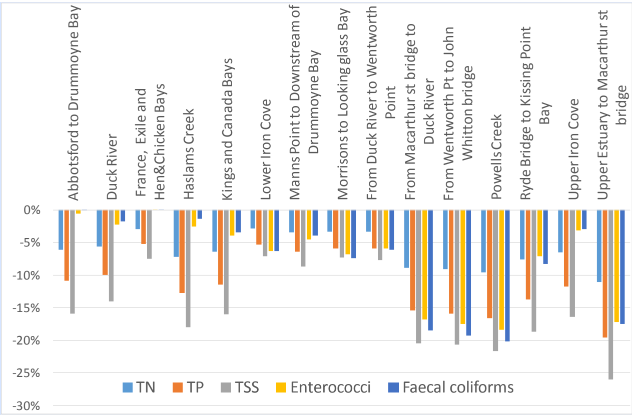
Estuary condition

Changes in the future estuary condition (as measured by pollutant concentration) have been projected for estuary zones associated with the major subcatchments of Sydney Harbour (Parramatta, Lane Cove, Middle Harbour and Sydney Harbour) by estimating increases in pollutant loads of TN, TP, TSS, *Enterococci* and *faecal coliforms* if infill redevelopment with 70% WSUD and retrofitting of 10% of remaining urban subcatchment areas was implemented.

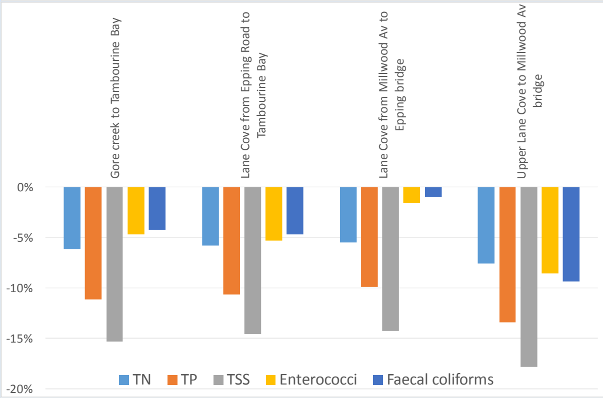
Future changes in pollutants estimated for estuary zones associated with each of the major subcatchments for the scenario of 70% WSUD in infill redevelopment and retrofitting of 10% of the remaining urban subcatchment area are represented in figure 3.30.

Pygmy Leatherjacket (*Brachaluteres jacksonianus*) Fairy Bower – Manly

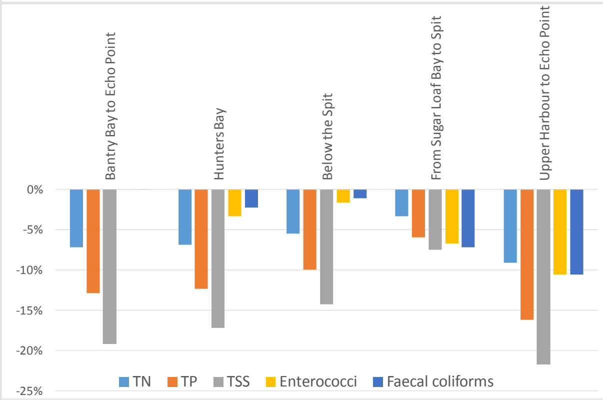
Parramatta



Lane Cove



Middle Harbour



Port Jackson

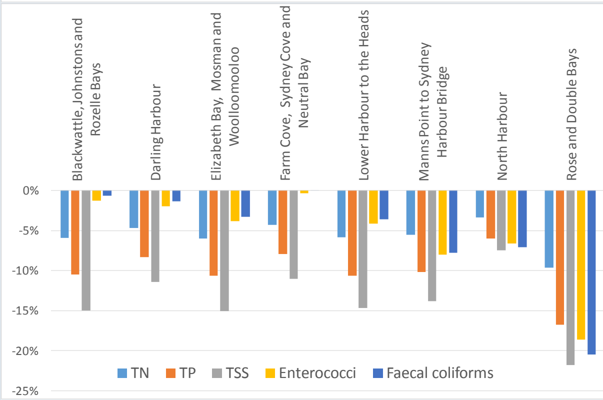


Figure 3.30 **Estuary impacts of infill redevelopment with 70% WSUD and retrofitting of 10% of remaining urban subcatchment area for estuary zones associated with each of the major subcatchments**

Figure 3.30 shows that:

- Estuary zones in Parramatta that are estimated to most benefit in overall pollutant reductions (TN, TP, TSS, *Enterococci* and *faecal coliforms*) with the implementation of 70% WSUD and retrofitting of 10% of the remaining urban subcatchment area are: Upper Estuary to Macarthur St Bridge; from Macarthur Street Bridge to Duck River; from Wentworth Point to John Whitton Bridge and; Powells Creek. In these four areas reductions in TSS are estimated to be around 20% or greater, TP, *Enterococci* and *faecal coliforms* around 15% or greater and TN around 10%. Pollutant reductions in the rest of the Parramatta estuary are varied and generally to a lesser extent. There is a general pattern indicating that TSS loads will be reduced the most in any of the subcatchment areas under the scenario applied, however the difference between TSS reductions and other pollutants in some areas is marginal.

- In Lane Cove, estimated reductions in TN, TP and TSS are similar for all 4 subcatchment areas considered (around 5%; 10% or greater and; around 15% respectively) with pollutant reductions estimated to be slightly higher in the Upper Lane Cove to Millwood Avenue Bridge compared to the other three zones. In comparison, reductions for *Enterococci* and *faecal coliforms* for the 4 zones considered in Lane Cove are varied. Lane Cove from Millwood Avenue to Epping Bridge is estimated to have the lesser marginal reductions in *Enterococci* and *faecal coliforms* compared to the other Lane Cove areas (each around 1%). In the estuary zones of Gore Creek to Tambourine Bay and Lane Cove from Epping Road to Tambourine Bay reductions in *Enterococci* and *faecal coliforms* are expected to be similar (~5% and <5% respectively). The greatest reductions in *Enterococci* and *faecal coliforms* are estimated to be the greatest in the Upper Lane Cove to Millwood Avenue ridge estuary zone (just under 10% for each pollutant).

- Estimated reductions in pollutants for each estuary zone in Middle Harbour were also considered. At Bantry Bay to Echo Point and Hunters Bay, estimated pollutant reductions are over 15% for TSS, over 10% for TP and greater than 5% for TN. The reductions in *Enterococci* and *faecal coliform* loads at Hunters Bay are estimated to be below 5% however at Bantry Bay to Echo Point there is expected to be no change in *Enterococci* and faecal coliform loads. Below the Spit, reductions in all key pollutants are estimated to occur but to a lesser extent than at Bantry Bay to Echo Point and Hunters Bay. Reductions in TSS are estimated to be the greatest in this zone; nearly 15%. For TP a reduction of 10% is estimated and for TN approximately a 5% reduction is predicted. Reductions in *Enterococci* and *faecal coliforms* are also expected but marginal (around 1% each). In the area from Sugar Loaf Bay to the Spit, a change in pollutant loads is expected to result in reduced TP, TSS, *Enterococci* and *faecal coliforms* loads by over 5% each and the TN load less than 5%. The Upper Harbour to Echo Point is estimated to experience the greatest reductions in all pollutant loads investigated compared to other areas in Middle Harbour with 70% WSUD and retrofitting of 10% of the remaining urban subcatchment area applied. These estimated reductions are around 10% for *Enterococci* and *faecal coliforms*, just under 10% for TN loads, more than 15% for TP loads and over 20% for TSS.

- In Port Jackson, the greatest load reductions for all pollutants are expected to occur in Rose and Double Bays, with decreases in TSS and *faecal coliforms* around 20% each, TP and *Enterococci* over 15% each and TN approximately 10%. All other (7) estuary zones are expected to experience less and varying degrees of pollutant reductions. Reductions in TSS are estimated to be between 10- 15% for all of the remaining subcatchments apart from North Harbour where decreases are estimated to be under 10%. Reductions in TP loads throughout the seven subcatchments are generally estimated to be between 5 -10% and for TN around a 5% or lower load decreases is estimated. *Enterococci* and *faecal coliform* load reductions are more varied with Manns Point to Sydney Harbour Bridge and; North Harbour estimated to have reductions of over 5% for each pollutant. The estuary zones of Elizabeth Bay, Mosman and Woolloomooloo and Lower Harbour to the Heads are estimated to have reductions less than 5% for each of the pollutants *Enterococci* and *faecal coliforms*. The remaining subcatchments: Blackwattle, Johnstons and Rozelle Bays; Darling Harbour; and Farm Cove, Sydney Cove and Neutral Bay are estimated to have no change or marginal reductions in *Enterococci* and *faecal coliform* loads.

- In general the greatest improvements in estuary water quality are seen in upper estuary zones, in particular in the Lane Cove and Parramatta estuaries. This is because the greater flushing of the lower estuary and outer Harbour zones provides a buffer to changes in loads in these subcatchments.

3.4.3 Assessment of management options to maximise benefits

Load and condition targets

A Decision Support System (DDS) was used to explore the potential impacts of land use change and management actions as well as to derive load and condition targets for Sydney Harbour. To model pollutant loads, the DSS uses a metamodel of several component models that have been calibrated and tested for Sydney Harbour:

- The Source Catchments model, which is used to estimate diffuse catchment loads given land use.
- The MUSIC model, which estimates the impacts of various WSUD options on pollutant loads from urban areas.
- Empirical data derived from models and monitoring held by Sydney Water on the quantity and quality of sewer overflows.

These metamodels are simplified versions of the original models. They abstract away from more complex calculations of daily and in some cases subdaily loads and flows to directly produce estimates of average annual loads. The metamodels in the DSS very accurately reproduce estimates of average annual loads from these source models. This allows the DSS to produce estimates of changes in annual loads in line with the original models so that differences between scenarios can be determined. The DSS does this without the overheads of the original more complex models, such as long run times. This type of model is best used to estimate the magnitude and direction of changes from a base case scenario, rather than to forecast specific loads. The variability of actual loads on a year to year basis is strongly affected by climate. As such, load targets that focus on relative changes to average annual loads, which remove this climate influence, are more appropriate than fixed loads. The DSS is designed to be able to model relative changes in loads that underpin load targets as accurately as the more detailed calibrated original models. A more detailed description of the Sydney Harbour DSS can be found in Appendix A.

Catchment load and estuary condition targets have been developed using feasible scenario options for both the management of stormwater and improvements in sewer overflow performance. These targets are based on assumptions of feasible change developed in scenarios:

- 70% WSUD applied to infill redevelopment and 10% retrofit of existing areas.
- Improving sewer overflow performance to limit overflows to no more than 40 events in 10 years.

While targets have been developed considering feasible levels of change defined by these options, there are many other combinations of actions that could achieve these targets. These targets are designed to provide direction to change rather than being prescriptive of the exact management actions that should be undertaken to achieve these goals.

Load targets are presented as a trajectory showing both the target level of improvement in water quality as well as the potential worst-case scenario if management is not improved. This worst-case outcome assumes:

- Infill redevelopment with increased urban density with no WSUD.
- Declines in sewer overflow performance due to increases in stormwater volumes. The volume of sewer overflows under this scenario is assumed to increase proportional to the increase in stormwater.

In reality the benefits from management come from maximizing the differences between these two outcomes rather than simply in terms of any improvement in water quality. Table 3.6 shows the change in catchment loads under the target and worst case scenarios for the entire catchment and the major subcatchments. Detailed load reduction targets for individual subcatchments and LGAs are given in Appendix A.

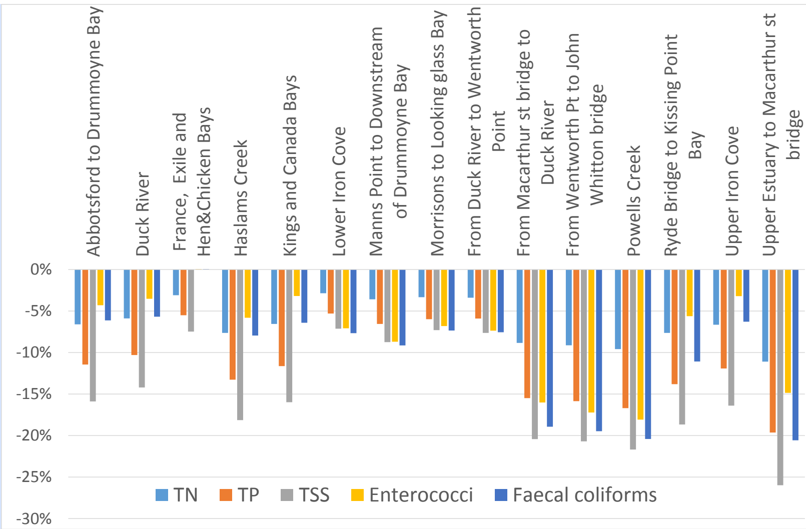
Table 3.6 Catchment loads changes under target and worst case scenarios

Catchment	Scenario	TN	TP	TSS	*Enterococci*	*Faecal coliforms*
Parramatta	Target	-0.1	-0.13	-0.16	-0.13	-0.14
	Worst case	0.02	0.02	0.02	0.02	0.02
Lane Cove	Target	-0.11	-0.16	-0.21	-0.1	-0.12
	Worst case	0.02	0.02	0.03	0.03	0.02
Middle Harbour	Target	-0.06	-0.09	-0.11	-0.06	-0.07
	Worst case	0	0.01	0.01	0.01	0.01
Port Jackson	Target	-0.12	-0.17	-0.21	-0.18	-0.21
	Worst case	0.01	0.02	0.02	0.29	0.02
Total	Target	-0.1	-0.14	-0.17	-0.12	-0.13
	Worst case	0.01	0.02	0.02	0.02	0.01

As can be seen here the catchment load targets are for decreases in pathogens between 6 and 21%, nutrients between 6 and 17% and sediments between 11 and 21%. Total loads for all pollutants would decrease by more than 10%. Without improved management, worst case increases in loads are between 0 and 29%. Total catchment loads would be expected to increase between 1 and 2%. Figure 3.31 shows the change in estuary water quality under the target scenario.

Figure 3.31 shows that significant improvements in water quality would be expected across most zones of the estuary. In most zones the greatest improvement would be seen in TSS, although this is not always the case.

Parramatta



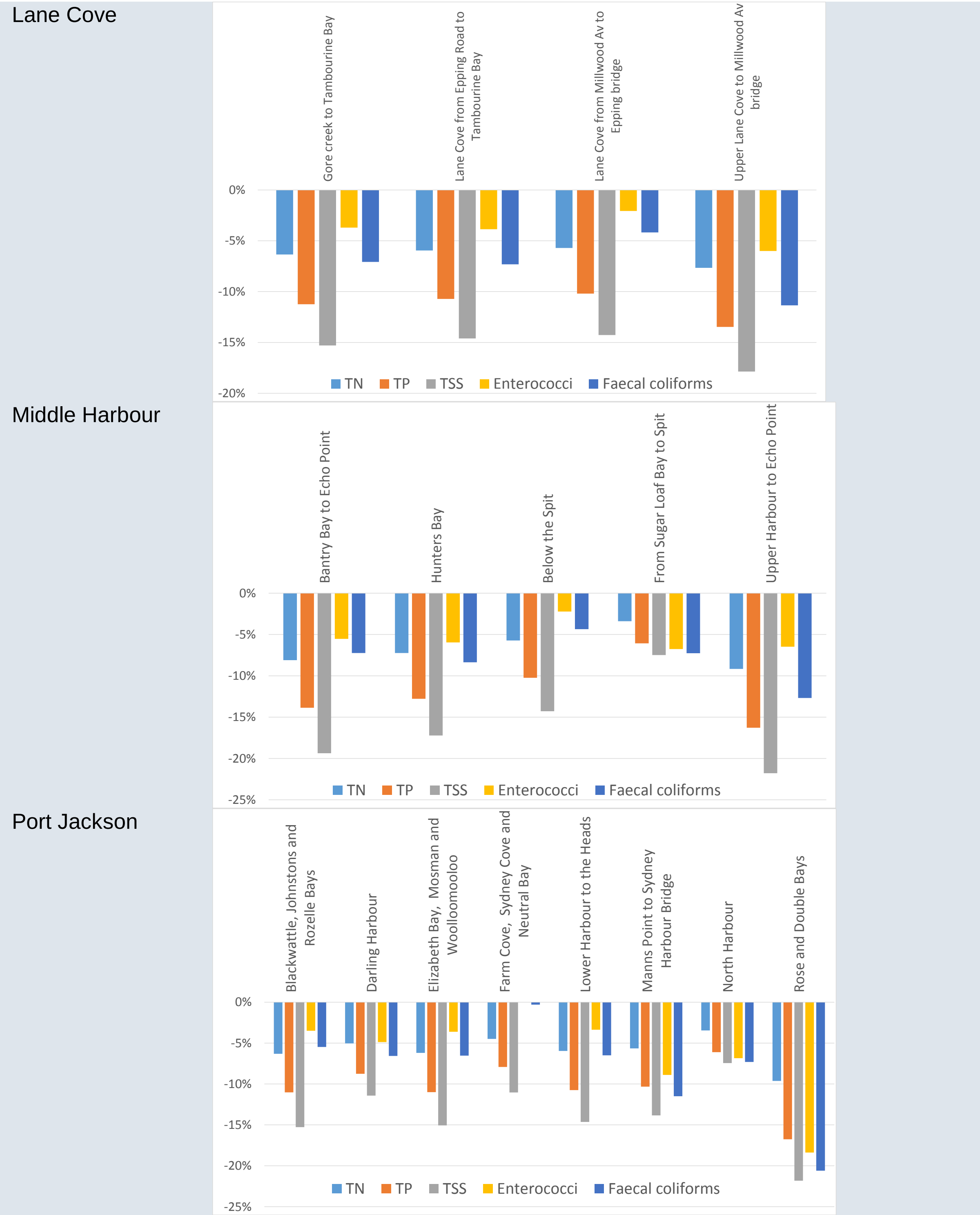


Figure 3.31 Estuary water quality changes under target scenarios

The Sydney Harbour Catchment Water Quality Improvement Plan (Appendix A) provides a list of evaluated actions to address identified threats. These recommendations were developed based on feedback from stakeholders received through the key stakeholder and community workshops and in consultation with the project Advisory Committee. The relative priority of each recommendation has been addressed based on: the risk level of the threat it addresses; and, the relative contribution the action is likely to make in addressing the threat.

4 ECOLOGY

As part of the NSW Government's response to the Independent Scientific Audit of Marine Parks in NSW, Cabinet requested delivery of a number of projects, including:

> "*a multidisciplinary project on whether Sydney Harbour or parts thereof should be recognised as a marine protected area(s) and/or a recreational fishing haven(s), by June 2013. This is to include consideration of current and likely future contamination status of fish and sediments, and social and economic costs and benefits of fishing and other activities in the Harbour.*"

The Marine Estate Management Authority (MEMA) is overseeing the Sydney Harbour project which has three stages:

- Stage 1: Identify the assets and benefits of Sydney Harbour
  Stage 1 was the collation of existing background information on the ecological, economic and social assets and benefits of Sydney Harbour. The Sydney Institute of Marine Science (SIMS) was commissioned to prepare this work (Hedge *et al.,* 2014a,b).
- Stage 2a: Identify threats to the benefits of Sydney Harbour
  Stage 2a is an initial identification of the values of Sydney Harbour and the potential threats to those values. It uses information from stage 1 and the results from MEMA's community survey to undertake a preliminary assessment that is consistent with MEMA's threat & risk approach (*Unpublished – see Chapter 5*).
- Stage 2b: Assess marine protected areas and recreational fishing havens
  Stage 2b considers whether any threats identified in stage 2a could be effectively and efficiently managed through the establishment of marine protected areas (MPAs) and/or recreational fishing havens (RFHs). It summarises the pros and cons of these management tools and presents options for consideration, including options for management initiatives that could be implemented with, or instead of, MPAs or RFHs.
- Stage 3: Implement Government decision
  Stage 3 would involve implementing any agreed decision on options that emerge from consideration of the two reports from stage 2 by Ministers and Cabinet. An option, or combination of options, could be implemented in the short to medium term, or as a component of a larger piece of work exploring enhanced conservation measures in the entire Hawkesbury Shelf bioregion, which itself is a Government commitment in its response to the Independent Scientific Audit of Marine Parks in NSW.

Striped Anglerfish (*Antennarius striatus*) with Paddle weed (*Halophila ovalis*)

Greater Sydney Local Services also commissioned SIMS to develop conceptual models of the Harbour and to investigate how anthropogenic activities influence ecosystem processes. This chapter brings together the recent collaborative ecological studies on Sydney Harbour. Key reports, sourced in this chapter (4) are also appended to this Study (Appendix D).

Brief descriptions of the Harbour's marine ecosystem are provided here but fuller descriptions and further details such as maps of the distribution of habitats, species lists, and associated scientific literature are provided in Hedge *et al.* (2014a, b - Appendix D.1 & D.2).The following sections contain basic information about the two environmental components (environmental assets) that formed the basis of a preliminary threat assessment – habitats and species groups.

4.1 Habitats

Saltmarsh

Saltmarsh habitat consists of a community of plants (e.g. sedges, rushes, reeds, grasses, succulent herbs and low shrubs) which can tolerate high soil salinity and occasional inundation with saltwater. Saltmarsh occurs on soft sediments in the highest intertidal parts of estuaries, providing habitat, shelter, and food for a range of fishes, birds, mammals, insects and invertebrates and contributing to the base of estuarine food chains through decomposition of vegetation. Saltmarsh acts as a buffer and filter of nutrients, reducing erosion and maintaining water quality. It also acts as a 'carbon sink' by storing large quantities of carbon within plants and sediment (DPI, 2014). In Sydney Harbour, there has been a significant decline in saltmarsh since colonisation. In the most recent census, only 37 ha of fragmented saltmarsh remained in the Harbour. More than 70% of patches were small (<100m2), isolated and of poor quality (Hedge *et al*., 2014b). Remaining saltmarsh occurs primarily in the upper Parramatta River, with over 23 ha around Sydney Olympic Park (Hedge *et al.,* 2014b). The largest contiguous patch of saltmarsh is within the Newington Nature Reserve. Saltmarsh has been listed as an Endangered Ecological Community (EEC) under the *Threatened Species Conservation Act 1995*.

Further information on the saltmarsh is provided in Chapter 2 (*2.6.2 Foreshore and Estuarine Vegetation*).

Mangroves

Mangrove habitat occurs at the fringe of intertidal shallows, primarily in marine and estuarine waters. In most places mangroves occur seaward of saltmarsh, and there can be patchy mosaics of the two habitats. Mangroves facilitate the deposition of fine particles and aid stabilisation of the sediment. They support terrestrial, estuarine and marine species and are considered key habitats for fish and invertebrates. Fallen mangrove leaves and branches contribute to a complex detrital food web. Mangroves act as a buffer between the terrestrial and marine environment, helping to maintain water quality by trapping and stabilising sediment, nutrients and contaminants from runoff and by protecting against erosion caused by storms, tides and wave action (DPI, 2014). Mangroves were apparently relatively uncommon in Sydney Harbour until the 1870's, but have colonised new sedimentary deposits in the upper Harbour and gradually replaced saltmarsh in certain areas. Most of the current mangrove forest occurs in the Parramatta River (134 ha) and upper Lane Cover river (36 ha), with only a small amount in the upper reaches of Middle Harbour (Hedge *et al.,* 2014b).

Seagrass

Seagrass beds play a key role in estuarine and coastal ecological processes, being important for primary production, detrital pathways and nutrient cycling. 'Wrack' or dead seagrass, is often washed up on beaches and forms an important part of the food chain. Seagrasses provide habitat, shelter and food for a diverse range of species including algae, crabs, prawns, fishes, sponges, bryozoans, ascidians, amphipods and molluscs. In particular, they are vital habitats for the juvenile stages of many commercial and recreational species such as snapper, yellowfin bream, tarwhine and luderick. Seagrasses also help to reduce erosion by stabilising sediments and shorelines, and improve water quality by extracting nutrients from shallow water. Seagrasses within NSW estuaries have declined in condition and extent, with an estimated 50% decline in seagrass in Sydney Harbour since 1943.

Approximately 52 ha of seagrass habitat remained in Sydney Harbour in 2000, with most occurring in the lower reaches of the Harbour (Hedge *et al.,* 2014b).

Figure 4.1 provides a map of estuarine macrophyte habitats in the Harbour (mangroves, saltmarsh and seagrass).

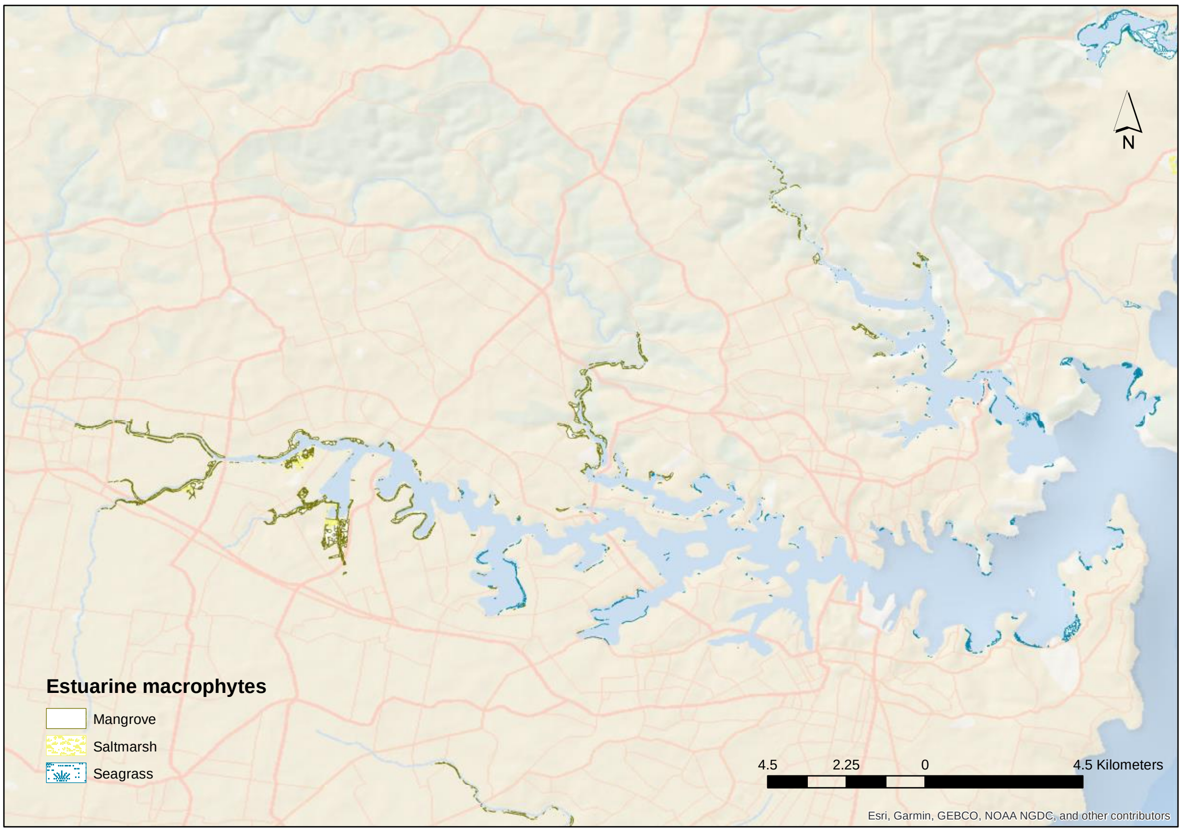


Figure 4.1 Estuarine macrophyte habitats in Sydney Harbour (mangroves, saltmarsh and seagrass).

Macroalgae

Algae are primitive photosynthetic plants that can range in size from microscopic to massive seaweeds such as bull kelps (Miller, 2011). Few species grow in soft-sediments or persist when detached from the substratum. Macroalgae grow in intertidal and subtidal areas and can occur to depths where sufficient light penetrates to allow photosynthesis. Macroalgae are an important source of food and shelter and nursery habitat for a large range of fishes and invertebrates. Drift seaweeds provide shelter in the pelagic environment for small organisms. When washed onto beaches they become food sources for invertebrates, before rotting and returning vital nutrients into beach ecosystems. More than 133 species of seaweed have been recorded in Sydney Harbour (Farrant and King, 1982). Kelp forests are a particularly prominent feature of the Harbour's underwater landscape, and provide essential habitat for a variety of fishes and invertebrates such as lobsters. Human activities have significantly impacted some seaweeds in the Harbour and surrounding coastline. Bennetts seaweed, which was only ever collected from Sydney Harbour, is now presumed extinct in NSW. Cray-weed, an important habitat-forming alga, has disappeared from the Sydney region within the last half century, and its demise has been related to the presence of ocean outfalls (Coleman *et al.,* 2008). Despite improvements in water quality with the installation of deep water outfalls and cray-weed being found to the north and south of Sydney, it has not re-established naturally.

Mudflats

Mudflats occur primarily in the lower tidal reaches of NSW estuaries. The underlying biological structure of mudflats is provided by bacteria which occur in high densities, and the surface is often densely coated by mats of filamentous plants. These form the basis of an important food chain, providing habitat and resources for a diversity of juvenile and adult invertebrates, fishes and birds. The distribution of mudflats in Sydney Harbour was not provided in the Background Report, but organisms associated with mudflats west of the Harbour Bridge have been documented by the Australian Museum.

Subtidal Rocky Reef

Hedge *et al*. (2014a) indicate that reefs are dominated by macroalgae (37%), urchin barrens (18%) or a mixture of both. In these reefs, beds of *Ecklonia* spp. support very diverse assemblages of green (e.g. *Enteromorpha* sp., *Codium* sp.), brown (e.g. *Zonaria* spp., *Dyctyota* spp.) and red understory algae (e.g. *Amphiroa* spp., *Delisea* spp.), invertebrates such as sponges (e.g. *Myxilla* spp.), bryozoans (e.g. *Watersipora* spp.), cnidarians (e.g. *Sertularia* spp.), annelids (e.g. syllid polychaetes), echinoderms (e.g. *Centrostephanus* and *Heliocidaris* spp.), molluscs (e.g. *Turbo torquatus*), crustaceans (e.g. barnacles and crabs), and chordates such as ascidians (e.g. *Didemnum* spp.) and fish (e.g. luderick *Girella tricuspidata*, kelp fish *Chironemus marmoratus*). They note the importance of rocky reefs for fish diversity in the Harbour is highlighted by the observation that of the 586 species of fish recorded in Sydney Harbour, over 60% inhabit subtidal reefs.

Rocky Intertidal Shores

According to Hedge *et al*. (2014a), more than 50% of the intertidal shoreline has been replaced with artificial breakwalls, that are now “artificial” rocky shores. 127 different taxa are known to inhabit intertidal reefs in Sydney Harbour, with a diversity of animals around the shoreline. The mid shore areas are generally dominated by the Sydney Rock Oyster *Saccostrea glomerata*, while the ascidian *Pyura preaputialis* dominates the low shore, particularly in the outer Harbour areas.

Above the low water mark, large, foliose, algal species form patchy mosaics throughout the estuary. Lower shorelines are dominated by foliose algae and tubiculous polychaetes.

Processes influencing patterns of distribution and abundance are varied and differ spatially and temporally. For example, grazing can remove early stages of development of macro-algae, which can create space used for settlement by sessile species. Similarly, competition is a major factor controlling the abundance and distribution of intertidal-dwelling gastropods. Intra- and inter-specific interactions are responsible for the co-existence of the limpets *Cellana tramoserica* and *Siphonaria denticulata* at mid-tidal levels. Other species of grazing gastropods also inhabit the same areas and compete for similar resources, leading to complex interactions (Hedge *et al*., 2014a).

Subtidal Rocky reefs

Rocky reefs are made up of many habitats including fringe, turf, macroalgal beds, urchin- grazed barren areas and, in deeper water, ascidian and/or sponge gardens. Rocky reefs provide habitat, food and shelter for a diverse assemblage of sharks and rays, fishes and invertebrates. These range from reef-attached species to transient species that move between reef systems. Snapper, red morwong, yellowfin bream, luderick, rock blackfish (drummer), wobbegongs, bullseyes, eastern blue groper, and many species of wrasse and leatherjackets are common residents on reefs in NSW, while pelagic species such as yellowtail kingfish and silver trevally visit reefs intermittently. Most of the rocky reef in Sydney Harbour is found in the lower catchment with dominant reef habitats being fringe, kelp and barrens. Some reef is also distributed throughout the Parramatta River, Middle Harbour and Lane Cove River arms of the Harbour. The sheltered reefs of Sydney Harbour are avidly used by recreational divers and snorkelers, particularly those which are easily accessible from the shore (e.g. Fairlight, Camp Cove, Chowder Bay).

Soft Bottoms and Beaches

Soft sediment habitats are dominated by sandy sediments, but also commonly contain pebbles, cobbles and boulders. Marine assemblages associated with these habitats are influenced by sediment type and size, organic content, the depth at which the habitat occurs and the degree of fine scale habitat structuring (ripples, pits, mounds). Many of the animals live within the sediment, including amphipods, bivalves and marine worms. Unconsolidated habitats also commonly contain large sessile macrofauna (sponges, ascidians, bryzoans, seawhips) that increase the diversity and complexity of the habitat. These are particularly prevalent in areas of higher current flows adjacent to offshore islands and pinnacles. Soft sediment habitat also provides important foraging and nursery areas for higher trophic levels such as dolphins, seabirds, fishes, sharks and rays. Bottom-sediments in Sydney Harbour consist of mud, gravel and sand, but there are limited data on the marine assemblages associated with these environments.

Whilst no comprehensive surveys of soft bottom benthic communities of Sydney Harbour have been undertaken, some indication of the diversity is given by Australian Museum collection records (Hutchings *et al.,* 2013). The spatial extent of these records, however is limited. They report 10,091 taxanomic units from 262 Orders, 122 Classes, and 54 Phyla in Sydney Harbour sediment.

The distribution of sediment dwelling fauna vary according to the myriad of reproduction strategies employed (Hedge *et al*., 2014a). Many taxa have directly developing larvae that allow for quick colonisation of nearby areas, whereas others have planktonic larvae that allow organisms to drift and colonise sites much further away.

Soft Sediment Macrophytes

The best estimates of mangrove, seagrass and saltmarsh extent in Sydney Harbour exist as a series of NSW Government reports. Mapping of sub-tidal macrophytes was done using aerial photographs. Mangroves and saltmarsh are restricted to intertidal regions in Lane Cove River, Middle Harbour, and Parramatta River. Saltmarsh has declined in Sydney Harbour and less than 37.5 ha remain. Of the 757 patches of saltmarsh remaining, most are small (< 100 m^2) and isolated. The largest contiguous patch of saltmarsh exists within the Newington Nature Reserve in the Parramatta River.

Conversely, mangrove extent has increased to be approximately 184 ha. This despite being relatively uncommon prior to the 1870's (Hedge *et al*., 2014a). In some parts of the Harbour, mangrove forests are replacing the saltmarsh systems.

There are several species of seagrass in Sydney Harbour, including the eel grass *Zostera muelleri* and the endangered strap grass *Posidonia australis*. Seagrass cover in the estuary was estimated to be around 59.2 ha in 1978. In 1986 to the estimate was 87.4 ha, before falling to an estimated 49.5 ha in 2003 (Hedge *et al*., 2014a).

A more detailed discussion on mangrove and saltmarsh habitats within Sydney Harbour is provided in section *2.4.2. Foreshore and Estuarine Vegetation*.

Open Water / Pelagic Systems

Open water habitat in this report refers to the water column between habitats on the seafloor and the surface. This habitat is influenced by a range of chemical, physical, and biological parameters. Open water intuitively influences all marine and estuarine organisms, but provides primary habitat for plankton and microbes, fish and sharks, and marine mammals such as whales and dolphins. It is particularly important in contributing to population connectivity through the transportation of organisms which have a pelagic life-history phase. Factors influencing open water habitat within Sydney Harbour such as hydrology, circulation and flushing and ocean exchange are described in Hedge *et al*. (2014b).

According to Hedge *et al*., (2014b), little is known of the flora and fauna that inhabit the water column in Sydney Harbour. There has been some historical analysis of algal blooms since European colonisation, and algae with direct toxic effects to biota have been observed during 1983, 1996 and 1999. It is expected that other outbreaks have occurred, both post and prior to these dates, but there is a paucity of records on pelagic microalgae. The most comprehensive survey was collected for the Sydney Harbour Catchment Water Quality Improvement Plan (Freewater and Kelly, 2015). This collection identified the six dominant taxa from a variety of locations around the Harbour. Diatoms and dinoflagellates were the most common (Table 4.1), however, various unidentified cryptomonads and flagellates were also recorded.

Table 4.1 Phytoplankton collected during the winter 2012 (unpublished)

Bacillariophyceae (Diatoms)	Dinophyceae (Dinoflagellates)
Chaetoceros spp.	*Prorocentrum minimum*
Minidiscus trioculatus	*Alexandrium sp.*
Rhizoselenia setigera	*Scripsiella trochoidea*
Thalassiosira spp.	*Protoperdinium spp*
Chaetoceros spp.	*Prorocentrum gracile*
Cylindrotheca longissima/closterium	*Gymnodinoid sp*
Thalassionema nitzchioides	*Prorocentrum micans*
Navicula spp.	
Skeletonema spp.	

Zooplankton is also poorly understood in Sydney Harbour. There are, however, estimates of the abundance of larger invertebrates from commercial fishing operations prior to 2006. Almost 100 individuals per day of mantis shrimp *Squillidae spp* and blue swimmer crab *Portunus armatus* were caught as bycatch prior to commercial fishing bans in the Harbour imposed in 2006 (Hedge *et al.,* 2014a).

Artificial habitats

Over 50% of the foreshore of Sydney Harbour has been artificially constructed replacing naturally occurring habitat (Hedge *et al*., 2014b). Various structures have been erected in the form of seawalls, wharves, jetties and pontoons. These areas are now utilised as habitat by a range of marine organisms, although assemblages differ from those on 'natural' habitats. For example, White's seahorse which is endemic to temperate Australia is commonly found holding onto the mesh of swimming enclosures in the Harbour; and little penguins currently nest under Manly Wharf. There are several initiatives in the Harbour to design structures which minimise impacts to natural habitats and biodiversity and to maximise the potential of existing and future structures to be used as habitats – so called 'green engineering'. Examples include construction of environmentally friendly seawalls and 'fish-friendly' marinas.

4.2 Fauna

In December 2011, Australian Museum database records of polychaetes, crustaceans, echinoderms, molluscs and fishes were extracted from the Sydney region (Hutchings *et al*., 2013). Less diverse groups of marine invertebrates, such as sponges, bryozoans and cnidarians, having relatively few collection records, were not included. This report is the first attempt to collate the marine fauna of Sydney Harbour in more than 100 years. Because of the importance of this work, the entire paper is enclosed as Appendix E.

According to the Australian Museum, Sydney Harbour is the most biodiverse Harbour in the world, with over 3500 marine species recorded. Current inventories, include 1300 molluscs (e.g. snails, mussels, octopus), 670 crustaceans (e.g. crabs, lobsters, prawns), 586 fish (bony fish, sharks and rays), 300 polychaetes (marine worms), 210 bryozoans (lace corals and sea mats), 160 sponges, 130 cnidarians (jellyfish, anemones and corals), 118 echinoderms (e.g. sea urchins, sea-stars), and 80 ascidians (cunjevoi and sea squirts) (Hutchings *et al.,* 2013).

These are almost certainly underestimates, and did not include assessments of other major species groups found in the Harbour (e.g. macroalgae). The key results are summarised below:

Bony fishes

Bony fish are an extremely diverse and abundant group, which occupy a range of ecological niches. It includes small site-attached fish which live in near-shore habitats (e.g. damselfish, seahorses) to large oceanic species which are capable of migrating large distances (e.g. tuna, dolphinfish). Bony fishes are a key component of marine and estuarine food webs, and support recreational, commercial and subsistence fisheries. Almost 600 fish species (includes rays and sharks) have been recorded as occurring in, or entering Sydney Harbour. Tropical vagrant fishes can also be found in the Harbour during the warmer months. Many species such as snapper, flathead, bream, whiting and kingfish are highly valued by fishers. Iconic species are regularly enjoyed by divers and snorkelers and include the eastern blue groper, weedy seadragons, the Sydney pygmy pipehorse, Sydney scorpionfish (only recorded in Sydney Harbour), and the red indian fish (endemic to Australia). Of these, Sydney Harbour is an important stronghold for the sygnathiformes (seahorses, seadragons, pipefish, pipehorse) which are listed as 'protected' under the NSW Fisheries Management Act 1994. The condition of fish assemblages (fish diversity and composition, species abundance, nursery function, trophic integrity) in Sydney Harbour was recently assessed as 'fair' relative to similar estuaries in NSW (Roper *et al.,* 2011). The Harbour also contributes to coastal fish populations and fisheries due to its role as a nursery area (e.g. snapper, blue groper).

Hutchings *et al.,* (2013) indicate 586 species of fishes from 391 genera and 160 families are known to occur in Sydney Harbour. Many species of fishes collected from coastal areas of Sydney have not been recorded from the Harbour. The outer Harbour is essentially a marine environment that contains suitable habitats for many of these coastal species (Hutchings *et al.,* 2013). Hutchings *et al*., (2013) suggest that unrecorded coastal species occur in the Eastern region of the Harbour.

Many records are based on vagrant fishes such as tropical species (e.g. butterflyfishes, cardinalfishes, damselfishes, surgeon fishes, gobies) and pelagics (e.g. billfishes, lamnid sharks, drift fishes, trevallies). Their occurrence may be based on a single record (Hutchings *et al*., 2013) and this report includes 175 species (29.9%) for which the collection contains only a single specimen. It is unclear how many species are resident, how many are vagrants and how many are simply rare (Hutchings *et al*., (2013).

Large areas of the Harbour (primarily in the Northern and Western regions) exist in which there has been no fish collecting undertaken by the Australian Museum (Hutchings *et al.,* 2013). If these areas are targeted, current knowledge of fish distributions will improve (Hutchings *et al.,* 2013).

Sharks and rays

Sharks and rays are fish which have a cartilaginous skeleton. Top order sharks are considered to be apex predators at the top of their food chain. These predators play an important role in maintaining healthy marine ecosystems. Well known species include great white sharks, hammerheads and tiger sharks. Top order sharks generally occupy coastal and oceanic habitats and can travel large distances. However, they may also use estuaries intermittently, particularly for breeding or as nursery habitats. Sydney Harbour is a breeding area for bull sharks, and a nursery area for whalers. Other top order sharks have been recorded in the Harbour (e.g. tiger sharks, great whites) but are considered transitory. Anecdotally, the critically endangered grey nurse shark was once found in Sydney Harbour. Lower order sharks and rays occupy the middle of the food chain, prey on other species (e.g. small fishes, crustaceans, and worms) and are consumed by top order predators such as pelagic sharks, dolphins and seals. In Sydney Harbour species in this group include bottom-dwelling sharks and rays. Some of these are seasonally abundant; for example, adult Port Jackson sharks primarily occur in the Harbour during the colder months, when they aggregate at specific sites to breed 9. Juvenile Port Jacksons then utilise shallow waters in the Harbour as nursery areas before moving to offshore habitats as adults.

Marine turtles

There are no breeding populations of turtles in Sydney Harbour, but the green turtle (listed as vulnerable), loggerhead turtle and the leatherback turtle (both listed as endangered) regularly visit Sydney waters including the Harbour. All marine turtles have suffered significant population declines due to pollution, marine debris, habitat loss, and predation and disturbance at nesting sites.

Invertebrates (intertidal & subtidal)

Marine invertebrates lack a backbone. Some are soft-bodied, others have evolved shells or exoskeletons for protection. The group is extremely diverse and includes marine worms, cnidarians (e.g. sea anemone and corals), crustaceans (e.g. crabs, lobster, shrimps, and barnacles), echinoderms (e.g. sea stars, urchins, crinoids), molluscs (e.g. sea snails, octopus, cuttlefish), sponges, bryozoans, and sea spiders. Intertidal invertebrates have adapted to an environment of extremes. For example, at high tide they are exposed to inundation, wave action and marine predators; and at low tide they must withstand drying out, changes in salinity and temperature, and terrestrial predators. Invertebrates are important food sources for a range of fish and birds. More than 2,700 species of marine invertebrates have been recorded in Sydney Harbour.

Polychaetes

The investigation produced 1250 records of polychaetes representing 40 families, comprised of 308 species belonging to 189 genera. Polychaetes were recorded throughout the catchment although records from Middle Harbour and Lane Cove are sparse and restricted to the lower reaches (Hutchings *et al.,* 2013). This may be because polychaetes are primarily marine and while the upper reaches of the Harbour are fully marine during dry conditions, salinity levels fall in these regions after periods of heavy rain. The bulk of polychaete species are from the East and Central regions, mostly from the shores or shallow water. Few are recorded from deeper water, especially in the Eastern region as little sampling of sediments has occurred there. Many polychaete species occur in sediments and have very specific habitat requirements so additional new species may be in deeper water sediments in the Harbour reaches (Hutchings *et al.,* 2013).

