

Table of Contents

Preface	i
Acknowledgements	iii

Chapter 1 - Indigenous Knowledge and Culture

Quandamooka Country: The role of science and knowledge in Traditional Owner-led land and sea management.....	3-28
<i>Mibu Fischer, Darren Burns, Joel Bolzenius, Cameron Costello, Darryl Low Choy</i>	
A custodial ethic, Indigenous values towards water in Moreton Bay and Catchments.....	29-44
<i>Breanna Pinner, Helen Ross, Natalie Jones, Sally Babidge, Sylvie Shaw, Katherine Witt, David Rissik</i>	

Chapter 2 - Communities and Values

Values towards Moreton Bay and catchments.....	47-60
<i>Helen Ross, Natalie Jones, Katherine Witt, Breanna Pinner, Sylvie Shaw, David Rissik, James Udy</i>	
Community knowledge about water and engagement in waterway protection in South East Queensland	61-72
<i>Angela J Dean, Kelly S Fielding, Fiona Newton, Helen Ross</i>	
Stewardship as a driver for environmental improvement in Moreton Bay	73-88
<i>Rachael Nasplezes, Joel Bolzenius, Apanie Wood, Ryan Davis, Anne Cleary, Paul Maxwell, David Rissik, Helen Ross</i>	
Managing the public health paradox: Benefits and risks associated with waterway use.....	89-104
<i>Anne Roiko, Sonya Kozak, Anne Cleary, Zoe Murray</i>	
Education in <i>Quandamooka</i> – A long and evolving tradition.....	105-118
<i>Emily Casey, Timothy Roe, Ian Tibbetts, Dianne Aylward</i>	

Chapter 3 - History and Change in Moreton Bay

An environmental history of Moreton Bay hinterlands.....	121-136
<i>Justine Kemp, Jon Olley, Samantha Capon</i>	
Historical changes of the lower Brisbane River	137-152
<i>Jonathan Richards</i>	
Holocene history of Moreton Bay reef habitats.....	153-162
<i>Matthew J. Lybolt, John M. Pandolfi</i>	

Trace metal contamination and distribution in sediments of Moreton Bay: An historical review	163-178
<i>Guia Morelli, Massimo Gasparon</i>	

Chapter 4 – Water Quality, Land-Use and Land-Cover

Moreton Bay and catchment urban expansion and vegetation change.....	181-186
<i>Mitch Lyons, Stuart Phinn, Chris Roelfsema</i>	
Water quality in Moreton Bay and its major estuaries: Change over two decades (2000-2018)	187-210
<i>Emily Saeck, James Udy, Paul Maxwell, Alistair Grinham, David Moffatt, Sivakumar Senthikumar, Danielle Udy, Tony Weber</i>	
Wetland and benthic cover changes in Moreton Bay	211-226
<i>Eva M. Kovacs, Hannah L. Tibbetts, Simon Baltais, Mitch Lyons, Jennifer Loder, Chris Roelfsema</i>	
The impact of marine pollutants and debris in Moreton Bay	227-244
<i>Kathy A. Townsend, Christine Baduel, Vicki Hall, Jennifer Loder, Veronica Matthews, Jochen Mueller, Rachael Nasplezes, Qamar Schuyler, Heidi Taylor, Jason van de Merwe, C. Aleander Villa, Liesbeth Weijs</i>	
Projected changes to population, climate, sea-level and ecosystems	245-256
<i>Megan I. Saunders, Elin Charles Edwards, Rebecca Runting, Jozef Syktus, Javier Leon</i>	

Chapter 5 - Habitats, Biodiversity and Ecosystem Function

Primary producers in Moreton Bay: Phytoplankton, benthic microalgae and filamentous cyanobacteria	259-278
<i>Emily Saeck, Alistair Grinham, Jack Coates-Marnane, Tony McAlister, Michele Burford</i>	
The seagrasses of Moreton Bay <i>Quandamooka</i> : Diversity, ecology and resilience...	279-298
<i>Paul Maxwell, Rod M. Connolly, Chris Roelfsema, Dana Burfeind, James Udy, Kate O'Brien, Megan I. Saunders, Richard Barnes, Andrew D. Olds, Chris Henderson, Ben L. Gilby</i>	
Mangroves and saltmarshes of Moreton Bay	299-318
<i>Catherine E. Lovelock, Arnon Accad, Ralph M. Dowling, Norm Duke, Shing Yip Lee, Mike Ronan</i>	
Freshwater wetlands of Moreton Bay, <i>Quandamooka</i> and catchments: Biodiversity, ecology, threats and management	319-334
<i>Angela H. Arthington, Stephen J. Mackay, Mike Ronan, Cassandra S. James, Mark J. Kennard</i>	
Zooplankton of Moreton Bay	335-360
<i>Sarah Pausina, Jack Greenwood, Kylie Pitt, David Rissik, Wayne Rochester,</i>	

<i>Jennifer Skerratt, Julian Uribe-Palomino, Anthony J. Richardson</i>	
Coral and micro-benthic assemblages from reef habitats in Moreton Bay	361-378
<i>John M. Pandolfi, Matt Lybolt, Brigitte Sommer, Roshni Narayan, Paola G. Rachello-Dolmen</i>	
Fishes of Moreton Bay: Ecology, human impacts, and conservation	379-400
<i>Andrew D. Olds, Ben L. Gilby, Rod M. Connolly, Ian R. Tibbetts, Christopher J. Henderson, Tim Stevens, Sarah K. Thackwray, Thomas A. Schlacher</i>	
Marine turtles in Moreton Bay	401-414
<i>Colin J. Limpus, Owen I. Coffee</i>	
Ecology of the marine mammals of Moreton Bay	415-430
<i>Janet M. Lanyon, Michael J. Noad, Justin Meager</i>	
Migratory shorebirds of Moreton Bay	431-444
<i>Richard Fuller, David A. Milton, Peter C. Rothlisberg, Robert S. Clemens, Jon Coleman, Kristy Murray, Kiran L. Dhanjal-Adams, David Edwards, Paul G. Finn, Greg Skilleter, Madeleine Stigner, Bradley K. Woodworth</i>	

