Sydney Harbour

A systematic review of the science 2014

Sydney Institute of Marine Science Technical Report

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Cover Photo | Mike Banert *North Head*
The light was changing every minute. I climbed over some huge rocks to get into a great position to take some surfing shots, when suddenly this huge cloud covered up the sun. Suddenly the beautiful light illuminating the waves the surfers were riding was gone. I looked to my left and noticed the light here. Quickly, I grabbed my stuff and setup this shot…..only got one frame, because soon after this the light here was also gone.

Design: Luke Hedge and Marian Kyte

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Executive Summary

The Sydney Harbour estuary is renowned for its biological diversity. Despite the importance of the estuary for the social, economic and environmental health of the city of Sydney, and the nation more generally, there has been no comprehensive compilation or synthesis of the biophysical scientific research conducted within the waterway.

This report collates the currently available information within the world's peer-reviewed, scientific literature. It systematically examines scientific databases and canvasses local, national and international scholars. The result is a comprehensive list of published biophysical information sources. Our report synthesizes this information into a succinct document accessible to stakeholders, policymakers, and the general public. This is produced as a guide to the current state of knowledge of the harbour and readers are directed to the references for further information.

Geological History and Geomorphology

The Sydney Harbour estuary is a drowned river valley, characterized by steep sided banks carved into Sydney sandstone between 25 and 29 million years ago. Approximately 17 000 years ago, the sea level rose, flooding the river valley and forming a flood tide delta.

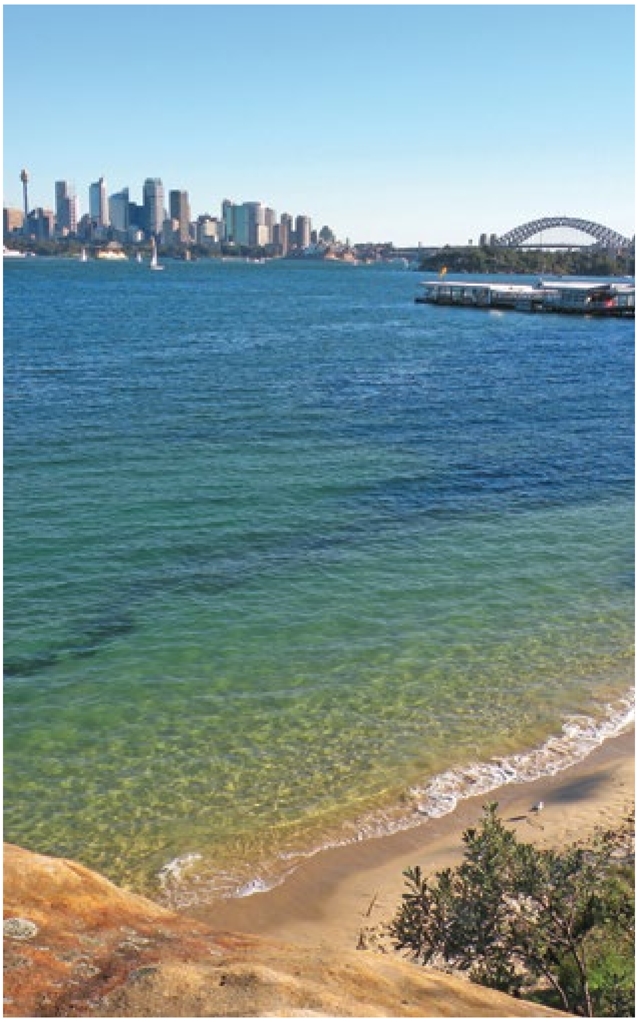
While there are several articles discussing the geology and geological history of the estuary, there has been a greater focus on sedimentology. This includes examinations of land reclamation in the estuary, the effects of sediment characteristics on burrowing crabs, and the effects of coastal cities on surficial sediments.

Hydrology and Circulation

The East Australian Current (EAC) delivers nutrient depleted waters just off Sydney's coast at between 16 °C to 25 °C during the winter months and 12 °C to 20 °C for the rest of the year. The colder, up-welled, water during summer may be a potential source of nutrients into the Sydney Harbour estuary.

Salinity in the harbour is generally the same as the ocean (35 psu). After rainfall, waters in the Parramatta River can be near fresh for a short time. Salinity at the harbour mouth can be reduced to about 30 psu in the top water layers (upper 4m) after very heavy rain.

The most frequent wind patterns are from the northeast and are observed 22 % of the time. The strongest winds are from the south and are only observed 17 % of the time.



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Tides in the harbour are semi diurnal and reverse every six hours. Towards the harbour entrance, tidal velocities can be as high as 0.25 $m.s^{-1}$. Modeled of velocities in the upper branches of the estuary, however, are only one tenth of those near the entrance.

We have little knowledge of how the EAC and continental shelf circulation interacts with the Sydney Harbour estuary. Previous studies of circulation do not take into account the circulation or hydrology seaward of the heads. This is important, as predicted changes to the EAC due to global climate change may have implications for water flows on the continental shelf and tidal exchange in Sydney Harbour.

Subtidal Rocky Reef

Most studies in this category focus on the habitat-forming algal species that dominate subtidal reefs in Sydney Harbour. Particular attention has been given to the effects of artificial structures on natural reef, and fragmentation of these habitats. Species richness and composition are generally altered by the fragmentation of natural reefs by dissecting breakwalls and shipping infrastructure. Artificial hard substrata typically support different organisms and greater numbers of non-indigenous species than natural reefs.

A NSW Government study has comprehensively mapped an area of reef in the harbour. This remains unpublished, but was included due to the ease of access to the report and rigorous analyses used. Here they found reefs dominated by macroalgae (37 %), urchin barrens (18 %) or a mixture of both.

We do not know whether natural processes observed on the outer coastline can be generalized to harbour systems, where wave action and storm activity are dramatically reduced.

Rocky Intertidal Shores

The natural rocky shores of Sydney Harbour are often gently sloping or horizontal sandstone platforms, some boulder fields or vertical steps. Much of the intertidal shoreline (> 50 %) has been replaced with artificial breakwalls that now represent artificial rocky shores.

Approximately 127 different taxa have been observed inhabiting intertidal reefs in Sydney Harbour, though there is much variability in the diversity of animals around the shoreline. This finding is consistent with other studies conducted on the open coast. The mid shore areas in Sydney Harbour 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. Just above the low water mark, relatively large, foliose, algal species form patchy mosaics throughout the estuary.

Soft Bottoms and Beaches

While there are more publications on the sediment of Sydney Harbour than any other system, most of these papers describe the spatial patterns of chemical contamination. Only 13 of the 91 publications investigate elements of sediment ecology and biology *per se* and only four of these publications investigate the iconic beaches of Sydney Harbour.

In a recent examination of sediment diversity, the Australian Museum collated records for 2472 different mollusc, polychaete, echinoderm and crustacean species. The spatial extent of these records, however is limited. Of the four publications that examine beaches in Sydney Harbour, only one made a holistic assessment of beach diversity in areas of the outer harbour.

Sediment systems are difficult to sample due to depth constraints and the small size of sediment infauna. Newly developed gene sequencing techniques have been used to uncover over 10 091 Operational Taxanomic Units (OTU's) from 262 Orders, 122 Classes, and 54 Phyla in Sydney Harbour sediment.

Soft sediment systems are one of the least studied in Sydney Harbour, despite the relatively large research effort placed into characterizing sediment contamination. Only a few, relatively recent, studies are matching these well characterized contaminant distributions with biologically meaningful indicators such as diversity and community composition.

Soft Sediment Macrophytes

The best estimates of mangrove, seagrass and saltmarsh extent in Sydney Harbour exist as a series of NSW Government reports. Although not published within a peer reviewed journal they were included in this report due to the comprehensive nature of the analyses and the ease of access.

The extent of saltmarsh in Sydney Harbour has declined dramatically since colonisation and it is estimated only 37 ha remain. The largest contiguous patch of saltmarsh exists within the Newington Nature Reserve in the Parramatta River.

Conversely, mangrove extent has increased recently and there is thought to be approximately 184 ha in the Sydney Harbour estuary. In some parts of the harbour, mangrove forests are replacing the more fragile 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.

Open Water / Pelagic Systems

Very little is known of the flora and fauna that inhabit the water column in Sydney Harbour, and most of the existing 32 publications in this area focus on characterizing water quality.

There has been some historical analysis of algal blooms since European colonisation, and algae with direct toxic effects to biota (including humans) 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. Concentrations of chlorophyll (a measure of algal abundance) are very high in the Parramatta River.

Zooplankton has received no empirical attention 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.

Metalloids, Organometallic and Metallic Contamination

The contamination status of Sydney Harbour has been well characterized. Early work highlighted the extensive metal contamination in the sediment, while more contemporary analysis has also confirmed the presence of non-metallic contaminants such as organohaline pesticides and polycyclic aromatic hydrocarbons. These relatively recent findings have led to restrictions on commercial fishing, and strong recommendations to avoid consuming seafood west of the Sydney Harbour Bridge.

Over 50 % of the sediment in Sydney Harbour exceeds Interim Sediment Guideline-High concentrations for Pb, and 100 % of the sediment exceeds trigger values that prompt further investigation of activities that may disturb the sediment. The highest levels of contamination are found in the upper reaches of harbour embayments, due to small sediment size and reduced flushing.

Emerging contaminants such as nanoparticles and microplastics have not been assessed in Sydney

Harbour. Additional knowledge gaps also exist concerning the feasibility of restoration of degraded systems within contaminated environments.

Non-point source pollutant inputs such as from urban run-offf and storm water drains have also received little attention.

Nutrients and Turbidity

Most scientific investigations into nutrients and turbidity in Sydney Harbour have involved catchment and freshwater inputs of suspended particles. Freshwater inputs of nutrient and suspended particles change dramatically depending on rainfall events. During wet periods, stormwater and riverine flows bring large quantities of nitrogen and phosphorous into Sydney Harbour. In areas of poor flushing, this can stimulate algal growth, such as that seen in the Parramatta River. After storms , almost 90 % of the total suspended solids (TSS) come from rivers, resulting in high turbidity (poor water clarity). Aging sewage and stormwater infrastructure has been implicated as additional sources of phosphorous and nitrogen contamination in the harbour.

Neo Biota: Non Indigenous and Novel Species in Sydney Harbour

There is a large diversity of non indigenous species (NIS) in Sydney Harbour predicted to be the result of recreational boating, commercial shipping and, more recently, cruise shipping. We have little data on the effects of most of these invaders. One algal species, *Caulerpa taxifolia,* is considered invasive and is currently being monitored by NSW authorities.

Increased shipping activities in Sydney Harbour are thought to increase the rate at which invasive larvae and juveniles are released into the harbour. Shipping related infrastructure also create novel habitats that are conducive to 'weedy' NIS establishment.

Modeling has been conducted by the NSW Government on potential risk of new invasions into Sydney Harbour by species known to be marine pests elsewhere in the world. Results are not published academically, but the report is included here as a reference. Several notorious invasive species do have high risk of establishment in Sydney Harbour, including the asian shore crab *Potamocorbula amurensis*, the Chinese mitten crab *Eriocheir sinensis* and the brown mussel *Perna perna*.

We have little knowledge of how regional transport patterns of recreational vessels, or coastal trading vessels, might increase risks of NIS establishment from other Australian ports. Nor do we know the risk of spreading NIS already established in Sydney Harbour, to other Australian ports and harbours.

Habitat Modification

Sydney Harbour is extensively modified and > 50 % of the shoreline has been replaced by artificial structures. Almost 77 km of the original 322 km of original shoreline has been removed due to reclamation and infilling.

Most of the publications in this category investigate the differences in community assembly between natural rocky reef and artificial structures such as seawalls, piers, and floating marina pontoons. Differences in shade, orientation and water flow are consistently cited as strong drivers of floral and faunal changes in these artificial habitats, although ecological interactions are also important. Similarly, populations of seahorses on Sydney Harbour's shark nets have been explored in several papers. Increased food availability, and refuge from predation, have both been cited as drivers of increased populations of Whites seahorse *Hippocampus whitei* around these structures.

Fragmentation of rocky reef is also examined, with lower diversity found within natural reefs dissected by artificial infrastructure. Similar studies for soft sediment macrophytes such as seagrass and mangroves are lacking.

Despite a relatively good characterization of the effects of habitat modification in Sydney Harbour, there is a paucity of studies that have examined the effects of habitat modification on soft sediment infauna. We also have little understanding of how design changes and engineering solutions can be used to enhance diversity amongst subtidal artificial environments.

Fishing and Aquaculture

Half of the publications in this category consist of unpublished reports from the NSW Government, but are included due to their rigorous methods and ease of access.

The NSW Government conducted the last major assessment of recreational fishing in Sydney Harbour in 2008. An estimated 62 % of fishing was conducted from land and 38 % by boat. This is different to other estuaries in NSW, which are dominated by boat-based fishing. Over a 3-month period, recreational fishers were estimated to have caught approximately 74 tonnes of finfish, crabs and cephalopods. Almost 293 000 individuals are thought to have been caught and released over the same period. There are greater amounts of undersized fish caught in Sydney Harbour compared to nearby estuaries.

Climate Change

Our knowledge of climate change relies solely on studies conducted in similar estuaries or on similar suites of species found within Sydney Harbour. This is surprising as Sydney is located in a region of the coastline that is warming at a rate much faster than the rest of the world.

The two studies classified here investigated the establishment of 'over wintering' populations of tropical fish species in Sydney Harbour. These tropical species are brought into the harbour by the strengthening EAC.

Stressor Interactions

Much of the literature cited in this report examines threats and stressors in isolation, with little consideration of how they interact. Recent evidence from around the world suggests that many stressors can act synergistically.

Recent evidence, for example, suggests that the effects of nutrients and metals may be antagonistic. Sydney Harbour has high concentrations of both, leading to the prediction that nutrient enrichment may actually be masking stronger effects of metal contamination. Similarly, increased pH and temperature both increase the toxicity of dissolved contaminants. Global climate change may therefore interact synergistically with the well-characterized contamination in Sydney Harbour to increase the toxicity of sediment bound contamination Given this highly urbanized estuary is in a region undergoing rapid climate change, we identify this as a key area of research for Sydney Harbour.

Sydney Harbour

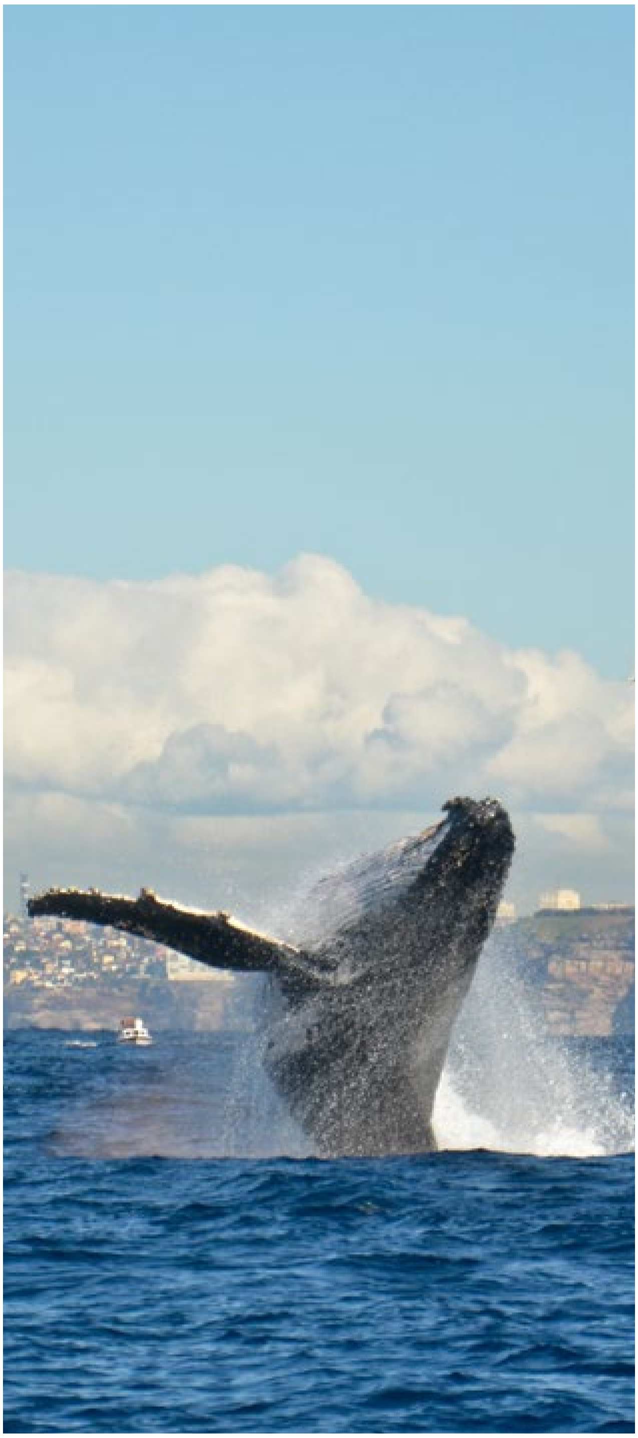
A systematic review of the science

Introduction

Sydney Harbour is renowned for its diversity and beauty, both above and below the water. At the heart of Australia's largest city, the harbour is viewed as a natural wonder on which the commercial and social foundations of Sydney, and indeed Australia, lay. However, the confluence of intense human activity with great natural diversity presents managers with a multitude of challenges. The sustainable management of Sydney Harbour requires a sophisticated understanding of the structure, dynamics and threats to this complex natural ecosystem, and how these feedback into the socio-economics of the surrounding community. Despite the importance of this iconic estuary, there has been no previous synthesis of scientific knowledge or identification of knowledge gaps.

Sydney Harbour is a drowned river valley; a special type of estuary that, for geological reasons, is able to host a wide variety of habitats (Roy et al., 2001). These habitats in turn support a great diversity of organisms; a diversity rarely matched in other estuaries or coastal systems globally (Roy et al., 2001; Clynick, 2008a,b; Clynick and Chapman, 2002; Chapman, 2006; Creese et al., 2009). For example, there are more fish species in Sydney Harbour (586) than for the entire coast of the United Kingdom (authors, *unpublished data*). Estimates of the biodiversity of Sydney Harbor for other taxonomic groups are considered conservative because there has never been a comprehensive survey (Hutchings et al., 2013). Recent estimates of microbial life in the sediment alone stand at over 10 000 taxa (Wilson et al., 2010; Sun et al., 2012) while surveys of other sediment-dwelling fauna are scarce. Based on studies of drowned river valleys throughout the world, the total diversity of the harbour is likely enormous.

This astonishing biological diversity in the harbour coincides with heavy modification. Deep bathymetry and sheltered waters make drowned river valleys an ideal place for port operations and associated commercial and urban development (Edgar, 2000). Since British colonisation in 1788, the City of Sydney has steadily grown on its southern shore and 75 % of the city's northern boundary is still formed by the harbour foreshore (NSW Government, 2012). 185,000 people live in the City of Sydney Local Government Area (SCLGA) (NSW Government, 2012). The Greater Sydney Metropolitan Area (GSMA) however,



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above: Humpback Whales *Megaptera novaeangliae* often visit Sydney Harbour. There are no data on this species for the harbour, although charismatic megafauna are generally well studied worldwide.

right: The view from the Sydney Institute of Marine Science, overlooking Clifton Gardens in Chowder Bay. Sydney residents take great pride in their beaches, yet there is very little work that currently examines the biology, sociology, or economy of these ubiquitous environments.

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is home to over 4.63 M residents (ABS, 2012). This is in an area that stretches over 60 km south, almost 30 km north, and 50 km west of the city centre. The population in this area continues to rise and is 1.9 % higher in 2013 (the time of writing of this report), than in 2010 (NSW Government, 2012). Population density in the GSMA is around 380 people.km^{-2}, compared with the NSW state average of 9.1 people.km^{-2} . The total floor space in 2006 for multipurpose use in the city itself is in excess of 32 million m^{-2}, making it one of the top 20 largest CBD office markets in the world (NSW Government, 2012).

Industrial and urban activities bring with them many potential threats to biodiversity. We are fortunate that the structure of drowned river valleys also provide some natural resistance to many of the common stressors (Morrisey,1995). The scientific literature emphasizes water quality as the major environmental threat in estuarine systems. However, relatively good water quality can be maintained in heavily modified river valleys if they are lined with bedrock (Roy et al., 2001), seawater dominated, and do not trap substantial amounts of fine fluvial sediments (Roy et al., 2001). So while the innermost reaches and protected inlets of Sydney Harbour are heavily contaminated (Birch, 1996), a much larger area of the harbour is relatively well flushed. The ecology of the middle and outer zones of Sydney Harbour are instead threatened by foreshore development (Chapman and Bulleri, 2003; Glasby et al., 2007), vessel activity (Widmer and Underwood, 2004), resource extraction (Ghosn et al., 2010) and invasive species (Glasby and Lobb, 2008).

