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Use of Sediment Risk and Ecological/Conservation Value for Strategic Management of Estuarine Environments: Sydney Estuary, Australia

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Abstract Sediment mantling the floor of Sydney estuary contains a wide range of chemicals at highly elevated concentrations over extensive areas. Appropriate sediment management decisions are urgently required to prevent further degradation of sediment quality and to minimize resulting adverse ecological effects. The objective of the present work was to provide a systematic, estuary-wide assessment of sediment risk and ecological/conservation value throughout the harbor to guide sediment management decisions. Sediment risk is the likelihood of sediment chemistry causing adverse biological effects to bottom-dwelling animals and was conducted using national sediment quality guidelines (SQGs) for single contaminants and the mean SQG quotient approach to assess chemical mixtures. Sediment risk was negligible at the mouth of the estuary, but increased strongly landwards. The ecological/conservation value assessment was conducted to identify sites that warrant different levels of protection and was conducted using the value of ecological communities and priority waterway use. Consideration of these two parameters combined enabled the estuary to be prioritized for management attention. The prioritization and identification of appropriate management strategies were determined through the use of management matrices also based on sediment risk and ecological/conservation value. A computer package is being developed to provide managers with information on sediment risk, ecological/conservation value, the urgency and the type of management intervention required for any location in Sydney estuary, in real-time. This approach to estuarine management is unique and will greatly improve effective management of Sydney estuary, and other harbors in urgent need of management action and protection.

Keywords Estuary · Management · Sediments · Contamination · Sediment quality guidelines · Sydney

Introduction

Large human populations worldwide live near the ocean and Australia is no exception with 85% of the population living within 50 km of the coastline (ABS 2001). Increasing population densities are accompanied by heightened environmental stress on adjacent aquatic ecosystems due to a variety of anthropogenic activities. Sediment mantling the floor of a water body is frequently the final depository for contaminants released into the aquatic environment, and as a result, high contaminant concentrations in fresh and marine sediment are associated with areas of high human and industrial activity (Birch 1996; Breen and McKenzie 2001; McLusky and Elliot 2004; Allanson and Baird 1999; Jones and others 2005; Barbosa and others 2004; Birch and Taylor 2002a, b, c). Sydney estuary catchment (500 km^2), with a population of 2.5 million people (Birch and Taylor 1999), has had a marked impact on estuarine sediments, which are highly enriched in heavy metals, organochlorine pesticides and polycyclic aromatic hydrocarbons (Birch and Taylor 1999, 2000; McCready and others 2000) Stormwater runoff and past industrial discharge have been identified as major sources of contaminants in this estuary (Birch and Taylor 2004).

The Sydney estuary comprising Sydney Harbour and other waterways (50 km^2) supports a diverse ecosystem, however degradation of sediment quality through accumulation of

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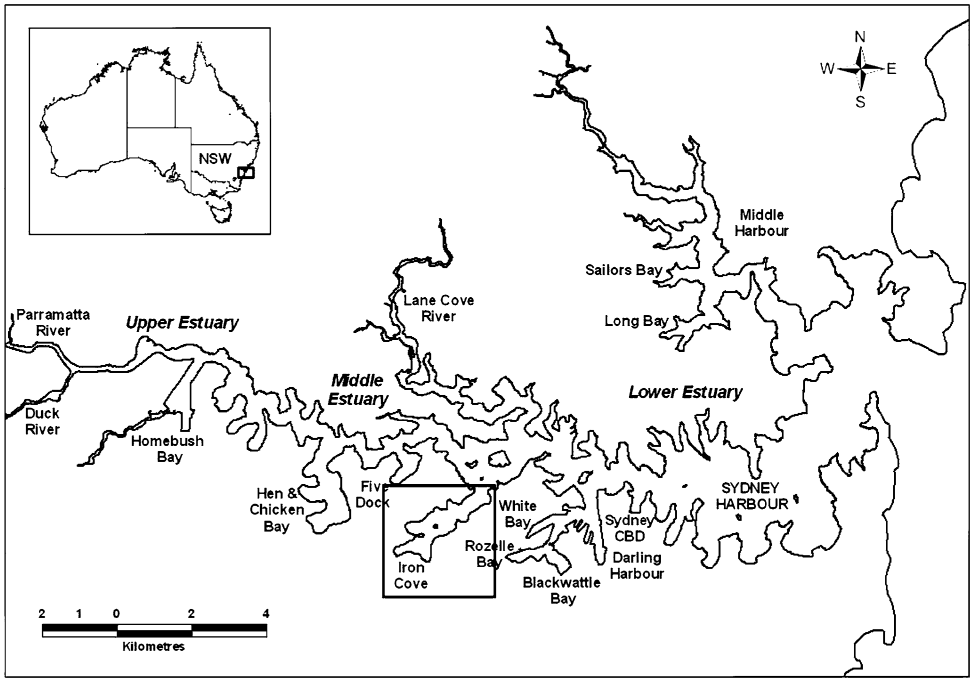
Fig. 1 Sydney estuary locations with the embayment used as a case study (Iron Cove) outlined (see Fig. 7)



contaminants has adversely impacted the aquatic environment (Birch and others 2008) (Fig. 1). Bioaccumulation of contaminants has resulted in adverse effects on higher-trophic level organisms, e.g. oysters (Scanes and Roach 1999) and fish (Roach and Runchie 1998). Adverse effects of sediment contamination on wildlife are of concern in waterways, such as Sydney estuary, as these water ways are important breeding grounds and nurseries for many aquatic species.

Effective management of estuaries requires rigorous, science-based data to make informed decisions to minimize adverse impacts from contaminated sediment. Although Sydney estuary has been the focus of sustained environmental research in recent years (Birch and Taylor 1999, 2000, 2004; McCready and others 2004, 2005, 2006a, b, c), information resulting from these studies has not yet been incorporated into strategic-management plans. This high-quality scientific information should be integrated into a data retrieval platform and coupled to a decision support system to assist managers of this unique and beautiful waterway.

Sediment attributes have been increasingly used in management of aquatic ecosystems and as indicators of ecosystem health as sediments accurately record and integrate adverse events over time (Forstner and Calmano 1998; Birch and Olmos 2009). Assessment of sediment quality has advantages over the use of water to judge ecosystem quality. Sediment integrates effects over time and provides spatial and temporal information using considerably lower sampling intensity than water. Sediment contains high contaminant concentrations and therefore analyses are easier, cheaper and more accurate. The importance of sediment quality is supported by studies which demonstrate sedimentary contaminants have a larger impact on survival of benthic organisms than contaminants present in the water column (Virginia Department of Environmental Quality 2004; Forstner and Calmano 1998). Adverse ecological effects have been observed in contaminated sediment despite the overlying water column meeting water quality standards (Baker and Kravitz 1992).

