
Sydney Estuary, Australia: Geology, Anthropogenic Development and Hydrodynamic Processes/Attributes

Serena B. Lee and Gavin F. Birch

Abstract

The Sydney Estuary is the focal point of the intensely developed city of Sydney. Since European settlement in 1788 the waterway has undergone many changes, including reclamation, contamination, modified fresh-water flow regimes and altered rates of sedimentation. The various alterations and their impact on the system is the focus of this chapter. Research undertaken over the past thirty years identified the threat of contamination on estuary health. This issue came to a head in 2006 with the closure of the Sydney commercial fin fish and prawn industries due to high concentrations of dioxins detected in fish and prawn tissue. Improved understanding of the impact of different chemicals on estuarine species has led to changes in policy and practices within the waterway and adjacent catchment. Despite better practices contaminants continue to be supplied to the estuary via the complex stormwater network draining the surrounding highly urbanised catchment. Stormwater runoff represents the major contemporary source of estuary contamination. Recent field and numerical investigations show that in order to reduce contaminant concentrations stormwater runoff must be treated before being discharged into the waterway. Due to the hydrodynamic behaviour of this geometrically complex waterway rather than rapidly flushing out of the estuary to the open ocean contaminants supplied via stormwater runoff become entrained down the water column and settle on the estuary bed. Whilst many improvements have been made to address processes affecting estuary health, continued monitoring of contaminant concentrations within estuary waters, bed sediments and species are required to determine the success of past management strategies and to better inform decisions about the future management of this highly prized waterway.

Keywords

Estuary • Sediment • Toxicity • Urbanisation • Reclamation • Stratification

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Box 1

Serena Lee and Gavin Birch studied Sydney Estuary, an urban estuary dissecting Sydney. Since European settlement in 1788 the waterway has undergone many changes, including reclamation, contamination, modified fresh-water flow regimes and altered rates of sedimentation, that now threaten the estuary health. In 2006 Sydney commercial fin fish and prawn industries were closed due to high concentrations of dioxins detected in fish and prawn tissue. Improved understanding of the impact of different chemicals on estuarine species has led to changes in policy and practices within the waterway and adjacent catchment. Stormwater runoff represents the major contemporary source of estuary contamination. Recent field and numerical investigations show that stormwater runoff must be treated before being discharged into the waterway because contaminants supplied via stormwater runoff are not flushed to the sea, but instead they are entrained down the water column and settle on the estuary bed.



Whilst many improvements have been made to address processes affecting estuary health, continued monitoring of contaminant concentrations within estuary waters, bed sediments and species are required to determine the success of management strategies and to better inform decisions about the future management of this highly prized waterway.

Introduction

Much of the beauty of Sydney can be attributed to four deeply-incised estuaries, which dissect the raised coastal margin of the region. These waterways have provided an extensive shoreline and have brought marine conditions deep into the catchment. These attributes have made Sydney

one of the most beautiful cities in the world. This chapter describes one of these waterways – Sydney Estuary.

Physical Description

The Sydney Estuary, classified as a ria, is approximately 30 km in length, ranging in width from approximately 60 m near the headwaters to approximately 3 km approaching the estuary mouth. The total surface area of the water body is approximately 50 km² and surrounding catchment is close to 500 km². Parramatta River, Duck River, Lane Cove River and Middle Harbour Creek are the four principal estuary tributaries, however additional creeks and canals flow into numerous off-channel embayments, which join the main channel along the length of the waterway (Fig. 1).

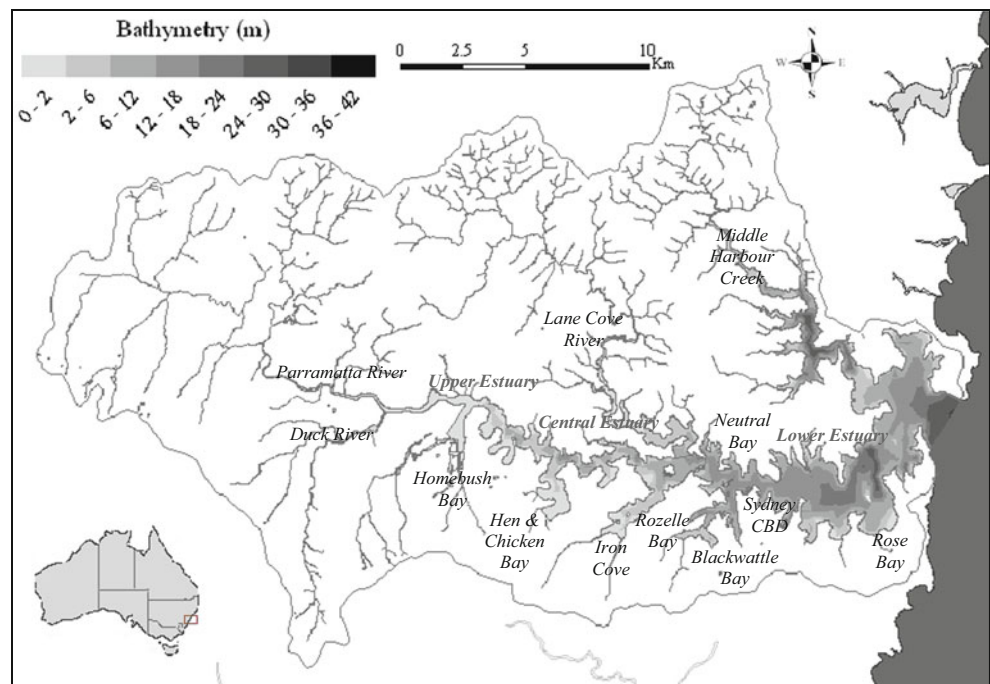
The estuary has a convoluted shape owing to the inherited dendritic drainage pattern. Bathymetry is irregular, ranging from less than 3 m within shallow off-channel embayments to over 40 m within deep water holes along the main channel of the middle to lower estuary. The irregular bathymetry, presence of islands along the main channel and geometrically intricate shoreline all contribute to the complex three dimensional current patterns within the water body.

Sydney Estuary has a microtidal regime with a maximum tidal range of 2.1 m. Tides are semidiurnal with a diurnal inequity, and maximum tidal lag from the mouth to the headwaters is approximately 10 min. During quiescent weather conditions, tides are the dominant process affecting hydrodynamic behaviour, with the influence of ocean swell restricted to the lower estuary. While residence times within the lower estuary are in the order of days, it is estimated that complete tidal flushing for embayments in the upper estuary may take up to 7 months (Das 2000).

