Moreton Bay and Its Estuaries: A Sub-tropical System Under Pressure from Rapid Population Growth

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Abstract

Moreton Bay and its associated estuaries are an example of a complex aquatic system that is under increasing pressure from rapid population growth and urbanisation. Although the extent of decline in ecosystem health within Moreton Bay and its associated estuaries is significant and well documented, a range of innovative management responses have been implemented to reverse current declines. An overview of the development of Moreton Bay is provided, highlighting the dynamic and resilient nature of the system over geological time. The ecological responses that occur at decadal timeframes are presented along with a summary of the current state of the Bay's ecology. The future challenges that are posed by predicted population increases, urbanisation and changes to the region's climate are also discussed. The highly variable nature of the system over relatively short timeframes (i.e. flood vs non-flood conditions) as well as the ability of the system to adapt to long term changes (i.e. past morphological and ecosystem shifts) suggests that Moreton Bay and its associated estuaries have significant capacity to adapt to change. Whether the current rate of anthropogenically induced change is too rapid for the system to adapt, or whether such adaptions will be undesirable, is unable to be ascertained in any detail at this stage. Notwithstanding the above, the combination of a science-based management framework and the collaborative decision making processes that have been implemented to halt the decline of Moreton Bay have shown remarkable progress in a relatively short period of time.

Keywords

Moreton Bay • Sub-tropical estuary • Water quality • Ecosystem health • Ecosystem resilience • Marine park • Environmental management

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Box 1

Badin Gibbes and colleagues studied Moreton Bay and its associated estuaries that are under increasing pressure from rapid population growth and urbanisation. They document the decline in ecosystem health as well as a range of innovative management responses to reverse current declines. The ecological responses occur both at decadal timeframes as well as over relatively short timeframes (i.e. flood vs. non-flood conditions). Whether the current rate of anthropogenically induced change is too rapid for the system to adapt, or whether such adaptions will be undesirable, is unknown at this stage. Nevertheless the science-based management framework that has been implemented to halt the decline of Moreton Bay has shown remarkable progress in a relatively short period of time.

Introduction

Moreton Bay and its associated estuaries provide an example of a complex aquatic system that is under increasing pressure from rapid population growth and urbanisation. The region has a human population of more than three million people and is one of the fastest growing regions in Australia with an expected population of over four million people by 2026 (QOESR 2011). The region's history of rapid population growth has also shaped the current condition and function of its waterways. The region has experienced significant land use change, dominated by the removal of native vegetation since European settlement approximately 200 years ago. Although the extent of decline in ecosystem health within Moreton Bay and its associated estuaries is significant and well documented, the characteristics and values of the region have also inspired the development and application of a range of innovative management responses in an attempt to reverse current declines. In this regard it provides an instructive case study for management of estuarine systems that are undergoing rapid transformations. This chapter provides an overview of the development of Moreton Bay and highlights the dynamic and resilient nature of the system over geological time, as well as investigating the ecological responses that occur at decadal timeframes. A summary of the current state of the Bay's ecology is also provided before discussing the future challenges that are posed by predicted population increases, urbanisation and changes to the region's climate.

Site Geomorphological and Hydrological Settings

Moreton Bay is a semi-enclosed subtropical embayment of considerable geomorphic, ecological and economic significance, and an important recreational and aesthetic resource for the people of southeast Queensland. The Bay lies between 27° and 28° south latitude, approximately 110 km north to south, and has its major opening to the north (Fig. 1). It is roughly triangular in shape with a 15.5 km wide north entrance opening (Skirmish Point to Comboyuro Point) tapering to the mouth of the Nerang River in the south. The seabed in Moreton Bay slopes from west to east with a gradual slope near the western shore that transitions to a steep slope on the eastern shoreline. The deepest waters of the Bay are at 20–29 m along the west coast of Moreton Island and the northwest margin of the South Passage flood tide delta.

The Bay is defined on the east by the large dune island barriers of Moreton Island (198 km^2; 37 km long), and North Stradbroke Island (285 km^2; 36 km long), and the barrier island South Stradbroke Island (26 km^2; 20 km long), and the Southport Spit. Formation of the eastern margin of the Bay was by aeolian dune building, onshore sand transport and northward longshore spit formation during the sea level oscillations of the late Quaternary, with the modern shoreline a product of the last stages of the post-last glacial sea level rise and the late Holocene sea level high stand. Although these sand islands have formed over several hundred thousand years (Ward 2006), continual changes to their

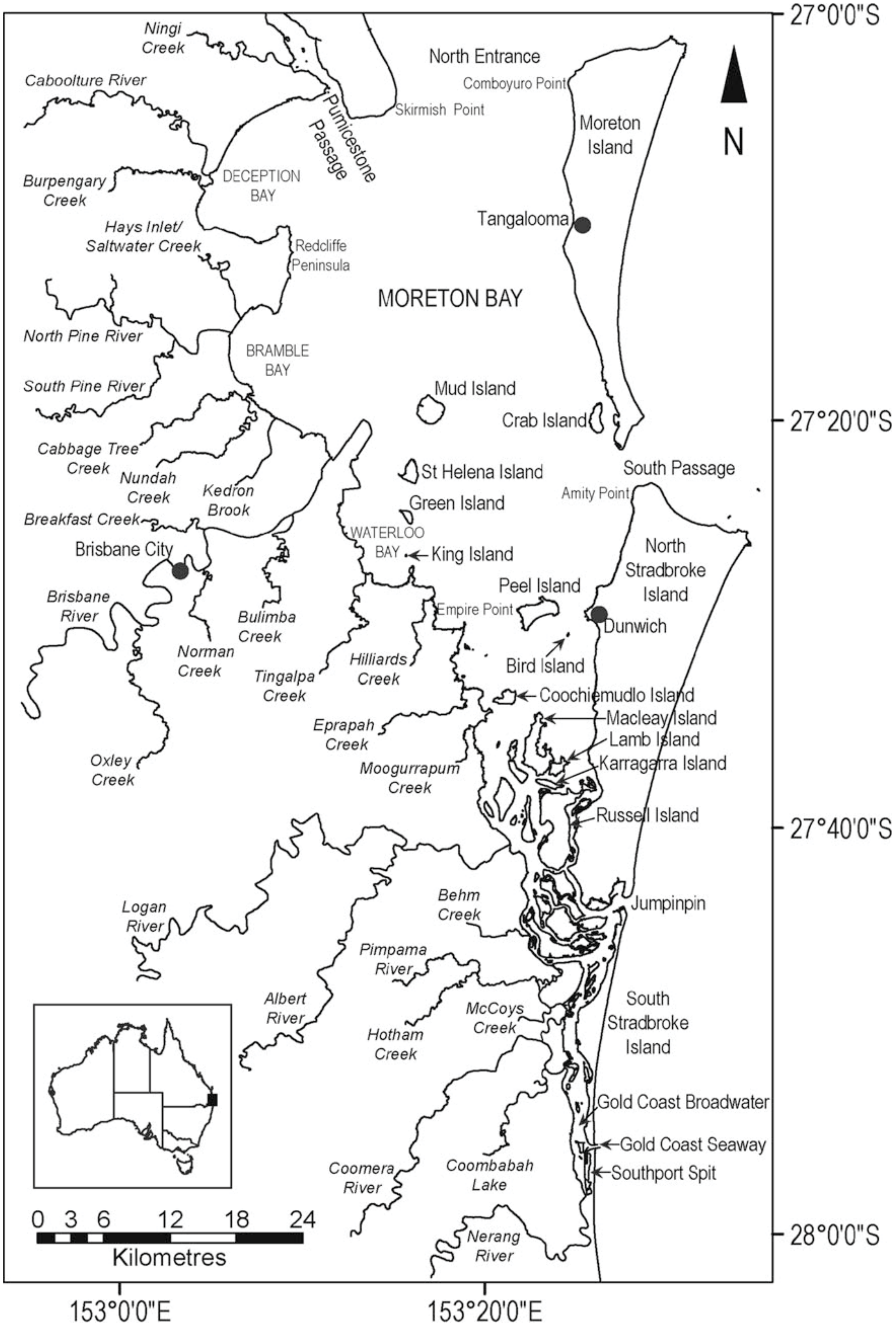

Fig. 1 The Moreton Bay estuary illustrating the major river systems draining to the Bay and the major tidal entrances that connect the Bay to the adjacent Coral Sea

Fig. 2 Photographs of the Moreton Bay estuary illustrating (**a**) the relatively undeveloped shoreline of the eastern Bay at Tangalooma, (**b**) marina and new residential canal estate development (*foreground*) adjacent to a relatively undeveloped island (*middle* to *background*) in the southern Bay, (**c**) urbanisation of the lower Nerang River, and (**d**) the Luggage Point sewage treatment plant (*foreground*) and Port of Brisbane (*background*) at the mouth of the Brisbane River

shorelines during the course of the last several thousand years have in turn resulted in changes to the Bay's bathymetry, tidal exchange, flushing and the existence and characteristics of islands and ecosystems within the Bay. The eastern shoreline of the Bay is largely in a natural state with very limited areas of human settlements, infrastructure and disturbance (Fig. 2a).