Contamination of sediment presents a significant risk to the health of benthic organisms (Krahn and Stein 1998; Canadian Council of Ministers of the Environment 2001; Baker and Kravitz 1992), i.e. reduction in survival, growth and reproduction (MacDonald and others 2003). Contaminated sediment impairs development of vegetation and bacteria, which may have a flow-on effect to other forms of aquatic life as these organisms are the foundation of the food chain (MacDonald and others 2003). Sediment is vital to many organisms for spawning during breeding, and sediment vegetation is necessary for protection and shelter of juveniles (MacDonald and others 2003). Adverse effects are observed in higher trophic organisms through direct contact with contaminated sediment and through consumption of contaminated organisms (Baker and Kravitz 1992; MacDonald and others 2003; National Guidelines and Standards Office of Environmental Canada 2003a, b). Bioaccumulation of contaminants poses a risk to direct or indirect consumers (MacDonald and others 2003; Baker and Kravitz 1992). A ban on prawn trawling and fin fishing effective for the entire Sydney estuary is an example of an adverse economic effect due to contaminated sediment and bioaccumulation. Effective management maximizes the use of scarce financial resources for research, management and remediation.

It is important to determine the type of information required when making management decisions regarding contaminated sediment. Although many factors have been considered in guiding sediment management decisions, the dominant parameter used has been the level of risk posed by sediment to the ambient environment (Long and MacDonald 1998; MacDonald and others 2003). Sediment risk is the likelihood of sediment causing adverse biological effects and is frequently the first factor assessed to determine whether further environmental investigation is required and whether management actions are necessary (ANZECC/ARMCANZ 2000). The level of risk has also been used to indicate the most appropriate management strategy, as different sediment management actions are suited to different levels of sediment risk (Barbosa and others 2004). Approaches used in determining sediment risk include screening sites for remediation (Forstner and Calmano 1998; Varnavas and others 2001; The International Association for Great Lakes Research 2005), prioritizing areas for further investigation (Long and Macdonald 1998), identifying chemicals of concern (Jones and others 2005; Birch and Taylor 2002a, b, c) and matching management action to site attributes (Barbosa and others 2004).

The level of sediment risk will determine whether a remedial or a preventative strategy is appropriate for a particular location. A preventative management strategy attempts to curtail contaminants from reaching the aquatic area of concern, whereas a remedial management strategy focuses on removing the contaminants already in sedimentary aquatic environment. A preventative management strategy is appropriate for locations of low-sediment risk to protect the area from becoming contaminated. A location of high-sediment risk is suited to a combination of remedial and preventative management strategies to rapidly decrease the risk posed by sediments and to reduce future impacts due to sedimentary contaminants.

Ecological or conservation value is another important factor to be considered in making environmental management decisions (McLusky and Elliot 2004; MacDonald and others 2003; ANZECC/ARMCANZ 2000). However, unlike sediment risk, ecological or conservation value is rarely used alone to determine appropriate sediment management actions. Ecological or conservation value is used to identify areas that warrant an additional level of protection or special consideration when making management decisions (MacDonald and others 2003; ANZECC/ARMCANZ 2000). Ecological/conservation value will affect the type of sediment management strategy selected for a particular location, i.e. a management strategy will be triggered at a lower level of sediment degradation in locations of high ecological/conservation value to afford a higher level of protection, compared to a location of low conservation value (MacDonald and others 2003; ANZECC/ARMCANZ 2000). The ecological/conservation value is considered before selecting the type of sediment management strategy to ensure the ecological/conservation value of a location is not compromised. In South Africa, estuaries of ecological/conservation importance were given a higher level of protection than estuaries considered to be slightly, moderately or highly modified (McLusky and Elliot 2004). The Contaminated Sites Regulation in British Columbia, Canada requires ecological value to be assessed in deciding site-management plans for high ecological value, or 'sensitive' areas supporting threatened flora or fauna (MacDonald and others 2003). Sediment chemical data are compared to sediment quality guidelines (SQGs) to determine whether a site warrants further investigation and lower SQGs are used for sensitive sites. The Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC/ARMCANZ 2000) likewise, provide a higher level of protection for locations of elevated ecological/conservation value.

The aim of the current study is to provide high-quality, science-based information to facilitate effective and strategic decisions on sediment management on an estuary-wide scale for harbour-estuaries, such as Sydney Harbour. This information will identify the type of management initiative required at locations of different sediment-risk and ecological/conservation value. Sediment risk and ecological/conservation value have frequently been considered when making management decisions, but these attributes have not been used previously in combination to undertake a systematic, estuary-wide assessment to facilitate sediment management decisions.

Methods

Chemical data for Sydney estuary sediments used in the current work were collected during several field investigations which took place over 4 years (1996–2000). Due to funding limitations, different numbers of samples were analyzed for different classes of contaminants (Table 1). Samples were analysed for nine metals, Cd, Cr, Cu, Co, Fe, Mn, Ni, Pb and Zn for both total sediment and normalised (<62.5 µm) sediment chemistry, a suite of organochlorine pesticides (OCs); (DDT, DDD, DDE, chlordane, aldrin, heptachlor, dieldrin, heptachlor epoxide, lindane), hexachlorobenzene (HCB) and total polychlorinated biphenyls (PCBs, reported as Aroclors), for 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, napthalene, phenanthrene and pyrene), as well as 2-methylnaphthalene. The methodology for sampling and analyses of these materials has been described previously (Birch and Taylor 1999, 2000, McCready and others 2000). Briefly, sampling was undertaken with a stainless steel box corer and only the most recent upper 2–3 cm layer was taken for analysis. All sampling materials were acid cleaned and washed in deionised water under a fume hood. Metals were sampled with plastic spatulas and stored in plastic containers at 4°C, whereas organic contaminants were sampled with stainless steal spatulas and stored in glass in the dark at −20°C. Samples were stored with no head space and analyses were conducted within specified holding times (6 months for metals and 14 days for extraction and 40 days for analyses for organics). Metals were digested in aqua regia (50:50 HNO_3:HCl) and were analysed using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES), OCs by the 'one–step method' of Ahmad and Marolt (1986) and PAHs by Gas Chromatograph/Mass Spectrometry (GC/MS). Total organic carbon (TOC) analyses were by Coulometer and Loss-On-Ignition (LOI) (Schumacher 2002). Results were mapped using the inverse squared interpolation tool in ArcGIS.

