Gold Coast Broadwater: Southern Moreton Bay, Southeast Queensland (Australia)

Ryan J.K. Dunn, Nathan J. Waltham, Nathan P. Benfer, Brian A. King, Charles J. Lemckert, and Sasha Zigic

Abstract

The Gold Coast Broadwater, a large shallow estuarine water body, is a central feature of the Gold Coast City in Southeast Queensland (Australia) and forms the southern part of Moreton Bay. The Broadwater has undergone dramatic changes over the past few decades, including the construction of an extensive number and network of artificial waterways that account for up to 90 % of Australia's canal estates. Positioned in one of the fastest growing regions in the developed world, urbanisation surrounding the Broadwater will continue. The region has important biodiversity values that have led to areas of the Broadwater being listed as an international Ramsar site and inclusion to international migratory bird agreements. The Broadwater provides a vital function in the provision of feeding, spawning and nursery sites for recreationally and commercially important finfish species. Key to the protection of the Broadwater is a reduction of pollutant loads from urban and agricultural stormwater run-off, golf courses and industrial infrastructure/areas and replacement of natural habitats with urban development. Collectively, initiatives undertaken by regulatory authorities have been successful to date and demonstrate that future conservation requires the integration of multidisciplinary science and proactive management driven by the high ecological, economical and community values placed on the Broadwater and adjoining waterways.

Keywords

Gold Coast Broadwater • Urban expansion • Coastal waterways • Artificial residential waterways • Urban run-off • Vessel pollution

R.J.K. Dunn (✉) • N.P. Benfer
B.A. King • S. Zigic
Asia-Pacific ASA Pty Ltd, P.O. Box 1679, Surfers Paradise, QLD 4217, Australia
e-mail: rdunn@apasa.com.au

N.J. Waltham
Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER), James Cook University, Townsville, QLD 4811, Australia

C.J. Lemckert
Griffith School of Engineering, Griffith University, Gold Coast Campus, Nathan, QLD 4222, Australia

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Box 1

Ryan Dunn et al. studied the Gold Coast Broadwater, a large shallow estuarine water body with an extensive number and network of artificial waterways that account for up to 90 % of Australia's canal estates. The region is one of the fastest growing regions in the developed world with rampant urbanisation. Nevertheless the region has important biodiversity values that have led to areas of the Broadwater being listed as an international Ramsar site and inclusion to international migratory bird agreements. Key to the protection of the Broadwater is a reduction of pollutant loads from urban and agricultural stormwater run-off, golf courses and industrial infrastructure/areas and replacement of natural habitats with urban development. Evidence from previous modelling suggests that under a scenario of current and future urbanisation, sediment and nutrient loads far exceed that which is sustainable for local waterways. As such, the "business as usual" option is not sustainable and major stormwater capital infrastructure works are therefore required.

Additionally, restoration projects such as weed removal, foreshore stabilisation works, revegetation of cleared areas, community education/and capacity building and flood mitigation programs are necessary to achieve the values that the population demands and expects. This is probably the best case in Australia of planning for the future by integrating multidisciplinary science and proactive management driven by the high community values placed on Broadwater and its waterways.

Site Introduction

Promoted as a leading tourism and lifestyle destination, the Gold Coast City in Southeast Queensland, Australia, boasts an image of the 'Green behind the Gold' with its 52 km of white sandy beaches, in front of a backdrop of subtropical rainforest in hinterland areas. The Gold Coast Broadwater, a large shallow estuarine water body, is a central feature of the Gold Coast City and forms the southern part of Moreton Bay, a national and international significant coastal system (27.88 S; 153.41 E, Fig. 1). The Broadwater is positioned in one of the fastest growing regions in the developed world with the Gold Coast population increasing from 110,900 in 1976 (ABS 1986) to 497,848 in 2008 (ABS 2008). The forecast population is projected to reach 900,000 by 2030. As a consequence of continued population increase, the Broadwater will experience further large-scale urban expansion, including residential canal, marina facilities and commercial infrastructure that are already present along the region's intertidal waterways and catchments.

Geomorphological and Hydrological Setting

Climatic Settings and Physical Characteristics

The climate of the Southeast Queensland region is subtropical, with most rainfall occurring during the summer period (December to February). The Broadwater has an average annual rainfall of 1,094 mm (Gold Coast Seaway) (Eyre et al. 2011a) and an average regional mean air temperature range of 13–29 °C. Winds are predominantly from the southeast to northeast from October to March and from the southwest at other times, with a daily pattern of strengthening afternoon sea-breezes superimposed. The region experiences regular severe summer storms, while tropical cyclones are known to affect the region, although infrequently. Depressions of subtropical origin, such as east coast lows, are more frequent but less intense than tropical cyclones. However, both storm systems are capable of generating severe rainfall and elevated coastal sea levels that can lead to coastal flooding (McInnes et al. 2000).

The Broadwater's catchment covers an area of 108,000 ha of which 30 % has undergone urban development with the remainder being undisturbed forest (40 %), cleared grazing land (12 %), crop land (10 %) and road networks (8 %) (Waltham 2002). The Broadwater catchment has experienced moderate to high soil erosion and land degradation over the past few decades, which represents an

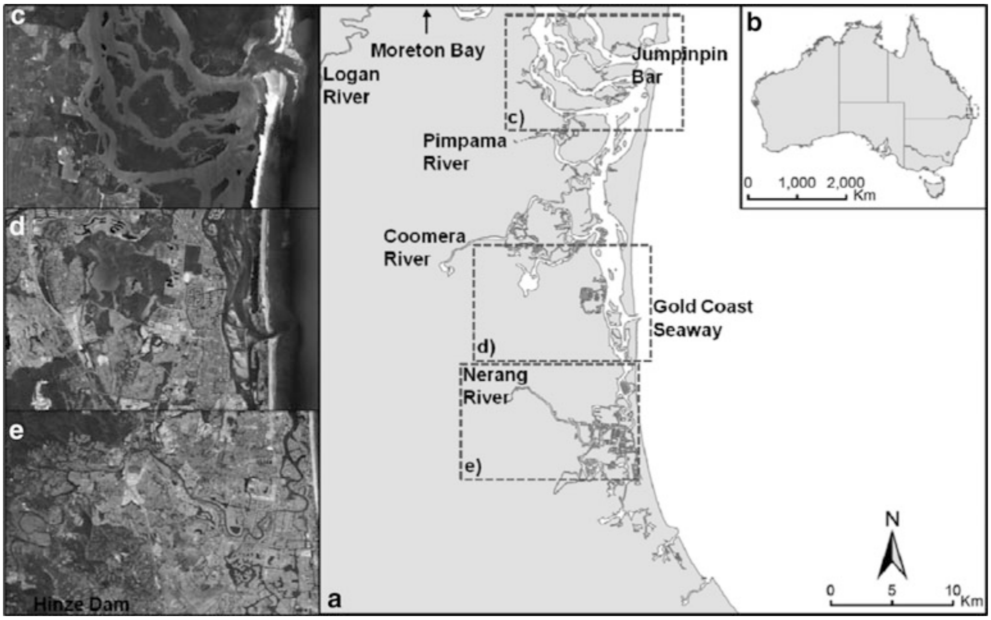


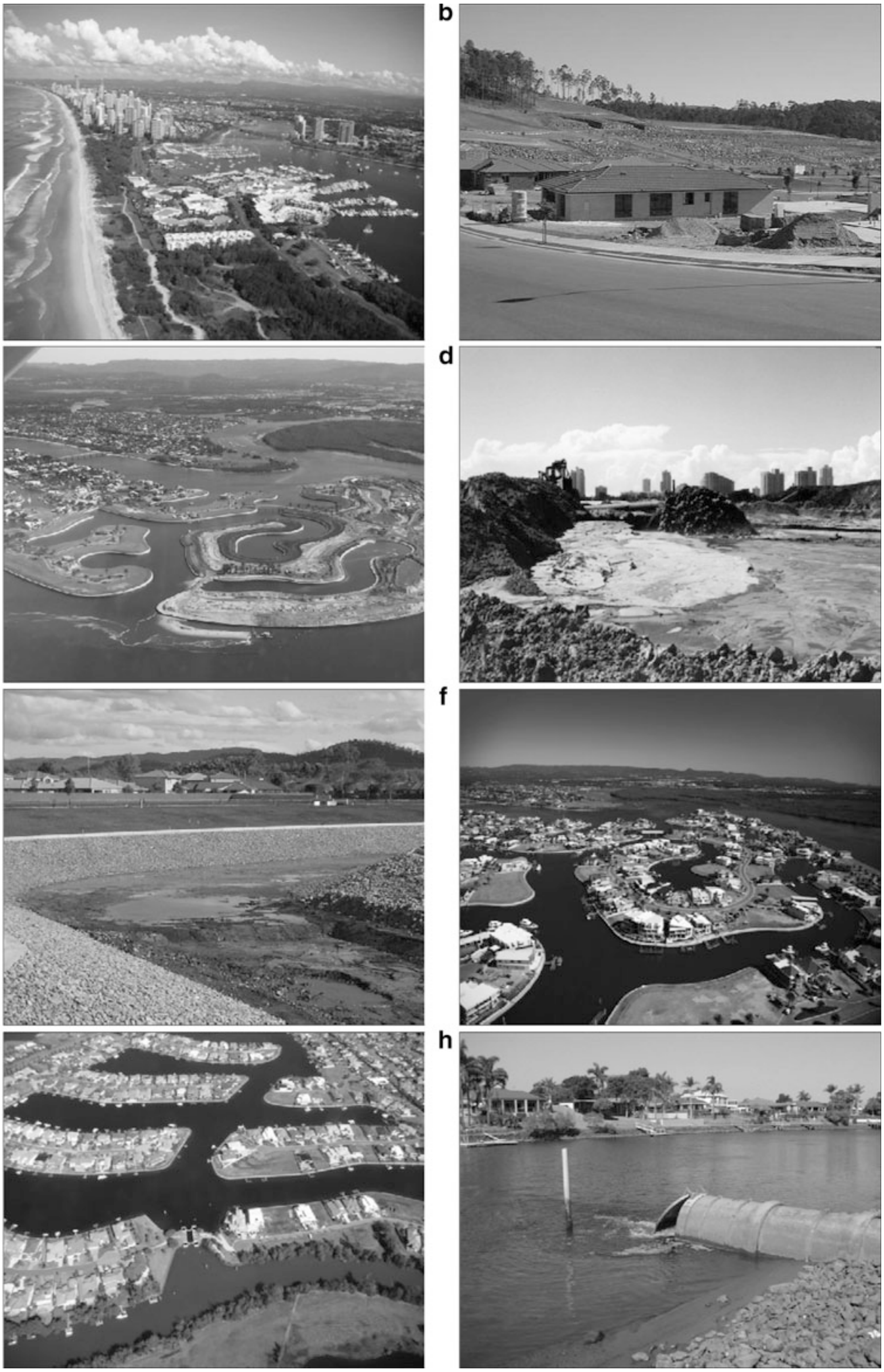
Fig. 1 Location of the Gold Coast Broadwater (**a**); Southern Moreton Bay, Australia (**b**); including the regions of the four principal rivers entering the Broadwater and inset images of; (**c**) Jumpinpin Bar; (**d**) Gold Coast Seaway and (**e**) Nerang River including the Hinze Dam (Satellite images sourced from Google Earth)