Crustaceans

Crustaceans are the dominant marine arthropods and include crabs, shrimps, lobsters, isopods, amphipods and barnacles (Hutchings *et al.,* 2013). They occur throughout the Harbour and are represented by 2778 records distributed in 163 families, 434 genera, and 672 species. The crustacean fauna of the Harbour is rich, comprising temperate species along with warm water species that are temporary residents brought by the East Australian Current, or for which Port Jackson is part of their southern range limit (Hutchings *et al.,* 2013).

Many species are of significant commercial value, such as School Prawns (*Metapeneaus spp*.), Blue Swimmer Crabs (*Portunus armatus*), Mud Crabs (*Scylla serrata*) and Eastern Rock Lobsters (*Sagmariasus verreauxi*).

Echinoderms

Echinoderms, which include sea urchins, sea-stars and sea cucumbers, are a relatively small group with around 1200 species known from Australia (Hutchings *et al.,* 2013). Sea urchins and sea-stars can be numerically abundant, especially on rocky reefs and other hard substrates. For Sydney Harbour 1017 records, distributed in 45 families, 91 genera and 118 species exist in the Australian Museum collections (Hutchings *et al.,* 2013).

Molluscs

Molluscs comprise the greatest number of records among the taxonomic groups (10,598), families (224), genera (725) and species (1339). Hutchings *et al*., (2013) indicate that there are significant areas of the Harbour that have not been sampled. The Eastern and Northern regions have the greatest number of specimen records and the greatest number of species (1201 and 788 respectively). Within these zones the most extensively sampled regions are at depths of less than 10 m. Some areas appear to have been targeted, with 301–1000 records indicated for the following locations: Middle Harbour, Manly Cove, Middle Head, Watsons Bay, Shark Bay, Berry's Bay, and off Bradley's Head, Taylor's Bay and Chowder Bay (Hutchings *et al.,* 2013).

The Central and Western regions have been poorly collected and only in recent years have Australian Museum malacologists focused on freshwater and brackish water molluscs, which are likely to occur in the westernmost arms of the catchment area of the Harbour (Hutchings *et al.,* 2013). The paucity of specimens from these areas is reflected in the number of records as well as the number of species, with 234 species recorded from the Central region and only 31 in the Western zone (Hutchings *et al.,* 2013).

Hutchings *et al.,* (2013) suggest that rather than reflecting collecting effort, this pattern of decreasing diversity from east to west may be real. It may relate to the decreasing diversity of habitat types and depths and fluctuating salinity, which decrease and increase respectively from east to west.

Seabirds

Seabirds spend most of their lives at sea, but use coastal areas to breed (e.g. albatross, gannet, shearwater). Seabirds may occasionally visit Sydney Harbour but are not a conspicuous feature of the Harbour's biodiversity and there are no breeding colonies within or around the Harbour.

Shorebirds

Shorebirds live and forage close to shore and most are migratory. Shorebirds are common in wetlands and marshes of Sydney Harbour (e.g. pelicans, cormorants, oystercatchers, plover, sandpiper, herons). The white-fronted chat lives in saltmarsh and other damp, open areas with low vegetation. Once common in Sydney, their Sydney distribution is now restricted to two small populations living in wetlands in Botany Bay and the Parramatta River. The latter population is expected to become extinct within the next few years.

Little penguins

Sydney Harbour is home to one of only five Little Penguin *Eudyptula minor* colonies on the south-east coast of Australia. This colony is located along the northern foreshore of the Harbour from Manly to North Head. At last count there were 56 breeding pairs in the Sydney colony. Reports from 1912, however, indicate that this colony was much larger (Hedge *et al*., 2014a). In 1954 unverified anecdotal reports suggested that approximately 300 penguins were shot (NPWS, 2000). Habitat destruction, dog predation, car accidents, and human vandalism are blamed for the steep decline in Little Penguin numbers in Sydney Harbour.

Marine mammals

Marine mammals are occasional visitors to Sydney Harbour. Humpback and southern right whales, often with calves, intermittently enter the Harbour from late April to November during their annual migrations; dolphin and seals are also seen on an irregular basis. There is little published data on the occurrence and behaviour of marine mammals in Sydney Harbour.

4.2.1 Discussion

The paper by Hutchings *et al.* (2013) reported 632 families, 1830 genera and 3023 species. However, the authors believe that this is an underestimate of the diversity of the Harbour as groups such as sponges, ascidians, bryozoans and many of the smaller groups, have not been included.

Hutchings *et al.,* (2013) indicate that Eastern and Central areas have the greatest number of records for all groups excluding polychaetes. They state that the Western area has the least. They believe this may be due to inadequate sampling, but it is also the area with the lowest diversity of habitats and, periodically, the lowest salinities, especially after heavy rain. This may severely impact some taxa; for example, echinoderms are almost completely marine and polychaetes largely so and would not survive under these conditions (Hutchings *et al.,* 2013). Another contributing factor may be poor water quality. Further east, good tidal flushing has reduced the impact of land-based pollution from Harbour foreshore Industries (Hutchings *et al.,* 2013).

The most speciose area is the Eastern region, which has more habitat types, rocky shores, soft substrates, pelagic habitat, is essentially an extension of the coastal marine environment (Hutchings *et al.,* 2013). Species data is summarised in figure 4.2.

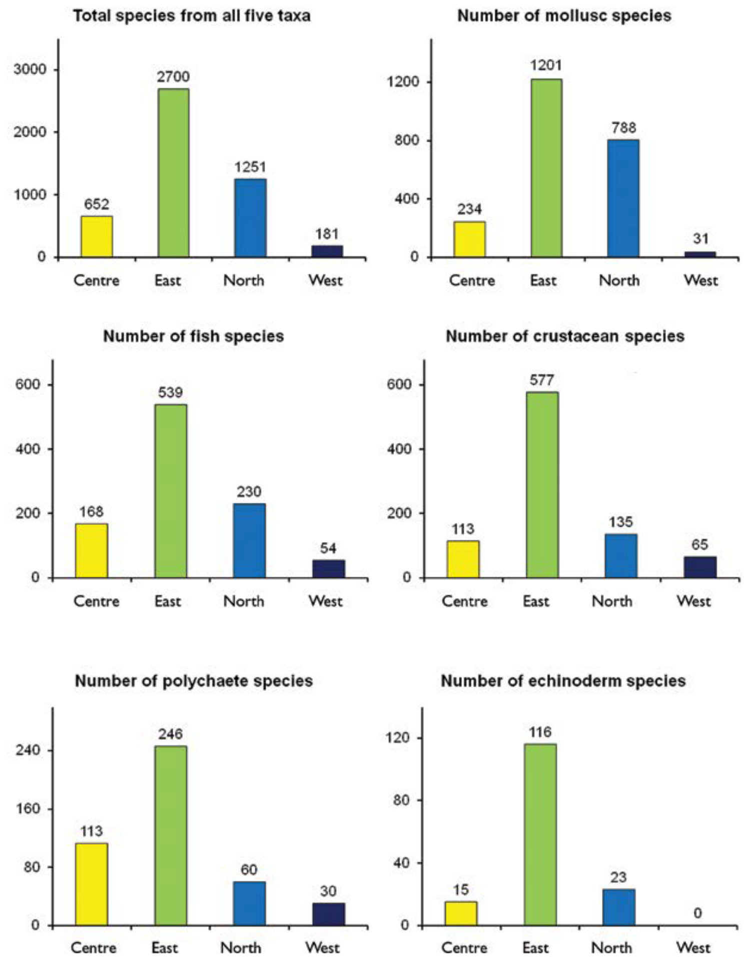


Figure 4.2 Number of species recorded from each of the four regions of the Harbour (Hutchings *et al.,* 2013).

4.3 Anthropogenic impacts on the biodiversity and ecosystem function

4.3.1 Threats to biodiversity and ecosystem functioning of the Harbour

A SIMS report (**Sydney Harbour: a review of anthropogenic impacts on the biodiversity and ecosystem function of one of the world's largest natural harbours)** Mayer-Pinto *et. al.* (2015) published in Marine and Freshwater Research is summarised below and enclosed in Appendix D.4.

Chemical contamination

According to Mayer-Pinto *et. al*. (2015) Sydney Harbour is one of the most contaminated environments in the world. Irvine and Birch (1998) demonstrated that sediments contained high concentrations of a suite of metals. Other studies have shown that sediments also contain a wide range of non-metallic contaminants, e.g. organochlorine pesticides (OC; Birch and Taylor, 2000), polycyclic aromatic hydro-carbons (PAH) and polychlorinated dibenzo-para-dioxins (dioxins) and dibenzo-furans (Birch *et al*., 2007). Commercial fishing was banned in 2006 and recreational fishing severely restricted based on dioxin contamination in fish tissues (Birch *et al*., 2007). An oil spill of over 296,000 L in 1999 caused a decrease in the abundances of intertidal organisms in the most affected sites (Mayer-Pinto*, et. al.,* 2015).

In Sydney Harbour, over 50% of the surface sediment exceeds Interim Sediment Quality Guidelines – High (ISQG-H; a value that indicates a high risk of adverse effects to benthic populations) for some metals such as lead (Mayer-Pinto, *et. al.*, 2015). Organochlorine pesticides also exceeded ISQG-H concentrations over extensive parts of Sydney Harbour, including the lower estuary. Sediments in almost all upper and middle parts of Sydney Harbour, including Middle Harbour, had at least one metal, OC or PAH concentration exceeding ISQG-H values (Mayer-Pinto *et. al.,* 2015). The greatest concentrations of contaminants are generally restricted to the bedded sediments of the upper reaches of embayments and decrease markedly seaward in the Harbour (Birch and Taylor 2004). Not only are the fish and the sediments contaminated, some macro- algae within the Harbour contain concentrations of metals that are high enough to cause mortality of associated herbivores; oysters contain concentrations of metals associated with high cellular stress (Hedge *et al*., 2014a; Birch *et al*., 2014) and the grey mangrove (*Avicennia marina*) contains high levels of copper, lead and zinc on its roots and leaves (Mayer-Pinto *et al.,* 2015). There is also a high frequency of gastropod imposex in Sydney Harbour, associated with high concentrations of tributyltin (TBT) in the water, even after several years of partial ban of TBT-based anti-fouling paints (Mayer-Pinto *et. al.,* 2015).

Most of the contamination results from a combination of historical inputs by the direct disposal of commercial and urban waste into the estuary and current inputs such as untreated stormwater and urban run-off (Mayer-Pinto *et al.,* 2015). Hotspots of metal and TBT contamination are also associated with the Harbour's enclosed marinas.

Chemical contaminants are detrimental to the diversity and functioning of ecological systems (Mayer-Pinto *et al.,* 2015). In Sydney Harbour, contaminated sediments are associated with increased abundances of opportunistic colonisers such as the green algae *Ulva* spp. and some families of polychaete worms, as well as significant changes in the structure of infaunal and benthic assemblages (Mayer-Pinto *et al.,* 2015).

4.3.2 Elevated nutrients and turbidity

According to Mayer-Pinto *et al.* (2015), excessive nutrients and changes to nutrient ratios (stoichiometry) contribute to changes in ecology, resulting in algal blooms, loss of seagrasses and depletion of oxygen in the water. Increases in the nutrient load are often attributed to human activities such as land clearing, fertiliser application and sewage discharges. In Sydney Harbour, large loads of total suspended solids (TSS) and nutrients are delivered during high rainfall periods, whereas under 'baseflow' conditions TSS is lower and high levels of total nitrogen (TN) and phosphorus (TP) dominate (Mayer-Pinto *et al.,* 2015). This can lead to complex responses because impacts of nutrients in estuarine systems depend on a range of factors such as the mode and timing of delivery, the residence time and the type of sediments present in the systems.

Modelling of overflows and discharges reported in (Mayer-Pinto *et.al.,* 2015) suggest that sewage contributes about 50% of TN and TP loads to the Sydney estuary. However, modelling and intensive sampling undertaken to inform the Sydney Harbour Catchment Water Quality Improvement Plan (Freewater and Kelly, 2015) indicates that sewage only contributes about 10% of TN and TP loads and about 3% of the TSS. That study indicated that residential land use was the major contributor of nutrients (approximately 45% - see *3.2.1 Major sources of pollutant loads* and Appendix A).

According to Mayer-Pinto *et al.* (2015), the fate of nutrients in Sydney Harbour is strongly dependent upon rainfall conditions. In high rainfall events (> 50 mm day^{-1}), the estuary becomes stratified and nutrients are either removed from the estuary directly in a surface plume or indirectly by advective or dispersive remobilisation. Under low to moderate rainfall (5–50 mm day^{-1}), nutrients (and contaminants) tend to be biologically incorporated into the food web and deposited into adjacent sediments close to discharge points (Mayer-Pinto *et al.,* 2015).

Marine debris

Mayer-Pinto *et al.* (2015) define marine debris as any persistent, manufactured or processed solid material discarded, disposed of, or abandoned in the marine and coastal environment. Plastics make up most of the marine litter and reach the estuary by accidental release and indiscriminate discard. Plastic debris can harm organisms physically and chemically, by releasing toxic substances that they either absorb or contain (Mayer-Pinto *et al.,* 2015). Large pieces of plastic can kill and injure marine species such as marine mammals and sea birds by ingestion or entanglement. Marine debris has, therefore, the potential to greatly affect the diversity and functioning of Sydney Harbour (Mayer-Pinto *et al.,* 2015).

NSW Roads and Maritime Services (RMS) collects approximately 3500 m^3 of litter per year in the Harbour. This amount of marine debris is comparable to some of the most polluted beaches in the world (Mayer-Pinto *et al.,* 2015).

Non-indigenous and novel species in Sydney Harbour

Native systems can be affected by introduced species through the displacement of native biota, changes to predation and herbivory rates, introduction of new diseases and parasites and the destabilisation of micro-environments (Mayer-Pinto *et al.,* 2015). Many non-indigenous species (NIS) have established in Sydney Harbour. According to Mayer-Pinto *et al.* (2015) NIS occur in most habitats within the Harbour such as artificial substrata (e.g. the tunicate, *Styela plicata*), natural intertidal (e.g. the Pacific oyster, *Crassostrea gigas*) and subtidal rocky reefs (e.g. the tropical goby fish *Abudefduf vaigiensis* and the introduced bryozoan *Membranipora membranacea*), soft sediment sub-strata (e.g. the green alga, *Caulerpa taxifolia* and mantis shrimp, *Oratosquilla oratoria*) and upper intertidal plant com- munities (e.g. the saltmarsh plant, *Juncus acutus*). can be found in A report by the Australian Museum (AM 2002) contains a detailed list of NIS known to occur in Sydney Harbour.

Little is known of the establishment and the impacts of invasive microbes in Sydney Harbour (Mayer-Pinto *et al.,* 2015). Mayer-Pinto *et al.* (2015) indicate that Sydney Harbour may be frequently invaded by microorganisms from ballast water and that given the risks that invasions pose to local ecosystems, this is an important knowledge gap to fill.

Climatic change is also contributing to the spread of some species (Mayer-Pinto *et al.,* 2015). The incursion of tropical marine fish into NSW, for example, has been growing in frequency and intensity, with several species now with regular 'overwintering' adults. In some circumstances, these species have been referred to as invasive species in their extended range. In Sydney Harbour, studies have shown the presence of tropical fishes (Booth *et al*. 2007, in Mayer-Pinto *et al.,* 2015), which has been linked to the southward strengthening of the East Australian Current. They suggest that the full consequences of such range expansions, coined 'tropicalisation', are likely to alter Harbour ecosystems, resulting in community phase shifts.

Habitat modification

Sydney Harbour has been extensively modified since European settlement. Approximately 77 km of the original 322 km of shoreline has been removed due to reclamation and infilling; 22% of the area of the estuary has been reclaimed, mainly for industrial, recreational and residential uses; and more than 50% of the shoreline has been replaced with artificial structures such as seawalls (Mayer-Pinto *et al.,* 2015).

In Sydney Harbour, intertidal seawalls support fewer organisms than adjacent natural rocky shores. Chapman (2003, 2006 in Mayer-Pinto *et al.,* (2015)) found that this is mainly due to the absence of several species of mobile organisms on seawalls, including some gastropods. Important ecological processes and interactions among organisms occur-ring on seawalls such as competitive interactions and recruitment, also differ from those occurring on natural rocky shores, leading to differences in the composition of assemblages compared to natural shores. These structures impair the reproductive output of limpets, which are important structuring agents of intertidal assemblages (Mayer-Pinto *et al.,* 2015).

The most common types of artificial structures in the subtidal systems of Sydney Harbour are pier pilings and floating pontoons in marinas and wharves. According to Mayer-Pinto *et al.* (2015) the composition of assemblages and the relative abundance of organisms living on these structures differ from those on natural rocky reefs. They indicate that fish assemblages surrounding pier pilings in marinas often differ from those in natural reef habitats and that important habitat forming species growing on artificial structures, such as kelps, support different species and greater cover of epibiota (e.g. encrusting bryozoans and hydroids) than those on adjacent natural reefs.

Fragmentation of habitats also has a significant impact. In Sydney Harbour, most natural shores are currently fragmented by seawalls and there is a greater abundance of taxa on natural shores compared to mixed shores (ie. bordered at one end by artificial habitat and at the other end by natural shore) or complete (ie. bordered by artificial habitats at both ends) fragments (Mayer-Pinto *et al.,* 2015).

Research, however, has indicated that patchy landscapes should not necessarily be considered poor habitats and because a range of patch sizes may be necessary to maintain species diversity in certain systems (Mayer-Pinto *et al.,* 2015).

In addition to the hard, artificial structures, several beaches in Sydney Harbour have swimming enclosures constructed with shark nets. These nets are a suitable habitat for seahorses in Sydney Harbour supporting the species *Hippocampus whitei* (Mayer-Pinto *et. al.,* 2015). However, the nets are often removed during winter or when being repaired. The removal or cleaning of the nets reduces local seahorse abundance, but whether nets are actually increasing seahorse populations (by providing new habitat) or acting as sinks, taking these organisms away from their natural habitats is unknown (Mayer-Pinto *et. al.,* 2015).

Habitat modification through reclamation and dredging has contributed to the significant decline of salt marshes in Sydney Harbour. Although it appears that mudflats and saltmarshes communities dominated much of the intertidal zone of the Harbour in the 19th century (Mayer-Pinto *et. al*., 2015), in 2007 they occupied an area of approximately 37 ha (Kelleway *et al.,* 2007). The cause of the decline has been linked to habitat modification, sea level rise and elevated concentrations of atmospheric carbon dioxide.

Fishing

Sydney Harbour is known to include about 580 species of fish (Hutchings *et al.,* 2013), and although commercial fishing was banned in 2006 due mainly to dioxin contamination, recreational fishing is still allowed and fishing pressure can be intense in some areas of the Harbour (Hedge *et al*. 2014a). Between 1980 and 1982, 108,000 kg of fish were caught commercially and the recreational catch was 164,700 kg of fish (Hedge *et al.* 2014a).

Many species caught in Sydney Harbour, such as mulloway (*Argyosomus japonicus*), kingfish (*Seriola lalandi*), snapper (*Pagrus auratus*) and yellowfin bream (*Acanthopagrus australis*), have been listed as overfished or growth overfished in NSW (Mayer-Pinto *et al*., 2015). On-site surveys indicate that Sydney Harbour experiences approximately twice the effort and catch of other estuaries in the state, dominated by local residents fishing from shore (Mayer-Pinto *et al*., 2015).

The North (Sydney) Harbour Aquatic Reserve (260 ha) was established in 1982. Although, line fishing is allowed in the park, spearfishing and mollusc collecting is prohibited. This reserve has been used as part of a larger study, which demonstrated that protection can enhance the abundance of targeted fish species (Mayer-Pinto *et al*., 2015).

Climate change

Estuaries are exposed to changes in climate by changes to freshwater inputs, atmospheric influences and oceanic systems (Mayer-Pinto *et al*., 2015). Sydney Harbour is located in the western Tasman Sea, a region known to be warming relatively quickly compared to the global average, with the water temperature regime shifting 350 km southwards due to the increasing extent of the East Australian Current (Mayer-Pinto *et al*., 2015). Some of the observed consequences of the strengthening of the East Australian Current (EAC) are a drop in concentrations of dissolved silicate (an essential element for growth of silicifying phytoplankton such as diatoms) and drop in the size of the spring phytoplankton bloom and its growth rate (Mayer-Pinto *et al*., 2015). Such observations come from a substantial water quality time series collected from Port Hacking, 27 km south of the Harbour's entrance. These changes suggest that water entering the Sydney estuary from the ocean is becoming warmer as well as less productive, with potential implications for recruitment of organisms into the Harbour and other processes.

Ocean acidification, one of the consequences of climate change, is likely to result in reduced capacity for marine calcifiers such as corals, molluscs and some plankton to produce their skeletons (Mayer-Pinto *et al*., 2015). Under such conditions, non-calcifying species (e.g. ascidians and siliceous sponges) may have a competitive advantage over calcifying species such as habitat forming invertebrates and commercially important shellfish (e.g. mussels and oysters).

Sea level rise, has been of most concern to governments, particularly in view of dramatic shifts in beach sands because of climate-driven storms. Waters along Australia's eastern seaboard are rising in line with global averages (3.1 ± 0.6 mm year^{-1}) and are acting in opposition to vertical accretion of sediments in nearshore habitats (Mayer-Pinto *et al*., 2015). It has been demonstrated that the surface elevations within Sydney Harbour exceeded the 85-year sea level trend, suggesting that sea level rise is likely to diminish key habitats in the Harbour such as saltmarsh, mangrove and seagrass (Mayer-Pinto *et al*., 2015).

4.4 Biodiversity Conservation

Sydney Harbour supports rich biodiversity (> 3000 species) Threats to biodiversity arise from the wide range of activities associated with Harbours, and these pressures on the natural environment increase as Harbour cities become more populous. Banks *et al.* (2016) outlines approaches for biodiversity conservation in Sydney Harbour.

Shipping, boating and associated infrastructure impact Harbour ecosystems via the discharge of pollutants such as oil, sewage, rubbish and antifouling paints, and hydrological and sedimentological disturbances (Banks *et al*., 2016). Terrestrial runoff and industrial activities also impact Harbour waters and sediments. Potential contaminants include metals, organic hydrocarbons, sewage bacteria, viruses, pharmaceuticals and excess nutrients (Banks *et al*., 2016). Harbour sediments may act as a reservoir for legacy and incoming pollutants that can be resuspended, for example via dredging and propeller wash (Banks *et al*., 2016).

Banks *et al.* (2016) summarise some of the management plans that regulate human activities and associated impacts, and promote biodiversity conservation in Sydney Harbour. They then describe the NSW Marine Estate Management Authority approach, designed to produce an overarching plan to ensure the long-term viability of the state's marine environment. The management plans summarised by Banks *et al.* (2016) are provided below:

Managing recreational fishing

The NSW Department of Primary Industries regulates recreational fishing. The ecological sustainability of the fishery is managed through state-wide assessments and associated bag and size limits, gear restrictions, fishing closures and protection of individual species. Harbour-specific management of recreational fishing includes fisheries closures and marine protected areas introduced for conservation and for reasons of seafood safety due to the presence of contaminants, such as dioxins. There are currently 14 recreational fishing closures, which include total fishing closures, seasonal fishing closures (e.g. in little penguin critical habitat, spear- fishing closures, and intertidal protected area closures).

Sydney Harbour is one of nine Intertidal Protected Areas introduced in 1993 in response to the extensive harvesting of intertidal invertebrates that was taking place on many of the intertidal rock platforms in the Sydney Metropolitan Region. Intertidal protected areas are temporary fishing closures renewable every five years; these prohibit collection of sea- shore animals from the mean high water mark to 10 m seaward from the mean low water mark. The objectives of Intertidal Protected Areas are to protect intertidal community biodiversity and structure, and to provide biological reservoirs of breeding stock that assist in sustaining populations in nearby exploited areas.

North Harbour Aquatic Reserve was declared in 1982 to protect biodiversity within one part of the Harbour. It is 261 ha and incorporates a variety of habitats, including rocky shores, beaches, shallow soft sediments, shallow rocky reefs and seagrass. The reserve is a partial-take marine protected area (line-fishing is permitted) and utilised for a range of recreational activities (e.g. swimming, diving and snorkeling, boating, line fishing, kayaking).

Managing threatened and protected species

Threatened and protected species that reside or intermittently visit Sydney Harbour are protected under various state and commonwealth legislations that prohibit direct and indirect harm to these species and/or provide for the declaration and mapping of habitats that are critical to their survival. For example, the seagrass *Posidonia australis* now occurs mainly around the northern shores close to the entrance.

These meadows have been listed as Endangered Populations under the *NSW Fisheries Management Act (FMA) 1994*, and as Threatened Ecological Communities under the Commonwealth's *Environment Protection and Biodiversity Conservation Act (EPBCA) 1999*. Saltmarsh is similarly protected in Sydney Harbour due to historical declines. Saltmarsh originally dominated the intertidal zone in the Harbour but by 2005 there was less than 37 ha left, located mainly in the upper reaches of the Harbour. Saltmarsh in NSW is listed as an Endangered Ecological Community under the *Threatened Species Conservation Act (TSCA) 1995* and further protected on public land below the astronomical high tide via the *FMA Act 1994*.

Sygnathiformes (seahorses, seadragons, pipefish, and pipe- horses) are iconic in Sydney Harbour. Of the 31 species known to occur in NSW, 25 have been recorded in Sydney Harbour, including the weedy seadragon (*Phyllopteryx taeniolatus*), the only known seadragon recorded in NSW waters (Hutchings *et al.,* 2013). Sygnathiformes are listed as protected species in NSW under the *FMA 1994*, due to threats from harvesting and habitat degradation and modification.

The only mainland breeding colony of little (blue) penguins in NSW occurs in Sydney Harbour, and it is listed as an endangered population under the *TSCA 1995*. As well as protecting individuals from harm, the Act has allowed for the establishment of critical habitat areas in the Harbour, which impose restrictions on companion animals, fishing and boating. Tampering with or damaging little penguin nest boxes, burrows or molting penguins or approaching within 5 m of a penguin on land is also prohibited.

Regulating boat use

Various authorities manage the impacts of boating. For example, the NSW Roads and Maritime Services manage safety compliance, regulation of commercial and recreational boating, property administration, and infrastructure (Banks *et al.,* 2016). Local councils manage stressors associated with general visitation and interactions with wildlife in foreshore areas of the Harbour. The NSW National Parks and Wildlife Amendment (Marine Mammals) manages interactions between vessels and marine mammals in Sydney Harbour (Banks *et al.,* 2016).

Creation of 'Fish Friendly' marinas

NSW Department of Primary Industries developed the 'Fish Friendly' marinas initiative in collaboration with the Marina Industries Association and the Boating Industry Association (Banks *et al.,* 2016). Two of the 11 'Fish Friendly' accredited marinas in NSW occur in Sydney Harbour. The program gives information on how managers can provide marina services while minimising impacts on fish and fish habitat. This includes design or modification of infrastructure to improve their value as fish habitat and reduce potential impacts to existing habitats, education and employment of practices to reduce the risk of introduction and spread of invasive species, and effective management of stormwater and waste, including chemical spills. The program is not compulsory and accreditation recognises operators actively working to achieve improved fish habitat (Banks *et al.,* 2016).

Introduction of environmentally friendly moorings

Traditional swing moorings in seagrass scour the seabed causing fragmentation and loss of seagrass habitat. Seagrass within Sydney Harbour has already declined by > 50% since 1943 due to various anthropogenic pressures (Banks *et al.,* 2016). Manly Cove, Watson's Bay and Vaucluse Bay are high-priority sites for management intervention within the Harbour as many block-and- chain moorings occur within seagrass areas and habitat damage is highly visible. Several alternative mooring designs, called Environmentally Friendly Moorings (EFMs), are now available that are being tested for their role in minimising damage to sensitive seabed habitats without compromising safety or reliability in mooring a vessel. Extensive loss of seagrass at Manly Cove, quantified by on-the-ground surveys, directly links moorings with habitat damage Banks *et al.,* 2016). Potential recovery of seagrass after replacement of some block and chain moorings with EFMs is being monitored to determine effectiveness of these management. To optimise the use of moorings in Sydney Harbour requires the environmental performance of moorings to be improved and acceptance of the new EFM designs by stakeholders. A program to roll out engagement with stake- holders and further research on the environmental performance of designs is required (Banks *et al.,* 2016).

Eco-engineering and restoration

Eco-engineering of the terrestrial environment has been an accepted mode of construction in the terrestrial environment for a couple of decades. Today 'green' and 'eco' cities are very much at the forefront of urban planning. Eco-engineering and eco-restoration projects, in which scientists, engineers and managers collaborate to build a more resilient marine environment, are on the rise (Banks *et al.,* 2016). Eco-engineering of new and existing marine structures is becoming more common, e.g. by adding structural complexity to sandstone seawalls in Sydney Harbour. These techniques are increasingly used to improve the conservation and recovery of threatened species and species that are desirable in terms of the ecosystem services that they provide, e.g. bivalves such as mussels and oysters for their role in providing habitat structure and water filtration capacity (Banks *et al.,* 2016).

There have been several eco-engineering projects in Sydney Harbour and more are currently underway. In addition, there are major foreshore developments ongoing (e.g. Barangaroo) or proposed (e.g. White Bay) for Sydney Harbour and each of these new developments have displayed a sophisticated approach to remodelling foreshores considering biodiversity (Banks *et al.,* 2016).

Coordinating conservation in Sydney Harbour

Recognising the ongoing role of the many agencies involved in managing the Marine Estate in NSW waters and following the independent scientific audit into NSW marine, the NSW government established the Marine Estate Management Authority (MEMA) in 2013 to better coordinate the management of activities in the marine environment, including Sydney Harbour.

The establishment of MEMA has resulted in a more structured and wide-ranging assessment process for prioritising threats to the marine environment and to the social and economic benefits derived from it. This process provides a sound framework for assessing threats and developing management responses to them for key locations such as Sydney Harbour (Banks *et al.,* 2016).

Marine Estate Management Authority

The vision of MEMA for the NSW marine environment is 'to have a healthy coast and sea, managed for the greatest wellbeing of the community, now and into the future'. One of the first actions of MEMA was to develop new legislation, the *Marine Estate Management Act 2014*, jointly administered by the Minister for Primary Industries and the Minister for the Environment. The Planning and Transport departments are also key partners in MEMA, facilitating a much greater level of management integration. Thus, MEMA can now conduct detailed assessments of threats and risks to marine biodiversity at a range of scales and recommend management responses. The relevant agencies, including local government, must then deliver a range of programs with technical and funding assistance that contribute to the management of the coastal zone and the conservation of biodiversity, and are responsible for the development and implementation of local environment plans (Banks *et al.,* 2016).

Many Harbours globally can be conceptualised as a single water body and managed accordingly. There are unique conservation opportunities in Sydney Harbour. It is a multiuse system with a diverse set of human uses and variety of habitats.

The approach adopted by MEMA to managing the NSW marine estate is based on 5 steps: (1) initial community engagement; (2) threat and risk assessment (TARA); (3) development of management responses to key threats; (4) implementation of efficient and cost-effective management initiatives within the ongoing monitoring strategies; and (5) evaluation of those initiatives. A MEMA project to assess options for the enhancement of marine biodiversity conservation in the Hawkesbury Marine Bioregion, which includes Sydney Harbour, had completed the first three steps by late 2015, with details of proposed management initiatives released for public consultation in March 2016.

Prior to commencing a comprehensive TARA for the Hawkesbury bioregion, MEMA prepared or commissioned relevant background material, including specifically on Sydney Harbour. In that process, five key threats to Sydney Harbour were recognised following a comprehensive search of the published scientific literature: resource use, land-based impacts, marine biosecurity, marine industry pollution, and climate change threats commonly reported in marine environments (Banks *et al.,* 2016).

Qualitative assessment of the specific stressors under each of these threat categories that are causing the greatest impacts in Sydney Harbour, and bearing in mind the effectiveness of current management, suggest that there are some activities which still generate high risks to the environment and that may require further consideration. An important first step in progress is the ongoing mapping of the biophysical conditions within the Harbour and the beginning of an assessment of human uses (Banks *et al.,* 2016).

4.5 Understanding the function of shallow embayments using a biogeochemical model

In 2016 GS LLS commissioned OEH to develop a biogeochemical model of Sydney Harbour, which could be applied to understanding ecological change since urbanization. Staff from the Estuary and Catchment Science team worked in collaboration with the author, consulting engineers and researchers from SIMS to produce the report, which was summarised and published in the proceedings of the 2016 NSW Coastal Conference (Freewater *et al.,* 2016).

Introduction

Estuaries are among the most productive marine ecosystems in the world, supporting a diverse array of foodwebs and commercially valuable species. This arises from the unique situation of estuaries being at the interface of freshwater runoff and coastal oceanic waters, where material (e.g. nutrients and organic matter) delivered by both freshwater and oceanic flows is processed across a wide spectrum of habitat types depending on the particular morphology of the estuary. Nutrient inputs support high rates of primary productivity in both pelagic and benthic compartments (Cloern *et al.,* 2014), which in turn supports a wide variety of invertebrate, fish and bird life (Jickells, 1998). Particular focus has historically been given to the productivity of phytoplankton and seagrass systems within estuaries, however in recent decades the important role of benthic microalgae (BMA) growing in soft sediment habitats has been increasingly recognised (McIntyre *et al*., 1996; Underwood & Kromkamp, 1999). In many shallow Australian estuaries it has been estimated that BMA may constitute the main source of primary production supporting estuarine foodwebs.

The balance between pelagic and benthic productivity (and the food chains they support) is highly variable in time in space due to interactions among controlling factors including: seasonal and inter-annual variability in freshwater runoff; channel morphology; and the quality and quantity of nutrients and organic matter inputs. In estuaries with smaller catchments, the nature of fringing environments is also critically important in regulating terrestrial runoff and the supply of nutrients and organic matter (OM). For example, fringing environments in many smaller estuaries along the Australian coastline are dominated by low lying swamps (e.g. saltmarsh and mangroves), where freshwater delivery is primarily via a mixture of groundwater seepage and episodic pulses of overland flow. These inputs are characterised by high concentrations of dissolved organic nutrient forms and refractory particulate OM, and tend to favour BMA productivity.

Sydney Harbour estuary is classified as a drowned river valley (Roy *et al.,* 2001), characterised by a deep central channel flanked by multiple shallow embayments flanked by steep sided banks of Sydney sandstone (Figure 4.3). Much of scientific and public attention is focused on the ecology of sub-tidal reefs (Larkum, 1986; Underwood *et al*., 1996; Byrne *et al.,* 2011; Wilson *et al*., 2010) and inter-tidal rocky shores (Underwood *et al*., 2008; Matias *et al*., 2010), however a cursory inspection of Harbour bathymetry shows that shallow soft sediment habitats are quantitatively important. Despite their potentially important ecological role, these habitats have primary been studied as sites of chemical contamination (Batley *et al*. 1989; Birch and Taylor 2000; McCready *et al*. 2000; Roach *et al*. 2009; Birch 2011), with relatively few studies of their ecology (Bishop 2005; Chariton *et al*. 2010; Hutchings *et al*. 2011) and even fewer describing biogeochemical processes (Chapman & Tolhurst 2007; Sutherland *et al*. 2016). They are also arguably the most impacted habitats, by the development of Sydney city, since European settlement. In this study, we use a combination of conceptual models, biogeochemical models and experimental data to illustrate the changes in function between pre-European settlement times and the present.

Changes since European settlement

Early maps and paintings of the Harbour reveal insights into the likely morphology and ecology of shallow embayments (Figure 4.4A). A conspicuous feature shown in these maps is the presence of low lying swamps at the embayment heads drained by small tidal creeks. Most of these bays have relatively small catchments, therefore it is likely that freshwater runoff volumes were low and dominated by groundwater seepage. Since the earliest days of the colony, approximately 22% of the total 50 km^2 area of the estuary, including bay ends (Figure 4.4B) and adjacent low-lying swamps, were progressively reclaimed for industrial, recreational and residential uses (Birch, 2007a; Birch *et al.* 2009). Significant sedimentation of the bays also occurred due to catchment clearing.

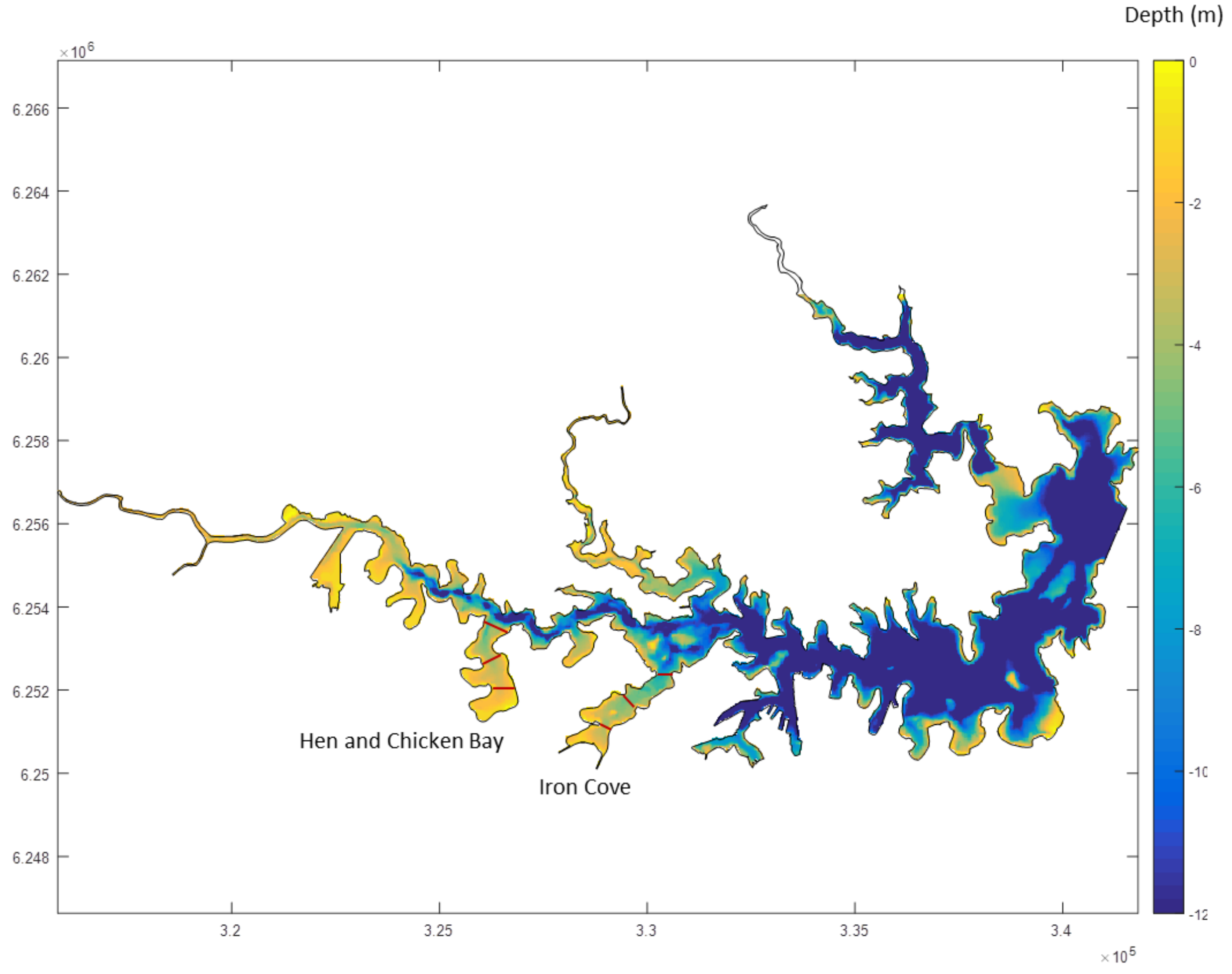


Figure 4.3 **Bathymetry of Sydney Harbour, showing locations of study bays. Also shown are the model box boundaries (red lines).**

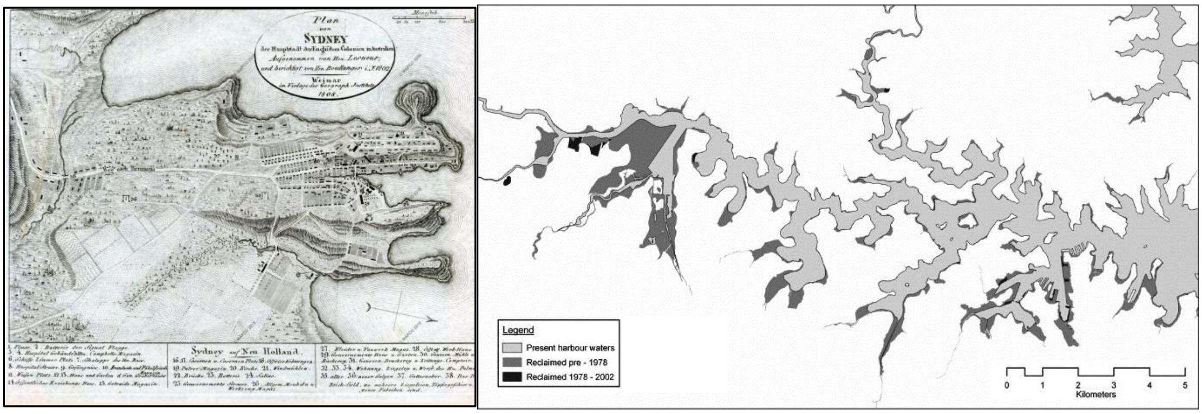


Figure 4.4 **A) Sydney in 1808, showing the low lying swamp environments at the head of Wooloomooloo Bay and Darling Harbour. B) The estimated areas of reclamation since European settlement (from Birch *et al.* 2009).**

At the same time, urbanistion of the bay catchments resulted in a dramatic increase in impervious surfaces and stormwater drainage channels fundamentally changing the nature of freshwater delivery to the bays (Figure 4.5). It is estimated that total freshwater flows to the Harbour have doubled, while baseflows increased by up to five-fold (CERAT). Changes to flows were coupled with a combination of industrial, urban and agricultural diffuse and point source pollution, changing the quality and quantity of nutrient and OM loads to the bays. Recent studies on the impact of stormwater on sediment biogeochemistry in Iron Cove and Hen and Chicken Bay have shown strong gradients in processes and benthic microbial communities from stormwater outlets to the central bays (Sutherland *et al.,* 2016). In particular, sediment organic carbon and respiration are highly elevated adjacent to stormwater outlets and display high variability in association with runoff events.

Modelling the impacts of urbanisation on the embayment biogeochemistry

We used a simple box model approach with a spatially resolved bathymetric grid to test the impacts of changes to freshwater delivery, nutrient supply and OM supply since European settlement. We focus on Iron Cove and Hen and Chicken Bay as major examples of Sydney Harbour embayments that were the subject of the study by Sutherland *et al.* (2016). The model uses a nutrient-phytoplankton-detritus based approach, comprising three coupled boxes for each bay operating at daily timesteps. Water exchange between boxes and across the downstream boundary is estimated as a function of freshwater inflows and tidal exchange. Water quality, light attenuation and pelagic processes are calculated for the boxes within each bay. Benthic light climate and sediment processes are solved on a 30 m X 30 m bathymetric grid. Model stocks and boundary conditions are presented in Table 4.2.

The results presented in this study are based on a comparison of pristine and current upstream boundary conditions coupled with ‘dry weather’ downstream boundary conditions in order to highlight the impacts of changes to the delivery of material from the individual bay catchments. Pelagic and benthic stocks for both simulations were intialised using current conditions. Simulations were run for an eighty-day period encompassing multiple rainfall events during the initial half of the simulation period, followed by dry conditions for the remainder of the simulation. Catchment flows for the current scenario were estimated using the Source catchment model developed as part of the Sydney Harbour Catchment Water Quality Improvement Plan (Freewater and Kelly, 2015). Pristine (pre-development) flows were estimated from the current scenario flows by distributing flows on any particular day over the subsequent eight days in order to mimic a slower delivery of runoff as groundwater seepage. For the purposes of this simulation, the total volume of freshwater flows was not changed, only the timing of delivery.

Figure 4.5 **Homebush Bay in 1943 showing the newly constructed stormwater channel cut through the original meandering course of Powells Creek (image from SIX Maps, NSW Department of Finance, Services and Innovation).**

The model was calibrated using a combination of data collected as part of the NSW Monitoring Evaluation and Reporting program, and data collected as part of the Sydney Harbour Stormwater Project (Sutherland *et al.,* 2016).

Table 4.2 Boundary conditions adopted for the model simulations

Paramater	Upstream		Downstream
	Pristine	Current	Dry
salinity	0	0	35
TSS (mg L-1)	1	20	1
DON (mg L^{-1})	900	600	200
DIN (mg L^{-1})	150	2200	20
DIP (mg L^{-1})	15	150	20
Chl-*a* (mg L^{-1})	0.1	0.1	1
labile OM (mg L^{-1})	100	1550	150
refractory OM (mg L^{-1})	2500	50	20

Results and discussion

The simulation of pristine catchment conditions resulted in marked different responses within both embayments (Figure 4.6). Although both simulations delivered the same volume of freshwater runoff, the lower concentrations of bio-available nutrients, suspended sediments, and labile organic matter in the pristine scenario resulted in a complete shift from pelagic to benthic productivity. Phytoplankton became nutrient limited due to lower concentrations in runoff coupled with competition for available nutrients by benthic microalgae (BMA). In contrast, phytoplankton bloomed following the major rainfall events, stimulated initially by the nutrient-rich stormwater runoff, and then by recycling of bio-available nutrients from the sediments. We chose to present simulations using ‘dry’ weather downstream boundary conditions (i.e. close to oceanic conditions), however in reality these bays are influenced by the import of material and freshwater from the main channel across their downstream boundary which would tend to exacerbate the impacts demonstrated by our study.