Scientific knowledge is often disparate; conducted by disconnected research groups at different universities and governmental departments. Synthesising what we know is therefore an important endeavour, but it is perhaps equally important to assess what we do not know. This allows research effort to be directed into the most appropriate areas. This report comprehensively reviews the current science concerning the natural systems of Sydney Harbour. We systematically review the published literature, and we also include many of the easily accessible non-published technical literature (so-called 'Grey Literature'). 'Grey Literature', however, is generally not as accessible and was not a focus of this report. An attempt is therefore made to include most of the relevant studies that can be accessed easily by managers, scientists, the public and other stakeholders. Some information is also presented as unpublished work by this reports authors, representing ongoing study, however, this only occurs very rarely. All of the information is synthesized and presented in a structure that incorporates our current knowledge of all habitat types in Sydney Harbour, the natural drivers of these systems and the distribution of the flora and fauna. We first present a basic 'General Introduction and Context' of the system on a worldwide scale and the important physical and chemical factors that govern the distribution and abundance of plants and animals. Then we explore the natural habitats specific to Sydney Harbour, utilising the literature uncovered during our systematic review process (described below). We then present our understanding of the threats and stressors that impact Sydney Harbour. Importantly, some areas and systems of Sydney Harbour are well studied leading to a more comprehensive summary of our current knowledge. Some areas have received little attention, and for these habitats or processes, much of our understanding comes from examples outside of the Sydney Harbour estuary. In each section of this report we provide the reader with a rigorous assessment of our current knowledge gaps. We include all of our references uncovered during a review process, and intend the reader to use this document as a guide for further research of the available published literature.

Systematic Literature Review

Our review of current knowledge used four search methods to uncover information:

a) a systematic literature search of databases;

b) a voluntary questionnaire;

c) direct approaches to Sydney-based research groups; and

d) a two-day workshop and discussion with all the authors of this document to further interrogate the current state of knowledge of Sydney Harbour.

Using all four of these methods allowed us to comprehensively review the historical and contemporary literature focused on Sydney Harbour. Importantly, we avoided purely taxonomic literature or literature concerned only with historical descriptions of species (although some early historical work is included as a reference). Instead we focus on the core areas of geology, oceanography, geography, ecology and environmental threats to the harbour

Questionnaire

A questionnaire (Appendix 2) was distributed to 111 scientists from around the world who had used the facilities at the Sydney Institute of Marine Science for work within Sydney Harbour. Instructions to further distribute to students and collaborators were also given. This questionnaire asked the receivers to state their published and unpublished work concerning habitats, threats and issues of Sydney Harbour (Appendix I).

Systematic Literature Search

We utilised the Web of Science search engine to examine approx. 20 000 journal titles within the Science Citation Index Expanded Social Sciences Citation Index, Arts and Humanities Citation Index, and the Conference Proceedings Citation Index. Titles from 1898 to 2012 were available. Titles and 'Topic Keywords' were examined using the search terms 'Sydney Harbour' or 'Sydney Harbor', and 'Port Jackson' or 'Parramatta River'. Citations were filtered by the categories 'Environmental Science', 'Marine Freshwater Biology', 'Ecology', 'Oceanography', 'Geosciences multidisciplinary', 'Fisheries', 'Toxicology', 'Water Resources', 'Limnology', 'Zoology', 'Microbiology, 'Geography', 'Environmental Studies', 'Biodiversity Conservation', 'Remote Sensing', 'Soil Science', 'Plant Sciences', 'Biology' and 'Chemistry'. The titles and abstracts of each citation were examined and the study included in our review, if it discussed or assessed any physical, chemical or biological aspect of Sydney Harbour (see definition of extent below).

Workshop

On 1–2nd May 2012 the study's authors attended a workshop at the Sydney Institute of Marine Science (SIMS). During this workshop, the combined group examined the literature on their particular fields of expertise and added to the database any work not included in our initial search. This allowed relatively obscure yet important texts to be included, as well as highlighting many unpublished works not available on searchable databases. This was a key component of our search methods, as many important texts fail to include 'Sydney Harbour' or similar search terms in either the article title or its keyword list.

Analysis

All articles and reports were included in the review if they presented data wholly or partially collected from Sydney Harbour. Sydney Harbour was defined to include all of Parramatta River, Lane Cove and Middle Harbour. This included a distance of 200 km extending seaward from North and South Head, Sydney. It also included papers and reports with data collected from locations up to 1 km along the coastline north and south of the Sydney Harbour entrance. Each article was assigned, where appropriate, to a Field of Study (e.g. Ecology, Oceanography), a Habitat Type (e.g. rocky intertidal, open water) and a 'Threat/ Issue term' (e.g. contamination, fisheries). When an article was considered fundamental research or was independent of an anthropogenic threat or concept, no Threat/Issue term was assigned. Similarly, articles with no clear habitat focus were not assigned a habitat term (e.g. management related articles).

below: While the structure of a drowned river valley can provide some resilience to common human stressors, we now beginning to understand that shoreline modification, resource extraction and boating and shipping activity can shape the diverse habitats of Sydney Harbour.

Results

Some 310 different journal articles and reports were included in our systematic review (Fig. 1). There were far more studies with a clear applied focus (200 publications) than those dealing predominately with issues of natural history (110 publications). There were more than double the number of publications on the ecology of Sydney Harbour (161 publications, Fig. 2) compared to those describing its chemistry (66 publications, Fig. 2). Despite the long history of commercial fishing and the continued use of the harbour by a large number of recreational fishers, there has been little scientific examination of its fisheries (8 publications, Fig. 2).

Contamination research and habitat alteration studies were numerous in soft sediment and subtidal reef habitats (Fig. 3). This pattern is mainly reflected by the heavy investment in pollution research by both government and academic bodies since the late 1970's. Soft sediment research into other potential threats such as nutrient addition or climate change were rare, and despite the large abundance of contamination studies, soft sediment processes that do not concern contamination remain largely un-studied (Fig. 3).

There is comparatively little investigation of mangrove/saltmarsh and freshwater systems in Sydney Habour (26 publications, Fig. 3). Moreover, while we have a generic understanding of beach systems from other areas of the world, only four studies have investigated Sydney's sandy intertidal environments (Fig. 3). This lack of research somewhat reflects the relative scarcity of these environments in the harbour compared with other habitat types.

Much of the research that had no habitat classification concerned weather monitoring (for example see Dunsmuir 2003), geological engineering of the seabed (for example see Mulhearn 2003), or modeling the risk of non-indigenous species introduction (for example see Glasby and Lobb 2008).

In the following pages we present a synopsis of Sydney Harbour science that arose from these searches. We utilise the research uncovered in our review process, but also cite published science from many other locations in order to demonstrate a point, or qualify a statement. This distinction is made clear in the reference section of this document.

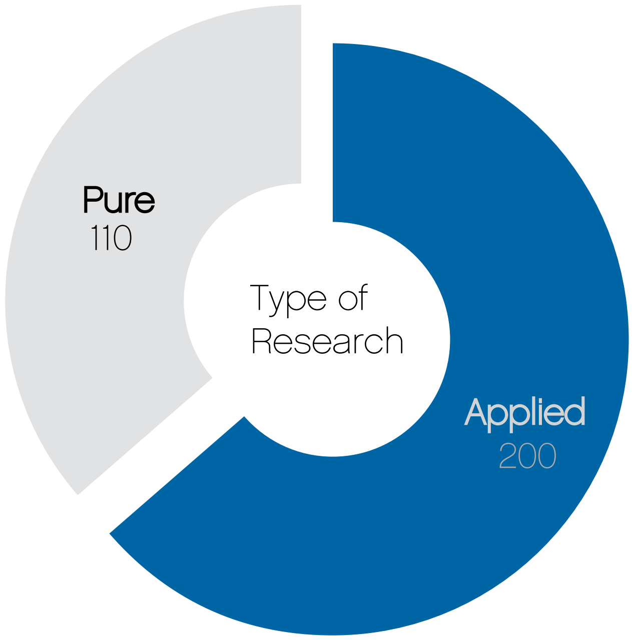


Figure 1: Studies were divided into those concerned with human centric issues (Applied), and those that investigated 'blue sky' topics such as natural history and weather forecasting.

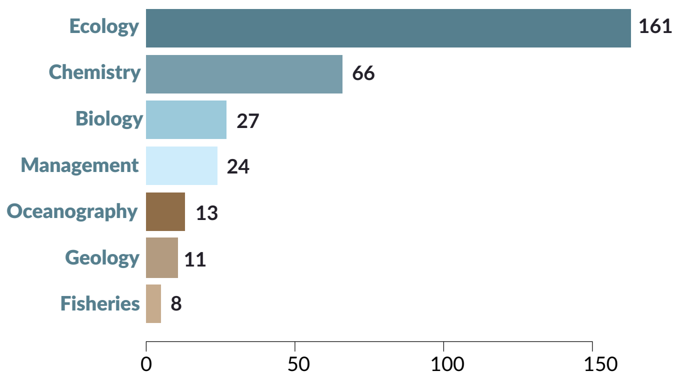


Figure 2: Studies were further separated into basic 'Types'. Ecology, or the use of logic and mathematics to determine pattern and process in nature, is the most studied scientific field in Sydney Harbour. Chemistry studies were generally focused on ecotoxicological investigations and spatial contaminant modeling. Fisheries was the least studied field in the harbour, which is surprising given the well represented and important recreational fishing industry in the area.

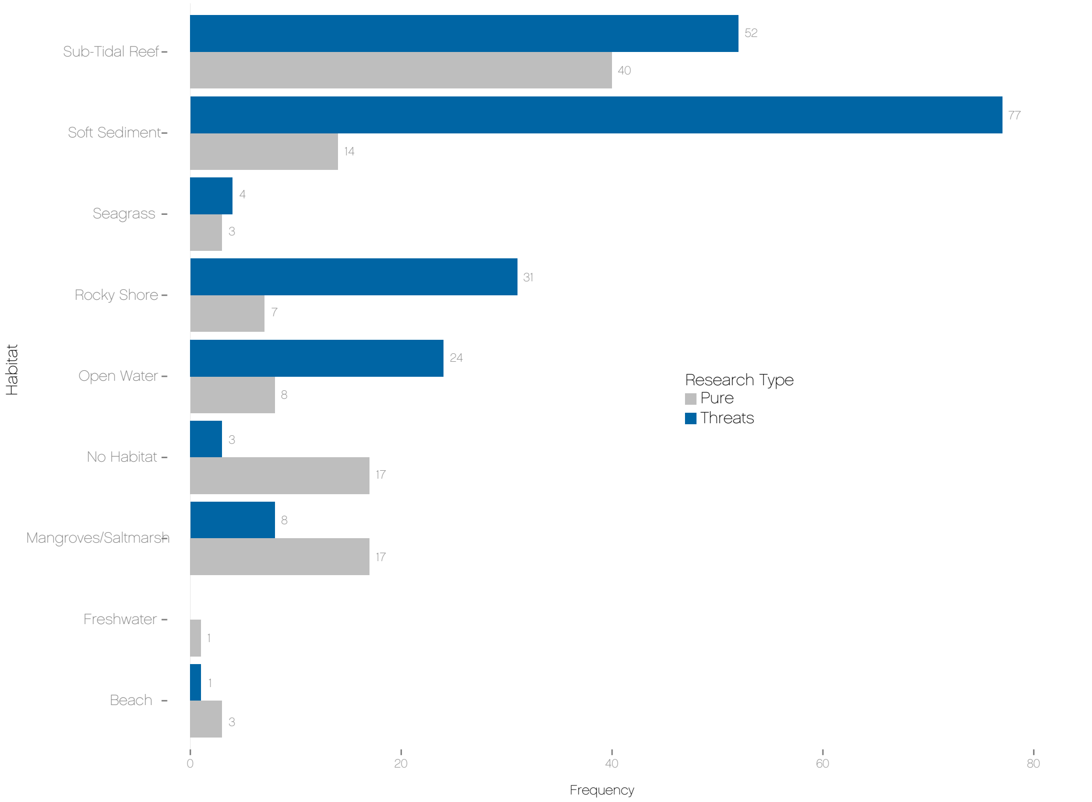


Figure 3: Studies were separated by Habitat and Type of research. While there have been many studies of the sediment of Sydney Harbour, these were mostly concerned with contaminant modeling. We still have little idea of the natural processes that occur in this system. Note that beaches are one of the least studied environments in the harbour.

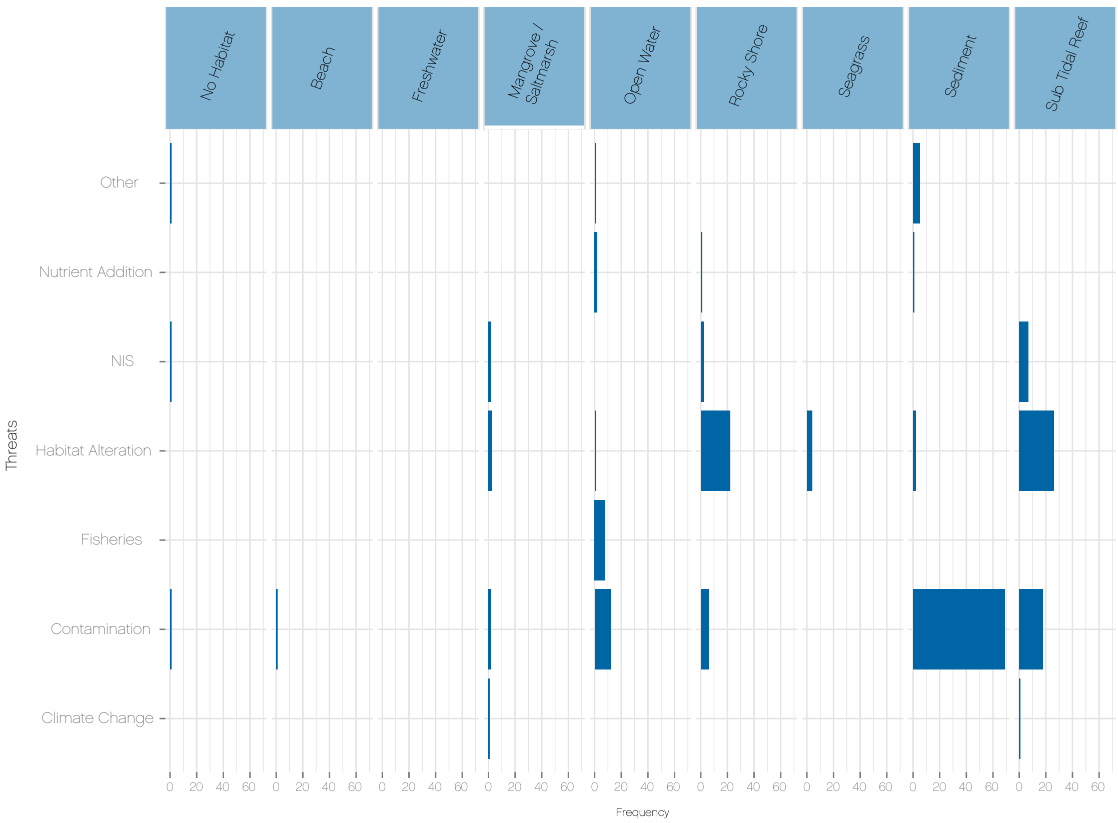


Figure 4: Studies were separated by Habitat and Type of research. While there have been many studies of the sediment of Sydney Harbour, these were mostly concerned with contaminant modeling. We still have little idea of the natural processes that occur in this system. Note that beaches are one of the least studied environments in the harbour.

The Shape and Form of Sydney Harbour

Geological History

Sydney Harbour is a drowned river valley.

The Parramatta River eroded into Hawkesbury sandstone between 15 and 29 M years ago.

Sea level rose sharply from approximately 17 000 years ago, filling the river valley and forming the flood tide delta of the Sydney Harbour estuary.

Sydney estuary is located in the Permian to Triassic (300-220 million years) Sydney Basin and is dissected into Hawkesbury Sandstone and overlying Ashfield Shale (Roy, 1981). The configuration of the Sydney estuary catchment drainage system and the orientation of bays and shorelines are controlled by geologic structure (faults and fractures).

The Parramatta River, which eroded the now Sydney estuary, may once have been connected to the Nepean River, which may later have been 'captured' by the Hawkesbury River between 15 and 29 M years ago (*authors unpublished*). During periods of uplift, the river eroded into bedrock forming steep-sided banks, whereas during interglacial periods, sea level rose and the 'river' was flooded, leaving deep deposited sediments in the estuary.

Oscillations of sea level every 100 000 to 150 000 years during the Quaternary were the result of global climate change and glaciation. However, for the majority of the last 135 000 years, sea level was 20 to 70 m below the present and therefore erosion of estuaries is more pronounced than deposition during this period (Roy, 1981). Sea level started to rise quickly at the end of the last glacial period about 17 000 years ago from approximately 100 m below present and about 25 to 30 km east of its present position to 25 m below today's sea level and only 3-5 km off the present coastline by 10 000 years before the present (BP). The sea advanced into the now drowned Sydney river valley (estuary) forming a flood tide delta and sediment transported by rivers was deposited in the upper parts of the estuary as fluvial deltas.

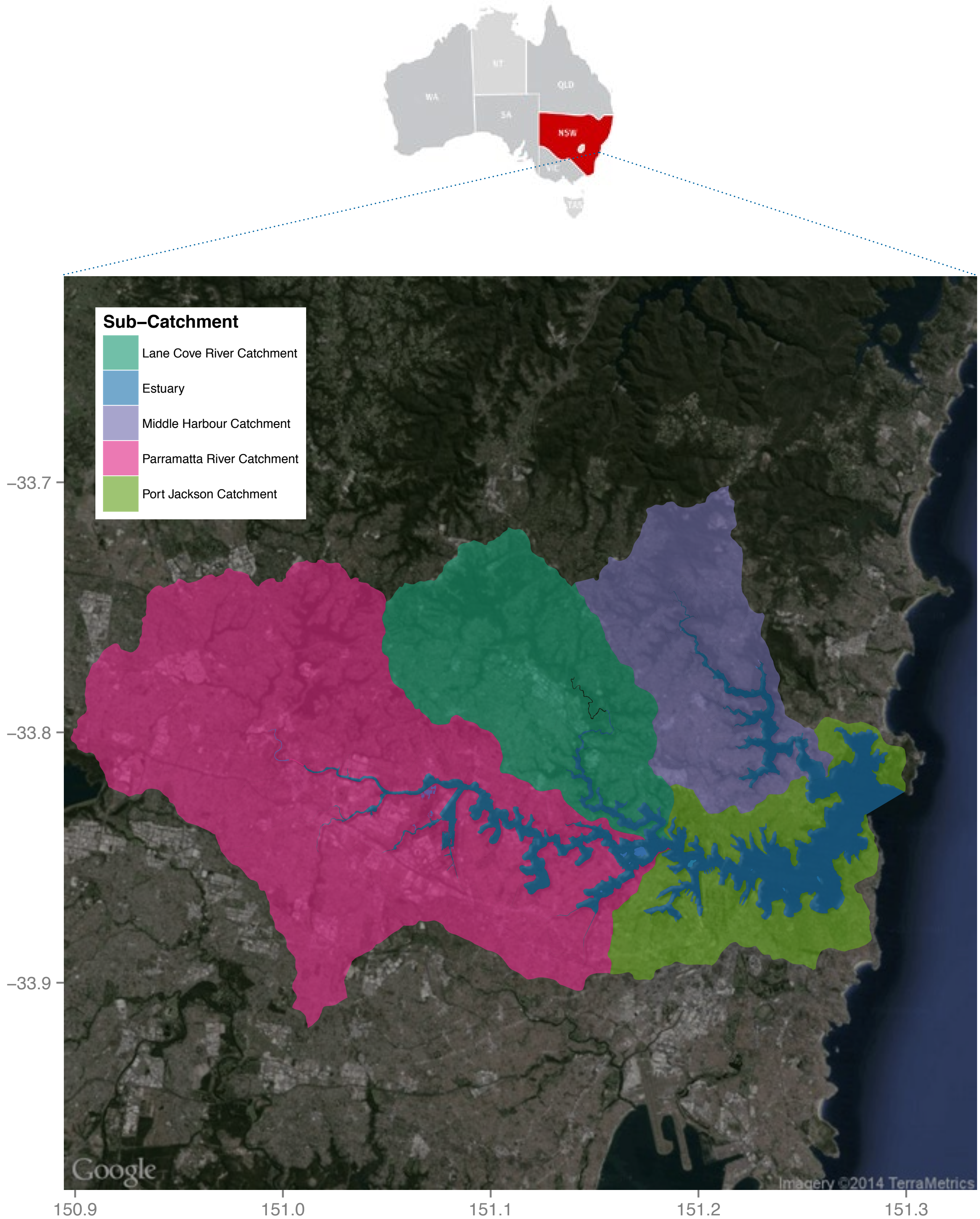
Hydrology

The East Australian Current (EAC) delivers nutrient poor waters (12 °C to 25 °C) to the heads of Sydney Harbour.

Salinity in Sydney Harbour is modified by precipitation, freshwater inflow and evaporation. During dry periods the estuary is well mixed (ocean salinity ~35 psu). In heavy rainfall, salinity may drop substantially in the top 1-2 m of water.

The poleward flowing East Australian Current (EAC) and its eddy field off the coast of Sydney provides what is generally considered a nutrient deplete sub-tropical water mass (Roughan and Middleton, 2002, 2004). Current speeds offshore can be up to 1.5 $m.s^{-1}$ in as little as 65 m of water (Middleton et al., 1997), and water flowing past the entrance to the Harbour is continually being renewed. Ten km offshore at the 100 m isobath, oceanic temperatures range between 12 °C and 25 °C in February. Temperatures are generally more mixed in winter ranging between 16 °C and 20 °C in June (*authors unpublished data*), with salinity ranging from 35.2 to 35.6 psu. The colder bottom waters during summer are typically the result of wind- and current-driven upwelling and are high in nutrient concentrations (Schaeffer et al., 2013). This upwelled water is a potential source of nutrient enrichment in the estuary.