Sediment Risk Assessment (SRA)

Sediment risk assessment was conducted in the current work by comparing total sediment chemistry data to Australia and New Zealand Environmental Conservation Council (ANZECC) SQGs (ANZECC/ARMCANZ 2000). These guidelines are adopted from North America (Long and MacDonald 1992; Long and others 1995; Long and others 1998) and consist of two values for each individual chemical for which data are available. The lower level (Effects Range Low, or ERL) denotes the concentration below which adverse biological effects are seldom observed and the Effects Range Median (ERM) level distinguishes concentrations above which adverse biological effects are expected to occur frequently. Concentrations between ERL and ERM guidelines indicate intermediate, often irregular biological response. ERL and ERM values equate to local Interim Sediment Quality Guidelines-Low (ISQG-L) and -High (ISQG-H) for the ANZECC guidelines.

Contaminants rarely occur individually in natural systems and sediment quality was determined for contaminant mixtures using the mean ERM quotient (MERMQ) approach (Long and McDonald 1998; Long 2000; Long and others 2006). In this approach, contaminant concentrations are divided by the respective ERM value, the quotients are summed and divided by the total number of contaminants. The results of these computations were plotted using ArcGIS to obtain distributions of MERMQ for all contaminants (Long and MacDonald 1998; Long 2000; Long and others 2006). Sediments were categorised into four MERMQ categories <0.1, 0.1–0.5. 0.5–1.5 and >1.5 (Long 2000). Sediment risk involved three types of assessment: No ISQG-L trigger values exceeded; delineation into the three SQG ranges (<ISQG-L; >ISQG-L < ISQG-H; >ISQG-H); mean SQG quotients.

The requirement that organic contaminants be normalised to 1% TOC adopted by the ANZECC SQGs was assessed by undertaking sediment risk assessment on total sediment organic chemistry data with and without TOC normalisation.

No Interim Sediment Quality Guidelines Trigger Values (ISQG-L) Exceeded

The ISQG-L value is locally important as further environmental investigation is triggered for concentrations exceeding these values (ANZECC/ARMCANZ 2000). Sediment chemistry was compared to relevant ISQG-L values and samples were assigned whether it contained none, one or more concentrations exceeding this guideline.

Delineation Into Three SQG Ranges

The ANZECC ISQG-L (∼ERL) and ISQG-H (∼ERM) values delineate three ranges of risk posed to sediment-dwelling organisms. Sediment samples were divided into one of three categories, i.e. no contaminant concentrations exceeding ISQG-L, one or more ISQG-L values exceeded, but not ISQG-H value exceeded, and one or more ISQG-H value exceeded (McCready and others 2006a).

Mean SQG Quotients (MERMQs)

Mean SQG quotients were used to develop four levels of site priority to gain greater differentiation in assessment of sediment risk (Long and MacDonald 1998). Increasing MERMQ has been related to increasing incidence of sediment toxicity (Long and others 1998). The method used in the current study follows Fairey and others (2001) who, after assessing 18 methods of calculating MERMQ, determined that using nine of the most predictive SQGs resulted in a closer relationship between toxicity and sediment chemistry. The SQGQ1 model is calculated as follows:

$$\begin{aligned}\mathrm{SQGQ1} = {} & [(\mathrm{Cd}/4.21) + (\mathrm{Cu}/270) + (\mathrm{Pb}/112.18) \\ & + (\mathrm{Ag}/1.77) + (\mathrm{Zn}/410) \\ & + (\mathrm{Total\ Chlordane}/6) + (\mathrm{Dieldrin}/8) \\ & + (\mathrm{Total\ PAH_{OC}}/1800) + (\mathrm{Total\ PCB}/400)]/9\end{aligned}$$

Table 1 Summary statistics for selected sediment chemistry data

Data set/contaminant type	No. samples	Mean	Maximum	Minimum
Metals total (μg g^{-1})	875			
Copper	874	131	1060	Bd
Lead	875	206	1932	Bd
Zinc	874	481	11300	Bd
Nickel	818	15	118	Bd
Chromium	543	84	298	Bd
Cadmium	498	0.9	52	Bd
Metals fine (<62.5 μm) (μg g^{-1})	834			
Copper	834	210	1225	9
Lead	834	360	3841	2
Zinc	832	743	8411	71
Nickel	784	23	118	3
Chromium	434	118	346	22
Cadmium	599	1	24	Bd
PAH data set (μg kg^{-1})	227			
Anthracene	227	433	5810	Bd
Napthalene	227	212	13187	Bd
Benz(a)anthracene	227	1431	29200	Bd
Chrysene	227	1446	26128	Bd
Pyrene	227	3264	64682	Bd
OC data set (μg kg^{-1})	258			
DDE	258	20	188	Bd
DDT	258	10	216	Bd
DDD	258	44	4980	Bd
Dieldrin	258	7	162	Bd
Total Chlordane	258	39	416	Bd
PCB data set (μg kg^{-1})	238			
Total PCB	238	115	2601	Bd

Bd Below detection (in mg kg^{-1}) 0.05 for OCs, 0.5 for PAHs, 0.1 for PCBs and 0.1 μg g^{-1} for metals

Ecological/Conservation Value Assessment

The ecological/conservation value assessment was based on the importance of conserving the natural state of a site and focused on the benefit gained through a higher level of protection (Department of Infrastructure, Planning and Natural Resources 2004a).

The ecological/conservation value assessment in Sydney estuary involved three phases: Identification of aquatic community value; identification of priority waterway use; and combining these results to calculate an ecological/ conservation value.

Aquatic communities of value within Sydney estuary were identified by the New South Wales (NSW) Department of Infrastructure, Planning and Natural Resources (DIPNIR) (Table 2) (Department of Infrastructure, Planning and Natural Resources 2004a). Priority water use areas based on wildlife communities and human activities within the harbour were based on zoning maps created by Department of Infrastructure, Planning and Natural Resources (2004b) (Table 2). Aquatic communities and priority water use data sets were ranked (1–4, with 4 being the highest value) based on importance of protection (Table 2). The ecological/ conservation value was established by combining aquatic ecological communities of value (Department of Infrastructure, Planning and Natural Resources 2004a) and waterway priority use (Department of Infrastructure, Planning and Natural Resources 2004b) (both ranked out of 4) and rescaling to a total of 4 ranks.