Generally, the water body is well-mixed, with salinity ranging from ~27 PSU at the headwaters to ~35 PSU at the mouth, due to low fluvial supply from the catchment and tidal forcing (Irvine 1980). During quiescent weather conditions when rainfall is low (<5 mm day⁻¹), fresh water flow exerts little influence on hydrodynamic behaviour. Following high precipitation intermittent stratification develops due to the rapid influx of stormwater runoff from the urbanised catchment. The resulting high freshwater runoff volumes act to increase surface water current speeds in the down-estuary direction and increase near-bed current speeds in the up-estuary direction due to gravitational circulation (Lee and Birch 2012).

Winds within Sydney Estuary are complex, influenced by sea breezes, synoptic flow and the larger Sydney basin drainage flow superimposed onto intricate terrain (Spark and Connor 2004). The surrounding topography generates local wind patterns within the estuary, which are capable of

Fig. 1 Site map displaying the extent of the Sydney Estuary, tributaries catchment and bathymetry



generating surface wind waves of up to 0.5 m during periods of prolonged high wind. Wind also plays a role in estuarine circulation patterns (Lee and Birch 2012) and wind waves are largely responsible for resuspension events within shallow embayments along the southern shoreline (Taylor 2000; Birch and O’Hea 2007).

Geological History

Sydney estuary is located in the Permian to Triassic age (300–220 Ma) Sydney Basin. Most of the high land in the catchment is comprised of Ashfield Shale, which overlies the Hawkesbury Sandstone. Sydney Estuary is a large drowned river valley, which has cut up to 85 m into Hawkesbury Sandstone.

The ancient river, which is now Sydney estuary, was eroded down into an elevated coastal plain forming steep-sided banks and the old, mature river that meandered across a flat plain 80 Ma ago. This river was once considerably larger than it is today, but was ‘captured’ by the Hawkesbury River leaving it considerably smaller. During interglacial periods, sea level rose and the ‘river’ was flooded to form an estuary.

During the Quaternary period, sea level oscillated from 5 m above to 120 m below the present day position every approximately 100,000–150,000 years due to global climate change. However, for the majority of the last 135,000 years sea level was 20–70 m below the present and erosion was more pronounced than deposition during this period. The last glacial period ended about 17,000 years ago and sea level

started to rise from a position about 30 km east of its present location. By 8,000 years ago, sea level stood at 5 m below present and the sea reached its present position about 6,000 years ago. Sand swept ahead of the advancing sea was pushed into embayments to form spits behind which lagoons and estuaries formed. Some of this sand was transported into the mouth of Sydney estuary forming a tidal delta, while a fluvial delta was deposited in the upper parts of the estuary. The central basin became mantled in fine-grained sediment carried in suspension after floods.

Anthropogenic Modification of the Estuary

Reclamation

Sydney estuary has been extensively modified by reclamation since settlement, especially in the upper regions. Reclamation and infilling of intertidal areas has reduced the shoreline by approximately 77 km of the 322 km of original length (Pitblado 1978) and 13.4 km² (23 %) of the total 50 km² area of the estuary has been lost (Murray 2003; Birch et al. 2009). Approximately 9×10^6 m³ of water has been lost on each tidal cycle through reclamation resulting in poor water quality, sedimentation and loss of habitat, e.g mud flats, and mangroves and salt marsh.

The head of Sydney Cove was the first to be reclaimed and remodelled into a semi-circular sandstone quay with the Tank Stream channelled in the period 1835–1854 and Mort and Walsh Bays were infilled (Fig. 1). Settlement began to spread out from the city with the introduction



Fig. 2 (Top left) Photograph displaying the urbanised nature of the Sydney Estuary. (Top right) Aerial image of the central/lower Sydney Estuary. Examples of estuarine areas reclaimed for parks or other land uses are indicated at the bayends of Rozelle, Blackwattle Bay and Darling Harbour. This image exemplifies extensively modified

estuary shorelines approaching the city centre. (Bottom left) Gross pollutant stormwater trap device installed along the Duck River. (Bottom right) Remediation works, Homebush Bay. Following remediation formerly industrial sites were converted to residential land uses

of trams and trains during the period 1854–1889 resulting in reclamation of Blackwattle Bay, Pyrmont Bay, Darling Harbour, Woolloomooloo Bay and Rushcutters Bay (Fig. 2) (Stephensen 1966; Shore 1981). Reclamation was undertaken using domestic waste, sewerage, offal and dead animals in the second half of the eighteenth century which lead to foul odours and the fear of disease (Solling and Reynolds 1977).

A major contributing factor to rat infestation and outbreak of bubonic plague in 1898/99 was considered to be due to the continued widespread disposal of garbage in intertidal swamps (Coward 1988). During the period 1889–1922 dilapidated and rat infested foreshores in Walsh Bay and Darling Harbour were replaced by Sydney Harbour Trust (SHT) under an Act of Parliament in 1900. At the same time extensive reclamation took place further afield, i.e. in Canada Bay, Kings Bay, Hen and Chicken Bay, Iron Cove, White Bay, Rozelle Bay, and Rose Bay. Most reclamation took place in Sydney estuary when the foreshore was extended at

Silverwater, Homebush Bay, Garden Island, Exile Bay, Kings Bay, Iron Cove, Glebe Island and Darling Harbour between 1922 and 1955 to create 5.7 km² of new land.

Environmental Impacts of Reclamation

Approximately 100×10^6 tonnes of garbage, industrial waste and contaminated estuarine sediments were used to undertake 11.35 km² of reclamation in Sydney Estuary. Not much is known about the composition of this material, except at Homebush Bay, which was remediated in association with the Sydney 2000 Olympic Games (Suh et al. 2003a, b, 2004a, b). A total of \$137 million was allocated for clean-up of the site in one of the largest remediation projects carried out in Australia. Here waste comprised putrescible, building, chemical and garbage municipal waste, construction debris, household garbage, demolition

waste, ash fill and dredged sediment containing heavy metals, asbestos, a range of hydrocarbons, including dioxins benzene, toluene, ethylbenzene and xylene (BTEX) compounds and polycyclic aromatic hydrocarbons, as well as organochlorine pesticides. A total clean-up of 400 tonnes of hazardous waste classified as Scheduled Chemical Waste, which had to be destroyed by a thermal/catalytic treatment under NSW EPA license. Estuarine sediment from the adjacent bay used as infill material contained elevated concentrations of metals, which polluted groundwater. Leachate produced in reclaimed lands due to rainwater filtration and tidal action was studied by Suh et al. (2003a, b) at Bicentennial Park adjacent to Rozelle Bay. Results showed that during dry periods when water tables recede, oxygen ingress led to decreasing acidity (pH) and increasing metal (copper, lead, zinc, arsenic and chrome) concentrations and that metals enter the estuary by tidal action and during periods of rainfall. High metal concentrations in sediments at the heads of most estuary embayments are juxtaposed adjacent reclaimed lands. The total mass of metals associated with reclaimed land is unknown, however 1Mt of this estuarine material was used for this purpose in Iron Cove; 4.6 Mt in Homebush Bay and 2.8 Mt on the banks of the Parramatta River (McLoughlin 2000), which gives an idea of the potential of this source. However, stormwater canals also discharge to the estuary at these locations (Barry et al. 1999, 2000; Birch et al. 1999) and differentiating the relative magnitude of each source has not been attempted.