Chapter 6 - Citizen Science

How does citizen science contribute to sustaining the Bay? A discussion of approaches and applications	447-458
<i>Jennifer Loder, Chris Roelfsema, Carley Kilpatrick, Victoria Martin</i>	
Building an understanding of Moreton Bay Marine Park's reefs through citizen science	459-474
<i>Chris Roelfsema, Jennifer Loder, Kyra Hay, Diana Kleine, Monique Grol, Eva Kovacs</i>	
Citizen science photographic identification of marine megafauna populations in the Moreton Bay Marine Park.....	475-490
<i>Christine L. Dudgeon, Carley Kilpatrick, Asia Armstrong, Amelia Armstrong, Mike B. Bennett, Deborah Bowden, Anthony J. Richardson, Kathy A. Townsend, Elizabeth Hawkins</i>	

Chapter 7 – Industry and Planning

Tourism in the Moreton Bay Region	493-504
<i>Lisa Ruhanen, Mark Orams, Michelle Whitford</i>	
Aquaculture in Moreton Bay	505-520
<i>Elizabeth West, Carol Conacher, John Dexter, Peter Lee, Michael Heidenreich, Brian Paterson</i>	
Fishers and fisheries of Moreton Bay	521-536
<i>Ruth Thurstan, Kerrie Fraser, David Brewer, Sarah Buckley, Zena Dinesen, Tim Skewes, Tony Courtney, Barry Pollock</i>	

Marine transport infrastructure development in Moreton Bay: Dredging, monitoring and future directions	537-546
<i>Adam Cohen, Daniel Spooner, Samuel M. Williams</i>	
Charting a course by the stars; a review of progress towards a comprehensive management plan for Moreton Bay 20 years on	547-560
<i>Andrew Davidson, Darryl Low Choy</i>	

Chapter 8 – Moreton Bay Marine Park

Managing for the multiple uses and values of Moreton Bay and its catchments.....	563-578
<i>Helen Ross, David Rissik, Natalie Jones, Katherine Witt, Breanna Pinner, Sylvie Shaw</i>	
Performance of marine reserves for fish and associated ecological functions in the Moreton Bay Marine Park	579-592
<i>Ben L. Gilby, Andrew D. Olds, David Rissik, Christopher J. Henderson, Rod M. Connolly, Tim Stevens, Thomas A. Schlacher</i>	
Changes in fish and crab abundance in response to the Moreton Bay Marine Park rezoning.....	593-614
<i>Mick Haywood, Richard Pillans, Russ Babcock, Emma Lawrence, Ross Darnell, Charis Burridge, Darren Dennis, Anthea Donovan, Sue Cheers, Robert Pendrey, Quinton Dell</i>	
Non-extractive human use and vessel characteristics in Moreton Bay Marine Park following rezoning	615-638
<i>Rob Kenyon, Russ Babcock, Quinton Dell, Emma Lawrence, Christian Moeseneder, Mark Tonks</i>	

Appendices

Maps of Moreton Bay and catchment

A. Southern Moreton Bay and Islands	641
B. Northern Moreton Bay, Moreton and Bribie Islands	643
C. Brisbane River catchment	645
D. Greater Moreton Bay catchment rivers	647
E. Electronic appendix	639

Trace metal contamination and distribution in sediments of Moreton Bay: An historical review

Guia Morelli^{1,2}, Massimo Gasparon^{1,3}

Author affiliations: 1. School of Earth and Environmental Sciences, The University of Queensland, St Lucia Qld, 4072, Australia; 2. CNR-Centre for National Research, Istituto di Geoscienze e Georisorse, 50121, Florence, Italy; 3. EIT RawMaterials GmbH, 10789 Berlin, Germany.

Corresponding author: morelliguia@gmail.com

ORCID

Guia Morelli: <https://orcid.org/0000-0001-5467-325X>

Massimo Gasparon: <https://orcid.org/0000-0001-7788-6768>

Abstract

Trace metals identified as priority contaminants (Pb, Zn, Cu, Cd, Ni, Cr, As, Hg) in estuarine and coastal marine sediments represent a challenging issue because of their toxicity, persistence and their potential to become bioavailable to aquatic organisms. Estuarine embayments have provided the most favourable sites for the settlement of Europeans in Australia. Since the 1840s, following the rapid development of the Moreton Bay region, metal contaminants used in many human activities started to disperse into the Bay. Here we present a review of recent studies aimed at quantifying trace metal concentrations in the sediments of Moreton Bay and at describing sedimentation patterns. The effects of rapid catchment modifications are recorded in sediment cores from intertidal and subtidal areas where increasing concentrations of metals correlate with the history of development in the region. Also, metal concentrations in surficial sediments at many sites are above local natural background levels and above sediment quality guidelines used to assess the ecological effects of sediment contamination, implying ecosystem deterioration. Moreton Bay is recognised for its ecological significance and, with predicted increases in the frequency of extreme weather events, mobilisation of contaminated sediments represents the main pathway for trace metal dispersal. This paper highlights the importance of monitoring metal contaminants in the Bay's sediments together with water quality parameters, and provides an overview of areas where contamination occurred in the past and of areas most likely to be impacted by metal contamination in the future. The data reported in this review can play an important role in local and regional management strategies for the preservation of a healthy estuarine ecosystem in Moreton Bay.

Keywords: metal contaminants, metal distribution, intertidal sediments, subtidal sediments, sedimentation rates, sediment mixing, environmental monitoring

Introduction

Maintaining a healthy ecosystem is linked to natural and human-induced changes, and to its capacity to recover after perturbations (1). Human activities have modified the magnitude and composition of inputs from watersheds to estuaries, thereby putting pressure on the ecological health of the coasts. Major modifications of the Moreton Bay catchment after European

settlement in the early 1830s (e.g. clearing of vegetated areas converted to croplands and cattle grazing, urbanisation) (2-4) led to increased erosion from channels and gullies, resulting in increased sediment yield into the Bay (5-9). The environmental impact in the region was particularly marked after 1960 when fertiliser use and the introduction of many new chemicals resulted in nutrients and pollutants entering the waterways when there was a lack of understanding of their toxicological consequences.