The reduction in labile OM in catchment runoff in the pristine scenario, coupled with the reduction in phytoplankton biomass, meant that OM supply to the sediments was greatly reduced resulting in the gradual decline in sediment OM during the course of the simulation as the system approached a new steady state. This suggests that OM content of sediments in the pristine bays would have been far lower than today. In contrast, the sediment OM pool in the current scenario simulation displayed high temporal variability in response to freshwater inflows, highlighting the impact of both catchment-derived OM and settled phytoplankton biomass as important sources of sediment enrichment. BMA productivity was not limited by either light or nutrients under pristine conditions, while under the current scenario light was limiting following runoff events due to a combination of suspended sediments and phytoplankton biomass. The net result of these factors was that sediments were a net source of bio-available nutrients in the current scenario, and a net sink under the pristine scenario (Figure 4.7).

The results of this study give an insight into the likely biogeochemical function of shallow embayments in Sydney Harbour under pre-European conditions. The much clearer water and lower nutrient statues would have greatly favoured BMA productivity over phytoplankton, resulting in highly diverse and productive benthic-based food-chains. While not included in the current model setup, it is likely that these conditions would have also been favourable to seagrass growth and expansion, suggesting a much wider range of seagrass distribution throughout the Harbour than at present. Scaled up to the entire Harbour upstream of the bridge, our results indicate that BMA and seagrass may have dominated primary production in the system (Figure 4.8). We suggest that the rehabilitation or recreation of low-lying swamp environments, as filters for stormwater drainage, would greatly improve the function and ecology of these critical Harbour habitats.

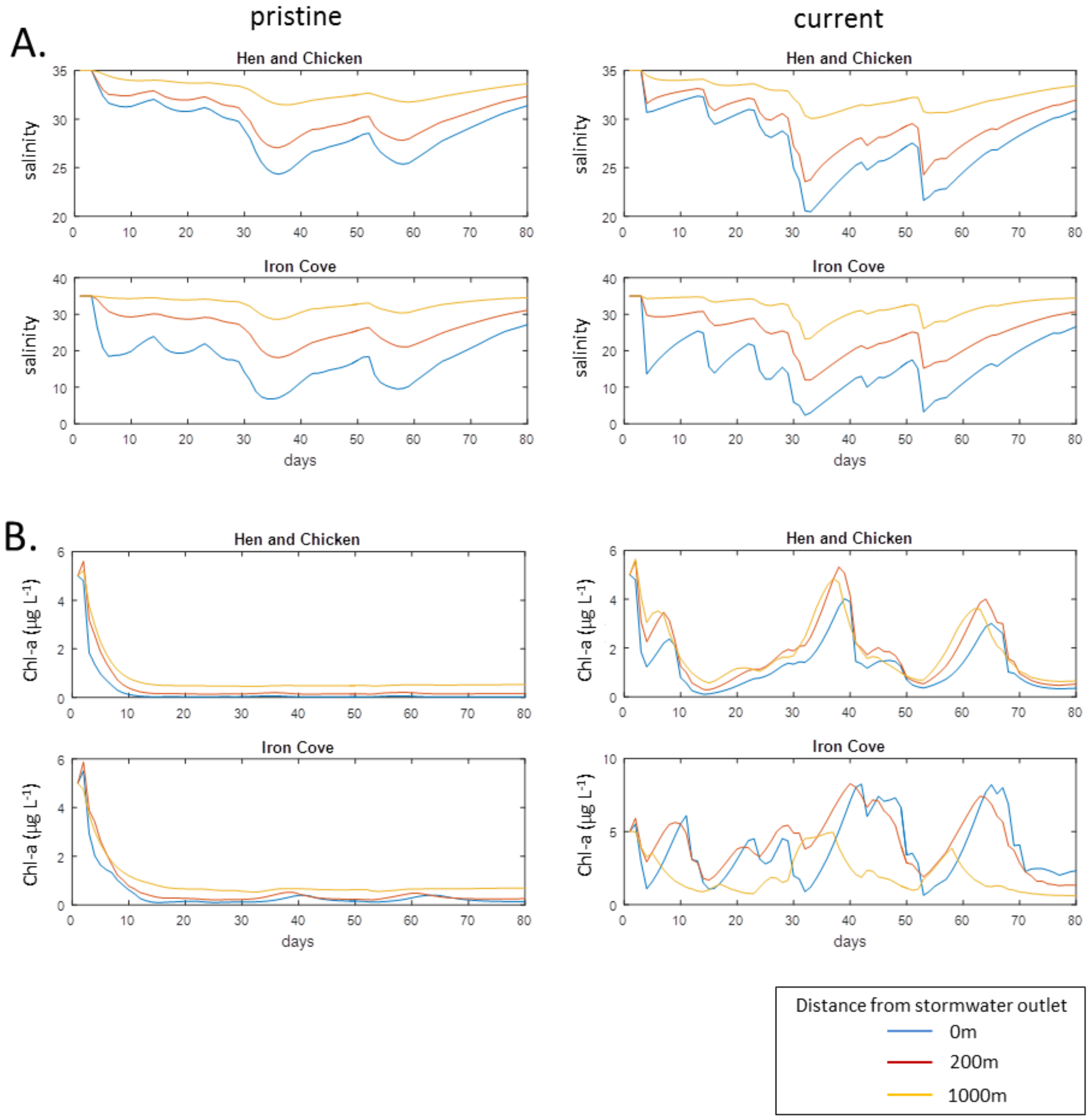


Figure 4.6 **Model outputs for A) salinity and B) phytoplankton (converted here to units of chlorophyll-*a*)**

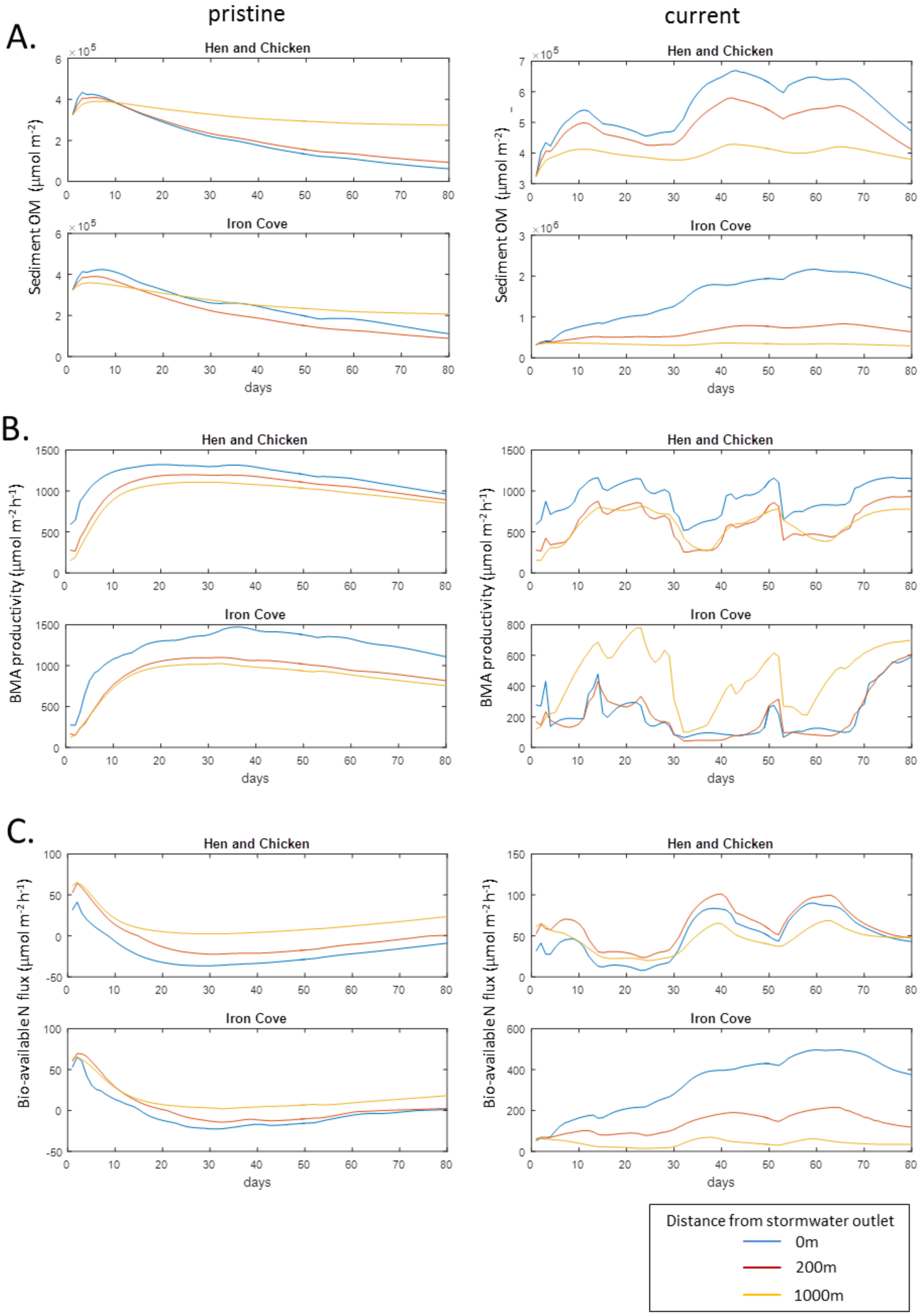


Figure 4.7 **Model outputs for A) sediment organic matter, B) Benthic microalgae productivity; and C) Bio-available nitrogen flux from the sediments (note that positive value equals a flux of nitrogen from the sediments to the overlying water).**

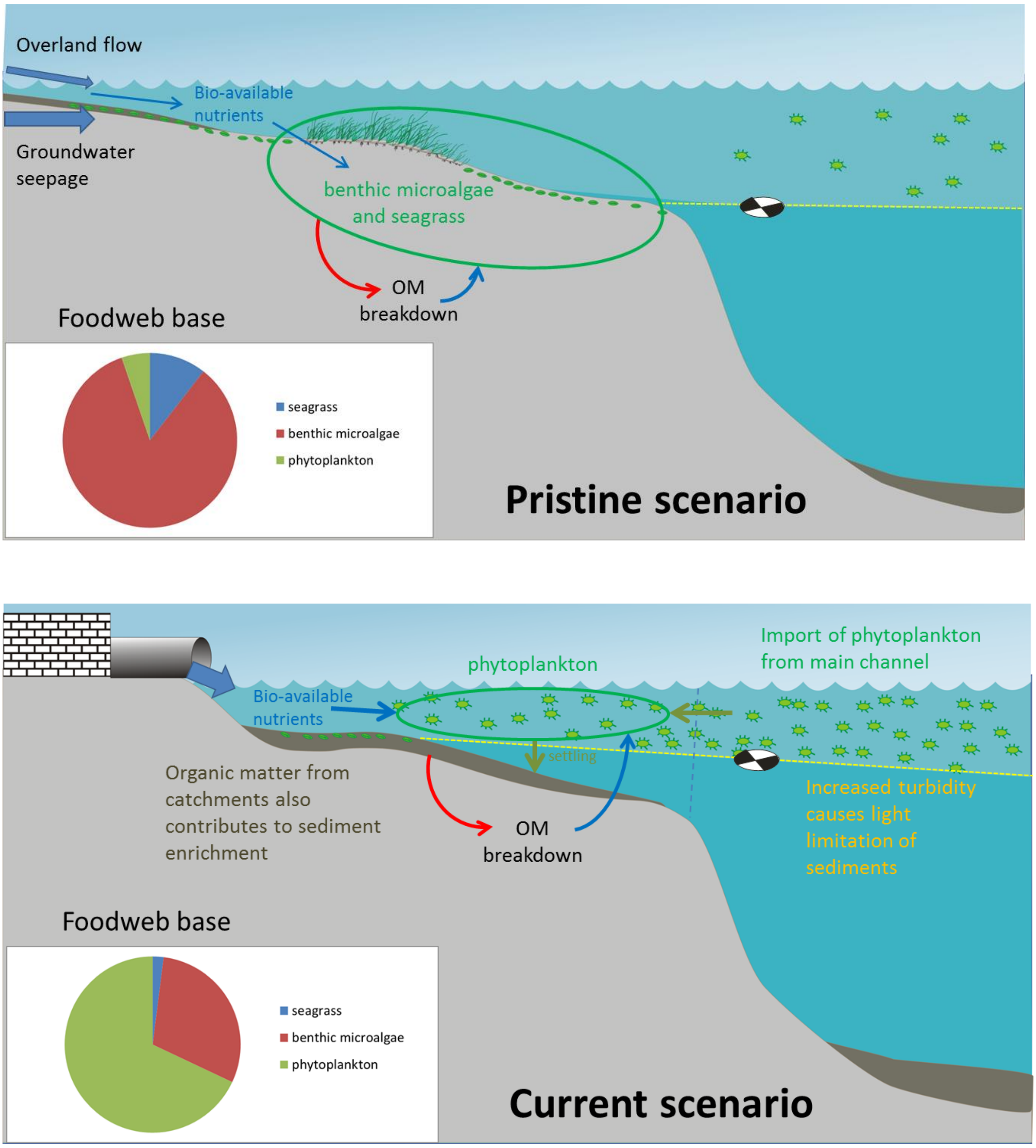


Figure 4.8 **Conceptual models of biogeochemical function in Sydney Harbour embayments under pristine and current conditions. Also shown is an estimation of primary productivity contributions for the Harbour upstream of the bridge.**

4.6 Conceptual model of estuarine processes in Sydney Harbour

In 2016 GS LLS worked collaboratively with SIMS and the Estuary and Catchment Science team at OEH to develop conceptual models of estuarine processes in the Harbour. The work should be cited as:

> Sun, M., Dafforn, K.A., Scanes, P., Ferguson, A., Freewater, P. and Johnston, E.L. (2017) Conceptual model of estuarine processes in Sydney Harbour. Report prepared for Greater Sydney Local Land Services. University of New South Wales, Sydney.

4.6.1 Summary

As coastal environments continue to experience increasing pressure from anthropogenic activities, ecosystem processes such as the rates of biogeochemical transformation are also experiencing change. In the Australian context, the drowned river valley estuarine system of Sydney Harbour supports one-tenth of the nations population (2.5 million). In the following conceptual model, we summarise the historic changes of ecosystem processes in Sydney Harbour that have resulted from urban and industrial activities. Stark shifts are seen in both pelagic and benthic ecosystem processes between the pre-European settlement state - forested catchment area with extensive intertidal and subtidal habitats, and the urbanised catchment state, with a large percentage of artificial foreshores and legacy contaminants from times of heavy industrial activity. Under the current environmental management framework, stormwater has become a significant ongoing threat to sustaining the ecological wellbeing of Sydney Harbour, as the quality and quantity of stormwater determines the dominant state of many ecosystem processes in both the water column and benthos. This model provides a more holistic pelagic-benthic coupled view of changes in ecosystem processes over Sydney Harbour's history under the different management regimes. The presented trends in ecosystem processes are a summary of the last 20-30 years of field monitoring and experiment data.

Overall, ecosystem processes in Sydney Harbour indicate a trajectory of recovery, largely due to better regulation of environmental discharges, discharge of sewage offshore, and also the well- flushed nature of the estuary. With coastal population pressures expected to increase, forward- thinking management driven by scientific research will be essential to mitigating the evolving modern as well as legacy issues experienced by the estuary to protect our environmental, economic and social assets. As our holistic understanding of Sydney Harbour's ecology and ecosystem function continues to improve, future efforts to mitigate the deterioration of human-impacted coastal systems should encourage ecosystem function closer to the estuary's pre-European state, particularly in the most vulnerable off-channel environments of the estuary. Additionally, greater understanding of the ecological impacts related to emerging contaminants is required to keep increasing the informative ability of these conceptual ecosystem views.

4.6.2 Introduction

More than 40% of the world's population is concentrated within 100 km of the coast (Vitousek *et al*., 1997), which places significant anthropogenic pressure on coastal systems around the globe (Tibbetts, 2002; Rabalais *et al,.* 2009). In Australia's largest city, one-tenth of the nation's population (2.5 million) resides in the catchment surrounding the drowned river valley of Sydney Harbour (Birch *et al.,* 2010). Sydney Harbour is endowed with a range of estuarine assets, some which are more obvious than others, such as waterfront real estate pricing (incremental value of $3.7 billion per year), recreational boating activities (>1 million people per year) and tourism ($13.5 billion in 2012) (Hoisington, 2015). The value of these social, economic and environmental assets relies on the health and preservation of ecosystem processes, such as the filtering of water, stabilisation of shorelines, moderation from temperature swings and carbon sequestration. These ecosystem processes have significant economic value, as they support and maintain the aesthetic appeal and recreational functionality of the estuary (Hoisington, 2015). In Sydney Harbour, ecosystem processes and the environmental assets they directly support alone are estimated to exceed $160 million/year in value (Hoisington, 2015). As such, the estuary and its ecosystem services contribute significantly to the region's socioeconomic wellbeing (Hedge *et al.,* 2014b).

The ecological status of Sydney Harbour has degraded since European settlement due to a variety of threats associated with ongoing anthropogenic activity. Toxicants, nutrients, siltation, sediment resuspension, artificial structures, reclamation and changing hydrological regimes, to name a few, continually threaten the stability of the foundational ecosystem processes, i.e. the rates of biogeochemical transformation in the system (Kennish, 2002). Under the current environmental management framework, stormwater has become a significant ongoing threat to sustaining the ecological wellbeing of Sydney Harbour (Birch, 2007a; Freewater and Kelly, 2015), as the quality and quantity of stormwater determines the dominant state of many ecosystem processes in both the water column and benthos. Over time, pelagic material becomes deposited in benthos where is it either transformed or stored. As a result, benthic processes are responsible for a greater volume of biomass turnover and biogeochemical transformation in comparison to water column processes (Hulth *et al.,* 2005). Understanding the coupled, but temporally segregated relationship between pelagic and benthic processes is essential to building a more holistic view of the ecosystem processes that ensure a system’s ecological integrity (Burgman, 2005; Birch *et al*., 2010).

In a series of conceptual models, this report provides a more holistic pelagic-benthic coupled view of changes to ecosystem processes under the different environmental management regimes in Sydney Harbour, building on existing knowledge of pelagic threats by Freewater and Kelly (2015). We outline the changes in ecosystem processes that have occurred since European settlement throughout different habitats in the Harbour. We summarise the general trends from field monitoring and experiment-based data within Sydney Harbour over the last 20-30 years (Irvine and Birch, 1998; McLoughlin, 2000a; Coleman *et al.*, 2008; Booth, 2010; McKinley and Johnston, 2010; Dafforn *et al.,* 2013; Sun *et al.,* 2013; Clark *et al.,* 2015; Sutherland *et al.* 2016). This conceptual study is complemented by the Sydney Harbour biogeochemical (Section 4.5). While stormwater presents an ongoing threat to the estuary’s ecosystem processes, threats such as resource extraction, catchment modification, changes in community structure and climate change are also discussed.

4.6.3 Physical characteristics of Sydney Harbour

The iconic drowned river valley system of Sydney Harbour carves 30 km west to east through Wianamatta Shale in the elevated upper estuary which transitions into the underlying Hawkesbury Sandstone in the lower estuary. The estuary is supplied by three tributaries (Parramatta River, Lane Cove River and Middle Harbour) and drains a relatively small catchment of 500 km^2 (Birch, 2007a).

Five distinct sedimentological units are found along the estuary; marine sands in the estuary mouth, mixed marine and fluvial deposits in the lower estuary (marine flood-tide delta), fluvial deposits in the central basin and main channels of the upper estuary (fluvial delta) and thick mud in off-channel embayments (Birch, 2007a; Johnston *et al*., 2015a) (Figure 4.9). These five sedimentological units can be grouped into two functional zones that differ in hydrology and sediment characteristics to directly influence many ecosystem processes; the well-flushed main channel (consisting of estuary mouth, marine flood-tide delta, the central basin, fluvial delta) and high-retention embayments (off-channel embayments). Natural geological features along the estuary have resulted in irregular bathymetry, ranging from 1-46 m deep, being deepest at the estuary mouth and in areas of the central basin near the Harbour Bridge (Birch *et al.,* 2015) (Figure 4.10).

Hightail Shrimp (*Thor amboinensis*) in Sand Anemone at Clifton Gardens

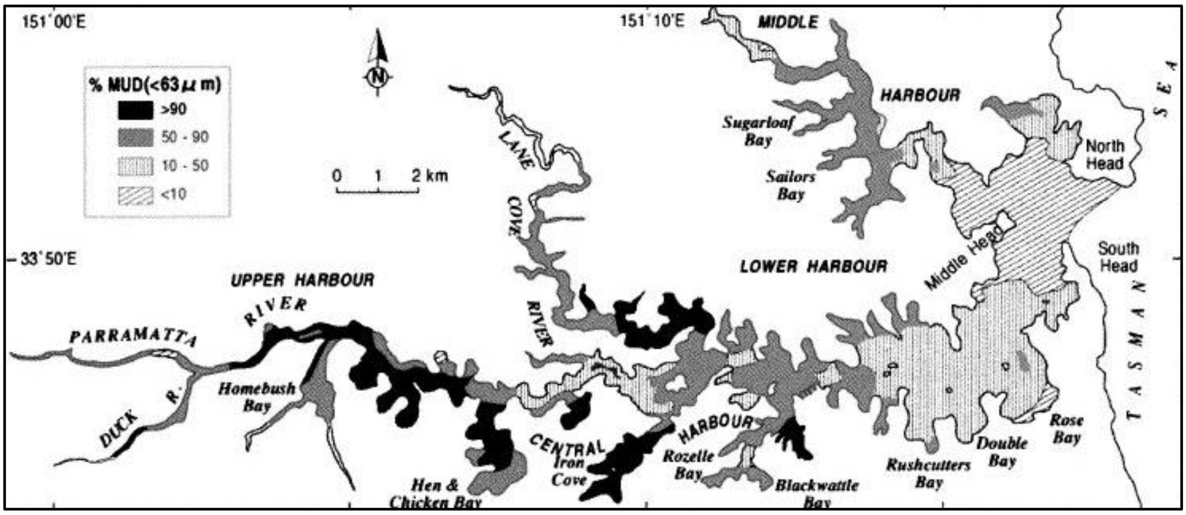


Figure 4.9 Map of mud-sized (<63 μm) sediment (Irvine and Birch 1998).

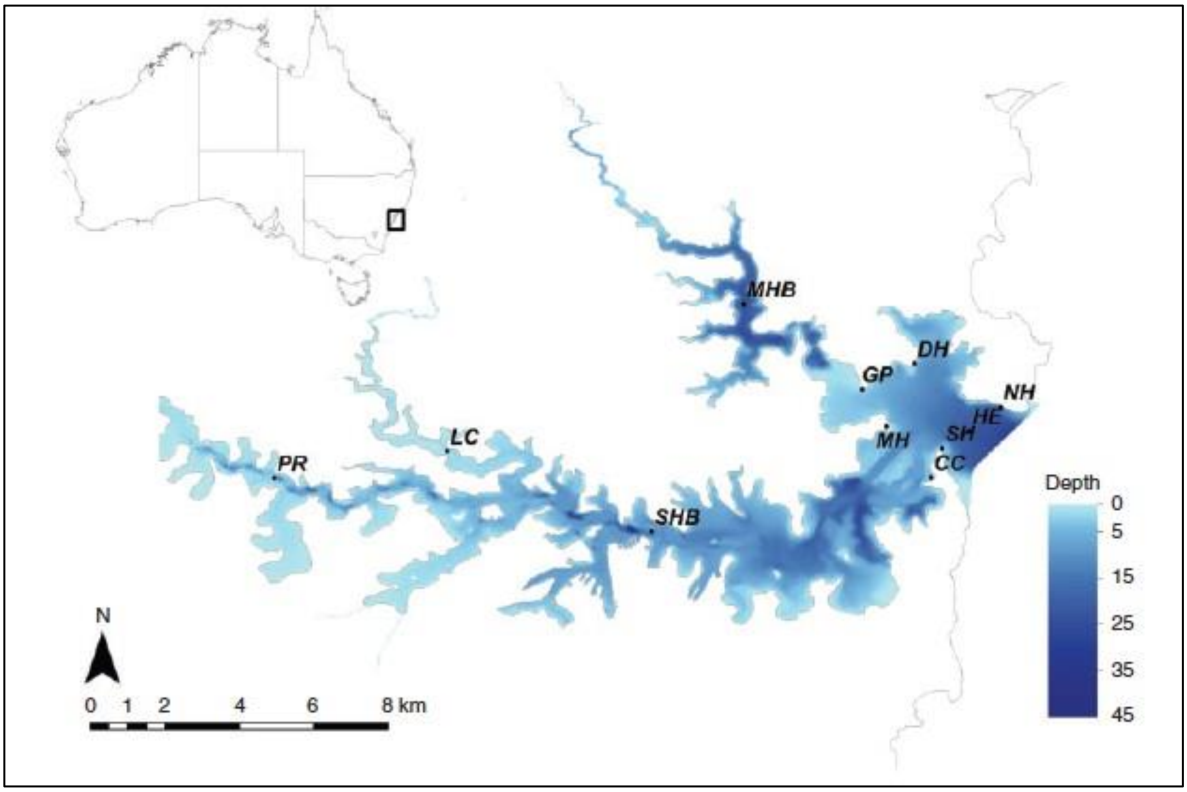


Figure 4.10 Bathymetry of Sydney Harbour (Johnston *et al*. 2015)

A wide, unconstricted estuary mouth bound by steep, rocky shores allows unimpeded tidal flushing (tidal range of 2.1 m) (Birch *et al*., 2015) to supply much of the lower estuary with oxygenated marine water. Sandy sediments in the lower estuary are indicative of high-energy conditions (wind and tidal mixing) and the overall transport of fine material in the lower estuary out onto the coastal shelf. Retention of organic-rich and fine sediments in the upper estuary and central basin reflect conditions of slower water velocities and flushing (Figure 4.9). Water velocities are lowest in off- channel embayments (Figure 4.11), where sediments consist of thick mud (Figure 4.9). Water residence time vary from 0-20 days in the lower estuary up to 130 days in the upper reaches of the Parramatta River (Hedge *et al*., 2014a).

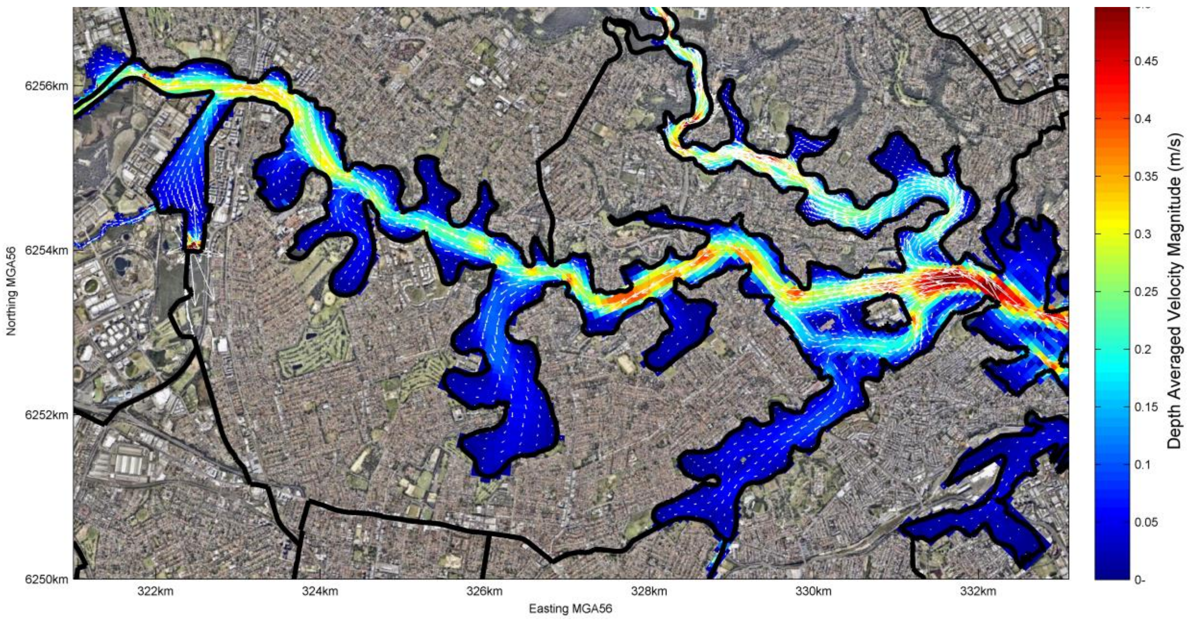


Figure 4.11 Mean velocity (ms^{-1}) of the peak flood tidal current in the upper estuary (Parramatta River) and off-channel embayments of Sydney Harbour. (Freewater and Kelly, 2015)

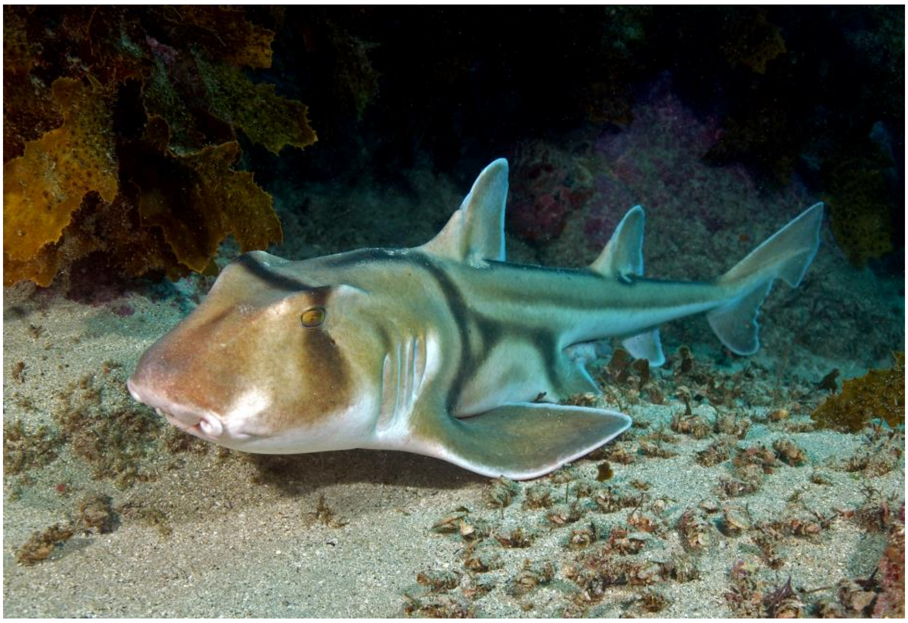
In an international setting, Sydney Harbour represents a relatively narrow and short estuary with a strong marine influence due to the relatively dry Australian climate and small catchment size (Birch, 2007a). Freshwater input is limited under dry weather conditions (<0.1 m^3/s) (Birch and Rochford, 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 following low to moderate rainfall events (5–50 mm day^{-1}) where salinity drops significantly in the upper estuary (20). Particles flocculate when fresh and saline water mix and allochthonous materials are distributed through a significant portion of the estuary (Birch *et al.,* 2010). Following high rainfall events (>50 mm day^{-1} for at least two days) that is characteristic of the regional climate during warmer months, stratification occurs along the estuary and a near freshwater plume of terrestrial inputs forms in the top 1-2 m to be transported offshore (Birch and Taylor, 1999; Birch, 2007a), until stratification breaks down within a few days of rainfall (Birch and Richards, 2013). This strong stratification is characteristic of Sydney Harbour's narrow and short estuary and rarely occurs in larger, less marine influenced estuaries (Birch, 2007a).

4.6.4 Description of Sydney Harbour ecology pre-European settlement

Heavily forested catchment

The surrounding catchment was heavily forested, with Swamp Oak Floodplain Forest (swamp oak, casuarina, swamp mahogany, red gum) atop Hawkesbury Sandstone bedrock in the outer estuary (Figure 4.12) and Turpentine-Ironbark Forest and Blue-gum High Forest atop Wianamatta shale in the upper estuary (Chapman, 1981) (Figure 4.13).

Figure 4.12 **Photograph of a remnant area of the endangered Swamp Oak Floodplain Forest on the Hunter River, NSW, Australia (ABC 2013). Similar forested ecology is described for Sydney Harbour before Europeans cleared the land for agriculture and industry at the end of the 18th century.**



Port Jackson Shark (*Heterodontus portusjacksoni*) at Bluefish Point - North Head

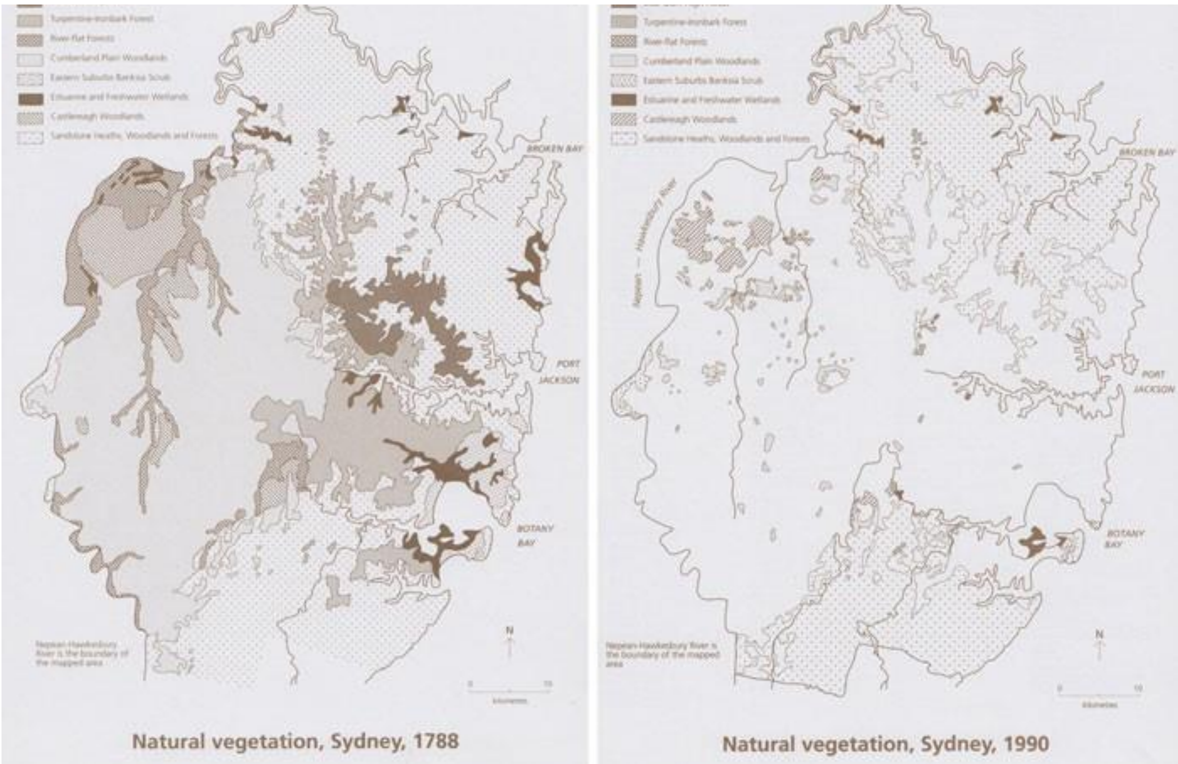


Figure 4.13 **Comparison panels depicting changes in vegetation in the Sydney Metropolitan area from pre-European settlement to 1990 (includes Sydney Harbour and Hawkesbury River catchments) (from Benson *et al*., (1990)).**

Extensive intertidal and subtidal habitats

Low-energy intertidal areas in the upper estuary supported extensive saltmarsh and mudflat communities. Mangroves were relatively uncommon in the estuary before the 1870s and were limited to lining creeks (McLoughlin, 2000a; Hoskins, 2009). Benthic microalgal mats (BMA) and seagrass meadows extended from the lower estuary well into the upper estuary (Hoskins, 2009). The most extensive biome in the Harbour was and remains areas of soft sediment (Mayer-Pinto *et al.,* 2015) (Figure 4.14).

4.6.5 Dominant ecosystem processes in Sydney Harbour pre-European settlement

Oligotrophic, clear waters supporting a productive benthic biomass

Like most Australian waterways, Sydney Harbour was an oligotrophic system before European settlement (Roy *et al.,* 2001). Forests and wetlands would have acted as sponges for nutrients and sediments from terrestrial sources. Extensive subtidal areas of primary producers such as BMA, seagrass meadows and kelp forests also facilitated the uptake of any excess nutrients providing food, nursing habitat and increased sediment stabilization (Hoskins, 2009).

The estuary supported a smaller fishery than the adjacent estuary of Botany Bay, indicative of the nutrient-limited conditions (Chapman, 1981). Increased fishery production occurred during the summer months as a result of coastal upwelling of nutrient rich waters (Chapman, 1981). An abundance of filter feeding shellfish (oysters, mussels, cockles) (Chapman, 1981) further contributed to the maintenance of oligotrophic pelagic and benthic conditions through the incorporation of phytoplankton N and P.

The wide distribution of shellfish suggests that erosion and sedimentation was not a significant process in the pre-European settlement estuary. With limited organic deposits, soft sediment communities in both photic and disphotic sediments likely sustained a deep layer of oxic sediment through bioturbation, enough to meet the oxygen demands for any heterotrophic organic decomposition (Banks *et al.*, 2013). These ecosystem processes that represent the predominant state of function in the pre-European settlement estuary are summarized in Figure 4.15a.

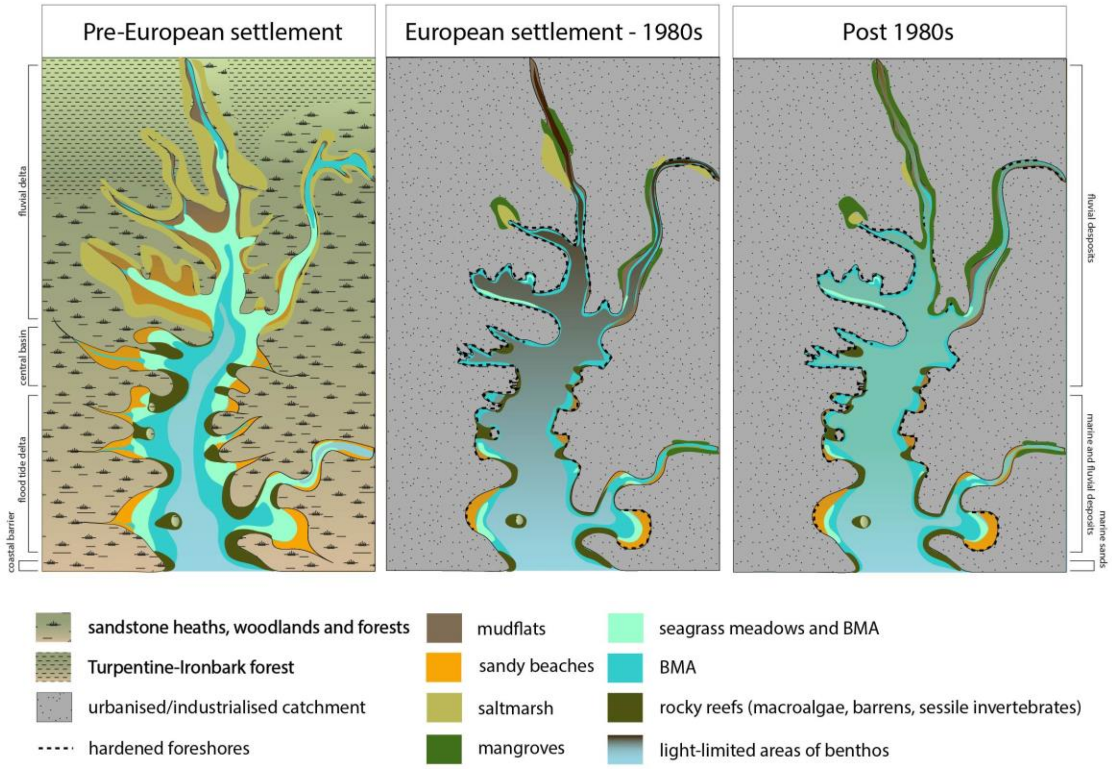


Figure 4.14 **Representation of habitat changes under three management regimes common to many drowned river valley estuarine systems like Sydney Harbour; presettlement (traditional management practices), European settlement up to times of growing environmental awareness in the 1970's (exploitation of environmental services) and the post 1980s modern state that has exhibited recovery in some aspects of ecosystem health such as water quality through coordinated environmental management actions.**

4.6.6 The arrival of Europeans and subsequent changes to Sydney Harbour's ecology

The anthropogenic modifications in Sydney Harbour and its surrounding catchment have evolved over the last 220 years, resulting in a variety of environmental impacts (Table 4.3, Figure 4.145b).

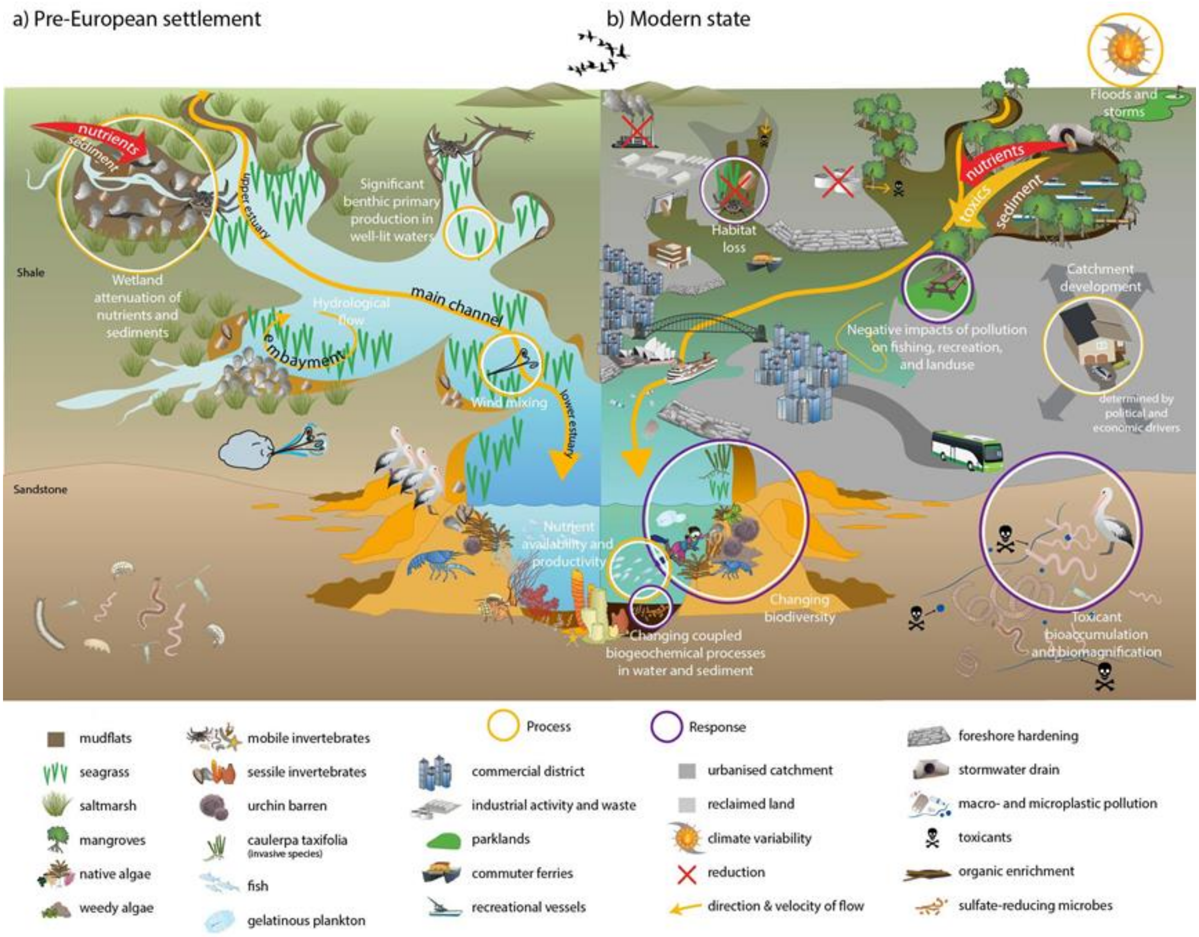


Figure 4.15 **a) Pre-European settlement ecosystem processes. b) Modern ecosystem processes. Threats to ecosystem processes are represented by icons: reclamation, changes to hydrology, chemical leaching, stormwater and sewage, recreational activities, resource extraction, maritime traffic, marine debris, invasive species). In many developed modern estuaries, stormwater presents a significant ongoing threat to the ecosystem processes that maintain environmental, social and economic values of the estuary.**

Clown Nudibranch (Cerastoma amoena) on Halophila ovalis

Table 4.3 Timeline of anthropogenic modification in Sydney Harbour and its surrounding catchment over the last 220 years.

