Turbulent Mixing and Sediment Processes in Peri-Urban Estuaries in South-East Queensland (Australia)

Hubert Chanson, Badin Gibbes, and Richard J. Brown

Abstract

An estuary is formed at the mouth of a river where the tides meet a freshwater flow and it may be classified as a function of the salinity distribution and density stratification. An overview of the broad characteristics of the estuaries of South-East Queensland (Australia) is presented herein, where the small peri-urban estuaries may provide an useful indicator of potential changes which might occur in larger systems with growing urbanisation. Small peri-urban estuaries exhibit many key hydrological features and associated ecosystem types of larger estuaries, albeit at smaller scales, often with a greater extent of urban development as a proportion of catchment area. We explore the potential for some smaller peri-urban estuaries to be used as 'natural laboratories' to gain some much needed information on the estuarine processes, although any dynamic similarity is presently limited by a critical absence of in-depth physical investigations in larger estuarine systems. The absence of detailed turbulence and sedimentary data hampers the understanding and modelling of the estuarine zones. The interactions between the various stakeholders are likely to define the vision for the future of South-East Queensland's peri-urban estuaries. This will require a solid understanding of the bio-physical function and capacity of the peri-urban estuaries. Based upon the current knowledge gap, it is recommended that an adaptive trial and error approach be adopted for their future investigation and management strategies.

Keywords

Peri-urban estuaries • Mixing • Dispersion • Sediment processes • Water quality • Ecology • South-East Queensland • Australia

---

H. Chanson (✉) • B. Gibbes
School Civil Engineering, The University of Queensland, Brisbane,
QLD 4072, Australia
e-mail: h.chanson@uq.edu.au http://www.uq.edu.au/~e2hchans/

R.J. Brown
Faculty of Science and Engineering, Queensland University
of Technology, 2 George St, Brisbane, QLD 4000, Australia

E. Wolanski (ed.), *Estuaries of Australia in 2050 and Beyond*, Estuaries of the World,
DOI 10.1007/978-94-007-7019-5_10, © Springer Science+Business Media Dordrecht 2014

Box 1

Hubert Chanson and colleagues studied South-East Queensland (SEQ) peri-urban estuaries. These are the many small estuaries that drain highly-urbanised to semi-urbanised small catchments along Moreton Bay. They explore the potential for some smaller peri-urban estuaries to be used as ‘natural laboratories’ to gain some much needed information on the estuarine processes of the larger estuaries, such as the Brisbane River estuary, which is the dominant estuary in SEQ and which is virtually not studied. They provide detailed turbulence and sedimentary data to help advance science-based models of these estuaries. These models are needed to enable an interaction between the various stakeholders who will define the vision for the future of SEQs peri-urban estuaries.

Based upon the current knowledge gap, they recommend that an adaptive trial and error approach be adopted for the management of peri-urban estuaries.

Introduction

An estuary is formed at the mouth of a river where the tides meet a freshwater flow and where some mixing of freshwater and seawater occurs. Estuaries may be classified as a function of the salinity distribution and density stratification, and the wind, the tides and the river are usually major sources of inputs. Altogether the study of mixing in estuaries is more complicated than in rivers. Estuaries have long been important to the development of communities. Some ancient civilisations thrived in such estuarine systems, such as the lower region of the Tigris and Euphrates Rivers in Mesopotamia, the Nile River delta in Egypt and the Ganges River delta in India. Through some important scientific contributions (Fischer et al. 1979; Dyer 1997; Savenije 2005), the community gained a clearer understanding of the relative sensitivity of estuarine systems and their vulnerability to human and climatic interference. Herein an overview of the broad characteristics of the estuaries of South-East Queensland (Australia) is presented, before exploring the potential for some smaller peri-urban estuaries to be used as ‘natural laboratories’ to gain some much needed information on the estuarine processes. In the Australian context, small peri-urban estuaries are an emerging concept of estuaries that are increasing in number with the increasing urbanisation of the continent. Small peri-urban estuaries are an interesting sub-class of estuary in their own right, with many unique characteristics making them potentially useful environmental sentinels for larger estuarine systems. They exhibit many key hydrological features (e.g. tidal range, stratification, salt-fresh transition, turbulent mixing processes) and associated ecosystem types (e.g. mangroves, salt-marsh, riparian forests, seagrass, benthic communities) of larger estuaries, albeit at smaller spatial and temporal scales, often with a greater extent of urban development as a proportion of catchment area. The small peri-urban estuaries may provide an useful indicator of potential changes which might occur in larger estuarine systems as the trend of urbanisation grows. For the research community, the smaller spatial scales of such systems have significant advantages in terms of the logistics of field measurement programs, and offer the management organisations with some opportunity to more effectively experiment with management approaches and a reduced number of stakeholders. Furthermore it can be argued that, while adaptive management approaches are not well suited to larger environmental systems due to the lack of controllability of the system (Allen and Gunderson 2011), an adaptive management approach might be successfully applied to smaller systems with a higher level of controllability. In these smaller systems, both uncertainty and controllability are high and there is a potential for learning how the system can be manipulated.