Among trace elements, trace metals (e.g. lead (Pb), zinc (Zn), cadmium (Cd), copper (Cu)) are an important source of pollution. Their non-biodegradability and inherent toxicity make them some of the most persistent pollutants (10). Introduced in the aquatic environment by atmospheric deposition, weathering or erosion, anthropogenic sources (e.g. ore mining, fossil-fuel combustion, industry, agriculture) are major contributors of metals in coastal areas. In sediments, their concentrations include the natural and anthropogenic components. The mineralogical or chemical form in which a metal occurs will greatly affect how readily it is released into the environment. Trace metals have high affinity for fine particles because of their high adsorption capabilities and are bound to sediments by particle surface absorption, ion exchange, co-precipitation, and complexation with organic matter (see example in (10)).

In coastal and estuarine regions, sediments play an important role in contaminant distribution by transporting and accumulating high concentrations of potentially toxic metals into low-energy areas. After deposition, disturbance of sediments induced by natural (e.g. storms, waves) or anthropogenic (e.g. dredging) factors may redistribute anthropogenic metals associated with previously deposited sediments into the environment (10). Additionally, changes in bio-geochemical conditions (redox potential, pH and salinity) at the water-sediment interface may affect the partitioning of sediment-bound metals, thus facilitating their mobility and controlling their potential toxicity (see example in (10)). Once remobilised, metals transported in the water column may become bioavailable and toxic to marine organisms via bioaccumulation processes (10). Thus, once deposited into the Bay, sediments could act as non-point pollution sources by releasing their toxic metal load, thus adversely affecting the ecosystem.

Today, the Moreton Bay catchment is one of the fastest growing regions of Australia and rapid population growth poses a significant threat to the environment and the quality of its waterways (2, 11). Increased suspended sediment load transported in the water column from the catchment together with the associated nutrients and contaminants is causing ecosystem health decline in various areas of the Bay (5, 12, 13). To address this problem, the regional management plan has set a target of reducing the suspended sediment input to the Bay by 50% (6).

This review integrates the available knowledge on sediment accumulation and metal concentrations in sediments deposited in Moreton Bay since the onset of industrialisation, providing a reference point for future works on trace metal contamination in Moreton Bay.

Assessing metal contamination in sediments

Metals' inherent toxicity can be used as an indicator to monitor the quality and ecologic health of estuarine environments. Assessment of trace metal contamination in sediments is made by comparison with the natural geochemical variability and/or by comparison with sediment quality guidelines (see examples in (14–16)). In order to quantify metal contamination, it is essential to distinguish between the anthropogenic and natural contribution of trace metals in sediments. Enrichment factors ($EF = \text{metal concentrations}_{\text{sample}} / \text{metal concentrations}_{\text{background sample}}$) (16) are commonly used as a means of quantifying anthropogenic contribution of metals by comparison with background concentrations, which represent concentrations of metals in pre-anthropogenic uncontaminated sediments (16). Based on EFs classification, $EF = 1-1.5$ indicates that metals are mostly sourced by crustal material, $EF = 1.5-3$ denotes moderate enrichment, $EF = 3-5$ implies moderate to severe enrichment and the need for further investigation, while $EF = 10-25$ represents severe enrichment and serious environmental contamination.

The environmental risk to the aquatic ecosystem associated with metals, organic chemicals or nutrients is defined by water and sediment quality guidelines that set acceptable levels for chemical substances. Sediment quality refers to the ability of sediments to support a healthy benthic ecosystem. For Australian sediments, it is assessed by applying the Australian and New Zealand Guidelines for Fresh and Marine Water Quality – ANZECC and ARMCANZ (Australian and New Zealand Environment and Conservation Council, and Agriculture and Resource Management Council of Australia and New Zealand) interim sediment quality guidelines (ISQGs) for fresh and marine water quality (1). Metal concentrations below ISQG-Low values (ISQG-L) are unlikely to have adverse effects on the environment or aquatic organisms, whereas concentrations higher than ISQG-High values (ISQG-H) indicate highly contaminated sediments, which are likely to have adverse biological impacts (17). Reference median ranges for metals occurring naturally in Queensland estuarine sediments (18) are also used as benchmark guidelines for comparison of metal contamination in sediments (Table 1).

Metal contamination in Moreton Bay

The ranges of concentrations (maximum and minimum) of trace metals (Cu, Pb, Zn, chromium (Cr), nickel (Ni), arsenic (As), and Cd) found in intertidal and subtidal sediments of Moreton Bay are summarised in Table 1. Mercury (Hg) values were not listed in Table 1 because there were analysed in only very few studies (19–21) (Fig. 1). Details of the location of sampling sites, sediment characterisation, and concentrations of other metals are found in each cited work. Although results from these studies are difficult to compare because of the different analytical methodologies used, assessment of contamination was generally made against a) enrichment factors (EFs) and b) by comparison with sediment quality guidelines.

Background concentrations

To date, few studies have defined metal background concentrations to assess contamination in Moreton Bay sediments. Some studies have used as a reference, benchmark metal concentrations defined for sediments of Queensland freshwater

Table 1. Ranges of total metal concentrations (mg/kg) in Moreton Bay sediments (modified from (18)). ICP-MS: Inductively Coupled Plasma Mass Spectroscopy, ICP-OES: Inductively Coupled Plasma Optical Emission Spectroscopy, AAS: Atomic Absorption Spectroscopy, XRF: X-ray Fluorescence.