approximate 10 % increase in nutrient and sediment loads (BMT WBM Oceanics 2010). Four principal rivers drain the catchment: Nerang River, Coomera River, Pimpama River and the Logan-Albert Rivers, in addition to several smaller creeks (Fig. 1). The volume of water entering the Broadwater from the river systems is of lesser magnitude than tidal inputs, with the exception of periods following heavy rainfall (Moss and Cox 1999).

The Broadwater's main tributary to the south, the Nerang River, is largely urbanised throughout its estuarine reaches and features extensive residential canal developments. Land use upstream from the estuarine zone of the Nerang River is mainly rural residential and grazing, with forested areas upstream of the Hinze Dam (Fig. 1e), approximately 37 km from the river mouth. Upper catchment flow of the Nerang River has been limited since the construction of this dam, which is the major water supply for the Gold Coast. The main catchment to the north is the Coomera. This catchment is currently less urbanised than the Nerang, but rapid urban development in its lower reaches, including extensive residential canal, golf course and periurban development, have occurred on the lower flood plains (Waltham 2002). Land use in the mid Coomera catchment includes acreage housing estates with grazing land and a forested upper catchment. No water storages have been built on the Coomera River. The Pimpama and Logan-Albert Rivers located further to the north drain into the upper portion of the Broadwater.

The Broadwater has undergone dramatic changes, including construction of the Gold Coast Seaway, commercial developments, residential canal and artificial lake estates and dredging operations for navigation purposes. Additionally, increased human activities and intervention within the Broadwater has led to land reclamation to extend portions of the western foreshores to increase recreational and development purpose areas. Indeed a striking feature of the Gold Coast is the extensive number and network of artificial waterways, including canal estates, built for the purpose of increasing useable waterfront property development (Figs. 2 and 3). Since initial canal developments in 1956 (Johnson and Williams 1989) artificial waterways within the Broadwater system have progressively expanded from the initial confines of the Broadwater and lower Nerang River to include a widespread network contributing to approximately 500 km of tidal waterfront (www.ozcoasts.gov.au) with a surface area exceeding 200 km^2, accounting for up to 90 % of Australia's canal estates (Waltham and Connolly 2011). More recently, a shift occurred away from the construction of narrow open canals leading directly off estuarine stretches of coastal rivers, to the construction of artificial tidal lakes with restricted exchange with natural estuarine waters (Zigic et al. 2002) in order to minimise the tidal prism. Presently, the number of artificial lakes connected to the Broadwater system accounts for approximately 95 % of the total Oceania number, where the Oceania number represents 63 % of the global number (Waltham and Connolly 2011). The Gold Coast Broadwater foreshore has also been widely modified during the last decade in response to community aspirations and economic objectives.

a b



c d

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Fig. 2 Gold Coast Broadwater and surrounding landscapes; (**a**) skyline of residential and commercial buildings behind the golden beaches; (**b**) expansion of residential suburbs has changed forested catchments to urban residential estates; (**c**) canal estate construction; (**d**) dredging shallow freshwater wetlands for the construction of canal estates; (**e**) construction of canal estate over terrestrial land; (**f**) construction of houses in canal estate including pontoons and jetties; (**g**) artificial lake system separated from estuary via a tidal control device and (**h**) tidal gate controlling exchange of water between estuary and artificial lake system

Fig. 3 Global extent of artificial residential estuarine systems (canal and lake estates combined), by country and (where relevant) state or province within country. *Grey scale* gradient represents total linear length (km) (Source: Waltham and Connolly 2011)

The low wave-energy environments of protected beaches, sand flats, mud banks and mangrove habitats of the Broadwater provides economical and recreational benefits to the regional community including: boating, jet skiing, parasailing, fishing, swimming, and diving, supporting a range of vessels and also water float plane activities.

Hydrological Setting and Features

The Broadwater is a micro-tidal, estuarine lagoon, characterised by exposed sandbanks, mangrove systems, islands, and seagrass beds, which are protected from the Pacific Ocean by a barrier island system (South Stradbroke Island, located between Jumpinpin Bar and the Gold Coast seaway) (Fig. 1). Tidal channels within the region are up to 9 m deep, however the system is typically shallow, with a mean mid-tide water depth of 1.74 m (Eyre et al. 2011a). The Broadwater is connected to the adjoining Pacific Ocean through the Gold Coast Seaway in the south, and Jumpinpin Bar to the north (Fig. 1). The tidal exchange of waters through the two oceanic connections is important in the exchange and flushing of the Broadwater (Mirfenderesk and Tomlinson 2008). The hydrodynamics of the Broadwater environment is well known (e.g. Mirfenderesk and Tomlinson 2007, 2008; Mirfenderesk et al. 2007; Sennes et al. 2007; Knight et al. 2008; Ali et al. 2009, 2010; Davies et al. 2009), including the adjoining artificial environments (e.g. Zigic et al. 2002, 2005; Benfer et al. 2010). Collectively, these studies provide important insight into the hydrodynamic characteristics and are important in understanding the hydrodynamic consequences (and related water quality aspects) under past and future land use.

The Gold Coast Seaway (Fig. 1d) is a man-made 250 m wide rock retaining wall entrance constructed in 1985, and serves as the primary navigable connection from the Broadwater to the Pacific Ocean. The mean water depth of the Seaway is 11 m (Mirfenderesk and Tomlinson 2008). In a morphological sense, features of a wave-dominated estuary are visible at the Broadwater, including a barrier system, ebb tide shoals and flood tide shoals in the outer zone of the estuary and mudflats, and mangroves and salt marsh in the central zone of the estuary. The hydrology and geomorphology of the southern region of the Broadwater is influenced by the Seaway entrance. Alternatively, the opening at the Jumpinpin Bar in the north of the Broadwater is not navigable due to the dynamic nature of the opening, with a shallow shifting sand bar dominated entrance.

The central Broadwater is predominantly a marine system (approximately 33 ppt) where the salinity reduces upstream in the adjoining river systems (approximately 10 ppt). At the Gold Coast Seaway and Jumpinin Bar, the tidal range varies between 1 and 2 m (Mirfenderesk and Tomlinson 2008), and this range is the main driving force for horizontal water flow and exchange with the Pacific Ocean (Mirfenderesk and Tomlinson 2008). Tidal characteristics at the Seaway and Jumpinpin Bar have been identified as predominantly semi-diurnal with a diurnal inequality (ebb dominant). Calculation of the total flux through Seaway during a typical flood tide is approximately 66×10^6 m^3, for an approximate cross section area of 3,500 m^2. The same calculation for Jumpinpin Bar is approximately 50×10^6 m^3 (approximate cross section of 3,000 m^2, Mirfenderesk and Tomlinson 2008).

Measured tidal velocities within the Seaway range between 0.001 and 0.909 m s^{-1} and 0.018–1.8 m s^{-1} (Dunn et al. 2012a). Strong tidal flows through the Gold Coast Seaway effectively provide resilience against minor to moderate changes in the catchment conditions and associated stormwater pollution (Davies et al. 2009). Similar resilience is not provided in the upper major tributaries of the Broadwater due to narrow channels and a longer residence time for tidal flushing. From a hydrodynamic point of view the volume of the Broadwater varies between 30 × 10^6 m^3 during low tide to more than 50 × 10^6 m^3 at high tide (Davies et al. 2009). Indeed historic development of the artificial canal estates initially resulted in an increase in tidal volumes and subsequently increased tidal velocities in the lower reaches. This altered flow has contributed to bank erosion and undercutting of revetment walls, which leads to failure and damage to residential properties and infrastructure (Zigic et al. 2005). In response, flow structures have been installed to regulate the exchange of water with the adjacent estuary to ensure restricted water exchange, where the tidal range of the adjacent estuary is not desired within the canal system, and in some cases, with careful timing, they can be used upstream to reduce the tidal demands at the mouth of the estuary.