Results and Discussion

Sediments mantling Sydney estuary contained some of the highest reported concentrations of a wide range of contaminants (Birch and Taylor 1999, 2000;, McCready and others 2000) (Table 1). Contaminant concentrations increased markedly landward with highest concentrations in the upper parts of embayments and tributaries. Stormwater-derived contaminants exhibited similar distributions for all

Table 2 Aquatic community value and water use priority

Aquatic community	Value	Water use priority	Value
Rocky platform	4	Maritime waters	2
Mixed rock intertidal and sand	4	Environmental protection	4
Mudflats and mangroves	4	Naval waters	1
Mixed rock intertidal and mudflats	4	Aviation waters	1
Seagrass	4	Water recreation	4
Mixed rocky intertidal and rock platform	3	Scenic waters—Active use	3
Sandy beaches	3	Scenic waters—Casual use	3
Mudflats	3	Scenic waters—Passive use	3
		National parks	4

Data from DIPNIR 2004a, b; Rank 4 has the highest value

four major contaminant classes (metals, OCs, PAHs and PCBs) and were highest in the upper reaches of embayments close to major stormwater inputs, especially on the southern shores of the middle estuary. Concentrations were elevated due to the proximity to source, a mainly muddy substrate and poor flushing by tides and currents. Discrete contaminant 'hot spots' were associated with historical discharge from specific industries located on the shores of the estuary.

Sediment Risk Assessment (SRA)

Sediment in areas of the harbour exceeding SQGs were determined for four chemical classes individually and for contaminant mixtures (Birch and Taylor 2002a, b, c) to better delineate the estuary for management actions. Areas of Sydney estuary with sediment exceeding ISQG-H/ ERM concentrations for Cu, Pb and Zn, which were the most prevalent contaminants in the Harbour, represented approximately 2, 50, and 36% area of the estuary, respectively. Sediment in all parts of the harbour, except a small area near the entrance, exceeded ISQG-L/ERL concentrations for at least one metal.

Organochlorine pesticides exceeded ERM 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 ISQG-H/ERM values. Sediments in almost all upper and middle parts of Sydney estuary, including Middle Harbour, had at least one OC or PAH concentration in excess of ISQG-L/ERM values.

Sediment Risk Assessment of Sydney Estuary

No Interim Sediment Quality Guideline Trigger Values (ISQG-L) Exceeded

Only sediment at the estuary mouth and in small areas in Middle Harbour contain contaminant concentrations <ISQG-L. Sediment at the mouth is medium-grained sand, the area is located further from major sources of contamination and flushing rates are high (<1d). Middle Harbour catchment is poorly urbanised and industrialised resulting in minimal impact.

ANZECC guidelines require that organic contaminants be normalised to 1% total organic carbon (TOC) to account for the reduction in bioavailable organic contaminant with increased TOC content (Fig. 2). However, distributions of organic contaminants normalised and not normalised to TOC were spatially similar. The similarity in distributions was not due to low concentrations of TOC (the estuary had high TOC—average 5.6%), but because of high concentrations of organic contaminants even after normalisation.

The ANZECC guidelines require further investigation or management action if the ISQG-L value is exceeded for any chemical (ANZECC/ARMCANZ 2000). If this guideline is applied to Sydney estuary, the only areas that would not require further investigation would be the estuary mouth and small areas of the upper reaches of Middle Harbour.

Delineation of Three Ranges of Risk Posed by Contaminated Sediment

Sediment samples were assigned to one of three categories before and after TOC normalisation of organic contaminants based on contaminant concentrations relative to the two ANZECC guideline values (ISQG-L and -H). Samples with no ISQG-L values exceeded were assigned to category 1, samples with one or more chemicals exceeding ISQG-L, but none exceeding ISQG-H, were assigned to category 2 and samples with one or more chemicals exceeding ISQG-H were assigned to category 3 (Fig. 3).

Sediment containing concentrations below ISQG-L levels near the estuary mouth was identified as category 1 (Fig. 3). Sediment in the main channel in the Central to Upper Harbour, Middle Harbour and the upper portion of Lane Cove River contained one or more contaminant concentrations exceeding ISQG-L values, but not exceeding

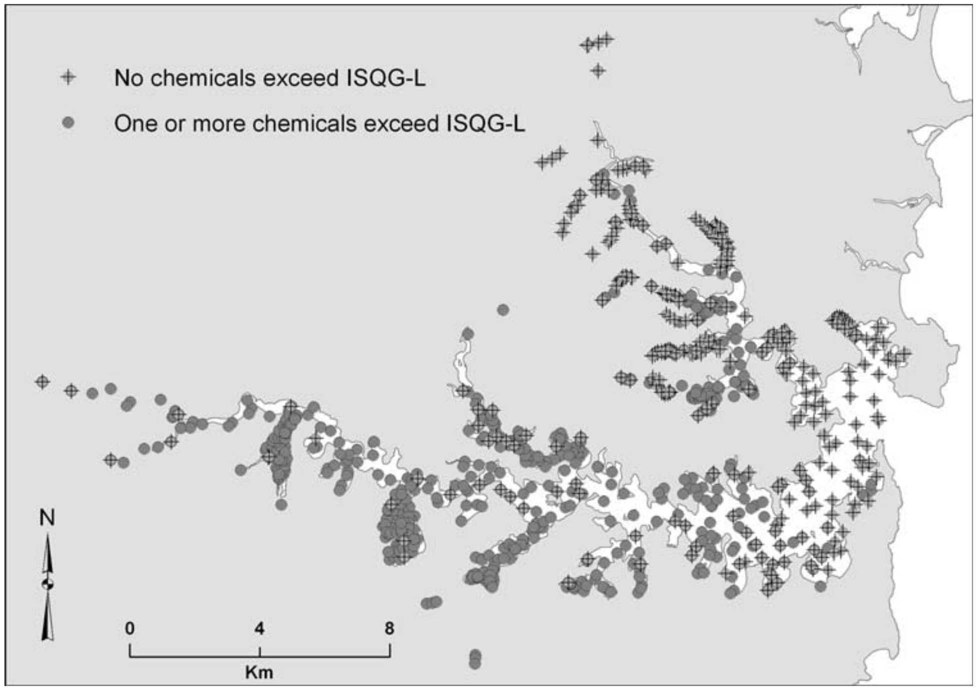


Fig. 2 Samples with at least one chemical exceeding the Interim Sediment Quality Guideline-Low (trigger) value are located over the majority of the estuary, except for the area near the mouth