Turbulent Mixing

In natural estuaries, turbulent mixing is one of the most important and challenging processes to investigate. Turbulent mixing exerts a controlling influence on key estuarine processes including sediment transport, storm-water runoff and associated chemical and sediment dynamics during flood events, the release of nutrient-rich wastewater into ecosystems and the exchange of chemicals between benthic and surface water systems. Why? The Reynolds number associated with estuarine flows is typically within the range of 10^6–10^7 and more. The flow is turbulent and characterised by an unpredictable behaviour, a broad spectrum of length and time scales, and its strong mixing properties: “turbulence is a three-dimensional time-dependent motion in which vortex stretching causes velocity fluctuations to spread to all wavelengths between a minimum determined by viscous forces and a maximum determined by the boundary conditions of the flow" (Bradshaw 1971, p. 17). Turbulent flows have a great mixing potential involving a wide range of vortice length scales (Tennekes and Lumley 1972; Hinze 1975). Importantly the velocity field does not map directly to the scalar field (e.g. concentration, temperature). The range of length scales is significantly different at the lower end. The turbulent length scales are bound by the Kolmogorov scale whereas the scalar length scales are bound by the Bachelor scale, which is significantly smaller than the Kolmogorov scale for liquid flows such as that in estuaries (Appendix I). This lower bound in terms of length scales is linked with the viscous dissipation process when the energy of the micro-scale turbulence is converted to heat. Appendix I presents a brief summary of the Bachelor and Kolmogorov scale calculations in estuarine zones, highlighting key differences between small and large estuaries. The turbulent and scalar length scales have practical significance for dispersion and micro scale mixing which is relevant for nutrient uptake of some estuarine and marine organisms (Batchelor 1959; Bilger and Atkinson 1992).

Although the turbulence is a pseudo-random process, the small departures from a Gaussian probability distribution constitute some key features. Further the measured data include usually the spatial distribution of Reynolds stresses, the rates at which the individual Reynolds stresses are produced, destroyed or transported from one point in space to another, the contribution of different sizes of eddy to the Reynolds stresses, and the contribution of different sizes of eddy to the rates mentioned above and to the rate at which Reynolds stresses are transferred from one range of eddy size to another (Bradshaw 1976). Turbulence in natural estuaries is neither homogeneous nor isotropic. A characterisation of turbulence must be based upon long-duration measurements at high frequency to characterise the small eddies and the viscous dissipation process, as well as the largest vortical structures to capture the random nature of the flow and its deviations from Gaussian statistical properties (Chanson 2009). The estuarine flow conditions and boundary conditions may vary significantly with the falling or rising tide. In shallow-water estuaries and inlets, the shape of the channel cross-section changes drastically with the tides. Further the stratification of the water column may hinder vertical diffusion during some wet weather periods. Simply it is far from simple to characterise in-depth the estuarine flow turbulence, and an understanding of turbulence in natural estuaries is particularly important for the accurate prediction of the fate of scalars (chemicals) that might be important for water quality. The challenges associated with field measurements are far from trivial in both large and small estuaries (Lewis 1997).

Sediment Processes

Waters flowing in rivers and estuaries have the capacity to scour channel beds, to carry particles and to deposit sediment materials, hence changing the bed morphology (Graf 1971; Chanson 1999). This phenomenon, called sediment transport, is of great economic significance. For example, to assess the risks of scouring of river banks and bridge piers; to estimate the siltation of a river mouth; to predict the possible bed form changes in estuaries and impact on navigation. Sediment transport also has a significant impact on water quality and ecosystem health through both the direct influence of suspended sediment on the light regime in the water column and the modification of benthic habitats due to erosion and deposition processes. Further many nutrients and chemicals of concern in relation to water quality and human health are often bound to sediment particles or have significant interactions with sediments.

The transported sediments are called the sediment load and some distinction is made between the bed load and the suspended load. The bed load motion characterises sediment grains rolling along the bed while the suspended load refers to grains maintained in suspension by turbulence. While the distinction is often arbitrary when both loads are of the same material, the suspended load can be considerable in fine-particle systems, as observed in the Brisbane River during the January 2011 flood (Event Monitoring Group 2011; Brown and Chanson 2012). The transport of suspended matter occurs by a combination of advective turbulent diffusion and convection (Nielsen 1992; Chanson 1999). Advective diffusion characterises the random motion and mixing of particles through the water depth superimposed to the longitudinal flow motion. Sediment motion by convection may be simplified as the entrainment of particles by very-large scale eddies: e.g. in a sharp river bend.

Outline of Contribution

Herein some particular attention is given to the potential use of small peri-urban estuaries to better understand the turbulent mixing properties that exert a controlling influence on sediment dynamics and water quality and ecosystem health. The challenges associated with up-scaling are discussed with a focus on larger estuarine systems. The estuaries of the future cannot be managed without basic understanding of the physical processes, particularly to support predictive models including computational fluid dynamics (CFD) modelling. However at present there are gaps in both knowledge and data for these systems. As outlined below, developing this understanding and addressing the current knowledge gap will be essential to explore the potential future states of estuaries, a process that is likely to place increasing emphasis on the development and use of predictive models.