Evolution of Sydney Harbour	
Holocene	**Pre-European settlement** - Traditional land care practises of the Aboriginal people
	- Heavily forested catchment - Expansive seagrass and wetland habitat - Oligotrophic, low-turbidity waters - Records suggest the estuary supported a relatively small fishery, but significant shellfish biomass
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 and turbidity beginning to impact intertidal and seagrass communities
1800-1854	**Early industrial revolution** - Heavy industries established in embayments along the waterfront on the south side of the lower estuary (tanneries, metal foundries, abattoirs) - Industry expanded and moved to upper estuary tributaries in 1848
	- 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 1848, which lead to the relocation of industries to the upper estuary - Increasing areas of aphotic sediments
1860	**Industrial revolution builds momentum with technological advancement** - Industry and urbanisation spread rapidly and replaced agriculture as the prominent land use (metal working and engineering, building materials, clothing and textiles, brickworks)
	- Eutrophication and pollution issues continued to spread in the upper estuary
1898	**Three coastal outfalls constructed** - Raw sewage and industrial effluent discharged into surf zone outside the estuary
	- Pollution issues significantly impacted offshore ecosystems
Early 20th century	**Industry continued to expand during World Wars**
	- Additional manufacturing of electrical products, oil refineries, automobiles
Post war industrial period	**Heavy industries replaced by light industry, transport companies and urbanisation** - Significant reclamation activity with chemical wastes - Decrease in the influx of metal, polycyclic aromatic hydrocarbon and polychlorinated biphenyl compounds into the estuary following the relocation of heavy industries
	- Further loss of intertidal and shallow subtidal habitat with reclamation and foreshore hardening - Changes to upper estuary hydrology, reducing tidal flushing - Contaminant-laden leachate released from reclaimed lands after rainfall
1960s	Tributyltin (TBT) enters aquatic systems as marine antifouling paint
	- TBT linked to shell abnormalities and imposex in invertebrate species
1970s	**Improved control of environmental discharges** - Clean Waterways Act introduced in 1972 - Reduced waste generation as industry forced to discharge waste into the sewerage system
	- Dramatic increase in the use of organochlorine compounds (DDT, agent orange, other pesticides, dioxins, furans) and plastic products - Public awareness of health issued caused by organic pollutants heightened, studies reveal highly contaminated sediments in Homebush Bay area
1983	Construction of engineered landfills at Homebush Bay in attempt to manage contaminated soil
1989	**Total catchment management approach formalised in NSW Catchment Management Act**

	- Fishing banned in Homebush Bay - legacy contaminants found to bioaccumulate in harvested seafood - First Clean-up Australia Day
1990	**Deep ocean sewage outfalls** - Sewage dispersed 4km offshore in 80 m of water - First reclaimed land clean-ups begin in Homebush Bay
	Water and beach quality sees improvement
1992	**Attention shifts to the removal of persistent pollutants** - Dredging activity ceased in Parramatta River
	Reduced risk of sediment resuspension and release of legacy contaminants
1997	**NSW Government initiated 'whole-of-government' approach to management** - Introduction of the Contaminated Land Management Act gave the EPA legislative power to push for the remediation of contaminated sites - Mandatory Stormwater Management Plans to be prepared by local councils - Cleanup of chemical factory site at Wilson Park, Silverwater, begins
	- Catchment management facing challenges due to lack of cohesion between the many local and state government bodies involved
2000	**NSW EPA licencing of sewer overflows introduced** - Northside storage tunnel commissioned, designed to store overflows of raw sewage and stormwater
2001	Remediation efforts begin on shipyards of Cockatoo Island
2002	Remediation of the contaminated site of Mortlake gasworks, Breakfast Point
2003	**TBT-antifouling paint banned**
2004	**UN Treaty - Stockholm Convention on Persistent Organic Pollutants in force** - Remediation efforts begin for dioxin-contaminated sediments in Homebush Bay
2005	Remediation efforts begin in naval base HMAS Platypus, North Sydney
2006	Commercial fishing and prawn trawling banned in Sydney Harbour
2015	Remediation efforts at contaminated site Millers Point Gasworks, Barangaroo, begin
Summary of modern state	**Stormwater inputs remain a threat to ecosystem processes in Sydney Harbour** - Stormwater quality improvement devices fitted at many stormwater outlets (65) 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 - There remain contaminated sediments in the harbour in need of remediation - Progress being made to better coordinate Sydney's stormwater management and pollution control measures across local councils (detention basins, grass swales, gross pollution traps, litter booms)
	- Biological oxygen demand and nutrients remain elevated in the upper estuary - Community structural shifts are reported between sites of differing pollution: 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 - Further management is necessary to better manage stormwater and sewage overflows that leave chemical signatures of 'emerging contaminants' in the waterway, even during dry periods

Catchment clearing

Landuse changes dramatically increased the volume of allocthonous materials arriving in the estuary after European settlement (Hoskins, 2009). The first task of the European convicts was to clear the land using European farming methods (Figure 4.16), and as a result, "The soaking rains turned the cleared land to mud" (Chapman, 1981). Clearing started in the forests surrounding the outer Harbour, but poor soil quality atop the Hawkesbury sandstone bedrock soon pushed the settlers towards more fertile soils from the Wianamatta Shale group overlying the sandstone basin, west of Kissing Point, in the Parramatta tributary. Much of the topsoil from these cleared areas was eroded and washed into the estuary, resulting in turbid waters, and sediments with greater fines and organic content, especially in the upper estuary and off-channel embayments. Over time, stream mouths were silted up with an expanse of mud spreading some distance into the Harbour (McLoughlin, 2000b; Hoskins, 2009). Sedimentation rates after European settlement have been estimated at 8 to 27mm y^{-1}, which is elevated in comparison to presettlement rates of 1 to 5 mm y^{-1} (Kilby and Batley, 1993; Taylor *et al*., 2004).

Figure 4.16 Forest clearing in Sydney Harbour catchment (Kerry and Co, 1905)

Catchment development - reclamation of intertidal 'wastelands' and foreshore hardening

The area of the estuary since European settlement has been reduced by 22% as a result of almost constant reclamation (Figure 4.17). The most activity occurred between 1922 and 1955 (Birch *et al.,* 2009). Upstream of the Harbour Bridge in the upper estuary, 70-80% of intertidal wetland habitats consisting of mudflats, saltmarsh and seagrass have been replaced by reclaimed land and vertical rock-stabilised walls, which now represent approximately 50% of the foreshore environment of Sydney Harbour (Bulleri *et al*., 2005; Kelleway *et al.*, 2007).

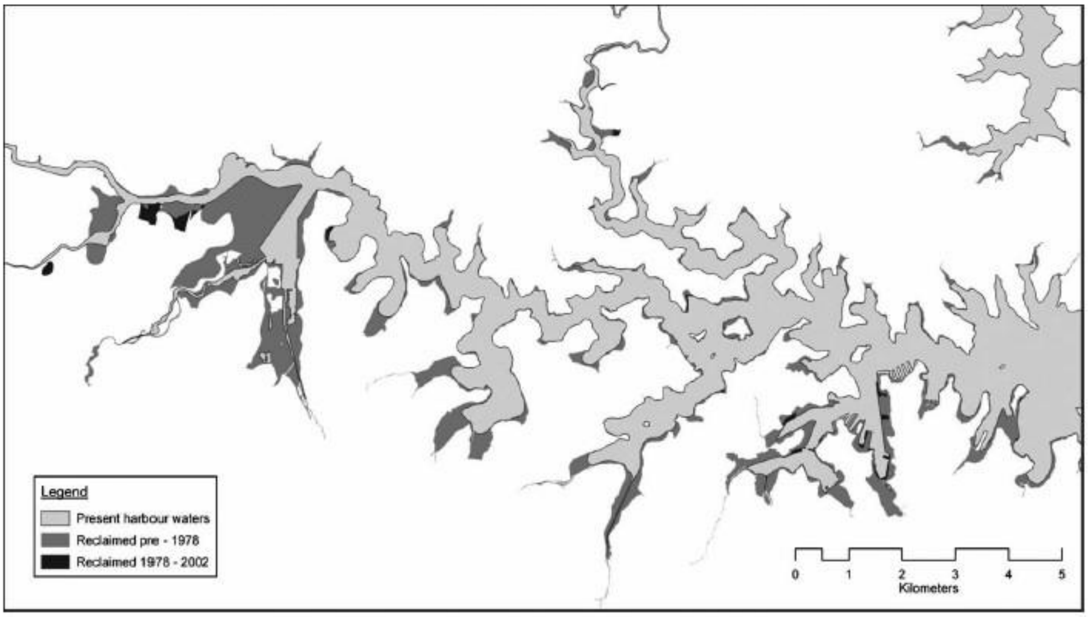


Figure 4.17 Reclaimed land in Sydney Harbour from 1978 to 2002 (Birch *et al*., 2009).

Catchment development - industry and urbanization

In the heavily urbanised modern catchment (86%) (Birch, 2007a), landuse consists of mainly low to medium density residential housing. Other landuses include parklands and commercial or light industrial centres, with the extent of these landuses differing between the four sub-catchments of the estuary (Table 4.4).

Table 4.4 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 (47%), 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 (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%

Urbanised areas discharge a mixture of inorganic toxicants (industrial process effluents) and nutrient-bearing organic substrates (such as animal and human waste) directly into surrounding waterways as stormwater (Hoskins, 2009). Stormwater delivers 90% of nutrient (990 kg km^{-2} $year^{-1}$ of total nitrogen and 132 kg km^{-2} $year^{-1}$ of total phosphorus) and 98% of sediment (715 t km^{-2} $year^{-1}$ of total suspended solids) in to the estuary. In the modern estuary, industrial and municipal waste are diverted as sewage for treatment before discharge into the environment. However, sewer overflows are a common occurrence in Sydney Harbour, adding significant nutrient and toxicant loads (see Chapter 2, *Figure 2.4 Sewer overflow points in the Sydney Harbour catchment*). Sewer overflows also represent the greatest source of pathogens (Birch *et al.,* 2010, Freewater and Kelly, 2015). As such, stormwater and sewer overflows represent the most significant modern threat in the estuary (Birch and Taylor, 1999 2002, 2004; Birch *et al.,* 2009; Freewater and Kelly, 2015). The combined effects of eutrophication and toxicant stress are largely concentrated to the low-energy regions of the upper estuary and off-channel embayments. Bacterial levels are above the safe swimming guideline values in the upper estuary, even during periods of dry weather (Birch and Taylor, 2004). The main channel of the upper estuary and the lower estuary receive sufficient tidal flushing that resupplies oxygen and limits the accumulation of waste products and toxicants.

Nutrients and toxicants pose a significant threat to the established stable state and rate of ecosystem processes. The full extent of their impact on ecosystem processes remains largely undiagnosed due to complicated interactions that occur between compounds in the environment (Crain *et al.,* 2008). While nutrients are either transformed or removed from the system by biogeochemical transformations (Herbert, 1999), many toxicants persist in the environment for decades, or longer. Toxicants are not only limited to the water column and sediment (Birch and Taylor, 1999; Birch *et al*., 2015), but a portion have also bioaccumulated and biomagnified in algal, invertebrate and vertebrate tissue (Roach and Runcie, 1998; Roberts *et al.,* 2006; Losada *et al.*, 2009). The largest proportion of toxicants flocculate with fine particles in the water column to settle in the sediments where they are stored in less bioavailable forms (Eggleton and Thomas, 2004). Elevated nutrient and toxicant concentrations are most concentrated surrounding terrestrial discharge points.

As such, a legacy of pollution is prominent in the sediments of Sydney Harbour. This is the result of poor environmental management pre-1980's as a range of unregulated industries moved through significant areas of the estuary, detailed in Taylor *et al.* (2004). During the first 110 years of European settlement, untreated waste was released directly into the estuary (Irvine and Birch, 1998; Mayer-Pinto *et al.*, 2015). The earliest industries started circa 1800 in embayments along the south side of the lower estuary, the most polluting of which were tanneries (from 1803) and metal foundries (established in the 1820s). Pollution in the lower estuary was noticeable by 1848, and polluting industries were moved from the then city limits to Willoughby and Parramatta in the upper tributaries (Taylor *et al.,* 2004). After the introduction of new technologies such as steamboats in the 1860s, industry and urbanization spread rapidly along the catchment and replaced agriculture as the prominent land use. In 1898, three coastal sewage outfalls were constructed to direct effluent away from the estuary into the surf zone. While this reduced pollution stress in the estuary, it had significant negative impacts on adjacent offshore ecosystems (OEH, 2008). Heavy industries relocated out of the estuary after WWII and were replaced by light industry, resulting in a decrease in the influx of metals and polycyclic aromatic hydrocarbons (PAHs) into the estuary (Taylor *et al.*, 2004). However, poorly-regulated industrial production of persistent organic pollutants (POPs) continued until the 1970s, when greater awareness of their toxicity came to the public foreground (Jones and De Voogt, 1999). Tributyltin (TBT) pollution also appeared later, being introduced into the marine environment during the 1960's as antifouling paint (Batley *et al*.,1989; Dafforn *et al.*, 2011).

The Clean Waterways Act was introduced to control environmental discharge into the estuary in 1972, marking the start of an era of environmental awareness and management. Since 1990, deep ocean sewage outfalls 4 km from the coast and 80 m deep has helped reduce organic pollution in the estuary, and improvements in water and beach quality in the Sydney area have been notable (Birch, 2000). With improved regulation of environmental discharges and the decommissioning of heavy industries, concentrations of industrial toxicants in surface sediments, particularly metals, PAHs and POPs, have decreased since the 1970s (Taylor *et al.*, 2004) (Figure 4.18). However, some of the world's highest reported concentrations of metals, PAHs and POPs remain in the subsurface sediments from early industrial activities as legacy contamination (Birch and Taylor, 1999, 2004). Pollutant concentrations remain highest in poorly-flushed off-channel embayments surrounding modern point sources such as stormwater drains (Roach and Runcie, 1998; Alquezar *et al.,* 2006; Roberts *et al.*, 2008; Birch and Richards, 2013).

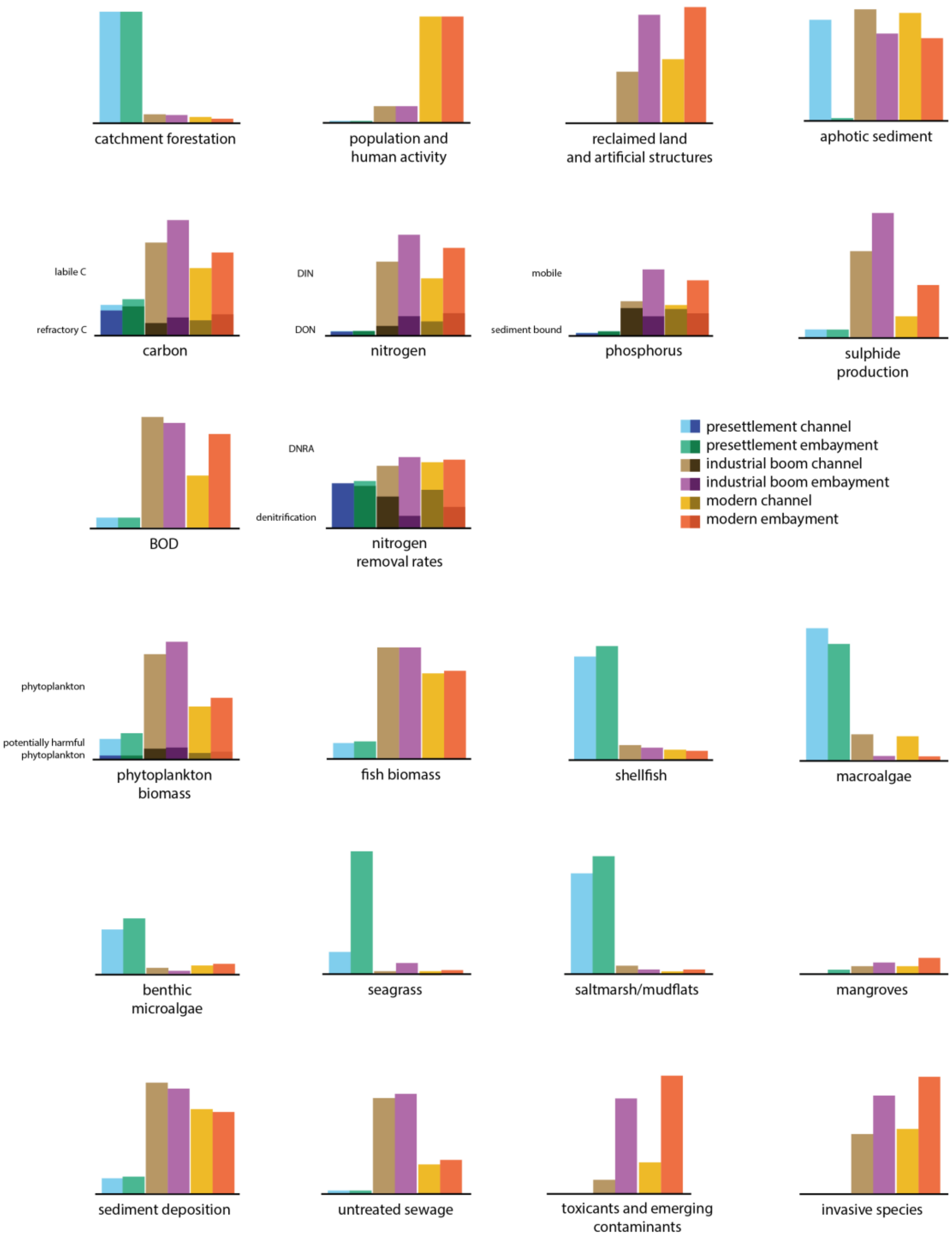


Figure 4.18 **Qualitative plots of changes in estuarine ecological properties over time in Sydney Harbour**

Direct human interaction

Direct human interactions with the estuarine environment, through commercial and recreational activity present further threats to ecosystem processes (Hardiman and Burgin, 2010; Burgin and Hardiman, 2011; Hedge *et al*., 2014a). Boating activities present increased boat strike risk to marine organisms, increase turbidity and act as vectors for the transport of pests and disease (Hedge *et al.*, 2009). Dredging to support shipping activity still occurs in the lower estuary, as Sydney Harbour remains a leading destination for cruise ships (Circular Quay and White Bay). Dredging also maintains access to oil refinery facilities (Gore Cove) and cargo berths for dry bulk and bulk liquids (Glebe Island) (Hedge *et al.*, 2014b). Commuter ferries operate along the Parramatta River tributary and throughout the lower estuary. The resulting sediment resuspension can remobilize sediment- bound toxicants into the water column for transport within the estuary (Hedge *et al.,* 2009). Sydney Harbour experiences significant recreational fishing pressure, and although minimum catch sizes and fishing pressure are regulated, abuse of these laws due to lack of public awareness and understanding remains an issue (McPhee *et al.*, 2002). Moorings for recreational vessels, located mostly in the lower estuary, have contributed to fragmentation of remaining seagrass beds, reducing their integrity (Creese and Wales, 2009) (Figure 4.19). Swimming, snorkeling and diving can result in some trampling of intertidal and subtidal habitats.

Figure 4.19 Holes created in a *Posidonia australis* meadow by boat moorings in Lake Macquarie (Creese and Wales, 2009).

Climate change

The survival of tropical fish species in Sydney Harbour over winter (Figueira and Booth, 2010), increased occurrences of climate-mediated disease and algal bleaching (Campbell *et al.*, 2012), and the warming coastline driven by the southward expansion and strengthening of the East Australia Current (EAC) (Ridgway, 2007) suggest associated changes in composition of ecological communities in the estuary in the future as climatic behavior continues to change (Vergés *et al.,* 2014). Although Ji *et al.* (2015) predict decreased intensity and frequency of east coast low systems along the east Australian coast, increased storm rainfall intensities from warmer ocean waters (CSIRO, 2001) could pose additional pressure on Sydney Harbour's dated and congested sewage system.

4.6.7 Resulting ecosystem process shifts following European settlement

European catchment modifications forced shifts in the dominant state of many ecosystem processes, as the physical and ecological characteristics of Sydney Harbour underwent tremendous changes for many years of the estuary's history.

Turbidity and increased sedimentation

The drastic increase in water turbidity has had lasting implications for ecosystem processes in the estuary, decreasing areas of photic sediment (BMA and seagrass meadows). This has resulted in reduced benthic productivity in the system (Kelleway *et al*., 2007), with follow on effects to the range of coupled biogeochemical transformations facilitated by benthic organisms, e.g. nitrification and denitrification which rely on oxygen supply to the sediments (Figure 4.20) (Hulth *et al.*, 2005). Few studies have estimated the impact of losses in benthic primary production on ecosystem processes as of yet (Johnston *et al.,* 2015a).

Increased sedimentation has also resulted in increased mangrove distribution in the limited intertidal zone (Figure 4.14). They have further displaced remaining saltmarsh and mudflat communities that were more common pre-European settlement (McLoughlin, 2000b; Birch, 2007a) (Table 4.5).

Habitat loss and significant reductions in benthic productivity

The reclamation of hundreds of square metres of wetland and seagrass habitat has also significantly reduced the benthic productive capacity of the estuary (Table 4.5). Instead, increased terrestrial inputs from impervious urban areas now enter directly into the water column without bypassing filtering habitats (Harris, 2001; Barbier *et al.*, 2011). This has contributed to the eutrophic conditions now experienced in the upper estuary of a once oligotrophic Sydney Harbour (Scanes *et al.,* unpublished data)(Birch *et al.*, 2010). The loss of intertidal and wetland habitat filtering in the modern estuary has also compounded the impacts of catchment deforestation on turbidity and rates of sedimentation. Toxicants may also have increased in their distribution to beyond wetland areas.

Table 4.5 Area (km^2) of estuarine macrophytes found in Sydney Harbour sub-catchments in 2009 (Creese and Wales, 2009).

	Seagrass	Mangrove	Saltmarsh
Middle Harbour	0.058	0.142	0
Port Jackson	0.34	0*	0
Lane Cove	0.015	0.359	0
Parramatta River	0.105	1.346	0.095

* indicates that the calculated area values were too small to show up in the table

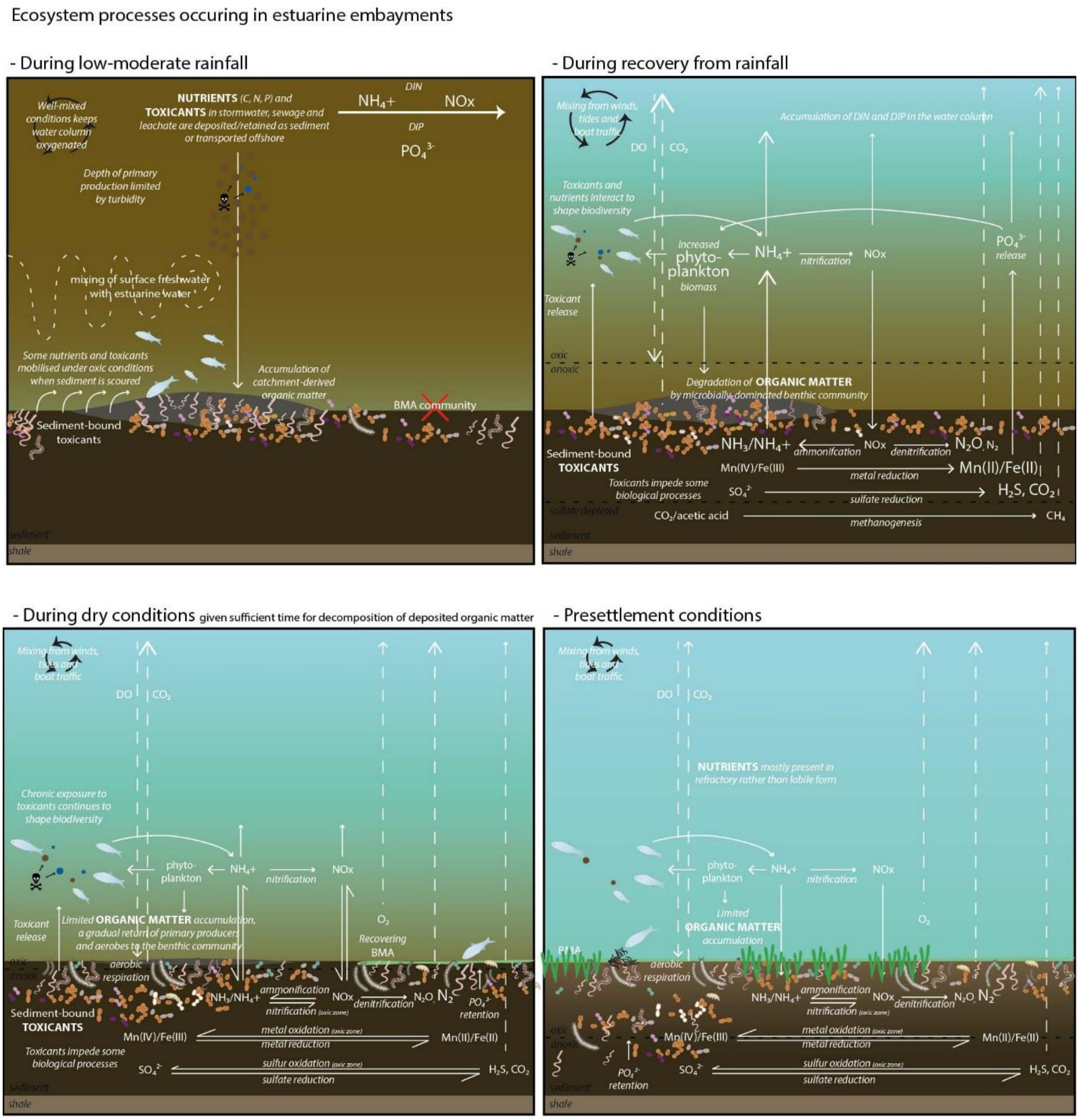


Figure 4.20 **Coupled benthic-pelagic biogeochemical processes dominant under 1) rainfall conditions (low to moderate where runoff is retained in the upper estuary), 2) conditions during which excess urban inputs remain in the estuary, but are in the process of being integrated into the system, 3) average state of biogeochemical cycling in the embayments of the modern estuary, 4) average state of biogeochemical cycling in the embayments of the estuary pre-European settlement.**

Marine urban infrastructure (seawalls, dykes, breakwaters, groynes, jetties, pilings, bridges) have reduced the amount of natural light reaching shallow benthic areas, further inhibiting benthic primary productivity. These artificial environments also provide favourable conditions for hull-transported invasive species (Airoldi and Bulleri, 2011; Dafforn *et al.,* 2012).

Alterations to hydrology

Infilling and vertical rock-stabilised walls have changed the hydrology of reclaimed channels and embayments (Figure 4.14). These changes include decreased tidal flushing rates, which encourage conditions for sediment anoxia that is associated with decreased benthic production (Birch *et al*., 2009).

Antagonistic ecological response to toxicant and nutrient pollutants

The dominant threats to ecosystem processes in Sydney Harbour arise from pollution and the loss of habitats that are able to rapidly transform or store pollutants. The modified state of the estuary has interfered with the natural biogeochemical and biological functions of both pelagic and benthic systems. While our understanding of the ecological impact of individual pollutants continues to grow, there is also a need to understand the combined impacts from the range of pollutants affecting urbanized environments. Conceptually, the concentration and nature of nutrient (influenced by C:N:P) and toxicant (influenced by the class of toxicant, e.g. carcinogen, mutagen, endocrine disrupter) contaminants determine ecosystem processes, such as the biogeochemical pathways available for elemental cycling, as well as influence ecosystem process rates (Figure 4.20).

Research from the estuary suggests that the ecological impacts of toxicant and nutrient pollutants are antagonistic in nature (Hedge *et al.*, 2014a). The 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 diversity and changes in community structure, indicating lethal responses (Johnston and Roberts 2009). However, these metrics do not reflect how toxicants may influence the rate of different ecosystem processes, as a range of sublethal impacts influence organism physiology and behavior (Islam and Tanaka, 2004). To bridge this gap in knowledge, complementary community-level process measurements are needed to provide insight into any implications for ecosystem processes.

Several biological processes are negatively impacted by toxicants (Islam and Tanaka, 2004). For example, some enzymes that facilitate primary production have been found to be sensitive to certain toxicants (Johnston *et al.*, 2015b). There are also ecosystem processes, such as carbon cycling, that remain relatively stable when exposed to toxicants (Islam and Tanaka, 2004). From an ecosystem perspective, toxicants reduce the overall diversity of biological functions occurring within the system, which may have follow-on effects such as the impairment of higher-level ecosystem functions that rely on linkages between functions within complex pathways (Islam and Tanaka, 2004). This may translate as impairments to productivity, maintenance of water quality and decreased resilience to perturbations (Worm *et al*., 2006).

Encapsulating the full range of toxicant impacts is a challenge, as many emerging contaminants (many of which are artificially synthesised compounds) are constantly introduced into the environment (Islam and Tanaka, 2004). Despite the challenge, numerous ecological impacts caused by certain toxicants have been identified. Commonly used herbicides, such as diuron, simazine and atrazine, and pharmaceuticals and personal care products (PPCPs) have been detected during dry periods in Sydney Harbour (Birch *et al.*, 2015). Herbicides are known to restrict electron transfer within the photosynthetic chloroplast, limiting primary production (Jones, 2005). Some PPCPs have been identified as endocrine disrupting toxicants, being linked to reproductive failure of wild populations (Snyder *et al*., 2003; Alquezar *et al*., 2006; Booth and Skene, 2006), and antimicrobial resistance in the natural environment is of concern (Allen *et al.,* 2010). Plastic pollution is also of concern, as plastic particles ingested by both vertebrates and invertebrates increase exposure to hydrophobic surface-bound toxicants (do Sul and Costa, 2014). Plastic debris also poses a suffocation and entanglement threat (Wright *et al.*, 2013). The bioaccumulation of toxicants ultimately poses 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 new classes of chemical compounds continue to emerge with the evolution of technology and commercial activities, continuing research is needed to keep abreast with the ecological impacts of these emerging toxicants (Mayer-Pinto *et al.,* 2015).

Nutrient pollution in Sydney Harbour has been seen to have a positive effect on both pelagic (McKinley *et al.,* 2011) and benthic (Dafforn *et al*., 2013) biomass and diversity, despite simultaneous toxicant pollution (Johnston and Roberts, 2009). Given the estuary's oligotrophic state pre-European settlement, nutrient pollution has acted to increased pelagic primary production and resource heterogeneity across the system. There is evidence that this has ameliorated some of the negative impacts of toxicants on species richness, although disproportionately favouring opportunistic or nutrient-loving species, e.g. weedy algal species such as *Caulerpa taxifolia*, and disadvantaging native species (Creese and Wales, 2009; Johnston and Roberts, 2009; McKinley and Johnston, 2010; Dafforn *et al.,* 2014).

Although species diversity increased, high species diversity is not analogous to the preservation of diverse ecosystem processes, as proliferation and divergence within a subset of species supports a limited metagenome of potential ecological functions (Riesenfeld *et al.*, 2004; Gillan *et al.,* 2005).

Diversity measures need to be extended to encompass functional traits or changes in Order, Class or higher-taxonomic level so that implications to ecosystem processes can be determined. Although Sydney Harbour supports a relatively high diversity of species (Booth, 2010), there is evidence that the communities have experienced functional shifts, represented as changes in species composition (McKinley *et al.*, 2011; Sun *et al*, 2013), shifts in ecosystem states, e.g. from kelp dominated to filamentous turfing algae dominated rocky reefs (Connell *et al.*, 2008), as well as changes to ecosystem process rates such as nutrient cycling (Sutherland, 2016).

In the global context of human-modified cities, Sydney Harbour's nitrogen discharge is considered moderate and phosphorus discharge below average (Birch *et al.*, 2010). Although nutrients have a positive influence on productivity and species diversity, this productivity is ultimately limited above a certain threshold by the negative impacts of eutrophication - oxygen depletion due to increased biological oxygen demand (BOD) and sulphide accumulation (Figure 4.20). As benthic organic material accumulates from terrestrial inputs or pelagic productivity, eutrophic conditions persist beyond rainfall or sewage overflow events. Such is the situation in the upper estuary and embayments of Sydney Harbour. 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 concentrations of bioavailable toxicants in the water column and their biotic uptake (Lithner *et al*., 2000). However, sulphide itself is toxic to organisms (Cohen *et al*., 1986; Wang and Chapman, 1999).

The low-oxygen conditions also threaten the health and survival of higher trophic level aerobic organisms (Burgin and Hamilton, 2007; Rabalais *et al.*, 2009). As such, microbial activity in eutrophic systems often becomes an increasingly dominant pathway for the degradation of organic matter (Pinckney *et al.*, 2001). As benthic primary production is limited in eutrophic environments, beneficial ecosystem processes such as oxygenation and sediment stabilisation are lost. Under these conditions, nitrogen removal shifts from nitrification-denitrification towards nitrate ammonification (Hulth *et al*., 2005). The suite of microbes that perform nitrification-denitrification will act to remove excess nitrogen as harmless dinitrogen gas or nitrous oxide greenhouse gas when incomplete denitrification occurs in low oxygen systems (Seitzinger and Kroeze, 1998; Burgin and Hamilton, 2007). However, less desirable nitrate ammonifying microbes transform NOx into toxic ammonia which may be retained in the system (Camargo and Alonso, 2006). Therefore, a greater amount of ammonia is retained in eutrophic systems.

Low oxygen conditions also increase phosphorus release into the water column, further exacerbating the eutrophic conditions in the surrounding areas (Correll, 1998). With these positive feedback processes occurring, nutrients accumulate in eutrophic systems unless the addition of organic material and nutrients can be stemmed (Figure 4.20). Fortunately for Sydney Harbour, the short length of the estuary and the well-flushed conditions currently ensure sufficient water exchange to meet the eutrophied estuary's BOD requirements, as well as dilute ammonia and sulphide concentrations. Algal blooms are rarely observed in Sydney Harbour (Birch *et al.,* 2010), and widespread hypoxic events have yet to occur. However, if nutrient loads increase, the risk of hypoxia, particularly in the upper estuary and off-channel embayments, increases accordingly (Howarth *et al.*, 2011).

4.6.8 Summary and future management directions

Since European settlement, the ecology and ecosystem processes of Sydney Harbour have experienced significant change due to human impacts from catchment development, industry and urbanization. Despite these threats and a shift from oligotrophic to eutrophic conditions, the current state of ecosystem processes indicates a trajectory of recovery. As a result of the environmental management efforts since the 1980s, such as better regulation of environmental discharges and discharge of sewage offshore, some aspects of ecological function in Sydney Harbour have taken a turn for the better. However, there is no room for complacency as coastal populations are projected to increase (Martínez *et al*., 2007), and new chemical compounds continue to be released into the environment where we have limited understanding of their impacts (Mayer-Pinto *et al*., 2015).

As our holistic understanding of Sydney Harbour's ecology and ecosystem function continues to improve, future efforts to mitigate the deterioration of human-impacted coastal systems should encourage ecosystem function closer to the estuary's pre-European state. Maintaining a balanced relationship between resource and consumer to achieve this will rely on close communication and collaboration between scientists, engineers and policy makers.

In order to preserve our valuable ecosystem processes, forward-thinking management driven by scientific research will be essential to mitigating the evolving modern threats experienced by the estuary. This is particularly true for stormwater management, which was identified in this model as having the greatest potential impact to the state of ecosystem processes in Sydney Harbour.

Current management (Table 4.3) includes a variety of actions to reduce stormwater and sewage release into the estuary. The North Side Storage Tunnel was built by Sydney Water to store stormwater and sewage overflow from heavy rainfall. The tunnel, which is connected to the North Head wastewater treatment plant, has the capacity to prevent 470 megalitres of wastewater from entering the Harbour (Hoisington, 2015). Additionally, local councils within the Sydney Harbour catchment have implemented Stormwater Management Plans where engineering solutions, such as runoff detention basins, grass swales, gross pollution traps and litter booms, are employed to reduce urban runoff (O'Loughlin *et al*., 1995; Van der Sterren *et al.,* 2012). Remediation efforts for contaminated landfill and contaminated sediment have been implemented to reduce the diffusion of legacy contaminants further afield in the estuary (Birch *et al*., 2009). Eco-inspired engineering designs for foreshore structures, such as the Barangaroo Foreshore completed in 2015 (Gorman, 2015), will help to lessen the impacts of human modifications to estuarine fringe environments and return the hydrology of the mostly artificial shoreline to a more natural state (Dafforn *et al.,* 2015). These management actions are in line with the vision for water sensitive urban design (WSUD) in global cities (Wong and Brown, 2009). Such practices are increasingly being integrated into more conventional city designs in order to build resilience to the pressures of climate change and population growth.

With ongoing management efforts, Sydney Harbour should continue to provide significant environmental, economic and social value (Hedge *et al.*, 2014b; Hoisington, 2015). As differences in latitude, geomorphological properties and the industrial history that is unique to each location shape variation around the ecological response to threats, this conceptual model best represents conditions found in Sydney Harbour. However, the threats discussed in this conceptual model may be common to other drowned river valley systems worldwide that face similar threats from growing coastal populations, e.g. the Hudson River, Chesapeake Bay and San Francisco Bay in the United States, Guanabara Bay in Brazil, the Thames River in England, the Ems River in Germany and the Seine River in France.

Horned Blenny (*Parablennius intermedius*) at Clifton Gardens

5 ASSESSMENT OF VALUES THREATS AND OPPORTUNITIES

This chapter is mostly sourced from an unpublished report prepared in 2014. The original work was compiled as a collaboration between the NSW Office of Environment and Heritage, NSW Department of Primary Industries and the Sydney Institute of Marine Sciences (SIMS) on behalf of the Marine Estate Management Authority (MEMA). The objective of the report was to undertake a preliminary assessment that is consistent with MEMA's threat and risk assessment (TARA) approach.

5.1 Community values

A Marine Estate Community Survey was conducted (Sweeney Research, 2014) to evaluate the values and attitudes of the NSW community and interest/user groups towards the entire NSW Marine Estate in terms of:

- values and benefits the NSW community derives from the Marine Estate
- threats to the Marine Estate that need to be managed now and in the future
- opportunities in the Marine Estate for future use and enjoyment, to address key threats and for improved community engagement.

The results for the Greater Sydney Region were extracted from the statewide survey. The findings are summarised below in Table 5.1.

Table 5.1 The views of Sydneysiders about the benefits, threats and opportunities for the Marine Estate

Benefits	• Economic: the Marine Estate is a source of income for locals, however, this finding was significantly lower for Sydney than for other NSW regions; it is home to iconic images of Australia which promotes tourism. • Social: the ability to enjoy the natural beauty of the Marine Estate; its role as a safe space to spend time with family and socialise with friends. • Environmental: clean waters supporting a variety of habitats and marine life; the abundance of marine life.
Threats	• Economic: water pollution affecting local tourism; the loss of natural areas for nature tourism. • Social: loss of appeal due to water pollution; anti-social behaviour affecting the community's safety and enjoyment. • Environmental: litter, rubbish or marine debris within the Marine Estate; oil and chemical spills.
Opportunities	• Economic: marketing the beauty and biodiversity of the Marine Estate to promote tourism; developing and implementing management responses to storm surges, coastal erosion and inundation. • Social: more education programs for the community; improving public access. • Environmental: protecting and rehabilitating remaining coastal wetlands; providing more effective litter collection services.

Results were analysed for four sub-regions based on Local Government Area (LGA). This was done by matching the respondent's postcode with the corresponding LGA using data sourced from the Australian Bureau of Statistics (2014). The four sub-regions (Upper Harbour, Lower Harbour, Southern Sydney and Western Sydney) were identified based on their proximity to Sydney Harbour. In interpreting the findings from this analysis, results from the two sets of intercept surveys done in the Sydney region were used where appropriate.

Analysis of the data show that people in Sydney are more likely to interact with the Sydney region than any other region and therefore are more likely to formulate their views based on the Sydney region. For example 68% of people responding from the Lower Harbour sub-region visited Sydney Harbour in the past 12 months. People from all four sub-regions visited Sydney Harbour more than any other area in Sydney or any other part of the entire NSW Marine Estate.

Online respondents were asked if they were to visit Sydney Harbour over the next year, what would be the main reason for their visit. The most popular activity listed by respondents from all sub-regions was sightseeing. People from the Upper Harbour and Western sub-regions were more likely to go sightseeing compared with Lower Harbour and Southern sub-regions.

The most frequently undertaken recreational activity for all sub-regions was walking-exercising-sunbathing, with people from the Lower Harbour more likely to undertake these activities than any other sub-region. As would be expected, people from the Western sub-region are significantly less likely to undertake these activities in the marine estate and, in general, had fewer people interacting with the Marine Estate.

The next most common activities identified for all sub-regions were: taking a ferry, socialising in the marine estate, and swimming-surfing-boarding. People from the Lower Harbour sub-region were significantly more likely than any other sub-region to go swimming-surfing.

Overall, approximately one third of people from all sub-regions fish from the shore, but the majority undertake this activity less than once a month. Two thirds of people from all sub-regions don't fish from the shore or don't fish at all. These figures are similar for people fishing from a boat. Data from the intercept survey suggest that the proportion of people who fish from the shore is lower.

People from the Lower Harbour are significantly more likely to engage in wildlife appreciation activities than from any other sub-region, and people from the Upper Harbour are much less likely. For all sub-regions, most people never undertake voluntary environmental work.

For all sub-regions the percentage of people kayaking-canoeing, power-boating, sailing, snorkeling-scuba diving or undertaking education activities is similar but significantly more people in each of these sub-regions never do these activities.

The two highest priority values of the marine estate for all sub-regions were environmental values: the marine estate should stay clean and unpolluted; it is important to maintain the abundance and diversity of marine life. The third highest was a social value: the natural beauty and marine wildlife are a key reason why NSW is a great place to live and visit.

Respondents were asked to identify what they considered to be the highest priority benefits, threats and opportunities from an economic, social and environmental viewpoint for the marine estate. A compilation of their responses by sub-region allows a finer scale interpretation of Sydneysiders' views (Table 5.1).

Pot Belly Seahorse (*Hippocampus abdominalis*) Manly

Table 5.2 The views of Sydneysiders about the Marine Estate by sub-region

Benefits	For all sub-regions the two highest priority **economic** benefits were: source of income for locals; and home to iconic images of Australia which promotes tourism.
	For all sub-regions the highest priority **social** benefit was: the ability to enjoy the natural beauty of the marine estate even if they can't visit it regularly. The second priority for all sub-regions except the Lower Harbour was: provides a safe space to spend time with family and friends. The second priority for the Lower Harbour was: can help people achieve an active, healthy lifestyle. For all sub-regions the highest priority **environmental** benefit was: clean waters supporting a variety of habitats and marine life. This also had a strong response within the Intercept surveys. The second highest priority for Upper Harbour and Southern sub-regions was: abundance of marine life. The second highest priority for Lower Harbour and Western sub-regions was: contains unique biodiversity that cannot be found anywhere else in the world.
Threats	For all sub-regions the two highest priority **economic** threats were: water pollution affecting local tourism; and the loss of natural areas for nature tourism.
	For all sub-regions the two highest priority **social** threats were: loss of appeal due to water pollution, litter; and anti-social behaviour affecting their safety. For all sub-regions the highest priority **environmental** threat was: litter, rubbish or marine debris within the marine estate. The second priority for all sub-regions except the Western sub-region was: oil and chemical spills. The second priority for the Western sub-region by a small margin was: water pollution from sediment or run-off.
Opportunities	For all sub-regions the three highest priority **economic** opportunities were: market the beauty and biodiversity of the Marine Estate to promote tourism; develop and implement management responses to storm surges, coastal erosion and inundation; and improve public access to areas of the marine estate. This last opportunity was particularly important for Upper Harbour and Southern sub-regions. For intercept surveys the second highest priority was: allow more environmentally sensitive coastal development.
	For all sub-regions except the Upper Harbour, the highest priority **social** opportunity was: more education programs for the community. The highest priority for the Upper Harbour was: improve public access. The second priority for all other sub-regions was: provide community environmental action support programs to involve volunteers in delivering on-ground outcomes. For all sub-regions the two highest priority **environmental** opportunities were: protect and rehabilitate remaining coastal wetlands; and provide more effective litter collection services. The Southern sub-region had greater interest in the provision of more effective litter collection services. Rehabilitating wetlands also featured heavily for intercept surveys.

Survey respondents were asked to identify changes that they had noticed over the last 20 years. For all sub-regions more people had noticed an increase in extreme weather events, litter, coastal erosion, coastal infrastructure, and water pollution in ocean waters.

Significantly greater numbers of respondents for the:

- Upper Harbour sub-region noticed an increase in extreme weather events, litter and coastal infrastructure.