The balance between freshwater inflow, precipitation and evaporation modifies salinity concentrations in the estuary. 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 (Beck and Birch, 2012 a.b.). Stormwater reaching the estuary under these conditions forms a buoyant layer one to two metres thick above saline estuarine waters. Roughan et al. (2012; *unpublished*), for example, show salinity observations from July 2011 after one of the largest rainfall events recorded. Salinity variations at the mouth of the harbour (30–35 psu) were restricted to the top 4 m of the water column in a shallow less saline lens, below which the waters were well mixed. 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; Lee et al., 2011). Further numerical modeling (Lee and Birch, 2012 *unpublished data*) showed stratification in Sydney Harbour dominated by fresh water discharge from Parramatta, Duck



WA
NT
QLD
SA
NSW
Sub–Catchment
Lane Cove River Catchment
Estuary
Middle Harbour Catchment
Parramatta River Catchment
Port Jackson Catchment
–33.7
–33.8
–33.9
150.9
151.0
151.1
151.2
151.3
Google
Imagery ©2014 TerraMetrics

and Lane Cove rivers and that spring tides and up-estuary winds contributed to mixing, whereas neap tides and down-estuary winds enhanced stratification.

Wind velocities recorded at an oceanic buoy over the coastal ocean were compared with measurements from within Sydney Harbour as well as other nearby land-based sites in Wood et al. (2012) from 2001 to 2005. Results showed three dominant wind patterns affecting Sydney Harbour. The strongest winds (occurring 17 % of the time) are from the south, although the most frequently observed direction was from the northeast (22 % of the time). The third most common wind pattern was from the west, occurring primarily during winter (18 % of the time). The diurnal sea breeze, determined by the land-sea-air temperature differential, also influences the circulation of Sydney Harbour (Dunsmuir et al., 2003). The northeasterly sea-breeze typically forms each day in summer, but only 40 % of the time during winter (Dunsmuir et al., 2003) and can extend anywhere from 2 to 60 km inland. The effect of the sea breeze is greatest when synoptic forcing is weak, and can be accentuated when the gradient breeze is from the north. The oceanography of the harbour contributes to the complexity of the sea breeze and can have a channeling effect on the surface wind fields (Connor et al., 2003). This in turn will impact on the circulation under periods of higher wind speeds.

Circulation

Circulation in Sydney Harbour is dominated by the tides, which are periodic and reverse every 6 hours.

Tidal flow is strongest near the northern side of the harbour entrance, and clockwise eddies are formed. Here, tidal velocities can be up to 0.25 ms^{-1} in surface waters.

Discharge volumes are around 6000 $m^3.s^{-1}$ near the heads on an ebb tide. Water age can vary between 20 d in the main body of the harbour, to 130 d in the upper reaches.

We have little knowledge of how the EAC can interact with harbour water to influence circulation.

Circulation within Sydney Harbour is dominated by the tide, with some influence from prevailing winds. Tidal forcing is predominantly semi-diurnal with amplitude M2 = 0.501 m, S2 = 0.126 m, K1 = 0.148 m and O1 = 0.096 m (Das et al., 2000). Tidal velocities are periodic, reversing every 6 h (Roughan et al., 2012 *unpublished*) and vary considerably in magnitude 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 $m.s^{-1}$ over the spring neap cycle (in 15 m of water; Roughan et al., 2012 *unpublished*). In the furthest branches of the estuary, both modeling and observations reveal velocities an order of magnitude lower.

Middleton et al. (1997) found that 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. Repeat velocity transects across the mouth (Roughan et al., 2012 *unpublished*) show some vertical velocity variation, with inflow on the southern side. Maximum velocities are approximately 0.25 $m.s^{-1}$ in the surface waters at the mouth of the harbour.

Das et al. (2000) estimated discharge volumes to be up to 6000 $m^3.s^{-1}$ across the heads, at the peak of the ebb tide, with more than 4000 $m^3.s^{-1}$ coming from the main branch of Port Jackson (including the Parramatta and Lane Cove Rivers) and less than 1500 $m^3.s^{-1}$ coming from Middle Harbour. Offshore surveys reveal that even under dry conditions, tidal outflows from Sydney Harbour can extend several kilometres offshore (Middleton et al., 1997).

Residual flows can be produced by local wind forcing or lateral density gradients driven by variations in temperature or salinity. Within Sydney Harbour, the tide-induced residual circulation forms a number of gyres at regions of complex geometry and bathymetry (Das et al., 2000). This interaction of the tidal current with the topography could result in retention of organisms or pollution. While the residual circulation patterns were not highly sensitive to wind forcing, the prevailing southeasterly winds in winter should increase the tidal asymmetry in the estuary (Das et al., 2000).

Circulation patterns vary depending on the wind direction, which contributes to a difference in harbour retention and flushing. Roughan et al. (*unpublished data*) found that, under southerly wind forcing, flushing was a maximum near the mouth of Sydney Harbour with greater retention times under easterly and northeasterly winds. In the upper reaches of Sydney Harbour (Walsh Bay) northeasterly winds resulted 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 (Roughan et al., 2012 *unpublished*).

Knowledge Gaps

To date there have been no circulation modeling studies of Sydney Harbour that investigate the interactions between the EAC offshore, coastal waters and the circulation within the Sydney Harbour estuary itself. Previous modeling studies of Sydney Harbour have generally been forced at the entrance to the harbour (the open boundary of the model domain) with a simple tidal paddle, with no regard to circulation or hydrography eastward (offshore) of this boundary. Thus the more complex interactions of exchange with the coastal ocean, including oceanic nutrient injection into the estuary and exchange of the ebb tide plume with coastal waters have not been resolved. This could have implications for the heat, mass and nutrient budgets within the estuary. Furthermore there have been limited modeling studies investigating freshwater inflow. Coupling these two forcing mechanisms in a modeling framework would provide the basis for realistic hindcast and forecast scenarios and thus significantly improve our understanding of the estuarine ecosystems.

The Natural Environments of Sydney Harbour

Subtidal Rocky Reef

One study that mapped 1.58 km^2 of reef along the north head shoreline found that the reef comprised of macroalgae (37 %), urchin barren (18 %), and a mixture of barrens and algae (25 %).

Most other research focused on *Sargassum* and *Ecklonia* spp. and associated epifauna.

Small scale processes (10 cm's) rather than larger scale processes, seem to determine patterns of turfing algae and associated epifauna in Sydney Harbour.

Natural disturbances, such as storms, swell, and grazing by herbivores can affect kelp abundances and associated diversity.

We have no knowledge of the dynamics of urchin barrens in Sydney Harbour, nor how differences between coastal and estuarine conditions can affect Sydney Harbour's biota.

General Introduction and Context

We use the definition of subtidal reefs put forward by Witman and Dayton (2001), that is "any benthic habitat composed of hard substrate from the intertidal / subtidal fringe down to the upper limit of the deep sea". Importantly for Sydney Harbour, this definition includes cobble and boulder fields as well as solid rock walls (artificial as well as natural).

Subtidal rocky reefs are some of the most diverse and productive environments in the world (Dayton, 1985; Schiel and Foster, 1986; Steneck et al., 2002). This diversity mainly stems from the dense kelp beds that have come to define these systems (Mann, 1973; Schiel and Foster, 1986; Steneck et al., 2002). Unlike the well studied giant kelp forests in western USA, the dominant form of kelp in eastern Australian coastal waters is the much smaller *Ecklonia radiata* (Connell, 2007). Along the east coast of Australia, the shallowest areas of subtidal reefs are dominated by fringe habitat, composed of patchy *Ecklonia*, fucoids (e.g. *Sargassum* spp.), dictyotalean algae (e.g. *Zonaria* spp.) and geniculate corallines (e.g. *Amphiroa* spp. and *Corallina* spp.) (Underwood et al., 1991). There is, however, large temporal and spatial variability in macrophyte distribution and abundance. Similar areas in other places, particularly south of NSW, are often dominated by the fucoid *Phyllospora comosa*, with the exception of open-coast reefs surrounding Sydney Harbour where this alga appears locally extirpated (Coleman et al., 2008). These habitats support large numbers of the sea-urchins *Heliocidaris erythrogramma* and *Centrostephanus rodgersii* and turbinid snails. In addition, *Ecklonia* provides habitat to many mobile and sessile epibiota. For instance, the canopy-dwelling sea-urchin *Holopneustes purpurascens* inhabits the thalli of *Ecklonia* spp. (Steinberg, 1995; Marzinelli et al., 2011) and the surfaces of kelp fronds often are colonised by filamentous algae, bryozoans and hydroids (Fletcher and Day, 1983; Marzinelli et al., 2009, 2012). *Sargassum* spp. beds also support diverse assemblages of organisms, particularly isopods and amphipods

left: Subtidal rocky reefs in Sydney Harbour are dominated by sea urchins that create 'barrens' of bare rock. We have little data on the role of these barrens in the natural ecology of the harbour, or whether the abundance of these barrens has changed through time.

top right: Subtidal rocky reefs are some the most diverse environments in the harbour. In this photo the solitary ascidian *Herdmania momus* can be seen growing amongst the algae *Dilophus* sp.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(Poore and Lowry, 1997; Poore and Hill, 2005). Beds of the ascidian *Pyura* spp. may also dominate the shallowest areas, supporting several species of snails and chitons (Underwood et al., 1991). Although some habitats (e.g. fringe) appear to follow a depth gradient, the two main types of reef habitats < 25 m deep in the harbour, i.e. kelp beds and barrens, do not seem to be related to depth (Underwood et al., 1991). It is only at much deeper depths (> 25 m) where kelp abundance decreases and other taxa such as sponges start to dominate (Underwood and Kennelly, 1990).

The slope of the underlying bedrock can strongly influence community composition. The kelp communities discussed above often dominate horizontal substrates. However, vertical areas, such as rock walls, have higher abundances of sessile epifaunal invertebrates (Witman and Dayton, 2001). Even within invertebrate communities there are strong differences between assemblages on vertical and horizontal substrates. On the east coast of Australia, barnacles (such as *Amphibalanus variegatus*) and serpulid worms (including *Hydroides elegans* and *Pomatocerus taeniata*) dominate on horizontal surfaces, while abundances of spirorbid worms increase on vertical surfaces (Glasby and Connell, 2001). The angle of underlying rocky reef substrata therefore plays an extremely important role in structuring the epibiota that grows on it. The structural differences between communities on horizontal and vertical surfaces is one of the most noticeable differences in this habitat worldwide (Witman and Dayton, 2001).

Subtidal Reef in Sydney Harbour

Only one study has quantified the abundance of reef habitat within Sydney Harbour. Creese et al. (2009) mapped approximately 1.58 km^2 of reef in Middle Harbour. These reefs are dominated by macroalgae / kelp (37 %), barrens (18 %) or a mix of macroalgae and barrens (25 %). Turfs and sessile invertebrates are less dominant (58 %). The types of reef habitats within the Harbour are similar to those found on the open coast of NSW (Underwood et al 1991).

Most of the research on natural subtidal reefs in the Harbour has focused on habitat-forming macroalgae, particularly *Ecklonia* and *Sargassum* spp., and/or the organisms they support. Despite the occurrence of macroalgal dominated reefs in the Inner Harbour (King and Farrant, 1987), most studies have been done in Middle Harbour, near the entrance to the estuary (Table 1).

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*) (see Kennelly,1987; Connell and Glasby, 1999; Glasby, 1999; Clynick et al., 2008, for a list of species found in these communities in Sydney Harbour). Of 586 species of fish recorded in Sydney Harbour, over 60 % inhabit subtidal reefs (Booth 2010) highlighting the importance of rocky reefs for fish diversity in the Harbour.

Few studies have focused on subtidal reef habitat forming species other than kelp in the Harbour. Communities of turfing algae varied in composition and relative abundances at very small spatial scales (10's of centimetres), suggesting that small scale processes influence patterns of distribution and abundance of these subtidal turfs in the estuary (Coleman 2002). These results are consistent through time, suggesting that larger scale processes may not have discernible effects on Sydney's turfing algae (Coleman, 2002). There are also several deep-water reefs (> 20 m) in the Harbour, supporting very diverse assemblages of sponges, as well as ascidians, bryozoans and cnidarians (Roberts et al., 2006).

In Sydney Harbour, several studies have gone beyond establishing ecological patterns to determine key processes acting on subtidal reef communities. Natural disturbances, such as storms, are generally seen as a strong structuring force in these kelp communities (Dayton,1985). In the Harbour, natural disturbances influence the composition and relative abundance of understory assemblages in Ecklonia beds (Kennelly, 1987a.b). Storms can dislodge the kelp creating clearings

Table 1. Ecological studies published on the extensive Kelp beds that can be found throughout the entire Sydney Harbour estuary. The kelp species that dominate the sub-tidal rocky reefs in Sydney Harbour are more well studied than most other systems.

Locations	Research topic	References
Balmoral, Taronga Zoo, Mrs Macquaries point and Drummoyne	Patterns of abundance of understory algae	Farrant and King (1982)
Fairlight	Colonization of understory species	Kennelly (1983), Kennelly and Larkum (1983)
Fairlight	Patterns of abundance of understory species	Kennelly and Underwood (1984, 1985, 1992)
Fairlight	Growth and primary productivity of kelp	Larkum (1986)
Fairlight	Patterns of abundance and reproduction of understory algae	King and Farrant (1987)
Fairlight	Effect of physical disturbance on understory species	Kennelly (1987, 1987b and 1989), Kennelly and Underwood (1993)
Fairlight	Effect of turfing algae on kelp recruitment	Kennelly (1987c)
Fairlight	Effect of fish predation on understory species	Kennelly (1991)
Nielsen Park	Chemical defences and other factors influencing epiphytes on kelp	Jennings and Steinberg (1994 and 1997)
Dobroyd Head, Grotto point and Middle Head	Cover of subtidal habitats	Creese et al. (2009)
Chowder Bay, Balmoral Beach and Quarantine Station	Effects of man-made structures on ecological patterns and processes of kelp epibiota	Marzinelli (2012), Marzinelli et al. (2009), Marzinelli et al. (2011 and 2012)
Watsons Bay, Balmoral, Little Manly, Cobblers Beach, Nielsen Park, Obelisk Bay	Effects of storm-water runo on mobile epibiota on kelp	Ghedini et al. (2011)

within the bed. Experiments in Sydney Harbour have shown that this leads to a decrease in abundances of encrusting algae, sponges and colonial ascidians and an increase in covers of turfing algae (Kennelly, 1987). Another important process shaping kelp forests is grazing (Dayton, 1985; Steneck et al.,2002). Grazing by fish influenced covers of some understory species in *Ecklonia* beds in the Harbour (Kennelly, 1991). Conversely, herbivory by mesograzers in the kelp beds of Sydney Harbour do not seem to affect their host *Sargassum* sp. (Poore et. al., 2009).

Knowledge Gaps

There are obvious differences in physical properties between estuarine and coastal systems (e.g. salinity, wave-exposure, nutrient loading). Despite this, no studies have determined whether these differences influence ecological patterns and processes in subtidal reef habitats in the harbour compared to those on the open coast or nearby estuaries such as Botany Bay. This is important, as the same types of subtidal reef habitats; kelp beds, turfs and barrens, occur in the harbour and on the open coast. There is still little understanding on whether these habitats support similar species and whether the processes that influence them are similar.

In contrast to kelp beds, urchin barrens in Sydney Harbour have not been studied. This is despite them being the second most abundant habitat type within subtidal reef environs. On the open coast, barrens are generally dominated by the sea-urchin *Centrostephanus* spp., the turbinid snails *Turbo turquatus* and *Astralium tentoriiforme* and several species of limpets, such as *Patelloida alticostata*, *P. mufria* and *Cellana tramoserica* (Fletcher, 1987; Underwood et al., 1991; Underwood and Kennelly, 1990). Grazing of the substratum by urchins and limpets keep covers of foliose algae low (< 10 %) and dominated by encrusting coralline algae (> 80 %) (Fletcher, 1987; Andrew and Underwood 1989; Andrew 1993).

right: The ubiquitous gastropod snail *Austrocochlea porcata* (Adams, 1851) can be found on many rock platforms in Sydney Harbour. The ecology of the species has been heavily investigated by Sydney based scientists since the early 1980's.

Rocky Intertidal Shores

Sydney Harbour's natural shoreline is dominated by horizontal, or gently sloping sandstone platforms. Natural intertidal shores, however, are rare and fragmented. Breakwalls and other artificial surfaces cover around 50 % of the harbour shoreline.

Approx. 127 taxa are dispersed along the rocky shoreline.

Lower shorelines are dominated by foliose algae and tubiculous polychaetes.

Sydney Rock Oysters *Saccostrea glomerata* dominate the mid-shoreline, with barnacles, limpets and encrusting algae species.

Most studies on rocky shores have compared natural reef to artificial structures. Little consideration has been given to differences between estuaries, or between Sydney Harbour and the outer coast.

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General Introduction and Context

above: The islands of Sydney Harbour are dominated by intertidal rocky reefs. Clark Island, below, is the site of early biological exploration, and students from the University of New South Wales still visit the island to study the ecology of rocky shores.

Rocky shores lie between the low and high water marks that fringe entire countries, coasts and estuaries (Menge and Branch, 2001). The importance of these areas for the advancement of conceptual and experimental ecology cannot be overstated. This has occurred because the animals that live in this habitat, the ambient environmental conditions, and the habitat itself can be easily accessed and manipulated. Key theories regarding predation (Underwood and Jernakoff, 1981), disturbance and competition (Menge, 1976; Menge and Sutherland, 1987) and recruitment (Caffey, 1985), among many others, have all been explored on the rocky shore found between the low and high water mark, especially around Cape Banks in Botany Bay (Underwood and Chapman, 2007). Many of the methods and statistical techniques developed in this system have now been adapted to other systems throughout the world (Underwood and Chapman, 2007).

The community composition on the rocky shoreline is determined by a combination of biotic and abiotic factors. Wave exposure, for example, can vary dramatically at sites along a coastline, within an estuary or even within a small embayment. Wave exposure is often greatest at the tips of headlands, with energy levels far greater than what you would find in sheltered bays This distribution in wave energy can dramatically alter the invertebrate communities in these areas (Menge and Branch, 2001). It is, however, the vertical zonation of animals up a shoreline that is most noticeable in this environment. Colman's (1933) seminal work on the British coast at the beginning of last century, led many ecologists to believe that animals in this system simply 'clumped' according the amount of time they were emerged from water. This early work analysed emersion times down a rocky shore in the intertidal zone and correlated this zonation with species abundance and composition. These beliefs were a dominant paradigm up until the 1970's. It was not until Underwood (1978) refuted the work of Colman (1933) that cracks in this long-standing belief in 'zonation' appeared. Using more robust statistical techniques, Underwood (1978) showed species do not clump according to emersion times on British shores and hence showed no evidence for intertidal zonation. The very noticeable differences in assemblages vertically up a shoreline *can* be non-random, more accurately, are generally driven by a combination of biotic and abiotic functions that vary over scales from 10s of m to hundreds of km.

The factors that promote species abundance patterns on rocky shores are varied and differ in both space and time. Grazing, for instance, can remove early stages of development of macro-algae, which can create space used for settlement by sessile species (Underwood et al.,1983). Similarly, competition is one of the major factors 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 on the NSW rocky shores (Creese and Underwood, 1982). Although *C. tramoserica* is competitively superior, it is unable to exclude the siphonarian limpets from an area of the shore due to strong intra-specific competition (Creese and Underwood, 1982). Other species of grazing gastropods also inhabit the same areas and compete for similar resources, leading to complex interactions (Underwood, 1978).

Rocky shores in Sydney Harbour

In Sydney Harbour, intertidal shores are usually horizontal and/or gently-sloped sandstone platforms (Bulleri et al., 2005; Cole et al., 2007; Cole, 2009), which are very similar to most shores in NSW. They have relatively little exposure to waves and have a tidal range of about 1.5 m (Cole, 2009). There are, however, some fully vertical natural rocky shores about 15–20 m long (e.g. Chapman, 2003; Bulleri, 2005; Bulleri et al., 2005). Similarly, intertidal boulder fields, although not particularly common in Sydney Harbour, support a great diversity of organisms living on or under the boulders (Chapman, 2002, 2003).

Chapman (2003), in a comprehensive study of sea-walls and natural shores in Sydney Harbour, found a total of 127 taxa dispersed along the shoreline. There was great spatial variability in the diversity of species at the different heights of the shore and from place to place, which is consistent with other studies done on sheltered and wave-exposed shores on the open coast (Chapman and Underwood, 1998). The low part of the shores in Sydney Harbour can be characterised by large covers of foliose algae, the tubiculous polychaete *Galeolaria gemineoa* and/or the ascidian *Pyura praeputialis*, while the mid-shore assemblages are generally dominated by the presence of the Sydney Rock Oyster *Saccostrea glomerata*, limpets, barnacles and encrusting algae (Chapman, 2003; Goodsell, 2009). For a list of the many species found on natural shores in the harbour, see Bulleri (2005). Many of the species listed above form important biogenic habitats such as oyster, worm or algal beds (Coleman, 2002; Cole et al., 2007; Cole, 2009; Matias et al., 2010). The distribution of these habitat-forming organisms on intertidal shores in Sydney is naturally patchy, forming mosaics on and around the shoreline (Cole et al., 2007). Such habitats support a great diversity of additional organisms (Bruno and Bertness, 2001).