Four entrances provide oceanic exchange by tidal flushing of the Bay. The North Entrance is the largest and the most significant contributor to oceanic exchange. It is ≈15.5 km wide and the subtidal banks penetrate up to 18 km into the Bay. South Passage is ≈3.7 km wide with associated flood tide delta deposits (intertidal and subtidal) that extend 13.5 km, more than half way across the Bay. The Jumpinpin Entrance between North and South Stradbroke Islands is ≈0.8 km wide. Both the South Passage and Jumpinpin entrances are dynamic in response to changing wave and sediment transport conditions. The Southport Entrance between South Stradbroke Island and the mainland Southport Spit was replaced by an artificial, rockwall stabilised entrance (the Gold Coast Seaway) opened in 1986, which has increased tidal flushing of the southern Bay and Broadwater areas. Moreton Bay has semi-diurnal tides and, in the eastern Bay (at Amity Point), the mean tidal range is 1.48 m (springs) and 0.84 m (neaps). The tidal range is about 15 % higher in the western Bay (Brisbane Bar). The coastal ocean to the west of Moreton Bay is dominated by the East Australian Current (EAC) which allows the tidal exchange of warm tropical water (and associated biota) with the Bay through its four entrances. The EAC adjacent to Moreton Bay is relatively consistent in both flow rate and water temperature, and has a low frequency of upwelling events (i.e. there is little evidence to suggest that oceanic upwelling is a source of nutrients for the Bay, however this aspect still needs further investigation).

The west (mainland) coast of the Bay is characterised by a number of relatively erosion resistant headlands of Tertiary volcanics with extensive deposits of Quaternary alluvium in intervening embayments and adjacent to river and creek mouths. From the Pumicestone Passage in the North to the Gold Coast Broadwater in the south there are 20 estuaries (as well as many smaller ephemeral creeks) that connect to the western shoreline of the Bay which has seen significant alteration and disturbance by human activities. Habitat disturbance by both commercial and recreational activities is widespread (e.g. Fig. 2b–d). Land 'reclamation' and seawall construction is ubiquitous between Redcliffe Peninsula and Redland Bay, including works for the Brisbane Airport and Port of Brisbane (both located adjacent to the mouth of the Brisbane River – see Fig. 2d). Urban areas dominate the immediate hinterland of much of the western shoreline. Greater than 10 % of the catchment area of the Bay is urban and less than 25 % is remnant natural vegetation with the dominant land use agricultural (grazing ≈65 %; cropping ≈5 %) (Capelin et al. 1998).

There are no islands in the northern 30 km of the Bay. Between Mud Island (7 km northeast of the Brisbane River mouth) and the Logan River mouth there are reefal islands (comprised largely of biogenic marine sediments; Mud, Green, King, Bird), high (continental; bedrock) islands (topographic prominences associated with mainland terrains; eg. St Helena, Peel, Coochiemudlo, Macleay, Lamb, Karragarra and Russel Islands) and tidal delta islands. South from the Logan River mouth to the Nerang River estuary the southern Bay is 'choked' with numerous tidal delta islands. The high islands have been largely subdivided for residential and other development. The reefal islands, although not settled per se, have been subject to significant disturbance, including clearing of littoral rainforest and noxious weed invasion (Green Island; Neil 2000) and dredging of the adjacent reef flat resulting in erosion and mangrove mortality (Mud Island; Allingham and Neil 1995). Both Mud and Green Islands are of considerable geomorphic significance as high latitude occurrences of reef island types which otherwise only occur on the northern Great Barrier Reef (Allingham and Neil 1995; Neil 2000).

Moreton Bay is characterised as a modified wave dominated estuary with semi-diurnal tides (Digby et al. 1998). Key physical characteristics of the Moreton Bay estuary (Table 1) include the large catchment area to water area ratio (≈15:1) from which it can be inferred that, while the Bay is wave dominated for the majority of the time, the large catchment area is able to produce significant inflows that are capable of transforming the hydrodynamics and ecosystem processes in the system. This is particularly true of the two large river systems (Brisbane and Logan-Albert Rivers, catchment area >1,000 km^2) which exert a significant influence on the sediment and water quality characteristics of Moreton Bay during large rainfall events (Davies and Eyre 1998; DERM 2011).

Table 1 Summary of physical characteristics of Moreton Bay (After Digby et al. 1998)

Parameter	Units	Value
Back barrier	km^2	436.6
Central basin	km^2	1057.0
Fluvial Bay head	km^2	35.9
Flood ebb delta	km^2	149.0
Intertidal flats	km^2	75.7
Mangrove	km^2	80.3
Saltmarsh	km^2	22.8
Tidal sand banks	km^2	422.8
Seagrass meadow	km^2	189.0^a
Rocky reef	km^2	0.5
Coral	km^2	13.5^a
Channel	km^2	77.1
Floodplain	km^2	25.4
Bedrock perimeter	km	8.1
Perimeter	km	297.6
Catchment area	km^2	22,807.0
Water area	km^2	1,493.7
Maximum length	km	78.0
Maximum width	km	33.8
Entrance width	km	21.6
Mean wave height	M	0.7
Mean wave period	S	5.9
Maximum wave height	M	1.8
Maximum wave period	S	9.8
Tidal range	M	1.6

Note: ^{a}Indicates data not included in Digby et al. (1998)

Geomorphology

To explore the current and potential future states of Moreton Bay and its estuaries it is instructive to understand the range of different states that this system has existed in over geologic timeframes. In particular the ability of the system to transition between these states (i.e. from a non-marine river valley to a more oceanic embayment) provide a guide as to the possible range of future states that the system could operate within when subject to human population increases, land modification and changes in climate. Neil (1998) provides a comprehensive overview of the geomorphology of Moreton Bay and this section is largely based on this work and references therein with some more recent sources.

Orbitally-forced global-scale oscillations in temperature have resulted in significant variation in the accumulation of ice caps which, in turn, have resulted in variations in sea level of amplitude >100 m and period of >100 ka. Over the last several million years (>20) such oscillations have occurred. During warm (interglacial) periods sea levels may remain relatively constant for several thousand years. Reviewing the record of such fluctuations, it can be inferred that, over the last several million years, Moreton Bay, in something like its present form, has existed for <10 % of the time, and then each time of occurrence of the Bay differs according to maximum sea level height and duration and the antecedent conditions. The present area of Moreton Bay is a non-marine, broad river valley for about 50 % of the time. At low sea levels, most of the catchment drains east and north across the present Bay and flows north along the west coast of Moreton Island (Lang et al. 1998).

The Bay filled from about 11 ka as sea levels rose following the last glacial maximum. Present sea level was reached about 7.8 ka and maximum sea level, about 1.5 m higher than present, was reached by about 7.4 ka (Sloss et al. 2007), establishing the general form of the current Moreton Bay, but with very different characteristics. With sea level about 1.5 m higher the mainland coast was, in places (e.g. Deception Bay, Brisbane River mouth, Coomera River mouth) up to 9 km west of its present location. Most of the fluvially-derived sediment in the western Bay was not yet present. Although wave energy would have been higher, deeper water and the relative absence of muddy sediments are likely to have resulted in lower rates of wave resuspension of bottom sediments. Thus the Bay was wider, deeper, more open to seaward, better flushed and more oceanic in character with higher wave energy but lower sediment resuspension and turbidity than is the case today.

These morphological characteristics were accompanied by warmer air temperatures, warmer sea surface temperatures, higher rainfall and reduced rainfall intensity and variability – a so called 'climatic optimum' and a pre El Nino–Southern Oscillation (ENSO) climate. A mid-Holocene climatic optimum has been widely reported from locations around the world including eastern Australia, although direct evidence from the Moreton Bay region is lacking. At the mid-Holocene sea level high stand, sea surface temperature (SST) in Moreton Bay would have been both warmer (similar to Hervey Bay or Shoalwater Bay today) and less variable, due to deeper water and more oceanic exchange. Catchment characteristics under climatic optimum, very weak ENSO conditions are likely to have been of higher rainfall, higher vegetative cover and higher but less variable runoff carrying low sediment and nutrient concentrations. Thus catchment impacts on the water quality and ecosystems of the Bay would have been much lower than are currently observed.

From the mid-Holocene optimum to the time of European settlement conditions in both the Bay and its catchment deteriorated. Drier and more variable conditions associated with the onset of stronger ENSO forcing (about 3 ka; Donders et al. 2008) resulted in decreased vegetative cover, increased soil erosion and sediment yield, and lower but more variable runoff (more flood events). In the Bay, a decrease in water depth associated with a marked fall in sea level (about 2 ka; Sloss et al. 2007; Lewis et al. 2008), and coastal progradation on both the mainland coast and on the seaward Bay margins resulted in reduced volume, reduced tidal flushing and declining water quality. These changes in the physical environment of the Bay altered habitats and species composition of the Bay. Indications of these changes can be seen in the transition from Acroporid corals to mangrove communities at Empire Point on the mainland coast (Flood 1978), from coral fragments to shell fragments in a beach ridge sequence on Green Island (Neil 2000) and from Acroporid to Favid corals at Peel Island (first reported by Stutchbury 1854 (Saville-Kent 1893)). Additional conclusions of Lybolt et al. (2011) relevant to this discussion were that the depth of coral growth (controlled for the fall in sea level) had decreased by 2 m during the late Holocene as a result of decreased volume, decreased flushing, increased thermal stress and increased flood impacts in the Bay (all attributed to sea level fall) and coral growth in the Bay was episodic, not continuous. Such 'switch on – switch off' patterns of coral growth have been reported from marginal reef environments elsewhere (e.g. Smithers et al. 2006). Five phase shifts occurred over the 7,000 year age range of the coral death assemblage, demonstrating the feasibility of reversible phase shifts in coral communities in the Moreton Bay environment, at least under pre-European settlement conditions.