Source	Location	Sample	Metals	Cu	Pb	Zn	Cr	Ni	As	Cd	sediment fraction (mm)	analytical method
[18]		RMR-median	mg/kg	17	5	5	60	10	n/a	0.5	< 0.063	
[17]		Australian ISQG-L		65	50	200	80	21	20	n/a		
		Australian ISQG-H		270	220	410	370	52	70	n/a		
[30,31]	Boggy Creek	surficial sediments mangroves	pre 2005	min 3	8	41	8	2	n/a	n/a	bulk	aqua regia ICP-OES
[33]	Kedron Brook Floodplain	surficial sediments		117	118	184	n/a	n/a	n/a	0.3	bulk	seq.extraction AAS
[28]	Whinnum	surficial sediments	pre 2005	min 25	8	46	n/a	n/a	n/a	n/a	bulk	aqua regia AAS
				max 134	27	211	n/a	n/a	n/a	0.15		
[32]	Bulimba Creek	sediment core	pre 2005	min 20	10	30	33	18	ns	0.1	< 0.063	aqua regia ICP-OES
				max 50	62	96	69	30	ns	0.3		
[34]	Waterloo Bay	sediment core	pre 2005	min 20	2	20	n/a	n/a	0.1	0.1	bulk	aqua regia ICP-OES
				max 42	20	52	n/a	n/a	2.4	0.8		
[36]	Logan River	surficial sediments	pre 2005	min 15	2	45	23	23	n/a	0	< 0.063	aqua regia ICP-OES
				max 38	21	72	49	35	n/a	0		
[23]	Beachmere	sample 39	pre 2005	2	n/a	35	19	7	5	n/a	bulk	aqua regia ICP-OES
		sample 40c clay		2	5	53	20	9	9	n/a		
[37]	Gold Coast Broadwater	surface sediments		min 4	6	2	0.2	3	n/a	n/a	< 0.063	HNO3-H2O2-HCl AAS
				max 2990	166	596	31	24	n/a	n/a		
[35]	Waterloo Bay	surface /subsurface		min 2	3	4	n/a	3	n/a	0.5	< 0.063	HNO3-H2O2-HCl AAS
				max 61	56	117	n/a	27	n/a	2		
	Sandstone Point	surface		4	4	14	3	1	n/a	0.02		
	Beachmere	surface		1	3	8	6	2	1	0.04		
	Deception Bay	surface		14	5	11	4	1	1.4	0.03		
	Redcliffe	surface		5	6	10	18	2	3.6	0.11		
	Nudgee Beach	surface		6	6	34	14	9	2.2	0.10		
[21]	Fishermans Island	surface	2005	26	16	35	331	13	2.4	0.09	bulk	aqua regia ICP-OES
	Wynnum	surface		11	27	58	23	10	n/a	0.04		
	Waterloo Bay	surface		4	4	13	6	3	2.9	n/a		
	Ormiston	surface		6	7	31	10	8	5.3	n/a		
	Point Halloran	surface		31	5	20	6	1	n/a	n/a		
	Point Talburpin	surface		18	13	89	26	20	5.5	0.01		
[15]	Moreton Bay	intertidal sediment cores	2007-2009	min 3.2	4.5	9.3	15.5	3.7	5.9	0.02	< 1	HNO3, HF, HCl ICP-MS
				max 30	38	103	116	36	18	0.3		
			post-2011	min 4	3	9	123	9	3	0.02		
			Apr-12	max 26	17	118	358	36	13	0.08		
[19]	Deception Bay	subtidal	post 2011	min 3	2	5	8	3	3	0.01	< 0.10	3HNO3+1HCl ICP-MS
		surface sediments	June2012	max 21	18	91	95	34	12	0.06		
			post-2011	min 2	3	5	8	2	3	0.01		
			Nov-12	max 23	19	99	111	37	17	0.09		
[14]	Deception Bay	subtidal surface sediments	post-2011	Max 1.9	3.4	4.9	107	6.5	0.7	n/a	< 2	XRF
				Min 20.8	14.7	548	186	35.3	10.0	n/a		
	Moreton Bay	intertidal surface sediments	2007-2009	min 3.1	3.2	11.3	11.5	3.5	2.7	0.02	< 1	HNO3, HF, HCl ICP-MS
				max 30.1	37.7	103.0	116	36.2	18.5	0.3		
[24]	Moreton Bay	intertidal sediment cores	2007-2009	min 2.0	0.1	5.5	7.6	2.2	0.4	0.01	< 1	HNO3, HF, HCl ICP-MS
				max 45.6	21.2	117	116	51.7	24.0	3.7		
[22]	central Moreton Bay	surface subtidal	post-2011	min 6.0	10	17	13	10	n/a	n/a	bulk	3HNO3+1HCl ICP-OES
				max 40	26	140	257	54	n/a	n/a		

streams, estuaries and coastal waters calculated between 1975 and 1992 (18). In the central Moreton Bay mud-dominated zone, a geochemical background representing metal concentrations deposited before the onset of urban and industrial development was defined, based on the geochronology of two subtidal sediment cores (22). Metal concentrations prior to European development were also defined for intertidal areas in Deception Bay, Bramble Bay and in southern Moreton Bay (15). In Deception Bay, three sites were selected to define background concentrations (14), but a site near Rocksberg in the upper Caboolture River, the major contributor to sediments in Deception Bay (14, 19), was chosen to best represent the background geochemical composition of Deception Bay. Background values in the Pumicestone region were established for local bedrock, estuarine sediments and soils (23). Given the hydrodynamic variability of the Bay, contamination assessments should carefully select background concentration ranges