Naturally occurring rocky shores in Sydney Harbour are, however, extremely fragmented (Goodsell et al. 2007, Goodsell 2009), with most of the natural coast replaced by sea-walls (see Habitat Modification). This may be one of the reasons few studies have been done on intertidal shores in the Harbour. These studies are needed to understand the ecological processes occurring on these systems and, consequently, determine and manage possible impacts on these shores.

Knowledge Gaps

Although rocky intertidal assemblages in NSW and the processes occurring in these systems have been extensively studied throughout the years (Rocky shores- General Introduction and Context), very little is known about these systems inside Sydney Harbour. Much like subtidal reefs, the processes that act on these communities on the open coast may differ greatly than those that are experienced by estuarine rocky shore communities.

The great majority of research articles on Sydney Harbour compared assemblages on natural shores to those on adjacent seawalls (Chapman and Bulleri, 2003; Chapman, 2003; Bulleri et al., 2004, 2005) or studied the effects of the fragmentation caused by these interspersed artificial structures on natural shores (Goodsell et al., 2007; Goodsell, 2009). A few studies have also assessed the effects of matrix and/or complexity of foundation species on communities, using artificial structures such as pot scourers (Cole et al., 2007; Cole, 2009) and artificial grass (Matias et al., 2010) placed on natural shores. These studies are further discussed in the Habitat Modification section of this report. Only one study evaluated the distribution and abundance of algae on an intertidal natural shore in Sydney Harbour (Coleman, 2002). Although sampling was done inside and outside of the Harbour, results showed that most of the variability in the composition of algal turfs occurred at the smallest spatial scale with little differences between the estuary and open coast (Coleman, 2002). Despite significant research on the effects of artificial structures in the Sydney Harbour (see also Habitat Modification), further studies on ecological patterns and processes on natural shores in the Harbour are necessary to (i) identify whether these are the same occurring in similar shores in NSW and, if not, (ii) what are the processes influencing these differences. This basic science is necessary to prevent and/or manage further impacts that these habitats.

Soft Bottoms and Beaches

Over 2473 species of molluscs, polychaetes and echinoderms have been recorded in Sydney Harbour. This is likely an underestimate, given the poor state of sampling within Sydney Harbour.

Sydney Harbour's beaches are one of the least studied ecosystems. Only four peer-reviewed articles have analyzed data from these systems despite the social and economic importance of these areas.

Richness estimates, like those above, are largely based on sub-tidal environments. Intertidal and foreshore communities have received no scientific attention.

Gene sequencing and other molecular techniques are in development to try to address the difficulties of sampling sediment meiofauna.

General Introduction and Context

The sedimentary seafloor of an estuary can be extremely diverse. Biota in this system range from bacteria to benthic feeding whales and sharks (Lenihan and Micheli, 2001). Most of the species, however, are small invertebrates such as worms and molluscs that burrow into the sediment and live entirely hidden from view (Snelgrove, 1997). In some instances the abundance of these taxa can be enormous. Over 78 000 worms alone can inhabit one square metre of sediment (Lenihan and Micheli, 2001). The composition of these communities varies according to sediment size, type, and organic content. These parameters are, in turn, controlled by abiotic factors such as current strength, wave activity and successional processes after disturbance (Lenihan and Micheli, 2001).

Most of the sediment infauna can be found within the top few centimetres (Hutchings, 1998; Lenihan and Micheli, 2001). These organisms often act as bio-turbators, having profound effects on nutrient cycling, oxygenation, water content, porosity and chemical make-up (Kogure and Wada, 2005). Sediment infaunal communities can include a myriad of functional groups that are an important food source for higher trophic levels, including benthic fish, prawns, and wading seabirds (Snelgrove, 1997).

Distribution of sediment dwelling fauna can vary according to the myriad of reproduction strategies employed. 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 (Grassle and Grassle, 1974). Most of this activity goes unnoticed by the casual observer, and often the only signs of sediment infauna are pits and mounds on the seafloor, creating the appearance of a moon like environment. Additionally, various 'islands' of small hard substrate can become available within a 'sea' of soft sediment (Hutchings, 1990). These islands can form three-dimensional structures that determine fish community composition, and settlement patterns of other invertebrate species (Hutchings, 1990).

left: Balmoral Beach, locatied on the northern side of Sydney Harbour. Sydneysiders take great pride in their harbour's beaches. These environments, however, are one of the least studied in the estuary.

Sediment Flora and Fauna in Sydney Harbour

No comprehensive surveys of soft bottom benthic communities of Sydney harbour have been undertaken, but some indication of the diversity is given by Australian Museum collection records (Hutchings et al., 2013). To date the total number of polychaete, crustacean, echinoderm and molluscan species recorded from Sydney Harbour stands at 2473. This compares with 1636, 981 and 1335 species known from nearby Botany Bay, Port Hacking (Fraser et al. 2006) and the Hawkesbury River (Hutchings & Murray, 1984), respectively. The infauna tallied above is certainly a significant underestimate of true species richness since many areas of the harbour are poorly sampled.

There has been little work identifying the species present in the iconic sandy beaches of Sydney Harbour. Only four studies were classified as having investigated infaunal communities within beach sediment environments (Dexter, 1983, 1984; Keats, 1997; Jones, 2003). Jones (2003) conducted a rigorous assessment of the impact of an accidental oil spill on the abundance of a single amphipod species (*Exeodiceros fosser*) at several harbour beaches west of the Sydney Harbour Bridge. And Keats (1997) made a qualitative assessment of the Gastropod fauna of Spectacle Island, found near the western suburb of Drummoyne. Only Dexter (1983, 1984) has made a holistic assessment of the communities found within sandy sediments in Sydney Harbour's outer beaches. Mud flats west of the bridge, however, have been sampled by the Australian Museum and these data have been incorporated into the above indications of sediment diversity (Hutchings et al., 2013). The richness estimates above are largely based on subtidal species, and specific site records are yet to be accurately correlated with the major sedimentological types identified in the harbour, each of which will probably have a characteristic infaunal community.

There have been only two studies found during our systematic review process that quantified diversity within the sediment using newly developed gene sequencing methods (Chariton et al., 2010; Sun et al.,2012). Here, 4640 Operational Taxonomic Units (OTUs) were uncovered in the muddy, fine fraction of sediment at sites including Balmain, Glebe, North and South Heads, Rushcutters and Rose Bay and Clifton Gardens (Sun et al., 2012). This is likely to be a conservative estimate as Sun et al. (2012) used 454 Pyrosequencing; where debate exists as to the interpretation of 'rare' sequences. Chariton et al. (2010) also used 454 Pyrosequencing on a smaller scale to determine the abundance of taxonomic groups in only two sites within the main estuary, the Lane Cove and Parramatta Rivers: 10,091 different OTUs were identified in 262 Orders, 122 Classes, and 54 Phyla. Note that this estimate of diversity included metazoans (such as bivalves and polychaetes) as well as microzoans (e.g. Ascomycota and Bacillariophyceae) and similar precautions in data analysis to Sun et al. (2012) need to be taken.

Knowledge Gaps

Sediment systems in Sydney Harbour are one of the most understudied of all its environs. Only a single study is currently published (at time of publication of this report) that has comprehensively investigated the diversity of bottom sediments (Hutchings et al., 2013). Even here, this examination focussed on only four taxonomic groups (molluscs, crustaceans, echinoderms and polychaetes), and did not sample any sandy beaches that are common east of the Sydney Harbour Bridge (Hutchings et al., 2013). Only two studies have investigated sandy beach communities east of the Harbour Bridge, and so we have little understanding of beach sediment fauna. Much of the work on the sediment of Sydney Harbour has been in the context of contamination modelling and, even here, fewer than 10 studies examine effects of this contamination on the sediment fauna, and these only generally investigate sub-tidal areas.

Our understanding of bacterial communities also lacks detail. Many workers worldwide are highlighting the importance of microbiota to stable functioning of ecosystems (Sun et al., 2012). These microbial taxa are particularly important as they form the basal elements of many food chains, can alter the sediment chemistry and restrict nutrient availability (Gadd and Griffiths, 1977; Sun et al., 2012).

We hypothesise that overall benthic species richness and diversity is higher in the harbour than in adjacent estuaries (Botany Bay, Port Hacking and the Hawkesbury River) owing to the more complex geomorphology, diversity of sediment types and high degree of tidal flushing. However, a competing hypothesis is that increased diversity results from strong nutrient enrichment from human activities in Sydney Harbour. Our contentions cannot be robustly tested with the current state of knowledge. Although substantial areas of Botany Bay have been surveyed (Wilson 1993, 1998) and selected habitats (sandy sediments) have been systematically sampled in Pittwater and Port Hacking, similar studies have not been conducted in Sydney Harbour, highlighting the priority for detailed benthic surveys of the area. Only after examining what is present in Sydney Harbour sediment, can we begin to ask the more complex and nuanced questions that have been being examined in other habitat types in estuaries around the world.

Soft Sediment Macrophytes

The NSW Government has undertaken mapping of sub-tidal macrophytes in Sydney Harbour 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.

Mangroves have become more common in Sydney Harbour. Over 184 ha have been observed in the Harbour, despite being relatively uncommon prior to the 1870's.

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General Introduction and Context

Estuaries contribute US$7.9 trillion annually to the global economy (Costanza et al., 1998). Much of this wealth can directly or indirectly attributed to estuarine flora. In estuaries, the main vegetation types are seagrasses (worth AUS$19,000 $ha.yr^{-1}$), saltmarsh and mangroves (AUS$9,990 $ha.yr^{-1}$ combined; Costanza et al., 1998)). These three habitats support the ecological and economic wealth of Australia's productive estuarine ecosystems. In this section of the report we deal with seagrasses, mangroves and saltmarsh collectively. However, it is important to note that the three floral types are not without significant differences in ecology.

Seagrasses are the only estuarine plants that can live totally submerged in oceanic water. While not truly grasses (i.e. not in the family Poceae), they are angiosperms (flowering plants). The term seagrass itself refers to a taxonomic grouping with much convergent morphology (Connell and Gillanders, 2007). Like most angiosperms, seagrass roots provide a mechanism for nutrient uptake. Unlike many terrestrial plants, however, a complex rhizome system linking individual shoots across several square km provides much of the structural support needed in high energy submerged environments. Rhizomes, shoots and roots often form extensive biological mats over the seafloor. *Posidonia* spp. in southern Australia, for example, are sometimes known to form mats almost 7 m high (Kuo and den Hartog, 2006). The fibrous leaves, roots, shoots and rhizomes can provide much of the primary production in estuarine systems (Connell and Gillanders, 2007). *Posidonia australis* is implicated as an extremely important food source, even when dead. Here, large amounts of decaying 'wrack' are often washed up onto south east Australian shorelines to form the base of extensive food chains (Kuo and den Hartog, 2006).

The term mangrove refers to a group of about 55 species of phylogenetically unrelated plants that have adaptions allow for living in high salinity environments (Tomlinson, 1986). Mangroves form extensive forest systems along the intertidal areas throughout the tropical and warm-temperate world (usually between 25° N and 25° S, Connolly and Lee, 2007). In these areas, water temperatures do not usually fall below 20°C during winter.

Like mangroves, the term saltmarsh refers to an ecological grouping, and includes grasses and herbaceous shrub-like plants that inhabit the upper shoreline above the mean tidal height. Saltmarshes provide a number of important ecosystem services. These include sediment stabilisation and

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protection, filtering of sediments and nutrients, and supporting fisheries (Pennings and Bertness, 2001). Unlike saltmarshes in the United States and Europe, saltmarshes in Australia exist in the zone immediately above mangrove forests along sheltered estuarine shorelines (Adam, 1990). While mangroves are predominantly tropical in their distribution, saltmarsh are primarily temperate (Connolly and Lee, 2007). In Australia, however, it is interesting to note that saltmarsh area is generally greater in estuaries along the tropical Queensland coast (Connolly and Lee, 2007).

In NSW there are only two common species of mangrove: the grey mangrove *Avicennia marina* and the river mangrove *Aegiceras corniculatum*. Several species of seagrass have been recorded but seagrass beds are dominated by three taxa: *Posidonia australis; Zostera* sp. and *Halophila* spp. (Creese et al., 2009). Saltmarsh in south eastern Australia is comprised of a large and diverse assemblage of plant species. Coastal saltmarsh is listed as an endangered ecological community in NSW (NSW Threatened Scientific Committee 2004) and *P. australis* (seagrass) has six listed endangered populations in NSW including Sydney Harbour (NSW Fisheries Scientific Committee 2010).

Soft Sediment Macrophytes in Sydney Harbour

Aerial photographs have been used to map estuarine macrophytes for NSW estuaries including Sydney Harbour (Creese et al., 2009). Some historical aerial photographs have also been analysed, but much of this information is currently unpublished (see West et al., 2004). Mangroves and saltmarsh are generally restricted to the intertidal margins of sheltered bays and inlets of the Middle Harbour, Lane Cove River and Parramatta River arms of the upper harbour (Kelleway et al., 2007). Conversely, seagrasses are found intertidally and subtidally in the lower reaches of the harbour.

The spatial extent of saltmarsh in Sydney Harbour has declined significantly since colonisation (Mcloughlin, 2000; West et al., 2004; West and Williams, 2008), and the area mapped from aerial photographs in 2005 was less than 37 ha. It is difficult to identify small patches from aerial photographs, and the extent is probably slightly underestimated (Kelleway et al., 2007). The largest contiguous patch of saltmarsh remaining in Sydney Harbour occurs in Newington Nature Reserve (approx 6 ha.), but over 70 % of the 757 patches identified by Kelleway et al. (2007) are small (< 1 ha) and isolated. In contrast, mangroves have increased their distribution, being relatively uncommon until the 1870's (McLoughlin, 2000). Their mapped extent has continued to increase between the 1940's and the 2000's (NSW Government *unpub*.), with the current estimate being nearly 184 ha. In many places in the harbour, mangroves have replaced saltmarsh habitats (Kelleway et al., 2007). Seagrass has also declined in extent, and is now estimated to occupy less than half the area (approx 51.7 ha) it did in 1943. The reasons for declines in saltmarsh and seagrass and increases in mangrove area are discussed further in the Threats section of this review.

In Sydney Harbour, mangrove litter material forms the basis of detrital based food webs, which support a variety of species from most trophic levels (e.g. algae, barnacles, molluscs, fish; Ross and Underwood, 1997; Chapman, 1998; Ross, 2001; Clynick and Chapman, 2002; Chapman et al., 2005; Tolhurst, 2009), although the communities are not exceptionally different from those found in other mangroves forests in NSW.

Several species of seagrass have been reported from Sydney Harbour (Creese et al 2009), including: *Halophila ovalis, H. minor, H. major, H. decipiens, Posidonia australis, Zostera capricorni and Hetrozostera nigricaulis.* Mapping usually cannot distinguish between the species, and most studies simply categorise taxa to the level of genus (e.g. West and Williams 2008, Creese et al 2009).

The extent of seagrass is mapped using aerial photographs. Suitable photographs for Sydney Harbour go back to the 1940's. The NSW Government has used aerial photographs to generate orthorectified imagery from those photographs from 1978, 1986, 2000 and 2003 (West and Williams 2008). Recent analysis (DPI unpublished) has now investigated aerial photographs from pre-1978. This work is ongoing and is likely to be reported in the next several years.

Seagrass cover in the estuary was around 59.2 ha in 1978. In 1986 this had grown to 87.4 ha, before being reduced to an estimated 49.5 ha in 2003. Seagrass persistence in certain areas of the harbour are variable. Seagrass meadows around Rose Bay and Middle Harbour, for example, show dramatic changes in the extent of seagrass (West and Williams 2008). Across the whole harbour, 25 % of all mapped seagrass meadows were consistently present over all time periods. The other 75 % of seagrass meadows were ephemeral and were not present over all time periods.

Knowledge Gaps

Currently, there are no harbour wide management strategies for mangroves, seagrass and saltmarsh in Sydney Harbour. This is despite the suggestion the future of mangroves in the harbour is threatened by their supposed low genetic diversity (Melville and Burchett, 2002). However, under the *Fisheries Management Act 1994,* harm to vegetation (including all three macrophyte types) is illegal. Therefore removal or damage can result in fines. Further, there are now 'Habitat Protection Guidelines' set out by the NSW Government.

Practices that aim to minimise disturbance to mangroves, but at the same time allow public access, such as the building of walkways, can themselves have effects on the local biota. For example, Kelaher et al. (1998) demonstrated that the abundance of the semaphore crab, *Heloecius cordiformis*, was higher closer to boardwalks than further away due to the environmental changes (e.g. changes in sediment structure) associated with the boardwalks.

Other than distributional data, the only species we have substantial information on are mangroves, and even that is limited (Ross and Underwood, 1997; Chapman, 1998; Ross, 2001; Clynick and Chapman, 2002; Chapman et al., 2005; Melville et al., 2005; Melville and Pulkownik, 2006; Tolhurst, 2009). We have little understanding of how the resilience of these valuable habitats respond to environmental change (see Threats), and how changes in the abundance and structure mangroves, seagrasses and saltmarsh affects associated biodiversity and ecosystem function within Sydney Harbour.

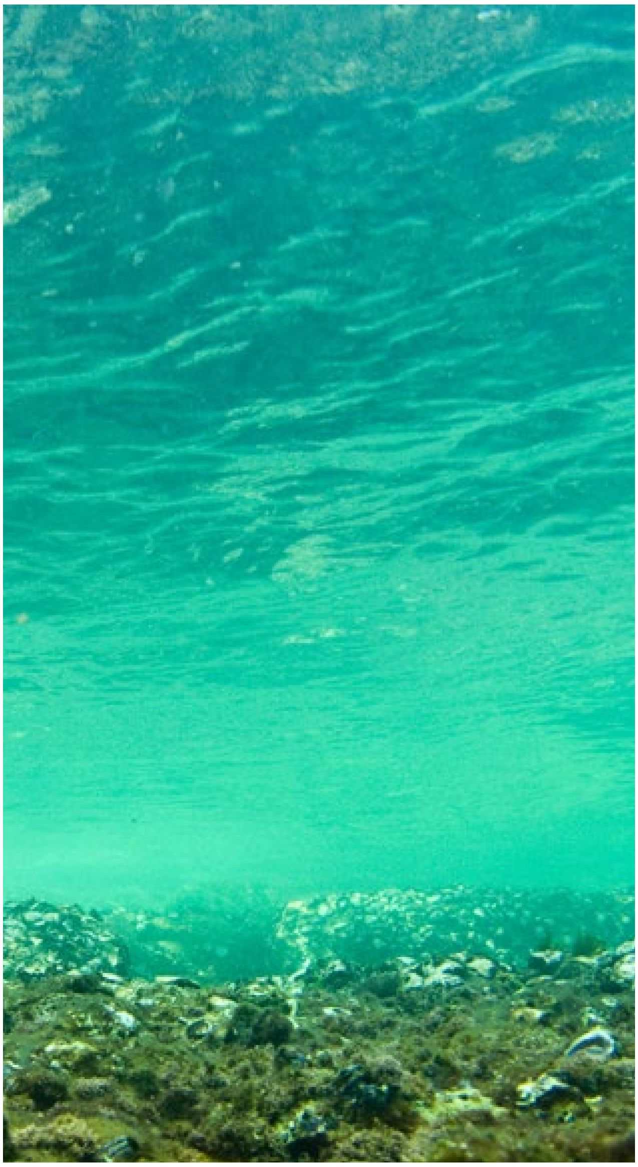
Open Water / Pelagic Systems

Little is known of pelagic flora and fauna in Sydney Harbour, with most studies focusing on water quality.

Outbreaks of both toxic and non-toxic algal blooms have been observed since the 1930's. Blooms of toxic algae have occurred in the estuary in 1983, 1996, and 1999, however similar outbreaks have thought to have occurred prior to this.

A single study has examined the sizes of fin-fish in Sydney Harbour, using commercial fishing by-catch. 90 % of all by-catch were found to be less than 20 cm in length. Invertebrate species such as shrimp and crabs were consistently caught at around 100 individuals per day.

Sydney Harbour is home to one of five little penguin colonies found on the eastern coast of Australia.



General Introduction and Context

Open water is a major habitat in estuaries and marine embayments. The contribution of this habitat to sustaining biodiversity and ecosystem function is well recognised through its role in the transport, dilution and transformation of dissolved and particulate materials that impact estuarine ecology. It also provides habitat for planktonic food webs (Cloern 2001), facilates life-stage transitions for meroplankton and fishes (Potter and Hyndes, 1999), and acts as a corridor for the movement of species at higher trophic levels such as fishes and mammals (Gillanders et al., 2011; Gaos et al., 2012).

The species that occupy these habitats span orders of magnitude in terms of size (microorganisms to mammals; 10^{-6} to 10's m), and spend at least part of their lifecycle in the water column with little direct interaction with the benthos. For the purposes of this review, we do not consider organisms attached to free-floating debris or watercraft to be open water biota (see Sant, 1990; Widmer and Underwood, 2004).

Much of the global literature on estuarine open water habitats is dominated by impacts on water quality, i.e., responses by lower trophic levels to nutrient inputs, contaminants, changes in hydrology and translocation of species (Cloern 2001). However, the dependency of larger organisms on open water habitats is being increasingly recognised through use of stable isotopes (Fry, 2008), geochemical signatures in fish otoliths (Campana and Thorrold, 2001) and more recently with observation technologies such as remote underwater video, global positioning satellite and underwater acoustic tags, that show use of estuaries by apex predators and marine mammals (Becker et al., 2010; Carlson et al., 2010).