Ecological Effects of Reclamation

Approximately 50 % of the shore of Sydney Estuary is composed of retaining seawalls or other built structures (Chapman and Bulleri 2003). Construction of seawalls alters intertidal habitat by reducing the intertidal area and producing fewer crevices and overhangs compared to natural rocky shores and some rock pools and other habitats are absent. The majority of seawalls in Sydney estuary have been constructed to support reclamation activities at the heads of embayments (Fig. 2). The change from muddy, mangrove and saltmarsh wetlands with gentle slopes to vertical seawalls has resulted in major alterations to ecological function and biological productivity, as well as changes in hydrology and physio-chemical attributes of the estuary.

Effect of Urbanization and Industrialization on Sydney Estuary

Studies of historic changes in land use in the Sydney Estuary catchment and potential adverse effects on estuary condition have been undertaken by the School of Geosciences at Sydney

University over a considerable period (Birch 2000; Murray 2003; Jolley 2005; Taylor et al. 2004; Birch et al. 2007, 2013; Townsend 2011; Lee et al. 2011; Lee and Birch 2012; Lee 2012). Sediment cores were used to determine effects on the estuary and historical maps and charts provided information on changes to land use. Hydrological modelling of catchment attributes (landuse, rainfall, runoff coefficients) provided metal loading to the estuary via stormwater discharge for various time slices. Twelve sedimentary cores taken in nine highly contaminated embayments were analysed for metals and dated using radioisotopes lead 210 and caesium 137 (Taylor et al. 2004).

Sediment in Blackwattle Bay, Iron Cove and Homebush Bay are highly contaminated by metals and these bays are located 2, 5 and 12 km, respectively from central Sydney. Metal concentrations (copper, lead and zinc) at the bottom of cores from these bays show low values and at some depth concentrations increase markedly. The depth at which metal concentrations begin to increase is the point or time where contaminants start to be discharged from the catchment, e.g. the onset of contamination. Contamination commenced in about 1860 in Blackwattle Bay, in approximately 1910 in Iron Cove and at about 1925 in Homebush. This spatio-temporal distribution reflects the spread of urbanization and development of industry outwards from central Sydney. Similar down-hole trends are evident for organic contaminants (organochlorine compounds) which are entirely man-made and introduced into Australia after the Second World War (Taylor et al. 2004). The onset of contamination by these chemicals was dated at 1945 in these cores, i.e. the same time as they were introduced into the catchment.

Data from cores and surficial sediments indicate that metal concentrations in surficial sediment have been declining in the upper estuary and increased in the lower harbour, in Lane Cove and in Middle Harbour over the last 25 years (Birch and Taylor 2004). Introduction of the Clean Waters Act in 1978, which required industry to discharge waste into the sewerage system and to reduce waste, contributed to reduction of metal supply to the harbour. Relocating industry away from the water front has also reduced contaminants discharged directly to the estuary. Increased concentration of metals in sediments of the lower estuary is due to rapid expansion of residential and commercial property and increased transport services (Birch and Taylor 2004).

Sediment Quality and Toxicity

Sediments mantling the Sydney Estuary contain high concentrations of a wide range of contaminants, including metals (Irvine and Birch 1998; Birch and Taylor 1999) organochlorine pesticides (Birch and Taylor 2000) polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls

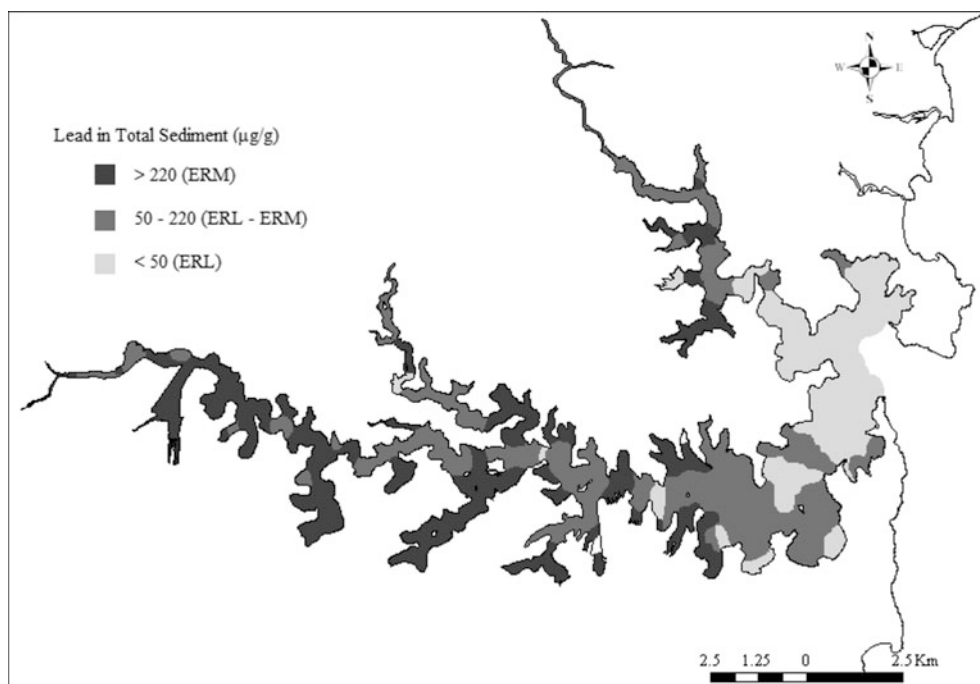


Fig. 3 Distribution of Pb in total surficial sediment (Adapted from Birch et al. 2008)

(PCBs) (McCready et al. 2000), and polychlorinated dibenzo-*p*-dioxins and dibenzofurans (Birch et al. 2006). The major source of these chemicals is related to historic industrial activities, and past and present stormwater discharge with minor leachates from reclaimed areas. High concentrations of contaminants, mainly metals, discharged to the receiving basin indicate continued supply of stormwater-related anthropogenic materials.