The Broadwater and associated development infrastructure also experience periodic flooding from both intensive and prolonged rainfall events. In fact, Gold Coast region has long been rated as the most vulnerable area subject to flooding in Australia (Smith 2002). Hence flood risk maps are published by the Gold Coast City Council. As a result flood defences of variable style and quality are located throughout the system, including weir structures and restrictions of developments on the floodplains. Current building regulations have been informed by knowledge of past extreme events. The current Disaster Management Plan (GCCC 2010) contains a co-ordinated approach to floods, storms and other potential risks (Cooper and Lemckert 2012). The typical ground elevation in waterfront developments is approximately 2 m above mean high tide level and periodic flooding occurs in the lowest lying areas after extreme rainfall. The floodplains of the Broadwater are developed with a number of dwellings at risk of flooding during major rainfall events. Storm tides within the Broadwater can exacerbate flood events by elevating sea levels at the outflow regions of rivers and streams thereby reducing flow rates. In many situations, the weather conditions that cause storm tide events are also accompanied by severe rainfall. The establishment of design storm tide levels for planning and development purposes is therefore of critical importance to minimise the risk of damage to infrastructure during such events. Previous studies conducted in this region relating to storm surges include those by Harper et al. (1977), Blain, Bremner and Williams Pty Ltd (1985) and McInnes et al. (2000). Land use adaptation options for the Broadwater region as a result of potential rises in sea level is discussed by Cooper and Lemckert (2012). Furthermore, Mirfenderesk (2009) presents discussions of flood risk on the Gold Coast and a system that has been developed to support decision-making in the region.

Ecological and Physico-chemical Aspects

Ecological Importance

The region has important biodiversity values, including important populations of sea turtles, dugongs and annual shorebird migrations that have led to areas of the Broadwater being listed as an international Ramsar site,[1] including Chinese-Australia Migratory Bird (1974) and Japan-Australia Migratory Bird Agreement (1986) status. Additionally, the Broadwater, as part of the *Marine Parks (Moreton Bay) Zoning Plan 2008*, is zoned as a habitat protection zone and contains Marine National Parks including the Coombabah Lake region. Furthermore, the Broadwater also hosts the Southern Moreton Bay Islands National Park, which covers an area over 1,500 ha and supports greater than 50 % of the mangroves of Moreton Bay (DERM 2012). In an effort to protect turtle and dugongs from boat strikes in critical feeding and resting areas, designated vessel "go slow" zones are implemented within the Broadwater. The Broadwater also provides an important nursery for recreationally and commercially important finfish species (*Queensland Fisheries Act 1994*).

Seagrasses, saltmarshes and mangrove communities occupy the Broadwater environment, which are vital in the provision of feeding, spawning and nursery sites for local aquatic fauna (Ross 1999; Thomas and Connolly, 2001; Connolly 2003; Hollingsworth and Connolly 2006; Waltham and Connolly 2006, 2007). The modification or removal of seagrass and mangrove nursery habitats for urban expansion should be viewed with their ecological importance in mind. Large areas of seagrass occur in the northern region of the Broadwater with smaller fragmented areas occurring within the southern sector (Moss and Cox 1999). A 1997 survey of seagrass composition and distribution revealed three species

[1] The Convention on Wetlands, signed in Ramsar, Iran in 1971, is an intergovernmental treaixty dedicated to the conservation and wise use of wetlands. The Convention's mission is the conservation and wise use of wetlands by national action and international cooperation as a means to achieving sustainable development throughout the world (Environment Australia 2003).

of seagrass occurring in the Broadwater; *Zostera capricorni, Halophila ovalis* and *Halophila spinulosa* over an area of 304 ha (McLennan and Sumpton 2005). Mangrove communities include *Avicennia marina* and, to a lesser extent, *Rhizophora stylosa* and *Aegiceras corniculatum,* while salt marsh communities include *Sporobolus virginicus*.

Carbon Flow and Ecology

The determination of organic matter sources and flow within the Broadwater, which provide nutrition for estuarine species remote from carbon sources is important in understanding the functioning and management of the estuarine environment. A number of studies investigating organic matter sources and connectivity within the Broadwater have been undertaken using C/N ratios, stable isotopes ($\delta^{13}C$ and $\delta^{15}N$) and fatty acid biomarkers (e.g. Connolly 2003; Thomas and Connolly 2001; Melville and Connolly 2003, 2005; Guest and Connolly 2004; Waltham and Connolly 2006; Werry and Lee 2005; Dunn et al. 2008, Spilmont et al. 2009; Oakes et al. 2010; Werry 2010; Lee et al. 2011). Results of these studies have demonstrated the importance of both autochthonous and allochthonous organic matter sources, including terrestrial and planktonic (i.e. mangroves, seagrasses, zooplankton, diatoms and other algal species) sources.

Resident first order and higher consumers within the Broadwater include recreationally and commercially important fish species, including: *Arrhamphus sclerolepis* (snub-nosed garfish), *Acanthopagrus australis* (yellow fin bream), *Sillago ciliate* (sand whiting), *Platycephalus fuscus* (dusky flathead) and *Mugil cephalus* (mullet). The Broadwater also provides an essential nursery for coastal water fish species (e.g. snapper, mackerel and tailor species). Shark and ray species (e.g. *Carcharhinus leucas* (bull sharks) and *Dasyatis fluviorum* (estuary stingray)), mud crab (*Scylla serrate*) turtles (*Chelonia mydas,* green sea turtle), dolphin (*Tursiops aduncus*n) and dugong (*Dugong dugon*) also inhabit the estuarine environment. The Broadwater is an important region for large communities of resident bird species (e.g. *Phalacrocorax varius* (pied cormorant), *Ardea novaehollandie* (white-faced heron) and *Haematopus longirostris* (pied oyster catcher)) which are routinely found in large numbers on the exposed sand and mud flats. In addition to resident bird species the Broadwater is an important bird staging area along avian migratory flyways (routes) with birds (e.g. *Tringa brevipes* (grey-tailed tattler), *Charadruis leshenaultii* (greater sand plover)) arriving from Europe and Asia during the southern hemisphere summer. Readers are referred to Shorebird Management Strategy Moreton Bay (EPA 2005) for a detailed list of resident and migratory bird species of the Broadwater. Communities of soft sediment benthic infauna which provide food sources for both bird and fish species have been investigated in the Broadwater waterways, as part of baseline and urban development impact assessments (e.g. GHD Pty Ltd. 2003; Dunn 2009) and include amphipod, crab, bivalve, worm and yabby species. Initial information suggests large heterogeneity in assemblages, presumably owing to different grain size and organic matter content in surficial sediments, pollutant accumulation, and also water quality conditions (e.g. Stephenson and Cook 1977; Poiner 1977; Young and Wadley 1979; Stephenson 1980). In a study of the benthic faunal assemblages in canal estates, Cosser (1989) reported 65 taxa present, with 25 taxa comprising approximately 95 % of the total abundance. In that study, two broad community types were identified, one community restricted to dead-end canal locations and characterised by low diversity, low species richness, while the other was distributed in connecting canals and characterised by high species richness and diversity. This spatial arrangement of species followed a progressive transition between community types resulting from deterioration in the concentration of dissolved oxygen; a lower species richness and abundance in dead-end canal sites where dissolved oxygen concentration is low while higher richness and abundance in oxygen rich canal opening areas. Within the Broadwater recreational fishing applies pressures on the benthic communities through the collection of animals for the use of bait. Species particularly targeted and collected by fishing enthusiasts include bloodworms (*Marphysa* sp.), the marine yabby (*Trypaea australiensis*) and soldier crabs (*Mictyris longicarpus*). Additionally, these species are also collected commercially and sold at fishing outlets within the Broadwater region. The removal of benthic species not only alters important trophic links within the Broadwater but potentially influences benthic metabolism, rates of organic matter turnover, efflux rates of regenerated nutrients and also nitrogen cycle pathways (Jordan et al. 2009; Dunn et al. 2009, 2012b; Eyre et al. 2011b).

The construction of extensive artificial residential waterways have replaced natural wetlands and created new estuarine habitats throughout the Broadwater. Comparisons of the fish fauna in the artificial waterways of the Broadwater and in adjacent natural wetlands of mangrove, saltmarsh and seagrass have shown almost complete overlap in the species present (Morton 1989, 1992). Although differences in the relative proportions of species are detectable, all of the economically important species found in adjacent non-disturbed estuarine waters are also present in artificial waterways (Morton 1989, 1992), additionally some critic species to wetlands have also been recorded in canals (e.g. Waltham and Connolly 2007 recorded the Beady Pipefish (*Hippichthys penicillus*)). This same pattern of species overlap is similar to canal developments elsewhere in the world (e.g. Baird et al. 1981; Maxted et al. 1997).

Connolly (2003) provided the first account that some species are able to derive nutrition from local sources in

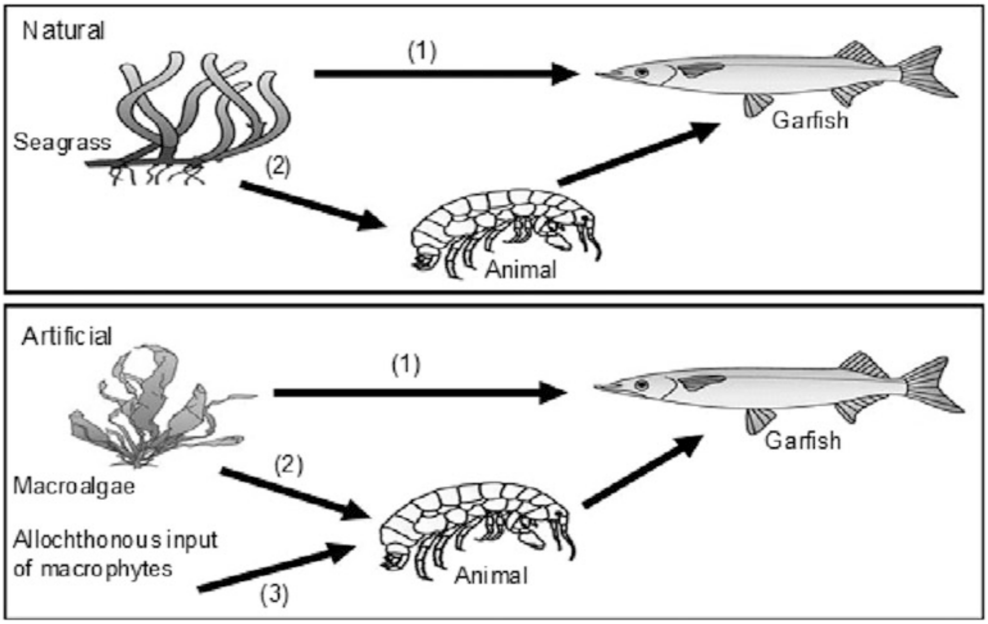


Fig. 4 Trophic models for *Arrhamphus sclerolepis* in natural and artificial urban waterways: (*1*) direct consumption of autotroph; (*2*) direct consumption of an animal intermediary that utilises autotroph; and (*3*) consumption of animal intermediary that utilises detrital macrophytes (having both enriched and depleted $\delta^{13}C$ values) transported from adjacent natural wetlands (Source: Waltham and Connolly 2006)

artificial systems using alternative sources to those available in natural systems within the Broadwater. In an additional study, Waltham and Connolly (2006) provided conclusive evidence of the plasticity of fish to adapt to the created estuary environment within the Broadwater. In that study, the authors combined stomach contents with stable isotope analysis to demonstrate the basal sources of nutrition and uptake pathway in the snub-nosed garfish (*Arrhampuhs sclerolepis*) (Fig. 4).