The physical changes in the Bay and its catchment thus led to a change from oceanic to estuarine, decreased sea SST and increased SST variability, a decline in water quality and declining habitat quality for some taxa (e.g. corals), improved for others (e.g. saltmarsh, mangrove, seagrass) and a mixed outcome for yet others (e.g. dugongs). Costs/benefits of the changes in the Bay are also likely to have varied spatially for many taxa. Using reconstructions of aeolian sediment transport rates from swamp sediments on North Stradbroke Island, McGowan et al. (2008) report significant climate instability in the Moreton Bay region during this period. Thus it seems likely that the late Holocene transition in the geomorphology and ecology of the Bay was a complex combination of gradual change, both synchronous and asynchronous between forcing factors, punctuated by episodic events of changing recurrence intervals and infrequent episodic phase shifts.

It has been suggested (Walters 1989; Hall 1990) that aboriginal land use ("fire stick farming" (Jones 1969)) was responsible for "changing the ecosystem to one more suitable to their needs" where increased erosion led to the "formation of large areas of mud and sand flats covered with shallow turbid waters and seagrass beds, permitting the evolution of fish stocks on a scale which today form the basis of large contemporary commercial fisheries". Based on a number of admittedly untested assumptions, Neil (1998) argued that the likely contribution of aboriginal burning to sediment yield was probably <10 %. Sediment yield occurs naturally, sediment yield was increasing due to climate shifts (e.g. onset of ENSO) and the aboriginal population was small (c. 5,000 (Hall 1990)). Given that sediment yield was just one of many factors driving geomorphic and ecological change in the Bay, it seems likely that the role of aboriginal people in this transition was negligible.

Hydrology

The sub-tropical climate of Moreton Bay is dominated by a distinct seasonal rainfall pattern that is characterised by high rainfall during summer months that can lead to large runoff events and occasional floods. Large scale floods are typically caused by degraded tropical cyclone or east coast lows that can persist over the region for several days and produce large volumes of rainfall in short periods of time. This seasonal, event-driven hydrology can result in rapid shifts between two distinct hydrological modes: (1) Wind, wave and tidally dominated; and (2) Freshwater inflow dominated. It has been hypothesised that the rapid and highly variable nature of the shifts between these two modes has influenced the ecosystems capacity to alter its processing pathways to adapt (and therefore become more resilient) to these episodic inputs of freshwater, sediment and nutrients.

The region also experiences a significant east–west rainfall gradient with average annual rainfall on the eastern edges of the Bay (e.g. Cape Moreton Lighthouse) exceeding that of the western edge by approximately 26 % (i.e. Cape Moreton Lighthouse cf. Brisbane Aero stations; Table 2). A similar comparison of annual average rainfall at the western edge of the Bay compared to the western edge of the larger river catchments that drain to the Bay shows a 35 % decrease in rainfall near the inland boundaries of these catchments (e.g. The University of Queensland Gatton cf. Brisbane Aero stations; Table 2). This gradient results in more rainfall in the smaller coastal catchments compared to the larger catchments which have the majority of their area to the west of the Bay. This in turn causes the smaller estuaries to be characterised by more frequent, short-duration, episodic inflows of freshwater compared to the larger catchments. During these event flows the smaller estuaries can be flushed before developing significant vertical stratification for short periods (days to weeks).

In the absence of significant rainfall events the catchments are characterised by very little or no flow (i.e. baseflow is minimal during the winter dry season). During these dry periods a residual clockwise circulation pattern is established within the Bay due to the asymmetry of the flood and ebb tide flows through the passages (i.e. North Passage, South Passage, Jumpinpin and the Gold Coast Seaway – refer to Fig. 1) that allow water exchange with the adjacent Coral Sea (Dennison and Abal 1999). This residual circulation creates a pattern of northward water movement on the western edge of the Bay and southern movement on the eastern edge. These circulation patterns combine with seasonal wind patterns and the complex morphology in the southern parts of the Bay to establish a strong gradient in water residence time in different parts of the Bay (refer to Table 3). It is noted that, while the residence times of the embayments on the western edge of the Bay can be significant (50–60 days) the residual northerly movement of water provides an important pollutant removal mechanism for these areas which receive large pollutant (predominantly sediment and nutrients) loads from the adjacent river estuaries.

Table 2 Selected long-term meteorological statistics

		Station		
Meteorological statistic	Units	Cape Moreton Lighthouse	Brisbane Aero	University of Queensland Gatton
Station reference number	–	40043	40223	40082
Period	–	1869–2012[a]	1950–2000	1897–2012[a]
Mean annual rainfall	mm	1,494.1	1,186.2	771
Mean annual days of rain	d	142	122.7	90.6
Highest recorded daily rainfall	mm	339.9	307.4	199.4
Mean 9 am air temperature	°C	20.8	20.8	20.4
Mean 9 am relative humidity	%	75	66	67
Mean 9 am wind speed	km h^{-1}	25.2	11.2	10.4

Source: Australian Bureau of Meteorology

[a] The period used for individual statistics varies within this range with maximum available periods used for all statistics

Table 3 Summary of average water residence times in different parts of Moreton Bay and is estuaries (After Dennison and Abal 1999)

Site	Residence time [d]
Ocean boundaries	3–5
Central Bay	50–55
Mouth of Brisbane River	63–68
Lower Brisbane River	110–120
Middle Brisbane River	154–162
Bremer/Brisbane junction	187–189
Bramble Bay	59–62
Deception Bay	54–57
Pumicestone Passage	43–53
Pine River	55–62
Caboolture River	53–57
Logan River	66–75

Ecology: Turbidity, Bio-sedimentary Aspects, Living Communities and Processes

Bio-sedimentary Processes

Under current conditions terrigenous sediment and nutrient input to Moreton Bay is delivered in a significantly variable (over both space and time) manner. This is primarily due to the concentration of catchment development along its southern and western shores and regional weather patterns described above. Over 30 major sewage plants and industrial wastewater treatment plants discharge directly into the Bay (e.g. Fig. 2d) and its associated waterways and these are the largest source of nutrients during average years (Eyre and McKee 2002). Episodic flows associated with high rainfall events deliver the majority of sediment inputs through highly turbid inflows into Moreton Bay consisting primarily of suspended silts and clays. These small particles are highly charged and carry a relatively large nutrient (2.8 % organic carbon; 0.3 % nitrogen and 0.1 % phosphorus) and metal (4.8 % iron and 0.3 % manganese) load (Grinham et al. 2012). This results in western and southern areas having the highest sediment mud content, the highest nutrient availability (Heggie et al. 1999) and the lowest water clarity (Longstaff 2003) relative to northern and eastern areas of Moreton Bay (Fig. 3). In the western Bay, particularly north of the Brisbane River, muds and silts extend to 10–20 km offshore (Jones and Stephens 1981). Sediments in the eastern Bay are predominantly tidal delta sands which extend from the North Entrance banks along the west coast of Moreton Island to the southern extent of the South passage flood tide delta south of Dunwich (Fig. 3). In the southern Bay, adjacent to South Stradbroke Island, sediments of the eastern Bay are predominantly tidal delta sands with fluvial sands and muds adjacent to the mainland coast (Lockhart et al. 1998).

The impact of this nutrient and sediment loading on autotrophic primary productivity suggest the system is undergoing a typical response of shallow-water ecosystems where benthic primary production decreases in favour of pelagic primary productivity (Meyer-Reil and Koster 2000). Pelagic primary productivity is estimated to have increased tenfold since European settlement of the area (McEwan et al. 1998). Large declines in benthic microalgal productivity have occurred particularly in subtidal habitats of western and southern Moreton Bay, this has resulted in an estimated 50 % reduction in baywide primary productivity compared with pre-European settlement (Grinham 2007). This decline in benthic primary productivity as well as a decline in clean sand facies within Moreton Bay is of concern as further declines could result in periodic anoxia of the sediment surface particularly in western and southern areas. This would directly couple sediment microbial nutrient remineralisation to the water column, further stimulating pelagic productivity and allowing these degraded conditions to persist (Meyer-Reil and Koster 2000).

Seagrass and Ecosystem Functioning: Processes That Promote Resistance to Impact and Restrict Recovery

Moreton Bay supports 189 km^2 of seagrass (Figs. 3 and 4) comprised of seven different species (Roelfsema et al. 2009). Seagrasses in coastal and nearshore environments, like Moreton Bay, perform a range of services, which are lost as seagrasses decline. Large-scale loss of seagrass meadows to unvegetated substrate has occurred particularly in western embayments of Bramble Bay (the receiving body for the Brisbane River) and southern Deception Bay (Fig. 4) (Dennison and Abal 1999). This loss of seagrass to unvegetated substrate is not easily reversed, and considerable resources have been invested to aid ecosystem recovery in the Bay and worldwide, but with little success (de Jonge et al. 2000; van der Heide et al. 2007). This section describes the processes that promote resistance of seagrass to impacts in Moreton Bay and those that prevent its recovery once lost.