The quality of sediment mantling Sydney Estuary was determined in a three-tiered approach (Birch et al. 2008). The chemistry of surficial sediment was initially established through detailed sampling and analysis of >1,000 samples for a suite of metals (Cd, Cr, Cu, Co, Fe, Mn, Ni, Pb and Zn), and a smaller number of samples ($n = 140$) analysed for organochlorine pesticides (OCs) (DDT, DDD, DDE, chlordane, aldrin, heptachlor, dieldrin, heptachlor epoxide, lindane), hexachlorobenzene (HCB) and total polychlorinated biphenyls (PCBs, reported as Aroclors), whereas 16 priority pollutant polycyclic aromatic hydrocarbons (PAHs) (acenaphthene, acenaphthylene, anthracene, benz(a)anthracene, benzo[a]pyrene, benzo[b+k]fluoranthene, benzo[ghi]perylene, chrysene, dibenz[ah]anthracene, fluoranthene, fluorene, indeno[1,2,3-*cd*]pyrene, naphthalene, phenanthrene and pyrene), as well as 2-methylnaphthalene were determined on 124 samples (Birch and Taylor 1999, 2000; McCready et al. 2000).

Studies in the first tier of assessment showed sediments of the upper estuary, landward of the Sydney Harbour Bridge, contain some of the highest reported concentrations of a

wide range of contaminants. Contaminant concentrations increased markedly in the upper parts of most embayments and in the western tributaries of Middle Harbour close to major stormwater inputs (Fig. 3 for lead). Contaminant concentrations were elevated due to proximity to source, a mainly muddy substrate and poor flushing by tides and currents in these areas. Discharge from industries located on the shores of the estuary resulted in contaminant 'hot spots'.

Sediment quality guidelines (Long et al. 1995; ANZECC/ARMCANZ 2000; Simpson et al. 2005) were used to assess the probability of toxicity in the second tier of investigation. These guidelines consist of two concentrations, namely the lower level (Effects Range Low, or ERL), which denotes the concentration below which adverse biological effects are seldom observed and the Effects Range Median (ERM), which distinguishes concentrations above which adverse biological effects are expected to occur frequently. Concentrations between ERL and ERM guidelines indicate intermediate irregular biological response. Chemicals were assessed for possible adverse biological effects by comparing concentrations at each site to the respective ERL and ERM values. Australia has adopted similar guideline values named Interim Sediment Quality Guidelines–Low and –High (ISQG-L and -H), respectively.

Areas exceeding SQGs were determined for single chemicals and contaminant mixtures in the second tier of assessment (Birch and Taylor 2002a, b, c). Sediment in approximately 2, 50, and 36 % of the estuary exceeded the high SQG value (ERM or ISQG-H) for Cu, Pb and Zn,

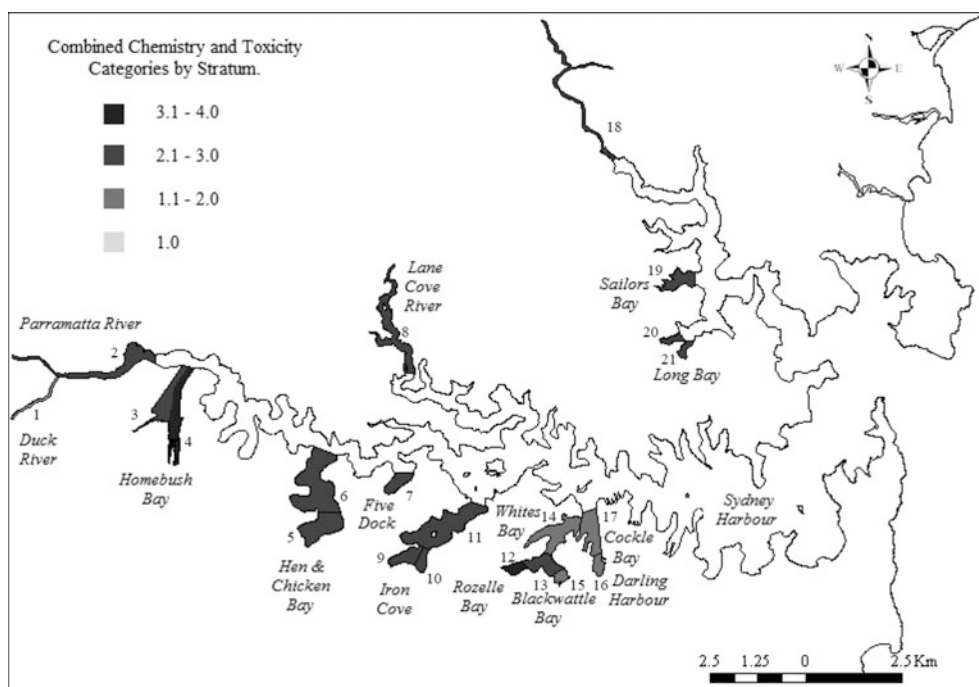


Fig. 4 Combined chemistry and toxicity categories by stratum based on mean chemistry/toxicity scores. Strata are numbered from 1 to 21 (Adapted from Birch et al. 2008)

respectively. Estuarine sediment exceeded ERL (or ISQG-L) concentration for at least one metal in all but one small area near the entrance. Organochlorine compounds exceeded ERM concentrations over most of Sydney Estuary, however PCB concentrations were above the ERM value in only a small part of the waterway (Birch and Taylor 2002a, b, c). Sediments in almost all upper and middle parts of Sydney Estuary and Middle Harbour had at least one OC or PAH concentration which exceeded ERM values.

Results of the sediment quality study were used to compartmentalize the estuary for detailed chemical/ecotoxicological studies in the third and final tier of investigation. The five bays exhibiting high contaminant concentrations were divided into 12 strata and 7 strata were selected from areas with intermediate contaminant concentrations. An additional two strata were chosen from areas with low contaminant concentrations to determine sediment toxicity in the least impacted locations. Samples were randomly collected within each stratum.

Surficial sediments ($n = 65$) were analysed for 12 metals, 21 OCs, 24 PAHs, 7 Aroclor mixtures of PCBs and total organic carbon (TOC). Samples were tested in a 10-day, whole-sediment amphipod survival test (*Corophium colo*) and a pore water sea urchin (*Haliocidaris tuberculata*) fertilisation test to assess both contaminant uptake routes, i.e. via the gills for the dissolved phase and by ingestion for the solid phase. Pore water were also tested in sea urchin larval development ($n = 61$) and microbial bioluminescence

Microtox[®] ($n = 57$) tests (McCreedy et al. 2004, 2005, 2006a, b, c; Spyraakis 2002).