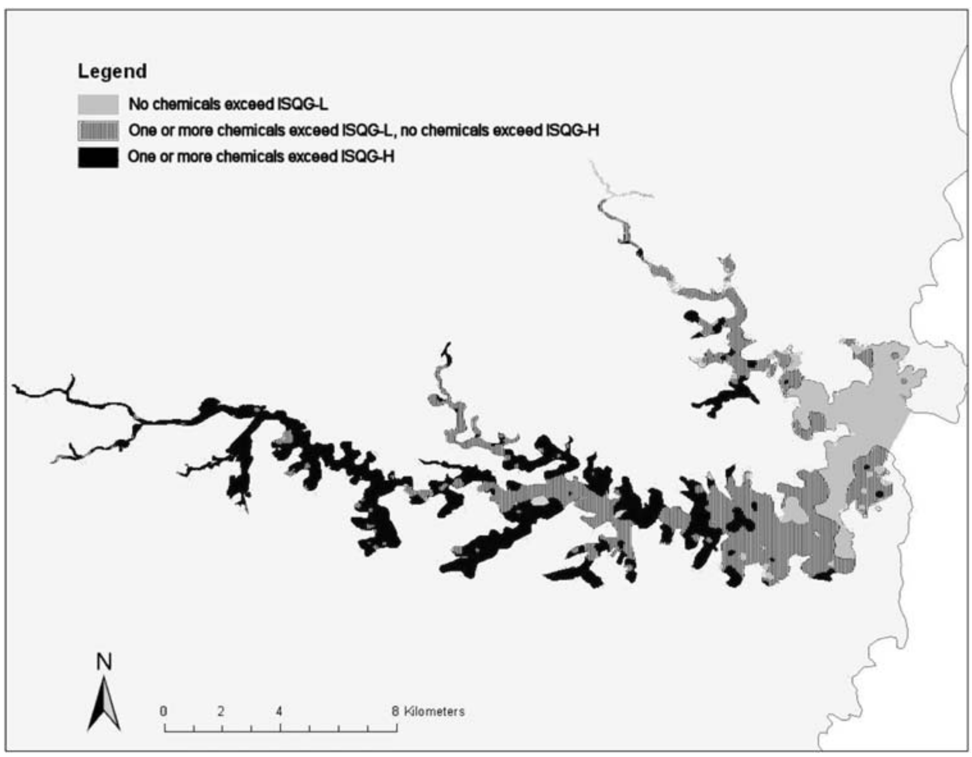


Fig. 3 Three ranges of sediment risk for data not normalised to 1% TOC for organic contaminants. Areas with one or more chemicals exceeding Interim Sediment Quality Guideline-High (ISQG-H) occupy almost all of the upper estuary and areas where one or more chemicals exceed ISQG-Low but do not exceed ISQG-H are located over most of the central estuary

ISQG-H and was classified as category 2. Sediment in the lower part of Lane Cove River, bay ends in Middle Harbour, Parramatta River, and embayment in south central part of the estuary contained one or more contaminant concentrations exceeding ISQG-H values and was ranked as category 2.

Effect of TOC Normalisation on Risk Analysis

To examine the effect of TOC normalisation on sediment risk, normalised and un-normalised distributions were produced for PAHs, OCs and PCBs separately. Distributions of individual contaminant classes showed minor spatial differences due to the reduction in risk by high TOC (5–8%) content in sediment in some areas. TOC levels >1% result in a reduction in risk for organic contaminants following normalization and conversely TOC levels of <1% result in an increase in calculated risk (limited to 0.5%, ANZECC/ARMCANZ 2000). However, an increase in sediment risk following TOC normalisaton was not common for Sydney estuary, as TOC levels of <1% were infrequent.

Risk of Contaminant Mixtures (Mean SQG Quotients)

The use of mean SQG quotients enabled a greater level of differentiation to be achieved in the level of sediment risk. A general increase in sediment risk up the main channel was observable, with the highest risk associated with the upper Parramatta River and the upper reaches of many embayments.

Conducting sediment risk assessment using mean SQG quotients is not described by the ANZECC guidelines, however the use of this technique to predict sediment risk has been extensively applied in North American for site-specific evaluations (Long and others 1998). The seven levels of risk produced by the SQGQ1 model (Fairey and others 2001) was reduced to four levels in the current study to be consistent with ecological subdivisions and was found more useful in guidance of management decisions (Long and MacDonald 1998) (Fig. 4; Tables 3, 4).

Ecological/Conservation Value Assessment

Factors Used to Identify Areas of Ecological/Conservation Value

The ecological/conservation value of a site is an important factor in considering the need and type of management required at a site and may include, the presence of endangered species (MacDonald and others 2003; NSW National Parks and Wildlife Services 2002; Department of Infrastructure, Planning and Natural Resources 2004a), habitat vital to supporting endangered species (MacDonald and others 2003; NSW National Parks and Wildlife Services 2002; Department of Infrastructure, Planning and Natural Resources 2004b), unique habitat (MacDonald and others 2003), environmentally sensitive areas (MacDonald and others 2003) and areas of high biological productivity (MacDonald and others 2003).

Besides some preliminary investigations of rocky reef fauna (Glasby and Connell 2001), little is known of aquatic invertebrates, microalgae and microbial function in Sydney estuary. In the absence of this information practitioners have deemed it appropriate to use the habitat with which they interact as a basis for segregation and management until more data become available (Department of Infrastructure, Planning and Natural Resources 2004a). In the current investigation ecological communities that formed

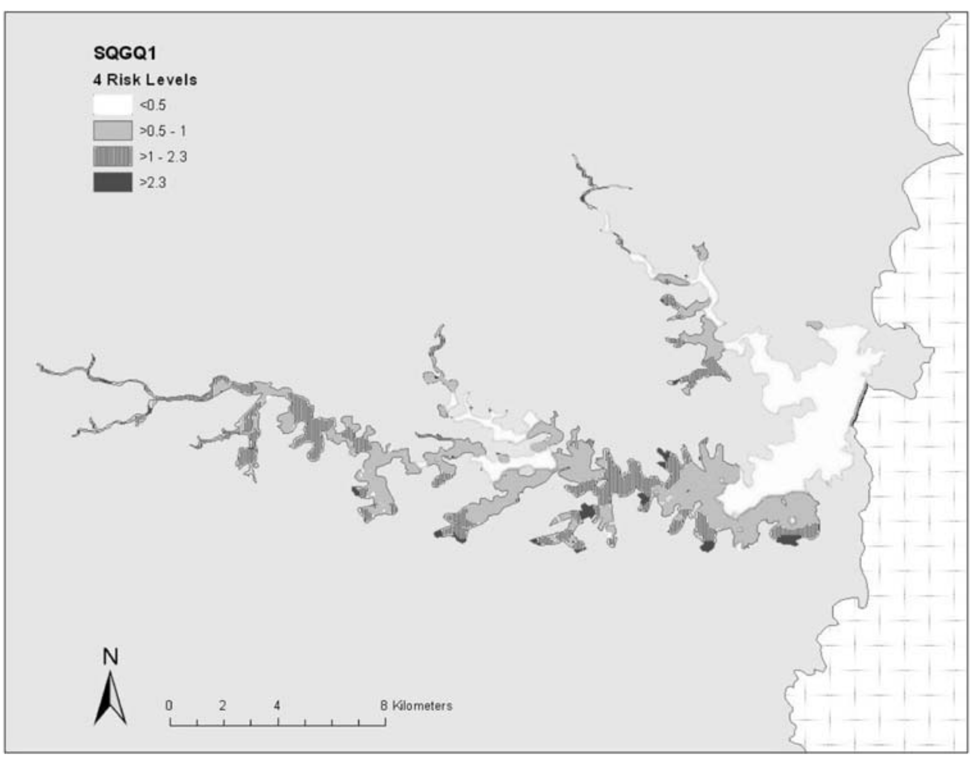


Fig. 4 Four levels of sediment risk using the Mean Effects Range Median Quotient approach (MERMQ1). Areas exhibiting the highest risk occupy many of the uppermost reaches of embayments and tributaries of the central estuary