The use of pelagic habitat by different organisms is highly size-dependent and determines their risk to habitat degradation. Most microscopic holoplankton (e.g., phytoplankton) are incapable of independent movement (their position is primarily determined by the surrounding currents), and are therefore at greatest risk to deterioration in water quality through constant exposure. Local flow dynamics such as estuarine plumes and fronts are very important to the growth and transport of plankton and small fish (e.g. Kingsford and Suthers, 1994). However, some planktonic organisms can modify their position within these flows by migrating vertically (Epifanio, 1988; Doblin et al., 2006). For larger organisms, pelagic habitat may serve primarily as a corridor for movement. Such meroplanktonic organisms that actively enter or exit the pelagic habitat on various time scales are likely at less risk of declines in habitat quality. Indeed Zhang et al. (2009) found that pelagic fish and mesozooplankton change their behavior and spatial distribution due to hypoxia in the northern Gulf of Mexico.

Open Water Habitats in Sydney Harbour

Surprisingly, little is known of the open water habitats of Sydney Harbour. Most studies in this environment have focussed on water quality and contamination (see Contamination), or the input of nutrients from the surrounding catchment. Studies on fish are generally focussed on benthic reef dwelling species (see Rocky Reef), or the effects of commercial and recreational fishing in the harbour (see Fishing).

Studies of phytoplankton in Sydney Harbour have been limited to those on saxitoxin-producing species involved in harmful algal blooms (Murray et al., 2011) due to their role in the oyster industry. Sydney Harbour has been identified, however, in a contemporary synthesis of locations of both harmless and harmful algal blooms along the coast of New South Wales (Ajani et al. 2001). Algae with direct toxic effects on either humans or harbour species have been reported in Sydney Harbour since colonisation, but blooms of these algae are rare. *Alexandrium catenella, Chattonella gibosa* and *Alexandrium* sp. have had reported outbreaks throughout the Parramatta River during October 1983, November 1996, and November 1999 (Ajani et al., 2001). *C. gibosa* is linked to high mortality of yellowtail and sea bream, as well as farmed bluefin tuna (Marshall and Hallegraeff, 1999). Other unidentified blooms in Sydney Harbour have been reported since European colonisation, but our limited taxonomic knowledge has meant these blooms have gone without study, and potential effects are unknown (Ajani et al., 2001).

Several 'potentially harmful' blooms of dinoflagelate algae have been reported. Both *Scrippsiella trochoidea* and *Gonyaulax polygramma*, while not toxic, have been known to grow to such densities as to create anoxic conditions in the water column. *S. trochoidea* last bloomed in Sydney Harbour in 1890, while *G. polygramma* bloomed in July 1984 (Ajani et al., 2001). During the period between 1890 and 1999 several outbreaks of harmless micro algae occurred, including *Gymnodinium sanguineum* (1930–1932), *Trichodesmium* sp. (1984) and most recently *Noctiluca scintillans* (1999). These blooms had no discernible impact on either human health or the ecology of Sydney Harbour and simply discoloured the water (Ajani et al., 2001). This discolouration was particularly evident during outbreaks of *N. scintillans*, a large (200-280 μm), pink, heterotrophic dinoflagellate that can cause a notorious 'Red Tide' event. Interestingly, the first recorded outbreak of *N. scintillans* was in Sydney Harbour in 1860 when George Bennet noted the sometimes-luminescent

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properties of the alga (Bennet, 1860). Blooms of *G. sanguineum* were also noted early last century. These blooms occurred every July to August from 1930 to 1932. Again, this large dinoflagellate is harmless and causes simple discolouration of the water column.

There are no published studies on zooplankton in Sydney Harbour, however, there have been assessments of larger pelagic invertebrates such as prawns in trawl by-catch (Liggins et al., 1996). By-catch refers to the incidental catch of non-targeted species by fishing trawlers. Commercial fishing was banned in 2006 within Sydney Harbour due to high levels of organic contamination in fish. However, prior to the cessation of fishing, Liggins et al. (1996) quantified the abundance of organisms caught by trawlers to give an assessment of open water fin-fish and invertebrate abundances in the harbour. Almost 219 000 fish were caught as by-catch during two years of sampling. Interestingly, most of the by-catch species noted by Liggins et al. (1996) were small. Twelve commercially important species of fin-fish were identified, seven of which were consistently caught at very small sizes (90 % were less than 20 cm). While most of the by-catch ‘community’ consisted of fin fish, crustaceans were also caught in large numbers. Two-spot crab *Ovalipes australiensis*, blue swimmer crab *Portunus armatus* (previously *P. pelagicus i*n Australia), and mantis shrimp (family: *Squillidae*, several species) were consistently caught at over 100 individuals per day during the study. Work on higher trophic level, open water species, such as fish with only intermittent benthic associations has been restricted largely to recreational fisheries studies which look at catch and release mortality (Roberts et al., 2011) or levels of effort and catch in the fishery (Sant, 1990; Ghosn et al., 2010; Steffe and Murphy, 2011) (see Fishing).

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 (Priddel et al., 2008). At last count there were 56 breeding pairs in the Sydney colony. Reports from 1912, however, indicate that this colony was much larger (Priddel et al., 2008). 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. Studies of other macro-fauna, including large mammals, is completely lacking in Sydney Harbour, or is not presently published, although there are periodic sightings of humpback and Southern Right whales in the harbor during the months May-September. There is ongoing acoustic tagging study of bull sharks *Carcharhinus leucas* in the harbour (NSW Government *unpublished*), but there is no published work to date.

Knowledge Gaps

The open water habitat is characterized by many transient taxa with movements driven by ontogeny or by tidal, diel, seasonal or even annual migrations. The ecological and biochemical importance of materials and biota exchanged through the entrance to the harbor remains a significant knowledge gap. In a manner similar to San Francisco Bay, where shifts in the northwest Pacific Ocean from a warm to cold phase alter the immigration patterns of predators into the bay (Cloern et al. 2007), changes in near and offshore oceanography, including increased influence of the East Australia Current, have the potential to strongly influence the open water habitats of Sydney Harbour.

While the delivery of nutrients and contaminants to open water habitats of the harbour is beginning to be understood (see Contamination and Nutrients and Turbidity), we currently know very little about either the direct or indirect effects of these processes on open water or benthic biota. We know of typically strong links between water quality and planktonic organisms but this has not been well studied in Sydney Harbour. This is alarming given that run-off, contamination, and nutrient inputs are delivered directly into the water column and may be exacerbated by climate change. This may be particularly important for areas of the harbour that are slower to flush, such as the inner parts of Port Jackson and the Parramatta River.

Threats to Biodiversity and Ecosystem Function

Despite relying heavily on Sydney Harbour for services such as food and recreation, the continual growth of the city of Sydney has placed several pressures on our iconic harbour. In the past we disposed of various commercial and urban waste directly into the estuary. While this practice has largely been prohibited, it has left a legacy of sediment contamination that will take centuries to dissipate. Storm water and urban run-off continue to be released directly into the harbour with negligible treatment. Locally this can alter the salinity of the water column; however, it is the resulting nutrient and contaminant enrichment that has caused concern to managers. Contemporary threats also arise from the increasing connectedness between the Port of Sydney and the rest of the world. Non-indigenous species have invaded and spread into the harbour on an extensive scale. These have predominantly arrived on the hulls of ships but other vectors include aquaculture and tropical vagrants that have traveled further on the strengthening East Australian Current. Habitat modification proceeds in the form of foreshore developments and the provisioning of artificial habitat in such as wharves and pontoons. This aids the spread of non-indigenous species as well as fundamentally changing and fragmenting native benthic communities.

In this section, we review and present what is currently known about these threats and stressors. Again we first put the Threat / Stressor within a worldwide context. We then use the results of our systematic literature review process to discuss how these threats and stressors relate specifically to Sydney Harbour, and present what we believe to the be the most concerning gaps in our current knowledge.

Metalloids, Organo-metallic and Metallic Contamination

Sediments in Sydney Harbour have concentrations of Copper, Zinc and Lead that exceed quality guidelines.

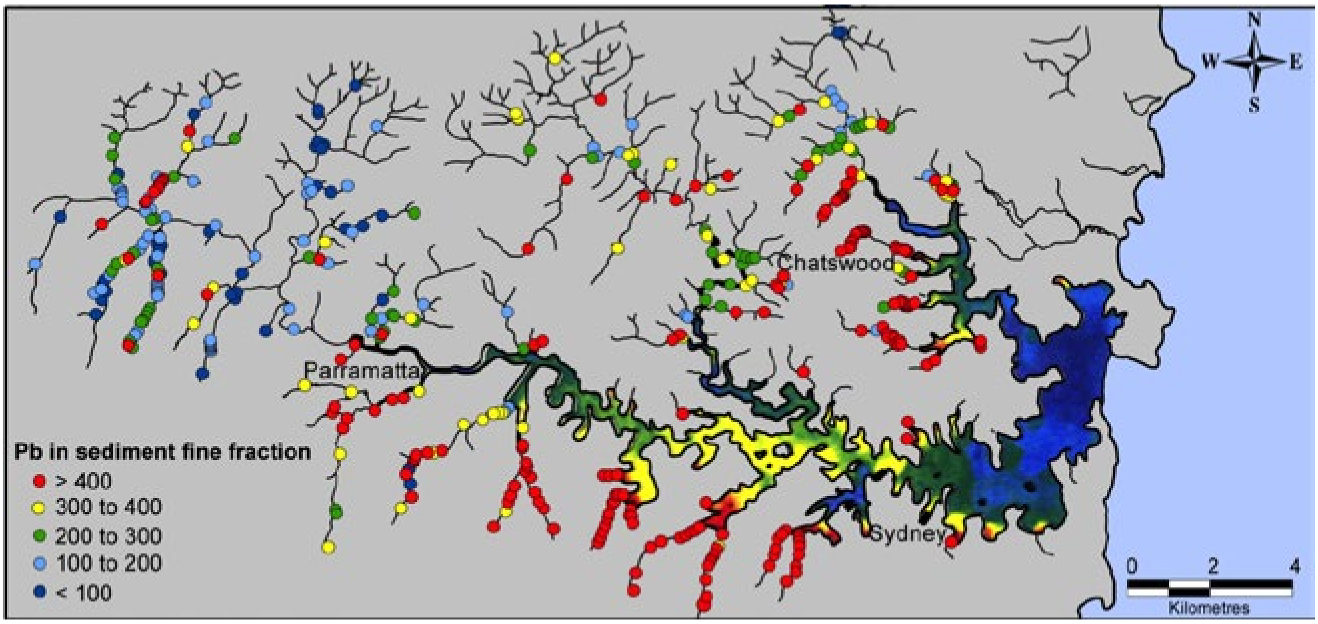
Sediment contamination in much of the harbor is above levels that trigger additional examination.

Most of contamination in Sydney Harbour results from historical inputs that remain in the sediment, and current inputs through storm water inflow.

In areas of high contamination, dramatic changes in sediment biota, fish and bacterial communities have been observed.

When contaminated sediment is disturbed by storms or human activity, contamination can be released from the sediment and affect nearby ecosystems.

right: The shallow embayments of Sydney Harbour, such as Gore Bay (pictured) have generally elevated levels of metalloid contamination within the sediment. This is largely due to past industrial practices, rather than any contemporary threats.



above: The distribution of Lead in the bottom sediments of Sydney Harbour. Figure reprinted from 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'. Published by the Geological Society of Australia, Environmental, Engineering and Hydrogeology Specialist Group, 101p.

General Introduction and Context

Coastal estuaries provide easy access to freshwater and transport, are generally buffered against climate extremes, and allow for easy trade and commerce. Given the proximity of these estuaries to a variety of urban, industrial and agricultural activities, contamination loads into these systems can be heavy. Indeed estuaries are generally believed to be exposed to the highest levels of contamination of any marine system (Kennish 2002). Hence, estuarine animals and plants may be exposed to elevated levels of a variety of toxicants. Some of these toxicants can show mild or even advantageous effects on biota (e.g. nutrient enrichment, McKinley and Johnston, 2010); however, vast majorities have obvious deleterious effects (Johnston and Roberts 2009). Toxic contaminants in fish in several estuaries around the world are found in levels that can impair growth and survivorship (Miskiewicz and Gibbs, 1994). Negative effects on reproduction and development are also observed (Hose et al., 1989). Community-level effects can also occur, with dramatically different species compositions in fish and invertebrates found between contaminated and uncontaminated areas (Johnston and Roberts 2009; McKinley et al., 2011).

Contamination in Sydney Harbour

Sydney Harbour, like most deep-water ports, has considerable foreshore development. The City of Sydney Local Government Area is now the biggest city in Australia and its harbour experiences some of the most contaminated environments in the world (Roberts et al., 2008b; Davis and Birch, 2010, 2011).

Early work (Irvine and Birch, 1998) showed sediments in the estuary to contain high concentrations of a suite of metals. Contemporary studies have confirmed that sediments in large areas of Sydney Harbour are not only highly polluted by metals (Birch and Taylor, 1999; Dafforn et al., 2012), but also a wide range of non-metallic contaminants, e.g. organochlorine pesticides (OCs, Birch and Taylor, 2000), polycyclic aromatic hydrocarbons (PAHs, McCready et al., 2000; Dafforn et al., 2012) and polychlorinated dibenzo-para-dioxins (dioxins) and dibenzofurans (furans, Birch et al., 2007). These organic contaminants have led to restrictions on the consumption of seafood from locations west of the Sydney Harbour Bridge (NSW Government, *unpublished*).

Most of the harbour's contamination results from a combination of historical inputs that remain in the sediments and some current sources of input such as stormwater (Birch and McCready, 2009). The very highest contamination concentrations are generally restricted to the bedded sediments and macroalgae of the upper reaches of embayments and decrease markedly seaward in the harbour (Roberts et al., 2008; Davis and Birch, 2010, 2011; Dafforn et al., 2012,). Contaminant sources have been identified as present and past stormwater discharges close to major inputs and discrete contaminant 'hot spots' associated with disposal from specific industries located on the shores of the estuary (Birch and Scollen, 2003; Snowdon and Birch, 2004). High pollutant concentrations in fluvial particulates are testament to the importance and ubiquitous nature of catchment-derived contamination. Relative concentrations of Cu, Pb and Zn in estuarine sediments of Sydney Harbour are similar to distributions in adjacent catchment soils, suggesting soils may be an important source of metals to the waterway (Snowdon and Birch, 2004; Davis and Birch, 2010; Birch et al., 2011).

Contaminants associated with freshwater plumes migrate beyond off-channel embayments and into the main estuary channel and a small proportion may exit to the ocean in a highly-diluted state depending on the intensity precipitation events (Lee et al., 2011). It is possible that contaminants associated with high- and intermediate-rainfall events (5–50 mm.day^{-1}) may also eventually be removed to the ocean by multiple re-suspension events. In addition, over 100 million tonnes (Mt) of material has been used to undertake 11.35 km^2 of reclamation in Sydney estuary (Mcloughlin, 2000). The most common material used was garbage, industrial waste and sediments removed from the adjacent estuary. Leachate is produced in reclaimed lands due to rainwater filtration and tidal action, which results in an increase in concentrations of copper, lead, zinc, arsenic and chromium in groundwater (Suh et al., 2003a.b.). Although the magnitude of the leaching process has not yet been quantified, the juxtaposition of high contaminant concentrations in sediments at the heads of most estuary embayments and extensive reclamation in adjacent lands is observed in many parts of the estuary.

Where contamination does exceed sediment quality guidelines it is associated with strong changes in the structure of infaunal assemblages (Birch et al., 2008; Dafforn et al., 2012) and benthic larval fish assemblages (McKinley et al., 2011). Contaminated sediments are associated with large abundances of opportunistic species such as capitellid polychaetes and gobies. Recent advances in molecular technology now allow for the census of bacterial communities and contamination loads are associated with substantial changes in sediment bacterial communities within the Harbour (Sun et al., 2012). Increases in the frequency of occurrence of sulphur liking bacteria, as well as bacteria that are associated with oils spills, are observed in contaminated sediments. Changes to all of these structural parameters would be expected to have functional consequences such as changes to the nitrogen cycle. Changes to these functions will have substantial consequences for the entire ecosystem of the harbour.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A comprehensive analysis of sediment chemistry and toxicity was undertaken in a recent study of the harbour (McCready et al., 2004, 2005b., 2006a.b.c; Birch et al., 2008). Results of chemical analyses were compared to sediment quality guidelines (ANZECC & ARMCANZ 2000; Simpson et al., 2005) to assess the probability of sediment toxicity. Areas of Sydney Harbour with sediments exceeding Interim Sediment Quality Guideline–High (ISQG-H) concentrations – a value which indicates a high risk of adverse effects to benthic populations - for Cu, Pb and Zn represented approximately 2, 50, and 36 % of the estuary, respectively (Birch and Taylor, 2002a,b,c). Sediment in all of the harbour, except for a small area near the entrance, exceeded the trigger concentration that requires additional environmental investigation for any activity which disturbs bottom sediment (Simpson et al., 2005; ANZECC & ARMCANZ 2000). Organochlorine pesticides exceeded ISQG-H concentrations over extensive parts of Sydney Harbour, including the lower estuary, whereas sediments in only a small part of the port had PCB concentrations above the ISQG-H value (Birch and Taylor, 2002a.b.c.). Based on guidelines, sediments in almost all upper and middle parts of Sydney Harbour, including Middle Harbour, had at least one metal, OC or PAH concentration in excess of ISQG-H values. The probability of sediment toxicity was determined for mixtures of contaminants using the mean ERM quotient (MERMQ) approach (Long et al., 1998). Sediments in the highest toxic threat (MERMQ) category (4) were located in central estuary embayments (Iron Cove, Rozelle Bay) and category 3 sediments mantled the Parramatta River and other embayments of the central estuary (Homebush Bay, Iron Cove, Five Dock, Rozelle and Blackwattle Bays). Category 2 sediments were located in the main channel of the central and lower harbour, Lane Cove and Middle Harbour, whereas the mouth of the harbour was mantled in category 1 sediment. Category 1, 2, 3 and 4 sediments comprised 19 %, 54 %, 25 % and 2 % of the harbour, respectively (Birch and Taylor, 2002a,b,c). The estuary was then stratified into 21 compartments based on the results of the SQG assessment and each stratum was sampled randomly for detailed chemical/ecotoxicological study (McCready et al., 2005a, 2006c; Birch et al., 2008). Overall, the spatial trends in the original prioritisation of the harbour, based on MERMQ closely predicted outcomes obtained in the combined chemical/ecotoxicological study. Highly toxic, moderately and slightly toxic areas mantle 3, 8 and 5 % of the total area of the estuary. In a survey of 25 estuaries from the three North American coasts, 7 % of the combined area was toxic (Long 2000), i.e. similar to the 11 % toxic plus moderately toxic proportion of Sydney Harbour.

Table 2. The Recommended maximum intake of fish species based on eating a single species caught east of the Sydney Harbour Bridge. Courtesy of NSW Department of Primary Industries (Fisheries)

Species	Number of 150 gram serves	Amounts per month
Prawns*	4 per month	600 g
Crab	5 per month	750 g
Bream	1 per month	150 g
Flounder	12 per month	1800 g
Kingfish	12 per month	1800 g
Luderick	12 per month	1800 g
Sand Whiting	8 per month	1200 g
Sea Mullet	1 every 3 months	50 g
Silver Biddie	1 per month	150 g
Silver Trevally	5 per month	750 g
Tailor	1 per month	150 g
Trumpeter Whiting	12 per month	1800 g
Yellowtail Scad	8 per month	1200 g
Squid	4 per month	600 g
Dusky flathead	12 per month	1800 g
Fanbellied leather-jacket	24 per month	3600 g

Important Note: This advice is provided if one single species is being eaten. For example eating 150 grams of Bream and 600 grams of prawns in one month would exceed the recommended intake. Eating 300 g prawns, 300g sand whiting and 300g yellowtail scad in one month would equal the recommended maximum intake

When bedded sediments are disturbed by natural (storms and tides) or anthropogenic activities (vessel activity and dredging), contaminants become more widely distributed and may affect biogenic habitats and water quality (Birch and O'Hea, 2007; Hedge et al., 2009; Burton & Johnston 2010;). Contaminated sediments have been collected from water column sediment traps within the harbour, bedded sediments and from tissue analysis of deployed Sydney rock oysters (Dafforn et al., 2012). All three monitoring tools are highly correlated suggesting localised resuspension processes are important. Changes in the distribution of sessile invertebrates that live above sediments are associated with metal contamination (Dafforn et al., 2012) as are changes to seaweed tissue contamination and their associated herbivores (Roberts et al., 2008a). Increased tissue concentrations of metals are observed in small toothed flounder and are associated with lower growth rates (McKinley et al., 2012). Two flounder collected from Woolomoloo Bay had Pb concentrations that exceeded food health guidelines (McKinley et al., 2012).

Knowledge Gaps

New compounds and chemicals are being synthesised every day. The impacts of 'emerging contaminants' on natural systems are rarely understood, but are a globally recognised area of concern (Barnes et al., 2008; Phillips et al., 2010). Much of this concern stems from the non-traditional pathway in which the contaminants make it into the environment; from manufacturing plants to the consumer, then through established consumer waste systems. These contaminants can be from pharmacological cosmetic products, through to new waste material from the emerging field of nano-technology (US EPA http://www.epa.gov/nanoscience/ accessed 15/11/2012). Many emerging contaminants may be seen as simple re-formulations of existing compounds. There has been a relatively recent trend, for example, of adding biocides and anti-scalants to the anti-fouling paints commonly applied to vessel hulls and industrial seawater piping. While we have some understanding of the effects of copper in natural systems, we know little about biocides and anti-scalants and their possible interactions with other contaminants.