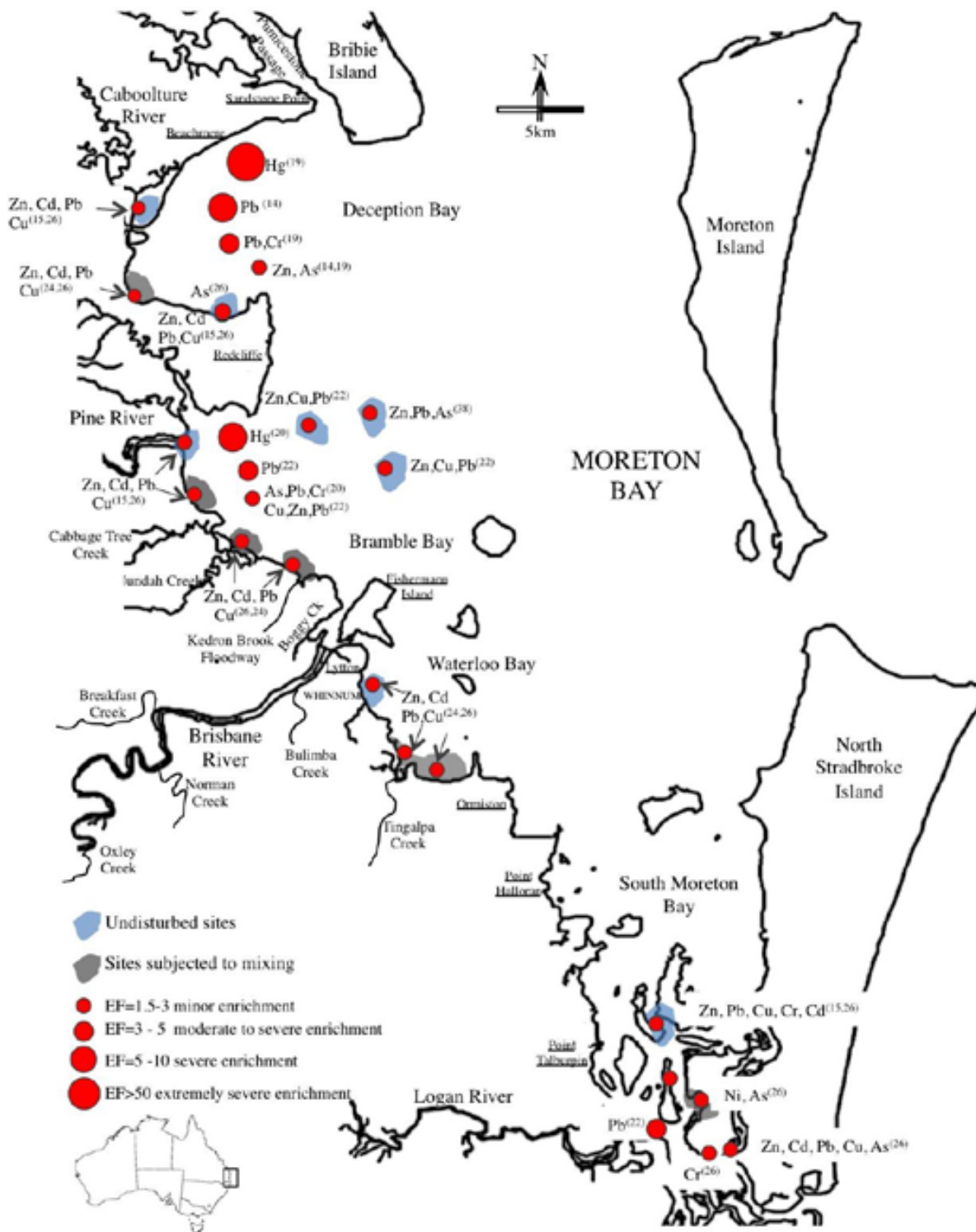


Figure 1. Distribution of trace metal enrichment factors (EF) in intertidal and subtidal sediments of Moreton Bay. Dots indicate ranges of enrichment factors for the metals listed. In the map only EFs>1.5 are included. Details of the sediment locations are found in each cited work (reference numbers in the map).

that best reflect the site-specific depositional environment of the area where contamination is assessed (16, 24). Most of the studies on sediment contamination in Moreton Bay are focused on small sampling areas or localised zones (e.g. 28, 29, 33, 40). Few studies (14, 19, 22, 25) have analysed sediments deposited in the period following the 2011 Brisbane River flood. Some large-scale investigations evaluated metal concentrations in sediments from the northern to the southern part of Moreton Bay (14, 19, 22, 25), while others provided a temporal record of metal contamination from sediment cores (21, 22, 24, 26, 27). An outline of the sites in Moreton Bay where sediments were found to be enriched in metals ($EF > 1.5$) is shown in Figure 1.

Bay-wide studies

Pollution levels in surficial sediments across Moreton Bay were investigated in several studies. The regional distribution of metals within intertidal sediments along the western Moreton Bay shoreline was investigated in a 2005 study (21) integrating new results together with previously existing data. The most significant contaminants identified in this study were Ni, Pb, Hg, Zn, and occasionally Cd, As and Cr. The highest concentrations of metals were associated with fine estuarine sediments close to urban and industrial areas (maritime and port facilities, light industries) and concentrations were two to three times higher than in nearby sediments from sandy shorelines (21).

Another study has assessed contamination in 15 intertidal sites sampled between 2007 and 2009 (26). Chromium, Ni and Cu were found to be the main contributors to sediment pollution, with Cr and Ni exceeding the ISQG-L levels in Deception Bay, in the Pine River and in southern Moreton Bay (26). Sediments were also enriched in Zn, Cd and Pb by 1.5–3 times the background levels. A more recent work (unpublished thesis (27)) has analysed 43 intertidal surface sediments in mangrove areas from northern to southern Moreton Bay (27). Sediments in Deception Bay showed minor enrichment ($EF < 2$) for most of the metals, while minor to severe enrichment ($EF < 10$) was found in Waterloo Bay (EFs : As=2.25, Cr=3.56, Cu=2.55 and Zn=2.05) and southern Moreton Bay (EFs : Cr=2.93, Cu=7.74, Pb=2.26 and Zn=2.05). Average metal concentrations fell between the ‘high’ and ‘low’ range of ANZECC/ARMCANZ (17) and Queensland estuarine sediment (18) guidelines, while maximum values of As, Cr and Ni exceeded the ISQG-H at some sites (27). These results were not included in Figure 1 and Table 1 as they have not been published. Other investigations were aimed at assessing metal concentrations in restricted areas of the Bay.

Deception Bay

Thirteen subtidal sediment samples from Deception Bay were analysed three times over a period of seven months (4) and Hg was identified as the element of highest enrichment, posing moderate to severe risk to the local ecology of Deception Bay (19). Another study undertaken in the same area revealed severe Pb pollution (average $EF=13$) and minor to moderate enrichment of As, Zn and Cr (average EFs were 2.3, 2.7 and 3.7, respectively) (14). These concentrations reflect the rapid population growth and the expansion of industrial activities that has occurred in Deception Bay since the 1980s (4).