- Lower Harbour sub-region noticed an increase in extreme weather events, litter, coastal erosion and coastal infrastructure.
- Southern sub-region noticed an increase in extreme weather events and litter.
- Western sub-region noticed an increase in litter.
- Western sub-region noticed a decrease in fish catch.

Respondents were asked, without any prompting, what they considered to be the key threats to the Marine Estate. All sub-regions considered pollution to be the key threat and it was considered to be much larger than the next most commonly listed threat – overfishing.

The top three attitudes for all sub-regions to the Marine Estate were:

- It is the responsibility of all NSW residents to protect the Marine Estate
- Scientific information should be used to inform the management of the Marine Estate
- Some areas of the Marine Estate should be protected, even if it means recreational and commercial fishing is excluded.

People from the Lower Harbour sub-region also agreed significantly more with the statement: 'The NSW Marine Estate is an important part of why I like living in NSW'.

There are no marine parks in the Greater Sydney region but Sydneysiders are likely to visit marine parks in other regions. Two-thirds of on-line respondents from all sub-regions of Greater Sydney either hadn't visited a marine park or didn't know whether they had visited a marine park. From the intercept surveys of Sydneysiders and visitors at Circular Quay and Pittwater, however, it was found that:

- Most people had visited a marine park.
- People intercepted in Pittwater were more likely to have visited a marine park than those intercepted at Circular Quay.
- Visitors to Sydney were significantly less likely to have visited a marine park than a local resident.

Most Sydneysiders 'strongly supported' or 'somewhat supported' using Marine Parks to manage the use and conservation of the marine environment. Respondents from the Lower Harbour sub-region significantly supported marine parks compared with other sub-regions. Approximately a third of people across all sub-regions were unsure. Across all sub-regions very few people do not support marine parks – the highest rate was 5% 'somewhat against marine parks' for the Southern sub-region.

5.1.1 Sydneysiders' views of Sydney Harbour

Sydneysiders value Sydney's waterways and beaches and value Sydney Harbour in particular. Walking-exercising-sunbathing is the most commonly enjoyed recreational activity by Sydneysiders within the Marine Estate irrespective of the sub-region they are from.

Sightseeing around Sydney Harbour is an important pastime for Sydneysiders themselves irrespective of sub-region, while they also view the Harbour as a major tourist drawcard nationally and internationally. The Harbour as a focus for sightseeing is relevant economically as well as socially, with interest ranging from local to international.

The importance of Sydney's waterways as a source of income for locals was a priority economic benefit across all sub-regions, although this was a less significant issue in the Sydney region than it was when compared with the rest of the Marine Estate. It seems reasonable to infer that regional areas are more reliant on the Marine Estate for an income than Sydneysiders. Never-the-less for all Sydney sub-regions the two highest priority economic threats were considered to be water pollution affecting local tourism and the loss of natural areas for nature tourism. The highest priority economic opportunity for all sub-regions was to market the beauty and biodiversity of the Marine Estate to promote tourism. These results seem to reflect the significance that Sydneysiders place on sightseeing around Sydney's waterways and that to them, tourism is the most obvious economic use of the Marine Estate around Sydney.

From a social viewpoint, a key benefit of Sydney's waterways is that it is an important place for the Sydney community to socialise with friends and family. This was considered the second highest priority for all sub-regions except the Lower Harbour sub-region for which respondents considered Sydney's waterways an important area to help people achieve an active and healthy lifestyle. An identified key threat from the quantitative surveys for all sub- regions that could be related to these pastimes was anti-social behaviour negatively affecting the community's safety and enjoyment.

From an environmental perspective, Sydneysiders consider clean water supporting a variety of habitats and an abundance of marine life as critical benefits that the Marine Estate provides. The significance of clean water for marine life was reflected in the results for all sub-regions. Indeed it was also reflected in the priority environmental threats listed for all sub-regions as all of them related to water quality in some form: litter, oil and chemical spills, and sediment or run-off. Respondents from the Upper Harbour and Southern sub-regions also emphasised the importance of the abundance of marine life as an environmental benefit whilst those from the Lower Harbour and Western sub-regions focussed on unique biodiversity that cannot be found elsewhere.

From responses to a number of different questions, it can reasonably be deduced that it is important to Sydneysiders that marine biodiversity is protected. Healthy, diverse and abundant marine life is clearly a key value. This is further reflected in the environmental and social opportunities identified by people from all sub-regions to protect and rehabilitate remaining coastal wetlands, and to provide community environmental action support programs to involve volunteers in delivering on-ground outcomes. This last opportunity is despite the fact that for all sub-regions, significantly more people never undertake voluntary environmental work. Perhaps this suggests that the community would like to be involved in volunteering to help the environment but need some persuasion and more information on how to take the first step.

Costs to access, traffic to reach and crowding on Sydney's beaches as well as litter, pollution and fishing were important threats identified by Sydneysiders in the qualitative studies. However, litter and pollution of Sydney's waterways were the major causes for concern for Sydneysiders in the quantitative studies. This focus on pollution was reflected across all the sub-regions. Indeed, the majority of benefits and threats for economic, social and environmental values related in some way to water quality indicating that it is uppermost in the thoughts of the Sydney community. In contrast, only one opportunity listed by Sydneysiders from all sub-regions related to directly managing pollution and litter, and that was to provide more effective litter collection services. The strength of this response about litter was reflected in the fact that the only perceived change common across all sub-regions was an increase in litter. Litter is a highly visual result of pollution and the general community would be more familiar with solutions to litter than, for example, oil spills or sediment input.

Improved public access to Sydney's Marine Estate was a high priority economic opportunity for all sub-regions but particularly for the Upper Harbour and Southern sub-regions. The Upper Harbour sub-region also emphasised public access as a social opportunity. This may indicate that access to the Upper Harbour foreshore is limited and opportunities to improve access to these areas should be considered. Alternatively, or as well as, it may reflect the difficulty people from the Upper Harbour have in accessing other areas of the Marine Estate, such as beaches, due to Sydney traffic and costs such as beachside parking charges.

A final priority opportunity was to develop and implement management responses to storm surges, coastal erosion and inundation. This reported opportunity is probably a result of the fact that people from all sub-regions, except the Western sub-region, had noticed an increase in extreme weather events over the last 20 years, and people from the Lower Harbour sub-region had noticed an increase in coastal erosion.

When asked about threats to the Marine Estate without any prompting, respondents from all sub-regions considered overfishing to be the second highest threat, although this was much less significant than pollution. However, only the Western sub-region had noticed a decrease in fish catch over the last 20 years.

Respondents from all sub-regions considered it to be the responsibility of all NSW residents to protect Sydney's waterways. Sydneysiders appear to want proactive management of the Marine Estate which would include monitoring as well as preventative measures. The community also wanted to be involved in decision-making.

Education programs for the community and particularly for school children were strongly emphasised in the Sydney focus group undertaken as part of the qualitative studies. This opportunity was reflected as the highest social priority in the quantitative study across all sub-regions except the Upper Harbour. Education programs about the benefits of the marine estate and marine parks were specifically recommended in responses during the qualitative research and, further, it was thought that education should consist of positive messages around what people can do to protect Sydney's waterways.

5.1.2 Synthesis of information about community values

Despite the fact that Sydney Harbour was not the primary focus of the community survey, the results from it have allowed a preliminary understanding about how Sydneysiders interact with their Harbour and what they perceive as threats and opportunities. Further, the synthesis undertaken by SIMS for the Background Report highlighted similar issues. Socially, that report acknowledges three sorts of values:

- Option value - representing the knowledge that one will have the option of visiting and experiencing the Harbour in future; ie that it will be protected until then,
- Bequest value - reflecting the importance of leaving a healthy Harbour to be inherited by future generations,
- Existence value - representing the comfort of knowing that the Harbour is there and being looked after.

The Australian Natural Landscapes Program, in recognising Sydney Harbour as its latest National Landscape, promotes the natural values of what they considered was one of the world's finest Harbours as well as the significant features of the built environment on its shores. Although Sydney Harbour remains a working Harbour with many economic values, it is its natural beauty that now underpins its value for most Sydneysiders and visitors. Threats to that value are centred around maintaining good water quality, a healthy marine ecosystem, and adequate access so that it can be appreciated.

Given the strength and variety of comments about maintaining and/or improving water quality, effective communication around this issue is needed. A lot is already being done in the Sydney region to improve water quality but information about these programs needs to be communicated and additional coordinated opportunities should be explored.

5.2 Threats to environmental assets in Sydney Harbour

The Marine Estate Community Survey provided a general overview of what activities people consider as threats to their environmental values (Sweeney Research, 2014). More specific information relevant to Sydney Harbour was extracted from that survey as described in section 5.1. When identifying threats to the Marine Estate, the advice from the Marine Estate Expert Knowledge Panel is that community perception of threats should be tempered by expert opinion because the general public is not always fully aware of relevant scientific literature. Following a comprehensive search of the published scientific literature (Hedge *et. al*., 2014a) and in line with other assessments of threats to marine environments, the Sydney Harbour Background report (Hedge *et. al*., 2014b) identified 5 key threats to Sydney Harbour:

- Resource use
- Land-based impacts
- Marine biosecurity
- Marine industry pollution
- Climate change

Hedge *et. al*. (2014a) summarised the available information about these 5 threat categories and the activities associated with them. This material, supplemented where necessary by additional information, particularly around historical contexts, trends and management arrangements, informed a preliminary assessment of current threat levels. This assessment was done using a framework similar to that used in the Great Barrier Reef Marine Park in which relevant pressures were identified for each threat category, the activities contributing to that pressure noted and the stressors associated with each pressure considered (Table 5.3).

For each pressure under each of the 5 key threat categories a four-point scale, ranging from low threat to very high threat (Table 5.4), was used to categorise each stressor within each of the key threats. Wherever possible, threat levels were based on reported effects of stressors within Sydney Harbour (i.e. where directly relevant published information exists) (row A in the table). When published information on effects was not available or was limited, threat levels were based on the estimated magnitude of the stressor and more general scientific evidence of effects (eg in other geographic regions) (row B in the table). Suggested management responses to each of the 4 assigned threat levels are also given.

Giant Australian Cuttlefish *(Sepia apama)*

Table 5.3 **The major threat categories, the pressures associated with those threats in Sydney Harbour, the activities likely to cause that pressure and the specific stressors associated with those activities**

Pressures within threat categories	Activities contributing to pressures	Key stressors
Resource use		
Recreational fishing	Legal fishing from shore or boat	Removal of top and lower order predators, removal of lower trophic orders and herbivores, death of discarded species, habitat damage, marine debris
	Illegal fishing	Unsustainable harvesting
Boating & visitation	Moving vessels	Vessel strike on wildlife, bank erosion
	General boat use	Habitat damage
	Visitation	Habitat damage, wildlife disturbance, physical damage of biota and compaction of soils, marine debris
Extraction	Dredging of shipping channels	Habitat damage and modification
Land-based impacts		
Foreshore development	Shoreline hardening, reclamation, clearing and draining, vehicle and foot access	Loss of intertidal and subtidal habitat, wildlife disturbance, physical damage of biota and compaction of soils, altered tide and flow patterns
Urban, rural & industrial development	Catchment alteration	Increased nutrients, organic matter and sediment, input of toxic pollutants, litter contributing to marine debris, altered runoff, thermal pollution, modification of supporting terrestrial habitats
Modified freshwater flows	Water extraction, artificial barriers to riverine and estuarine flow	Barriers to connectivity, reduction and changes to timing of inflows
Marine biosecurity		
Introduction of exotic species	Recreational and commercial boating, shipping, artificial habitats, use of imported bait	Introduction of exotic marine species
Introduction of exotic diseases		Introduction of exotic diseases affecting marine species
Marine industry pollution		
Dredging	Spoil dumping	Nutrient, sediment and pollutant input from dredge spoil
Shipping	Large commercial vessels	Oil/chemical spill, marine debris, vessel strike on wildlife
	Small commercial vessels (e.g. ferries, water taxis)	Oil/ chemical spill, vessel strike on wildlife, wildlife disturbance, bank erosion
	Fishing vessels	Waste discharge, oil spill, wildlife disturbance, vessel strike on wildlife
Climate change		
Climate change	Global greenhouse gas emissions	Altered currents & changes in upwelling frequency (dispersal), sea temperature rise, ocean acidification, sea level rise & increased storm frequency, altered nutrient, sediment and freshwater input

Table 5.4 Levels used to guide assessment of threats to environmental assets

	Low threat	Moderate threat	High threat	Very high threat
(A)	Effects reportedly attributable to the stressor are generally localised and/or of rare occurrence	The effects may be reported throughout the component's distribution, but are not very frequent OR are frequent but not widespread	The effects are reported to be widespread and frequent	The effects reportedly occur across most of the component's distribution on an almost constant basis
(B)	The stressor is generally localised and/or of rare occurrence	The stressor may be reported throughout the component's distribution, but occurs infrequently, OR is frequent but not widespread	The stressor is reported to be widespread and frequent	The stressor occurs across most of the component's distribution on an almost constant basis
Response	No immediate action necessary	Further detailed assessment of the stressor and its effects may be desirable	Further detailed assessment of the stressor and its effects is required	Further detailed assessment and/or management action is required

5.2.1 Resource use

5.2.1.1 Fishing

Sydney Harbour has a long history of resource use by subsistence, commercial and recreational fishers. Fish and shellfish were important food sources and cultural components for aboriginal communities, with finfish taken using baited hand lines and multi-pronged spears from shore or bark canoes. Fish were an important fresh food source for the first European settlement, and although catches in the Harbour were considered to be 'unpredictable', it remained the primary fishing ground for the colony up to the 1830s (Henry, 1984). After this (up until 1860), fish supplied to the Sydney Fish Market were harvested mainly from Sydney Harbour and rivers, Botany Bay, Georges river and Broken Bay. Fine-meshed seine or 'beach haul' nets were used extensively and without regulation throughout the Harbour in the first 100 years of settlement. Catches included bream, flathead, tailor, whiting and garfish. Snapper or 'light-horseman' were a primary target and highly prized (Pepperell Research & Consulting Pty Ltd., 2017).

Commercial/government controlled fishing activity in the Harbour began in the 1880s with the introduction of fisheries legislation (e.g. methods, size limits, closed areas and seasons) 70-100 commercial fishers operated within the Harbour over the next 100 years or so. The fishery was considered 'artisanal', dominated by small boats, and employed a variety of methods including trawl, seine and gill nets, fish traps and handlines (Henry, 1984). At least 8200 tonnes of marine organisms including sharks, finfish, and invertebrates were harvested from Sydney Harbour between 1940 and 2006. Eighty-seven species were documented in catch records, with sea mullet, luderick, bream and school prawns being heavily targeted (NSW DPI, 2001).

Recreational fishing also grew with the expanding urban population and was promoted as an attraction in Sydney in the NSW tourist guide of 1907 (Henry, 1984). Conflict between amateur and professional fishermen began as early as 1820 and became increasingly common with respect to perceived overfishing and by-catch by commercial fishers (Henry, 1984; Liggins, *et al.,* 1996). However, by 1980-81, recreational catch exceeded commercial catch (164 vs 108 tonnes).

In 2006, commercial fishing was banned entirely from Sydney Harbour due to concerns over elevated levels of dioxin contamination in the flesh of fish, prawns and cephalopods. Recreational fishing continued to be permitted with recommendations that recreational fishers should consider the estuary as a ‘catch and release’ fishery. Precautionary health warnings were issued, and remain in place, to avoid eating marine organisms caught west of the Sydney Harbour Bridge and to limit consumption of those caught in the eastern part of the Harbour. Recreational fishing remains a popular activity in Sydney Harbour. Over 300,000 daytime fisher hours were expended during the 2007/08 summer period and surveys conducted in winter 2013, recorded 1622 cast fishing rods in the Harbour (Hedge *et al*., 2014b). High levels of fishing activity in the Harbour have been attributed to the proximity of a large urban population, physical attributes that encourage recreational fishing (e.g. easy public access to boat ramps and shorelines adjacent to deep water, protection from weather and aesthetic appeal), and the availability of diverse and high quality fishing opportunities (Ghosn, *et al.,* 2010).

While fishing occurs throughout the Harbour, many areas have restricted access due to industrial estates, commercial wharves, military bases and installations, and fisheries closures (Ghosn, *et al.,* 2010). Fishing activity is highest on the weekends and during the warmer months with Manly, South Head and Chowder Bay being popular fishing locations. In contrast to other recreational estuarine fisheries in NSW, Sydney Harbour is dominated by shore-based fishing which accounts for 62% of total fishing effort and 74% by number of species harvested from the estuary (Ghosn, *et al*., 2010). Line-fishing is the most common method used in the Harbour, although spearing, recreational netting, and trapping also take place.

Levels of recreational harvest and discarded catch in Sydney Harbour are large compared to other estuaries in NSW (Henry, 1984; Ghosn, *et al.,* 2010). Daytime harvest of finfish, crabs and cephalopods was estimated to be ~74 tons or 225 000 individuals in 2007/08, with another 293 000 individuals estimated to have been caught and released over that period. About 36% of the total harvest was from the western estuary zone, despite recommendations not to consume seafood from this part of the Harbour. Many species have been recorded in recreational catches including 46 species of finfish. Fishers commonly target lower order predators such as bream, snapper and flathead but a large majority target ‘anything’. Estimates of recreational harvest are primarily based on line fishing; catches taken by other methods (e.g. spearfishing, nets, traps, pumps, lobster pots) have not been quantified for the Harbour.

Pressure from recreational fishing is likely to increase with increasing urban population, greater accessibility to the Harbour’s shore, and better navigation and positioning systems on boats to locate fishing spots.

Current Management

Recreational fishing within Sydney Harbour is regulated by the NSW Department of Primary Industries and fishers pay a NSW Recreational Fishing Fee. The ecological sustainability of the fishery is managed through state-wide stock assessments and associated bag and size limits, gear restrictions, fishing closures and protection of individual species. Harbour- specific fisheries management includes fisheries closures and marine protected areas (www.fisheries.nsw.gov.au). For example, no fishing is allowed in Homebush Bay, Duck River, and the Upper Lane Cove River. Intertidal organisms cannot be taken from anywhere in Sydney Harbour Intertidal Protected Area, and Sydney Harbour and all its tributaries are closed to the taking of shellfish (e.g. pipis, cockles, mussels, snails, whelks and oysters). Spearfishing, collection of shellfish or digging for worms is not permitted within North Harbour Aquatic Reserve, although line fishing for finfish is allowed (Fisheries, 2002). Temporal fisheries restrictions have also been implemented within Little Penguin Critical Habitats. Patrolling fisheries officers maximise compliance with fishing rules and provide advice to fishers.

Potential Impacts

Recreational fishing is a key extractive use of Sydney Harbour and marine populations have been exploited for longer than any other Australian stock (Henry, 1984). Fishing may directly affect populations of target species (e.g. altering abundances, size and age structure) and incidentally caught organisms (by-catch). Ecosystem-wide effects may also occur through changes within the food chain and in some cases may lead to alterations in habitats. Indirect effects of fishing include disturbance and damage to habitats and organisms (e.g. anchor damage, diver-species interactions, and marine debris) (McPhee *et al.*, 2002).

There are few quantitative studies on the impacts of fishing in Sydney Harbour. A lack of baseline data on the 'unfished' ecosystem impedes our understanding of the full extent of fisheries effects. Despite this, the impacts of fishing within the Harbour and in NSW, was recognised as an issue as early as 1880 when a Royal Commission into the Fisheries of NSW was appointed due to perceived overfishing of inshore fisheries. The apparent disappearance of very large old snapper (referred to as 'native snapper') from reefs and headlands close to Sydney was attributed to simple growth overfishing during early European settlement. Grey nurse sharks also appear to have been caught quite commonly inside both Sydney Harbour and Botany Bay where they no longer occur. The bluefish seems to have almost completely disappeared from the NSW coast, at one stage being reasonably common in the Harbour e.g. at Bluefish Point (Pepperell Research & Consulting Pty Ltd. 2017). The Royal Commission led to the implementation of the first fisheries regulations in NSW.

More recent impacts of fishing within Sydney Harbour have not been well documented. Exceptions include a study of the by-catch of commercial prawn trawlers in 1990-92 prior to the ban on commercial fisheries (Liggins, *et al.,* 1996) and recreational harvest assessments in 1980-82 and 2007-08 (Henry, 1984; Ghosn, *et al.,* 2010). The latter of these studies concluded that there were few indications that current levels of recreational fisheries in the Sydney Harbour estuary were unsustainable (Ghosn, *et al.,* 2010).

Legal fishing from shore or boat

There are 5 stressors commonly associated with permitted fishing activity:

Removal of top order predators

Marine top order predators play an important role in maintaining healthy marine ecosystems. Declines in top predators can initiate long-term changes in marine communities through direct and indirect effects (e.g. increase in prey species, behavioural changes) (Heithaus, *et al*., 2008). Top order predators in Sydney Harbour are generally migratory and include pelagic sharks (e.g. bull sharks, whalers), whales and dolphins. Of these, sharks could be threatened by extraction. However, there are no data on number of pelagic sharks caught in Sydney Harbour. Surveys of recreational fishing have been limited to day time harvests and indicated that sharks are not a primary target group (Ghosn, *et al*., 2010). While shark fishing is likely to occur at night, captures are presumably rare and localised, requiring targeted methods and fishing gear.

Removal of low order predators

Lower order predators occupy the middle of the food chain. In Sydney Harbour lower order predators include finfish (e.g. snapper, tailor, kingfish, bream and flathead), cephalopods (cuttlefish, squid and octopus), and small sharks and rays (e.g. wobbegongs, common ray). Lower order predators are the main target group for shore and boat-based recreational fishers in Sydney Harbour (Henry, 1984; Ghosn, *et al.,* 2010). More than 85% of surveyed fishers nominated bream, kingfish, and flathead as their main targets (Ghosn, *et al.,* 2010). Lower order predators accounted for 7 of the 10 most commonly harvested taxa by number: yellowfin bream (15.3%), snapper (7.9%), tailor (6.9%), dusky flathead (6.6%), kingfish (5.7%), trumpeter whiting (4.8%), and sand whiting (1.9%) (Ghosn, *et al.,* 2010). Kingfish, bream, dusky flathead, snapper, tailor, mulloway and sand whiting made up 81.6% of the estimated landed harvest of 69.7 tonnes. Although data indicates that lower order sharks and rays are captured in the eastern zone, they were commonly discarded.

Declines in low order predators may have direct and indirect effects on other organisms. However, there is little scientific evidence to support changes in lower order predator populations within Sydney Harbour. This could be due to lack of data collection early in the Harbour's fishing history. Historical accounts indicate declines in large snapper, sharks and other species in the 1800s. Furthermore, studies of marine protected areas within the Sydney and NSW region where fishing is excluded have found that these areas often have higher abundances and larger sizes of lower-order predators (e.g. snapper, red morwong) than fished locations (Curly *et al.,* 2013). Predator–urchin–kelp trophic cascade on temperate reefs have also been documented where removal of seaweeds by sea urchins is attributed to the depletion of sea urchin predators such as snapper and lobsters (Shears and Babcock, 2002; Shears *et al*., 2008). However, there are no data on which to assess such impacts in Sydney Harbour.

Removal of lower trophic orders

Lower trophic orders include omnivores, particle feeders and detritivores (e.g. some molluscs, fishes, lobsters, prawns and crabs). They are important food sources for species higher up in the food chain such as sharks, dolphins, and penguins. In Sydney Harbour, yellowtail scad is the most commonly harvested recreational species accounting for the largest component of landed harvest by number in the eastern (35.3%) and western (36.6%) estuary zone (Henry, 1984; Ghosn, *et al.,* 2010). Lower order trophic groups are also commonly used for bait with bait harvest by number dominated by scads (60.2%) and slimy mackerel (14.6%) in the eastern estuary zone, and scads (32.8%) and slimy mackerel (24.4%) in the western estuary zone (Ghosn, *et al.,* 2010). Pre-adult king prawns, school prawns and greentail prawns were taken in large quantities by commercial fishers prior to the ban on commercial fishing in the Harbour in 2006 (Liggins *et al.,* 1996). Current recreational harvest of prawns is unknown but should be moderate if maximum intake guidelines are being followed (i.e. 4 prawns per individual/month). Lobsters can be collected by hand or pot, but harvest estimates are not available for the Harbour. There are no data on direct or indirect effects of removal of lower trophic orders within the Harbour itself, although at a state-wide level, stocks of several of these species are considered to be 'fully fished'.

Removal of herbivores

Herbivores are organisms that feed on marine plants and this group includes some fishes, turtles, marine molluscs and urchins. In tropical regions herbivores play a key ecological role in determining the distribution and abundance of algae, and shaping shallow coral reef ecosystems. The importance of herbivorous fishes in temperate regions such as Sydney Harbour is not well understood. In contrast, urchins and marine snails are known to play an important ecological role in maintaining habitats on temperate rock platforms and reefs.

Herbivores in Sydney Harbour include luderick, herring cale, sea urchins, and marine snails such as turbo or cats eye. Luderick is the main herbivorous finfish recorded in recreational catches in the Harbour, and accounted for 2.6% of the 69.7 tonne landed harvest within Sydney Harbour fishery in the 2007/08 survey (Ghosn, *et al*., 2010). However, it is not one of primary target species and capture requires specialised angling techniques. Harvesting of marine snails is prohibited throughout Sydney Harbour, although illegal harvesting has been documented. There are no data on rates of removal of urchins from the Harbour.

Death of discarded species

Many non-target species are incidentally captured and released by fishers. High rates of discard may represent a significant risk to sustainability of stocks if associated mortality is high, as current assessments and management regulations assume that discard mortality is negligible (Stewart, 2008). 292 800 individuals or 56.6% of the total recreational catch, by number, was discarded during the 2007/08 summer survey of Sydney Harbour. Ninety four percent of the discarded catch across the estuary was accounted for by snapper (43.2%), bream (17.1%), scad (9.1%), sweep (6.9%), flathead (3.8%), tailor (3.8%), leatherjacket (3.2%), kingfish (2.4%), mado (2.4%) and whiting (2.2%).

The survival rate of discards within Sydney Harbour is largely unknown. Research has been limited to a single study on yellowtail kingfish (Roberts *et al*., 2011). Here, individual fish were found to suffer 15% mortality after being caught and released. Discard mortality has been studied in many species of finfish and is generally species-specific and influenced by several physical and environmental factors (e.g. hook type, confinement time). Studies of fishes commonly caught in the Harbour show that survival can be variable but high if appropriate methods are used (e.g. yellowfin bream 72-97%; snapper 67-92%) (Gillanders, 2002). NSW DPI actively promotes guidelines on (1) Responsible Fishing and (2) Catch and Release Fishing through various channels including the DPI Recreational Fishing Guides, the DPI website, recreational fishing newsletters to fishers and face-to-face public advisory activities.

Illegal fishing

If fisheries management is effective, permitted fishing activity is considered sustainable. However, illegal fishing can undermine this principle and hence result in a stressor termed 'unsustainable harvesting'. This includes all fishing activities that do not comply with current fisheries regulations (e.g.

exceeding bag limits, keeping under-size fish or protected species, using illegal gear, and poaching from protected areas). These practices influence the effectiveness of current management and conservation efforts, and thus the ecological sustainability of the fishery. Retention of undersized fish by recreational fishers in Sydney Harbour is common and reportedly much higher than from other NSW estuaries (Henry, 1984; Ghosn *et al.,* 2010). In 1980/82 surveys, 93% of snapper and 30% of bream harvested by recreational fishers were below the minimum legal size limit. Similar trends were reported in 2007/08 with 51% of kingfish, 97% of snapper, 76% of tailor and 11% of bream in harvests being undersized.

Overharvesting of small fishes within estuaries may influence adult stocks as estuarine habitats are important nursery areas for many species. For example, most snapper (89%) caught in the adult fishery in central NSW, originated from local nursery estuaries including Sydney Harbour, Hawkesbury Estuary, Botany Bay, and Port Hacking (Widmer and Underwood, 2004). Non-compliance in Sydney Harbour occurs particularly during the warmer months and by fishers from ‘English as a second language’ communities. Non-compliance hotspots include mudflats around the Harbour and the Parramatta River and the Intertidal Protected Areas, Aquatic Reserve or fishing closures (e.g. Port Jackson Shellfish Closure).

Summary

The threat levels associated with the 6 identified stressors arising from recreational fishing in Sydney Harbour are given in Table 5.5.

Table 5.5 Threat levels for stressors relating to recreational fishing

	Stressor	Comment
Low	• Removal of top order predators	• Low level of pressure • Presumed to be rare
Medium	• Removal of herbivores	• Moderate pressure • No evidence of effect
High	• Removal of lower order predators • Removal of lower trophic orders	• High level of pressure • Only state-wide stock assessments available to assess direct effects • Possible local depletions
Very high	• Unsustainable harvesting caused by illegal fishing • Death of discarded species	• High level of pressure • Removal of organisms under the legal size limit • Illegal collection of shellfish • Poaching from North Harbour Aquatic Reserve

5.2.1.1 Boating and visitation

Sydney Harbour has over 50 km^2 of navigable waterway and is one of the most intensely used areas for recreational boating in the southern hemisphere (Whitfield and Becker, 2014). There were over 220,000 recreational vessels registered in NSW in 2010 of which an estimated 17,000 used Sydney Harbour (NSW RMS, 2013). Recreational vessels include motor boats, rowing boats, yachts, sailing dinghies, kayaks, and sailboards and these account for an average of 70% of overall boating activity in the Harbour (Whitfield and Becker, 2014). Vessels are used for exercise, fishing, general sightseeing, cruising, or racing. Maximum recreational boat traffic occurs in the main section of the Harbour (Point Piper to Bradleys head), on sunny weekends in summer (Whitfield and Becker, 2014), public holidays and during special events. Infrastructure to support boating activities occurs throughout Sydney Harbour and includes: 15 public boat ramps, 80 public wharves, 700 private landing facilities, 5,000 private moorings, and 30 sailing clubs (Hedge *et al.,* 2014b). Smaller commercial vessels (e.g. water taxis, government owned vessels, charter boats) are also very common in the Harbour, with similar potential impacts and associated stressors.

Visitation for tourism and recreation includes activities such as swimming, sightseeing, walking, diving, fishing, scuba diving, wildlife watching, picnicking, and boating. The Harbour is an important focal point for recreational and social activities in the greater Sydney region. The Harbour contains over 70 lookouts, 160 foreshore parks, 50 beaches, and a myriad of walking tracks (e.g. Harbour Circle Walk) (Hedge *et al.,* 2014b). Divers and snorkelers frequent several areas within the Harbour (e.g. Fairlight, Chowder Bay, Camp Cove) and swimmers regularly use beaches and netted enclosures.

Increasing visitation, including recreational boating, is likely as urban population increases and the tourism industry expands. For example, the 'Destinations Plan' is an initiative of the NSW Government designed to increase the number of services and amenities available to the general boating public on Sydney Harbour.

Current management

The NSW Maritime Division of Roads and Maritime Services is responsible for safety compliance, regulation of commercial and recreational boating, property administration, and infrastructure management. Stressors associated with general visitation and interactions with wildlife in foreshore areas of Harbour are managed by several agencies. Interactions between vessels and marine mammals in Sydney Harbour are currently managed through the NSW National Parks and Wildlife Amendment (Marine Mammals) Regulation 2006 which outlines maximum approach distances, speed limit and approach directions for different vessel types and procedures if marine mammals approach. These regulations are publicised in NSW maritime guidelines for boat use in Sydney Harbour.

Potential Impacts

Potential environmental impacts of recreational boating are associated with actual boat use and boating infrastructure (Whitfield and Becker, 2014; Hardiman and Burgin, 2010). Boat use has been associated with damage to habitats by propellers and anchors, intentional or unintentional introduction of debris and pollutants, wildlife disturbance (e.g. shorebirds, fishes, marine mammals), and injury to marine mammals from vessel strike. Boating infrastructure, such as boat ramps, jetties, piers, marinas, groynes, breakwaters, pilings, pontoons and moorings, can result in a diversity of impacts. These include damage, loss or fragmentation of naturally occurring habitats and changes to local hydrodynamics. These processes coupled with the introduction of novel artificial habitats can result in localised changes to marine assemblages, and the establishment of non-indigenous species. Water and sediment contamination may also result from the concentration of boating activity and associated pollutants (e.g. fuel, antifouling paints) around infrastructures. Dredging for recreational boat Harbours and approaches to boat mooring areas can impact on marine organisms through altered water turbidity, dissolve oxygen, and habitat disturbance and damage (Hardiman and Burgin, 2010).

Sydney Harbour, particularly in the upper reaches, is highly susceptible to environmental damage from boating activities as potential impacts have been shown to be most prevalent in shallow areas and smaller/narrower water bodies (e.g. bays, rivers, estuaries) and areas of regular and intense activity (e.g. around moorings, boat ramps, docks) (Whitfield and Becker, 2014; Hardiman and Burgin, 2010). A number of studies conducted within Sydney Harbour have quantified such impacts. Stressors relating to boating infrastructure, marine debris, and the introduction of exotic species are dealt with under other threat categories. While rowing boats, sailing dinghies, kayaks, and sailboards contribute to impacts related to infrastructure, impacts due to actual use are considered to be minimal (Whitfield and Becker, 2014). Potential impacts of foreshore and water-based visitation (e.g. swimming, exercising, fishing) are generally associated with littering, habitat damage, wildlife disturbance, and visitor infrastructure (Davenport and Davenport, 2006; Van Waerebeek *et al*., 2007).

Moving vessels

Potential impacts arising from boats while underway can be broken down into 3 stressors.

Vessel strike on wildlife

Collision with a vessel may result in injury or death of marine organisms, with surface breathing animals such as whales, dolphins, turtles and dugongs being particularly vulnerable Hazel *et al*., 2007; Laist *et al*., 2014). Risk of collisions is more likely in areas where intense vessel activity overlaps with key habitats or migration pathways; and at higher vessel speeds and/or for large less manoeuvrable vessels (Bowman, 2008; Laist *et al*., 2014). While vessel activity in Sydney Harbour is high, most surface-breathing animals are occasional visitors only, thus minimising potential interactions. Humpback and Southern right whales intermittently enter the Harbour from late April to November during their annual migrations. Mothers with calves have often been sighted and are potentially at greater risk from collision due to a greater time spent on the surface.

Dolphins and seals are also occasional visitors to the Harbour. There are no published data on the number of vessel strikes to marine animals within Sydney Harbour, but reports can be found in the media. For example, a Humpback with calf was accidently hit and injured by a ferry in Sydney Harbour in August 2012. Collisions have also been reported in nearby estuaries, for example, a humpback was injured in the Hawkesbury river in 2001 (Hazel *et al.,* 2007). Jet skis, which were banned in the Harbour in 2001, were also reportedly responsible for the death of several resident little penguins at Manly in 1997.

Wildlife disturbance

Boating can impact the behaviour of marine and terrestrial organisms (e.g. reduce fitness to feed, breed, migrate, nest, and rest) (Hardiman and Burgin, 2010; Lemon *et al*., 2006). There is little quantitative data on wildlife disturbance from boating in Sydney Harbour, but disturbances have been documented in other parts of NSW. Powerboats were found to affect the surface behaviour and direction of travel on dolphins in Jervis Bay (Steckenreuter *et al.,* 2012a); and dolphin-watching boats have been associated with reduced time spent feeding, socialising and resting and changes in habitat use of dolphins in Port Stephens (Steckenreuter *et al*., 2012b; Stamation *et al.,* 2010). Off the south coast of NSW, 40% of humpback whale pods were found to alter their behaviour in the presence of commercial whale watching vessels (Bishop, 2008).

Boating may also disturb much smaller organisms. For example, the abundance and diversity of invertebrate assemblages found on seagrass blades in seagrass beds exposed to boat wake was lower than for undisturbed areas in Narrabeen Lake (Erbe *et al.,* 2014). Underwater noise from vessels may also impact marine animals and is now an important consideration in habitat quality assessments and marine spatial planning in some countries.

Bank erosion

Wash from moving boats can lead to significant bank erosion in estuaries which can result in damage to near-shore vegetation and increased turbidity (Hardiman and Burgin, 2010). The operation of River Cat Ferries in the Parramatta River has been associated with bank erosion, habitat loss and damage, and changes to macro-benthic infauna (Higham and Shelton, 2011).

General boat use

While not in use, many recreational boats are anchored (short-term) or moored (longer- term). A widely recognised stressor resulting from these activities is ‘habitat damage’. Physical damage from anchoring or mooring can have serious impacts on benthic habitats (e.g. seagrasses, macroalgae, sponge gardens), particularly in shallow and sheltered waters (Hardiman and Burgin, 2010). Similar damage can be caused by propellers when power boats are in very shallow water.

Scouring of seagrass beds by traditional block and chain moorings (BCMs) can be observed from aerial photos or from satellite imagery and may lead to significant habitat fragmentation, sediment erosion, reduced productivity, loss of detritus and nutrients, and localised changes to species assemblages (Gladstone, 2010). Anchoring occurs throughout the Harbour, but some areas have a greater intensity of use, particularly over the weekends (e.g. Manly, Chowder Bay) (Hedge *et al.,* 2014b). Large number of recreational boats also anchor in Spring Cove which is within the North Harbour Aquatic Reserve

(Whitfield and Becker, 2014). Private moorings are found throughout Sydney Harbour, while commercial moorings occur primarily in the Port Jackson, Middle Harbour and Parramatta River Sub-catchments (few in Lane Cove area) (Hedge *et al.,* 2014b). Manly Cove, Watson's Bay and Vaucluse Bay have been flagged as high priority sites for management intervention within the Harbour as a large number of BCMs occur within seagrass at these sites and habitat damage was highly visible (Gladstone, 2010). Extensive loss of seagrass at Manly Cove has been quantified by surveys and potential recovery of seagrass after replacement of some BCMs with seagrass friendly moorings is being monitored (Gladstone, 2013; Bishop, 2004). Seagrass is an important foraging habitat for Little Penguins in North Harbour.

Visitation

Three stressors have been identified as arising from large numbers of people passively visiting the Harbour by foot around the foreshore; some of these are effectively the same as described above for moving vessels.

Wildlife disturbance

Boating may be a large contributor to wildlife disturbance (see above), but general visitation may also be an issue. Endangered little penguins in Sydney Harbour can be disturbed at nesting sites, during foraging and resting, and domestic dogs and cats (associated with visitation and increased urbanisation) are considered a key threat (NSW NPWS, 2002; Barker *et al.,* 2011). There are few data on disturbances caused by divers, even when that wildlife is the focus of the activity. No such targeted diving occurs in Sydney Harbour.

Physical damage of biota and compaction of soils

Unfettered access can lead to significant damage to biota through trampling (rocky shore, seagrass, saltmarsh and mangrove habitats, and their associated flora and fauna) (Barnes *et al.,* 2009) and compaction of sediments. This can lead to local losses of species and subsequent reductions in biodiversity. Sediment compaction of intertidal flats can have adverse effects by decreasing both biodiversity and total numbers of benthic macro-invertebrates inhabiting the sediment, which in turn has an effect on the benthic metabolism and sediment-water nutrient flux rates. There are no specific studies about these effects within Sydney Harbour.

Marine debris

Marine debris (or litter) is any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine environment. Common articles include plastic bottles, fishing gear, plastic bags, drinking straws, cigarette butts, and packing materials. Debris may originate from land or marine-based sources and from accidental or deliberate littering by individuals, industrial and manufacturing facilities, construction and demolition sites or vessels. Land-based debris enters waterway through sewer and stormwater systems, land-runoff, tidal action (on beaches) or during natural events (e.g. cyclones, floods). Plastic and synthetic materials are considered to be the most problematic as they are resistant to natural biodegradation processes. Solar radiation and wave action can break down larger objects, but plastic fragments may last hundreds of years (Gregory, 2009).

Marine debris causes deterioration of the aesthetic value of marine environments, particularly as it concentrates along shorelines which are of high recreational value. Marine debris has been listed as a key threatening process under the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) due to its capacity to cause injury to or death of marine and terrestrial organisms through drowning, entanglement, immobilisation, internal trauma or starvation after ingestion (Mallison *et al*., 2013). In contrast, the impacts of micro-plastics are poorly understood and the abundance of plastic resin pellets (the industrial raw material used in plastic manufacturing) entering waterways has only recently been recognised. These pellets are about the size of a pea, absorb toxic compounds from the water column, and when ingested by fish and seabirds can cause starvation and death ingestion (Mallison *et al*., 2013).

Marine debris is one of the most visible impacts of human use within and surrounding Sydney Harbour, and therefore a high potential threat. Over 50 tonnes of rubbish was collected from individual foreshore locations around the Harbour between 1994 and 2004 (Hedge *et al*., 2014b), and numerous community-beach and underwater clean-ups have been instigated. Although the occurrence of plastic pellets has not been quantified throughout Sydney Harbour, they have been documented at Manly Cove, Fairlight and the upper reaches of the Parramatta River (Cunningham and Wilson, 2003). The magnitude of impacts of marine debris on wildlife within the Harbour is unknown, but individual cases are often reported by the community (e.g. by photo). Debris originating from Sydney Harbour catchments is likely to impact adjacent coastal areas, as debris can be carried large distances by currents, wind and tides (Gregory, 2009). The abundance of marine debris on beaches within the Greater Sydney Region is comparable to some of the most polluted beaches around the world, with 90% of debris being plastic (Connell and Glasby, 1999).

Summary

The threat levels associated with the stressors arising from boating and general visitation in Sydney Harbour are given in Table 5.6.

Table 5.6 Threat levels for stressors relating to boating and visitation

	Stressor	Comment
Low	• Vessel strike on wildlife • Wildlife disturbance (general)	• Vessel strikes on wildlife are reportedly rare • Wildlife disturbance occurs but is not reported to have significant effects on populations of marine organisms other than little penguins
Medium	• Physical damage of biota and compaction of soils	• Stressor is frequent & widespread • Effects are uncertain
High	• Wildlife disturbance (specific) • Habitat damage (bank erosion) • Marine debris	• Primarily of concern for little penguins in nesting areas. Rated 'high' due to endangered status of the Sydney Harbour population. • Bank erosion by River Cats is considered significant in upper Parramatta River. • Marine debris occurs everywhere and is evident almost all the time. It can cause damage to biodiversity & affects the aesthetic value particularly of open water, rocky foreshore and beach habitats
Very	• Habitat damage (anchoring & mooring)	• Anchoring & traditional moorings leading to fragmentation and loss of seagrass which has significantly declined in the Harbour.

5.2.1.3 Extraction

Mining for oil, gas or various minerals can have significant impacts on marine environments. However, apart from some anecdotal accounts of using sand from Sydney Harbour beaches for construction purposes in the past, there is currently no mining activity occurring in Sydney Harbour. The only potential stressor relating to this pressure is habitat damage resulting from the periodic dredging of the shipping channels in the Harbour. There are currently no major dredging works in Sydney Harbour, although Sydney Ports do occasionally dredge for operational purposes. This stressor was assessed as having a low threat level (Table 5.7).

Table 5.7 Threat levels for the one stressor relating to extraction

	Stressor	Comment
Low	• Habitat damage caused by dredging	• Dredging is currently rare and site specific

5.2.2 Land-based impacts

Background

The foreshore occurs where the land meets the water and is more specifically defined as the part of the shore between the average high and low water marks. In reality, many foreshore developments extend into both the terrestrial and sub-tidal environments. Development of foreshores includes a wide range of activities which can impact on the environmental values of the system. These activities include shoreline hardening by building of breakwalls, wharves, jetties, marinas, and boat ramps, increased recreational access by vehicles and people and land reclamation. These activities are mostly permanent and functionally irreversible and therefore have long-term consequences. Foreshore development can act through a number of different stressors and developments can have multiple stressors. The stressors can be similar for different forms of development.

Current management

The catchment lands and waterways are owned and managed by a wide variety of stakeholders. For example, there are 28 local council areas wholly or partly within the Sydney Harbour catchment and 14 state government agencies and at least 2 Commonwealth government agencies have a management and/or land ownership role. In addition numerous pieces of legislation and policy relate to the Sydney Harbour catchment. The NSW Maritime Division of Roads and Maritime Services are responsible for property administration and infrastructure management related to commercial and recreational boating. Sydney Ports Corporation manages cruise terminal assets at Circular Quay (Overseas Passenger Terminal) and White Bay and dry bulk facilities at Glebe Island.

5.2.2.1 Foreshore development

Many of the stressors arising from development activity on the Harbour's foreshores have equivalent effects to those described above for visitation – namely 'disturbance to wildlife', 'physical damage and compaction of soils' and 'marine debris'. One particular type of damage to foreshore/intertidal habitats that is likely to be both qualitatively and quantitatively different, however, relates to 'habitat fragmentation and loss'.

Intertidal habitats can be lost or significantly altered in form by foreshore developments involving shoreline hardening, reclamation, localised dredging and increased private and public access. In the case of shoreline hardening, horizontal soft sediments or natural reef platforms in both the intertidal and sub-tidal zones are often replaced by vertical, featureless seawalls. This can lead to a complete change in the available habitats and can significantly reduce biodiversity. Habitat modification in the form of foreshore developments and the provisioning of artificial habitat in the form of wharves and pontoons can assist the spread of non-indigenous species as well as fundamentally change and fragment native communities of invertebrates, algae or fish (Glasby, 1999; Glasby *et al.,* 2007; Marzinelli, 2012; Marzinelli *et al*., 2011; Clynick *et al.,* 2007; Birch, 2007).