Seagrasses are particularly susceptible to increases in nutrients and sediments, which in Moreton Bay are attributed to riverine inflows to the western and southern embayments (Dennison and Abal 1999). These can reduce the cover and extent of seagrass through smothering, by reducing light availability and promoting overgrowth of epiphytic algae (Neckles et al. 1993; Abal and Dennison 1996). Seagrass meadows do, however still exist in areas of the Bay that regularly experience poor water quality, which provides evidence of their ability to resist these impacts. Seagrasses resist impact through three processes: the uptake of nutrients from the water column, which

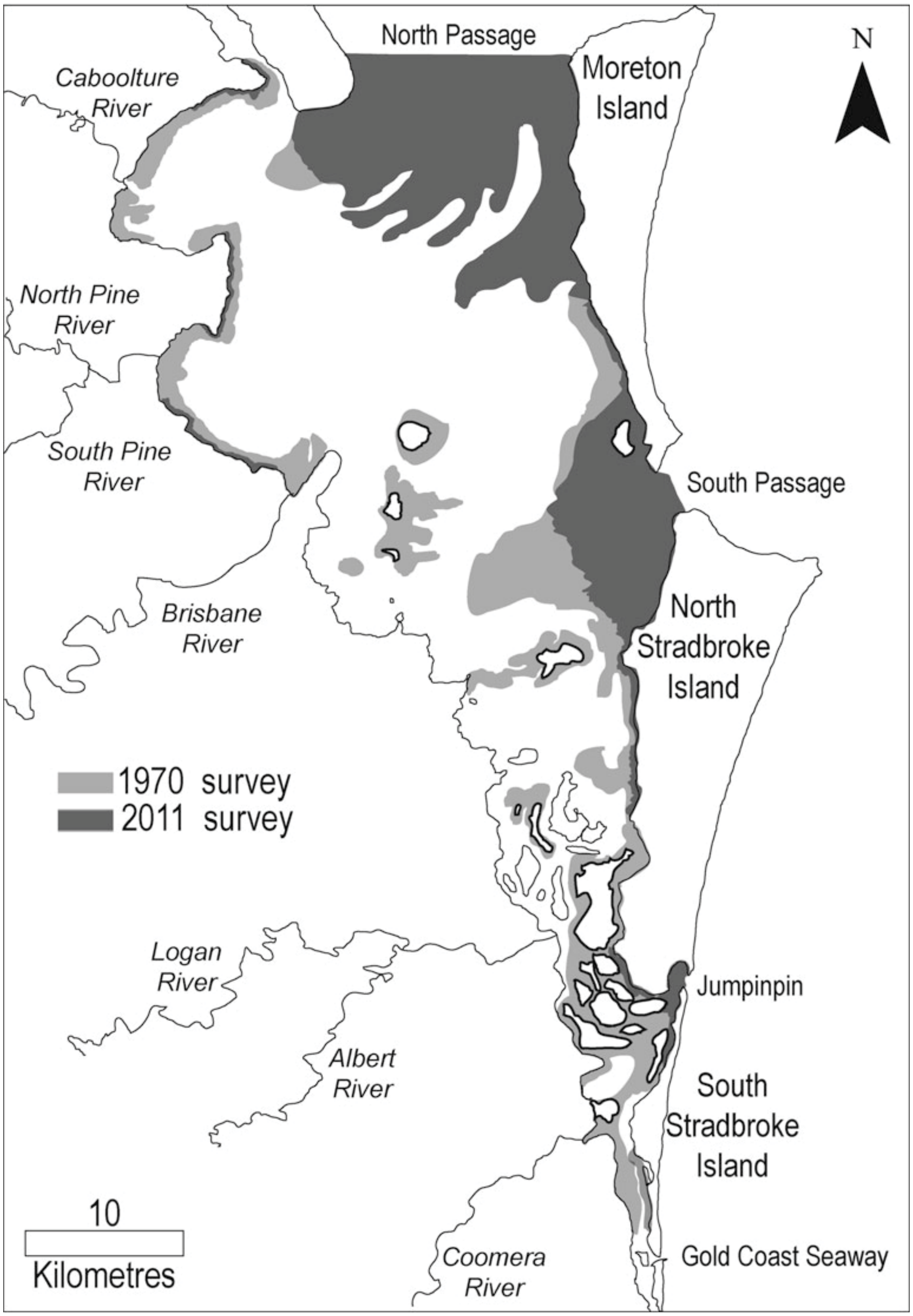

Fig. 3 Summary of sediment survey results showing clean sand substrate distribution in Moreton Bay. Results indicate a 20 % (260 km^2) decline of clean sand facies in Moreton Bay over a 30 year period from 1970 to 2011 (Maxwell 1970; O'Brien et al. 2012)

reduces the amount available for algal growth, the trapping of sediments from the water column, which improves water clarity, and the harbouring of vertebrate and invertebrate grazers that minimize the growth of epiphytic algae (Cornelisen and Thomas 2004; Heck and Valentine 2007; Carr et al. 2010) (Fig. 6b). In areas where seagrass has been lost, sediments are more easily resuspended, nutrients are released into the water column making them available for algal growth and grazing rates of algae are reduced, which limits the potential for seagrass recovery.

In January 2011, the Brisbane River flooded and reduced water clarity throughout most of Moreton Bay. Despite the

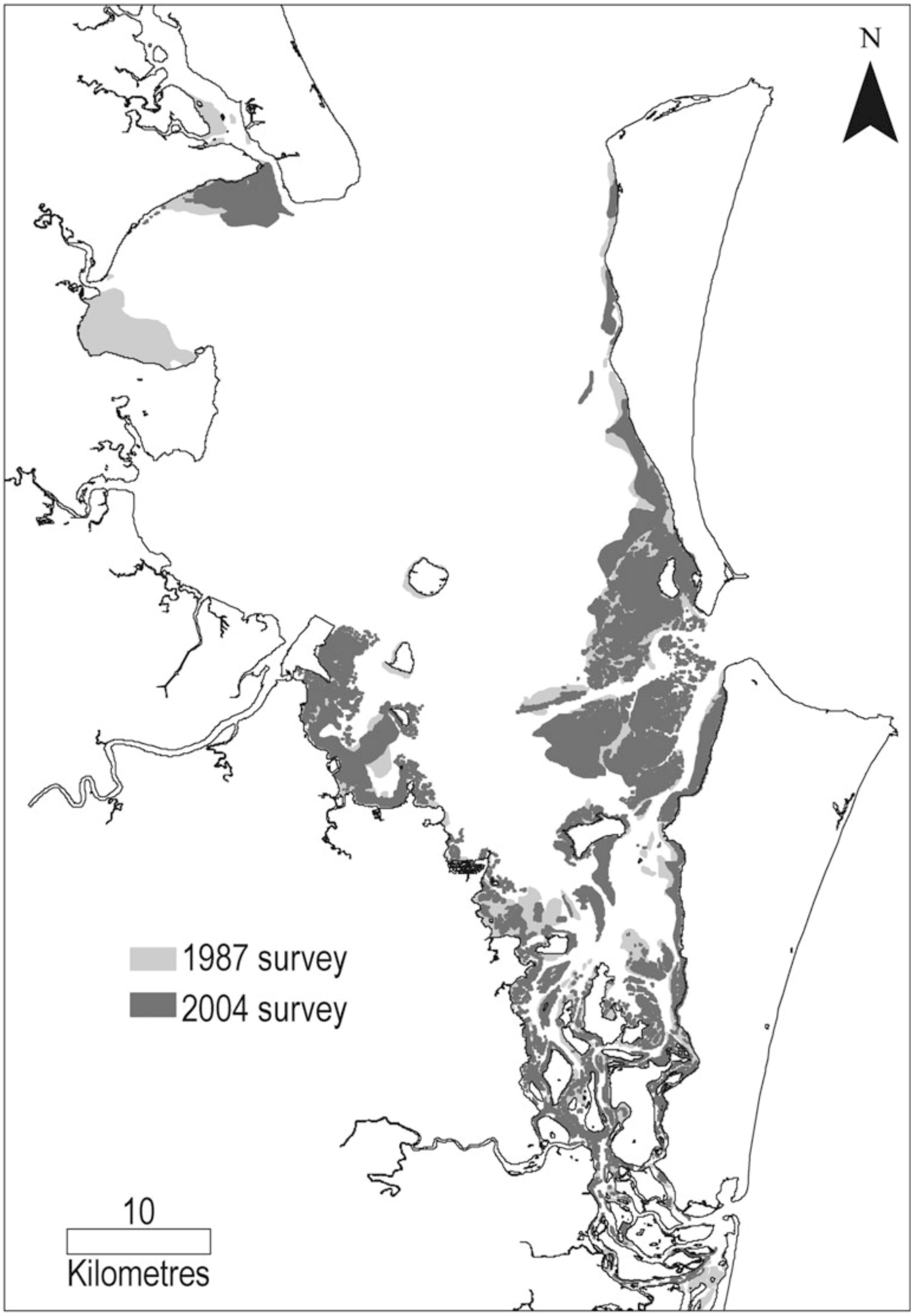

Fig. 4 Summary of seagrass survey results showing a 20 % (49 km^2) loss in seagrass coverage over a 20 year period from 1987 to 2004 (Hyland et al. 1989; Roelfsema et al. 2009)