The Broadwater, including the artificial waterways, provide additional habitat opportunity for Bull Shark (*Carcharhinus leucas*) populations. Sightings of *C. leucas* within the artificial waterways of the Broadwater are often reported (Zeller 1999; Werry 2010), where canal systems, in addition to low salinity river environment, have extended the extent of nursery habitat for newborn and juvenile *C. Leucas* outside the range of conventional natural estuaries (Werry 2010). An extensive investigation by Werry (2010) and Werry et al. (2012) within the Broadwater demonstrated the movement patterns of *C. leucas* within the Broadwater differs, with juveniles remaining within low salinity river reaches and canal systems, while older and larger sharks extend over much wider areas. Recorded movements of the older and larger sharks include extensive coverage of canal and river systems and movements between the Broadwater and adjoining oceanic environment (Werry 2010). Newborn and juvenile individuals remaining resident in single defined areas are susceptible to anthropogenic influences (e.g. fishing pressures, plastics and contaminants). Shark populations and their movement habits pose a safety concern for some local residents of the Broadwater where water activity pursuits are popular. With urban coastal development and recreational use of the Broadwater set to continue to grow, human interactions with *C. leucas* are likely to increase.

Sediment and Water Column Characteristics

Deep sand accumulations derived from long-shore ocean currents characterise the Seaway and eastern margins of the Broadwater. Surface sediments in the eastern shore regions of the Broadwater are predominantly composed of quartz sands, however canal locations typically exhibit relatively finer sediment textures (Burton et al. 2004). Sediment organic carbon content is greater within residential canals and very low within the central regions of the Broadwater. Increased fine sediments and organic carbon within the residential canals is attributable to inputs from urban sources, which receive loads of urban stormwater from surrounding residential areas. These inputs readily remain trapped within the residential canal due to their designs which often have reduced current velocities, and in turn flushing characteristics, particularly in dead-end areas. Northern Broadwater sediments, including Pimpama, Coomera and Merrimac/Carrara floodplains contain soils associated with mangrove and tea-tree wetlands (humic gleys, peaty gleys and meadow podzolics) and areas of pyrite-rich sediments, which when disturbed can produce sulphuric acid and associated elevated aluminium (Al) and

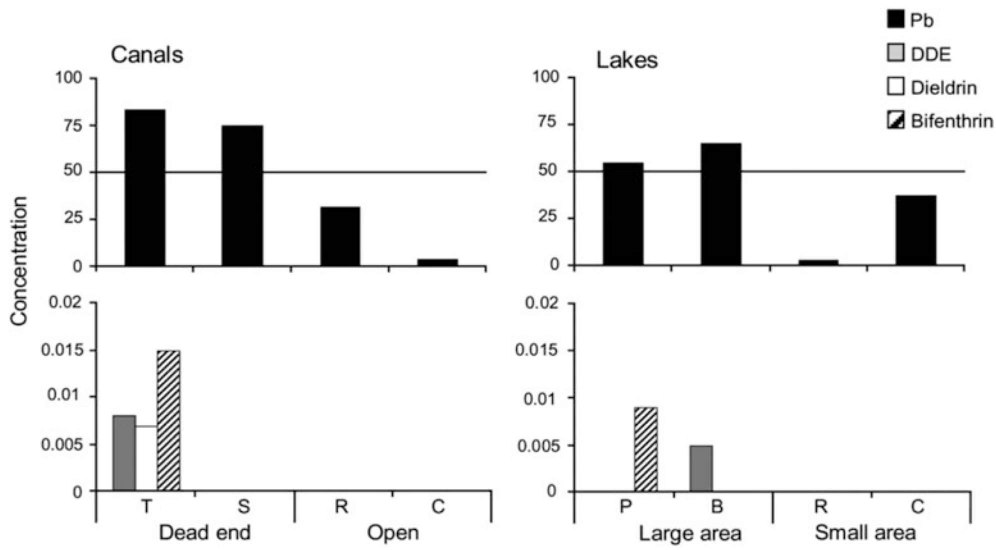


Fig. 5 Example lead (Pb) (mg kg^{-1}) and pesticide (mg kg^{-1}) concentrations in the sediment of single canal and lake systems in Broadwater region. Results shown are for a composite sample from three sediment grabs collected in each system. Interim Sediment Quality Guideline low trigger value for Pb shown, however, DDE, dieldrin and bifenthrin not shown, as concentrations comply with the guidelines (ANZECC/ARMCANZ 2000). For canals, dead end and open labels refer to flow characteristics of each system, while large (~280 ha) and small (~20 ha) area refers to the size of the catchment area draining to each lake system (Source: Waltham et al. 2011)

iron (Fe) concentrations. Discussions of iron-sulfide and trace element concentrations in sediments of the Broadwater region include those by Preda and Cox (1998), Burton et al. (2005, 2008), Robertson et al. (2009) and Pagès et al. (2011).

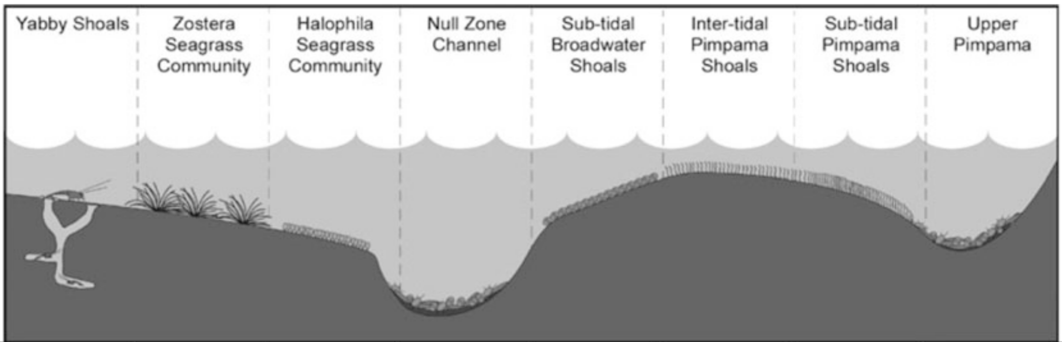
Salinities and temperature collected throughout the central Broadwater and the oceanic entrances of the Broadwater reflect a well-mixed, well flushed and dynamic system, with no notable stratification (e.g. Mirfenderesk and Tomlinson 2007; Davies et al. 2009). In contrast the prevailing flushing regime within studied canal systems has led to the establishment of an oxycline at a depth of approximately 10 m (depending on season), below which depth hypoxic conditions prevail (Waltham 2002, 2009; Lemckert 2006).

The hydrology, geochemistry and primary productivity of the Broadwater is linked to sediment and nutrient inputs from the catchment, ultimately as a result of freshwater inputs. Within the Broadwater much of the terrestrial loading occurs during episodic high-energy rainfall events. In addition to rainfall events influencing system behaviour, physical parameters, nutrient and trace metal concentrations within the natural and urbanised settings of the Broadwater and Seaway typically demonstrate cyclic variations, with the influence of tidal cycles apparent (e.g. Dunn et al. 2003, 2007a, 2012a).

As expected for a large dynamic estuarine environment, sediment and water column trace metal and nutrient concentrations between and within locations/habitat type in the Broadwater have been shown to vary significantly (for example concentration ranges see Moss and Cox 1999; Dunn et al. 2003, 2007a, b, c, 2012c; Burton et al. 2004, 2005; Warnken et al. 2004; Eyre et al. 2011b; Waltham et al. 2011). In general, undetectable to very low metal concentrations are located in the central Broadwater, whereas elevated concentrations are observed for sites located in residential canals and commercial marinas. This is attributed to the coarse texture of sediments and well-flushed hydrodynamic regime in the central Broadwater, and to the comparatively poorly flushed nature, finer sediment sizes and proximity to traffic and boat maintenance related metal sources in the residential canals and marinas (Burton et al. 2004). Evidence of spikes in sediment pesticide concentrations (some banned over 50 years ago) in some artificial residential waterways of the Broadwater has been reported by Waltham et al. (2011) (see Fig. 5). Nutrient concentrations measured within the Broadwater are typical of concentrations reported in Australian estuarine systems. Sedimentary and water column bacterial concentrations are presented in Pratt et al. (2007) and Dunn et al. (2012a).

The characteristics of sediment transport are important as they play a critical role in the functionality and health of the Broadwater (Webster and Lemckert 2002), as increased suspended sediments also limits light availability through the water column for primary producers. Additionally, when bottom sediments are resuspended trace metals, nutrients and organic contaminants can be released into the water column. The importance of understanding suspended sediment dynamics within the Broadwater has led to studies being completed in an attempt to increase conceptual understanding of sediment dynamics, including turbidity maxima, within the Broadwater (e.g. Hunt and Lemckert 2001; Webster and Lemckert 2002; Hunt et al. 2006; Davies et al. 2009).