When reclamation occurs there is total loss of often large areas of habitat. The area of Sydney Harbour estuary has been reduced due to reclamation by an estimated 22%, mainly for industrial, recreational and residential use since first European colonization (Eyre and Ferguson, 2009). This has disproportionately affected intertidal and sub-tidal macrophytes and intertidal soft sediment habitats in the head of bays where intertidal flats have been filled in. This has significant flow-on effects for the organisms that rely on these habitats. Hardening and reclamation can also disrupt natural carbon and nutrient flow between riparian ecosystems and the estuary.

Summary

The threat levels associated with the stressors arising from foreshore development in Sydney Harbour are given in Table 5.8.

Table 5.8 Threat levels for stressors relating to foreshore development

	Stressor	Comment
Low	• Wildlife disturbance (general)	• As for 'increased visitation' - see Table 4.4
Medium	• Physical damage of biota and compaction of soils	• As for 'increased visitation' - see Table 4.4
High	• Wildlife disturbance (little penguins) • Marine debris • Habitat fragmentation and loss	• As for 'increased visitation' - see Table 4.4 • As for 'increased visitation' - see Table 4.4 • Impact is widespread due to extensive and ongoing foreshore development & building of in-water structures

5.2.2.2 Urban, rural and industrial development

The Sydney Harbour estuary catchment has undergone dramatic development since the arrival and settlement of Europeans in 1788. The early settlers embarked on extensive land clearing and poor land practises that promoted erosion and increased sedimentation rates into the estuary (Eyre and Ferguson, 2009). From the early 1800s industries took shape on the banks of Darling Harbour, Cockle, Rozelle and Blackwattle Bays. Metal foundries, tanneries, coppersmiths and paint manufacturers were established there during this early period. As the population and industry grew so did increases in surrounding urban areas.

From the second half of the 1800's industries such as abattoirs, brickworks, boat building, metal working and chemical industries had expanded to Iron Cove and Homebush bays (Eyre and Ferguson, 2009). Between 1889 and 1922, Iron Cove, Hen and Chicken and Homebush bays became extensively urbanised and industrialised. A large base metal foundry and a smelter were established on the shores of Hen and Chicken bay during the early 1900s and industry replaced agriculture in the Parramatta River region. Factories manufacturing heavy electrical equipment, large oil refineries and power supply stations were constructed close to the estuary between the first and second world wars.

After the first 220 years of European settlement, approximately 86% of the Sydney Harbour estuary catchment is estimated to have been urbanised and industrialised (Eyre and Ferguson, 2009). Pollutant inputs can arise from direct discharge to waterways or via mobilisation of diffuse sources of pollution such as fertilisers, litter, organic matter and sediments. In urban environments, aerial deposition of pollutants from industry and vehicles on catchment surfaces is large. The increased amount of impervious hard surfaces in urbanised catchments leads to much greater and faster transmission of rainfall to waterways, resulting in small fast runoff events that can mobilise and export these pollutants easily. These developments give rise to runoff of bioavailable nutrients, sediments and toxic pollutants, which can impact components of habitats and species in NSW.

In dry weather, creeks, rivers and stormwater drains provide a small, but constant, input of nutrients that have a primarily local effect (10s to 100 of metres from source) (Hedge *et al.,* 2014a, 2014b). Heavy rainfall can lead to large amounts of runoff in waterways and drains. That runoff often contains large volumes of suspended sediments and heavy metals and other toxicants from hard surfaces such as roads (Hedge *et al.,* 2014a, 2014b). It also contains moderate concentrations of nutrients. Large developments, in particular, can also put added flows into existing stormwater and sewage infrastructure that can result in sewage overflows during large spates. Sewage overflows are a major source of nutrients and faecal microbes to the Harbour impacting on public health and amenity (swimming, boating rowing, fishing etc.).

Developments also affect the quantity and quality of groundwater seepage, particularly the composition and concentration of nutrients. Nutrient inputs from groundwater are widespread and constant, but only affect low energy intertidal and shallow soft sediment habitats. Inputs of nutrients, sediments and toxic pollutants from point sources are constant but localised, occurring in locations with large industries and cities.

Increased nutrients and organic matter

It is well established that catchment disturbance as well as fertiliser application, effluent discharges and urban stormwater can greatly increase the amount of nutrients and organic matter being exported to the receiving waterways. This can have profound effects on a number of key biogeochemical processes that are important in providing food to the system's broader food web as well as regulating carbon and nutrient cycling. Increased inputs of nutrients can cause excessive growth of micro- and macroalgae, leading to nuisance algal blooms and increased metabolism in both the sediment and the water column. Increased organic matter inputs from in-situ and ex-situ production can cause localised and broad scale depletion of oxygen (hypoxia and anoxia) and can greatly impact fish and invertebrates.

Sections of the Parramatta River estuary already show evidence of organic matter enrichment through low dissolved oxygen concentrations in bottom waters (OEH unpublished data). Increased benthic respiration can also reduce important nutrient depuration processes such as denitrification (Irvine and Birch, 1998) and lead to greater loading of inorganic nitrogen and phosphorus to the water column which further augments algal productivity.

Excessive production of epiphytic and pelagic algae can directly inhibit growth of seagrass by limiting light needed for photosynthesis. Loss of seagrass can impact on invertebrates, fish and some marine reptiles and mammals which use the seagrass as a habitat and food source. Nutrient inputs can impact mangroves and saltmarsh because they stimulate growth of weeds and have been implicated in the invasion of saltmarsh by mangroves. Seagrasses are system engineers, decreasing water flows above their fronds and facilitating deposition and consolidation of both organic and inorganic sediments.

Increased sediment input

Sediment inputs are generated by soil erosion in catchments disturbed by human activity as well as riverbank and shoreline erosion. Coarse sediment settles out along river beds, floodplains and at tributary mouths while finer suspended sediment fills bays and central basins and reduces water clarity. Sediment inputs can reduce water clarity with implications for seagrass and algae. Sediments can also smother sessile invertebrates and can cause gill irritation in fish.

Input of toxic pollutants (from catchment runoff & point sources)

Toxic pollutants can be present in the water column and be associated with and accumulate in intertidal, shallow and deep soft sediments and affect the invertebrates in those sediments. Extensive areas of Sydney Harbour estuary have sediments containing high concentrations of a wide range of contaminants (i.e. heavy metals (Irvine and Birch, 1998; Birch and Taylor, 1999; Daffron *et al.,* 2012; Birch and Taylor, 2000). organochlorine pesticides (McCready *et al.,* 2000), polycyclic aromatic hydrocarbons (Roach *et al*., 2009) polychlorinated dibenzodioxins (dioxins) and dibenzofurans (furans) and other organohalogenated hydrocarbons (Thompson *et al*., 2009; Roach and Runcie, 1998).

Toxic pollutants have, and continue to, come from a variety of industrial, urban and rural sources. Toxic polycyclic-aromatic hydrocarbons (PAHs) come from car and truck exhausts and enter receiving waters from atmospheric deposition and stormwater. Pesticides, herbicides and fertilisers routinely used in rural and urban areas are lifted away with the topsoil and enter the estuary via the creeks and the stormwater system. Metals come from discharges from smelters and chemical industries and dioxins are produced as by-products of industrial processes such as bleaching paper pulp, pesticide manufacture, and combustion processes such as waste incineration.

Contaminants can have lethal and sub-lethal effects on fish, elasmobranchs, birds, reptiles and mammals and be biomagnified through food chains. Numerous studies have reported significant levels of organic and inorganic contaminants in fish, crustaceans and molluscs in Sydney Harbour (Birch and Taylor, 2000; Losada *et al*., 2009; McKinley *et al*., 2012; Edge et al., 2012; McKinley *et al.,* 2011). In addition, sub-lethal effects in oysters (Edge *et al.,* 2014), changes in communities of larval fish (Sun *et al*., 2012), bacteria and invertebrates associated with contamination have been observed (Birch and Taylor, 2000; McMahon *et al.,* 2005). Herbicides entering estuarine waters can reduce growth of seagrass, saltmarsh, mangroves, and micro- and macro-algae (Gillanders and Kingsford, 2002).

Litter contributing to marine debris

Litter in runoff occurs constantly but not in all habitats. Litter is unsightly and is commonly linked to harming wildlife, encouraging pest animals and water pollution. Certain types of litter degrade and contribute to algal blooms (i.e. organics) or leach toxic chemicals (e.g. cigarette butts). See 'Marine Debris' for further details.

Altered runoff

The increased volume and intensity of runoff can impact components of all habitats. The greatest impacts are observed in estuarine habitats where both changes to the salinity and hydrodynamic regimes can have systemic effects (Carlton, 1985). Large runoff events can cause scouring and redepositing of sediment causing smothering of habitats such as seagrass and also resuspension of sediments affecting water column clarity. Decreases in water clarity can be particularly problematic for primary producers which require sunlight to fix carbon and grow.

Thermal pollution

Thermal pollution is the addition of heated water to the environment. Discharged heated water can directly affect photosynthesis, particularly the growth of seagrass, and be lethal to plankton and to invertebrates inhabiting mudflats and rocky shores. Fish, elasmobranchs and marine reptiles may experience thermal shock and become stressed leading to increased susceptibility to disease and alterations in behaviour. Persistent temperature shifts can also affect spawning timing and growth rates of both fish and invertebrates. Heated water may also have indirect effects because it can alter the toxicity of certain pollutants.

Increases in temperature also decrease the saturation concentration of oxygen.

Thermal pollution is a well-recognised issue for estuarine waters along the NSW Illawarra and central coasts receiving cooling discharge from coal-powered stations. However, it only occurs from a few sites in Sydney Harbour where industries and facilities use water for cooling, including air conditioner condensers.

Summary

The threat levels associated with the stressors arising from urban, rural and industrial development in Sydney Harbour are given in Table 5.9.

Table 5.9 Threat levels for stressors relating to urban, rural and industrial development

	Stressor	Comment
Low	• Thermal pollution	• Very few remaining discharges of heated water into the Harbour
Medium	• Altered runoff	• Some legacy issues, but currently well controlled except during very heavy rainfall events
High	• Litter contributing to marine debris	• As for 'ncreased visitation' – see Table 4.4
Very high	• Increased nutrients, organic matter and sediment (catchment runoff, sewage & stormwater outlets) • Input of toxic pollutants (runoff & point sources) • Legacy toxic pollutants in sediments (eg. heavy metals, dioxins, etc.)	• Stormwater is a pervasive pressure throughout almost the entire Harbour and impacts are apparent after every heavy rainfall event. • Contaminated sediments abound throughout the Harbour and their disturbance can cause a wide range of impacts

5.2.2.3 Modified freshwater flows

Two stressors have been identified as arising from this pressure.

Barriers to connectivity

Instream structures that span the whole channel (e.g. weirs, causeways) can impede natural flows and act as physical and hydrological barriers to fish movement thus isolating upstream and downstream habitats. Even structures such as road culverts and piped crossings can impact on fish passage if they are not designed correctly or adequately maintained.

Furthermore, structures installed in channel banks and floodplains such as levees, floodgates and other off-stream structures (e.g. detention basins and gross pollutant traps) can disrupt lateral connectivity by isolating seasonal or ephemeral habitats on floodplains and wetlands. Channelised and piped sections of waterways reduce the extent of aquatic habitat available and may deter fish movement. Many fish are reliant on a variety of different habitat types throughout their life cycle (e.g. sea mullet, eels). The free passage of fish within rivers and streams and between estuarine and freshwater environments is a critical aspect of aquatic ecology in coastal NSW.

Sydney Harbour catchments have a legacy of poorly designed structures which continue to detrimentally affect migratory fish. Like many rivers throughout NSW, the Parramatta River and its tributaries are highly regulated. Weirs in the Parramatta River have probably had a major effect on a number of migratory native fish such as Australian bass which is now seldom caught in most parts of the river. Many of the weirs along the Parramatta River are very old, and none have previously had fishways installed. For example, the Charles Street weir was built in 1950-51, while Marsden Street weir was originally constructed in 1818, and rebuilt in the 1920s out of concrete after being washed away during floods three times. Consequently, the upper Parramatta River has been fragmented by weirs for up to 190 years.

Potential barriers to fish passage within Middle Harbour/Lane Cove and Parramatta River catchments were reviewed extensively by Nichols (2005). Fourteen and thirty-seven structures were prioritised for remediation in the Middle Harbour/Lane Cove and Parramatta River catchments respectively, involving basic management/maintenance of sites, modification of structures, or complete removal and replacement.

In the past 2 decades, fishways have been installed and are functioning at three weirs along the Parramatta River (Charles Street, Marsden Street, Kiosk Weir). The upstream weir currently has no fishway but, if installed, it would open up the whole upper Parramatta catchment. One weir in the Lane cove river has been remediated with a partial-width rock-ramp fishway providing access to an extra 49 km of habitat.

Changes to freshwater inflow

Permanent water extraction from Sydney Harbour is currently rare, although it was likely a more significant pressure during earlier times. There is now only one licensed water extraction point at Marsden weir which is used by Parramatta council to fill up water tankers for garden watering. However, because of the extensive historical modification of freshwater flows into the Harbour, patterns of inflow remain compromised and therefore a moderate threat to marine biota and habitats.

Current management

The importance of free fish passage for native fish is recognised under the Fisheries Management Act 1994 which has provisions specifically dealing with the blocking of fish passage. In addition, the installation and operation of in-stream structures, and the alteration of natural flow regimes, have been recognised as Key Threatening Processes under this Act and also the Threatened Species Conservation Act 1995. These legislative tools, and associated NSW Government policies on fish passage, regulate the construction of structures that may be barriers to fish passage. In addition, reinstating connectivity between upstream and downstream habitats and adjacent riparian and floodplain is an essential part of aquatic habitat management and rehabilitation programs in NSW.

Summary

The threat levels associated with the stressors arising from modified flows in Sydney Harbour are given in Table 5.10.

Table 5.10 Threat levels for stressors relating to modified freshwater flows

	Stressor	Comment
Medium	• Barriers to connectivity • Reduction of volume and changes to timing of inflows	• In-stream infrastructure still limits connectivity of some parts of the Parramatta and Lane Cove rivers • Limited water extraction in Parramatta River but historical inflow modification

5.2.3 Biosecurity

Marine biosecurity threats refer to the adverse impacts arising from the introduction and spread of exotic marine species or diseases into a particular location – in this case Sydney Harbour.

Prior to the European colonisation of Australia, there was little human linkage between Sydney Harbour and other estuaries even along the NSW coast, let alone with other parts of the world. The arrival of the First Fleet in 1788 marked the beginning of an ever expanding maritime connection between Sydney Harbour and the rest of the world. Initially, journeys from Sydney Harbour were limited largely to explorations along the eastern seaboard or voyages back and forth to Europe via southern Africa. Once the colony in Sydney was well established, however, wooden sailing ships would have visited the Harbour with increasing frequency and after visiting several ports elsewhere. A boom in sea trade occurred following the establishment of timber, and later wool, as important exports, resulting in increased visitation. Wooden ships were supplemented by steam-powered metal vessels in the late 19th century and then replaced entirely by modern diesel-powered ships in the 20th century.

In the early days of Sydney, maritime voyages were made solely by commercial vessels for the transport of people or supplies directly associated with the colony, but by the mid 20th century there were increasing visits by large ships bringing tourists or by small, privately owned, ‘recreational’ vessels. Today, there are still some commercial shipping operations in the Harbour, although the volume of traffic is well beyond its peak. The Australian navy still has ships based in Sydney. Use of the Harbour by international cruise ships and recreational boats, however, continues to grow (Hedge *et al.,* 2014b), increasing the potential for the introduction of non-indigenous species, although these may be different to the ones previously identified as pests. Interchange between Sydney Harbour and other Australian ports and estuaries will likely remain high for recreational vessels.

Potential Impacts

Transport processes have been well studied globally and there is substantial evidence that shipping has spread marine organisms from one port to another, even across oceans and hemispheres. There is little doubt that marine non-indigenous species (NIS) have been arriving on, or in, almost every vessel that has visited Sydney from a foreign port. Most of the NIS associated with boats or ships reside in ballast water, on the ship’s hull or in the many pipes and other associated structures on the vessel (Carlton, 1985; Ruiz *et al*., 2000). Even if individual NIS or their progeny leave or are removed while a vessel is in port, the chances of them establishing a viable population is usually considered quite small (Glasby and Creese, 2007). Following establishment, an NIS would then need to spread, at which stage it would have the potential to impact on native habitats, biotic assemblages or Harbour infrastructure.
Deliberate translocation of species for aquaculture or the aquarium trade, and associated species that have ‘piggy-backed’ on live aquaculture imports, are also important mechanisms for the introduction of NIS into foreign waterways (Naylor *et al.*, 2001). These vectors can also introduce novel diseases to an estuary.

Once established, NIS can have a number of impacts. There are well documented cases around the world and in Australia involving displacement of native species through either predation or competition, smothering of rocky reefs or soft sediments and long-term changes to ecological processes. NIS are particularly adept at invading disturbed habitats and at colonising new surfaces in the sea, thereby excluding settlement by native benthic species. In addition to impacts on biodiversity, NIS and exotic disease can cause severe economic costs to aquaculture businesses, commercial fishing, coastal infrastructure and boating operations. Eradication attempts, if considered worth attempting, are usually expensive and can cause social disruption.

5.2.3.1 Introduction of exotic marine species

The most comprehensive assessment of NIS in Sydney Harbour was completed by the Australian Museum in 2002, which sampled 57 sites in the Harbour using a wide variety of sampling techniques (Australian Museum Business Services, 2002). Among the marine species collected, one dinoflagellate, one fish, one seaweed and 15 macroinvertebrates were confirmed as being exotic. A further 9 species were suspected of being introduced. That survey also mapped where the NIS occurred in the Harbour. None of the NIS identified at that time were considered as particularly troublesome. Since 2002, several more NIS have been identified, including an intertidal gastropod (Andrews *et al.,* 2010) and the seaweed *Caulerpa taxifolia* (Creese, *et al.,* 2004). The latter was considered a potential problem because of its ability to spread rapidly and completely cover sandy substrata and threaten native seagrass beds – as it had in the Mediterranean Sea. Despite becoming established in a number of NSW estuaries in the early 2000’s and becoming dominant in a few of them, this seaweed has not caused the major ecological or economic disruption that was initially feared (Glasby, 2013). However, it is still present in small pockets in the lower reaches of Sydney Harbour and could pose potential future risks if it was ever able to expand its distribution significantly.

In NSW a risk assessment approach has identified the most likely vectors and species to arrive and become established in Sydney ports (Glasby and Lobb, 2008). That modelling indicated that many species currently not found here, but common in ports worldwide, have an elevated chance of establishment in Sydney Harbour. These include high risk pest species such as the Asian shore crab, the Chinese mitten crab and the brown mussel. The probability of NIS introduction from the ports of Singapore, Auckland, Port Villa, Tauranga and Napier are particularly high due to similar environmental conditions and high rates of shipping to and from Sydney Harbour.

The proliferation of artificial structures and high levels of contamination within Sydney Harbour are likely to enhance the chances of establishment by NIS following introduction (Dafforn, *et al.,* 2008).

5.2.3.2 Introduction of exotic diseases affecting marine species

Risks associated with the introduction of new diseases are always high. Many toxic dinoflagellates and other microalgae have been spread around the world and can cause severe mortality of filter feeding organisms, including cultivated bivalves on marine farms. Similarly, diseased animals or seafood products can introduce pathogens that cause major problems. There have been no reported major outbreaks in Sydney Harbour in recent times, although Pacific Oyster Mortality Syndrome has killed many cultivated Pacific oysters in the neighbouring estuaries of the Hawkesbury and Georges rivers after being introduced from overseas. Although not specific to Sydney Harbour, a virus caused mass mortalities of pilchards around Australia in the late 1990s and had severe impacts on fishing businesses after having being introduced in contaminated imports.

Summary

The threat levels associated with the stressors arising from introduced marine species or disease into Harbour are given in Table 5.11.

Table 5.11 Threat levels for stressors relating to marine biosecurity

	Stressor	Comment
High	• Exotic marine species • Exotic diseases affecting marine species	• Currently known NISs pose little threat; potential threat high because of the many vectors present in SH, the widespread disturbed habitats that would enhance establishment and the potentially severe social & economic, as well as environmental, consequences of new exotic NISs • As above, but for novel diseases

5.2.4 Marine industry pollution

Large commercial vessels (>12 m) in Sydney Harbour include ferries, merchant ships, and government owned vessels, military vessels, cruise ships, cargo ships, pilot vessels, tankers, tow boats, and tug boats. The port of Sydney is extremely important for trade and tourism. Trade through Sydney Harbour now consists predominantly of dry bulk items such as sugar, salt, cement, gypsum and bulk liquids such as refined oil and vegetable oil (http://www.sydneyports.com.au/trade_services). The cruise industry reflects Sydney's role as a tourism gateway to NSW and Australia, with 240 cruise ship visits in 2013, including the world's leading luxury liners. Ferries also play an integral role in tourism and act as a key method of transport for local communities. In 2013, 174,029 ferry services were scheduled, carrying 14.9 million passengers.

The distribution of large commercial vessels and associated infrastructure in the Harbour varies according to their purpose. For example, Circular Quay is the hub of the ferry network, providing access to 37 other wharves including Manly, Eastern and Lower North Shore, the Parramatta River, the Balmain peninsula and Darling Harbour. Cruise industry vessels use the Overseas Passenger terminal at Circular Quay and White Bay Cruise Terminal, while dry bulk facilities occur at Glebe Island. Smaller commercial vessels (e.g. water taxis, government owned vessels, charter boats) are also very common in the Harbour.

The occurrence of commercial vessels in the Harbour is likely to increase with increasing trade and tourism opportunities and urban population growth.

Current management

The NSW Maritime Division of Roads and Maritime Services are responsible for safety compliance, regulation of commercial and recreational boating, property administration, and infrastructure management. Sydney Ports Corporation manages the commercial shipping requirements of the Harbour including: navigation and safety, pilotage, cruise, dry bulk and oil shipping, and the management of cruise terminal assets at Circular Quay (Overseas Passenger Terminal) and White Bay and of dry bulk facilities at Glebe Island. Both Maritime and Sydney Ports also aim to balance the function and growth of activities with commitments to environmental protection. The Australian Marine Safety Authority maintains a database of hourly ship positions for all ships in the Australian region, including Sydney Harbour.

5.2.4.1 Oil and chemical spills

Marine Industry Pollution is primarily due to marine oil / chemical spills and ship accidents. Significant instances of both are rare - there have been only two significant spills in the last 3 decades, both in the 1990s. If a spill occurred in Sydney Harbour it would be dealt with in accordance with the NSW State Waters Marine Oil and Chemical Spill Contingency Plan. The combat agencies would be the Port Authority of New South Wales in Sydney Port.

Each year there are numerous minor incidents or reports of oil on the water or ashore. This included a number of sunken or grounded recreational and fishing vessels. These vessels have either resulted in the vessel breaking up and small amounts of pollution entering the water or salvage of the vessel without a pollution incident. Minor chemical inputs mainly occur from leaking shipping containers in ports. These are dealt with by Fire & Rescue NSW in conjunction with NSW Port Corporations and the EPA. Crude oils are no longer brought into Sydney Harbour, so the only remaining major threats come from ship fuel (bunker oil) or cargo such as petroleum or diesel. There is some possibility of cumulative effects on organisms from minor inputs of oil and chemicals but little evidence to date. A major spill affects organisms in two ways, either due to acute toxicity from volatile components or by impacts due to physical coating by oil.

These impacts can range from suffocation to immobilisation and interference of buoyancy and thermoregulation in birds and mammals. The magnitude of impact will depend very heavily on the type of oil. The hundreds of tonnes of light crude oil that was released in the Laura D Amato spill in Sydney Harbour in 1999 evaporated quickly, little acute impact was observed and the oil left only a minor residue on rocks which is unlikely to have had significant impact on intertidal communities. Most major impacts have come from very heavy fuel (bunker) or crude oils that can coat surfaces and organisms. Inappropriate oil spill response techniques can drive oils deep into porous or complex substrata (eg rock walls or boulder fields) and prolong the impacts.

Summary

Commercial vessel activity contributes to several other stressors including marine debris, vessel strike on wildlife, wildlife disturbance and bank erosion. These were discussed earlier in section 5.2.1.2. Threat values for stressors associated with marine pollution are given in Table 5.12.

Table 5.12 Threat levels for stressors relating to marine industry pollution

	Stressor	Comment
Low	• Oil/chemical spills • Wildlife disturbance • Vessel strike on wildlife	• Major spills rare; little evidence of cumulative effects from minor spills or leakage • As for 'increased visitation' - see Table 5.6 • As for 'increased visitation' - see Table 5.6
High	• Marine debris • Bank erosion (Parramatta River)	• As for 'increased visitation' - see Table 5.6 • As for 'increased visitation' - see Table 5.6

5.2.5 Climate change

Climate modelling predicts that Australian waters will warm by 1–2°C by 2070. South East Australia is considered a global 'hot spot' for ocean warming, occurring at ~4 times the global average, due to increased strength and southward penetration of the East Australian Current (EAC) (Ridgway, 2007; Hobday *et al.,* 2006a).

The impacts of climate change on the biophysical environment of NSW, and limitations associated with predictions, have been assessed at a regional level (DECCW, 2010). By 2050, the climate in the Sydney/Central coast region (including Sydney Harbour) is virtually certain to be hotter, with mean daily maximum and minimum temperatures increasing by an estimated 1.5-3^{o}C. Rainfall is likely to increase in all seasons except winter, increased evaporation is likely in spring and summer, the impact of the El Niño-Southern Oscillation is likely to become more extreme, and sea level is virtually certain to keep rising.

Current management

Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions worldwide. Climate change has been identified as a key threat to marine environments in NSW and climate change adaptation strategies have become a core component of natural resource management (DECCW, 2009). Apart from some specific adaptation measures in Sydney Harbour, there is nothing that can be done at a local scale to control the pressures arising from climate change.

Potential Impacts

The impacts of climate change on the marine environment will occur at a global scale and be long term. Significant effects are expected to occur across South East Australia and include changes to: marine species distribution and abundance; phenology or timing of life cycle events; physiology, morphology and behaviour (e.g. rates of metabolism, reproduction, development); and biological communities (Hobday *et al.,* 2006b; Wernberg *et al.,* 2011). Climate change may also facilitate the spread and establishment of pathogens and exotic species (Wernberg *et al.,* 2011).

Estuaries, such as Sydney Harbour, are transition zones linking land, freshwater and marine habitat and are likely to be affected by interacting climatic and hydrologic variables (Gillanders *et al.,* 2011). Predictions of climate change are complex due to the dynamic nature of estuarine systems overlaid with anthropogenic stressors, but are summarised by (Gillanders *et al.,* 2011). Changes to dissolved CO^2 concentrations, temperature, precipitation, sea level will likely affect the circulation, levels of salinity, suspended sediments, dissolved oxygen and biogeochemistry of estuaries (Gillanders *et al.,* 2011).

Species that have a wide tolerance to multiple environmental variables (e.g. estuarine residents and marine migrants) are likely to survive and tolerate changing estuarine conditions, while early life history stages (i.e. eggs and larvae) are most likely to be impacted. Specific impacts, however, are poorly understood and there are few baseline data or ongoing monitoring programs with which to assess potential changes94,95. Several of the commonly recognised stressors are considered below (Hobday *et al.,* 2006b; Wernberg *et al.,* 2011).

Altered currents & changes in upwelling frequency

Continued global ocean warming will penetrate from the surface to the deep ocean and affect ocean circulation. Such effects have already been observed within South East Australia with the increased strength and southward penetration of the East Australian Current (EAC) (Ridgway, 2007). These changes, combined with increasing sea temperature are considered responsible for the southward range extension of a sea urchin into Northern Tasmania and the creation of previously absent urchin-grazed barrens habitat (Wernberg *et al.,* 2011).

Changes in the EAC and upwelling processes may affect ecosystems in estuaries like Sydney Harbour, with organisms that spend part of their lives on the open coast most likely to be affected. In particular, connectivity between estuarine and marine environments may change under climate change scenarios 96. For example, strengthening of the EAC may afford increased tropical-temperate connectivity exposing the Harbour to a greater diversity of subtropical and tropical species. Estuarine circulation may also change due to alterations in water temperature, salinity and flow but long-term impacts have not been studied for Australian estuaries (Gillanders *et al.,* 2011).

Sea temperature rise

Australia's temperate coast is predicted to continue warming, increasing by 1-3ºC over the next century. Temperature increases may influence the distribution and abundance of fishes (and other organisms) in estuaries through changes to recruitment and reproductive processes. The extent of impacts will depend on whether species are at the extremes of their distribution and temperature tolerance (i.e. northern or southern boundary of geographic range) (Gillanders *et al.,* 2011).

There is limited information on the response of marine organisms to climate change within the Harbour. However, current winter temperatures act as key bottlenecks for long-term survival and population establishment of tropical fishes which settle around Sydney during summer (Figueira and Booth, 2010). Current warming trajectories resulting from climate change predict that 100% of winters will be survivable by several tropical species as far south as Sydney by 2080, facilitating possible range expansions of these species into NSW waters (Figueira and Booth, 2010). Early development of the purple sea urchin, which is common in the Harbour, has shown to be retarded at sea temperatures predicted under climate change scenarios (Byrne *et al.,* 2009).

Ocean acidification

Elevated carbon dioxide may impact marine organisms through changes to metabolic physiology, calcification rates of hard structures (e.g. shells, external skeletons) and flow-on effects through changes to food webs (Gillanders *et al.,* 2011). Estuaries, like Sydney Harbour, may be more susceptible to reduced pH as they are shallower, less saline and have lower alkalinity than marine waters, but few studies have focused on potential effects to estuarine organisms (Gillanders *et al.,* 2011).

Sea level rise & increased storm frequency and intensity

The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia, and between 1901 and 2010, global mean sea level rose by 0.19 m. Global mean sea level will continue to rise, and is very likely to exceed rates observed during 1971 to 2010 due to increased ocean warming and increased loss of mass from glaciers and ice sheets. Sea level in the Sydney region is expected to rise 0.4 m and 0.9 m above the 1990 mean sea level by 2050 and 2100 respectively (Hobday *et al*., 2006). Flood frequency, height and extent are also likely to increase in the lower portions of coastal floodplains (Hobday *et al*., 2006).

Sea level rise and storms are virtually certain to increase coastal inundation and erosion, causing the erodible coastline to recede, typically by 20-40 m by 2050 and 45-90 m by 2100. Shoreline retreat is very likely to be higher in estuaries and where beaches are backed by seawalls there is likely to be narrowing and loss of sandy recreational areas (Hobday *et al*., 2006). Saline waters may move into new areas of the coastal plain inundating places with acid sulphate soils, causing soil structural decline (e.g. tidal foreshores of the upper Parramatta River).

Seagrasses, mangroves and saltmarshes are likely to be displaced (e.g. in Homebush Bay), but mangroves should re-establish in other areas currently occupied by saltmarsh. Infrastructure and development are virtually certain to impede re-establishment of estuarine habitats in the Parramatta River (Hobday *et al*., 2006).

Estuarine food webs and some fishes are likely to be adversely affected due to changes in species composition of estuarine invertebrates (Hobday *et al*., 2006). Loss of intertidal habitat is also expected to exacerbate the decline of migratory shorebird populations which use these areas for foraging and nesting. This includes internationally significant areas such as Homebush Bay (Hobday *et al*., 2006).

Little Penguins nesting areas within North Harbour may also be threatened by increasing sea levels, particularly during storm events (Dann and Chambers, 2013).

Altered nutrient, sediment and freshwater inputs

Soil conditions in spring are likely to be slightly drier in the Sydney region due to increased temperatures and evaporation (Hobday *et al*., 2006). A minor increase in annual run-off is projected, with summer run-off likely to increase substantially. Increases in suspended sediment due to increased freshwater input and flood events may limit primary productivity of seagrasses. Climate change may also alter nutrient input and the time they remain in an estuary (Gillanders *et al.,* 2011). Nutrients, light and freshwater flow may influence plankton assemblages and estuarine food webs (Gillanders *et al.,* 2011). Changes to salinity and freshwater-flow may alter species richness and abundance of estuarine fishes as these factors influence metabolism, movement, reproduction, growth, (Gillanders *et al.,* 2011). Alterations in dissolved oxygen due to changes in river flow and temperature may affect salinity, nutrient concentrations and phytoplankton influencing the estuarine food webs. Low concentrations of dissolved oxygen could also affect fish growth, mortality, distribution and abundance (Gillanders *et al.,* 2011).

Summary

Climate is almost universally accepted as the major threat facing the world's coastlines, including estuaries, especially where there is substantial urban development. Threat values from climate change stressors are all considered to be very high (Table 5.13).

Table 5.13 Threat levels for stressors relating to climate change

	Stressor	Comment
Very high	• Altered currents & changes in upwelling frequency	• Likely, but future impacts uncertain
	• Sea temperature rise	• Likely, but future impacts uncertain
	• Ocean acidification	• Likely, but future impacts uncertain
	• Sea level rise & increased storm frequency/intensity	• Likely, but future impacts uncertain
	• Altered nutrient, sediment and freshwater inputs	• Likely, but future impacts uncertain

5.2.6 Summary of threats to environmental values

The qualitatively assigned threat levels for those stressors considered to have some level of threat to the environmental assets in Sydney Harbour, in terms of both habitats and species groups, are shown below in Table 5.14. In the case of the pressures arising from climate change, the stressors are not listed separately.

Table 5.14 **Summary of threat levels to the environmental assets of Sydney Harbour**

	Habitats	Biodiversity
Low threat	• Oil & chemical spills • Dredging • Runoff from acid sulphate soils	• Removal of top order predators by rec. fishing • Vessel strike on wildlife • Wildlife disturbance (general) • Thermal pollution • Oil & chemical spills • Dredging
Medium threat	• Physical damage of biota and compaction of soils • Altered runoff • Barriers to connectivity & changes to inflows from in-stream infrastructure • Artificial structures	• Physical damage of biota and compaction of soils • Altered runoff • Barriers to connectivity & changes to inflows from in-stream infrastructure • Artificial structures
High threat	• Bank erosion (Parramatta river) • Habitat fragmentation & loss as a result of foreshore development • Introduction of exotic marine species & disease affecting marine species • Marine debris	• Removal of lower order predators & species at lower trophic levels by rec. fishing • Wildlife disturbance (little penguins) • Bank erosion (Parramatta river) • Habitat fragmentation & loss as a result of foreshore development • Introduction of exotic marine species & disease affecting marine species
Very high threat	• Habitat damage (anchoring, mooring) • Increased nutrients, organic matter & sediment (catchment runoff, sewage & stormwater outlets) • Input of toxic pollutants (runoff & point sources) • Legacy toxic pollutants in sediments (eg. heavy metals, dioxins, etc.) • Climate change (all stressors)	• Death of fish discarded by rec. fishers • Non-compliance by fishers with size/bag limits or spatial closures • Habitat damage (anchoring, mooring) • Increased nutrients, organic matter & sediment (catchment runoff, sewage & stormwater outlets) • Input of toxic pollutants (runoff & point sources) • Legacy toxic pollutants in sediments (eg. heavy metals, dioxins, etc.) • Climate change (all stressors)

5.3 Economic values of Sydney Harbour

5.3.1 Harbour functions

There are a great number of commercial activities that operate in or out of Sydney Harbour. Many of these area summarised in Hedge *et al.* (2014b).

5.3.1.1 Sydney Ports

Upgrading the Overseas Passenger Terminal to handle larger ships and provide quicker turnaround time will include projects totaling about $49.4 million. There were 240 cruise ship visits for the year, a compound annual growth of more than 26 % per year for the last several years. The White Bay Cruise Terminal was completed and opened with two berths; a $57 million facility. Sydney can now host three cruise ships simultaneously.

Sydney Ports Corporation financial accounts identify total operations, thus including Port Botany and the smaller ports. Sydney Harbour had 522 chargeable vessel visits in 2012/13, however, Botany Bay had about three times that number. Total revenue from operating activities in 2012/13 was listed as nearly $65 million, of which about $52.2 million was from port revenue and $12.8 million from rental revenue.

In last year's report, Sydney Ports Corporation stated that combined our ports handle more than $61 billion worth of trade each year, contribute about $2.5 billion to the NSW economy, and generate employment for more than 17,000 people throughout the logistics chain. (Sydney Ports Corporation Annual Report, 2012/13).

5.3.1.2 Maritime Activities

NSW Roads and Maritime Services (NSW RMS) manages a wide variety of marine and boat-related activities. It is the land owner of Sydney Harbour. It also leases facilities and provides an overview of the types of facilities covered, which include private and community boating facilities as well as commercial infrastructure.

NSW RMS managed projects include Rozelle Bay Maritime Precinct (boat repair and maintenance facility, super yacht marina, dry stack storage facility with marina, marine contracting facilities, catamaran facilities). Once complete, these projects will provide more than $150 million of infrastructure for the industry.

5.3.1.3 Royal Australian Navy

The primary site is Fleet Base East (FBE) in Sydney Harbour. Today HMAS Kuttabul is the administrative centre for FBE, a precinct that includes the Garden Island dockyard and adjacent wharf facilities at nearby Woolloomooloo. Training sites and medical facilities at HMAS Penguin are active and important facilities as well.

Fleet Base East and the navy training facilities are arguably of great value to Australia’s military and defence system. The monetary valuation of Sydney Harbour military operations or its infrastructure was found, however these facilities and visiting naval ships of Australian and overseas origin will inject significant economic activity into Sydney.

5.3.1.4 Harbour transport

Ferries

The NSW Ferries Annual Report (NSW Transport, 2012) reports total revenue at almost $163 million, costs were almost $153 million, and operating surplus was $9.8 million in 2011/12 Cost per passenger journey in 2011/12, was $8.50. Over 14.7 million passenger journeys were recorded in 2011/12 About 31 % of all passenger journeys were made by people commuting to work or education, while 47 % were for sightseeing/leisure and 21 % were for private business, such as shopping, meeting friends or attending appointments.

Harbour water taxis

There are around 15 water taxi companies operating on Sydney Harbour. Their fares are considerably higher than ferry services but financial information is lacking as they are private companies.

5.3.2 Tourism and the cruising industry

5.3.2.1 Tourism

`Destination NSW' provided annual data on tourism including numbers of visitors, their preferred activities and their expenditure (Destination NSW, 2013 in Hedge *et al.,* 2014b). Data was provided for both national (day-trippers and overnight) and international cruises. Sydney was judged to be Australia’s leading gateway, and the most popular destination for overseas visitors. It also stated whether the prime motivation of the visitors was holiday/pleasure, visiting friends and relatives, business or other. The total revenue that tourism brings to Sydney was $13.5 billion in 2012. It was not possible to separate out how much of the visitor's time and money was spent directly on activities in, on and around the Harbour. In a report on Australian tourism (BDA Marketing Planning, (no date) in Hedge *et al.,* 2014b) `aquatic wildlife experiences' topped the list of thematic appeals, averaging 50 % appeal. `Non-aquatic wildlife' and `beach/coastal/Harbour' scored 41 % each, and were ranked #2 and #3. The Destination NSW website (www.destinationnsw.com.au, accessed 20/5/2014) often refers to Sydney as the "Harbour City" in articles such as "Sydney FC to showcase our Harbour city in Japan" and "Vivid Sydney lights up Harbour City".

5.3.2.2 Cruising Industry

In its submission to the Barangaroo Review, `Carnival Australia' (Carnival Australia, 2011 in Hedge *et al.,* 2014b) presented summary statistics on the growth and value of the cruise industry, declaring it the best performing part of the tourism industry, with an estimated annual growth in the market of 24 % from 2005 - 2013. It projected that one million passengers would be cruising from Australia by 2015. The report also stated that cruising contributed $221 million to the NSW economy based on the 2007/8 data and projects it to be more than $660 million in 2011.

`Cruise Down Under' (AEC Group Ltd, 2013 in Hedge *et al*., 2014b) reported that the total output of the Australian cruise shipping industry in 2012/13 was $2.06 billion, including direct expenditure of $1.23 billion. This was a 20.6 % increase from 2011/12, when total output was estimated at $1.71 billion. The figures for Sydney Harbour showed a direct expenditure in Sydney by the cruise ship industry in 2012/13 of $1.0247 billion.

5.3.3 Harbour foreshore attractions and events

Tourism research suggests that NSW is well-placed to capture benefits from events and festivals, with Sydney recognised in 2010 and 2011 as the best festival and event city in the world (BDA, 2012, International Festival and Events Association 2012 in Hedge *et al.,* 2014b). Some results of special events are cited in media releases from the office of the Minister for Tourism. In one, for example (Souris, 2012 in Hedge *et al.,* 2014b) the NSW Events Calendar was estimated to generate more than $600 million in annual revenue for NSW. In a media report on the fireworks for New Year's Eve in 2013/14, (City of Sydney, 2014 in Hedge *et al.,* 2014b), Lord Mayor Clover Moore said the event's world-famous fireworks displays attracted more than 1.6 million people to the Harbour foreshore. The event generated an economic boost of about $156 million for local businesses.

NSW Roads and Maritime Services Annual Report for 2012 (NSW RMS 2012 in Hedge *et al.,* 2014b) states that New Year's Eve on Sydney Harbour celebrations annually attracted an estimated 2500 to 3000 spectator vessels. According to a Destination NSW media release, Last year the Sydney Festival attracted more than 500,000 people with more than 120,000 tickets sold to paid events, including more than 33,000 people who attended events in Western Sydney. In 2012, it injected almost $57 million into our economy, (Destination NSW 2014 in Hedge *et al.,* 2014b).

5.3.4 Land and real estate values close to the Harbour

Proximity to the Harbour drives a significant differential in land values and house prices. The increase in prices due to proximity to the Harbour has not been calculated, however it is significant that out of 25 of Australia's most expensive suburbs, 13 are Sydney Harbour-side suburbs including the most expensive suburb in Australia - Point Piper with a median house price of $7.38 million (http://www.realestate.com.au/blog/australias-25-most-expensive- suburbs-and-their-houses/).

5.3.5 Harbour-related businesses selling retail and offering services

Most Harbour attractions such as Luna Park, Taronga Zoo, all the activities in Darling Harbour and The Star are commercial or, in some cases, mixed commercial and government enterprises. Taronga Zoo received around half of its total income of about $83 million in 2011 - 2012 from admission, trading sales and franchise revenues (Taronga Conservation Society of Australia, 2013 in Hedge *et al.,* 2014b). There are many commercial businesses that benefit from proximity to the Harbour, but data on such private businesses are `commercial in confidence'.

A listing of such businesses may include:

- Water taxis and limousines
- Marinas and commercial dock businesses
- Boating related businesses: Boat mooring rental fees; sales of fuel, maintenance contracts; Boat sales, repairs, parts etc. (25 boat dealers in Sydney are listed on www.boatsonline.com.au, accessed 20/5/14)
- Fishing related businesses, bait and tackle shops; fishing gear sales
- Other water sport related businesses, sales and rentals of kayaks canoes; stand-up paddle (SUP) boards; scuba gear
- Sailing, scuba and kayak schools and trips
- Harbour organised activities and trips including wind, history and dinner cruises, SIMS ecology cruises; whale watch trips; fast thrill boats
- Boats to charter for numbers from under 36 passengers to over 800
- Seaplane sight-seeing flights and commuter flights
- Harbour-side dining businesses

There are websites for commercial companies offering all of the above. For example, `Sydney Harbour Escapes' website (http://www.sydneyHarbourescapes.com.au/ boat fleets/ view-all-charter-boat fleets, accessed 20/5/2014) offered almost 28 small boats, 22 medium sized and 16 that can take between 70 and 800 guests and claims to only offer boats from companies screened for quality and reliability.

5.3.6 Outdoor leisure and sporting activities

5.3.6.1 Outdoor and sporting activities on and around the Harbour

This outstanding environment is an extremely popular venue: The Boating Industry Association (BIA) estimated ten years ago that more than one million people use Sydney Harbour for water-based recreation activities each year (Access UTS, 2004 in Hedge *et al.,* 2014b). This confirms that boaters have leisure/ recreation and social/ community values through recreational use of the Harbour, and social clubs that offer services and access related to maritime uses.

The Transport for NSW Sydney Harbour Boat Storage Strategy 2013 states that in 2012 there were 217,000 recreational vessel registrations of which 8 % within Sydney Harbour, registrations growing at 2.9 % since 1999 and trend forecast to 2026. The rising trend in recreational vehicle registration and ownership confirms boater values for leisure/ recreation or social/ community.

5.3.6.2 Boating

There are about 10,000 storage spaces for Sydney Harbour, but 17,000 recreational vessels, so many boats are stored in Sydney's streets. A monthly berth east of the Sydney Harbour Bridge now costs on average $2600, up from $1900 a decade ago. The problem of boat storage is likely to continue as boat registrations in NSW are predicted to go from the present 219,000 to 335,000 by 2026 (Hasham, 2013 in Hedge *et al.,* 2014b). NSW RMS has now completed a draft Boat Storage Strategy for Sydney Harbour which has provided guidance on the development of new `off water' storage solutions, as well as a range of options for current and future `on water' storage solutions (NSW RMS 2013 in Hedge *et al*., 2014b).