There has been a recent effort to restore degraded systems globally, in particular for soft-sediment macrophtyes such as seagrass. Results from this research is mixed; however, it seems Sydney

Harbour would benefit heavily from this research due to the documented loss of this habitat in various locations around the estuary. Restoration efforts may be restricted by heavy sediment contamination observed in several locations. If seagrass, and other habitat restoration efforts (such as oyster reef replantation), are to be successful in Sydney Harbour, we need to be able to predict the response of incipient populations to the range of pollutants found in the harbour.

The manner in which stormwater is delivered to Sydney estuary and its ultimate fate has wide implication for management of stormwater discharge to this waterway. Priority for stormwater remediation should be given to creeks with high-metal loads in the upper and central estuary, as well as discharging to the western shores of Middle Harbour. Managerial strategies need to target dissolved and particulate metal phases to ensure effective remediation. Effective remediation will depend on the extent to which 'first-flush' contaminants associated with medium-flow conditions can be remediated (Davis and Birch, 2008). The manner in which stormwater is discharged to the Sydney estuary has important implications on how best to tackle the problem of continued degradation of the harbour, because if the majority of contaminants carried during moderate, and high-flow, are not deposited in the estuary, only low-precipitation conditions require remediation. If this is the case, remediation of stormwater using infiltration devices during low flow at discharge points have a good chance of success (Birch and Hutson, 2009; Birch, 2011). Extensive contemporary mapping of sediment contamination provides a comprehensive overview of pollution levels in the estuary; however, we have more to learn about 'point' sources of contamination. Is the contamination present in sediments and water of Sydney Harbour due to the continued estuary wide input and what role do discreet contaminant entry points, such as stormwater outflows, sewage overflows, landfill leachate and other infrastructure have in determining the spatial distribution of contamination?

Nutrients and Turbidity

Freshwater inflows deliver over 90 % of total suspended solids (TSS) and metals during high river flow. Conversely, dry river flow ('baseflow') delivers high levels of total nitrogen (TN) and total phosphorous (TP).

Aged and damaged drainage infrastructure is implicated as the cause of this nutrient flow in dry periods.

Modeling of overflows and discharges suggest that, in the past, sewage has contributed just over 50 % of TN and TP loads to the Sydney estuary.

Once deposited into the harbour, nutrients are either discharged through the heads in a plume under high rainfall conditions, or incorporated into food webs under low rainfall conditions.

Delivery of TSS into the harbour affects the quantity and quality of light available for photosynthesis.

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right: There has yet to be a comprehensive biological assessment of the effects of nutrient enrichment in Sydney Harbour. The Sydney Harbour Research Program, in association with the NSW Office of Environment and Heritage have begun a comprehensive survey, utilising modeling conducted by the Hawkesbury Nepean Catchment Management Authority.

General Introduction and Context

In addition to metallic and other toxic contaminants, the addition of nutrients to marine systems can deleteriously affect fauna and flora. Changes in nutrient inputs may be due to fertiliser use on land, accidental and planned sewage release and anthropogenic changes to estuarine and catchment hydrology that mobilise dissolved and particulate materials and increase downstream fluxes. Enrichment of estuaries stimulates plant growth and disrupts the balance between the production and metabolism of organic matter, sometimes leading to decreased ecological function (Cloern, 2001). Over two decades of eutrophication research has confirmed that estuaries do not respond similarly to nutrient and particulate loads (Cloern, 2001). For example, estuaries with fine, mobile sediments can limit light for autotrophic growth despite nutrient enrichment, and relatively strong tidal flows and water column mixing can result in high flushing rates (Cloern, 1996, 2001). Furthermore, for Australian estuaries, it is difficult to extrapolate from northern hemisphere systems because the vast majority of Australian estuaries are dominated by relatively low riverine flow, interspersed with episodic events that deliver the bulk of the water (Davis and Koop, 2006).

Nutrients and Turbidity in Sydney Harbour

Sydney Harbour has a wide, permanently open entrance that allows full tidal exchange of the estuary with the open coast. As a result, research on organic enrichment has mostly involved riverine and catchment inputs of suspended particles, and assessment of bedded sediments that have the potential to be resuspended and transported (Lee et al., 2011). It is now evident that freshwater inflows deliver suspended solids, nutrients and contaminants into the harbour, but with completely different dynamics (Birch and Rochford, 2010). In three Sydney estuary sub-catchments, Beck and Birch (2012b) determined that the majority (> 90 %) of total suspended solids (TSS) and metals was discharged during high river flow, whereas dry weather base-flow contributed considerable loads of total nitrogen and phosphorus (TN and TP). Birch et al. (2010) also found high concentrations of TN and TP in base-flow draining a neighboring catchment (Iron Cove Creek). Beck and Birch (2012b) indicate that nutrient export during base-flow is likely the result of leakage of sewage from aged and damaged drainage infrastructure and frequent (> 3,000 per year) sewage overflows (Bickford et al., 1999), though the new 'Northside Tunnel' may have reduced this severity of these overflows. Modelling of overflows and discharges suggest that sewage contributes just over 50 % of TN and TP loads to Sydney estuary (Birch et al., 2010).

The fate of nutrients in Sydney Harbour is strongly dependent upon water flow. Under high-rainfall conditions (> 50 mm.day^{-1}), the estuary becomes stratified and nutrients are either removed from the estuary directly in a plume or indirectly by advective / dispersive remobilisation (Lee et al., 2011). Under low to moderate rainfall (5-50 mm.day^{-1}), low flushing rates present favourable hydrological conditions for nutrients (and contaminants) to be chemically and biologically incorporated into the food web (Forstner and Wittman, 1981) and deposited into adjacent estuarine sediments close to discharge points and thereby remain in the estuary (Birch and McCready, 2009; Birch, 2011).

Regarding sediment nutrient inventories, concentrations of organic carbon increase regularly towards the upper ends of tributaries and embayments in Sydney Harbour and Middle Harbour (Birch et al., 1999). Organic-P levels are elevated in Middle Harbour. Elsewhere, high concentrations are irregular and isolated. Inorganic-P concentrations are elevated at the landward ends of Iron Cove, Rozelle Bay and small embayments of Central Harbour. Bioavailable-P exhibits an irregular distribution with isolated high values in Iron Cove, Lane Cove River, Sugarloaf Bay and at the entrance to Middle Harbour (Birch et al., 1999). All of the Sydney Harbour sediments analysed exhibited Total-P concentrations less than the world average of material being delivered to estuaries (Birch et al., 1999).

Knowledge Gaps

There are no studies of the causal effects of nutrient enrichment on the ecology of Sydney Harbour. There is potential for nutrient enrichment to increase productivity (suggested by increased biomass of sediment invertebrates and fish in Sydney Harbour – McKinley et al., 2012 and Dafforn et al., 2012). Nor are there studies that examine the stoichiometry of nutrients and how this has changed during urbanisation and development. Are we reaching any nutrient enrichment thresholds that may result in algal blooms and ecosystem collapse?

Reducing nutrient inputs requires a better understanding of the relative sources. Currently urban run-off and planned sewage overflows are two of the major nutrient sources but studies to quantify the relative importance of both pathways are limited.

It is somewhat surprising that a large-scale process-based biogeochemical modelling system has not yet been realised for Sydney Harbour. Such as system would require careful calibration and verification through a systematic field work campaign. However once undertaken this information will prove invaluable to scientists and managers alike.

Neo Biota: Non Indigenous and Novel Species in Sydney Harbour

Given the strong history of commercial and recreational boating in Sydney Harbour, many NIS have established populations.

There is a risk of further transport and establishment of NIS in Sydney Harbour, particularly for the asian shore crab, the chinese mitten crab, and the brown mussel.

Shipping related artificial structures harbour diverse and abundant NIS populations. Increased larval transport in these areas, increased space availability, high disturbance rates and unnatural shading and surface orientation are implicated as drivers of this increase.

The invasive green algae *Caulerpa taxifolia* has established in several areas of the harbour.

Tropical fish are beginning to be observed over-wintering in Sydney Harbour. They have been transported into the harbour through a strengthening East Australian Current.

We have little knowledge of regional scale processes affecting NIS transport.

General Introduction and Context

Invasive species are a major source of economic and biodiversity loss globally – up to $120 billion per year in the US alone (Pimentel et al., 2005). Native systems can be impacted through the displacement of native biota and destabilising microenvironments (Byers, 2000; Ruiz et al., 2000). Invasion can be categorised as a four step process – transport, establishment, spread and impact (Lockwood et al., 2005). Transport processes have been well studied globally and the large majority of introduced species – both between and within countries – has occurred via shipping (in ballast water or as hull-fouling; Carlton 1985, Ruiz et al., 2000). However, translocation of species for aquaculture or the aquarium trade, and associated species that have piggy-backed on live aquaculture imports, is also an important mechanism (Naylor et al., 2001). A more recent phenomenon is the rapid expansion of many native species outside their traditional range (Booth et al., 2007). The incursion of tropical fish into NSW has been growing in frequency and intensity, with several species now with established 'over-wintering' populations (Figuiera et al., 2009). In some circumstances, these species have been referred to as invasive species in their extended range. Far less is known about their establishment processes although propagule pressure (Lockwood et al., 2005), changes in resource availability (e.g. reduced competition) (Stachowicz and Byrnes 2006) and a reduction in natural enemies (de Rivera et al., 2005) and disturbance (Clark and Johnston 2009) have all been implicated in the success of invasive species in their introduced range.

Neo Biota in Sydney Harbour

Like most major ports, many non indigenous species (NIS) have established in Sydney Harbour. There are a variety of NIS that occur on artificial substrata (e.g. the tunicate, *Styela plicata*), natural intertidal (e.g. the Pacific oyster, *Crassostrea gigas*), subtidal rocky reefs (eg. the tropical fish *Abudefduf vaigiensis* and the introduced bryozoan *Membranipora membranacea*), soft-sediment substrata (e.g. the green alga, *Caulerpa taxifolia*) and upper intertidal plant communities (e.g. the saltmarsh plant, *Juncus acutus*). Modelling of shipping related NIS transport has identified several ports around the world from which the likelihood of further introduction is high

left: *Cirolana harfordi* is one of the most abundant non-indigenous species present in Sydney Harbour. It can reach densities over 1000 individuals per m^2. Like all NIS in Sydney Harbour, we have little data on any potential effects of *C. harfordi* on the native communities. Photo: Ana Bugnot

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left: While larger commercial vessels bring NIS from overseas, recreational vessels are thought to transport these species across a regional scale. No modelling has yet fully explored this possibility. Photo: DepositPhotos

(Glasby and Lobb 2008). These include Singapore, Auckland, Port Villa, Tauranga and Napier. Several high-profile marine pests, including the asian shore clam *Hemigrapsus sanguineus*, chinese mitten crab *Eriocheir sinensis*, and the brown mussel *Perna perna* are not yet established in Australia, yet are predicted to have a high chance of transportation into Sydney via commercial and recreational vessels, and high chance of establishment and survival once introduced (Glasby and Lobb 2007).

While shipping activities can directly act to transport species into Sydney Harbour, the establishment of a large shipping industry has also generated extensive amounts of artificial substrata (wharves, piers and floating pontoons, see Habitat Alteration). In Sydney Harbour, the abundance of NIS on these artificial structures can be over double that found on natural sandstone reef (Glasby and Connell 2007, Dafforn et al., 2012). Abundant invertebrate NIS, including the serpulid worm *Hydroides elegans*, solitary ascidian *Styela plicata*, colonial ascidians *Botrylloides leachii* and *Bottryllus schlosseri*, and the bryozoans *Watersipora subtorquata* and *Schizoporella errata* among others, are all found among the hard substrate, artificial habitats of Sydney Harbour (AMBS 2002).

The mechanisms behind NIS establishment on Sydney Harbour's artificial habitats are still unclear, and likely to vary between taxa and system. Increases in shipping traffic around commercial and recreational boating hubs would likely increase the non-indigenous propagule pressure recipient communities are exposed to (Carlton 1985, Floerl and Inglis 2003, Hedge et al., 2012a.b.), however effects of the receiving environment cannot be ignored. The establishment of new habitat would promote the establishment of early colonising species such as *W. subtorquata* and *S. errata* (Glasby et al. 2007). Subsequent continual mechanical disturbance by vessels docking, or by cleaning activities, may also increase the dominance of these early colonising NIS (Clark and Johnston 2005, 2009). Direct, preferential settlement of NIS onto artificial substrates has also been shown to occur, with effects of artificial shading and unnatural surface orientations also exacerbating invasion processes in artificial habitats (Glasby and Connell 2007, Dafforn et al., 2012). The high water flow that occurs around pier piles, and increases in heavy metal contamination in the surrounding sediment and water column, has also been implicated as increasing NIS abundance in Sydney Harbour (Glasby and Connell 2007; Dafforn 2008, see Contamination). The construction of artificial habitat in previously natural reef has been implicated as a stepping stone mechanism by which NIS can spread (Bulleri and Airoldi 2005, Forrest et al., 2009, Hedge and Johnston 2012). Under the conceptual model proposed by Forrest et al., (2009), areas of artificial habitat can form a transport network that aids in the spread of NIS over unsuitable habitat to 'High Value Areas'. While studies of NIS spread over the small spatial scale of Sydney Harbour are lacking, and we have no formal definition of 'High Value' Harbour areas, the substantial provisioning of artificial habitat cannot be ignored when considering invasion processes and modelling in Sydney Harbour.

Human activities are also largely responsible for the spread of the invasive green alga *Caulerpa taxifolia*. There are several populations of this species in Sydney Harbour, which are being continuously monitored by state agencies. The aquarium trade has spread this species globally, but once established in introduced regions its spread is greatly facilitated through asexual fragmentation generated by boating activity (either by propellors, or by anchors). Once transported to a new estuary, fragments can grow rapidly and form extensive beds (Wright 2005).

Another phenomenon is the presence of tropical fish on the NSW coastline. Although the larvae and/or recruits of tropical fish in NSW have been documented in summer months for 20 years (authors unpub.) data collected over the past 10 years shows a relationship between a southward strengthening of the East Australian Current (i.e. the occurrence of warmer waters further into southeastern Australia) and the presence of tropical fish. At some sites on the NSW coastline, these fish have established over-wintering populations in some warm years. Studies show that these tropical fish occur in Sydney Harbour (Booth et al 2007). Given the presence of suitable habitat and similar water conditions in the middle to outer harbour to those outside the harbour, it is likely that the influx and integration of tropical fish into local fish communities will be similar to those observed at coastal sites nearby. However, we know little about the temporal and spatial dynamics of tropical fish within Sydney Harbour.

Although the transport vectors and spread of NIS is Sydney Harbour are well known, their ecological and economic impacts are poorly understood. However, national and international research demonstrates that several of the NIS have significant negative impacts, that are also likely to occur in Sydney Harbour. For example, *Caulerpa taxifolia* was first discovered in Sydney Harbour in 2002 although it was present in nearby Port Hacking and Lake Conjola since 2000 (Creese et al. 2004). Extensive research conducted in NSW and overseas demonstrates *C. taxifolia* can affect the feeding behaviour and distribution of benthic fishes (Levi and Francour 2004; Longepierre et al., 2005) or support assemblages of fish (York et al., 2006) and invertebrates (McKinnon et al., 2009) that differ from those in adjacent native habitats. The recruitment of clams can be facilitated in *C. taxifolia* beds compared to non-vegetated habitats, but the growth, survivorship and reproductive capacity are reduced by the alga (Gribben and Wright 2006; Wright et al., 2007; Gribben et al., 2009). The large negative impacts on native biota are an indirect effect of *C. taxifolia's* extensive negative effects on sediment and water column properties (e.g. reduced sediment redox potential and boundary layer dissolved oxygen, Gribben et al., 2009; Galucci et al., 2012). Of particular concern are the potential impacts of *C. taxifolia* on seagrass beds.

Knowledge Gaps

Invasion processes operate on several scales; the transport of NIS propagules from source locations globally, regional transport on a national or coastline scale, and transport and dispersal between habitats within an area (i.e. spread). We have an understanding of the risks associated with the transport of NIS to Sydney Harbour from ports globally (see above, Glasby and Lobb 2008). Additionally we are starting to understand smaller scale 'between habitat' dispersal of NIS (see above, Glasby and Connell 2007; Forrest et al., 2009; Dafforn et al., 2012; Hedge and Johnston 2012). We know less, however, about the establishment risk posed by the regional transport of NIS already in Australia, or, indeed, if it has contributed to NIS populations already established in Sydney Harbour. It has been posited that unregulated recreational vessels is an important, but largely overlooked, mechanism affecting the distribution of NIS at regional scales (Clarke-Murray et al., 2011), yet quantifying this risk in southern Australia has not yet occurred.

We have even less knowledge of invasion processes in other systems. For species that do invade native habitats (e.g. the colonisation of soft sediments by *C. taxifolia*) we have no knowledge of the local conditions that promote the establishment and spread of these species, although disturbance does play a large role in the spread of some species, including invasive macrophytes in Australia (Valentine and Johnson 2003). Our search methods failed to find a single citation that investigates NIS distribution of soft sediment infauna or marine micro-biota. This reflects our lack of taxonomic knowledge in these systems more generally. It is possible that many invasive sediment in-faunal and micro organisms have been transported to Sydney since the establishment of the colony in 1788. Genetic techniques may be able provide evidence for these of NIS status and origin as this technology continues to improve.

Habitat Modification

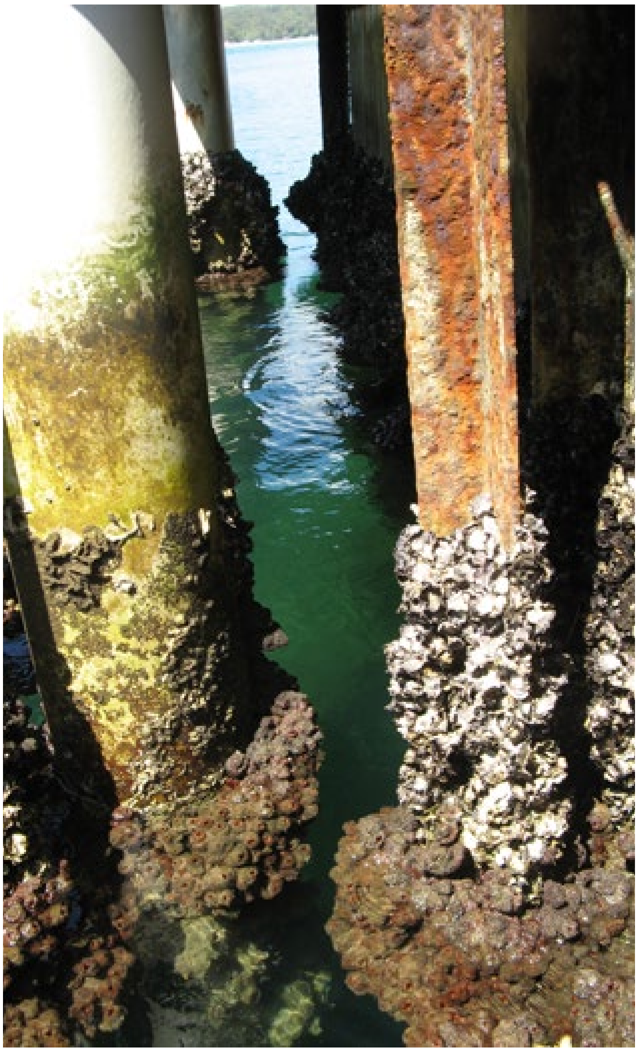
Approximately 77 km of the 322 km of original shoreline of Sydney Harbour has been removed due to reclamation and infilling.

Over 50 % of the shoreline has been replaced with seawalls, and there are over 40 functioning marinas.

The flora and fauna found on these artificial structures is dramatically different to natural rocky reef. This includes plants and animals living directly on the structures, and the fish communities inhabiting the surrounding waters. Artificial structures harbor many non-indigenous species.

Biogenic habitats found on piers and pilings harbour a greater abundance and cover of sessile epibiota, generally due to greater shade and less grazers.

Fragmentation of natural habitats by artificial structures reduce species richness, with un-fragmented natural shores in Sydney Harbour supporting greater biodiversity than natural shores that have been dissected by artificial structures.



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General Introduction and Context

Habitat structure is an important determinant of patterns of abundance and distribution of organisms (e.g. MacArthur and MacArthur 1961, Heck 1979, McCoy and Bell 1991). Therefore, any modification of structure will have ecological consequences. The most common types of modification of habitats in urbanized coastal areas are: (i) addition of artificial structures such as pier-pilings and pontoons; (ii) replacement of natural habitats by artificial structures such as sea-walls and breakwaters and (iii) fragmentation of habitats, mostly caused by the disturbances mentioned above. The purpose of artificial structures range from preventing erosion to recreational use and their construction is likely to increase in response to predicted global changes such as sea-level rise and increases in intensity and frequency of storms (Michener et al., 1997, Thompson et al., 2002, Bulleri and Chapman 2010).