Recent studies within the Broadwater have included investigations of baseline nitrogen cycling rates and have



Processes	Yabby Shoals	Zostera Seagrass Community	Halophila Seagrass Community	Null Zone Channel	Sub-tidal Broadwater Shoals	Inter-tidal Pimpama Shoals	Sub-tidal Pimpama Shoals	Upper Pimpama	Total
Denitrification (t N yr^{-1})	103.0 ± 6.8	318.4 ±143.5	176.5 ± 150.3	5.5 ± 0.4	61.2 ± 31.2	4.5 ± 1.5	9.0 ±1.0	10.3 ± 3.0	688.4 ± 337.7
N-fixation (t N yr^{-1})	1.3 ± <0.1	114.6 ± 114.6	147.6 ±147.6	<0.1 ± <0.1	1.0 ± <0.1	<0.1 ± <0.1	0.1 ± <0.1	<0.1 ± <0.1	264.6 ± 264.6
Net N_2 Flux (t N yr^{-1})	101.7 ± 6.8	203.8 ± 28.9	28.9 ± 2.7	5.5 ± 0.4	60.2 ± 31.2	4.5 ± 1.5	9.0 ± 1.0	10.3 ± 3.0	423.8 ±75.6
DIN Flux (t N yr^{-1})	86.7±15.1	14.0±14.3	-5.6± 0.6	0.8 ± 0.5	-7.6±9.4	0.4 ± 1.0	-0.2 ± 0.2	11.6 ± 3.3	100.1 ± 44.7
DON Flux (t N yr^{-1})	-29.2 ±54.9	48.7 ± 49.9	-43.7 ± 15.7	3.6 ±3.0	45.8 ± 73.0	-7.4 ±1.9	1.5 ±7.4	14.4 ±5.6	33.7 ± 211.5
N-Recycling (t N yr^{-1})	135.6 ± 162.1	1013.2 ± 157.3	412.8 ± 89.5	24.0 ± 2.5	584.0 ± 91.7	76.8 ± 10.4	250.7 ± 27.0	21.1 ± 17.2	2909.0 ± 557.9
DIP Flux (t P yr^{-1})	1.8 ± 8.7	1.6 ± 2.4	-0.1 ± 0.3	0.1 ± 0.1	-3.2 ±5.0	0.2 ± 0.2	-0.3 ±0.1	-0.3 ± 0.2	-0.2 ± 27.6
DOP Flux (t P yr^{-1})	10.8 ± 11.2	1.9 ± 9.2	0.7 ± 2.6	0.1 ± 0.1	-3.6 ± 5.0	-0.5 ± 0.5	0.0 ± 0.6	0.2 ± 0.4	9.7 ± 29.5
P-Recycling (t P yr^{-1})	8.5 ± 10.1	62.0 ± 9.8	25.3 ± 5.6	1.5 ± 0.2	36.5 ± 5.7	4.8 ± 0.7	15.7 ± 1.7	1.3 ± 1.1	168.6 ± 34.9
Area (km^2)	5.4 ± 0.3	3.2 ± 0.2	1.7 ± 0.1	0.4 ± <0.1	6.5 ± 0.3	0.6 ± ≤0.1	1.5 ± 0.1	0.9 ± ≤0.1	20.2 ± 1.0

Fig. 6 System wide annual estimates of denitrification, Nitrogen-fixation, net N_2 effluxes, dissolved inorganic nitrogen (*DIN*) fluxes, dissolved organic nitrogen (*DON*) fluxes, nitrogen recycling, dissolved inorganic phosphorus (*DIP*) fluxes, dissolved organic phosphorus (*DOP*) fluxes and phosphorus (*P*) recycling in the eight major open water benthic habitats in the Southern Moreton Bay study area (Source: Eyre et al. 2011b)

shown differences in denitrification rates according to different benthic habitat types and seasonal influences (e.g. Ferguson et al. 2004; Eyre et al. 2011a, b; Teasdale et al. 2009; Dunn et al. 2012c), additionally, manipulative investigations relating to the regulatory influences of burrowing infauna and organic matter have also been performed using Broadwater sediments and inhabiting macrofauna (e.g. Jordan et al. 2009; Dunn et al. 2009, 2012b). Collectively, these studies provide insight into the benthic metabolism and solute fluxes across the sediment-water interface in addition to a recent study by Eyre et al. (2011c) which presents the metabolism of different benthic habitats and their contribution to the carbon budget with regions of the Broadwater. Figure 6 provides annual estimates of biogeochemical processes throughout the Broadwater in varying open water benthic habitats determined by Eyre et al. (2001b). Furthermore, the denitrification efficiencies and ecosystem processes (functional values and mapping) of the Broadwater, is presented by Eyre and Ferguson (2009) and Eyre and Maher (2011), respectively.

Anthropogenic Influences

Key to the protection of the Broadwater is a reduction of pollutant loads from urban and agricultural stormwater runoff, golf courses and industrial infrastructure/areas and replacement of natural wetland habitat with artificial residential canal estates (Waltham et al. 2011). The often restricted flushing nature of the canal and artificial residential lakes developments, relative to nearby natural estuary waters, lends to exacerbation of this issue. This is most evident in dead-end canals where water exchange is low or for waterways that receive stormwater runoff from large urban catchments. Examination of historical data collected within a variety of canals in the Broadwater shows that some estates experience water quality problems mostly due to vertical and horizontal stratification influences (Lemckert 2006). However, canal estates that are shorter and well flushed, better resemble conditions of adjoining estuaries. Increases in nutrient, trace metal, pesticide and bacterial loads entering the Broadwater as a result of

Table 1 Contaminant studies performed within the Gold Coast Broadwater during 2003–2012

Element	Water sampling	Sediment sampling	Biological sampling	Broadwater habitat(s)	Conclusions	Source
Trace metals	X (Water and DGT[a])	–	–	Estuary	Regular pattern of variation in copper and nickel concentrations related to the movement of water past point sources with tidal flows, rather than due to conventional estuarine mixing of end-member waters	Dunn et al. (2003)
Trace metals		X		Estuary, canals and marinas	Sediment metal concentrations undetectable to very low in central Broadwater region, while elevated concentrations were observed in residential canals and marinas	Burton et al. (2004)
Trace metals	X (Water and DGT[a])	–	–	Estuary vessel anchorages	Correlation between recreational boat numbers at anchorage sites and water column copper concentrations for Gold Coast waterways	Warnken et al. (2004)
Nutrients	X	–	–	Creek and Intertidal lake	Nutrient concentrations demonstrated tidal influences, with increased concentrations observed during sampled high tide phases, indicating increased inputs of nutrients originating from external sources other than the study site	Dunn et al. (2007a)
Trace metals	X (Water and DGT[a])	–	–	Estuary, canals, vessel anchorages and marina	Significantly higher concentrations of copper, zinc and nickel concentrations related to the movement of water past point sources with tidal flows	Dunn et al. (2007b)
					DGT-reactive copper concentrations significantly decreased with increased tidal-flushing and vice versa within a marina. DGT measurements also recorded significant increases in copper and zinc after a 24 mm rainfall event	
					DGT-reactive copper increased significantly ($p < 0.001$) during peak boating times, due to increased numbers of Cu-antifouled boats	
Nutrients	–	X	–	Intertidal lake	Lower concentrations recorded for all nutrients in the surface and sub-surface sediments in sample grids dominated by sandy sediment compared to muddy sediments	Dunn et al. (2007c)
					Concentrations compared well with concentrations typically encountered within Australian estuarine systems	
Trace metals	–	–	–	Vessel anchorages	Modelling of copper loading to Broadwater based on boat number observations and literature leaching rates revealed that boat hulls are a major source of copper	Leon and Warnken (2008)
Trace metals	X (DGT[a])	–	X (oysters)	Estuary, canals and marina	Copper concentrations within marina were considerably higher than all other sites	Jordan et al. (2008)
Trace metals	X (DGT[a])	–	X (fish)	Estuary, canals, marina and artificial lakes	With the exception of copper, metal concentrations in water, measured using the DGT technique, complied with relevant Australian guidelines.	Waltham et al. (2011)
					All sediment metal concentrations measured were below the national guidelines, although copper, zinc and lead were found to vary significantly between habitat types.	
					Significantly higher concentrations of copper were found in the gills of fish species from marinas compared to fish caught in other waterways.	
Nutrients, bacteria	X	–	–	Gold Coast Seaway	Nutrient concentrations demonstrated cyclic variations with the influence of tide with near minimum and maximum concentrations generally observed at high and low water, respectively. This demonstrates the influence of oceanic water during flood tides and catchment waters during ebb tides.	Dunn et al. (2012a)

Note: This table is not an exhaustive list, but rather provides examples of previously completed works
[a]Diffusive gradients in thin films is an in-situ time-integrated sampling technique

anthropogenic sources have been reported for receiving sediment, water column and biota (Table 1). A synthesis of data sets reveals important information in understanding key processes and addressing environmental issues. In particular great effort has been made in measuring the natural and anthropogenic processes and associated pollutant concentrations within the Broadwater associated with hydrodynamic conditions (e.g. Dunn et al. 2003, 2007b), developed and undeveloped waterways (Waltham et al. 2011), stormwater runoff (Moss and Cox 1999; Dunn et al. 2007b), marina establishments and antifouled boats numbers (Warnken et al. 2004; Dunn et al. 2007b; Jordan et al. 2008; Leon and Warnken 2008).