Bramble Bay

In Bramble Bay, fine estuarine intertidal muds were enriched in Cu, Zn, Cd and Pb close to the reclaimed landfill site in Wynnum, and concentrations decreased at increasing distance from the landfill (28). Significant concentrations of Cu, Zn, Pb and Ni were found in mangrove sediments in the same area. Analysis of the transfer processes of metals to mangrove sediments revealed that in a 15-year period around 46kg of Pb, 137kg of Cu, 941kg of Zn, 0.2kg of Hg, 1kg of Cr and 127kg of Ni moved from the landfill to the mangroves through surface run-off (29).

A recent work examined trace metal contamination in post-2011 flood surficial subtidal sediments of Bramble Bay and determined the spatial patterns of pollution and the temporal changes in metal concentrations in February, April, June and November 2012 (20). The overall sediment health of Bramble Bay was assessed as good, and only Cr and Ni maximum concentrations exceeded the low thresholds of the ISQGs (ISQG-L). Compared to the geochemical background, sediments across Bramble Bay were found to be slightly enriched in Zn (max EF=1.8) and Pb (max EF=2.9), moderately enriched in As (max EF=4.1) and at some sites severely enriched in Hg (max EF=73) (20).

Brisbane River estuary

The Brisbane River estuary is downstream of the most heavily urbanised area in the region. Breakfast, Norman, Oxley, Boggy and Bulimba creeks and Kedron Brook Floodway have been exposed to urban and industrial contamination. Reports by the Department of Environment (18) found levels of Zn, Cu, Ni and Pb exceeded the environmental guidelines in Breakfast, Norman and Oxley creeks (18). Surficial sediment analysis within mangroves along the Boggy Creek inlet showed high levels of nutrients (due to Luggage Point sewage) and metals (Cu, Pb, Zn, silver (Ag), Cr, Ni, As) at the seaward edge of the woodland, reflecting the industrial and urban history of the Brisbane River estuary (30, 31). In the lower sections of Bulimba Creek, close to the industrial zone near the junction with the Brisbane River, sediments were enriched in Cr and Pb (21, 32). In the Kedron Brook floodplain, a low-lying area drained by artificial canals, the estuarine channel bed sediments were more enriched in Cu, Zn and Pb than the floodplain sediments (33).

Waterloo Bay

High concentrations of Cu, Zn and Pb were found in intertidal muddy sand in Waterloo Bay close to a drainage creek near an industrial area (34). Also, along the intertidal areas in Waterloo Bay, data obtained from surface samples at 19 sites found contamination in sediments, with Cu, Zn, Pb, Ni and Cd above natural background levels for Queensland estuaries and exceeding the ISQG-L (Pb at three sites, Ni at two sites and Cd at one site) (35).

Southern Moreton Bay

Analyses of 20 surface samples of estuarine silts from the Logan River in southern Moreton Bay showed high levels of Pb and Zn in the vicinity of populated areas. Concentrations of Cu, Zn and Pb decreased downstream, whereas Cr increased (36). Sediments from the Pimpama River (15 km south of the Logan River) were enriched in trace metals despite the river

catchment being characterised by low levels of anthropogenically introduced metals (23). Concentrations of Cu, Pb and Zn in sediments from residential canals and commercial marinas in the Southport Broadwater were found above Queensland natural background levels as well as Australian sediment quality guidelines in most of the sites. Those high concentrations were attributed to urban stormwater run-off, run-off from local industries, and to metals derived from maintenance of vessels (37).

Sediment cores

Sediment cores are excellent archives of past sediment deposition and vertical metal profiles in undisturbed sediments are used to reconstruct the history of pollution in coastal areas (see example in (15)). In the western side of Moreton Bay, analyses of nine sediment cores from intertidal flats that integrated sediment geochronology with vertical profiles of metal concentrations revealed the extent of trace metal contamination since European settlement (15). A consistent temporal increase in Pb, Zn, Cd, Cu and Ni concentrations was found in Deception Bay, Bramble Bay, Waterloo Bay and southern Moreton Bay. Compared to pre-European background levels, metal concentrations increased by up to two orders of magnitude (EF=2) after ~1923 and maximum metal input (EF=4) was recorded during the 1950s to 1970s. A similar trend was observed in sediment cores at two subtidal sites in central Moreton Bay (22). Enrichment in Zn, Pb and Cu in sediments deposited after 1959 corresponds to the period of increased population growth, and consequent intensification of metal inputs from industrial activities and urban run-off into the Bay. Similarly, temporal trends of increasing Zn, Pb, Cu and As concentrations in sediment cores in the northern part of Waterloo Bay were correlated with the expansion of the refinery in Lytton established in the 1960s, with run-off from the Brisbane Airport, and with the nearby wastewater treatment plants (24).

In the subtidal areas of Moreton Bay, an extensive study of sediment cores and surface sediments assessed the effects of the 2011 Brisbane River flood on trace metals deposition in Moreton Bay (22). Sediments deposited in central Moreton Bay after the flood, were highly enriched in Zn, Cu and Pb. The highest enrichment was recorded in Bramble Bay at the mouth of the Brisbane River, Cabbage Tree Creek and Kedron Brook, with Zn, Cu and Pb EFs as high as 2.7, 2.6 and of 3.4, respectively. Sediments in southern Moreton Bay were enriched in Pb (EF up to 5.3) close to the Logan River. The high metal concentrations found in the flood deposits were attributed to the remobilisation and redeposition of metal-rich sediments accumulated on the Brisbane River floodplain during the 10 to 40 years before 2011 (5, 22). Also, post-2011 flood sediments showed higher metal concentrations in subtidal areas in Bramble Bay and in central Moreton Bay (22) compared to concentrations found in pre-flood intertidal sediments along the western side of Moreton Bay (26).