Seawalls in the intertidal support fewer organisms than adjacent natural rocky shores (e.g. Chapman and Bulleri 2003; Bulleri 2005, Bulleri et al. 2005). Chapman (2003, 2006) found that many mobile organisms, including some common gastropods on natural shores, are rare or absent on seawalls. Ecological processes and interactions among organisms occurring on seawalls also differ from those occurring on natural rocky shores (e.g. Moreira 2006; Jackson 2008; Ivesa et al., 2010; Klein et al., 2011). For instance, the reproductive output of limpets on seawalls is smaller than that of limpets on natural shores (Moreira et al., 2006). Also, competitive interactions among key intertidal grazers are affected by these structures (Klein et al., 2011). Finally, seawalls also affect the recruitment of organisms, leading to differences in the composition of assemblages compared to natural shores (Bulleri 2005). Some of the factors that seem to drive these differences are differences in wave exposure (Blockley and Chapman 2008) and in the slope, i.e. seawalls are vertical and, consequently, have compressed intertidal zones, which could influence, for instance, competitive interactions and the availability of micro-habitats (rocky shores usually have more diverse range of microhabitats such as crevices and rocky pools; see e.g. Moreira et al. 2006; Chapman & Underwood 2011).

left: Almost 50 % of the shoreline of Sydney Harbour is modified. These modifications include the building of seawalls, as well as 'over water' constructions such as wharves and pilons. These artificial environments harbour a diverse group of flora and fauna that differs from natural rocky reef. Photo: Katherine Dafforn right: There are efforts to increase the diverstiy of flora and fauna on Sydney Harbour's seawalls. Researchers at the University of Sydney have trialled the addition of simple holes and crevices to promote species colonisation and growth. These methods have been successful here in Lavender Bay, just west of the Sydney Harbour Bridge. Photo: Paul Hallam


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Modified Habitats in Sydney Harbour

Sydney Harbour has been extensively modified by reclamation since European settlement over 200 years ago, especially in the upper estuary. Approximately 77 km of the 322 km of original shoreline has been removed due to reclamation and infilling (Pitblado, 1978). Approximately 22 % of the total 50 km^2 area of the estuary has been reclaimed mainly for industrial, recreational and residential uses (Birch, 2007; Birch et al., 2009). Almost 9 million.m^3 of water has been lost on each tidal cycle resulting in predicted changes in water movement, water quality, sedimentation and ecology of the upper harbour. Most of the shoreline has been replaced with artificial structures, such as seawalls (more than 50 %, Chapman & Bulleri 2003), and there are at least 40 functioning marinas that service more than 35 000 recreational vessels (Widmer et al. 2002). Artificial structures are, therefore, common habitats in the Harbour. These structures have inherently different features from natural habitats, such as the material with which they are built (Glasby 2000, Moreira 2006), their orientation (Connell 1999, Knott et al., 2004), shading (Glasby 1999b, Blockley and Chapman 2006, Marzinelli et al., 2011) and their distance to the sea-floor (Glasby 1999c, Glasby and Connell 2001). As a consequence, artificial structures often support assemblages that differ in many ways from those on natural substrata (see below).

The most common types of subtidal artificial structures in the Harbour are pier-pilings and floating pontoons in marinas and wharves. The composition of assemblages and the relative abundance of organisms living directly on these structures differ from those on natural rocky reefs (Connell and Glasby 1999, Glasby 1999a, 2001). Pilings not only affect organisms living on them, but also in their surroundings. For instance, assemblages of fish surrounding pier-pilings in marinas often differ from those in natural reef habitats; some species occur in greater abundances near pilings, while others are more abundant on reefs (Clynick et al. 2008). In addition, many habitat-forming organisms inhabit artificial structures. These biogenic habitats support many organisms that may also be affected by the artificial structures, but few studies have investigated this (but see People 2006, Marzinelli et al., 2009).

For instance, kelp – the main habitat-forming organism in subtidal reefs (see Subtidal Reefs) – also occur on pier-pilings. Kelp on pilings support different species and greater cover of epibiota, such as encrusting bryozoans and hydroids, than those on adjacent natural reefs (Marzinelli et al., 2009, Marzinelli 2012).

The addition of artificial structures can simultaneously modify multiple components of habitat. Differences in ecological patterns of subtidal biota between modified and natural habitats can be caused by physical properties. For example, experiments have shown that the shade caused by piers and the greater distance from the sea-floor influence abundances of fouling organisms (Glasby 1999c). Biological properties of these habitats may also be important. Pilings, for example, influenced abundances of Sydney Harbour kelp epibiota due to the provision of shade and indirectly due to smaller densities of sea-urchins in pilings, which affect covers of bryozoans (Marzinelli et al., 2011). Ecological processes also are affected by these structures. Recruitment and growth of sessile epibiota is often greater in pilings than in adjacent reefs in Sydney Harbour (Marzinelli et al., 2012).

Fragmentation of habitats, i.e. the division of large natural patches of habitat into smaller patches of habitat due to human disturbances, is a major problem caused by the addition of artificial structures. In Sydney Harbour for example, most natural shores are currently fragmented by seawalls (Goodsell et al., 2007). Goodsell (2009) found a greater abundance of several taxa on natural shores than on mixed (bordered on one end by artificial habitat and on the other end by natural shore) or complete (bordered by artificial habitats in both ends) fragments.

In addition to all the hard artificial structures, several beaches in Sydney Harbour have swimming enclosures constructed with hanging nets (Clynick 2008b, Hellyer et al., 2011). These are usually made from nylon or polyethylene and are designed to exclude sharks from popular swimming beaches. They are often, however, removed during winter or when being repaired (Clynick 2008b). These nets have been shown to be a suitable habitat for seahorses in Sydney Harbour, supporting a greater density of the species *Hippocampus whitei* than that found in natural habitats (Clynick 2008b). It is not known, however, what happens to these seahorses when the nets are removed. The addition and, consequently removal of these structures may have, therefore, serious implications to populations of these fishes.

Knowledge gaps

Despite the plethora of studies that have examined effects of modification of habitats on organisms on hard substrata, almost no studies have investigated effects on soft sediment assemblages in Sydney Harbour. Marinas, for instance, are built over soft sediments (e.g. Marzinelli 2012). Some of the features of marinas (e.g. increased shading and/or boating activity) may affect organisms in soft sediments in these areas. For example, waves caused by boats in the Harbour influence the composition of assemblages of soft sediments (Bishop 2007). More studies designed to determine the effects of habitat modification on ecological patterns and processes soft sediment assemblages are necessary to provide sound information for management and conservation.

Fishing and Aquaculture

Over 586 species of fish are found in Sydney Harbour.

There is almost twice the effort and catch of recreational fishing activities in Sydney Harbour, compared to nearby estuaries. An estimated 74 tonnes of fish were caught by recreational fishers during the 2008 summer period.

Commercial fishing in Sydney Harbour has been banned since 2006 due to high levels of dioxins in fish.

Unlike other estuaries in the area, the local fishing industry is dominated by local residents fishing from shore. Currently they are strongly advised to avoid seafood caught west of the Sydney Harbour Bridge, and limit consumption east of it, due to increased dioxin contamination.

There is a slightly higher catch of smaller fish in Sydney Harbour, compared to other estuaries in the area.

Mulloway *Argyrosomus japonicus*, kingfish *Seriola lalandi,* and snapper *Pagrus auratus,* among others, are listed as either overfished or 'growth overfished' in NSW with a large recreational component (< 50 %) to their catch.

General Introduction and Context

Worldwide demand for seafood products drives very high levels of wild harvest and aquaculture in marine systems (67 and 8 million tons in 2009 respectively, FAO 2010). While there are a variety of fisheries and an increasing number of aquaculture operations in the open ocean, the vast majority of catch is typically from the coastal regions and estuaries of the world (Blaber 2000). These regions are not only typically more productive but also much easier to access by commercial, recreational, artisanal and subsistence fishers as well as developers of aquaculture operations.

The impacts of fishing on ecosystems and species can occur at regional and local scales and in a variety of marine ecosystems including pelagic (Myers and Worm 2003), coastal (Blaber 2000), tropical reefs (Roberts 1995) and the deep sea (Roberts 2002). Impacts from fishing are generally classed into those affecting the target species, those affecting incidental captured species (bycatch) and those that directly or indirectly affect the ecosystem. Direct impacts on target species not only serve to increase mortality rates but can also reduce population growth rates by depressing demographic rates (growth and fecundity, Law 2000), or by altering size/age structure sex ratios (Rochet 1998, Hawkins and Roberts 2003). The impacts of bycatch can be very similar to those on target stocks and can be quite serious depending on the bycatch rates from fishery to fishery, especially since most yield assessments take account of the target species only. Fishery impacts on ecosystems can occur in either a bottom up (e.g., the destruction of habitat by benthic trawling, Wheeler et al. 2005) or top down (e.g., reduction of large pelagic predatory species by long-line fisheries, Myers and Worm 2003) manner. While the impacts of fishing can be seen even for entire ocean basins, it is at small scales that fishing can be most intense, especially adjacent to population centres such as coastal cities.

The rapid growth of the aquaculture industry has served to compensate for stabilization/decline of wild harvest on a global scale and indeed the aquaculture industry in the Australian region is developing rapidly (40 % since 2000; FAO 2010). While often considered more ecologically acceptable than extraction from wild stocks, issues such as escape of exotic species, disease transmission, use of unsustainable fishmeal, and localized habitat destruction during development of facilities, need to be addressed (Primavera 2006; Naylor, Hardy et al., 2009).

left: While commercial fishing in Sydney Harbour has been banned since 2006, hundreds of recreational fishers take to the estuary every year. Despite government warnings, fishers are still found west of the Harbour Bridge, such as here in the upper Parramatta River.

With over 85% of the population living within 50 km of the coast (http://www.abs.gov.au/Ausstats/abs@.nsf/Previousproducts/1301.0Feature%20Article32004, [accessed 30/7/14]), fishing has long been an important activity for Australians. Due to their close proximity to population centres, as well as relatively productive environmental conditions, estuaries have been host to the majority of this activity. Within NSW, approximately 45-50 % of total commercial effort (days fished) and 30-35 % of landings (by weight) come from estuaries (*authors unpublished*). The limited data available suggests the pattern is the same for recreational fisheries in the state (NSW Fisheries 2002).

Fishing and Aquaculture in Sydney Harbour

Sydney Harbour has a structurally diverse, though highly modified, (Chapman 2003) shoreline with water quality that generally meets or exceeds established guidelines (Hatje et al. 2003). The broad range of habitats within the harbour, including the modified habitats (Clynick 2008, Clynick et al. 2008) is home to over 586 species of fish. Within this setting, and on the steps of Australia's largest city, fishing of all varieties has long been a common and important activity in Sydney Harbour. While data on the recreational fishing sector in NSW is limited, on-site surveys have indicated that Sydney Harbour experiences approximately twice the effort and catch of other estuaries in the state (Ghosn et al., 2010). Unlike recreational fisheries in the Greater Sydney region (Steffe and Murphy 2011), the fishery in Sydney Harbour is dominated by local residents fishing from shore (Ghosn et al., 2010).

While the water quality in the harbour is generally good, benthic sediments are highly contaminated with heavy metals and organic pollutants such as dioxins (Birch and Taylor 1999). How the state of these two environments (pelagic, benthic) will interact with fishing will depend on target species and their behaviour, diet, and fishing methods. Commercial fishing was banned inside Sydney Harbour in 2006 and this ban continues, due to recorded high levels of dioxins in fish flesh. Recreational fishing is still allowed but with warnings to reduce weekly intake to 150 g east of the Sydney Harbour Bridge, and avoid eating any fish caught west of the Bridge.

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There have been few studies on the direct impacts of fishing in Sydney Harbour. As indicated previously, estuaries in the Sydney region account for a higher proportion of recreational catch than do estuaries for the state as a whole. While the specific data is not available for Sydney Harbour individually, there is no reason to think this would not have been true for the Harbour prior to the ban on commercial fishing in 2006. Bycatch from commercial prawn trawl fisheries was studied in the early 1990's. By-catch:catch ratios of about 2:1 in the harbour were found, which was less than nearby Botany Bay (Liggins et al. 1996). Data on directed recreational fisheries in the Harbour would suggest a relatively healthy fishery based on catch per effort but it does have a higher proportion of undersized catch than other estuaries surveyed (Ghosn et al., 2010). There are also several species such as mulloway *Argyosomus japonicas*, kingfish *Seriola lalandi,* and snapper *Pagrus auratus* listed as overfished, or 'growth overfished', in NSW (NSW Status of Stocks 2012) with a large recreational component (< 50 %) to their catch, which are commonly targeted and caught in Sydney Harbour (Ghosn et al., 2010). For these species the direct effects of recreational fishing in Sydney Harbour are likely to be the greatest.

Information on the impacts of by-catch from recreational fisheries in the harbour is limited to a study demonstrating approximately 15 % mortality of angled-and-released yellowtail kingfish *S. lalandi* (Roberts et al., 2011). Aquaculture or non-finfish harvesting in the Harbour has, at this stage, not become a commercial venture for any species, although Blount and Worthington (2002) investigated the viability of sea urchin *Centrostephanus rodgersii* roe from the Harbour compared to more southern locations.

Sydney Harbour is also home to the North (Sydney) Harbour Aquatic Reserve (260 ha). Established in 1982, line fishing is allowed in the park but not spearfishing or mollusc collecting. This reserve has been used as part of a larger study which demonstrated that protection can enhance the abundance of target species but that there also a significant effects of estuary modification on fish assemblages (McKinley et al., 2011).

Knowledge Gaps

All of the current fishing in Sydney Harbour is recreational. While several recent studies have served to better inform us of the effort and harvest that results from this fishing, ongoing monitoring is required to better understand the potential impacts of these activities, both direct and indirect (e.g. bycatch, foodweb modification, marine debris, invasive species transport). We also need additional information on the impacts of organic pollutants on food webs, including human consumption, of fish caught in the harbour. Such information is crucial for those who continue to consume fish caught west of the Sydney Harbour Bridge, despite the strong recommendations against such practices (Ghosn et al., 2010). This information can also be used to inform any discussions about re-opening the Harbour to commercial fishing. We also know relatively little about the ecosystem effects of the removal of the more popular fishery species, such as mulloway, which are now at low abundances. Nor do we understand the ecological ramifications of incidental and purpose-built artificial reefs that may be placed in and around the harbour to enhance fisheries.

While we have information on the catch and effort of recreational fishers on an estuary scale (Ghosn et al., 2010). It would be beneficial to understand local scale fishing effort. This would aid in understanding localised risk within the harbour, and be particularly important for future spatial based management plans.

Climate Change

Sydney Harbour is located in a region known to be warming faster than the global average.

The East Australian Current is extending polewards, and the water temperature regime has shifted approx. 350 km south.

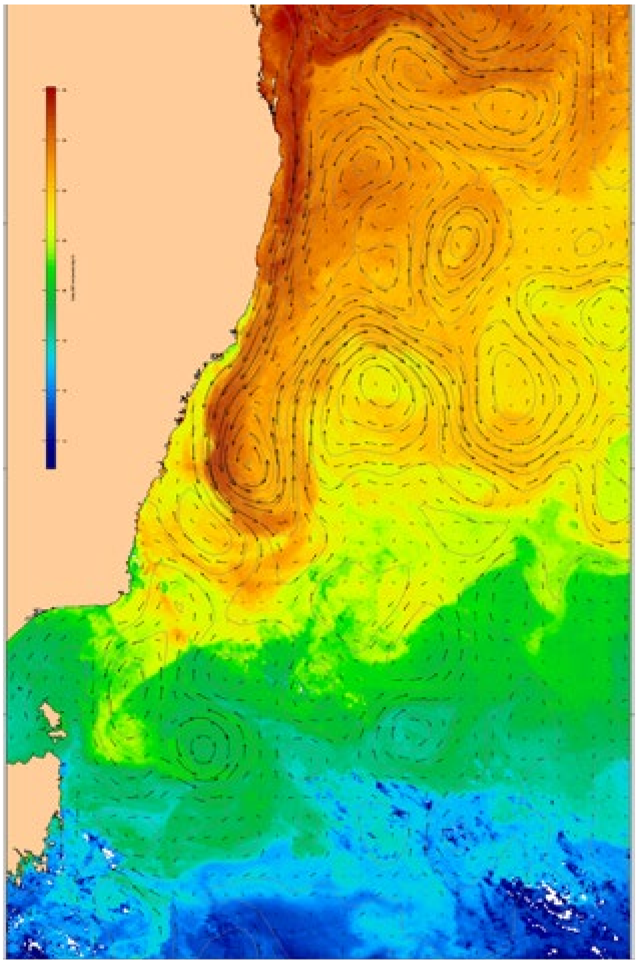
A 3°C rise in ocean temperature off Sydney Harbour is expected by 2070.

Growth and development of some species, particularly molluscs and echinoderms, is retarded at elevated temperatures and associated pH levels. Other species will be transported into the harbour from tropical areas.

Sydney rock oysters *Saccostrea glomerata* seem particularly resilient to increased temperatures.

Sea level rise of 1.7 mm a year is not predicted to impact mangrove habitats, however it is likely to diminish saltmarsh habitats.

Increased storm activities are likely to place coastal infrastructure under greater threat. Harbour barrier habitats such as mangrove and seagrass will become more important for infrastructure protection.



General Introduction and Context

Long-term climate change will simultaneously alter many environmental parameters (e.g., temperature, pH, physical water column structure, nutrient bioavailability) that regulate biodiversity and function of marine ecosystems (Boyd et al., 2010). Australian coastal landforms and ecosystems are strongly influenced by sea level variation, atmospheric, hydrologic and hydrodynamic processes (Roy et al., 2001), which are all predicted to shift under climate change. Despite moderate certainty around continental-scale drivers such as changes in boundary currents along Australia's western and eastern seaboard (Poloczanska et al., 2012), recent reviews of climate change impacts in Australia have revealed considerable uncertainty in the responses of coastal ecosystems to climate change (Hobday et al., 2006; Gillanders et al., 2011; Hadwen et al., 2011).

While drivers of ecological impacts of climate change operate globally, they vary in their intensity depending on region and habitat. Estuaries are especially exposed to changes in climate because impacts on both freshwater and marine systems will affect estuarine biota and ecosystem function. Moreover, human settlements are often located on estuaries and hence the vast majority of human adaptation to climate change (e.g. coastal armouring) will affect estuaries. However, estuarine organisms are also well adapted to withstand large fluctuations in environmental conditions and may be less sensitive than other organisms to water quality changes. For estuaries close to large urban populations, such as Sydney Harbour, climate change research has largely focused on evaluating risks to public and private infrastructure, as opposed to evaluating direct ecosystem effects. Impacts such as sea level rise have been of most concern, particularly in view of dramatic shifts in beach sands as a result of climate-driven storms (Short and Trembanis 2000). In this review, we evaluate evidence of, and future risks of, climate change impacts on Sydney Harbour marine organisms and habitats.

left: A strengthening East Australia Current (EAC) may increase the Sea Surface Temperature by up to 3 °C by 2070. This may lead to substantial range shifts for a variety of species. Recent research suggests that some species are already able to 'over winter' in Sydney Harbour during favrourable conditions.

Climate Change in Sydney Harbour

Sea Surface Temperature Rise

Sydney Harbour is located in the western Tasman Sea, a region known to be warming relatively quickly compared to the global average (Wu et al. 2012), with the water temperature regime shifting 350 km southwards due to the increasing southwards extent of the East Australian Current (EAC; Ridgway 2007). A rise of 3 degrees Celsius is predicted in waters off Sydney by 2070 which could contribute to increasing water temperatures in the estuary. Figueira and Booth (2010) showed that expatriating tropical fish species that are being transported southwards in the EAC rarely overwinter when SST drops below 17 ° Celsius. Along the SE Australian coast, Sydney is at the critical point where most winters dip slightly below this temperature, but occasionally (e.g., 2001, 2006) winter temperatures are warmer, and overwintering occurs for some species. Future scenarios suggest that overwintering may become an annual event in future, and may facilitate substantial range shifts. Studies conducted outside the harbour but relevant to its resident organisms suggest that climate change will result in species losses as well as new arrivals. Byrne et al. (2011) showed that growth and development of *Heliocidaris erythrogramma*, a common sea urchin along the Sydney coast, is reduced at high temperatures, with potentially negative consequences for recruitment. Apart from these examples, nothing is known regarding harbour organism responses to elevated temperature or changing temperature dynamics.

Acidification

Elevated atmospheric CO_2 concentrations and increased CO_2 dissolution into the surface ocean has caused a decrease in pH (increased acidity) in the ocean's surface layer (Sabine et al. 2004). The process of acidification affects dissolved inorganic carbon speciation, inducing further changes in seawater chemistry including a reduction in carbonate ion (CO_3^{2-}) abundance and a decreased aragonite saturation state (Feely et al. 2004). This results in reduced capacity for marine calcifiers to produce their $CaCO_3$ skeleton (Gattuso et al. 1998; Diaz-Pulido et al., 2007). Under such conditions, non-calcifying species may have a competitive advantage over calcifying species such as habitat forming invertebrates and commercially important shellfish (e.g. mussels and oysters, respectively). Although there is little data on either pH or PCO_2 in estuaries worldwide, and how estuarine ecosystems will respond to these changes, research on the Sydney rock oyster, *Saccostrea glomerata*, has shown that this organism may have the capacity to acclimate or adapt to elevated PCO_2 over the next century. Larvae spawned from adults exposed to

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elevated PCO_2 were larger and developed faster, but displayed similar survival compared with larvae spawned from adults exposed to ambient PCO_2 (Parker et al. 2012). Furthermore, selectively bred *S. glomerata* larvae were more resilient to elevated PCO_2 than wild larvae, suggesting that this species may be able to 'keep up' with rates of climate change.