impact of the flood plume, subtidal seagrass (*Zostera muelleri*) meadows closest to the river mouth had higher rates of nutrient uptake and algal grazing and lower sediment resuspension than meadows less impacted by the flood plume. As a result, seagrass biomass remained constant throughout the year at meadows close to the impact, but declined at meadows further away. The differing response to the flood impact was correlated with morphological differences between the two meadow types. Meadows closest to the river had longer and wider leaves with greater concentrations of chlorophyll-a than those further away, an adaptation which allows greater light capture and sediment baffling (Abal et al. 1994). In contrast, nutrient uptake and grazing rates were consistently lower, and sediment resuspension rates higher, in unvegetated areas following the flood than rates recorded in seagrass meadows. This resulted in sub-optimal light availability for seagrass colonisation and recovery for much of the year, and highlights the importance of understanding both the processes that promote resistance to impacts and those that restrict recovery following seagrass loss. Given the dynamic nature of the system at geological timescales, it is likely to have the capacity to shift between states, although further knowledge of local ecology is required to better understand whether the current rate of anthropogenically induced change is too rapid for the system to adapt.

Current management actions have focussed on reducing nutrient point source discharge into the system and appear to have shown ecosystem health recovery. Recent surveys in areas of historical complete seagrass loss have shown strong recovery of coverage (Fig. 5b). However, there is a need to reduce sediment loads during flood events as these both increase nutrient loading and allow persistence of turbid conditions following sediment resuspension events. This is potentially a crucial step in recovery or maintenance of current levels of ecosystem health as the likelihood of extreme rainfall events and associated inflows is projected to increase in this region (Cai and van Rensch 2012). Recovery of seagrass beds from areas of previous reported complete loss, highlights the need for better understanding as to why relatively minor flood events can result in complete loss whilst recovery occurs after major events in some areas. The extensive and obvious coverage of seagrass suggests current monitoring methods might need improvement.

Fish and Ecosystem Functioning: Effects of Connectivity, Coastal Development and Marine Reserves

Moreton Bay supports a high abundance and diversity of finfish and crustaceans, and is an important nursery for harvested species (Tibbetts and Connolly 1998). The embayment is a heterogeneous seascape containing a mosaic of estuarine habitats (e.g. saltmarsh, seagrass, mangroves and mudflats), shallow fringing coral reefs (interspersed with mangroves and seagrass) and deeper soft sediments (e.g. Stevens and Connolly 2005) (Fig. 5a). The level of connectivity among, and spatial arrangement of, these habitats affects both the distribution of fish and crustaceans (Skilleter et al. 2005; Olds et al. 2012b), and the productivity of dependent fisheries (Manson et al. 2005; Meynecke et al. 2008). The region has, however, been impacted by coastal development, terrestrial runoff and fishing, and supports modified habitats and altered fish assemblages (e.g. Lybolt et al. 2011; Waltham et al. 2011). The fish assemblages of Moreton Bay have been reviewed elsewhere (Tibbetts and Connolly 1998), and so this section describes the roles of fish in maintaining key ecological processes in the Bay.

The distribution and abundance of fish in central Moreton Bay is affected by the degree of connectivity among reefs, mangroves and seagrass (Olds et al. 2012b). Connectivity between reefs and adjacent mangroves is particularly important and enhances the ability of local marine reserves to promote the abundance of harvested and herbivorous fish species (Olds et al. 2012a). The synergistic effects of connectivity and marine reserves increase both the biomass and species richness of herbivorous fish, and thereby promote herbivory, which reduces algae cover and enhances coral recruitment (Olds et al. 2012c) (Fig. 5c). These effects on coral-algae recruitment dynamics and benthic succession serve to increase reef resilience (i.e. the capacity to absorb disturbance and regenerate without degrading, or changing state), and suggest that targeted seascape conservation may improve the resilience of other similarly degraded seascapes.

Extensive networks of canals and lakes have been constructed for residential purposes on the estuaries of Moreton Bay (Waltham and Connolly 2011). The Bay has the largest cluster of artificial estuarine waterways (about 250 km in length) outside of the USA (and almost ten times the extent of Venice). As fish habitat, canal estates have lower productivity and diversity than shallow vegetated habitats in the Bay (Morton 1989). Where the artificial waterways have been constructed in terrestrial habitat, however, they nevertheless provide a major new estuarine habitat. Fish aggregate at the canal edges (Waltham and Connolly 2007) and around jetties and pontoons (Moreau et al. 2008). Fisheries species have shown remarkable plasticity in diet to adapt to systems lacking conspicuous vegetated habitat. It has been demonstrated using stable isotope (Connolly 2003) and stomach content analyses (Waltham and Connolly 2006), for example, that snub-nosed garfish (Family: Hemiramphidae) consume algae (energy source) and insects (protein source) in canals, whereas in natural wetlands the species utilises seagrass and crustaceans.

Ecosystem Functioning and Resilience

Moreton Bay is a diverse and productive ecosystem, it supports a range of subtropical and temperate species, is socially and culturally important as a focus for recreation and fisheries, but is also heavily impacted by development, runoff and habitat modification. The ecological resilience of Moreton Bay relies upon its ability to resist or adapt to change without changing its structure and function. Components of the broader ecosystem that confer this ecological resilience

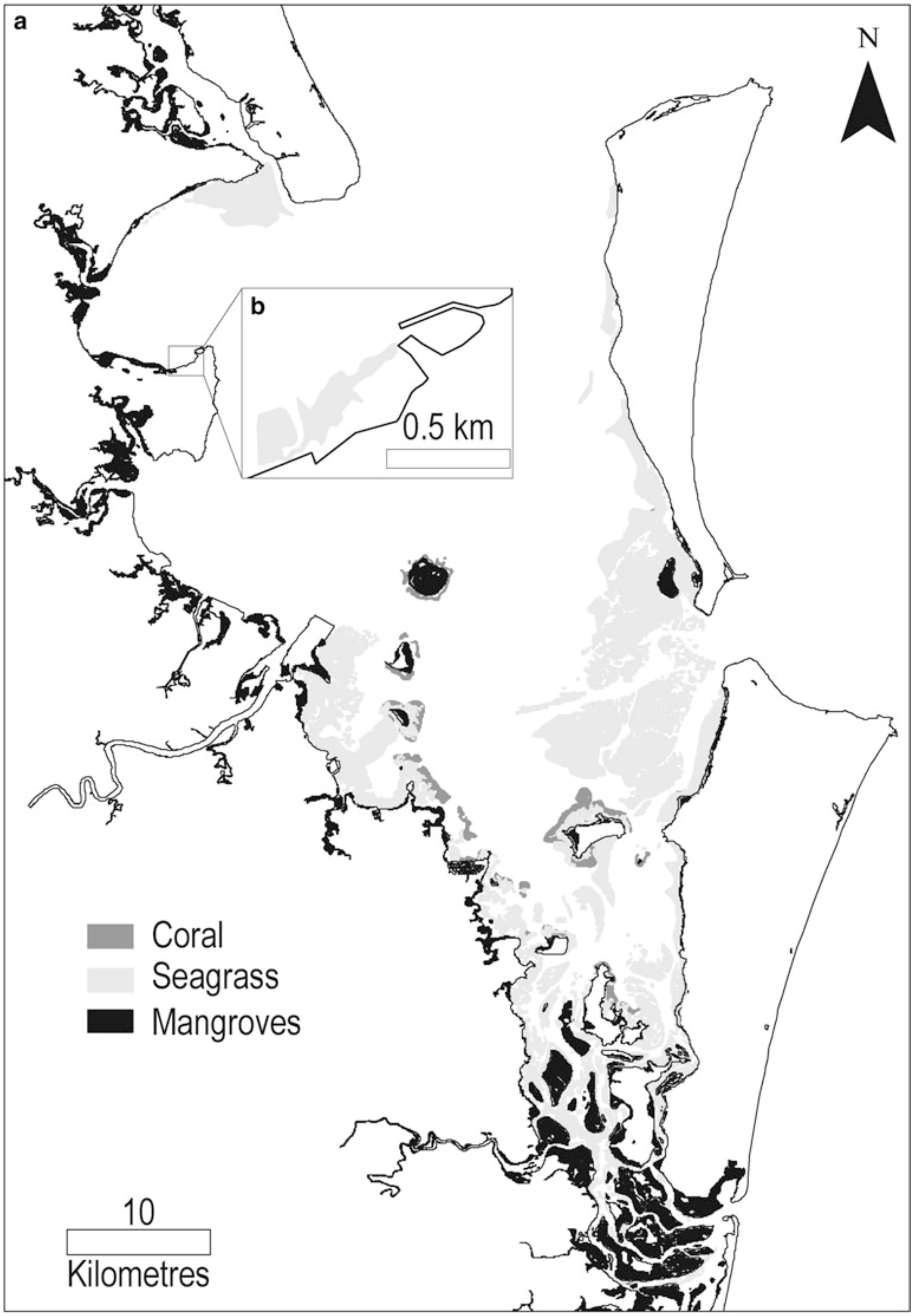

Fig. 5 Substrate distribution in Moreton Bay including: (**a**) Current best available estimated seagrass, mangrove and coral habitat distribution (Olds et al. 2012a) and (**b**) Recent survey (October, 2012) from historical seagrass loss area showing extensive recovery of seagrass beds

include: habitat-scale ecological processes that promote resistance and adaptation (e.g. seagrass feedback mechanisms and morphological flexibility), connectivity (e.g. links between mangroves and coral reefs), food web plasticity (e.g. fish in canals) and functional redundancy (e.g. herbivore diversity) (Fig. 6d). An increased understanding of how these components interact to drive resilience, and their incorporation into management decision-making, can underpin the long-term maintenance of ecosystem functioning in Moreton Bay.