In recent years there were over 40 private marinas (Widmer and Underwood, 2004), over 4,700 private moorings and about 570 private berthing pens or jetties and 14 rowing clubs with boat shed access (Williams, 2009 quoted in Ghosn *et al,* 2010). NSW Maritime has produced the report `Boat Ownership and Storage: Growth Forecasts to 2026' that covered the whole of NSW but also broke some of the data down into regions (NSW Maritime, 2010 in Hedge *et al.,* 2014b). It showed 19,128 recreational and commercial boats operating in Sydney Harbour out of a total of 228,643 in all NSW. With 18,011 recreational boats, Sydney Harbour accounted for only 8 % of the recreational boats in NSW but the 1084 commercial boats amounted to 20 % of NSWs commercial fleet. The report also forecasted boat growth and the need for more on-water boat storage, but did not include any financial data.

5.3.6.3 Boating and other clubs on Sydney Harbour

NSW has 90 sailing clubs, according to the website of `Clubs of Australia' (www.clubsofaustralia.com.au, accessed 20/5/2014); about 30 of them on Sydney Harbour. A web search for boating clubs on the Harbour comes up with more than 40 by name, including dragon boat racing clubs. These clubs generally charge membership fees, may have restaurants and bars, and some have retail sales or offer other services. No study of their economic value has been found, but it would be considerable.

5.3.6.4 Recreational fishers from boats and from land

A recreational fishing survey of Sydney Harbour found that over 300,000 hours of fishing was done in the Harbour over the summer of 2008 and over 32 different fish species were caught. The survey covered the area west of the Sydney Harbour Bridge, including the Parramatta and Lane Cove Rivers and east of the Bridge, including North and Middle Harbours.

5.3.6.5 Expenditure by recreational fishers

A nationwide survey published in estimated that 1 million people engage in recreational fishing in NSW waters each year (NSW DPI, 2008). A more recent report on the expenditure of recreational fishers in NSW (McIlgorm and Pepperel, 2013) reported an estimated 491,232 recreational fishers based in the greater Sydney region out of a total of 776,496 for NSW-based on adult fishers. The expenditure survey above was based on the residence of the respondents and not the location of expenditure. McIlgorm and Pepperel do not give value of expenditure on recreational fishing in Sydney Harbour, but given the results of a summer survey of recreational fishers in Sydney Harbour, where 96 % of the fishers were local day-fishers and most of the fishing is from shore (Ghosn *et al*. 2010), it is very likely that the average expenditure for fishing in Sydney Harbour would be considerably lower than the $250/trip average for Sydney fishers, roughly half of whom were estimated to have travelled to other parts of NSW to fish.

5.3.6.7 Swimming at Harbour beaches

Sydney Harbour offers a very large number of beaches for swimming, but the number of swimmers or swimmer-days seems to be unknown.

Under the category of ecosystem services, there is a category of valuing swimmable water. If the number of swimmer-days in the Harbour was known, and a reasonable value per swimming in one day found, a value could be estimated.

5.3.6.8 Snorkeling and scuba diving

Sydney is home to several hotspots that are reported among some of the best snorkelling sites in the country. (Time Out, http:// www.au.timeout.com/ sydney/ sports/ features/ 6735/ sydneys-top-5-snorkelling-spots, accessed 26/3/14). Several Harbour beaches are among the top recommended spots including Clontarf, Balmoral, Chowder Bay, Manly Cove and Little Manly Beach, Chinamans Beach, Bare Island and Congwong Beach, Camp Cove as well as ocean beaches.

Scuba diving in the ocean off Sydney, but also in Sydney Harbour, is highly praised by divers. Advertisements and individual websites indicate the popularity of the estuary for diving. The value of the industry is evidenced by there being around a dozen dive shops in Sydney and one individual site lists 14 dive sites within the Harbour.

5.3.6.9 Picnicking and walking at Harbour-side parks, and walking trails

The Sydney Harbour National Park Draft Plan of Management (NSW Environment, Climate Change and Water NPWS, 2010 in Hedge *et al.,* 2014b) made statements implying that there is a link between the park and financial revenues, and between the park areas and values that are important to people. Unfortunately, no economic values or quantitative measures are reported.

The value of Harbour-side parks is evidenced by visitation rates with Sydney Harbour National Park receiving 1.098 million domestic visitors, Lane Cove National Park 0.97 million visitors and Garigal National Park at the upper reaches of Middle Harbour, 388,000 visitors in 2012.

A National Parks and Wildlife Service visitor survey (NPWS, 2005 in Hedge *et al.,* 2014b) in several park areas showed that 71 % of visitors travelled less than half an hour to reach the park, suggesting parks around Sydney Harbour may be generally frequented by locals. Travel costs would therefore not adequately value these areas. At time of writing, we are not aware of any social surveys and valuation studies for use of the parks around Sydney Harbour, although a number are reported for NSW generally.

5.3.7 Ecosystem service values and indicators of valuing environmental quality

5.3.7.1 Ecosystem service values

A large number of studies have been conducted recently using the concept of `ecosystem services' to value specific natural resources. These are generally based on the work of Costanza *et al*. (1997). Similar studies from around the world have compiled regional and national data to come up with syntheses of methods and estimated values of these resources. Some studies have also focused on valuing coastal and ocean resources including an overview by Ledoux and Turner (2002) where 58 studies were listed from various countries, but none from Australia. Despite the popularity of these types of analyses for natural resources around the world, none have been completed for the Sydney Harbour estuary.

A valuation of estuarine systems in Australia more generally has been conducted (Blackwell, 2005) for a range of services including; protection, water quality, recreational boating, fishable water, swimmable water, fish conservation, fisheries food, port services.

Using these figures the total value of ecosystem services for Sydney Harbour would be over $175 million/year. Using the Constanza *et al.* (1997) figures (for the whole Sydney estuary) would give a value of about $150 million/year. These figures are only indicative.

5.3.7.2 Biodiversity values, endemism

Given the diversity of Sydney Harbour's marine life, biodiversity values are likely to be high and worth investigating. Attempts to value the biodiversity of Sydney Harbour have not been found.

There is still an issue of how to value the irreplaceable and fundamental supporting and regulatory functions of marine biodiversity and its intrinsic value when set against competing economic interests in marine spatial planning. This issue will continue to underpin the case that is made for designating marine protected areas on scientific criteria alone regardless of monetary values (Rees *et al*., 2010).

5.3.7.3 Valuing cleaner Harbour water

The Sewerage Overflow Licensing Project' (ACIL, 1996 in Hedge *et al.,* 2014b) was conducted as part of Sydney Waters investigations into reducing sewerage overflows into the Sydney Harbour and elsewhere in the Greater Sydney region. A study of willingness to pay for different degrees of cleaner water was carried out and resulted in large values equivalent to around $50 million to $75 million per year in 2012 dollars. These estimates would be a marginal value for increasing the water quality from the state it was in 1996 to hypothetically improved states.

Expenditure on measures to improve water quality in Sydney Harbour also provides some measure of the value the community places on the Harbour. Sydney Water spent around $466 million for the North Side Storage Tunnel that stores wastewater and stormwater and transfers it to North Head wastewater treatment plant and protects the Harbour. In addition, between 2007 and 2012, Sydney Water spent around $250 - $300 million on the part of the `Sewer Fix Program' that affected Sydney Harbour (Hall, 2010).

5.3.7.4 Volunteer Environmental Labour

The Sydney Metropolitan Catchment Management Authority (now merged and incorporated into NSW Local Land Services) reported that environmental volunteering in the Sydney Metropolitan region in 2009 totaled an equivalent value of $5.4 million in hours worked (CMA Sydney Metropolitan, now an archived website). The 2010 annual report stated that more than 17,000 Bushcare volunteers participated in on-ground environmental work across Sydney in 2009 (SMCMA, 2011). It is difficult to say how much of this can be attributed to Sydney Harbour, but clearly, a proportion of it will be.

5.3.7.5 Clean-up Australia Day activities in Harbour walks, beaches and in water

In its Annual Report of 2010 - 2011 (SMCMA, 2011) the (then) Sydney Metropolitan Catchment Management Authority cited the history of `Clean Up Australia Day', that started in Sydney Harbour. In 1989, Ian Kiernan initiated the first Clean up Sydney Harbour recruiting an unexpected and almost overwhelming 40,000 volunteers. The event grew into `Clean Up Australia Day', starting in 1990 with 300,000 volunteers, and in 1993 it became a global event with 30 million people in 80 countries participating. The Review of Operations for 2012/13 (Clean Up Australia, 2013 in Hedge *et al.,* 2014b) states its income as $1.4 million from corporate sponsorship, donations, in-kind contributions and revenue from activities.

5.3.7.6 Sydney Harbour Catchment Water Quality Improvement Plan

In 2015 Greater Sydney Local Land Services completed the Sydney Harbour Catchment Water Quality Improvement Plan (SHCWQIP) (Freewater and Kelly, 2015). A series of water quality and ecological response models of Sydney Harbour were developed to inform a Decision Support Tool that can highlight priority projects that need to be completed to improve the water quality of Sydney Harbour. This project was being funded by 16 local councils and 4 state government agencies which manage land draining into Sydney Harbour. The agencies willingness to contribute funding to this project emphasises the importance of improved water quality of Sydney Harbour and its tributaries.

Further details regarding the SHCWQIP are provided in Chapter 3 and the entire Plan is provided as Appendix A.

5.3.8 Landscape values

In February 2013, Sydney Harbour was declared an official National Landscape, a title that it shares with 15 other landscapes in Australia. These are promoted as part of a campaign titled the best destinations to experience Australia's outstanding nature and culture. It is impressive that Australia's largest city, with a population of over four million people, can be considered a prime destination to experience nature. That is part of the appeal and importance of the Harbour and its foreshores. The National Landscape website (http:// www.australia.com/ nationallandscapes/ sydney-Harbour.aspx , accessed 6/6/2013) describes Sydney Harbour as one of the most environmentally diverse landscapes in the world. These landscape and outdoor values are real, but attempts to quantify them at this point for Sydney Harbour have not been found.

5.4 Threats to economic values of Sydney Harbour

Water pollution affecting tourism and loss of natural areas for nature tourism were perceived as the highest priority threats to economic values by those surveyed in the Greater Sydney region for the

Marine Estate Community Survey (Sweeney Research, 2014). Other threats to economic values included overcrowding and the costs to access and use the marine estate, including the Harbour, overfishing and over-development of coastal areas.

5.4.1 Risk of losing environmental assets and natural areas

The total revenue in 2012 that tourism brought to Sydney was $13.5 billion. The number one reason that tourists visit Australia is to experience nature (Tourism Australia, 2010 in Hedge *et al.,* 2014b).

Barrowclough (2011) reported that Australia's advantage for tourism in due to unique experiences and particularly wildlife, outdoor activities and ecotourism. Another Australian tourism report (BDA Marketing Planning in Hedge *et al*., 2014b) noted that aquatic wildlife ranked number one for tourist experiences with non-aquatic wildlife second and beach/coastal/Harbour third. Clearly the environmental assets of Sydney Harbour are of high economic importance.

Therefore, a number of economic risks arise from threats to the environmental assets of Sydney Harbour. These include water pollution, damage to natural habitats (aquatic and terrestrial), invasive species, sea level rise, warming and increasing ocean acidification caused by climate change.

Losses in environmental value would have flow on implications in losses in the desirability of the Harbour as a tourism venue (e.g. to go boating, fishing, diving, swimming), somewhere attractive to live and in terms of the provision of other ecosystem services.

5.4.1.1 Contamination and health risks of recreational fishers consuming catch from Sydney Harbour

The NSW Food Authority strongly suggests limiting consumption of fish caught in Sydney Harbour (NSW Food Authority website, 2009 last update, in Hedge *et al.,* 2014b). Another report gives a good brief description of the extent of contamination in the Harbour and the resulting loss of fishing and danger of consuming fish (McGrath, 2012). There are indications that these recommendations are not fully followed (Ghosn *et al.,* 2010) but the extent of consumption is unknown. Therefore, the health implications of this are not known, nor are economic costs in terms of loss of work or medical costs, if any. If it was shown that contaminated fish were being eaten, that would lower the economic value of the fish caught. Widespread and effective education on the risks of eating fish from the Harbour may also reduce the economic benefit of recreational fishing due to reductions in participation.

5.4.1.2 Health risks of swimming in Sydney Harbour

Environment NSW, in its Beachwatch program, monitors quality of water for swimming in the Sydney region (and other) regions and posts daily updates. There is also a general warning not to swim in Sydney Harbour for up to three days following rainfall or for as long as stormwater is present. The health risks of swimming in Sydney Harbour, according to the NSW Beachwatch website (NSW Environment, Swimming illness, no date, in Hedge *et al.,* 2014b) include pathogens (bacteria, viruses and protozoa) which can easily enter the ears, eyes, nose and mouth of swimmers. The skin is also directly exposed to infectious agents and chemicals through swimming, playing or working in polluted waters. However, the risks to swimmers from the ingestion of particulate bound dioxins has never been established. For further information see Chapter 3 (*Section 3.2.4 Dioxin Contaminated Sediments*).

No estimates of the value of swimming or the economic costs of health issues arising from a stormwater polluted Harbour have been found, however media articles such as the one titled `Killer bugs lurk in Harbour' that described *Staphylococcus* infections from bacteria in waterways and particularly of two examples of infections that led to loss of toes in one case and a foot in the second (Cubby and Lockwood, 2009) are likely to have a significant short term impacts on Harbour beach visitation with local economic flow-on impacts.

5.4.1.3 Overfishing

Sydney Harbour is closed to commercial fishing, but it is a very popular recreational fishing destination and the positive economic benefits of this activity due to direct expenditure and flow-ons, while not estimated, is likely to be many millions of dollars per annum. The ecological impacts of fishing are presented in Section *5.4.2 Land-based impacts*. There are some negative economic impacts likely to result from these, including reductions in the value of dive tourism due to the degradation of fish communities. There may also be impacts on the value of commercial fishing and quality of recreational fishing due to sub-optimal yields per recruit due to high recreational fishing mortality on juvenile estuarine dependent life history stages of high value species such as snapper and kingfish.

5.4.2 Costs to access and use Sydney Harbour

5.4.2.1 Increased regulatory cost

MPAs, and particularly marine parks, may result in losses to some social and economic benefits due to increased regulatory controls primarily aimed at the protection of biodiversity ahead of a range of other social and economic objectives. Effective MPA planning should mitigate these impacts to some extent as a key principle of reserve design is to achieve biodiversity conservation objectives for least cost.

Costs and benefits are dependent on an individual's response to MPA management and this can vary. For example, someone may not go fishing but they may go snorkeling instead; or they may go fishing elsewhere; or they may not fish at all. Therefore, the likely costs and benefits of MPAs cannot be estimated without understanding the likely responses of those affected and the spatial distribution of values (Heagney *et al.,* 2015). A detailed socio-economic assessment could provide a greater understanding of the likely impacts, both negative and positive, for any proposed MPA for Sydney Harbour.

In general, MPAs may reduce fishing or boating satisfaction or increase travel costs for recreational fishers but this may be offset by enhanced catch per unit of effort or spill-over effects (Heagney *et al.,* 2015). There may be reduced recreational fishing tourism in the vicinity of MPAs as fishers avoid apparently heavily regulated areas; alternatively there may be increased crowding in other areas which reduces satisfaction and/or ecosystem quality in those areas (Heagney *et al.,* 2015). Similar scenarios would relate to boating.

Permits are required for certain activities undertaken within marine parks however, the types of permits are currently being revised to minimise red tape.

Examples of activities requiring permits in marine parks (but not aquatic reserves) over and above other areas of the marine estate include:

- Commercial activities – includes tourist operations but not commercial fishing
- Personal watercraft (jetskis) and hovercraft use
- Organised events (including weddings and competitions)
- Horse riding in permitted areas

5.4.2.2 Development

MPAs created adjacent to Sydney Harbour national parks will not require restrictions on urban development. A marine park created in Sydney Harbour adjacent to other land uses, such as residential areas, may require increased environmental controls particularly adjacent to any declared sanctuary zones. However, these are not likely to be much more than outlined in the Sydney Regional Environmental Plan (Sydney Harbour Catchment) 2005 (Harbour REP). Section 21 outlines matters to be taken into consideration in relation to biodiversity, ecology and environment protection and are quite detailed, including:

(a) development should have a neutral or beneficial effect on the quality of water entering the waterways,

(b) development should protect and enhance terrestrial and aquatic species, populations and ecological communities and, in particular, should avoid physical damage and shading of aquatic vegetation (such as seagrass, saltmarsh and algal and mangrove communities),

(e) development should protect and reinstate natural intertidal foreshore areas, natural landforms and native vegetation,

(h) the cumulative environmental impact of development,

(i) whether sediments in the waterway adjacent to the development are contaminated, and what means will minimise their disturbance.

Currently the North Harbour Aquatic Reserve does not provide additional regulations for development beyond what is required under the Harbour REP. Under NSW environmental law a full assessment of all likely environmental impacts is currently required during the approval process for any development. However, there are likely to be higher environmental assessment thresholds set and more active scrutiny for developments that are likely to negatively impact on areas of high value or sensitive biodiversity in marine parks.

However, the Harbour REP is currently under review will be consolidated into a new State Environmental Planning Policy (SEPP), the Coastal Management SEPP. Changes proposed include consolidating the following seven existing SEPPs:

- State Environmental Planning Policy No. 19 – Bushland in Urban Areas
- State Environmental Planning Policy (Sydney Drinking Water Catchment) 2011
- State Environmental Planning Policy No. 50 – Canal Estate Development
- Greater Metropolitan Regional Environmental Plan No. 2 – Georges River Catchment
- Sydney Regional Environmental Plan No. 20 – Hawkesbury-Nepean River (No.2-1997)
- Sydney Regional Environmental Plan (Sydney Harbour Catchment) 2005
- Willandra Lakes Regional Environmental Plan No. 1 – World Heritage Property.

5.4.2.3 Boating restrictions

Anchoring restrictions have been implemented for some sanctuary zones in existing marine parks to ensure the protection of key aquatic habitat within the zone. Any potential anchoring restrictions for a Sydney Harbour MPA could be offset with the implementation of a courtesy mooring plan using Environmentally Friendly Moorings (EFMs). There would be a cost associated with the installation and maintenance of courtesy moorings.

Currently EFMs are not required for any MPAs either for public or private moorings, however, the impact of block and chain moorings on key aquatic habitat needs to be addressed for all sensitive habitat, whether in a MPA or not. The commercial cost of installation of an EFM is more expensive than a block and chain mooring, however the commercial cost of maintenance is similar. The benefits of protecting key fish habitat which influences fisheries productivity would outweigh the cost of EFMs.

In some marine parks there are restrictions on types of boating activity that pose a high environmental risk such as high speed jet boats. There may also be an increased use of speed restrictions to reduce foreshore erosion, or to reduce risk of vessel strike on wildlife. These regulatory controls may result in losses of some economic activity.

5.4.2 Conclusions

There are a diverse range of activities and values that underpin the substantial economic benefit that NSW derives from Sydney Harbour. The environmental condition of the Harbour underpins a significant majority of this value. Environmental condition will remain largely unaffected by the option of creating a recreational fishing haven or havens and this option will be unlikely to provide any other economic benefit. Marine protected areas assist in maintain environmental values and can provide economic benefit by providing additional opportunities for eco-tourism and related activities that may not currently exist.

MPAs do introduce an additional regulatory layer that is likely to increase transaction costs for business and may reduce the benefits flowing from some activities such as fishing and boating. Large scale industrial and other developmental activity with potential to impact on values of MPAs may also face additional assessment and approval hurdles increased regulatory burden and be put under greater scrutiny by both government and the community.

MPA planning and operation would need to consider the “working Harbour” status of Sydney Harbour and well as existing industrial activities and potential future development opportunities to ensure that the full economic value of the Harbour is maintained and biodiversity conserved for least cost.

5.5 Opportunities to address identified environmental threats

Current management of Sydney Harbour and its catchments successfully mitigates the environmental impacts associated with a range of pressures. However, the preliminary assessment (Table 5.14) indicates that threat levels remain ‘high’ and ‘very high’ for some activities (reproduced in table 5.15 below), and these therefore require further detailed analyses and/or management action.

Table 5.15 Summary of environmental stressors which represent high or very high threats in Sydney Harbour

Very high threat	• Increased nutrients, organic matter & sediment (catchment runoff, sewage & stormwater outlets) • Input of toxic pollutants (runoff & point sources) • Legacy toxic pollutants in sediments (eg. heavy metals, dioxins, etc.) • Habitat damage (anchoring, mooring) • Death of fish discarded by recreational fishers • Non-compliance by recreational fishers with size/bag limits or spatial closures • Climate change (all stressors)
High threat	• Wildlife disturbance (little penguins) • Bank erosion (Parramatta river) • Habitat fragmentation & loss as a result of foreshore development • Introduction of exotic marine species & disease affecting native marine species • Marine debris • Removal of lower order predators & species at lower trophic levels by recreational fishing

An enhanced environmental package for Sydney Harbour to address these threats could comprise multiple approaches. A preliminary analysis of which threats identified during this assessment could be managed through the establishment of marine protected areas (MPAs) and/or recreational fishing havens (RFHs) is presented in a separate ‘options’ report. It summarises the pros and cons of those two particular management tools, as requested by Cabinet, and presents options for consideration, including options for management initiatives that could be implemented with, or instead of, MPAs or RFHs.

5.5.1 Very high threats

5.5.1.1 Increased nutrients, organic matter & sediment (catchment runoff, sewage & stormwater outlets) and input of toxic pollutants (runoff & point sources)

Sydney Harbour Catchment Water Quality Improvement Plan

Improving water quality in Sydney Harbour requires source control (changed behaviour) as well as interception and treatment. There is a State Diffuse Pollutants Strategy to minimise inputs of diffuse pollutants but further measurements are required in the Harbour.

The Sydney Harbour Catchment Water Quality Improvement Plan (Freewater and Kelly, 2015) was completed in June 2015. It was developed in partnership with 16 local councils and 4 state agencies. Models of the Sydney Harbour catchment have been designed to inform a Decision Support Tool to assist land managers to identify primary areas of input and sensitive receiving environments. This allows effective prioritisation of controls in the catchment to improve water quality and manage flows, helps in improving planning decisions and setting standards for retro-fitting of stormwater treatment technology. Similar programs have been successfully implemented in other regions (e.g. Botany Bay and The Great Lakes), partly due to changes in Developmental Control Plans.

This program is also a good vehicle for community engagement, which is essential to change behaviour. The community can also see why particular works are being proposed to help achieve the community's goal of improved water quality for Sydney Harbour. Funding is needed for the on-ground works phase of this project. On-ground works could be initiated via a devolved grants program open to local councils via the Greater Sydney Local Land Services.

Determining contemporary risks from dioxins in recreational fishes

In 2005/06, prior to the remediation of sediment within Homebush Bay, a sampling program (referred to as the Phase 1 study) was undertaken to measure concentrations of dioxins (PCDDs, PCDFs and dl-PCBs) in fish (Yellowfin Bream and Sea Mullet) and prawns (School Prawn and King Prawn). The study focused on four zones in the Parramatta River: Upper Parramatta River, Homebush Bay, Middle Parramatta River and Lower Parramatta River. The results showed that concentrations of dioxins were above a level considered safe for human consumption of 6 pg TEQ/g (pg dioxin toxicity equivalence per g).

During 2015/16, a follow-up study (referred to as the Phase 2 study – RMS, 2017) was conducted using the same experimental design, to determine if concentrations of dioxins in the same species had decreased following the remediation of Homebush Bay. When the results from the two phases of the study were compared, there was no overall change in the concentrations of dioxins in both of the fish species (Yellowfin Bream and Sea Mullet). This may be due to the presence of residual contamination in Homebush Bay/Parramatta River or indicate that insufficient time had passed between the two phases of the study to result in measurable changes for these species. The results also showed that the dioxin concentrations in fish and prawns from Homebush Bay were either equal to or higher than all the other zones.

In contrast to the fish, the dioxin concentrations in both of the prawn species showed a decrease when data were considered on a fresh weight basis. For the prawns, however, the lipid content in the Phase 2 study was considerably lower than in Phase 1. As dioxins are known to accumulate in the lipid of organisms, it was assumed that the decrease in lipid content may have a limiting effect on the capacity of the prawns to accumulate dioxins. Due to this, the dioxin concentrations on a lipid normalised basis were also considered. When the lipid normalised data were compared, overall there was no change in the concentration between the two phases of the project. This result suggests that the decrease in dioxin concentration on a fresh weight basis may have been driven by the observed drop in lipid content in the Phase 2 study. In future, if the lipid content of the organisms increases, for example in a change of season, the overall fresh weight concentration may also increase as their capacity to accumulate dioxins will increase.

Dioxin concentrations in all of the fish samples analysed during Phase 2 were considerably higher than the limit for human consumption of 6 pg TEQ/g. In contrast, all of the prawn samples were marginally lower than this limit, with the exception of School Prawn from Homebush Bay.

NSW DPI is planning to expand some current fish tracking work into a 'Sydney Harbour fish connectivity' project. The primary objective of this research is to use acoustic tracking to determine the time spent by key recreational fish species at the top of Parramatta River and their subsequent movements to other parts of the Harbour. This will provide information on species which pose a health risk to consumers when captured in different parts of the Harbour.

There is a need for a project that can report on current dioxin contamination in Sydney Harbour sediments and the potential for future dispersal. Such a project should investigate and provide a cost-benefit analysis of options to manage dioxins. A high resolution model of sediment resuspension and transport has been developed (see section *3.2.4 Dioxin Contaminated Sediments*) and can be calibrated with recent and new data. This would enable current and predicted future dioxin distributions and concentrations to be mapped. Management strategies could then be evaluated in collaboration with key state agencies and the Sydney Institute of Marine Sciences to inform the Sydney Harbour Coastal Management Program.

5.5.1.2 Habitat damage (anchoring, mooring)

Environmentally friendly moorings

Traditional swing moorings in seagrass scour the seabed causing fragmentation and loss of seagrass habitat. Seagrass within Sydney Harbour has already declined by ~50% since 1943 due to various anthropogenic pressures. A number of alternative mooring designs, called Environmentally Friendly Moorings (EFMs), are now available that help protect sensitive seabed habitats without compromising safety or reliability in mooring a vessel.

Manly Cove, Watson's Bay and Vaucluse Bay are high priority sites for management intervention within the Harbour as, a large number of block and chain moorings occur within seagrass areas and habitat damage is highly visible (Bowman, 2008). Extensive loss of seagrass at Manly Cove has been quantified by on-the-ground surveys and potential recovery of seagrass after replacement of some BCMs with seagrass friendly moorings is being monitored (Gladstone, 2010 & 2013).

To optimise the use of moorings in Sydney Harbour requires the environmental performance of moorings to be improved and acceptance of the new EFM designs by stakeholders. A program to roll out engagement with stakeholders and further research the environmental performance of designs is required.

A strategic courtesy mooring plan could be developed using a variety of EFM designs to compare their performance and as a starting point to engage stakeholders more generally on the benefits of using EFMs for private moorings.

Environmental education program for boaters and fishers

An environmental education program aimed at boaters and fishers and designed specifically for Sydney Harbour would assist to promote habitat protection and environmental stewardship. Education rather than regulation is a key issue for peak boating bodies such as the Boating Industry Association and the Boat Owners Association.

5.5.1.3 Death of fish discarded by recreational fishers and non-compliance by fishers with size/bag limits or spatial closures

Five year assessments of recreational fishery in Sydney Harbour

The most recent assessment of the recreational fishery in Sydney Harbour was conducted in 2007/08 and indicated that levels of recreational harvest and discarded catch were large compared to other estuaries in. Further, illegal fishing was considered problematic with high rates of retention of undersize fish. Given that recreational fishing pressure in the Harbour is likely to increase, regular assessments (every 5 years) are recommended. This would involve creel surveys, and in-depth assessment of age/length characteristics for a selection of indicator species. This is particularly important for lower order predators (e.g. snapper, flathead) and species at lower trophic levels (e.g. yellowtail scad) which are the main target groups for fishers and/or intensively harvested both within the Harbour and in NSW; and removal of which can lead to ecosystem wide effects. This data combined with ongoing research by SIMS scientists on fisher distribution in the Harbour would allow the fishery to be appropriately managed to ensure high quality recreational fishing opportunities persist.

Additionally a survey of the recreational fishing community in Sydney Harbour would also determine the reasons for non-compliance and canvas ideas to improve the design and delivery of education programs. This information would assist to improve the success of education programs.

Educational packages for Culturally And Linguistically Diverse (CALD) communities

Sydney is one of most culturally and linguistically diverse cities in the world. The NSW Government has led Australia and the world in addressing 'access and equity' issues faced by people from non-English speaking backgrounds, and more recently to recognise and celebrate the social, cultural and economic contribution that results from multiculturalism.

The NSW Government's Multicultural Policies and Services Program aims to ensure that all public sector agencies incorporate appropriate responses to cultural and linguistic diversity in their core business.

Many recreational fishers in Sydney Harbour have English as their second language. While some fisheries signage on the foreshores of Sydney Harbour is multi-lingual, most regulatory and educational material is provided in English only (e.g. saltwater fishing guide). NSW DPI ran some fishing workshops for Chinese and Filipino families from Western Sydney in 2013, but lack of resources has limited further engagement. Maintaining up-to-date multilingual versions of all key documents is an important first step to maximise voluntary fishing compliance by CALD communities in Sydney Harbour. The development of a multicultural plan to engage and educate CALD communities would be an integral part of the outreach and educational strategy for the Harbour.

5.5.1.4 Climate change (all stressors)

Planning for Climate change

Climate change is a large-scale threat that needs to be addressed at State/National scale. Management plans generally focus on adaptation, protection (research is looking at improving biodiversity outcomes of seawalls by altering structures and including additional elements like pools and benches for saltmarsh) and allowing retreat by mangrove/saltmarsh by ensuring there is adequate supra-tidal space. The Sydney Coastal Councils Group (SCCG) has developed tools to understand the likely effects that climate change will have on local council resources, including those in Sydney Harbour and a framework from which to develop community engagement plans and conduct various outreach activities. The Parramatta River CZMP and the Sydney Harbour Catchment WQIP consider climate change issues within the scope of the priority projects addressed.

Promote Sydney Harbour research

Current research initiatives that have the capacity to provide information about climate change impacts include the Sydney Harbour Research Program at the Sydney Institute of Marine Science and the Sydney Harbour biodiversity study by the Australian Museum. An ongoing strategic monitoring and evaluation program would also allow documentation of future changes and an assessment of whether implementation of management opportunities has been successful. It would also allow for adaptive management and hence ensure the optimal use of any future funding.

5.5.2 High threats

5.5.2.1 Wildlife disturbance (little penguins)

Expand existing aquatic reserve to protect little penguin habitat

The little penguin is listed as an endangered population under the Threatened Species Conservation Act 1995. Disturbance of little penguins is currently managed by declaration of critical habitat areas where restrictions on companion animals, fishing and boating have been implemented. Tampering with or damaging little penguin nest boxes, burrows or moulting penguins or approaching within 5m of a penguin on land is also prohibited.

Management options could include extending the existing North Harbour Aquatic Reserve to include all declared habitat areas and/or extend the reserve to include Little Manly, Manly Cove and North Harbour. Additional restrictions and management features could be implemented such as:

- environmentally friendly moorings in penguin habitat areas,
- implementing no-take fishing restrictions within the reserve,
- declaring Preservation Zones around actual nesting sites which would prohibit entry by persons without a permit.

The opportunity to extend the North Harbour Aquatic Reserve to include Little Manly, Manly Cove, and North Harbour was put forward in a 2008 resolution by Manly Council. The resolution was supported by community user groups, NGOs, research organisations and relevant agencies. Extending the boundaries of the North Harbour Aquatic Reserve would raise the profile of marine conservation in Sydney Harbour and would have positive impacts on other marine life, including endangered seahorses in Manly Cove.

Protecting little penguin habitat through extending North Harbour Aquatic Reserve and implementing additional restrictions has the advantage of having low financial impact and could be implemented over the short-term. Current reserve regulations offer limited protection, as line fishing for finfish is permitted, boating is not restricted and anchoring in seagrass beds is only discouraged. Declaration of a no-take fishing area would have a regulatory impact but could be off-set by improving recreational fishing opportunities elsewhere in the Harbour. Boating restrictions could potentially be offset by providing environmentally friendly courtesy moorings.

5.5.2.2 Bank erosion and habitat fragmentation & loss from foreshore development

Coastal Management Program

Coastal Management Programs (CMPs) for estuaries are the culmination of a process to identify the threats to estuary health and determine in consultation with key stakeholders and the community, priority management actions to address these threats. Currently a Greater Sydney Harbour Coastal Management Program is being scoped, the next step is to develop the full plan. Funds are being sought to develop this plan.

The Parramatta River Coastal Zone Management Plan has recently been completed by all relevant local councils and state agencies. Priority actions to address the identified threats include proposals to improve public access, rehabilitate eroding foreshores, improve degraded seawalls with environmentally friendly seawall designs, and advocate the use of environmentally friendly moorings and infrastructure improvements for recreational boating facilities. Funding is required to instigate on-ground works for this strategic plan.

On-ground works for certified Coastal Zone Management Plans and for new CMPs are eligible for funding under the Office of Environment and Heritage's Coastal Management Framework (www.environment.**nsw**.gov.au › … › Water › Coasts and floodplains).

Green engineering initiatives

There are increasing initiatives in the Harbour to design structures which minimise impacts to natural habitats and biodiversity and to maximise the potential of existing and future structures to be used as habitats - so called 'green engineering'. Such initiatives can also assist with existing habitat fragmentation and loss as a result of foreshore development, and preparing for habitat loss predicted by climate change induced sea level rise. Examples include construction of environmentally friendly seawalls and fish friendly marinas.

Over 50% of the shoreline of Sydney Harbour is comprised of seawalls. Guidelines developed by the Office of Environment and Heritage and Sydney Metropolitan Catchment Management Authority aim to maximise the incorporation of native riparian and estuarine vegetation, maximise the diversity and complexity of seawall surfaces and create, where possible, sloping seawalls and/or incorporating changes of slope. Vertical seawalls can be retrofitted with pots to increase habitat. Seawalls in the more marine sections of the Harbour could potentially be designed to enhance recreational fishing by incorporating specific design considerations, for example reef balls deployed at the toe of seawalls. Reef balls could potentially assist with the stability of the foot of the seawall as well as provide habitat for marine vegetation, fish and invertebrates.

Rehabilitating wetlands

Greater Sydney Local Land Services have identified priority wetlands in the Sydney region and encouraged local councils to develop Plans of Management (PoMs) for these wetlands. Priority actions from these PoMs could be funded to improve the habitat, biodiversity and water quality outcomes for the Harbour. Further PoMs could be developed, particularly for priority saltmarsh sites.

5.5.2.3 Introduction of exotic marine species & disease affecting marine species

Sydney Harbour is likely to be the first Australian point of invasion for exotic species from Singapore, Vanuatu, New Zealand and New Caledonia, and its considerable connectivity with other ports in NSW and Australia mean that it is at high risk of secondary invasion by existing and new non-indigenous species (especially from Victoria) (Glasby and Lobb, 2008).

Eradication or containment plans should be developed for NIS identified as being likely to invade Sydney estuaries and complemented with routine monitoring for high risk species.

Environmental education program for boaters and fishers

This environmental education program would include measures that can be implemented by boaters and fishers to reduce the likelihood of recreational vessels spreading marine pests.

5.5.2.4 Marine debris

Sydney Harbour Catchment Water Quality Improvement Plan

The implementation of this plan will assist in reducing marine debris, including microplastics.

'Operation Clean Sweep' in Sydney Harbour.

'Operation Clean Sweep' is an international initiative to help in prevention of plastic resin pellets entering the marine environment. Organised by the American Chemistry Council and Society of the Plastic Industry in the USA it provides detailed recommendations on mitigation of spills, education of employees on containment and prevention, and management of clean- ups if necessary. Ideally, these or similar recommendations should be adopted as legislation that is mandatory for plastic industries and manufacturers located within Sydney Harbour catchment to implement.

Marine debris prevention program

Marine debris is often a highly visible impact of human activity within and surrounding Sydney Harbour, with over 50 tonnes of rubbish collected from individual foreshore locations between 1994 and 2004. A crucial first step in combating marine debris is to prevent litter from entering the Harbour. This requires improved source control (changed behaviour) via public and industry education and interception (drain stencilling, gross pollutant traps). This should also involve assessment of the adequacy of waste management infrastructure at popular foreshore locations and major public events.

Removal of underwater marine debris at key recreational sites

Removal of debris from the intertidal foreshore and waterways of the Sydney Harbour estuary is done by the environmental services (ES) team at Maritime in co-operation with local councils. The ES team remove floating litter from Sydney Harbour. In contrast, there are no equivalent programs for the removal of sunken marine debris from the Harbour, with clean-ups generally being done by voluntary community dive groups. A specific underwater cleanup could target key recreational areas, particularly those used by fishers and divers. For example, popular fishing spots in Sydney Harbour, particularly wharves, can be laced with monofilament line and fishing hooks and lures.

5.5.2.5 Recreational fishing – removal of lower order predators & species at lower trophic levels

Establishment of long-term scientific reference sites to examine the potential impacts of environmental disturbances

Lack of baseline data on Sydney Harbour prior to intense human use impedes a comprehensive understanding of the scale of impact of some activities (e.g. fishing). The establishment of long-term scientific reference sites in the Harbour where activities are restricted (e.g. particular zones within MPAs) would allow for spatial comparisons with impacted areas and provide a greater understanding of ecosystem effects. The establishment of reference sites would also facilitate a more spatially consistent approach to monitoring in the Harbour and greater collaboration between government agencies and research institutions. These sites would be incorporated into a state-wide monitoring, evaluation and reporting program (MER) to improve knowledge of, and trends in the condition of marine resources in Sydney Harbour to complement such monitoring elsewhere in the NSW Marine Estate.

Ideal reference sites include areas where data have already been collected and where restrictions exist on some activities. For example, anecdotal evidence suggests that scuba diving and snorkeling are an increasingly popular past time in Sydney Harbour, with over 30 sites utilised. Fishes and large invertebrates at many of these sites have been surveyed by volunteer divers as part of the Reef Life Survey (RLS) program (Figure 5.21) and 10 sites have been surveyed on a regular basis since 2009 (Table 5.16). RLS is a non-profit organisation that trains volunteer divers to undertake scuba-based surveys throughout the world. Data are coordinated by RLS and are available for research purposes. Opportunity exists to make use of RLS sites as scientific reference sites for Sydney Harbour, particularly those in the outer Harbour. A reference site could also be established at Chowder Bay (which already has a spear-fishing closure) because of the vicinity of this site to the premier marine research institution in the Harbour i.e. SIMS). This would further foster reach into the understanding of ecological processes within in the Harbour as well as providing more general scientific insights. This model has been successful overseas (e.g. at the Leigh Marine Laboratory in New Zealand).

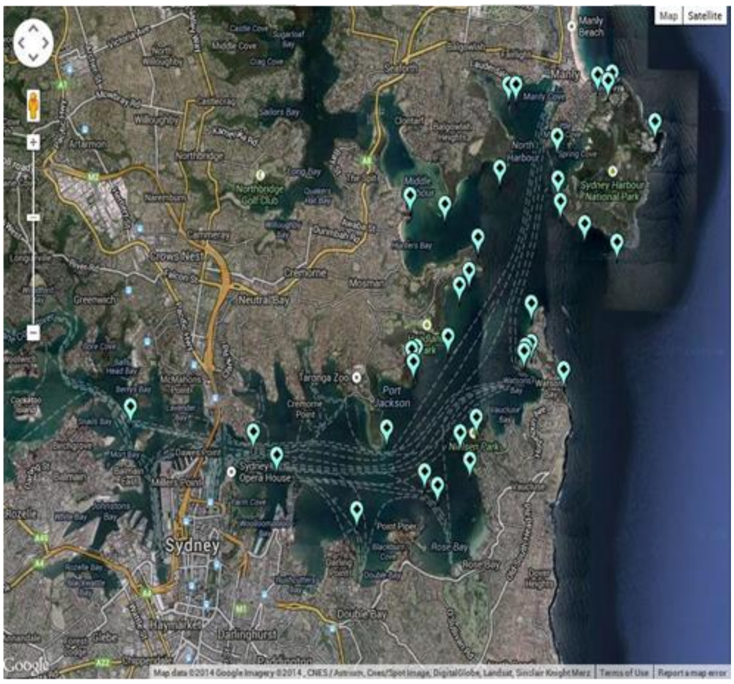
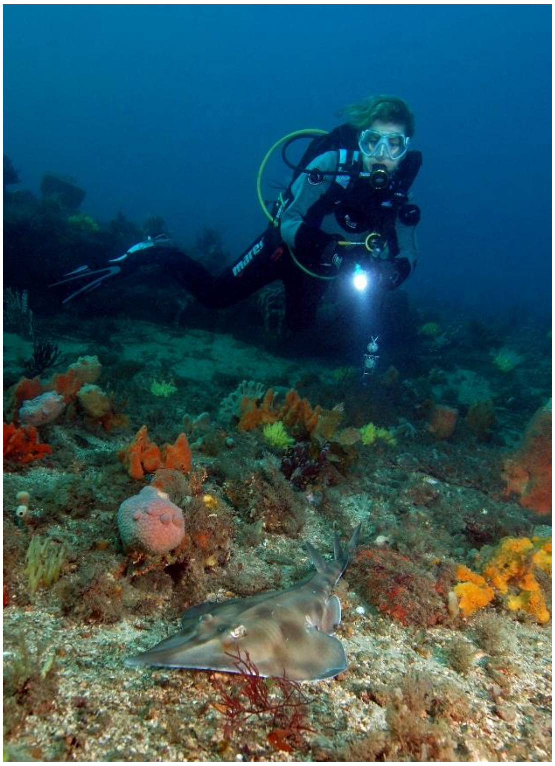


Figure 5.21 RLS dive survey sites within Sydney Harbour



Diver and Eastern Shovel Nose Shark (*Aptychotrema rostrata*) at Bare Island

Table 5.16 **Site names, number of surveys and years surveyed for RLS sites within Sydney Harbour**

Site Name	# Surveys	Years surveyed
Balmoral Bay	2	2010
Berrys Bay Point	2	2010
Blue Fish Point	7	2009; 2011; 2014
Bradleys Heads	2	2010
Camp Cove Green Pt	9	2009; 2011; 2012; 2014
Camp Cove Middle	9	2009; 2011; 2012; 2013; 2014
Camp Cove NE	10	2009; 2011; 2012; 2014
Chowder Bay	7	2009; 2010
Chowder Bay	1	2009
Clarke Island	2	2010
Clifton Gardens Wharf	5	2009; 2011; 2012
Dobroyd Head	8	2009 ;2010
Fairlight Point	1	2014
Fairlight	1	2014
Fort Denison	2	2010
Georges Head	2	2010
Grotto Point Lighthouse	7	2009
Inside North Head	21	2009; 2010; 2011; 2012; 2014
Inside South Head	11	2010; 2011; 2012; 2014
Kiribilly House	2	2010
Little Manly Bay	2	2009
Middle Head NE	14	2009; 2011; 2012; 2014
Middle Head Sth	12	2009; 2011; 2012; 2014
Middle Head Sth 2	6	2010; 2012; 2014
Neilson Bay	2	2010
Old Mans Hat	4	2009; 2014
Quarantine Jetty	3	2009
Shark Island	3	2010
Shark Island SE	4	2009; 2010
Steel Point	2	2010
The Blocks	3	2009

REFERENCES

ABC (2013). The Hunter River at Hexham. *Australian Broadcast Corporation, accessed Sept 2015*, http://www.abc.net.au/news/2013-01-14/reflections-captured-on-the-hunter-river-at-hexham/4463820.

Adam, P. (1995). Saltmarsh in State of the Marine Environment Report for Australia: The Marine Environment -Technical Annex: 1 (ed L Zann) *(Great Barrier Reef Marine Park Authority, Townsville).*

Airoldi, L., and F. Bulleri. (2011). Anthropogenic disturbance can determine the magnitude of opportunistic species responses on marine urban infrastructures. *PloS one 6:e22985*.

Allen, H. K., J. Donato, H. H. Wang, K. A. Cloud-Hansen, J. Davies, and J. Handelsman. (2010). Call of the wild: antibiotic resistance genes in natural environments. *Nature Reviews Microbiology 8:251- 259.*

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.*

AM (2002). Port Surveys for Introduced Marine Species. *(Australian Museum Business Centre: Sydney, NSW).*

Andrews, V., Middlefart, P., Creese, R. G., Broad, A. & Davis, A. R. (2010). Distribution & abundance of the introduced gastropod *Zeacumantis subcarinatus* in the Sydney region. *Molluscan Research 30, 131-137.*

Australian Museum Business Services. (2002). Port Surveys for Introduced Marine Species - Sydney Harbour Final Report. *Australian Museum Business Services, 146.*

AWACS (1989). Proposed Development of Homebush Bay Bank Protection Options. *Australian Water and Coastal Studies Pty Ltd, June 1989: pp. 18.*

Banks J.L., Hutchings, P., Curley, B., Hedge, L., Creese, B. and Johnston. E. (2016). Biodiversity conservation in Sydney Harbour. *Pacific Conservation Biology **22**, 98–109*

Banks, J. L., D. J. Ross, M. J. Keough, C. K. Macleod, J. Keane, and B. D. Eyre. (2013). Influence of a burrowing, metal-tolerant polychaete on benthic metabolism, denitrification and nitrogen regeneration in contaminated estuarine sediments. *Marine Pollution Bulletin 68:30-37*.