The accumulated body of evidence on contaminants within the Broadwater illustrates that there are no major threats of trace metal contamination, with concentrations complying with Australian guidelines (Waltham et al. 2011). The exception is marina facilities which are a source of copper within the Broadwater, additionally anchorages within the Broadwater correspond to elevated trace metal concentrations in the sediment and water column (Warnken et al. 2004). In fact, the potential for recreational and tourism vessels having an impact on ecosystem and public health in Moreton Bay has been one of the key processes identified by the Southeast Queensland Regional Water Quality Management Strategy (a joint whole-of-government and industry initiative) (Warnken and Leon 2006). Due to the large navigable areas of the Broadwater and high usage by recreational and commercial vessels, local marinas and anchorage facilities present notable point and diffuse sources of contaminants, including high loads of contaminants from urban run-off, hard stands and repainting and maintenance outlets (Jordan et al. 2008; Waltham et al. 2011), in addition to contaminant releases sourced directly from the operation of vessels within the Broadwater (Warnken et al. 2004; Leon and Warnken 2008; Dunn et al. 2007b). Warnken et al. (2004) provides data that illustrate relationships between heavy metal concentrations and boating activities at popular Broadwater anchor sites indicating copper emissions from antifouling paints may become an important source with high boat numbers and should be treated with caution by coastal waterway managers. Leon and Warnken (2008) provide an empirical model for the quantification of copper and nitrogen load inputs associated with recreational and tourist vessel numbers in Moreton Bay, including the Broadwater. The key findings of the study reported an estimated input of 141 $\pm$ 46 kg of copper and 1170 $\pm$ 0.38 kg of nitrogen annually. In a related study, Waltham et al. (2011) demonstrated significantly higher concentrations of copper in the gills of three economically important species of fish, with different feeding strategies (partly herbivore *Arrhamphus sclerolepis*, carnivore *Acanthopagrus australis*, detritivore *Mugil cephalus*) from marinas compared to fish caught in other adjacent Broadwater waterways, with fish caught in canals having the second highest copper concentrations and natural waterways the lowest. Concentrations were shown to translate to a low health risk for humans consuming local fish species, with all fish, regardless of feeding strategy (carnivore, herbivore, omnivore), declared safe to eat, complying with Australian Food Standard Code recommended limits for human consumption.

Due to the need for safe navigable waterways for recreational and commercial vessels, dredging regions of the Broadwater is periodically necessary (GCCC 2002). Such practices potentially produce elevated suspended sediment concentrations into the water column as a result of fugitive dredge-related sediment (depending on dredged sediment particle sizes) which in addition to reducing light availability throughout the water column, smother and may ultimately alter benthic communities and trophic linkages, liberate contaminants into the water column and alter nitrogen cycling pathways (Robinson et al. 2005; Erftemeijer and Robin Lewis 2006).

Although the Broadwater is the recipient of numerous point and diffuse sources of contaminants the high degree of mixing and the exchange with the ocean through the Seaway and Jumpinpin Bar aids in the amelioration of water quality (Mirfenderesk and Tomlinson 2008). In addition, this high flushing of the Broadwater is used to expel excess wastewater from the nearby Coombabah waste water treatment plant (WWTP) which services the majority of the Gold Coast City population. Four regional WWTPs have a combined capacity of 1.76×10^5 m^3 a day, with wastewater being treated to a secondary treatment level producing recycled water (Stuart et al. 2009). Presently, the Gold Coast reuses approximately 1.8×10^4 m^3 (10 %) a day of recycled water for irrigation and other commercial uses. The remaining excess treated wastewater (1.1×10^5 m^3 a day) is released to the ocean through a diffuser system (see Stuart et al. 2009) along the northern training wall of the Seaway (Stuart et al. 2009; Dunn et al. 2012a). Under typical operating conditions, treated wastewater is released on the ebb tide, allowing it to be dispersed to the Pacific Ocean, and limiting the recycled water from returning to the Seaway (and ultimately the Broadwater) on the following flood tide (Stuart et al. 2009). Additionally, a second diffuser system exists in the southern sector of the Seaway which also releases treated wastewater from WWTPs located in the south regions of the city. The timing, volume and quality of treated wastewater release are regulated under the *Queensland Environmental Protection Act 1994*. Anticipated population increases have raised concerns about the capacity of the Broadwater to assimilate a greater volume of treated wastewater. As a result, WWTP operators were granted an extension of the existing release licence from 10.5 h per day to 13.3 h per day from the Coombabah wastewater treatment plant (Stuart et al. 2009). The planning load for wastewater treatment on the Gold Coast is expected to grow to 3.51×10^5 m^3 a day over the next 50 years placing significant pressure on the existing release system (Stuart et al. 2009).

The creation of new canals and maintenance dredging of canal sections has resulted in changing the tidal prism of the Broadwater over time. This has resulted in a greater demand on the Seaway to provide greater volumes of water on each tide, increasing tidal currents and creating bank erosion issues. As a preliminary response, all new canal estates require restricted tidal exchange with their adjacent estuary. As a secondary response, in an effort to relieve the stress put on the Seaway, timed gates are installed to connect created brackish lake environments with the upper reaches of the Nerang River. By using carefully timed opening events, the gates are able to reduce the demand on the Seaway by providing the upper reaches with a source of tidal waters during a flood tide and a sink during ebb tide, which has been successful to date (Zigic et al. 2002, 2005). A trade-off though has been reduced flushing potential for the added artificial waterway (Benfer et al. 2010).

Summary

Ongoing urbanisation creates enormous challenges for the management of the Broadwater and thereby threatens the long term sustainability of the system. One example of this challenge is the balance between achieving community expectations and values with continued urban development. In an attempt to achieve this, the Gold Coast City Council has been actively involved with local and regional stakeholders to develop integrated catchment management strategies, which are supported by urban stormwater management plans. These catchment management plans need and indeed follow a total management approach, by combining a range of disciplines (e.g. engineering, environment, social, planning, architecture and management). A major achievement through this process has been the preparation of policies and guidelines relating to stormwater treatment and reuse (Alam et al. 2008). The Gold Coast City Council was one of the first local governments in Queensland (Australia) to implement water sensitive urban design (WSUD) practices (e.g. grass swales/bio-swales, bioretention basins, wetlands and gross pollutants traps) as a statutory requirement under the city's planning framework. In 2007, GCCC adopted WSUD guidelines as part of sustainable development practices for the city for all future urban development. Additionally, attempts have been made to examine opportunities to retrofit WSUD infrastructure to existing urban stormwater network, which involves installing various stormwater quality improvement devices within the existing urban footprint, and works completed have shown improvements to the quality of stormwater runoff, while also extending available habitat for local species (Alam et al. 2008).

As a consequence of the ecological and economic significance of the Broadwater and potential for anthropogenic disturbances, monitoring of the system has been routinely conducted by regulatory authorities (Moss and Cox 1999). Sampling during alternate high and low tides to obtain information on variation in water quality with tidal state, including physiochemical parameters: dissolved oxygen, pH, temperature, conductivity, turbidity, chlorophyll-*a*, nitrogen, phosphorus and faecal coliforms is routinely undertaken at monthly intervals. Routine ecosystem health monitoring within the Broadwater has been ongoing for the past 12 years (see http://www.healthywaterways.org). This program utilises a suite of indicators that provide an understanding of the ecosystem health and response to land use activities and sewage discharge to the Seaway focusing largely on physicochemical parameters along with nutrient and sediment concentrations in the water column, together with seagrass depth/range, nitrogen isotope and coral cover monitoring. Given that evidence suggests contaminants are entering fisheries food webs (e.g. Waltham et al. 2011), there is still a need to understand the ecotoxicological effects of contaminants on local biota, which would provide important data to develop conceptual models. In addition to more conventional water and sediment sampling approaches, time-integrated in-situ sampling (e.g. diffusive gradient in thin films [DGT], diffusive equilibrium in thin films [DET] and semipermeable membrane devices [SPMD]) and routine and experimental biomonitoring approaches including the use of oyster and fish have also been conducted in the Broadwater in an effort to measure and monitor trace metals and metalloids, pesticides, polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHs) and indicators of bacterial contamination (e.g. Mortimer and Cox 1998; Mortimer 2000; Jordan et al. 2008; Waltham et al. 2011).

Managers are concerned that the region's rapid urban expansion has and will continue to place considerable pressure on the waterway health, which in turn threatens natural processes of the system and the livelihood and lifestyle of residents and tourists. Consequently, the local authority has combined scientific investigations with community consultation to establish a vision and a modified set of water quality objectives (WQOs) for each catchment within the Gold Coast region. An outcome of these assessments is a detailed and targeted management action plan (Waltham 2002). The approach includes predictive computer models to simulate existing and future urban land-use, and to identify opportunities to reduce diffuse pollutant loadings in order to meet each identified WQOs. Under current land use conditions, sediment and nutrient loads may exceed that which is sustainable (Waltham 2002). As such, the "business as usual" option is not sustainable and major stormwater capital infrastructure works are further required. Additionally, restoration projects such as weed removal, foreshore stabilisation works, revegetation of cleared areas, community education/and capacity building and flood mitigation programs have also been implemented in an attempt to improve ecological habitat and aesthetic quality of Broadwater waterways. Such programs are important and necessary in order to protect and achieve the community

Fig. 7 Example restoration projects for the Gold Coast Broadwater and catchment waterways; (**a**) recolonisation of mangrove community at land reclamation beach area; (**b**) restoration of reach along local waterway in the city; (**c**) stabilisation project using soft engineering technology to reduce erosion and encourage natural habitat restoration; (**d**) example of urban sensitive urban design infrastructure to treat stormwater runoff and (**e**) on-going aquatic plant harvesting to improve waterway health

waterway values (Waltham 2002, e.g. Fig. 7). Restoration programs over the past decade have achieved major successes and include community tree planting and weed eradication programs, school group education and capacity programs, landholder financial support and training, and industry support and relations (for example see Griffith Centre for Coastal Management (http://www.griffith.edu.au/environment-planning-architecture/griffith-centre-coastal-management/community-projects/coasted), Gold Coast Catchment Association Inc. (http://www.goldcoast-catchments.org/goals.htm), SEQ Catchments (http://www.seqcatchments.com.au/programs/community-based-ambientwater-water-quality-monitoring-and-rainfall-event-monitoring), Gold Coast Water Watch (http://www.natura-pacific.com/news/article/waterwatch-queensland/) and Gold Coast Management Groups (http://www.goldcoast.qld.gov.au/environment/catchment-management-groups-576.html)). Collectively, initiatives undertaken have been successful to date and demonstrate that future conservation requires the integration of multidisciplinary science and pro-active management driven by the high community values placed on the Broadwater and its waterways.