Table 3 SQGQ1 ranges related to incidence of toxicity

SQGQ1 range	Incidence of toxicity (%)
>2.3	100
1.5–2.3	87
1.0–1.5	80
0.5–1.0	56
0.2–0.5	13
0.1–0.2	8
<0.1	4

After Fairey and others (2001)

Table 4 Four mean SQG quotient ranges developed from the 7 critical levels given in Table 3

Risk level	Mean SQGQ1 range	Incidence of Toxicity (%)
4	>2.3	87–100
3	1.0–2.35	56–87
2	0.5–1.0	13–56
1	<0.1, 0.1–0.2, 0.2–0.5	<13

wildlife habitats were given high conservation value. Habitat which supported survival of wildlife, e.g. seagrass, which plays an important role in the survival of endangered and vulnerable species and the only known breeding site on mainland NSW of an endangered species (little penguin) was ranked with the highest value in Sydney estuary (NSW National Parks and Wildlife Services 2002; Jones and others 2005). High ecological value was assigned to sites which supported endangered species, threatened species, species of concern, or contained habitat vital to preserving fish or wildlife. A similar value was assigned to sites which supported fish spawning, juvenile fish, or contained areas identified as unique habitat, or was within an existing reserve (MacDonald and others 2003).

Waterways priority use was obtained from zonings specifically tailored to suit the differing environmental characteristics and uses of the Harbour (DIPNIR 2004b). Two broad-water zones (Maritime Waters and Water Recreation) have been identified to meet the commercial and recreational functions of Sydney Harbour and its tributaries. Three close-to-shore zones (Scenic Waters: Active Use, Casual Use, Passive Use) aim to achieve an appropriate balance between development and conservation within 30 metres of the shore where there is the greatest pressure of development. The capacity of each zone to accept change dictates the range of private uses that can be sustained. These zones grade from the generally robust (Active) suitable for a variety of uses to the more sensitive Passive Use zones, suitable for low impact uses only. Maritime Waters covers the main navigation channels, public transport, port and maritime industry activities of the Harbour and permits a wide range of waterway activities and facilities. Environmental Protection zone provides for the protection, rehabilitation and long term management of the natural and cultural values of the waterways and adjoining foreshores. The zone covers a range of areas including significant estuarine ecosystems and habitats. Aviation zones give priority to and protects waters required for marine aviation activities. Water Recreation zones are public recreation areas which gives priority to public use and access. National Parks zone applies to parks in coastal water and on islands in the harbour.

A Decision Support System Based on Ecological/Conservation Value and Sediment Risk

Sediment risk and ecological/conservation value were ranked between 1 and 4, with 4 representing the highest level of risk and value, respectively.

The two important sediment management decisions which the sediment risk and ecological/conservation value assessments facilitated were identification of priority sites for further environmental investigation and management initiatives and identification of the type of management strategy required at a site/location.

Identification of Priority Sites for Further Environmental Investigation and Management Initiative

The process of identifying priority sites in Sydney estuary is an important part of sediment management as it ensures that the limited resources available are used efficiently and effectively. Likewise, protection of pristine environments is a necessary part of managing natural resources as it provides valuable sanctuaries for wildlife and important areas for tourism and leisure activities for humans (Batley 1997). Areas of high sediment risk should be managed to

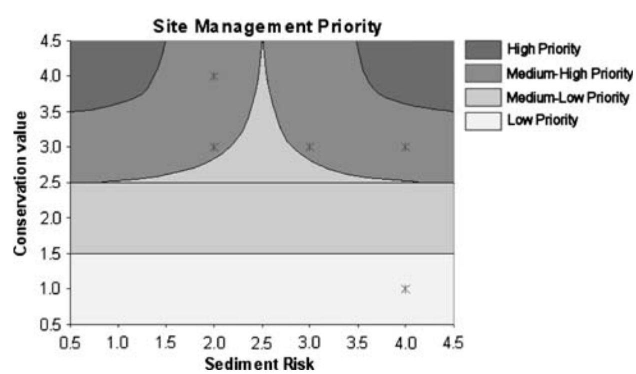


Fig. 5 Management Priority Matrix used to determine priority of undertaking environmental work in any particular area. Data points are for priority types determined in the case study of Iron Cove

Table 5 Recommended management strategy for the management areas (A–F) defined in Fig. 4

Sediment management strategy area (Fig. 4)	Sediment risk level	Ecological/conservation value	Recommended management strategy	Management actions
A	1–1.5	2.5–4	The site has low sediment risk and medium to high ecological/conservation value. A preventative management strategy is recommended to prevent degradation of sediment risk. Remediation of sediment is not required due to the low sediment risk. The high ecologica/conservation value of the area warrants preventative initiatives to maintain the areas current state	Control of point sources. Listing the site as a Protected area. Restricting use of the site. Public education of the value of the site
B	1.5–2.5	2.5–4	The site has low-medium sediment risk and medium to high ecological/conservation value. Management actions are only recomended if adverse effects to the value of the area can be confirmed. If so, a preventative management strategy is recommended. Curtaining future contaminant inputs into the area and allowing natural recovery is appropriate	Further investigation of sediment risk level. Control of contaminant point sources
C	2.5–3.5	2.5–4	The site has medium-high sediment risk and medium to high ecological/conservation value. A combination of preventative and remedial management strategies are recommended. The level of sediment risk is of concern as the site is of ecological/conservation value. If the sediment risk is advesely effecting the value of the area, remedial strategies will be required to remove the risk. The level of risk is not in the highest category and therefore lends itself to an on site/in-situ management plan	Control of contaminant point source. Onsite/in situ treatment
D	3.5–4	2.5–4	The site has high sediment risk and medium to high ecological/conservation value. A remedial-focused management strategy is suited such sites. The high risk from sediment needs to be quickly removed to minimise impact on an area identified as having high ecological/conservation value. Onsite/in-situ remedian is recommended unless the risk posed during onsite remediation is too great, in which case the removal and treatment of the sediment offsite/ex-situ is recommended	Onsite/in situ treatment or offsite/ex situ treatment if required. Investigate the need for management steps to protect the public from adverse effects (i.e. fishing restrictions). Identifying soures of contamination and prosecution of illegal inputs in to the system
E	1–2.5	1–2.5	The site has low-medium sediment risk and low ecological/conservation value. The low risk and low value of the area warrants no management action	No action recommended
F	2.5–4	1–2.5	The site has medium-high sediment risk and low ecological/conservation value. Monitoring is recommended, with management actions only implementd if a resource or activity of value is being substantially impacted as a result of sediment contamination levels	Monitor impacts