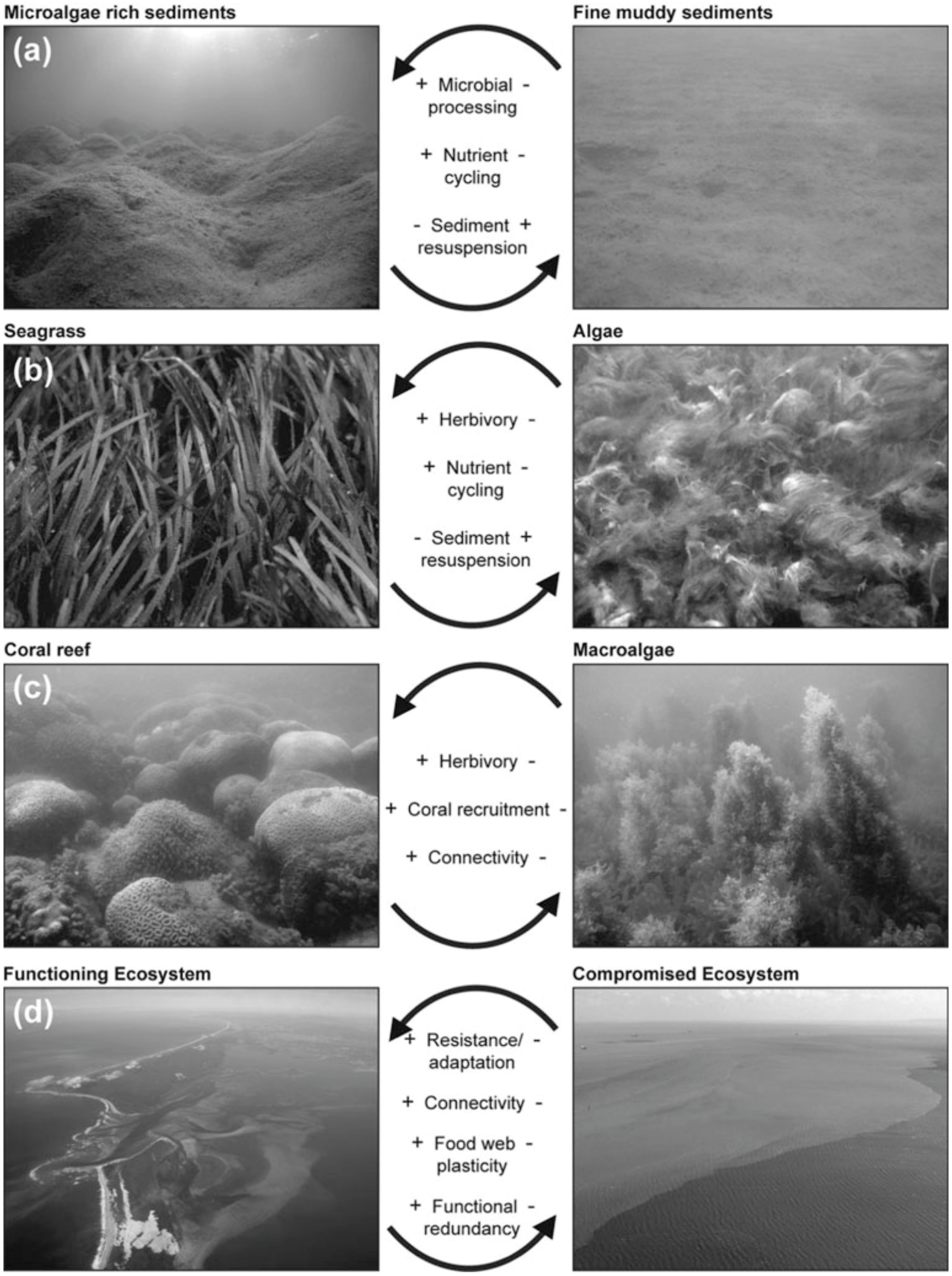

Fig. 6 Ecological processes that maintain or erode the resilience of (**a**) deep microalgae rich sediments, (**b**) seagrass meadows, and (**c**) coral reef seascapes in Moreton Bay, and (**d**) underpin the functioning of the ecosystem at the Bay scale (+/– symbols depict direction of effect)

Anthropological Influences: Resources, Pressures, Impacts and Remediation

The condition of the Moreton Bay estuary has been classified as 'modified' or 'extensively modified' with the major modifiers including: sewage treatment plant discharges, dams and weirs, wetland loss, urbanisation, dredging and entrance modification (Digby et al. 1998). Furthermore sediment and nutrient loads to Moreton Bay from its adjacent catchment systems have increased as a result of significant land use transformation from naturally vegetated catchments to a condition of extensive native vegetation loss as a result of agricultural and urban development within 200 years (e.g. Fig. 2b). Moreton Bay receives most of the development pressure on its western shore with most pollution being discharged into Moreton Bay from its four large estuaries (Logan, Brisbane, Pine, Caboolture – see Fig. 1). Both point source discharges from sewage treatment plants and industry as well as diffuse pollution from both urban and rural land uses have a chronic negative impact on water quality and aquatic ecosystem health in the western and southern sections of Moreton Bay (Deception Bay, Bramble Bay, Waterloo Bay and the Southern Bay), while the northern and eastern sections of Moreton Bay still have high water quality and ecosystem health, showing limited impacts of anthropogenic pollution (EHMP 2007). During periods of extreme weather, such as the 1974 and 2011 floods, the amount of sediment and nutrients delivered to the Bay increase dramatically, with the sediment delivered by the 2011 flood being estimated at 10–20 million tonnes. This equates to approximately 20–50 years of average annual sediment delivery in a single event (i.e. average sediment delivery in years without major floods). During the past 10 years significant investments have been made to upgrade sewage treatment plants and reduce the point source nutrient discharges into Moreton Bay. This has reduced the proportion of available nutrients, especially nitrogen, that are contributed from sewage treatment effluent and resulted in a decline in the occurrence of phytoplankton blooms in the western embayments, particularly Bramble Bay (SEQHWP 2007).

Sediment and Nutrient Loads

Sediments and nutrients have been identified as the major ‘pollutants’ of concern for Moreton Bay and the reduction of these pollutant loads have been the focus of recent management interventions (SEQHWP 2007). Initial management interventions aimed to reduce point source nutrient loads to the Bay which, prior to significant investment in sewage treatment plant and industrial process upgrades, were estimated to be approximately 3,383 t of nitrogen and 1,182 t of phosphorous per year (Eyre and McKee 2002). By 2011 these loads had reduced to approximately 995 ± 134 t of nitrogen and 536 ± 52 t of phosphorous per year (QDSITI 2011) as a result of major infrastructure investments and despite an increasing human population. However, as the human population transitions from three million to over four million people by 2026 (QOESR 2011) it is estimated that point source nitrogen and phosphorous loads will steadily increase over the long term if current management practices are maintained.

In the absence of suitable monitoring data, catchment-derived diffuse source sediment and nutrient (total nitrogen and total phosphorous) inputs to Moreton Bay have been estimated using a range of catchment modelling approaches (Chiew et al. 2002; WBM 2005; Stewart 2009). Recent estimates, using data from the Queensland Land Use Mapping Project (QLUMP) (Witte et al. 2006), suggest that annual total suspended sediment loads (in the absence of significant flood events such as the 1974 and 2011 events) are in the order of 345,000–390,000 t while annual total nitrogen and total phosphorous loads are in the order of 4,000–4,500 t and 500–580 t respectively (Stewart 2009). If the current land development and management practices are maintained it is estimated that these sediment loads will increase by approximately 17 % with diffuse source total nitrogen and total phosphorous loads projected to increase by 14 % and 21 % respectively by 2026 (SEQHWP 2007).

Sediment and nutrient load estimates for different population growth, land use pattern and climate scenarios have formed the basis of the ‘sustainable load’ management approach that has been applied to reverse the recent decline in ecosystem health of Moreton Bay and its associated estuaries. A sustainable load in this context is the target load which can be readily assimilated by the receiving waters to maintain a sustainable ecosystem health outcome. In the majority of cases predictive models have been used to identify the maximum load that can be delivered to a given system whilst still achieving the resource condition targets (RCTs – a combination of environmental values and associated water quality objectives). Application of this approach to Moreton Bay and its estuaries has shown that the target sustainable load requirements are often difficult to achieve using current approaches as often the sustainable load target is already being exceeded significantly, and even with all of the proposed management actions implemented, the target sustainable load would still be exceeded (Weber and Ramilo 2012). While this result might prompt the use of the sustainable load approach in determining the management action to be questioned, experience in Moreton Bay suggests that the central issues arises from the original water quality objectives used to determine the sustainable load (Weber and Ramilo 2012). These issues are explored in more detail in section “Management approach and Resource Condition Targets (RCTs)” below.