Amphipod survival, Microtox[®] pore water, sea urchin larval development and sea urchin fertilisation tests resulted in 17 %, 98 %, 59 %, and 98 % of the samples in Sydney estuary being toxic ($p < 0.05$) relative to negative controls, respectively. All samples were toxic in at least one test. In the sea urchin fertilisation test, 2 %, 31 %, 18 % and 49 % of samples were non-toxic, slightly toxic, moderately toxic and highly toxic, respectively. Sediments in Parramatta River (Stratum 2), the southern embayments of the central estuary (Strata 3, 4, 5, 6 and 7) and Long Bay (Strata 20 and 21) were highly toxic in the sea urchin fertilisation test, whereas sediments in Blackwattle Bay (Stratum 15), Iron Cove east (Stratum 10) and Upper Middle Harbour (Stratum 18) were moderately toxic (Fig. 3). Sediment in the remaining strata (Strata 3, 9, 11, 14, 16 and 17) were toxic. Only two sediment samples in Homebush Bay east and Hen and Chicken Bay were highly toxic in the amphipod survival test. Sediments in Five Dock Bay (Stratum 7), Homebush Bay east (Stratum 4) and Rozelle Bay (Stratum 12) were moderately toxic in this test. Microtox[®] test of pore water was less discriminative than the other three tests used in the investigation. Sediment containing high metal concentrations (Iron Cove, Rozelle Bay and Five Dock Bay) showed high toxicity.

The areas assigned highly toxic (score 3.1–4.0, Fig. 4), moderately toxic (score 2.1–3.0, Fig. 4) and slightly toxic

(score 1.1–2.0, Fig. 4) comprised 17 %, 52 % and 31 % of the estuary investigated, respectively. These results were similar to the sediment quality assessment in phase 2, which subdivided the area into high, medium-high and medium-low priority classes for 15 %, 54 % and 31 % of the same area, respectively. Although only 16 % of the estuary was investigated, it was estimated that 2.7 %, 8.3 % and 5 % of the total area of the estuary was highly toxic, moderately toxic and slightly toxic, respectively. Of 25 estuaries surveyed in a similar way in North America, 7 % of the total area of the estuaries were found to be toxic (Long 2000), i.e. similar to the 11 % proportion of Sydney Estuary, which was found to be toxic plus moderately toxic by Birch et al. (2008).

Stormwater

Annualised Loading

The average annual discharge of stormwater from the Sydney Estuary catchment was predicted using the Model for Urban Stormwater Improvement Conceptualisation (MUSIC) to be 215,300 ML and average annual loadings was As, Cd, Cr, Cu, Ni, Pb, and Zn were 0.8, 0.5, 1.7, 3.2, 1.1, 3.6 and 17.7 tonnes, respectively (Birch and Rochford 2010). The proportion of metals discharged under low- (<5 mm day⁻¹ rainfall), medium- (>5 <50 mm day⁻¹ rainfall), and high-flow conditions (>50 mm rainfall/day) was predicted to be approximately 10 %, 60 % and 30 %, respectively. Metal loading characteristics were determined to assist in the development of future, second-generation remediation technologies and science-based strategies. High metal concentrations in fluvial particulates and estuarine sediments adjacent to stormwater discharge points suggest creeks entering the upper (Duck and Parramatta Rivers) and central Sydney Estuary (Homebush and Hen and Chicken and Neutral Bays and Iron Cove) and rivers discharging to the western shores of Middle Harbour (Long and Sugarloaf Bays) be prioritised for remediation. Metals discharged under low-flow conditions (~10 % of total load) are trapped in adjacent embayments, but may be effectively remediated, however, metals associated with medium-flow events present a major future challenge for remediation.

High Precipitation Events

Typically, Sydney Estuary waters are predominantly saline since fresh-water supply is extremely low, reflecting the erratic rainfall regime consisting of long dry periods punctuated by short duration high-precipitation events. Based upon rainfall records from Sydney Observatory from

1858 to 2012, average daily rainfall in the Sydney region is less than 4 mm, with zero rainfall 65 % of the time and rainfall in excess of 50 mm day⁻¹ 1 % of the time. The typically low rainfall is reflected by low fresh-water runoff from the Sydney Estuary catchment. This runoff regime alters when the extended dry spells are broken by intense short period high-rainfall events. When high-precipitation events occur, rainfall is rapidly transported to the estuary due to the small, highly-urbanised catchment and efficient stormwater drainage system. When rainfall ceases it takes less than a day for fresh-water runoff rates to return to baseflow conditions. These short-lived high-runoff events cause intermittent stratification, which is most defined in the upper estuary (Fig. 5) (Wolanski 1977; Lee et al. 2011; Lee and Birch 2012; Lee 2012). The largest subcatchments of this system drain to the narrowest sections of the estuary, while the smaller subcatchments drain to the wider embayments. As a consequence, following high rainfall, freshwater dominates the water column within the Lane Cove, Duck and Parramatta River upper reaches with only a small component near the bed remaining brackish/saline. Within embayments, saline waters dominate the water column with a thin layer of freshwater forming on top of marine waters. A fresh-water plume develops along the main estuary channel from the confluence of the Parramatta and Duck Rivers (Figs. 5 and 6). A second fresh-water plume also develops along the Lane Cove River reaching the main channel in the central estuary (Figs. 5 and 6). While stratification may be well-defined in the upper estuary where surface water salinities can be lower than 5 PSU, typically the surface-water plume becomes brackish (~10–25 PSU) in the central estuary with salinities only slightly reduced (>28 PSU) in the lower estuary (Fig. 6). Rather than rapidly escaping the estuary via the mouth in a distinct lower-density surface plume, stormwater mixes with saline waters and is largely retained within the estuary until flushed due to tidal forces (Lee and Birch 2012). Since fresh-water runoff volumes are not sustained for more than one or two days, stratification begins to break down within days of rainfall ceasing. The time taken for stratification to break down depends upon the volume of freshwater discharged, the tidal regime and to a lesser extent wind conditions. Stratification is most defined when high catchment runoff coincides with neap tides and down-estuary winds. Spring tides facilitate mixing between saline and fresh waters as do high winds directed across or up the main channel (Lee and Birch 2012).