Factors influencing metal distribution in Moreton Bay

Most of the reviewed studies found that sediments were enriched in metals in different areas throughout Moreton Bay. Among the main risks leading to ecosystem deterioration is the redistribution of metals associated with old contaminated sediments, induced by sediment mixing (10, 24). Identifying areas prone to sediment disturbance is thus of critical importance in Moreton Bay (24). A few studies have shown that deposited sediments remained

undisturbed, thus providing a chronological record of metal input (15, 22, 38, 39). However, in some areas sediment deposition is mostly controlled by the local hydrodynamics of the Bay (24, 38) and vertical redistribution of metals may occur up to at least 80cm depth (24). For example, increasing concentrations of Pb, Zn and Cu towards surface sediments in Bramble Bay and Waterloo Bay correlate both with increased anthropogenic input in the last century and to post-depositional processes (e.g. bioturbation, sediment disturbance) (24).

Most importantly, in areas where sediment mixing occurs, changes in the environmental geochemical conditions may facilitate the desorption and remobilisation of sediment-bound metals (in particular the exchangeable or weak-bound metal fraction (10)), which may become bioavailable and toxic for aquatic organisms (10). For instance, high concentrations of As found at around 20cm depth in a sediment core from Waterloo Bay (24), following the resuspension of sediments, may represent a risk to biota. In Moreton Bay, the potential risk posed to the ecosystem by metals likely to become bioavailable (weakly bound metal fractions) was assessed only to a limited extent. Results of the available studies were not reported in Table 1 as they are difficult to compare because of the different analytical extraction methods used. Deception Bay and Bramble Bay were found to be the areas at higher risk (14, 26). Analyses of 15 surface intertidal sediments along the western side of the Bay found cobalt (Co), Zn and Cd falling into the medium risk category at almost all sites; Zn and Cd were found to pose high to very high risk to the aquatic biota at three sites in Deception, Bramble and southern Moreton Bay, while Ni, As, Cu, Pb and Cr may pose medium risk at all of the sites (26). Another study examined subtidal sediments in Deception Bay three times over a period of seven months, finding that the exchangeable fraction was relatively low compared to the guidelines for As, Cd, Cr, Cu and Pb, with the exception of Hg, which may pose some risk for the ecosystem (19).

Six sites (intertidal and subtidal) in Bramble Bay were analysed in four periods of the year to assess the temporal variability of the weak-bound metal fraction in sediments (20). The sediment guidelines were exceeded only for Ni and Cr, while Hg was found to be the most enriched metal with the highest Enrichment Factor in sediments collected in June. Also, Hg and Cd showed increasing trends over the entire sampling period, probably because of an ongoing pollution source in the area, while As concentrations were found to be more stable over the same period. Temporal variations in metal concentrations were also attributed to the occurrence of sequestration processes and to variation in sediment fluxes controlled by changes in water flow during the wet/dry season (see (20) for more details).

A study on Southport Broadwater sediments in southern Moreton Bay revealed that relatively small changes in the environmental conditions would cause the release of Cu, Pb and Zn associated with iron (Fe) and manganese (Mn) oxide minerals (7). The metal-exchangeable fraction was also quantified in 13 sediment cores from intertidal areas across Moreton Bay (41). Results showed that at least 20% of the total metal concentrations for Co, Cd and Zn in most of the sediments are potentially bioavailable. This study also correlated the temporal variability of the exchangeable fraction of Zn, Pb, Cr and Ni with the increase in metals usage

since the beginning of the century. These data have not been reported here as they have not been published (41).

Major sources of metal contamination in Moreton Bay

Most of the studies reviewed in this paper show that the main contribution to the metal contaminants load in Moreton Bay derives from the urban development of the catchment area, from the associated sewage discharge, industrial run-off, urban stormwaters, and wash off from urban surfaces (e.g. roads). In Bramble Bay and especially close to the Brisbane River, contamination (Pb, Cd, Zn, As and Ni) is mainly associated with urban stormwater drainage from municipal solid waste landfill, and the industrial area of Lytton Point (20, 21, 26). Heavy marine traffic, recreational and industrial marinas, and vessel maintenance are identified as the major sources for Cu, Ni and Hg contamination in Deception Bay and southern Moreton bays (14, 40, 42), with relatively high Cu levels found around marinas and mooring facilities due to the usage of Cu-based antifouling paints (37, 40, 43, 44). Significant amounts of Cd, Cr and Cu also derive from agriculture and fertilisers, while Pb, Zn and Ni originate mainly from combustion of fossil fuel (22) and using leaded gasoline (Pb), similar to other sites around Australia (15, 23).

Variability of sediment deposition in Moreton Bay

Sediments are the main drivers of trace metal distribution in estuaries. Sedimentation in Moreton Bay is largely controlled by tidal currents and by major flood events. Some studies have characterised sediment accumulation core rates in sediment cores, providing the geochronology of sedimentation in the last 150–200 years (Table 2).

Table 2. Sedimentation rates in Moreton Bay.

Source	Location	Dating method		dated material	Depth (cm)	Age (yBP)	Sedimentation rates (cm/yr)	Mass accumulation rates (g cm ⁻² yr ⁻¹)
[5]	central Moreton Bay mud dominated region	210Pb	137Cs	subtidal	core MB1	55	~59	0.66-0.82
		210Pb	137Cs	subtidal	core MB2	59	~59	0.83-0.84
[15]	Deception Bay	210Pb	137Cs	intertidal	core G37	0-17		0.13-0.27
	Deception Bay	210Pb	137Cs	intertidal	core G34	0-12		0.12-0.23
	Pine River	210Pb	137Cs	intertidal	core G6	0-44		0.31-0.71
	south Moreton Bay	210Pb	137Cs	intertidal	core G31	0-40		0.63-0.72
[38]	central Moreton Bay mud dominated region	210Pb	137Cs	subtidal	core MBSC2	0-85	~42	0.62
		210Pb	137Cs	sediment core		0-60	~60	1.2
[5]	central Moreton Bay mud dominated region	Optical dating	14C		core MB1		215 ± 50- 1440± 140	0.24 ± 0.02
		Optical dating	14C		core MB2		2900±250 - 462±43	0.09 ± 0.01
[7]	Moreton Bay					500	6500	0.08