Signs of Successful Management Interventions

Moreton Bay’s natural values have long been recognised as being worthy of protection. From as early as 1975 various studies were being undertaken to protect the Bay from the variety of pressures exerted by rapid urbanisation of the catchment and increasing use of the Bay itself. These eventually morphed into a Bay-wide approach to management in 1993 when the Queensland government adopted the Moreton Bay Strategic Plan (DEH 1993) and 3,400 km^2 of the Bay and adjoining Queensland coastal waters were gazetted as a multiple use marine park. Additionally, a significant portion of the Bay was listed as a wetland of international significance under the RAMSAR convention in the same year. The Moreton Bay Strategic Plan guided the management of the marine park until the first zoning plan

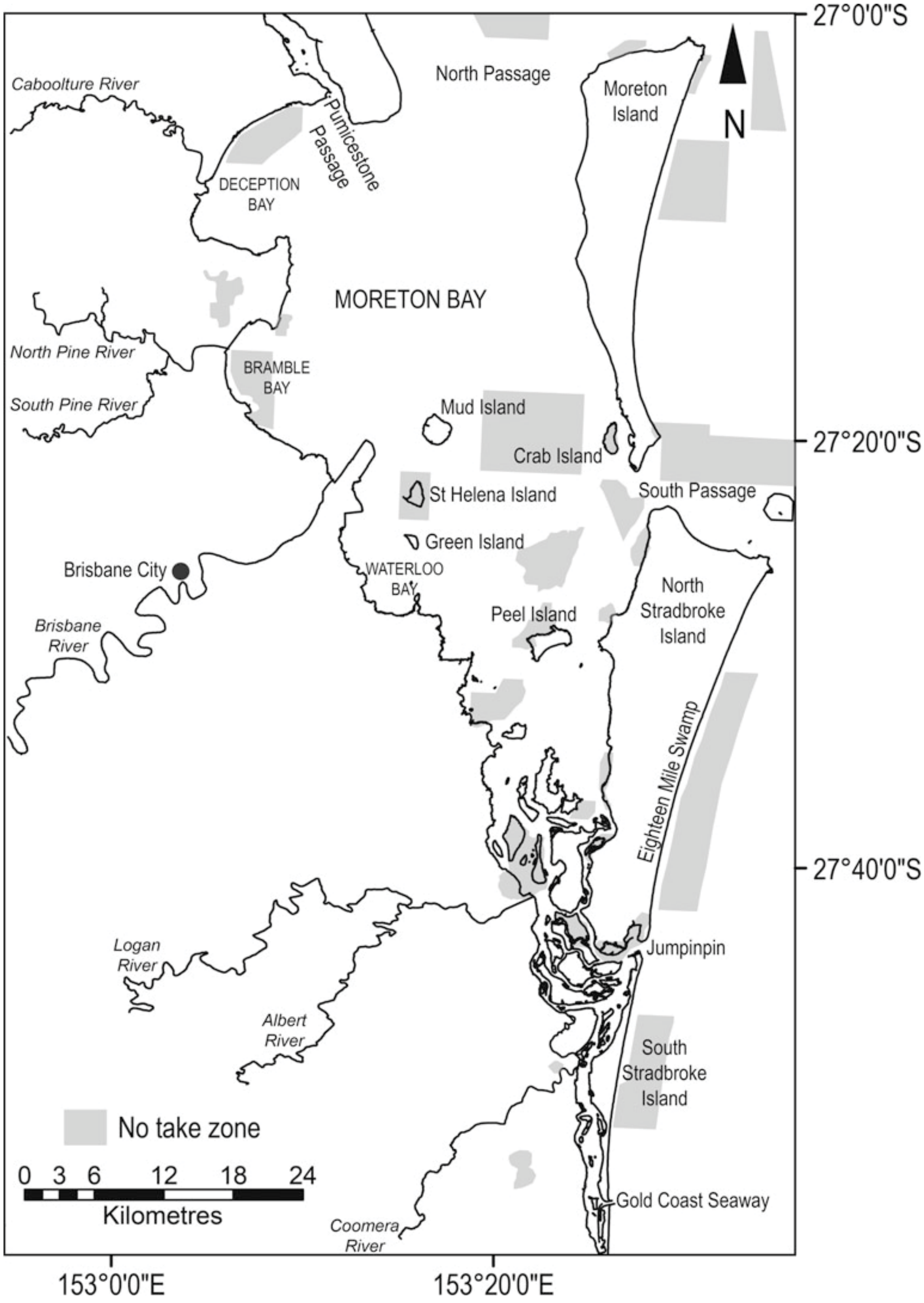

Fig. 7 Extent of "no take" zones in the Moreton Bay Marine Park

was implemented in 1997. At that stage, six areas, comprising 0.5 % of the marine park were protected from all extractive activities (e.g. fishing). These areas protected small examples of the iconic or well known habitats – mangrove forests, seagrass beds and inshore and offshore coral reefs. While several of these areas were delivering some conservation benefits (Pilans 2006), by the mid 2000s it was clear that the management of Moreton Bay as a whole was lagging behind world standards for marine park management and it was timely then that a legislative requirement provided the opportunity for the zoning plan to be thoroughly reviewed. This was undertaken based on the CAR (comprehensive, adequate, representative) principle to address biophysical needs, with the revised zoning plan taking effect in 2009 with considerable changes to the size and type of habitats protected (refer to Fig. 7). It is noted that, while several of the river estuaries draining to Moreton Bay are included in the marine park, few river estuaries have designated ‘no take’ zones (i.e. the level of conservation/protection in estuaries is lower than for other areas that are designated as habitat protection, conservation or marine national park zones). Socio-economic impacts of zoning were also considered resulting in 16 % of the marine park currently protected from all extractive activities and early monitoring of these areas suggests that the revised zoning is achieving good conservation outcomes such as increased abundance of fish and crab species (DERM 2010, 2012; Olds et al 2012a). The formation of the Moreton Bay Marine Park represents one of the earliest large-scale, planned conservation activities undertaken in the system and these recent results suggest that relatively long timeframes are often required to achieve the desired conservation outcomes (i.e. improvements not clearly evident until many years after management intervention).

Summary and Discussion: Moreton Bay and Its Estuaries from 2050 and Beyond

A significant feature of the recent management interventions targeted at halting the decline of ecosystem health in Moreton Bay has been the prominence of a science-based management framework. A science-based management was deemed necessary as past experience and knowledge of the system was limited and also was not likely to effectively predict the response of the system under different future conditions (i.e. different population growth, land use and climate scenarios). The science-based approach, combined with a significant investment in collaborative decision making processes that include community, industry and government stakeholders, has seen significant investment in actions to improve the state of waterways in the region. For example in excess of AUD$300 M was invested in wastewater treatment plant upgrades from 1998 to 2006 resulting in a 44 % reduction in point source nitrogen load entering Moreton Bay in 2006 compared to pre-2001 loads, with early indications of a positive ecosystem response (SEQHWP 2007). While the priority and cost-effectiveness of such management action can be argued there is general consensus that a science-based management framework has been successful and should be retained as a key feature when shaping the future of Moreton Bay and its estuaries from 2050 and beyond. Similarly there is a need to maintain the collaborative decision making and management framework to allow the future of Moreton Bay in 2050 and beyond to be determined by local communities, industry and government stakeholders. With these features (i.e. science-based management framework and a collaborative decision making and management framework) taken as a basis for the future the authors offer the following ideas to promote discussion on what sort of estuaries do we want to see in 2050 and beyond for Moreton Bay.

Management Approach and Resource Condition Targets (RCTs)

An adaptive management framework has been implemented by the various organisations involved in the management of Moreton Bay (SEQHWP 2007) however the long-term effectiveness of this approach remains uncertain. As noted by Allen and Gunderson (2011) since its initial introduction, adaptive management has been hailed as a solution to endless trial and error approaches to complex natural resource management challenges. However, its implementation has failed more often than not. It does not produce easy answers, and it is appropriate in only a subset of natural resource management problems. Furthermore Allen and Gunderson (2011) highlight that adaptive management functions best when both uncertainty and controllability are high as there is high potential for learning and the system can be manipulated. In the case of Moreton Bay and its estuaries, uncertainty is high however controllability of the system is low which suggests scenarios are a more appropriate approach and allow for the exploration of potential future outcomes of present actions (Baron et al. 2009). The management of Moreton Bay and its estuaries is shifting towards scenario planning based management (i.e. the SEQHWP’s Science Program has extensively used predictions of aquatic ecosystem response to a well-defined set of potential future land use and climate scenarios to inform the development of management actions) although most scenarios under consideration have short timescales in the order of 15–50 years (e.g. current Healthy Waterways vision has a 2026 target date for system improvements). These timeframes reflect the current transition in management approach from a mainly short-term economic based option to a more long-term economic-ecological approach.