The time required for the system to return to quiescent salinity conditions varies between events with the shortest recovery times predicted when high runoff coincide with spring tides. High fluvial supply contributes to increasing gravitational circulation increasing down-estuary currents at the surface and increasing up-estuary currents near the bed. Elevated current velocities are experienced during spring

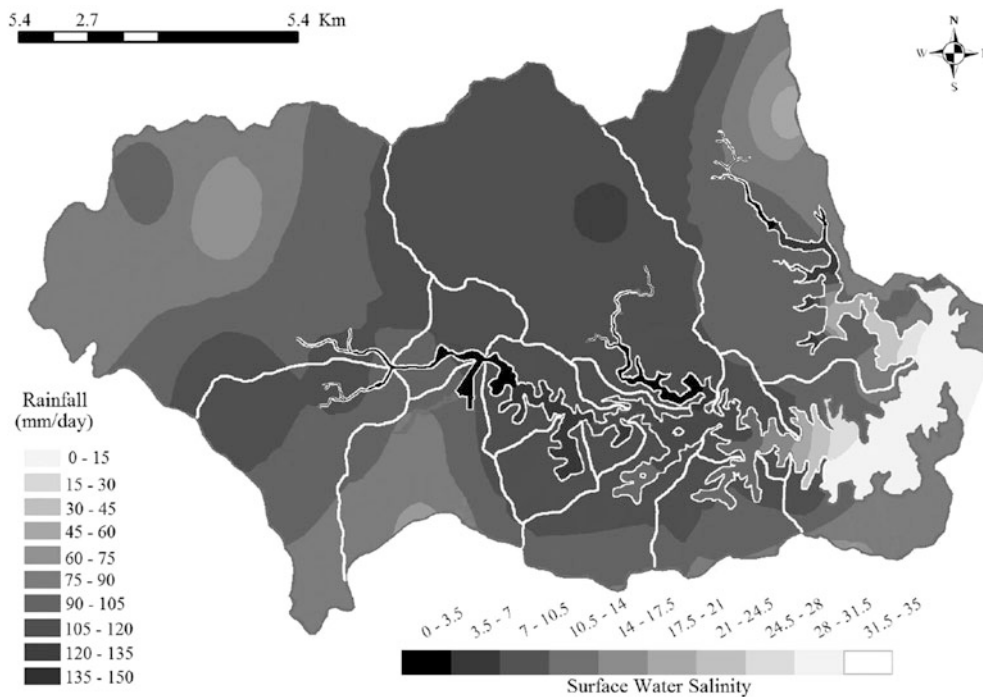


Fig. 5 Example of catchment rainfall and estuary response following a high-precipitation event in June 2007. Surface-water salinities reflect values 0.5 m below the water surface one day after

the day of highest precipitation. The major subcatchments of the Sydney estuary are *highlighted in white*

tides enhancing mixing and flushing. Numerical modelling predictions show recovery times for a June 2007 high-precipitation event (displayed in Figs. 5 and 6) was 19 days, while recovery time for an August 2007 event (Fig. 6) was 43 days. Runoff volumes for these events were similar, however the June event coincided with a spring tidal cycle and the August event coincided with a neap tidal cycle. While quiescent salinities are attained between 3 and 8 weeks, Das (2000) estimated complete tidal flushing of the waterway may take up to 225 days.

During quiescent conditions, suspended sediment concentrations throughout the estuary are relatively low (0.5–40.5 mg/l) and the low salinity zone where most flocculation processes occur is not found in the main channel (Hatje et al. 2001). Following high rainfall, surface water suspended sediment concentrations (SSC) up to 130 mg/l have been observed in upper estuary sections of the main channel. The amount of sediment generated by the catchment varies between high-precipitation events and between subcatchments, consequently stormwater SSC are temporally and spatially variable (Lee and Birch 2012). The length of the antecedent dry period and rainfall intensity influences stormwater runoff SSC, with longer dry periods and higher rainfall acting to increase SSC. Unlike salinity, SSC return to quiescent conditions within a few days of rainfall ceasing. This is due to particle/floc settling since stormwater does not rapidly migrate beyond the estuary therefore the majority of sediments

discharged into the waterway following high rainfall are retained within the system, settling on the estuary bed.

Sydney Estuary embayments are depositional environments. Terrigenous sediment discharged into embayments during low-flow conditions deposit close to stormwater outlets (Taylor 2000; Birch 2011). Sediments from adjacent subcatchments incrementally fill off-channel embayments, increasing bed thickness by between 0.6 and 2.7 cm/year (Taylor et al. 2004). Under high-flow conditions sand, silt and clay aggregates continue to settle to the bed within embayments, close to discharge locations, while individual clay particles remain suspended within the lower-density surface water plume, migrating with the plume beyond the low-flow regions of deposition. While the plume remains well-defined, clay particles are able to migrate beyond the embayments into the main estuary channel. In this way, sediment from subcatchments may be transported far from source, settling to the bed in adjacent embayments, in low-energy regions of the main channel or remaining suspended in the water column eventually flushing from the system.

Effects on Estuary Condition

Heavy metals, organochlorine compounds and polyaromatic hydrocarbons preferentially adhere to fine clay particles.