References

Alam K, Hossain S, Dalrymple B (2008) WSUD in the Gold Coast. In: New South Wales and Queensland Stormwater Industry Association Conference, 8–11th July 2008, Gold Coast, Australia

Ali A, Lemckert CJ, Zhang H (2009) Numerical study of the hydrodynamics of a very shallow estuarine system – Coombabah lake, Gold Coast, Australia. J Coast Res 56:922–926

Ali A, Lemckert CJ, Dunn RJK (2010) Salt fluxes within a very shallow sub-tropical estuary. J Coast Res 26:436–443

ANZECC/ARMCANZ (2000) Australian and New Zealand guidelines for freshwater and marine water quality, vol. 1. Environment Australia, Canberra

Australian Bureau of Statistics (ABS) (1986) Year book: Australia, Catalogue No. 1301.0

Australian Bureau of Statistics (ABS) (2008) Regional population growth, Australia, Catalogue No. 3218.0

Baird D, Marais JFK, Wooldridge T (1981) The influence of a marina canal system on the ecology of the Kromme Estuary. St Francis Bay S Afr J Zoo 16:21–34

Benfer N, King B, Lemckert C, Zigic S (2010) Modeling the effect of flow structure selection on residence time in an artificial canal system: case study. J Waterw Port Coast Ocean Eng 136:91–96

Blain, Bremner and Williams Pty Ltd (1985) Storm tide statistics – Surfers Paradise Region. Report prepared for the Beach Protection Authority, Queensland. January, 1985, 15 pp

BMT WBM Oceanics (2010) Gold Coast Sustainable Loads Study. Report prepared for Gold Coast City Council, 240 pp

Burton ED, Phillips IR, Hawker DW (2004) Trace metals and nutrients in bottom sediments of the Southport Broadwater, Australia. Mar Pollut Bull 48:378–402

Burton ED, Phillips IR, Hawker DW (2005) Geochemical partitioning of copper, lead, and zinc in benthic, estuarine sediment profiles. J Environ Qual 34:263–273

Burton ED, Sullivan LA, Bush RT, Powell B (2008) Iron-sulfide and trace element behaviour in sediments of Coombabah Lake, southern Moreton Bay (Australia). Mar Poll Bull 56:1353–1358

Connolly RM (2003) Differences in trophodynamics of commercially important fish between artificial waterways and natural coastal wetlands. Estuar Coast Shelf Sci 58:929–936

Cooper JAG, Lemckert CJ (2012) Extreme sea-level rise and adaptation options for coastal resort cities: a qualitative assessment from Gold Coast, Australia. Ocean Coast Manag 64:1–14

Cosser P (1989) Water quality, sediments and the macroinvertebrate community of residential canal estates in south-east Queensland, Australia: a multivariate analysis. Water Res 23:1087–1097

Davies S, Mirfenderesk H, Tomlinson R, Szylkarski S (2009) Hydrodynamic, water quality and sediment transport modelling of estuarine and coastal waters on the Gold Coast, Australia. J Coast Res 56:937–941

Department of Environment and Resource Management (DERM) (2012) Southern Moreton Bay. http://www.derm.gov.au/parks/southern-moreton-bay/about.html. Viewed 10 August 2012

Dunn RJK (2009) Biogeochemical processes of a sub-tropical coastal lagoon (Coombabah Lake, southern Moreton Bay, Australia): with emphasis on organic matter and nutrient dynamics. PhD thesis, Griffith School of Engineering, Griffith University, Australia

Dunn RJK, Teasdale PR, Warnken J, Schleich RR (2003) Evaluation of the diffusive gradient in a thin film technique for monitoring trace metal concentrations in estuarine waters. Environ Sci Technol 37:2794–2800

Dunn RJK, Ali A, Lemckert CJ, Teasdale PR, Welsh DT (2007a) Short-term variability of physico-chemical parameters and the estimated transport of filterable nutrients and chlorophyll-a in the urbanised Coombabah Lake and Coombabah Creek system, southern Moreton Bay, Australia. J Coast Res 50:1062–1068

Dunn RJK, Teasdale PR, Warnken J, Jordan MA, Arthur JM (2007b) Evaluation of the in situ, time-integrated DGT technique by monitoring changes in heavy metal concentrations in estuarine waters. Environ Pollut 148:213–220

Dunn RJK, Lemckert CJ, Teasdale PR, Welsh DT (2007c) Distribution of nutrients in surface and sub-surface sediments of Coombabah Lake, southern Moreton Bay (Australia). Mar Pollut Bull 54:606–614

Dunn RJK, Welsh DT, Teasdale PR, Lee SY, Lemckert CJ, Meziane T (2008) Investigating the distribution and sources of organic matter in surface sediment of Coombabah Lake (Australia) using elemental, isotopic and fatty acid biomarkers. Cont Shelf Res 28:2535–2549

Dunn RJK, Welsh DT, Jordan MA, Teasdale PR, Lemckert CJ (2009) Influence of natural amphipod (*Victoriopisa australiensis*) (Chilton, 1923) population densities on benthic metabolism, nutrient fluxes, denitrification and DNRA in sub-tropical estuarine sediment. Hydrobiologia 628:95–105

Dunn RJK, Catterall K, Hollingsworth A, Kirkpatrick S, Capati G, Hudson S, Khan S, Panther JG, Stuart G, Szylkarski S, Teasdale PR, Tomlinson RB, Welsh DT (2012a) Short-term variability of nutrients and fecal indicator bacteria within the Gold Coast seaway, southern Moreton Bay (Australia). J Coast Res 28:80–88

Dunn RJK, Welsh DT, Jordan MA, Arthur JM, Lemckert CJ, Teasdale PR (2012b) Interactive influences of the marine yabby (*Trypaea australiensis*) and mangrove (*Avicennia marina*) leaf litter on benthic metabolism and nitrogen cycling in sandy estuarine sediment. Hydrobiologia 693:117–129

Dunn RJK, Welsh DT, Jordan MA, Waltham NJ, Lemckert CJ, Teasdale PR (2012c) Benthic metabolism and nitrogen dynamics in a sub-tropical coastal lagoon: microphytobenthos stimulate nitrification and nitrate reduction through photosynthetic oxygen evolution. Estuar Coast Shelf Sci 113:272–282

Environment Australia (2003) Fact sheet Australia's Ramsar sites. Wetlands Section, Environment Australia, Commonwealth of Australia, Canberra

Environmental Protection Agency (EPA) 2005 Shorebird management strategy Moreton Bay, p 10

Erftemeijer PL, Robin Lewis RR (2006) Environmental impacts of dredging on seagrasses: a review. Mar Pollut Bull 52:1553–1572

Eyre B, Ferguson AJP (2009) Denitrification efficiency for defining critical loads of carbon in shallow coastal ecosystems. Hydrobiologia 629:137–146

Eyre BD, Maher D (2011) Mapping ecosystem processes and function across shallow seascapes. Cont Shelf Res 31:S162–S172

Eyre BD, Maher D, Oakes J, Erler DV, Glasby TM (2011a) Differences in benthic metabolism, nutrient fluxes, and denitrification in *Caulerpa taxifolia* communities compared to uninvaded bare sediment and seagrass (*Zostera capricorni*) habitats. Limnol Oceanogr 56:1737–1750

Eyre BD, Ferguson AJP, Webb A, Maher D, Oakes JM (2011b) Denitrification, N-fixation and nitrogen and phosphorus fluxes in different benthic habitats and their contribution to the nitrogen and phosphorus budgets of a shallow oligotrophic sub-tropical coastal system (southern Moreton Bay, Australia). Biogeochemistry 102:111–133

Eyre BD, Ferguson AJP, Webb A, Maher D, Oakes JM (2011c) Metabolism of different benthic habitats and their contribution to the carbon budget of a shallow oligotrophic sub-tropical coastal system (southern Moreton Bay, Australia). Biogeochemistry 102:87–110

Ferguson AJP, Eyre BD, Webb A, Maher D (2004) Sediment biogeochemistry. In Pimpama River Estuary ecological study: chapter 11. Report prepared for Gold Coast Water, SKM, Brisbane

GHD Pty Ltd (2003) Coombabah creek environmental inventory. GHD Pty Ltd, Brisbane

Gold Coast City Council (GCCC) (2002) Report No 47, Gold Coast Harbour Vision 2020 Project: Dredging of the Broadwater, Gold Coast City Council, Bundall

Gold Coast City Council (GCCC) (2010) Gold Coast City local disaster management plan. Gold Coast City Local Disaster Management Group Version 5.1 22 February 2010. http://www.goldcoast.qld.gov.au/attachment/publications/disaster_management_plan.pdf

Guest GA, Connolly RM (2004) Fine scale movement and assimilation of carbon in saltmarsh and mangrove habitat by resident animals. Aquat Ecol 38:599–609

Harper BA, Sobey RJ, Stark KP (1977) Numerical simulation of tropical cyclone storm surge along the Queensland coast part X – Gold Coast. Department of Civil and Systems Engineering, James Cook University, Townsville, p 15

Hollingsworth A, Connolly RM (2006) Feeding by fish visiting inundated subtropical saltmarsh. J Exp Mar Biol Ecol 336:88–98

Hunt S, Lemckert C (2001) Suspended sediment distribution within a partially mixed subtropical estuary. J Coast Res 34:382–387

Hunt S, Lemckert CJ, Schacht C (2006) Location of turbidity maxima with a microtidal estuary and some limitations of laser *in situ* particle sizing. J Coast Res 39:520–525

Johnson TC, Williams SH (1989) From canals to lakes in south-east Queensland (Australia); water quality aspects. Water Sci Technol 21:261–265

Jordan MA, Teasdale PR, Dunn RJK, Lee SY (2008) Modelling copper uptake by *Saccostrea glomerata* with diffusive gradients in a thin film measurements. Environ Chem 5:274–280