Data on sedimentation rates in Moreton Bay are in agreement with studies suggesting that modern rates of erosion in Australia have increased by a factor of up to 145 compared to the natural rates before European settlement (3, 25). One of the first studies estimated a long-term bulk accumulation rate of 0.08cm/yr since about 6,500 years ago in central Moreton Bay (7). In the mud-dominated zone in central Moreton Bay two sediment cores recorded an increase in sedimentation from 1840 to 1890, following the start of European settlement (5). The same study showed that sedimentation rates increased by 3–9 times in the last 100 years compared to the 1,500 years before (5). The intensification of cropping and grazing practices accelerated in the 1950s, and the effects of greater erosion from the catchment are reflected by the increase

in sedimentation rates recorded in central Moreton Bay between 1950 and 1967 (5). Similarly, an increase in sediment accumulation rates in intertidal areas was recorded in the same period in four sediment cores, which preserved the history of sediment deposition since approximately 1900 (15, 39). Average accumulation rates in the central part of the Bay were around $\sim 0.83 \text{ g cm}^2/\text{yr}$ between 1959 and 2011 (5), while in intertidal areas rates varied from about 0.16 to $0.72 \text{ g cm}^2/\text{yr}$ in the last 70 years (15, 38). Comparison of sediment accumulation rates (Table 2) highlights the spatial variability of Moreton Bay sedimentation, which reflects the complex hydrodynamics of the Bay (24, 41), mostly controlled by the local hydrologic, physical and tidal conditions (15). Also, evidence of post-depositional diagenetic processes and sediment mixing at different sites (24, 38) shows that the sedimentary record may be disturbed up to a depth of at least 1m, as found in cores from Waterloo Bay (24).

The risk of metal redistribution induced by mixing of old deposited sediments is of concern, especially where fine particles are dominant. Fine sediments represent the dominant fraction in Moreton Bay, covering about 860 km^2 and more than 50% of the area of the Bay (45). Compared to the sediment distribution map completed in 1970 (46), the area covered by fine sediments has increased and other extensive particle size mapping exercises published in 1999 have shown that the area of mud-rich sediments had expanded significantly at that time (47). Tide-induced resuspension is the primary driver of turbidity regimes and sediment transport within Moreton Bay, while flood events are episodic determinants of sediment distribution in the Bay (5, 22, 45). For example, an estimated 5.4Mt of sediments were transported into the Brisbane River estuary during the 1974 flood, while $\sim 10 \text{ Mt}$ of fine ($< 63 \text{ mm}$) sediments were deposited in Moreton Bay during the November 2011 flood (22). After this event, a 10–20cm layer of recent fine sediments was found in sediment cores within the central mud-dominated zone north-east of the mouth of the Brisbane River, showing that after big floods sediments are transported and reworked from shallow coastal areas to deeper regions of the Bay where they gradually accumulate (5, 22). The dramatic increase in fine silt and clay that occurred in recent decades is cause for ecological concern as it may enhance the risk of dispersal of associated trace metals into still pristine areas (45).

Implications for management of contaminated sediments in Moreton Bay

Health assessments of estuarine ecosystems are based on indicators relevant to the type of estuary, pressures on the estuary and management objectives. Indicators should be selected considering existing problems, and likely future scenarios, such as those posed by changes in catchment land use or climate change. Existing studies have demonstrated that metal contamination in Moreton Bay is mainly caused by (i) current pollution from point sources e.g. wastewaters, industrial areas discharge, water treatment plants or urban run-off, (ii) transport of contaminated sediments, and (iii) remobilisation of old contaminated sediments buried below new sediments. The nature and distribution of metal enrichment in the Bay is controlled by local pollution sources and by hydrodynamic factors and it is not consistent across the different embayments (22, 24). This site-specific variability must be considered when performing contamination assessment monitoring. The complex interactions among meteorological, hydrodynamic, biological and geochemical factors result in a metal transport system with spatial and temporal variability. Post-deposition sediment remobilisation induced

by natural (e.g. bioturbation) or by anthropogenic (e.g. dredging) processes increases the risk of metal redistribution (24). For example, strong tidal currents and large flood events transport fine particles into the central part of Moreton Bay, redistributing contaminated sediments from the western Bay (22). Hence, because of their inherent toxicity and the risk of becoming bioavailable (10), the monitoring of trace metal concentrations is needed to assess and thus preserve the quality and ecologic health of Moreton Bay.

Sediment contamination is complex to manage due to the tendency for metals to be retained within sediments for long periods, as shown by trace metal temporal trends recorded in sediment cores (15, 22, 24). Contaminated sediment can thus become a major obstacle to restoration efforts in degraded aquatic environments. Furthermore, climate change is increasing the frequency of extreme events (48) (e.g. storms, cyclones, floods) and it is expected to increase sediment loads, thus accelerating the redistribution of sediments and contaminants.

A regular environmental monitoring program is maintained in South East Queensland to support policy and planning decisions for the preservation of the natural ecosystem (49). The Healthy Land and Water (HLW) Report Card released each year delivers a measure of the pressures facing the Moreton Bay region and ranks its environmental condition grade from excellent (A) to fail (F) (49). Monitored indicators are freshwater communities, ecosystem processes, habitat, estuarine water quality, and sediment, nitrogen and phosphorus loads. However, the report card does not include metal contaminants as an indicator of environmental quality. Routine monitoring of trace metals in sediments could be added to the HLW program in Moreton Bay. Routine surveys would contribute to provide information for decision makers to take into account pollutant loads when restoring affected sites and/or preventing the disturbance of contaminated areas by, for example, improving management planning for dredging and maintenance of navigational channels preventing metal redistribution by sediment mixing.

Results summarised in this paper show that trace metals accumulated in sediments represent a risk to the Moreton Bay ecosystem. This review also identifies areas that are potentially more susceptible to metal deposition, and including these areas in future studies may contribute to future management strategies for Moreton Bay. The prevention of metal contamination will enhance the resistance and resilience of the ecosystems of the Bay and their ability to withstand the increased frequency and severity of disturbances caused by climate change. A more rigorous approach to managing contaminated sediments aimed at reducing the sources of metals into Moreton Bay should be embraced to preserve water quality and the health of the ecosystem.

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