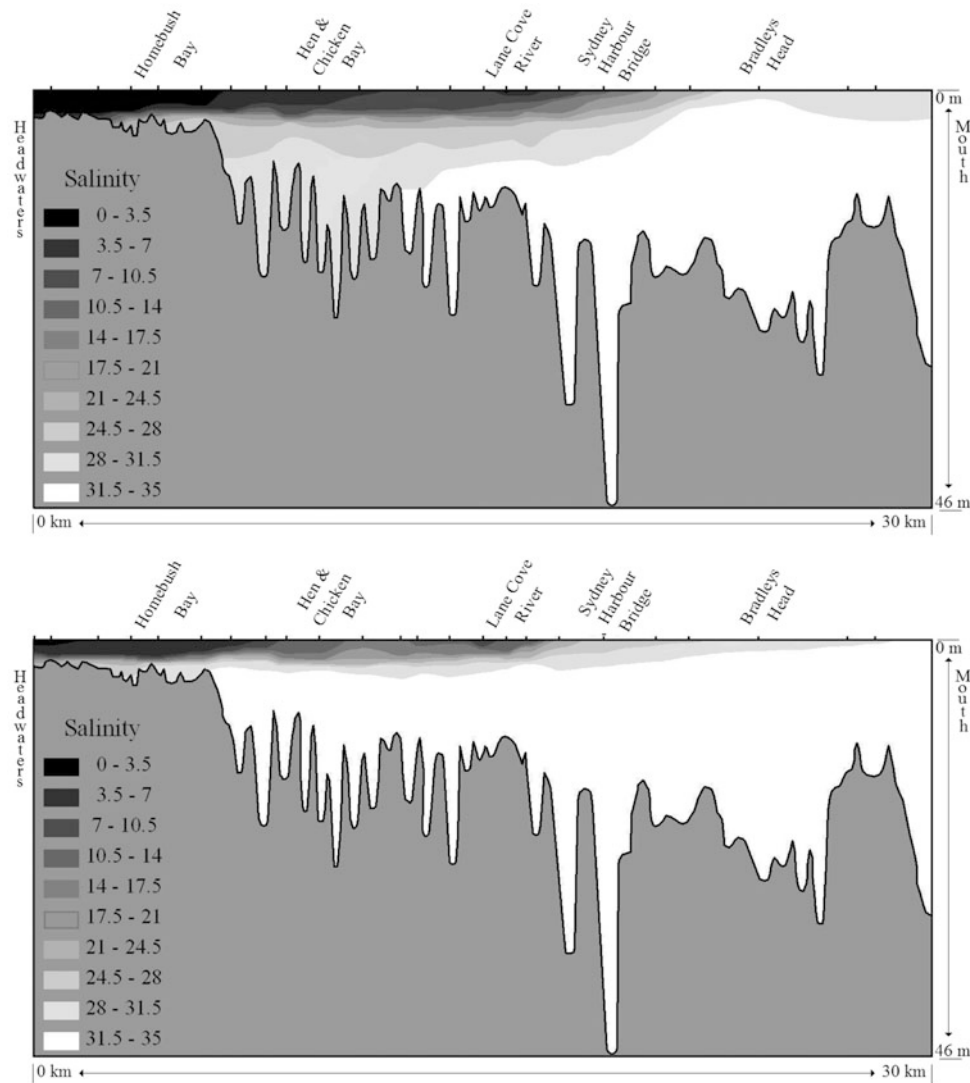


Fig. 6 Axial salinity distributions due to two separate high-precipitation events. The top image displays salinity distributions measured a day after high precipitation in June 2007, during a

spring tidal cycle. The bottom image displays salinity distributions measured a day after high precipitation in August 2007, during a neap tidal cycle

As a consequence, high-precipitation events and the resulting fresh-water plumes provide a mechanism via which particulate contaminants may be transported beyond the embayments into which they typically deposit. Of the material escaping an embayment via the fresh-water plume, the majority deposit on the bed further down estuary, while a smaller component deposit in the up-estuary direction (Lee 2012). A minor component is flushed from the estuary altogether. This mechanism contributes to the further degradation of the estuary bed by moving contaminated sediment from urbanised catchments well-beyond ranges of deposition experienced under baseflow runoff conditions.

Management Issues

Management of Dioxins

Sydney Estuary acts as a nursery for numerous fish species and is home to a wide array of marine organisms. Formerly these waterways were commercially fished, however in 2007 these activities were halted due to high concentrations of dioxins measured in fish and prawn tissue. Congeners of dioxins and furans are known to be highly toxic to animals. Animal feeding studies show that 2,3,7,8-Tetrachlorodibenzo-p-dioxins are

amongst the most toxic chemicals ever tested (Bopp et al. 1991), and both 2,3,7,8-TCDD and 2,3,7,8-TCDF are included in the list of persistent organic pollutants (POP) included in the Stockholm Convention 2001, of which Australia is a signatory. Signatories of this agreement are required to reduce and eventually eliminate all anthropogenic sourced POP (Ritter et al. 1995). The presence of 2,3,7,8-TCDD within estuary bed sediments poses a significant risk to the health of all species which inhabit the estuary or rely upon it as a food source, including humans.

The National Dioxin Study conducted by the Australian Government Department of Environment and Heritage in 2001 identified high concentrations of toxic dioxin and furan congeners within Sydney Estuary bed sediments (Birch et al. 2007). Sediments within Homebush Bay, an off-channel embayment in the upper estuary have the highest dioxin concentrations recorded in Australia, and amongst the highest reported in the world, second only to the Frierfjorden Estuary in Norway (Mueller et al. 2004; Bellucci et al. 2000). Homebush Bay was identified as the source of dioxin contamination of bed sediments, with contaminants sourced from this embayment detected a further 5 km up-estuary and 12 km down-estuary (Birch et al. 2007).

Contamination of Homebush Bay foreshore sediments occurred between 1928 and 1986 and subsequently led to contamination of bed sediment within the embayment. The region within Homebush Bay most affected by dioxin contamination is approximately 800 m long and 100 m wide, beginning near the eastern side of the embayment mouth encompassing the area directly adjacent to the reclaimed eastern foreshores (Fig. 7). Three processes are likely responsible for the migration of dioxins throughout the rest of the estuary:

1. Aerial deposition during the period when dioxins were produced as a by-product of combustion during pesticide production at Rhodes Peninsular.
2. Diffuse and point source stormwater runoff generated by periods of heavy rain may transport dioxin-laden sediment from the contaminated Homebush Bay foreshore areas into the embayment where they travel as part of the fresh-water plume on top of the marine water, escaping the embayment and moving down/up-estuary.
3. Spring tidal currents near the mouth of the Homebush Bay are sufficient to resuspend and mobilise newly deposited sediments, which may then escape into the main estuary channel during ebb tides. Once in the main channel successive flood and ebb tide currents may transport these contaminated sediments to other sections of the estuary.

In order to address dioxin contamination, Homebush Bay foreshore sediments and bed sediments within the section of the embayment containing the highest dioxin concentrations have been remediated (Fig. 2). This involved removal and