avoid adverse biological effects and areas of low sediment risk should be managed to protect wildlife populations and recreational areas (Long and MacDonald 1998; Batley 1997). Consideration of ecological/conservation value further facilitates the identification of priority locations for management initiatives, i.e. those areas which warrant a higher level of protection and priority. Therefore priority management sites are sites with high sediment risk and high ecological/conservation value and sites with low sediment risk and high ecological/conservation value.

A matrix was developed to identify priority management sites based on integration of the level of sediment risk and ecological/conservation value (Fig. 5). The top left corner (low risk, high ecological/conservation value) and the top right corner (high risk, high ecological/conservation value) have the highest priority for management attention. As ecological/conservation value decreases, the priority for management decreases. The priority for management also decreases as the sediment risk level changes from high risk or low risk and to higher levels for sites of high ecological/conservation value. The appropriate management strategy for different ecological/conservation and sediment risk, i.e. priority scenarios are suggested in Table 5 and discussed below.

Identification of Required Management Strategy

Following the identification of priority sites, sediment risk and ecological/conservation value have been used to assist in determining the type of management required at a location. Two broad types of sediment management strategies have been identified in the current study, i.e. 'remedial' and 'preventative'. Remedial management strategies attempt to reduce the risk that sediment poses to an area by focusing on reducing the risk from the contamination already in the sediment, whereas preventative management strategies concentrate on curtailing input of contaminants into the area and into sediment.

A site of high sediment risk is suited to a combination of remedial and preventative management strategies, with the focus on remedial activities to quickly reduce the risk posed by the sediment to the area. Preventative measures should also be investigated to prevent future contamination. A site with low sediment risk would not require remedial management, instead preventative management strategies should be implemented to ensure the current state of the site is maintained. These strategies are similar to other management practises of sediment quality (Batley 1997; Long and MacDonald 1998).

The ecological/conservation value also aids in the identification of the management strategy appropriate for a location. The impact of a sediment management strategy must be carefully considered at a site of high ecological/

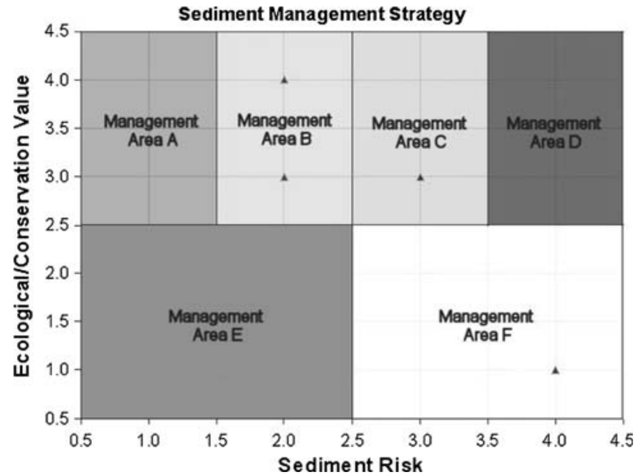


Fig. 6 Sediment management strategy matrix used to make decisions regarding the type of intervention required for any particular area. Data points are for the Iron Cove case study. The management strategy pertaining to Areas A–F are provided in Table 5

conservation value as it must not compromise its ecological/conservation value. For example, dredging would not be appropriate for a site of high ecological/conservation value containing important sea grass beds. The potential impact from contaminated sediment is higher in a site considered to be of ecological/conservation value, and therefore a higher level of management response is warranted.

A sediment management strategy matrix was developed to identify the type of management strategy appropriate for a location based on the level of sediment risk and ecological/conservation value (Table 5; Fig. 6). Management actions suggested in the current study for the six management areas are preliminary and should be discussed by an expert panel comprising estuarine managers, scientists and stakeholders before being finalised. Management actions are location specific and will vary dependent on different pressures and requirements.

Iron Cove as a Case Study

Iron Cove is a small (2.5 km long and 0.6 km wide), shallow (mean depth ~5 m) embayment on the central south coast of Sydney estuary (Fig. 7). The embayment is mantled in muddy sediments containing high concentrations of a wide range of contaminants, mainly heavy metals, but including organochlorine pesticides and polycyclic aromatic hydrocarbons (Birch and Taylor 1999, 2000, 2004; McCready and others 2000).

A case study is given for Iron Cove to demonstrate the process of assessing management priority and management strategy as outlined in the present work (Fig. 7a–d). The ecological/conservation value varies in the cove from high to low and includes seagrass meadows, mud flats (high