Barbier, E. B., S. D. Hacker, C. Kennedy, E. W. Koch, A. C. Stier, and B. R. Silliman. (2011). The value of estuarine and coastal ecosystem services. *Ecological Monographs 81:169-193*.

Barker, S. M., Peddemors, V. M. & Williamson, J. E. (2011). A video and photographic study of aggregation, swimming and respiratory behaviour changes in the Grey Nurse Shark (Carcharias taurus) in response to the presence of scuba divers. *Marine and Freshwater Behaviour and Physiology 44, 75-92.*

Barnes, D. K. A., Galgani, F., Thompson, R. C. & Barlaz, M. (2009). Accumulation and fragmentation of plastic debris in global environments. *Philosophical Transactions of the Royal Society B: Biological Sciences 364, 1985-1998.*

Barrowclough, N. (2011). Wish you were here. *Sydney Morning Herald, Good Weekend, 8 Oct 2011*

Batley, G., Mann, K., Brockbank, C., Maltz, A. (1989). Tributyltin In Sydney Harbor And Georges River Waters. *Australian Journal of Marine and Freshwater Research **40**: 39-48.*

Benson, D. H., J. Howell, R. B. Gardens, and N. Sydney. (1990). **Taken for granted: the bushland of Sydney and its suburbs.** *Kangaroo Press*.

Birch, G. (2000). Marine pollution in Australia, with special emphasis on central New South Wales estuaries and adjacent continental margin. *International Journal of Environment And Pollution 13, 573-607.*

Birch, G.F. (2006). The distribution of dioxins and furans in sediments of Port Jackson. *The Stockholm Convention, Sydney, 27-30 June, 2006.*

Birch, G. (2007). A short geological and environmental history of the Sydney estuary, Australia. **Water, Wind, Art and Debate**. *Sydney University Press 217-246.*

Birch, G. (2011). Contaminated Soil and Sediments In A Highly Developed Catchment-Estuary System (Sydney Estuary, Australia): An Innovative Stormwater, Remediation Strategy. *Journal of Soils and Sediments **11**: 194-208*.

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 Richards, R. (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., Taylor, S. (2000). Distribution and Possible Sources Of Organochlorine Residues In Sediments Of A Large Urban Estuary, Port Jackson, Sydney Australian. *Journal of Earth Sciences **47**: 749-756.*

Birch, G., Murray, O., Johnson, I., Wilson, A. (2009). Reclamation In Sydney Estuary, 1788-2002, *Australian Geographer **40**: 347-368.*

Birch G.F. and Lee S.B (2013). "Sydney Harbour, Australia: Geology, Anthropogenic Development and Hydrodynamic Processes / Attributes". Estuaries of Australia in 2050 and beyond. *Springer Dordrecht Heidelberg. pp 17-30. Dec 2013. ISBN 978-94-007-7018-8.*

Birch, G.F., and O'Hea, L. (2007): The chemistry of suspended particulate material in a highly contaminated embayment of Port Jackson (Australia) under various meteorological conditions. *Environmental Geology, 53, 501-516.*

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.*

Birch, G. and Taylor, S. (1999). Sources of heavy metals in sediments of the Port Jackson estuary, Australia. *The Science of the Total Environment 227 (2–3), 123–138.*

Birch, G. & Taylor, S. (2000). Distribution and possible sources of organochlorine residues in sediments of a large urban estuary, Port Jackson, Sydney. *Australian Journal of Earth Sciences 47, 749-756*.

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.F. and Taylor, S.E. (2004). **Sydney Harbour and Catchment: Contaminant status of Sydney Harbour sediments: A handbook for the public and professionals**. *Geological Society of Australia, Environmental, Engineering and Hydrogeology Specialist Group, Sydney, 101 pp.*

Birch, G. F., Harrington, C., Symons, R. K., & Hunt, J. W. (2007). The source and distribution of polychlorinated dibenzo-p-dioxin and polychlorinated dibenzofurans in sediments of Port Jackson, Australia. *Marine Pollution Bulletin, 54(3), 295-308*.

Birch, G. F., Harrington, C., Symons, R. K., & Hunt, J. W. (2007). The source and distribution of polychlorinated dibenzo-p-dioxin and polychlorinated dibenzofurans in sediments of Port Jackson, Australia. *Marine Pollution Bulletin, 54(3), 295-308.*

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

Birch, G., Nath, B., Chaudhuri, P. (2015). Effectiveness of remediation of metal-contaminated mangrove sediments (Sydney estuary, Australia). *Environmental Science and Pollution Research, 22(8), 6185- 6197.*

Bishop, M (2003). Making Waves, The Effects of Boat-Wash on Macro-Benthic Assemblages of Estuaries. *PhD thesis, University of Sydney.*

Bishop, M. J. (2004). A posteriori evaluation of strategies of management: the effectiveness of no- wash zones in minimizing the impacts of boat-wash on macrobenthic infauna. *Environmental Management 34, 140-149.*

Bishop, M. (2005). Artificial Sampling Units: A Tool for Increasing the Sensitivity of Tests For Impact In Soft Sediments. *Environmental Monitoring and Assessment* ***107****: 203-220*.

Bishop, M. J. (2008). Displacement of epifauna from seagrass blades by boat wake. *Journal of Experimental Marine Biology and Ecology 354, 111-118.*

Blackwell, B. (2005). The Economic Value of Some of Australia's Natural Coastal Assets: Their Ecoservice Values, Presentation to 2005 Australian and New Zealand Society for Ecological Economics conference, www.anzsee.org/ anzsee2005papers/ BlackwellAweb.ppt *Accessed 2014.*

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*.

Bowman, L. (2008). Seagrass friendly boat moorings: feasibility assessment. *Prepared for Department of Primary Industries. 55 (March 2008).*

Bulleri, F., M. Chapman, and A. Underwood. (2005). Intertidal assemblages on seawalls and vertical rocky shores in Sydney Harbour, Australia. *Austral Ecology 30:655-667.*

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

Burgin, S., and N. Hardiman. (2011). The direct physical, chemical and biotic impacts on Australian coastal waters due to recreational boating. *Biodiversity and Conservation 20:683-701.*

Burgman, M. (2005). **Risks and decisions for conservation and environmental management.** *Cambridge University Press.*

Burton, G. (2016). Vagrant migration of tropical reef fish into Sydney Harbour: interaction of spatial gradients and physical factors. *Honours thesis University of Technology Sydney.*

Byrne, M., Ho, M., Selvakumaraswamy, P., Nguyen, H., Dworjanyn, S.A. and Davis, A.R (2009). Temperature, but not pH, compromises sea urchin fertilization and early development under near-future climate change scenarios. *Proceedings of the Royal Society B: Biological Sciences 276, 1883-1888.*

Byrne, M., Selvakumaraswamy, M., Woolsey, H., Nguyen, H. (2011). Sea urchin development in a global change hotspot, potential for southerly migration of thermo tolerant propagules. *Deep Sea Research Two* **58**: 712-719.

Camargo, J. A., and Á. Alonso. (2006). Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: a global assessment. *Environment International 32:831-849*.

Campbell, A. H., A. Vergés, T. Harder, and P. D. Steinberg. (2012). Causes and ecological consequences of a climate-mediated disease. Wildlife and Climate Change: *Towards robust conservation strategies for Australian fauna: 52.*

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.*

Cardno and Baird (2017). Sydney Harbour Ecological Response Model - Estuarine Processes Investigations. *Prepared for Greater Sydney Local Land Services*

Carlton, J. T. (1985). Transoceanic and interoceanic dispersal of coastal marine organisms: the biology of ballast water. *Oceanography and Marine Biology: an Annual Review 23, 313- 371.*

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.*

Chapman, D. (1981). **1788 - the People of the First Fleet**. *Cassell Australia, North Ryde, NSW.*

Chapman, M., Tolhurst, T. (2007). Relationships Between Benthic Macrofauna and Biogeochemical Properties Of Sediments At Different Spatial Scales And Among Different Habitats In Mangrove Forests. *Journal of Experimental Marine Biology and Ecology **343**: 96-109.*

Chariton, A. A., Court, L. N., Hartley, D. M., Colloff, M. J., & Hardy, C. M (2010). Ecological assessment of estuarine sediments by pyrosequencing eukaryotic ribosomal DNA. *Frontiers in Ecology and the Environment **8**: 233-238*

Clark, G. F., B. P. Kelaher, K. A. Dafforn, M. A. Coleman, N. A. Knott, E. M. Marzinelli, and E. L. Johnston. (2015). What does impacted look like? High diversity and abundance of epibiota in modified estuaries. *Environmental Pollution 196:12-20.*

Cloern, J. E., Foster, S. Q., and Kleckner, A. E. (2014). Phytoplankton primary production in the world's estuarine-coastal ecosystems. *Biogeosciences*, ***11****:2477-2501*.

Clynick, B., Chapman, M. & Underwood, A. (2007). Effects of epibiota on assemblages of fish associated with urban structures. *Marine Ecology Progress Series.*

Coastal Eutrophication Risk Assessment Tool. NSW Office and Environment (2012). http://www.ozcoasts.gov.au/nrm_rpt/cerat/index.jsp

Cohen, Y., B. B. Jørgensen, N. P. Revsbech, and R. Poplawski. (1986). Adaptation to hydrogen sulfide of oxygenic and anoxygenic photosynthesis among cyanobacteria. *Applied and environmental microbiology 51:398-407.*

Coleman, M. A., B. P. Kelaher, P. D. Steinberg, and A. J. Millar. (2008). Absence of a large brown macroalga on urbanized rocky reefs around Sydney, Australia, and evidence for historical decline. *Journal of Phycology 44:897-901*.

Connell, S. & Glasby, T. (1999). Do urban structures influence local abundance and diversity of subtidal epibiota? A case study from Sydney Harbour, Australia. *Marine Environmental Research 47, 373-387.*

Connell, S., B. Russell, D. Turner, A. Shepherd, T. Kildea, D. Miller, L. Airoldi, and A. Cheshire. (2008). Recovering a lost baseline: missing kelp forests from a metropolitan coast. *Marine Ecology-Progress Series 360:63-72.*

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

Costanza, R., D'arge, R., De Groot, R., StephenFarber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., & Marjan Van Den Belt, M. (1997). The value of the world's ecosystem services and natural capital. *Nature, 387, 253 - 260 15/51997.*

Crain, C. M., K. Kroeker, and B. S. Halpern. (2008). Interactive and cumulative effects of multiple human stressors in marine systems. Ecology Letters 11:1304-1315.

Creese, R. G., Davis, A. & Glasby, T. M. (2004). Eradicating and preventing the spread of the invasive alga *Caulerpa taxifolia* in NSW. *NSW Fisheries Final Report Series 64, 100.*

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

CSIRO. (2001). Climate change projections for Australia. *Climate Impact Group, CSIRO Atmospheric Research, Aspendale, Victoria, Australia 8.*

Cubby, B. and Lockwood, D., (2009) Killer bugs lurk in Harbour. *Sydney Morning Herald, 6 Dec 2009.*

Cunningham, D. & Wilson, S. (2003). Marine debris on beaches of the Greater Sydney region. *Journal of Coastal Research 19, 421-430.*

Curley, B. G., Glasby, T. M., Curley, A. J., Creese, R. G. & Kingsford, M. J. (2013). Enhanced numbers of two temperate reef fishes in a small, partial-take marine protected area related to spearfisher exclusion. *Biological Conservation 167, 435-445.*

Dann, P. & Chambers, L. (2013). Ecological effects of climate change on little penguins Eudyptula minor and the potential economic impact on tourism. *Climate Research 58, 67-79*.

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*.

Dafforn, K. A., T. M. Glasby, L. Airoldi, N. K. Rivero, M. Mayer-Pinto, and E. L. Johnston. (2015). Marine urbanization: an ecological framework for designing multifunctional artificial structures. *Frontiers in Ecology and the Environment 13:82-90*.

Dafforn, K., Glasby, T., Johnston, E. (2008). Differential effects of tributyltin and copper antifoulants on recruitment of non-indigenous species. *Biofouling 24, 23-33*.

Dafforn, K. A., T. M. Glasby, and E. L. Johnston. (2012). Comparing the invasibility of experimental ‘reefs’ with field observations of natural reefs and artificial structures. *PloS One 7:e38124.*

Dafforn, K. A., B. P. Kelaher, S. L. Simpson, M. A. Coleman, P. A. Hutchings, G. F. Clark, N. A. Knott, M. A. Doblin, and E. L. Johnston. (2013). Polychaete richness and abundance enhanced in anthropogenically modified estuaries despite high concentrations of toxic contaminants. *PloS One 8:e77018.*

Dafforn, K. A., J. A. Lewis, and E. L. Johnston. (2011). Antifouling strategies: history and regulation, ecological impacts and mitigation. *Marine Pollution Bulletin 62:453-465*.

Dafforn, K., Simpson, S., Kelaher, B P., Clark, G., Komyakova, V., Wong, C., Johnston, E. (2012). The challenge of choosing environmental indicators of anthropogenic impacts in estuaries. *Environmental Pollution 163, 207-217.*

DECCW. (2010). NSW Climate Impact Profile: The impacts of climate change on the biophysical environment of New South Wales. *168*

DECCW. (2009). New South Wales State of the Environment 2009*, p. 338, Sydney*.

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*.

Eggleton, J., and K. V. Thomas. (2004). A review of factors affecting the release and bioavailability of contaminants during sediment disturbance events. *Environment International 30:973-980*.

EnRisks (2017). Wentworth Point Marina – Risk Assessment. Prepared for NSW Roads and Maritime. *Reference: RMS/16/001. 30 March 2017*

Erbe, C., Williams, R., Sandilands, D. & Ashe, E. (2014). Identifying modelled ship noise hotspots for marine mammals of Canada's Pacific Region. *PLoS ONE 9(3): e89820*.

EVS Environmental Consultants (1998). Detailed Human Health and Ecological Risk Assessment of Homebush Bay Sediments. Prepared for the Office of Marine Administration, Sydney, Australia. *Unpublished report, Final, September, 1998. Project No. 5/790-01*.

Eyre, B. D. & Ferguson, A. J. P. (2009). in **Eutrophication in coastal ecosystems** Vol. 207 Developments in Hydrobiology (eds. J. H. Andersen & D. J. Conley) *Ch. 12, 137-146 (Springer Netherlands).*

Farrant, K. and King, R.J. (1982). The Subtidal Seaweed Communities Of The Sydney Region. *Wetlands 2, 51-60*

Figueira, W. F., and D. J. Booth. (2010). Increasing ocean temperatures allow tropical fishes to survive overwinter in temperate waters. *Global Change Biology 16:506-516*.

Fisheries (2002). Fisheries Management (Aquatic Reserves) Regulation 2002, NSW Fisheries, 2 September 2002. http://faolex.fao.org./docs/texts/nsw43003.doc

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., and Gladstone, W. (2011). Determination and description of suitable saltmarsh reference sites within Patonga Creek. *University of Newcastle Coastal and Estuarine Research Facility*. *Prepared for Gosford City Council and*.

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

Freewater, P. and R. Kelly. (2015). Sydney Harbour Catchment Water Quality Improvement Plan. Prepared for Greater Sydney Local Land Services

Freewater, P., Ferguson, A. Scanes, P. Potts, J., Sutherland, M. and Sun, M. (2016). Reconstruction of critical habitats within Sydney Harbour: Understanding the function of shallow embayments using ecosystem response models. *NSW Coastal Conference proceedings*.

Geochemical Assessments and EnRisks (2017). Sediment Quality and Human Health Risk Assessment: Potential Swimming Locations in the Parramatta River. Wentworth Point Marina – Risk Assessment. *Prepared for City of Parramatta. September 2017*.

Ghosn, D., Steffe, A., Murphy, J. (2010). An assessment of the effort and catch of shore-based and boat-based recreational fishers in the Sydney Harbour estuary over the 2007/08 summer period. Final report to the NSW Recreational Fishing Trust Fund. Industry and Investment NSW, *Fisheries Final Report Series, Cronulla NSW, Australia. 122, 60*.

Gillan, D. C., B. Danis, P. Pernet, G. Joly, and P. Dubois. (2005). Structure of sediment-associated microbial communities along a heavy-metal contamination gradient in the marine environment. *Applied and Environmental Microbiology 71:679-690.*

Gillanders, B. M. (2002). Connectivity between juvenile and adult fish populations: do adults remain near their recruitment estuaries. *Marine Ecology Progress Series 240, 215-223*.

Gillanders, B. M. & Kingsford, M. J. (2002). Impact of changes in flow of freshwater on estuarine and open coastal habitats and the associated organisms. *Oceanography and Marine Biology: An Annual Review 40, 233-309.*

Gillanders, B.M., Elsdon, T.S., Halliday, I.A., Jenkins, G.P., Robins, J.B. and Valesini, F.J. (2011). Potential effects of climate change on Australian estuaries and fish utilising estuaries: a review. *Marine and Freshwater Research, 62 (9). pp. 1115-1131.*

Gladstone, W. (2010). Seagrass friendly moorings in Manly Cove: report of 2010 monitoring. *Report to Sydney Metro Catchment Management Authority.*

Gladstone, W. (2013). Seagrass friendly moorings in Manly Cove: report of 2013 monitoring. *Report to Sydney Metropolitan Catchment Management Authority.*

Glasby, T. (1999). Differences between subtidal epibiota on pier pilings and rocky reefs at marinas in Sydney, Australia. *Estuarine Coastal and Shelf Science 48, 281-290.*

Glasby, T. M. (2013). *Caulerpa taxifolia* in seagrass meadows: killer or opportunistic weed? *Biol Invasions 15, 1017-1035.*

Glasby, T., Connell, S., Holloway, M. & Hewitt, C. (2007). Non-indigenous biota on artificial structures: could habitat creation facilitate biological invasions? *Marine Biology 151, 887- 895.*

Glasby, T. M. & Creese, R. G. (2007). Invasive marine species management and research. Chapter 22 in: **Marine Ecology** (S. Connell & B. Gillanders, eds). *Oxford University Press, 569-594*.

Glasby, T.M., & Lobb, K. (2008). Assessing likelihoods of marine pest introductions in Sydney estuaries: a transport vector approach. *Fisheries Final Report Series 105, 78*.

Goda, Y (2000): Random Seas and Design of Maritime Structures. World Scientific, Volume 15.

Gorman, J. (2015). Welcoming a brand new view of city.

GSC (2018). Greater Sydney Region Plan 2018 A Metropolis of Three Cities. *Greater Sydney Commission*

Gregory, M. R. (2009). Environmental implications of plastic debris in marine settings - entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. *Philosophical Transactions of the Royal Society B: Biological Sciences 364, 2013-2025.*

Hall, S. (posted 02/01/2010). The Sewer Fix Wet Weather Alliancing story. http://www.alliancecontractingiq.com/articles/the-sewerfix-wet-weather-alliancing-story/ accessed 25 May 2013.

Hardiman, N., and S. Burgin. (2010). Recreational impacts on the fauna of Australian coastal marine ecosystems. *Journal of Environmental Management 91:2096-2108*.

Harris, G. P. (2001). Biogeochemistry of nitrogen and phosphorus in Australian catchments, rivers and estuaries: effects of land use and flow regulation and comparisons with global patterns. *Marine and Freshwater Research 52:139-149.*

Hazel, J., Lawler, I. R., Marsh, H. & Robson, S. (2007). Vessel speed increases collision risk for the green turtle *Chelonia mydas*. *Endangered Species Research 3, 105-113*.

Heagney, E.C., Kovac, M., Fountain, J. and Conner N. (2015). Socio-economic benefits from protected areas in south eastern Australia. *Conservation Biology, Volume 29, No. 6, 1647–1657.*

Hedge, L., N. Knott, and E. Johnston. (2009). Dredging related metal bioaccumulation in oysters. *Marine Pollution Bulletin 58:832-840.*

Hedge, L.H., Johnston, E.L., Ahyong, S.T., Birc,h 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., (2014a). Sydney Harbour: A systematic review of the science, *Sydney Institute of Marine Science, Sydney, Australia.* P*repared for the NSW Department of Primary Industries.*

Hedge, L. H., J. Turnbull, C. Hoisington, and E. L. Johnston. (2014b). Sydney Harbour Background Report. *Sydney Institute of Marine Science, Sydney, Australia. Prepared for the NSW Department of Primary Industries*.

Heithaus, M. R., Frid, A., Wirsing, A. J. & Worm, B. (2008). Predicting ecological consequences of marine top predator declines. *Trends in Ecology & Evolution 23, 202-210*.

Henry, G. W. (1984). Commercial and recreational fishing in Sydney estuary. New South Wales Department of Agriculture

Herbert, R. (1999). Nitrogen cycling in coastal marine ecosystems. *FEMS Microbiology Reviews 23:563-590.*

Higham, J. E. S. & Shelton, E. J. (2011). Tourism and wildlife habituation: reduced population fitness or cessation of impact? *Tourism Management 32, 1290-1298.*

Hobday, A., Okey, T., Poloczanska, E., Kunz, T. & Richardson, A. (2006a). Impacts of climate change on Australian marine life - Part B: Technical Report. *Technical Report. CSIRO Marine and Atmospheric Research, Canberra, Australia.*

Hobday, A., Okey, T., Poloczanska, E., Kunz, T. & Richardson, A. (2006b). Impacts of climate change on Australian marine life - Part A: Executive Summary. *Project Report. CSIRO Marine and Atmospheric Research, Canberra, Australia.*

Hoisington, C. (2015). Our Harbour Our Asset: An overview of economic activities and values associated with Australia's most iconic Harbour, and its use by the city that surrounds it. *Sydney Institute of Marine Science, Sydney, Australia.*

Hollingsworth, A. and Connolly, R.M. (2006). Feeding by fish visiting inundated subtropical saltmarsh. *Journal of Experimental Marine Biology and Ecology 336:88–98.*

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

Howarth, R., F. Chan, D. J. Conley, J. Garnier, S. C. Doney, R. Marino, and G. Billen. (2011). Coupled biogeochemical cycles: eutrophication and hypoxia in temperate estuaries and coastal marine ecosystems. *Frontiers in Ecology and the Environment 9:18-26*.

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.*

Hutchings PA, Ahyong ST, Ashcroft MB, McGrouther MA, Reid AL (2013). Sydney Harbour: Its diverse biodiversity, *Australian Zoologist, 36: 255-320.*

Irvine, I.A. (1980). Sydney Harbour: Sediment and Heavy Metal Pollution. *Unpublished PhD Thesis. Sydney University. 380 pg.*

Irvine, I., and G. Birch. (1998). Distribution of heavy metals in surficial sediments of Port Jackson, Sydney, New South Wales. *Australian Journal of Earth Sciences 45:297-304.*

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.*

Ji, F., J. P. Evans, D. Argueso, L. Fita, and A. Di Luca. (2015). Using large-scale diagnostic quantities to investigate change in East Coast Lows. *Climate Dynamics:1-11.*

Jickells T.D. (1998) Nutrient biogeochemistry of the coastal zone. *Science*, ***281****:217–222.*

Johnston, E., M. Mayer-Pinto, P. Hutchings, E. Marzinelli, S. Ahyong, G. Birch, D. Booth, R. Creese, M. Doblin, and W. Figueira. (2015a). Sydney Harbour: what we do and do not know about a highly diverse estuary. *Marine and Freshwater Research 66:1073-1087.*

Johnston, E. L., M. Mayer-Pinto, and T. P. Crowe. (2015b). 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.*

Jones, K. C., and P. De Voogt. (1999). Persistent organic pollutants (POPs): State of the science. *Environmental Pollution 100:209-221.*

Jones, R. (2005). The ecotoxicological effects of Photosystem II herbicides on corals. *Marine Pollution Bulletin 51:495-506.*

Kelleway, J., Williams R.J., and Allen, C.B (2007). An Assessment of the Saltmarsh of the Parramatta River and Sydney Harbour. *Report prepared for the NSW Department of Primary Industries*.

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*

Kennish, M. J. (2002). Environmental threats and environmental future of estuaries. *Environmental Conservation 29:78-107.*

Kerry and Co. (1905). A Forest Clearing. Tyrrell Photographic Collection. Powerhouse Museum, Sydney, Australia. Accessed Sept 2015, http://www.powerhousemuseum.com/collection/database/online/collection/database/?irn=29853&search=tyrrell+photographic+collection&images=&c=1&s=.

Kilby, G., and G. Batley. (1993). Chemical indicators of sediment chronology. *Marine and Freshwater Research 44:635-647.*

Laist, D. W., Knowlton, A. R. & Pendleton, D. (2014). Effectiveness of mandatory vessel speed limits for protecting North Atlantic right whales. *Endangered Species Research 23, 133-147.*

Larkum, A. W. D (1986). A Study Of Growth And Primary Production In *Ecklonia radiata* (C-Ag) J-Agardh (Laminariales) At A Sheltered Site In Port Jackson, New South-Wales. *Journal of Experimental Marine Biology and Ecology* ***96****: 177-190.*

Ledoux, L. and Turner, R.K. (2002) Valuing ocean and coastal resources: a review of practical examples and issues for further action. *Ocean & Coastal Management 45 (2002) 583616.*

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.*

Lemon, M., Lynch, T. P., Cato, D. H. & Harcourt, R. G. (2006). Response of travelling bottlenose dolphins (*Tursiops aduncus*) to experimental approaches by a powerboat in Jervis Bay, New South Wales, Australia. *Biological Conservation 127, 363-372*.

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 conceptual framework. *Environmental Modelling & Software 22 (5), 733-742.*

Liggins, G. W., Kennelly, S. J. & Broadhurst, M. K. (1996). Observer-based survey of by-catch from prawn trawling in Botany Bay and Port Jackson, New South Wales. *Marine and Freshwater Research 47, 877-888.*

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.*

Losada, S., A. Roach, L. Roosens, F. J. Santos, M. T. Galceran, W. Vetter, H. Neels, and A. Covaci. (2009). Biomagnification of anthropogenic and naturally-produced organobrominated compounds in a marine food web from Sydney Harbour, Australia. *Environment International 35:1142-1149.*

MacIntyre, H., Geider, R., & Miller, D. (1996). Microphytobenthos: The Ecological Role of the "Secret Garden" of Unvegetated, Shallow-Water Marine Habitats. Distribution, Abundance and Primary Production. *Estuaries, **19(2)**:186-201*.

Mallinson, L., Taylor, H. & O'Shea, O. (2013). A review of plastic resin pellet distribution throughout Australia and mitigation methods for reducing spill-over into the marine environment. *Report prepared for Tangaroa Blue Foundation, Australian Marine Debris Initiative.*

Martínez, M., A. Intralawan, G. Vázquez, O. Pérez-Maqueo, P. Sutton, and R. Landgrave. (2007). The coasts of our world: Ecological, economic and social importance. *Ecological Economics 63:254-272.*

Marzinelli, E. (2012). Artificial marine structures influence fouling on habitat-forming kelps. *Biofouling 28, 339-349.*

Marzinelli, E., Underwood, A., Coleman, R. (2011). Modified habitats influence kelp epibiota via direct and indirect effects. *Plos One 6.*

Matias, M., Underwood, A., Coleman, R. (2010). Effects of Structural Diversity and Identity of Patches of Habitat on Diversity of Benthic Assemblages, *Austral Ecology* **35**:743-751.

Mayer-Pinto, M., Johnston, E.L., Hutchings, P.A., Marzinelli, E.M., Ahyong, S.T., Birch, G., Booth, D.J., Creese, R. G., Doblin M. A., Figueiral, W., Gribben, P., Pritchard T., Roughan, M., Steinberg, P. D., and Hedge, L. H. (2015). Sydney Harbour: a review of anthropogenic impacts on the biodiversity and ecosystem function of one of the world's largest natural Harbours. *Marine and Freshwater Research, 66, 1088–1105.*

Mazumder, D., Saintilan, N. and Williams, R.J. (2006). Trophic relationships between itinerant fish and crab larvae in a temperate Australian saltmarsh. *Marine and Freshwater Research 57, 193–199.*

McCready, S., Slee, D., Birch, G., Taylor, S. (2000). The Distribution Of Polycyclic Aromatic Hydrocarbons in Surficial Sediments of Sydney Harbour. *Australia Marine Pollution Bulletin **40**:999-1006.*

McGrath, C. (2012). Sydney Harbour's toxic legacy shows value of green safety net. https:// theconversation.com/ sydney\-Harbours-toxic-legacy-shows-value-of-green-safety-net-11197 Accessed 2014.

McIlgorm, A. and J. Pepperell (2013). Developing a cost effective state wide expenditure survey method to measure the economic contribution of the recreational fishing sector in NSW in 2012. *A report to the NSW Recreational Fishing Trust, NSW Department of Primary Industries, November 2013. Produced by the Australian National Centre for Ocean Resources and Security (ANCORS), University of Wollongong.*

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.*

McKinley, A. C., A. Miskiewicz, M. D. Taylor, and E. L. Johnston. (2011). Strong links between metal contamination, habitat modification and estuarine larval fish distributions. *Environmental Pollution 159:1499-1509*.

McKinley, A., Taylor, M., Johnston, E. (2012). Relationships between body burdens of trace metals (As, Cu, Fe, Hg, Mn, Se, And Zn) and the relative body size of small tooth flounder (*Pseudorhombus Jenynsii*). *Science of The Total Environment 423, 84 – 94.*

McLoughlin, L. C. (2000a). Estuarine wetlands distribution along the Parramatta River, Sydney, 1788–1940: Implications for planning and conservation.

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

McMahon K, Bengtson Nash S, Eaglesham G, Müller JF, Duke NC, Winderlich S. (2005). Herbicide contamination and the potential impact to seagrass meadows in Hervey Bay, Queensland, *Australia. Marine Pollution Bulletin 51:325–334*

McPhee, D. P., D. Leadbitter, and G. Skilleter. (2002). Swallowing the bait: is recreational fishing in Australia ecologically sustainable? *Pacific Conservation Biology 8:40-51.*

Millar, A. J. K. (2011). Macroalgae: NSW Industry and Investment Factsheet. http://www.dpi.nsw.gov.au/ data/assets/pdf_file/0009/378774/Macroalgae-Primefact- 947.pdf.

Morrisey, D. (1995). Saltmarshes in Coastal Marine Ecology of Temperate Australia (ed Underwood, A.J. and Chapman, G.) *UNSW Press Syd, **5** pp.205-220*.

Naylor, R. L., Williams, S. L. & Strong, D. R. (2001). Aquaculture – a gateway for exotic species. *Science 294, 1655–1656.*

NSW Department Planning & Environment (2014). A Plan for Growing Sydney. http://www.strategy.planning.nsw.gov.au/sydney/wp-content/uploads/sites/2/2015/02/A-Plan-For-Growing-Sydney_2015_updated_20Feb_.pdf

NSW DPI (2001). Estuary general fishery- environmental impact assessment. Public consultation document, NSW Fisheries, Cronulla Fisheries Centre, Sydney. New South Wales Department of Primary Industries.

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

NSW DPI (2014). (New South Wales Department of Primary Industries), Estuarine Habitats; http://www.dpi.nsw.gov.au/fisheries/habitat/aquatic-habitats/estuarine. Accessed July 2014.

NSW NPWS (2002). (New South Wales National Parks and Wildlife Service). Declaration of critical habitat for the endangered population of Little Penguins (*Eudyptula minor*) at Manly- (Pursuant to s.40 and 43 of the Threatened Species Conservation Act 1995). NSW NPWS, Hurstville, NSW

NSW Transport (2012) NSW Ferries Annual Report 2012 www.manlymania.net/Ferry/pdf/sydney-**ferries-annual-report-2012**.pdf

OEH (2008). Beachwatch report. Prepared by Office of Environment and Heritage, Government of NSW.

OEH (2013) The Native Vegetation of the Sydney Metropolitan Area. Volume 1: Technical Report. Version 2.0. Office of Environment and Heritage, Department of Premier and Cabinet, Sydney.

OEH (2015). Beachwatch State of the Beaches 2014-2015. *Prepared by Office of Environment and Heritage, Government of NSW.*

O'Loughlin, G., S. Beecham, S. Lees, L. Rose, and D. Nicholas (1995). On-site stormwater detention systems in Sydney. *Water Science and Technology 32:169-175*.

Paramatrix and AWT Ensight (1996). Homebush Bay Screening-Level Risk Assessment. *Unpublished report prepared for Office of Marine Safety and Port Strategy, October 1996, Sydney, Australia*.

Parsons Brinkerhoff (2002). Environmental Impact Statement. Remediation of Lednez Site, Rhodes and Homebush Bay. *Unpublished report prepared for Thesis Services, Sydney, Australia*.

PCC (2003). Seawalls in Parramatta. August 2003. Parramatta City Council.

Pepperell Research & Consulting Pty Ltd. (2017). The good old days? Historical insights into New South Wales coastal fish populations and their fisheries. *Report to The NSW Recreational Fishing Trusts Expenditure Committee.*

Pinckney, J. L., H. W. Paerl, P. Tester, and T. L. Richardson. (2001). The role of nutrient loading and eutrophication in estuarine ecology. *Environmental Health Perspectives 109:699*.

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.*

PWD (1986). Investigation into a proposed rowing facility at Homebush Bay. *MHL Report No. 449. February 986. 27 pg.*

Rabalais, N. N., R. E. Turner, R. J. Díaz, and D. Justić. (2009). Global change and eutrophication of coastal waters. ICES Journal of Marine Science: *Journal du Conseil 66:1528-1537.*

Rees, S.E., Rodwell, L.D., Attrill, M.J., Austen, M.C. Mangi, S.C., (2010). The value of marine biodiversity to the leisure and recreation industry and its application to marine spatial planning. *Marine Policy 34:868-875*

Ridgway, K. R. (2007). Long-term trend and decadal variability of the southward penetration of the East Australian Current. *Geophysical Research Letters 34:1-5.*

Riesenfeld, C. S., P. D. Schloss, and J. Handelsman. (2004). Metagenomics: genomic analysis of microbial communities. *Annu. Rev. Genet. 38:525-552.*

RMS (2017). Dioxins in fish and prawns in Homebush Bay and Parramatta River, Australia. *Roads and Maritime Services Document # RMS 17.085*

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.*

Roach, A.C., Symons, R. and Stevenson, G.J. (2018). Variations in congener profiles and levels of PCDDs, PCDFs, dioxin-like PCBs and PBDEs in sediments from Sydney, Australia. *Unpublished OEH*.

Roach, A., Symons, R., Stevenson, G. (2009) Contrasting Patterns of Spatial Autocorrelation of PCDD/Fs, Dioxin-Like PCBs and Pbdes in Sediments In Sydney Harbour, Australia. *Organohalogen Compounds* **71**:366-371.

Rogers, K., Saintilan, N., Davies, P., Kelleway, J. and Mogensen, L. (2017). Mangrove and Saltmarsh Threat Analysis in the Sydney Coastal Councils Region. *Prepared for the Sydney Coastal Council Group.*

Roberts, L., Butcher, P., Broadhurst, M., Cullis, B. (2011). Using a multi-experimental approach to assess the fate of angled-and-released yellowtail kingfish (*Seriola lalandi*). *ICES Journal of Marine Science 68, 67-75.*

Roberts, D. A., Poore, A. G. and Johnston., E. L. (2006). Ecological consequences of copper contamination in macroalgae: effects on epifauna and associated herbivores. *Environmental Toxicology and Chemistry 25:2470-2479.*

Roper, T. Creese B, Scanes P, Stephens K, Williams R, Dela-Cruz J, Coade G, Coates B & Fraser M (2011). Assessing the condition of estuaries and coastal lake ecosystems in NSW, Monitoring, evaluation and reporting program, Technical report series, Office of Environment and Heritage, Sydney.

Roy, P.S., Williams, R.J., Jones, A.R., Yassini, I., Gibbs, P.J., Coates, B., West, R.J., Scanes, P.R., Hudson, J.P. & Nichol, S. (2001). 'Structure and function of south-east Australian estuaries', *Estuarine, Coastal and Shelf Science*, ***53****:351–384*

Ruiz, G. M., Fofonoff, P. W., Carlton, J., Wonham, M. J. & Hines, A. N. (2000). Invasion of coastal marine communities in North America: apparent patterns, processes, and biases. *Annual Review of Ecology and Systematics 31, 481-531*

Saintilan, N., Wilson, N.C., Rogers, K., Rajkaran, A., Krauss, K.W. (2014). Mangrove expansion and salt marsh decline at mangrove poleward limits. *Global Change Biology, 20, 147-157.*

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.*

Shears, N. & Babcock, R. (2002). Marine reserves demonstrate top-down control of community structure on temperate reefs*. Oecologia 132, 131-142*.

Shears, N. T., Babcock, R. C. & Salomon, A. K. (2008). Context-dependent effects of fishing: variation in trophic cascades across environmental gradients. *Ecological Applications 18, 1860-1873*,

SIMS (2012) Water Quality Sampling of Parramatta River – Methods & Sampling Protocol. Data collected by the Sydney Institute of Marine Science for the Hawkesbury Nepean Catchment Management Authority.

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.*

Steckenreuter, A., Möller, L. & Harcourt, R. (2012a). How does Australia's largest dolphin-watching industry affect the behaviour of a small and resident population of Indo-Pacific bottlenose dolphins? *Journal of Environmental Management 97, 14-21.*

Steckenreuter, A., Harcourt, R. & Möller, L. (2012b). Are speed restriction zones an effective management tool for minimising impacts of boats on dolphins in an Australian marine park? *Marine Policy 36, 258-264.*

Stamation, K. A., Croft, D. B., Shaughnessy, P. D., Waples, K. A. & Briggs, S. V. (2010). Behavioral responses of humpback whales (*Megaptera novaeangliae*) to whale-watching vessels on the southeastern coast of Australia. *Marine Mammal Science 26, 98-122.*

Stewart, J. (2008). Capture depth related mortality of discarded snapper (*Pagrus auratus*) and implications for management. *Fisheries Research 90, 289-295.*

Sun, M.Y., Dafforn, K.A. Johnston, E. L. and Brown M.V. (2013). Core sediment bacteria drive community response to anthropogenic contamination over multiple environmental gradients. *Environmental microbiology 15:2517-2531*.

Sutherland, M., Dafforn, K.A., Scanes, P., Potts, J., Simpson, S.L., Sim, V.X.Y. and Johnston, E.L. (2016). Links between contaminant hotspots in low flow estuarine systems and altered sediment biogeochemical processes. *Estuarine Coastal and Shelf Science*.

Sweeney Research (2014). Marine Estate Community Survey. Prepared for the Marine Estate Management Authority, July 2014.

Sydney Metropolitan Catchment Management Authority (2011) SMCMA Annual report 2010-2011.

Taylor, S.E., Birch, G.F. (2000). The distribution and possible sources of organochlorine residues in sediments of a large urban estuary, Port Jackson, Sydney. *Australian Journal of Earth Sciences 47, 749–756.*

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.*

Tibbetts, J. (2002). Coastal cities: living on the edge. Environmental Health Perspectives 110:A674. Van der Sterren, M., A. Rahman, and G. Dennis. 2012. Implications to stormwater management as a result of lot scale rainwater tank systems: a case study in Western Sydney, Australia. *Water Science & Technology 65*.

Thompson, J., Eaglesham, G., Roach, A., Bartkow, M., Mueller, J. (2009). Perfluorinated Carboxylates and Sulfonates in sediments from Homebush Bay, Sydney, Australia. *Organohalogen Compounds 71, 2418- 2423*.

Underwood, G. J. C., Kromkamp, J. (1999). Primary production by phytoplankton and microphytobenthos in estuaries. *Adv Ecol Res*, **29***:*93-153.

Underwood, A., Chapman, M. (1996). Subtidal Assemblages On Rocky Reefs At A Cliff-Face Sewage Outfall (North Head, Sydney, Australia): What Happened When The Outfall Was Turned Off? *Marine Pollution Bulletin* **33**:293-302

Underwood, A., Chapman, M., Cole, V., Palomo, M. (2008). Numbers and Density of Species as Measures of Biodiversity on Rocky Shores along the Coast of New South Wales, *Journal of Experimental Marine Biology and Ecology* **366**:175- 183

URS, (2002). Final Report, Homebush Bay Dioxins Remediation Project, Investigation of Dioxins in Homebush Bay Sediments. Unpublished report Prepared for Thiess Services and Waterways Authority, Sydney, Australia.an Geology and Geophysics, 17(5/6), 233-237

Van der Sterren, M., A. Rahman, and G. Dennis. (2012). Implications to stormwater management as a result of lot scale rainwater tank systems: a case study in Western Sydney, Australia. *Water Science & Technology 65.*

Van Waerebeek, K, Baker, A.N., Félix, F., Gedamke, J., Iñiguez, M. and Sanino, G.P. (2007). Vessel collisions with small cetaceans worldwide and with large whales in the Southern Hemisphere, an initial assessment*. Latin American Journal of Aquatic Mammals, 43-69.*

Vergés, A., P. D. Steinberg, M. E. Hay, A. G. B. Poore, A. H. Campbell, E. Ballesteros, K. L. Heck, D. J. Booth, M. A. Coleman, D. A. Feary, W. Figueira, T. Langlois, E. M. Marzinelli, T. Mizerek, P. J. Mumby, Y. Nakamura, M. Roughan, E. van Sebille, A. S. Gupta, D. A. Smale, F. Tomas, T. Wernberg, and S. K. Wilson. (2014). The tropicalization of temperate marine ecosystems: climate-mediated changes in herbivory and community phase shifts. *Proceedings of the Royal Society of London B: Biological Sciences 281.*

Vitousek, P. M., H. A. Mooney, J. Lubchenco, and J. M. Melillo. (1997). Human domination of Earth's ecosystems. *Science 277:494-499*.

Wang, F., and P. M. Chapman. (1999). Biological implications of sulfide in sediment—a review focusing on sediment toxicity. *Environmental Toxicology and Chemistry 18:2526-2532*.

Webb McKeown & Assoc. (1997). Parramatta River Seawall Audit. Parramatta River Foreshores Improvement Advisory Committee and the Department of Urban Affairs and Planning, November 1997: *pp. 15*.

Wernberg, T., Russell, B.D., Moore, P.J., Ling, S.D., Smale, D.A., Campbell, A., Coleman, M.A., Steinberg, P.D., Kendrick, G.A., and Connell, S.D. (2011). Impacts of climate change in a global hotspot for temperate marine biodiversity and ocean warming. *Journal of Experimental Marine Biology and Ecology. 400: 7-16.*

Whitfield, A. K. & Becker, A. (2014). Impacts of recreational motorboats on fishes: a review. *Marine Pollution Bulletin 83, 24-31.*

Widmer, W. & Underwood, A. (2004). Factors affecting traffic and anchoring patterns of recreational boats in Sydney Harbour, Australia. *Landscape and Urban Planning 66, 173- 183.*

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

Williams, B., Freewater, P., Garber, S., Phocas, C., Taylor, D., & Treloar, D. (2013). Towards the Development of a Detailed Water Quality Modelling System for Port Jackson and Parramatta River. *NSW Coastal Conference proceedings*.

Williams, R.J., Allen, C.B. and Kelleway, J. (2011). Saltmarsh of the Parramatta River-Sydney Harbour: determination of cover and species composition including comparison of API and pedestrian survey. *Cunninghamia 12(1): 2011.*

Wilson, G., Raftos, D., Corrigan, S., Nair, S. (2010) Diversity And Antimicrobial Activities Of Surface-Attached Marine Bacteria From Sydney Harbour, Australia, *Microbiological Research* ***165****:300-311.*

Wong, T. and R. Brown. (2009). The water sensitive city: principles for practice. *Water Science and Technology 60:673.*

Worm, B., E. B. Barbier, N. Beaumont, J. E. Duffy, C. Folke, B. S. Halpern, J. B. Jackson, H. K. Lotze, F. Micheli, and S. R. Palumbi. (2006). Impacts of biodiversity loss on ocean ecosystem services. *Science 314:787-790.*

WP Geomarine (1998). Parramatta River Seawall Damage Appraisal. Prepared for Parramatta City Council, January 1998: *pp. 20*.

Wright, S. L., R. C. Thompson, and T. S. Galloway. (2013). The physical impacts of microplastics on marine organisms: a review. *Environmental Pollution 178:483-492*.

APPENDICES

Appendix A	Sydney Harbour Catchment Water Quality Improvement Plan
Appendix B	Sydney Harbour Catchment Model
Appendix C.1	Sydney Harbour Delft3D Model final report
Appendix C.2	Sydney Harbour Delft3D ERM Model draft report
Appendix C.3	Sydney Harbour Ecological Response Model - Estuarine Processes Investigations
Appendix D.1	Sydney Harbour A systematic review of the science 2014
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Appendix E	Sydney Harbour its diverse biodiversity