A strong theme of past commentary on management approaches for Moreton Bay has been the idea of “management for millennia” (Davie et al. 1990; Tibbetts et al. 1998). While there are very practical reasons for using the current shorter timeframes for planning and management of Moreton Bay it might be timely to also incorporate longer term views (e.g. 1,000 year planning horizons). While it may be argued that there is little practical advantage in attempting to set specific management targets (and associated actions) for such extended periods the process of framing and examining such long-term questions is likely to allow the relatively short term (i.e. 2026) targets to be more effectively contextualised in relation to the broader dynamics of the system and the level of uncertainty associated with our current understanding of the processes that drive them.

A central element to the current approach for defining the desired future for Moreton Bay and its estuaries is a series of defined resource condition targets (RCTs). These resource condition targets use a combination of environmental values and specific water quality objectives to classify the current and future state of the region's waterways. Examples from the South East Queensland Healthy Waterways Strategy 2007–2012 include: (1) In 2026, 100 % of SEQ waterways classified in 2007 as having high ecological values retain this classification; (2) In 2026, 100 % of SEQ waterways classified in 2007 as meeting their water quality objectives retain this achievement; (3) By 2026, waterways classified as disturbed and/or degraded in 2007 have their ecosystem health and ecological processes reinstated. These RCTs represent the outcome of a pragmatic approach, based on the Queensland Environmental Protection (Water) Policy 2009, with the baselines for both the RCTs and Community Targets referenced to the 2007 levels established by accepted monitoring or benchmarking programs. The current set of targets are clearly designed to halt the current decline in water quality and ecosystem health. This is an important first step in any natural resource management process. When considering the desired future state(s) of Moreton Bay over the extended timeframes discussed above (i.e., >100 years) it is useful to note that the 2007 reference conditions used to set the short-term (i.e. 2026) RCTs are likely to be substantially different from a pristine condition or reference condition for biological integrity (as discussed in more detail by Stoddard et al. (2006)).

When considering the future state of Moreton Bay from 2050 and beyond it might be useful to consider whether the current goals of 'halting the decline' are appropriate in the longer term. Without resource limitations it might be argued that a more worthy condition target would be to move beyond some 'historical condition' or 'least/minimally disturbed condition' to the 'best attainable condition'. The 'best attainable condition' for Moreton Bay from 2050 onwards might be one in which ecosystem integrity is less than that currently observed (i.e. current degradation has resulted in an ecosystem shift that is not able to be reversed). Alternatively the 'best attainable condition' might be one that represents an enhancement over some reference condition for biological integrity. The current gaps in scientific understanding of the ecosystems of Moreton Bay and their function largely prevent us from defining the 'best attainable condition' with any certainty. This does not diminish the substantial progress that has been made in understanding Moreton Bay and its function. Rather, it highlights that additional information is needed to better explore what futures are achievable for this system. The 'best attainable condition' will also be determined by socio-economic factors (an aspect explored in more detail in the following section). Regardless of its feasibility the concept of managing Moreton Bay to achieve net positive gains (i.e. a condition that represents an enhancement over a pristine condition or reference condition for biological integrity) is worth investigating. Such thinking appears to have been deferred in past management planning processes due to the focus on the urgent need to halt the decline in ecosystem health but is likely to be useful to consider when framing the next revision of RCTs and associated management actions.

Cost-Benefit Framework to Attract and Guide Investment

As suggested above the 'best attainable condition' for Moreton Bay in 2050 and beyond will involve more than just a bio-physical assessment of the system. Moreton Bay and its estuaries show signs of significant impact and little assimilative capacity for increased pollutant loads. The catchments for these estuaries are also areas where population growth has been identified and as such balancing economic growth of an area while at the same time reducing pollution loads into an impacted estuary is extremely challenging. As highlighted by Weber and Ramilo (2012) environmental constraints in such systems are often viewed as sacrosanct, either in legislation or by the community or both, but at the same time that same community wishes to live in a region that has job provision, a range of services (schools, shops, health care) and future prospects for their community. As such socio-economic factors play a significant role in determining what the 'best attainable condition' might be with regard to the region's economic and cultural constraints. An effective cost-benefit framework will be required to balance the achievement of suitable environmental outcomes with competing sources and uses of water in the face of strong development pressure.

The current approach in the Moreton Bay region is to attempt to balance the desire for economic growth while attempting to reduce discharges to waterways from sewage, stormwater and agricultural land uses so that the community's environmental values are maintained. This is often done in the absence of information on the cost and effectiveness of different and often competing management actions. Therefore the current method of cost-effectiveness evaluation is largely a process that identifies a solution that delivers the required objectives or standards of service for the least overall cost and represents a simplistic view of what true least cost planning approaches should deliver (Weber and Ramilo 2012). If the approach does not adequately address all externalities, then some costs may not be properly accounted for (see Lane et al. 2010). In addition, if the benefits, both tangible and intangible, of such approaches are not accounted for, true cost-effectiveness may not be able to be delivered. Also, it may be that the cost burden for

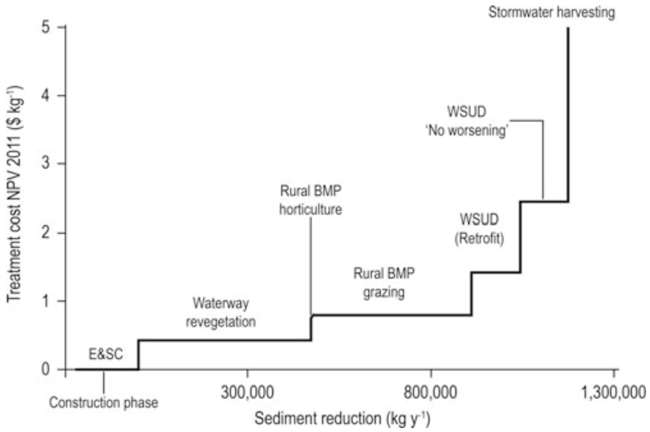

Fig. 8 Example of a cost-treatment curve (After Weber and Ramilo 2012). These cost curves can also show a specific target in terms of a pollutant load reduction or potable supply demand reduction. Sometimes those targets are beyond that which can be adequately achieved with current technology or within current resources availability. *BMP* Best Management Practice, *WSUD* Water Sensitive Urban Design

proposed management actions may be too high for the community to bear in order to achieve the required RCTs or environmental objectives. To address these issues approaches that include extended cost-effectiveness analysis (Hall 2011) can be usefully applied in decision making processes to demonstrate to decision makers how far towards achieving objectives they may get for a certain level of investment (refer to example in Fig. 8). Experience from the application of such an approach in the Moreton Bay region has been well received by political decision makers especially where benefits may not be adequately quantified (Weber and Ramilo 2012).

Concluding Remarks

Experience with the current management approach for the Moreton Bay estuary has highlighted the need to adopt a coordinated, multi-stakeholder approach to the management of the system. For example, while the existing marine park legislation provides an effective tool to address and manage direct impacts on the Bay's resources and values, it has no ability to ensure that activities in the catchment are managed in the best interests of the marine park. Furthermore it has been demonstrated that while the conservation approach taken within the Bay (via the marine park zoning) is beginning to show positive effects there is less value in protecting discreet areas without ensuring that the overall health of the Bay is maintained. Connectivity between habitats is important as well as the connectivity provided by the water itself.

Placed within the broad backdrop of global eutrophication and the predicted acceleration in the rate of land modification and urbanisation it is unclear as to whether the RCTs for Moreton Bay and its estuaries can be met by 2026. More fundamentally it is unclear as to whether the current RCTs are an appropriate long term (i.e. >100 years) target given that investment decisions that are being made now are resulting in the development of infrastructure with a design life much greater than the 2026 targets that have been adopted. Furthermore other pressures such as population growth, climate variability, sea level fluctuations and changes in ocean chemistry will also act over longer timeframes than those considered by the current management framework. It is anticipated that these issues will form part of the discussion to inform the process of updating the RCTs for the regional natural resource management planning process. Consideration of longer timeframes in conjunction with the development of locally relevant tools and methods that are able to effectively represent a range of relatively sophisticated management scenarios and their associated socio-economic cost-benefit profile appear to be some of the key components that are needed in the next evolution in our attempts to manage this complex system.

Overall the current gaps in our understanding of the ecosystems of Moreton Bay and their function largely prevents us from defining the best attainable future condition with any certainty. The highly variable nature of the system over relatively short timeframes (i.e. flood vs non-flood conditions) as well as the capacity of the system to adapt to long term changes (i.e. past morphological and ecosystem shifts) suggests that Moreton Bay and its associated estuaries have significant capacity to adapt to change. Whether the current rate of anthropogenically induced change is too rapid for the system to adapt (or whether such adaptions will be undesirable) is a key question when considering how the system may function from 2050 and beyond – and one that we current do not have the capacity to answer in any detail. Notwithstanding the above it can be argued that the combination of a science-based management framework and the collaborative decision making processes that have been implemented to halt the decline of Moreton Bay have shown remarkable progress in a relatively short period of time. This suggests we can be cautiously optimistic about our future capacity to manage the system well.

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