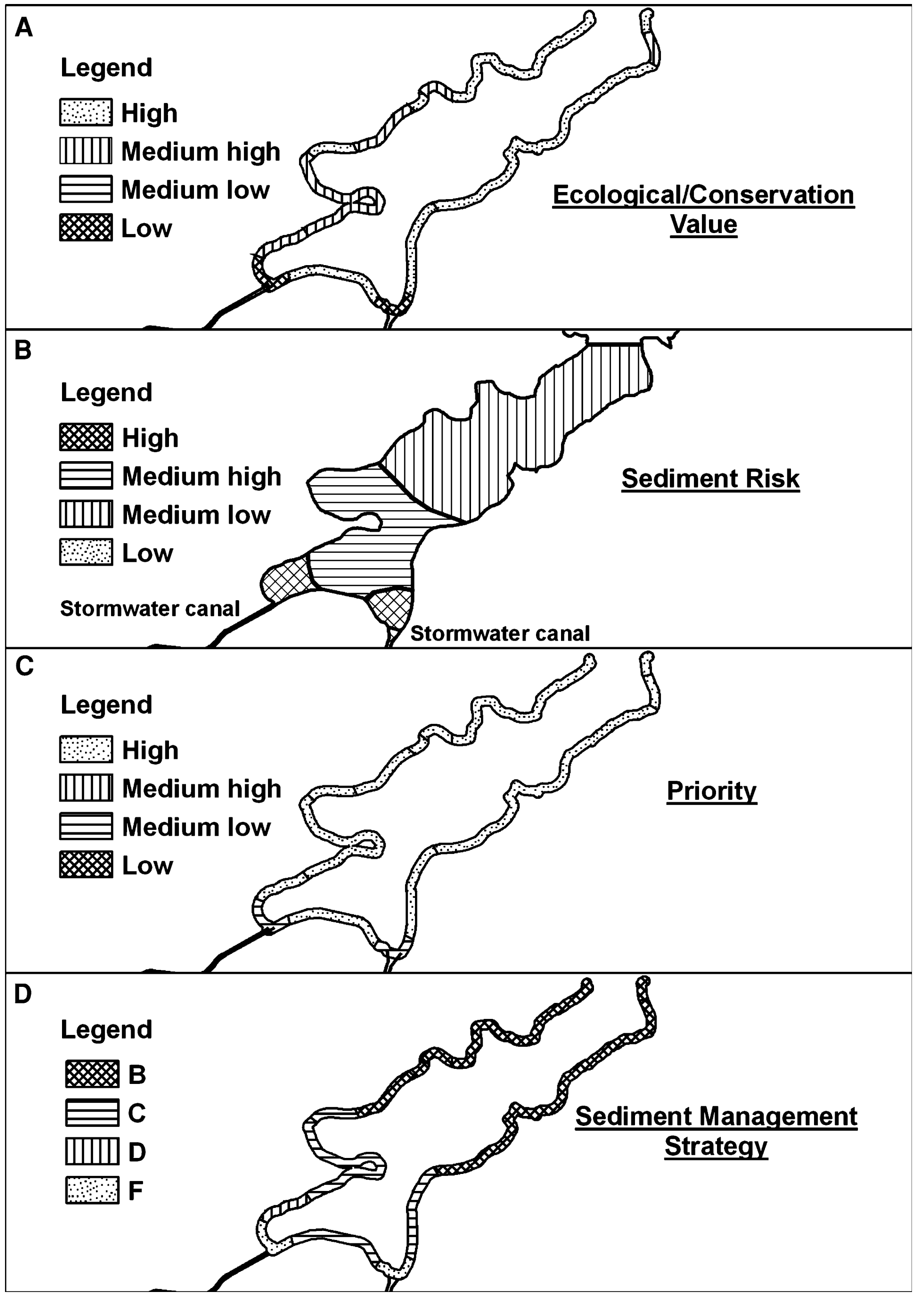


Fig. 7 Iron Cove: An embayment in the central estuary used as a case study to demonstrate use of the approach to decision making applied in the current work. **a** Ecological/ conservation value is determined from aquatic communities and water use data (Water Use data are consistently Scenic, rank 3 throughout the cove and have not been included in the figure). **b** Sediment Risk is estimated by nomalising metal concentrations to sediment quality guidelines. **c** Priority areas are a combination of A and B. **d** Sediment Management Strategy is developed from the most appropriate action based on Priority areas

value, rank 4), mixed rocky intertidal shore face denuded of mangroves (medium high value, rank 3) to the highly impacted mouths of two canals entering the cove (low value, rank 4) (Fig. 7a). Water use priority is for Scenic Water use throughout the cove, i.e. medium priority, rank 3 and has not been shown in Fig. 7. Sediment risk increases consistently towards the upper part of the cove from medium low risk (rank 2) at the mouth of the cove to highly contaminated sediment (sediment risk high, rank 4) at the mouths of the two canals in the south (Fig. 7b). Combining the ranks of ecological/conservation value and sediment risk provided priority for management action, which varies from medium high priority (rank 3) for most of the foreshores of Iron Cove to low priority (rank 4) for the highly impacted mouths of the two canals with low ecological/ conservation value and high sediment risk (Fig. 7c). The majority of the shoreline of Iron Cove had a High/Medium High ecological/conservation value and a Medium Low sediment risk, which translates to a Management Area B strategy (Fig. 7d). Management actions would only be recommended for this combination of ecological/conservation value and sediment risk if adverse effects posed by sediments could be confirmed (Table 5). Sediment risk increased with increasing proximity to the two stormwater canals in the south of the cove, whereas the combination of ecological/conservation value and sediment risk remained Medium High changing the suggested management strategy towards Management Strategies C and D. If adverse ecological effects could be demonstrated at these locations, then remedial strategies are recommended to remove the risk posed by the sediment. The areas immediately adjacent to the mouths of the two canals (Management Strategy F) has high sediment risk and low ecological/conservation value and monitoring is recommended and management actions are only suggested if a resource of substantial value was to be identified.

Conclusions

Busy, working capital ports in Australia and worldwide are frequently degraded through a long history of poor industrial practise and stormwater contamination. High concentrations of a wide range of chemicals often impair sediment in these estuarine environments adversely effecting bottom-dwelling flora and fauna. SQGs are commonly used to assess a particular site for remediation and ecological/conservation values have been used to identify areas for preservation. However, the current work is the first attempt to combine these assessment parameters into a science-based management tool to assist in efficient and effective management of a large, heavily impacted Australian harbour (Sydney estuary).

Estuary-wide assessment of sediment risk and ecological/conservation value provides a convenient methodology to facilitate sediment management decisions in estuarine environments. Sediment risk and ecological/conservation assessments conducted on an estuary-wide scale enabled the entire harbour to be prioritised for areas most in need of sediment management attention. Financial and management resources are limited and it is important that the attention of managers is focused to where need is greatest and where maximum benefit may be achieved most rapidly. Sites containing high sediment risk, high ecological/conservation value and sites of low-sediment risk, high-ecological/conservation value were identified as high priority sites for sediment management. Following the identification of priority sites, more detailed site investigation may be undertaken to confirm the need for management actions.

The sediment risk and ecological/conservation value assessments also enabled the most appropriate type of management strategy for a site to be identified. These tools provide guidance for regulators, management organisations, industry and development control agencies for any location in the estuary. The recommended management strategy for the site from the sediment risk and ecological/conservation value perspective provided a basis from which a specific management strategy for the site may be developed.

The current work includes a small amount of environmental data, however future management tools for this harbour will incorporate a more comprehensive array of information, e.g. stormwater inputs, Heritage and historical sites, foreshore type and condition, sensitivity to climate change, land clearance. This information will be combined into a single GIS-based dataset for rapid data retrieval and will provide a platform for a science-driven decision support system to allow a specific management strategy to be identified for any site within the estuary in real time. This will be a unique and powerful tool which will greatly improve effective management of Sydney estuary and potentially the management of impacted harbours worldwide.

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