Changes in Hydrology and Ocean Circulation

Despite the general lack of marine baseline data, long-term observations in several ocean basins show that plankton populations in the ocean fluctuate in synchrony with large-scale climate patterns including El-Niño-Southern Oscillation (ENSO) (Behrenfeld et al. 2006), but similar evidence is lacking for estuaries because of shorter observational records (Cloern et al. 2010). In Australia, there is already substantive evidence that the EAC is increasing its southward extent (Ridgway 2007). At Port Hacking, 27 km south of the Harbour's entrance, there has been a pronounced drop in dissolved silicate (an essential element for growth of silicifying phytoplankton like diatoms) over the last 30 years, alongside a decade long (1997 – 2007) drop in the size of the spring bloom and its growth rate (Thompson et al. 2009). These changes appear to be at least partly related to changing ocean circulation or decreased estuarine discharge, or both (Thompson et al. 2009), and suggest that water entering the Sydney estuary at the seaward end is becoming warmer as well as less productive, with potential implications for recruitment of organisms into the harbour and other processes.

Sealevel Rise

Waters along Australia's eastern seaboard are rising in line with global averages (1.7mm per year; Church and White 2011) and are acting in opposition to vertical accretion of sediments in nearshore habitats. Rogers et al (2005) showed that the surface elevation increase at sites within Sydney Harbour exceeded the 85-year sea level trend, suggesting that mangrove forest would not be inundated under future estimated sea-level rise conditions. However, given the limited opportunities for shoreward migration in some parts of the Harbour, sea-level rise is likely to diminish saltmarsh habitats.

Increased Storm Surge and Severe Weather

In recent years severe storm events generated by East Coast Lows (ECLs), have caused fatalities, severe flooding and erosion and caused hazards for shipping (e.g., grounding of ships; Mills et al. 2010). Estuaries with significant coastal infrastructure such as Sydney Harbour are therefore at risk of damage during these severe weather events, and it is likely that mangrove and seagrass habitats (which play a significant role in buffering coastal settlements from erosion), will become more important to maintain.

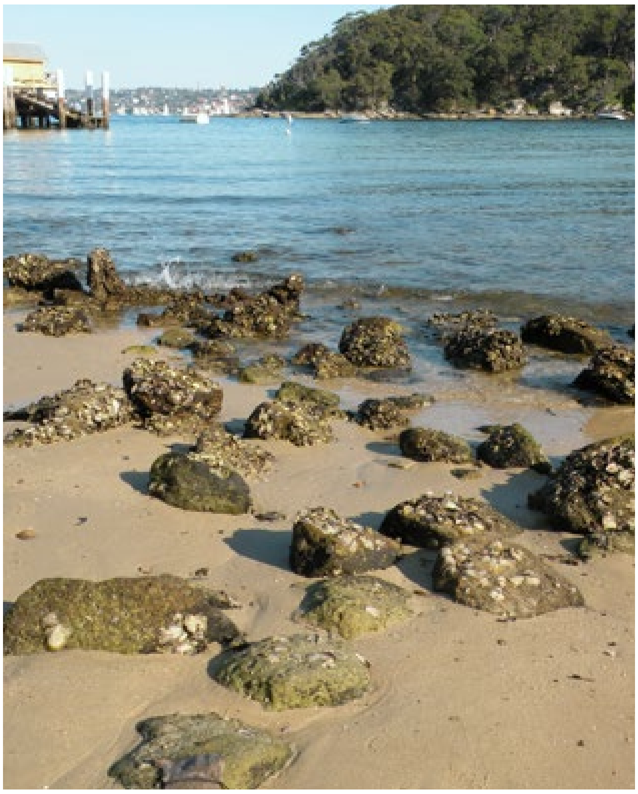
While not exhaustive, this review indicates that climate-driven changes in environmental factors will alter ecological dynamics both individually and interactively, and may lead to dampening or amplification (i.e., antagonisms and synergisms) of climate change signals. Furthermore, climate change is likely to interact with other stressors such as fishing and habitat modification.

Knowledge Gaps

The physical stressors that are affected by climate change are relatively well-known off the Sydney coast thanks to long-term data collection (Ridgway 2008, Thompson et al. 2009) and the newly established Australian Integrated Marine Observing System (IMOS), as well as other long term records (e.g., waverider buoys). However, there is a clear need to examine ocean and atmospheric linkages that influence coastal oceanography as well as watershed hydrology.

Huge gaps exist in our understanding of how climate change stressors will impact on ecosystems in and adjacent to the Harbour. Given the Harbour's large size, rich habitat diversity and relatively large tidal exchange, we might predict it is relatively resistant to climate change and variability, compared to other systems. However, gathering the evidence needed to manage the Harbour into the future presents a significant research challenge. New experimental approaches incorporating simultaneous changes in suites of variables (environmental clusters), including concurrent climate and non-climate stressors, and conducting broad-scale observations and field experiments to examine resilience and potential for adaptation have been recognised as fruitful approaches (Boyd et al., 2010, Wernberg et al., 2012).

The obvious next step is to use the improved modelling tools to investigate the impacts of climate change within the estuary. Changes in freshwater inflow are likely to have profound impacts on estuarine habitats and ecosystems. Such studies would include an investigation into the circulation, biogeochemistry and the implications for flushing and residence times. This could be either through downscaled climate change scenarios or from simple perturbation experiments where temperature and salinity are manipulated. For example, if flushing timescales were to decrease (with a reduction in freshwater inflow and more evaporation) this could have potentially detrimental impacts on water quality. The converse could also occur if there were an increased frequency of heavy rainfall events. Climate modelling studies such as these will be a valuable tool that can be used in anticipate and mitigate against severe environmental consequences and will readily feed into management and adaptation strategies.



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Stressor Interactions

Accounting for threats on an individual basis ignores the myriad of possible interactions that may occur between them.

Non-additive (synergistic) interactions between stressors are more likely than the additive accumulation of effects from single stressors.

Non indigenous species interact with increased metal contamination to reduce the abundance of native species in the harbour.

Nutrient enrichment ameliorates the effect of metal contamination. This may be masking potential effects of metals on natural systems above those currently observed.

Climate change effects are broad scale and generally synergistic. Increased pH, for example, increases the toxicity of a variety of common contaminants.

Sydney Harbour is both a working harbour and a large urban center. As such it is subject to multiple threats that impact biodiversity and ecosystem function. Above we have identified individual threats and how they vary in their relative importance for each habitat. The consideration of threats on an individual basis ignores the fact that multiple stressors overlap in space and time and act simultaneously. Management can achieve little unless consideration is given to all of the potential risk pathways and their interactions. In this section we discuss the potential interactions of threats and the resulting directions of impact.

Many studies assume the effects of multiple stressors on a single system act additively. That is, research has often assumed impacts result from the additive accumulation of effects by the addition of isolated stressors (Crain et al., 2008). A recent review and meta-analyses suggests that synergistic and antagonistic effects between stressors are also common and complex (Crain et al., 2008). This global review found that in the majority of cases, multiple stressors will either worsen impacts additively, or interact to exaggerate impacts. In a smaller proportion of studies, stressors interact to ameliorate impacts. We can make predictions regarding the basic direction of two-way interactions of stressors in Sydney Harbour. In some cases we base these predictions on empirical evidence collected from the harbour, in other cases our predictions are based on physics, chemistry, or reviews (Table 2).

Most of the interactions that are predicted to be important in Sydney Harbour are synergistic, or act together to exaggerate or ameliorate impacts. Importantly, many of the predicted interactions between stressors have not been investigated explicitly. So while we have some understanding of these effects in isolation, there needs to be much more research before we can confidently show how they may interact on Sydney Harbour's natural systems.

Experimental work in Sydney Harbour has demonstrated the facilitative effects of contamination on the spread of NIS (Piola et al., 2008, Dafforn et al., 2009). Increased copper and tin contamination results in recruitment of various NIS above that which occurs 'naturally' in the high traffic areas of the harbour. Interestingly, reduced native recruitment was also observed. Increased NIS recruitment and increased metal contamination may then have acted synergistically to impact on native species abundance, however this has yet to be explored experimentally. Similarly, habitat alteration can increase the recruitment of NIS species and also reduce light availability to surrounding systems. These factors may act synergistically or additively to impact on benthic seagrass and algae communities in a similar way to nutrient addition and turbidity.

Recent survey work has observed a greater diversity of fish and invertebrates in areas with high levels of metallic contamination and high levels of nutrient input. In this situation, we may predict an ameliorating relationship between the two types of contamination (see also Contamination). Again, this is yet to be explored experimentally and would be a very novel research direction. If nutrients act antagonistically against metallic contamination, they may be masking potential effects of these contaminants. That is, the effects of our current levels of metal contamination will worsen dramatically if the nutrient inputs are reduced.

Climate change impacts are generally broad scale and mostly synergistic. Increased temperature and decreased pH increase the toxicity of many common contaminants (Crain et al., 2008). Changes in natural environmental variables, such as increased storms will lead to greater disturbance regimes that have been found to facilitate NIS recruitment (Clark and Johnston, 2009). The advantageous effects of heavy metals on NIS recruitment is known (see above), so increased disturbance that mobilises sediment bound metal contamination may exacerbate the effects (Knott et al., 2009).

The investigation of stressor interactions should be a priority research goal for understanding the complex natural environment of Sydney Harbour. Investigating stressor interactions may be complex, altered by the temporal patterns of stressor occurrence, higher order interactions between species, and the intensity of stressors (Crain et al., 2008).

Science and Management

There is a variety of state and federal legislation relevant to Sydney Harbour, including the *Protection of the Environment Operations Act 1997*, the *NSW Coastal Protection Act 1979* the *Environment Protection and Biodiversity Conservation Act 1999* and the *Fisheries Management Act 1994*. Local environment plans control the types of development that takes place on harbour foreshores.

Development activities, media attention and political will are generally thought to control the extent to which these instruments are used to control and remedy legacy problems in Sydney Harbour.

There has yet to be a comprehensive Threat and Risk Analysis for Sydney Harbour that encompasses environmental assets as well as social and economic values. A full synthesis of threats and harbour resources are not currently available for such an assessment.

Like any other highly urbanised 'working harbour' around the world, Sydney Harbour faces many management challenges. There exists a need to balance the requirements and aspirations of residents, visitors, industry, shipping and other users. Similarly, Sydney has had to deal with an ongoing legacy of problems resulting from past activities in and around the harbour that have occurred since European settlement in the late 18th century.

The Federal and NSW governments have legislation and regulations in place to deal with these management issues; the *NSW Protection of the Environment Operations Act 1997,* the *NSW Coastal Protection Act 1979* and the *Environment Protection and Biodiversity Conservation Act 1999* to regulate the quality of the Harbour's water and to facilitate estuary planning and conservation; the *Fisheries Management Act 1994* to control species that are harvested for food and to protect important fish habitats, Local Environmental Plans to control the types of development permitted on the Harbour's foreshores (under the *Environmental Planning and Assessment Act 1979*), to name but a few examples.

The extent to which these legislative instruments have been used to effectively manage competing interests or to remedy legacy problems in Sydney Harbour has largely been a function of development activities, media attention and political will. For example, the construction of facilities and infrastructure around Homebush Bay in the lead up to the 2000 Olympic Games provided the opportunity to map the full extent of soil contamination on the shores of parts of the Harbour and in bottom sediments throughout much of the Parramatta River (Suh et al., 2004). This led to the initiation of sediment remediation activities, many of which continue today. Similarly, there were major improvements in water quality that occurred as a result of greatly increased storm-water management around Sydney Harbour in the 1970s.

There has not yet been a systematic examination of the major threats to the marine biodiversity of Sydney Harbour that would allow a comprehensive risk assessment to be done. However, there are clearly aspects, often restricted to particular sites around the harbour, where potentially high risks from such things as contaminated sediments, international shipping or small boat activity (jetties, moorings, etc) remain. Management responses, using the provisions of existing legislation and regulation, to some of these issues need to be informed by a good scientific understanding not only of the species or habitats involved or of the threats they face, but also of their likely response to management arrangements.

The Sydney Harbour Catchment Regional Environment Plan 2005 establishes several planning principles for the effective management of the catchment. It sets out a range of matters that need

Table 2. Predicted interactions between human stressors in the marine environment. Note that most predicted interactions are synergistic in nature. That is, combined effects are greater than the effect of each stressor in isolation. There is little data on interactions between fishing and both NIS and climate change and predictions are therefore difficult in Sydney Harbour.

	Contamination	NIS	Habitat alteration	Nutrients Turbidity	Fishing Aqua-culture	Climate Change
Contamination						
NIS	Synergistic					
Habitat alteration	Synergistic	Synergistic				
Nutrients and Turbidity	Antagonistic	Synergistic	Synergistic			
Fishing and Aquaculture	Synergistic	?	Variable	Antagonistic		
Climate Change	Synergistic	Synergistic	Synergistic	Synergistic	?	

to be considered before any development on the Harbour foreshore, and its aim is to ensure a more consistent approach for development decisions. In the mid-1990s the Sydney Olympic Park Authority also introduced a management plan for the shoreline marine habitats under its jurisdiction, which has included a major reconstruction of tidal flats followed by saltmarsh replanting. There is arguably a need for more plans like this, starting with NHAR, particularly in light of concerns surrounding boat moorings and anchoring in the small remnant patches of *Posidonia* spp. seagrass in this part of the harbour.

Conclusion

Sydney Harbour is a paradox; stunningly beautiful, astonishingly diverse but subject to serious threats. The geological structure of the estuary with its steep rocky shorelines and wide open mouth ensure that the Harbour is regularly flushed by the clean oceanic waters of the East Australian Current. Yet the impacts of human activity since settlement are easily observed and have changed the ecology of the system. Through this comprehensive review we have synthesized all that is published in the scientific literature in relation to the Harbour and have identified major knowledge gaps that should be filled if we are to manage this iconic estuary for all of the people and all of the biota that call it home.

The Sydney Harbour estuary is a steep-sided drowned river valley that sits at the heart of Australia's biggest city. Much of the circulation in the Harbour is driven by the tides and winds, and water speeds can reach almost 0.25 m.s-1 in eddies that form near the Harbour entrance. Water age in the Harbour can vary from 4 months in the upper reaches, to only several days in the outer harbour channels. Interestingly, we know little of how the predicted strengthening of the East Australian Current will affect the Harbour's circulation and hydrology, or the natural systems found above and below the water. How the Harbour and its people respond to climate change will determine further impacts in this estuary. This report did not find any significant literature published in scientific journals that investigated the Harbour's potential resilience or response to predicted climate shifts. This is interesting given the Harbour and city lie within a region known to be warming at a faster rate than most of the rest of the world.

The geological structure of Sydney Harbour allows for the existence of a diverse range of habitat types, from soft sediment and seagrasses to rocky reef and open water. Over 2472 different mollusc, polychaete, echinoderms and crustacean species have been reported from the Harbour in museum records, yet this is likely an underestimate due to the patchy sampling undertaken since European colonisation. New methods in microbial sampling have uncovered over 10 000 different microbial taxa in the sediment alone. Additionally, the fragmented rocky reefs in the Harbour are home to a diverse invertebrate and fish community with 127 small invertebrate species found on the rocks, including the popular Sydney rock oyster, *Saccostrea glomerata* and the cunjevoi *Pyura praeputialis*. NSW Government mapping reveals that only 37 ha of Sydney Harbour's original saltmarsh habitat remains, and remnant saltmarsh communities are being systematically replaced by expanding mangrove forests. There is currently only ~50 ha of seagrass and the Harbour is home to an endangered population of the Australian species *Posidonia australis*. Understanding the quality of fragmented and remnant habitat patches to other plants and animals would be a valuable research direction.

We know that Sydney Harbour hosts a vibrant recreational fishing community that adds to the social and economical value of the Sydney region and the state more generally. However, the fine scale distribution of fishing activity has yet to be resolved and our understanding of fish abundances and distributions in the Harbour is relatively restricted. Understanding this distribution would allow scientists to quantify the risk of fishing to the Harbour's natural systems at a scale relevant for future planning and management. Broad scale monitoring of fish catches within the Harbour has provided an estimate of the relative abundances of different fish, with yellowtail scad being the most caught species by anglers. In addition, larval fish tows along the seafloor and purse seine sampling of beaches in the Harbour indicate that Sydney Harbour may have a greater fish biomass and species richness of these taxa than nearby estuaries. Distribution and movement models of fish species in the Harbour are less mature, but would be a fruitful research direction. In addition, the current contaminant status of recreationally targeted fish requires attention in order to update fish consumption guidelines.

Pollution is a serious, contemporary challenge within the Harbour. Sydney Harbour has a strong history of industrial activities, commercial shipping and recreational boating. This has left it with a legacy of contamination and there is ongoing input of contaminants through stormwater and urban run-off. Sediment contamination in the Harbour by metals has been relatively well characterized, and almost the entire seafloor has been contaminated with a range of metals to some degree. In many poorly flushed areas of Sydney Harbour, sediment contamination is at levels harmful to biota. However, we know nothing of the distribution of important emerging contaminants such as flame retardants or microplastics and our understanding of stormwater impacts is limited. Studies that identified potential threats from emerging contaminants, quantified stormwater impacts on ecosystem function and identified safe and efficient means for restoring or remediating historically polluted sediments would be immediately useful to harbour management.

The distribution and effects of non-inidgenous species within the Harbour's natural systems are not well understood. Modeling has highlighted the risk of introduction of several high profile marine pest species, however, there is no biomonitoring program that might enable the early detection of such species and consideration should be given to how this can be addressed.

Habitat modification is an ongoing management issue as the industrial nature of the Harbour has meant substantial alteration to its shoreline and new residential, recreational and business developments continue to take place. Almost 50% of the foreshore has been modified in some way, generally by the construction of seawalls, pontoons and wharfs. The fauna and flora found in these modified areas differs from the communities found in natural rocky reef and Sydney Harbour would benefit from trials and implementation of green engineering programs that aim to minimise the ecological impact of artificial structures.

In writing this synthesis paper we have recognized both the value and the enigma that Sydney Harbour's natural environment represents. We have a significant published record of scientific understanding of the Harbour but there are still many knowledge gaps and we recognize that there has been valuable data collected in the Harbour that is not immediately accessible. We encourage the further development of our understanding of this system through strategic and integrated research programs that combine disciplines, experiment and observe the Harbour, and interrogate unpublished data. This iconic estuary has been subject to dramatic change and is facing enormous new challenges. The scientific community will be integral to providing independent, rigorous and credible data and analyses to manage the natural resources of Sydney Harbour into the future.

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* These references refer to papers cited within this report, however these papers are not directly related to Sydney Harbour. See Sydney Harbour Database below, for a complete list of all 310 papers with data from Sydney Harbour. It also includes management plans gazetted that include land and water within Sydney Harbour, but are generally not considered scientific publications.

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Sydney Harbour Questionnaire

SIMS Questionnaire sent to 110 Sydney based scientists and their students.

sims
sydney institute of marine science

SYDNEY HARBOUR RESEARCH PROJECT

Questionnaire

Thank you for taking the time to fill in this short questionnaire. We are collecting information regarding current, and previous research, conducted within Sydney Harbour. The information you provide may be used to publicise research strengths of the Sydney scientific community. It will also form the basis for a comprehensive synthesis of scientific information on the Harbour. If you have any questions regarding this survey, or the Sydney Harbour Research Project in general, please contact Info.shrp@sims.org.au.

Personal details

Title	Last name	First name

Institution	Department

email address	Phone-Work

1. Current projects

1.1) Please give the details of any research project that you are currently undertaking within the Sydney Harbour area.

Start year	Location/s	Research question	Data type/s	Collaborators
eg. 2010	North Head, Chowder Bay	Effect of sewage outflow on infaunal assemblages	Sediment infauna	Dr Marty McFly, Centre for Delorean Transport. Virginia Tech

1.2) Please provide details of any peer-reviewed studies, published in scientific journals, that you have already published on any aspect of the research that you are currently undertaking within Sydney harbour.

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2. Completed/ Past projects <10 years

2.1) Please give details of any project that you recently completed (between 2002-2012), that includes research within Sydney Harbour

Years	Location/s	Research question	Data type/s	Collaborators
1998-2005	Homebush Bay	Assessing impacts of Sydney Olympic park construction	Sediment PAH con. Fish abundance	Prof. S. Hawking, Oxford Uni.

2.2) Please provide details on any peer-reviewed studies published in scientific journals resulting from the projec detailed above.

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2.3) Please detail any grey literature that you published, resulting from work outlined above. These may be repo websites, media releases, software programs etc.

1	Brown E. McFly M. (2005) Effect of time travel on Sydney Harbour sediment infauna. Report to SMCMA
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4. Media and Future Work

4.1) Has your work in Sydney harbour received media attention in the last decade? If yes, please give details including year, type of media and story name.

Brown E., and McFly M., 2001, "Contempory threats of invasive species on Sydney harbour fish species" radio interview, Science Tuesdays with Biff Tannen, ABC National.

4.2) What do you think the key research questions should be for the Sydney Harbour Project?

Investigating how sediment composistion variance throughout the inner harbour influences contamination loads and subsequent diversity

4.3) If you are interested in contributing , what research capabilities could you bring to the project.

4.4) Do you know of any other non-SIMs scientist that the Sydney Harbour Research Project team might like to send this questionnaire to?

SUBMIT FORM

3. Other projects >10 years old

3.1) Please provide details on any peer- reviewed studies published in scientific journals resulting from research within Sydney Harbour and carried out before 2002

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3.2) Please detail any grey literature that you published, resulting from work outlined above. These may be repo websites, media releases, or software programs etc.

1	Brown E. and Hawking S. (1998) Blackholes under Chowder Bay?, Report to Sydney Ports
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