Jordan MA, Welsh DT, Dunn RJK, Teasdale PR (2009) Influence of *Trypaea australiensis* population density on benthic metabolism and nitrogen dynamics in sandy estuarine sediment: a microcosm simulation. J Sea Res 61:144–152

Knight JM, Dale PER, Dunn RJK, Broadbent GJ, Lemckert CJ (2008) Patterns of tidal flushing within a mangrove forest: lake Coombabah, south east Queensland Australia. Estuar Coast Shelf Sci 76:580–593

Lee KM, Lee SY, Connolly RM (2011) Short-term response of estuarine sandflat trophodynamics to pulse anthropogenic physical disturbance: support for the intermediate disturbance hypothesis. Estuar Coast Shelf Sci 92:639–648

Lemckert CJ (2006) A conceptual model for designing canal estates to maximise water quality. J Coast Res 39:822–825

Leon LM, Warnken J (2008) Copper and sewage inputs from recreational vessels at popular anchor sites in a semi-enclosed Bay (Qld, Australia): estimates of potential annual loads. Mar Pollut Bull 57:838–845

Maxted JR, Eskin RA, Weisberg SB, Chaillou JC, Kutz FW (1997) The ecological condition of dead-end canals of the Delaware and Maryland coastal bays. Estuaries 20:319–327

McInnes K, Hubbert G, Oliver S, Abbs D (2000) Gold Coast Broadwater study: storm tide return periods and 1974 floodwater modelling. Report prepared for Gold Coast City Council

McLennan M, Sumpton W (2005) The distribution of seagrasses and the viability of seagrass transplanting in the Broadwater, Gold Coast, Queensland. Proc R Soc Qld 112:31–38

Melville AJ, Connolly RM (2003) Spatial analysis of stable isotope data to determine primary sources of nutrition for fish. Oecologia 136:499–507

Melville AJ, Connolly RM (2005) Food webs supporting fish over subtropical mudflats are based on transported organic matter not in situ microalgae. Mar Biol 148:363–371

Mirfenderesk H (2009) Flood emergency management decision support system on the Gold Coast, Australia. Aust J Emerg Manage 24:48–58

Mirfenderesk H, Tomlinson R (2007) Numerical modelling of tidal dynamics and water circulation at the Gold Coast Broadwater, Australia. J Coast Res 50:277–281

Mirfenderesk H, Tomlinson R (2008) Observation and analysis of hydrodynamic parameters in tidal inlets in a predominantly semidiurnal regime. J Coast Res 24:1229–1239

Mirfenderesk H, Tomlinson R, Szylkarski S, Rasmussen EB (2007) Development of a three dimensional model using dye release experiment. In: Proceedings of 30th international conference of coastal engineering, San Diego (United States of America), World Scientific Publications, pp 2118–2129

Mortimer MR (2000) Contaminants in oysters collected from residential canals between Runaway Bay and the Sovereign Islands in January 2000. Report of a study conducted for Gold Coast City Council, January 2000

Mortimer MR, Cox M (1998) Contaminants in oysters and crabs in a canal adjacent to Lae Drive, Runaway Bay, Queensland. Report of a study conducted for Gold Coast City Council, September 1998

Morton RM (1989) Hydrology and fish fauna of canal developments in an intensively modified Australian estuary. Estuar Coast Shelf Sci 28:43–58

Morton RM (1992) Fish assemblages in residential canal developments near the mouth of a subtropical Queensland estuary. Aust J Mar Freshwa Res 43:1359–1371

Moss A, Cox M (1999) Southport Broadwater and adjacent pacific ocean: water quality study 1979–1998. Queensland Environmental Protection Agency, Brisbane, 28p

Oakes JM, Connolly RM, Revill AT (2010) Isotope enrichment in mangrove forests separates microphytobenthos and detritus as carbon sources for animals. Limnol Oceanogr 55:393–402

Pagès A, Teasdale PR, Robertson D, Bennett WW, Schäfer J, Welsh DT (2011) Representative measurement of two-dimensional reactive phosphate distributions and co-distributed iron(II) and sulfide in seagrass sediment porewaters. Chemosphere 85:1256–1261

Poiner IR (1977) Microvariation in the fauna of a sublittoral sand bank, Moreton Bay, Queensland. Aus Ecol 2:297–308

Pratt C, Warnken J, Leeming R, Arthur JM, Grice DI (2007) Detection of intermittent sewage pollution in a subtropical, oligotrophic, semi-enclosed embayment system using sterol signature in sediment. Environ Sci Technol 41:792–802

Preda M, Cox ME (1998) Pimpama River, an example of catchment drainage into Moreton Bay. In: Tibbetts IR, Hall NJ, Dennison WC (eds) Moreton Bay and catchment. School of Marine Science, The University of Queensland, Brisbane, pp 165–172

Robertson D, Welsh DT, Teasdale PR (2009) Investigating 2-dimensional distributions of iron (II) and sulphide in heterogenous sediment using DET and DGT. Environ Chem 6:60–69

Robinson JE, Newell RC, Seiderer LJ, Simpson NM (2005) Impacts of aggregate dredging on sediment composition and associated benthic fauna at an offshore dredge site in the southern North Sea. Mar Environ Res 60:51–68

Ross J (1999) The influence of residential canal estates on estuarine fish assemblages in the Gold Coast regions, Australia. MSc thesis, Department of Zoology, University of Queensland, St. Lucia, Australia

Sennes G, Castelle B, Bertin X, Mirfenderesk H, Tomlinson RB (2007) Modelling of the Gold Coast Seaway tidal inlet. Aus J Coast Res 50:1086–1091

Smith DI (2002) The what, where and how much of flooding in Australia. In: Smith DI, Handmer J (eds) Residential flood insurance the implications for floodplain management policy. Centre for Resource and Environmental Studies, Australian National University, Canberra, pp 73–98

Spilmont N, Meziane T, Seuront L, Welsh DT (2009) Identification of the food sources of sympatric ghost shrimp (*Trypaea australiensis*) and soldier crab (*Mictyris longicarpus*) populations using a lipid biomarker, dual stable isotope approach. Aus Ecol 34:878–888

Stephenson W (1980) Relationships of the macrobenthos of Moreton Bay to prawns and to abiotic factors. Aus Ecol 5:143–149

Stephenson W, Cook SD (1977) Aggregation of sublittoral macrobenthos in Moreton Bay, Queensland. Aus Ecol 2:419–428

Stuart G, Hollingsworth A, Thomsen F, Szylkarski S, Capati B, Khan S, Teo L, Tomlinson R, Kirkpatrick S (2009) Gold Coast seaway SmartRelease decision support system–optimising recycled water release in a sub tropical estuarine environment. Water Sci Technol 60:2077–2084

Teasdale PR, Welsh DT, Dunn RJK, Robertson D (2009) Investigating nutrient sources and processes in the saltwater creek catchment. Griffith Centre for Coastal Management, research report, Gold Coast, Australia, 113 p

Thomas BE, Connolly RM (2001) Fish use of subtropical saltmarshes in Queensland, Australia: relationships with vegetation, water depth and distance onto the marsh. Mar Ecol Prog Ser 209:275–288

Waltham NJ (2002) Health of the Gold Coast Waterways report. Gold Coast City Council, 181 pp

Waltham NJ (2009) Fish in artificial urban waterways: feeding, ecology and contamination. PhD thesis, Griffith School of Environment, Griffith University, Australia

Waltham NJ, Connolly RM (2006) Trophic strategies of garfish, *Arrhamphus sclerolepis*, in natural coastal wetlands and artificial urban waterways. Mar Bio 148:1135–1141

Waltham NJ, Connolly RM (2007) Artificial waterway design affects fish assemblage in urban estuaries. J Fish Bio 71:1613–1629

Waltham NJ, Connolly RM (2011) Global extent and distribution of artificial, residential waterways in estuaries. Estuar Coast Shelf Sci 94:192–197

Waltham NJ, Teasdale PR, Connolly RM (2011) Contaminants in water, sediment and fish from natural and artificial residential waterways in southern Moreton Bay. J Environ Monit 13:3409–3419

Warnken J, Leon M (2006) Recreational and tourist vessel traffic in south east Queensland's smooth coastal waters Moreton Bay and Gold Coast Broadwater. Sustainable Tourism Cooperative Research Centre (STCRC), 33 p

Warnken J, Dunn RJK, Teasdale PR (2004) Investigation of recreational boats as a source of copper at anchorage sites using time-integrated diffusive gradients in thin film and sediment measurements. Mar Pollut Bull 49:833–843

Webster T, Lemckert C (2002) Sediment resuspension within a microtidal estuary/embayment and the implication to channel management. J Coast Res 36:753–759

Werry JM (2010) Habitat ecology of the bull shark, *Carcharhinus leucas*, on urban coasts in eastern Queensland, Australia. PhD thesis, Australian Rivers Institute and School of Environment, Griffith University Gold Coast, Australia

Werry J, Lee SY (2005) Grapsid crabs mediate link between mangrove litter production and estuarine planktonic food chains. Mar Ecol Prog Ser 293:165–176

Werry JM, Lee SY, Lemckert CJ, Otway NM (2012) Natural or artificial? Habitat-use by the bull shark, *Carcharhinus leucas*. PLoS One 7:e49796

Young PC, Wadley VA (1979) Distribution of shallow-water epibenthic macrofauna in Moreton Bay, Queensland. Aus Mar Biol 53:83–97

Zeller BM (1999) Bull shark *Caracharhinus leucas* Valenciennes in estuarine and nearshore waters of the Gold Coast, Queensland. Department of Primary Industries and Fisheries, Brisbane

Zigic S, King BA, Lemckert C (2002) Mixing between two canals connected by an automated Bi-directional gated structure, Gold Coast, Australia. Estuar Coast Shelf Sci 55:59–66

Zigic S, King B, Lemckert C (2005) Modelling the two-dimensional flow between an estuary and lake connected by a bi-directional hydraulic structure. Estuar Coast Shelf Sci 63:33–41