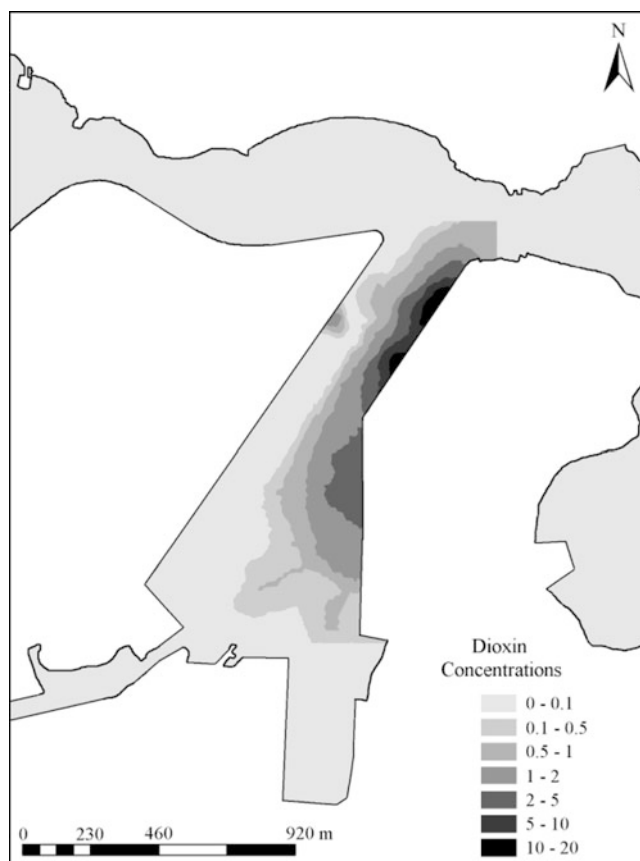


Fig. 7 Homebush Bay bed sediment dioxin concentrations before remediation commenced. 2,3,7,8 TCDD contours displayed are based on 1997 Surface Sediment Composites ($\mu\text{g/kg}$ dry weight) (Adapted from EVS 1998)

treatment of contaminated foreshore and estuary bed sediment using thermal/catalytic treatment, a high temperature heating process which converts the organic contaminants to carbon dioxide and water. The area from which bed sediment was removed was refilled with rubble-sized Virgin Excavated Natural Material. Presently the effectiveness of the Homebush Bay remediation program is unknown. Long-term monitoring of dioxin concentrations within suspended sediments and fish and prawn tissue is required to determine if the strategy implemented has been able to reduce the uptake of dioxins in species inhabiting the estuary.

Stormwater Management

Increasing population, higher housing density and more transport infrastructure have enhanced the generation of contaminants in the Sydney Estuary catchment, as well as the supply of contaminants to the adjacent receiving basin. Increasing contaminant loading via stormwater to the adjoining estuary has reduced water and sediment quality over the

past 100 years and stormwater remains a major source of concern. Retrofitting remedial devices in old, highly-urbanised catchments dominated by diffuse contaminant sources is long-term, costly and complex. In this respect the Sydney catchment-estuary system is similar to many other environments in highly-developed capital cities of the globe.

Contaminants associated with baseflow (none, or $<5 \text{ mm day}^{-1}$ rainfall) are deposited close to the mouths of canals discharging to the estuary and this sediment is often toxic to benthic animals, whereas chemicals carried by high flow ($>50 \text{ mm day}^{-1}$ rainfall) largely bypass embayments in a buoyant, freshwater plume. Off-channel sand infiltration systems located near the mouths of stormwater canals are capable of remediating very large quantities of contaminated catchment water during baseflow conditions inexpensively and are rapidly constructed (Birch 2011). Remediation of baseflow and some first-flush stormwater will remove approximately 10 % of total metals and 30–50 % of TN presently trapped in embayments. A continual flow of baseflow water will provide approximately $100,000 \text{ m}^3 \text{ day}^{-1}$ of harvested urban water runoff with minimal storage requirement in the Sydney Estuary catchment. The potential for recycling and harvesting of enormous volumes of non-environmental, treated stormwater is highly desirable in such intensely-urbanised environments to supply large recreational and sports facilities in the vicinity, especially with increased dry periods predicted by current climate models. The concept of converting contaminated waste water into a valuable resource, while cleaning up the environment, is highly desirable. The potential for recycling and harvesting enormous volumes of treated stormwater in intensely-urbanised environments is in keeping with the concept of 'cities as water supply catchments'.

Conclusions and Future Directions

Since implementing the Clean Waters Act, water quality within Sydney Estuary has markedly improved. Removal of industry from the estuary foreshore has further contributed to estuary health. Improved understanding of the impact of different anthropogenic chemicals on estuarine species has led to policy changes, including the restricted use of tributyl-tin, enabling species such as oysters to begin repopulating the intertidal zones of the estuary. Despite these improvements historical contamination and the continual supply of new contaminants via stormwater runoff present management challenges which must be addressed. Intense research is currently underway investigating the impact of different chemical contaminants on organisms within the estuary. The results of these studies may provide the impetus required to justify implementing an effective stormwater remediation strategy. Presently water sensitive urban design is a favoured

management option particularly for new developments. This strategy is an effective management tool for small sites, however when considering stormwater management of old, intensively-urbanised subcatchments, this method is too slow and too costly to implement on the scale required to achieve a marked improvement in stormwater quality. End-of-pipe remediation regimes are able to treat runoff from entire subcatchments and may be readily implemented and are relatively inexpensive. The foreshore areas adjoining most Sydney Estuary embayments are occupied by reclaimed parklands, consequently retrofitting stormwater remediation devices located in these areas may be easily achieved with little disturbance to the surrounding community. In order to manage stormwater in a way which best meets the needs of the community, while improving the health of the estuary, water sensitive urban design measures should continue to be implemented at new or redeveloped sites and end-of-pipe remediation devices should be put in place in old, densely urbanised catchments at the sites where stormwater discharges to the Sydney Estuary. Presently, sewerage overflows account for about one third of nutrient input to Sydney Estuary. The sewerage infrastructure is in need of reparations to replace derelict pipes and upgrading to increase capacity due to increased demand to reduce pathogen supply.

Due to the publicity surrounding dioxin contamination in fish caught in Sydney Estuary waters much has been done to attempt to remediate Homebush Bay bed sediments, the embayment from which the dioxins principally derived. With respect to the impact of dioxins on human health, long-term monitoring of fish tissue is required to determine the success of the dredging and capping program undertaken in the embayment. Long-term monitoring of bed sediment dioxin concentrations is required throughout the estuary to ensure the source of dioxin contamination has been effectively capped. Modelling investigations encompassing chemical, sediment and hydrodynamic transport would facilitate improved understanding of the long-term impact of dioxins and the potential recovery time for the estuary with respect to these chemicals. Uptake studies would further advance our understanding of the impact of these chemicals on estuarine species and enable appropriate guidelines for dioxin concentrations within estuary waters and bed sediment to be put in place.

As an urban water body, Sydney Estuary is subject to many pressures impacting upon the health of the system and the organisms living therein. On the whole, water quality has improved since the implementation of the Clean Waters Act, however illegal discharges, historical contamination and continued stormwater contamination present management challenges. Recent research investigating current patterns, stratification, mixing and residence times has improved our understanding of this complex system. Continued research addressing sediment transport, particularly resuspension

and subsequent dispersal of bed sediments, chemical partitioning, and the uptake of contaminants by estuarine species is required to facilitate improved understanding of long-term contaminant transport processes and the impact of contaminants on the health of estuarine species.

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