Site and Geomorphological and Hydrological Settings

South East Queensland is located in the sub-tropics. The weather is characterized by wet and hot summers, and dry and mild winters. The region is home to over three million people (QOESR 2011) and has undergone significant land use changes with less than 40 % of the catchment now classified as pristine (Catterall et al. 1996). Herein we focus on the South-East Queensland estuaries between Bribie Island and the Gold Coast Seaway (Fig. 1). The coastline includes the estuaries of a few large rivers (Brisbane, Logan/Albert, Nerang, Pine, Caboolture) and of a large number of small, sometimes ephemeral streams, all discharging into Moreton Bay. The combined catchment area discharging into the Bay is 21,220 km^2 (Dennison and Abal 1999). A key feature linking all of the estuaries of South-East Queensland is their common downstream receiving environment: the Moreton Bay. From the Pumicestone Passage in the North to the Gold Coast Broadwater in the South, there are 20 estuaries connecting to Moreton Bay (Figs. 1 and 2). These estuaries are ephemeral over geologic time (Neil 1998). Infilling by tidal deltas on the eastern side of Moreton Bay and by river/estuary deltas to the West combined with fluctuations in sea level have caused Moreton Bay and its estuaries to transition between terrestrial and coastal dominated environments over geological timeframes. This pattern of ongoing transition is likely to continue with the potential for the current in-filling phase accelerated by land clearing and other anthropogenic activities that cause or accelerate discharges of sediment and chemicals to the region's estuaries and Moreton Bay (Neil 1998). It can be argued that the small peri-urban estuaries of South-East Queensland exhibit a greater degree of catchment modification in proportion to their surface area than and provide an indication of the effects of such land transformation for the region's larger estuarine systems.

An overview of basic geomorphological characteristics of South-East Queensland estuaries is provided in Table 1. The estuaries can be categorised by their catchment area into either small, medium and large estuarine systems. The region is dominated by small- (eight with catchment area <100 km^2) and medium- (nine with catchment area 100–1,000 km^2) sized estuaries. Notably the region also contains two large estuaries (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). The South-East Queensland includes 4 major water storages: Lake Samsonvale on the North Pine River, Lake Somerset and Wivenhoe Reservoir on the Brisbane River, and Advancetown Lake on the Nerang River. There are a few further smaller storages, including Lake Kurwongbah, Enoggera Reservoir, Tingalpa Reservoir, Little Nerang Dam and Wyaralong Dam which have a smaller catchment area and storage capacity.

The estuaries of South-East Queensland are classified as wet and dry tropical/subtropical estuaries. The estuarine zones are typically partially mixed, although they tend to be partially stratified during ebb tides and could become stratified after some rainstorm events. Although each estuary is distinctly unique, since topography, river inflow and tidal forcing influence the shape and mixing that occur locally, the vast majority of estuaries of South-East Queensland were found to be a drowned river valley (coastal plain) type (Dyer 1973; Digby et al. 1998). The main topographical features of these coastal plain estuaries are shallow waters with large width to depth ratio, cross-sections which deepen and widen towards the mouth, a small freshwater inflow to tidal prism volume ratio, large variations of sediment type and size, a surrounding of extensive mud flats, and a sinuous central channel. All estuaries experience a mixed semi-diurnal tide with mean tidal ranges from 1.3 to 1.8 m depending on the estuary configuration (Digby et al. 1998). At the Brisbane River mouth, the tidal range is about 0.7 to 2.7 m: the mean neap tidal range is 1.0 m and the mean spring tidal range is 1.8 m. The predominant tidal constituents are the M_2, S_2 and K_1 components which have tidal periods of 12.42, 12.00 and 23.93 h respectively. Diurnal inequalities are observed in Moreton Bay under both spring and neap tidal conditions. A diurnal inequality occurs when the two tidal cycles that occur within the 25 h period of the semi-diurnal tide have different tidal amplitudes and periods.

All the estuaries draining into Moreton Bay experience a similar climate and hydrological regime (Table 2), although the annual averaged rainfall data show an East–West trend with the smaller coastal catchment experiencing higher annual average rainfall totals (1,600–2,000 mm/year) than the western edges of the larger catchments ($\approx$1,000 mm/year) (BOM 2009) (Table 2). The estuaries are characterised by short-lived, episodic, high freshwater inflows during the wet season, and very little or no flow during the dry season. During flood periods, an estuary is flushed to the mouth with freshwater. After flushing, the estuary may change from fully flushed to partially mixed (stratified) back to vertically homogeneous within a few days to a few weeks after the end of the high flow event, depending upon the flood event and river system. The seasonal, event-driven hydrology of the region causes the estuaries to operate in two distinct modes: tidally dominated periods and event dominated periods (Fig. 3).

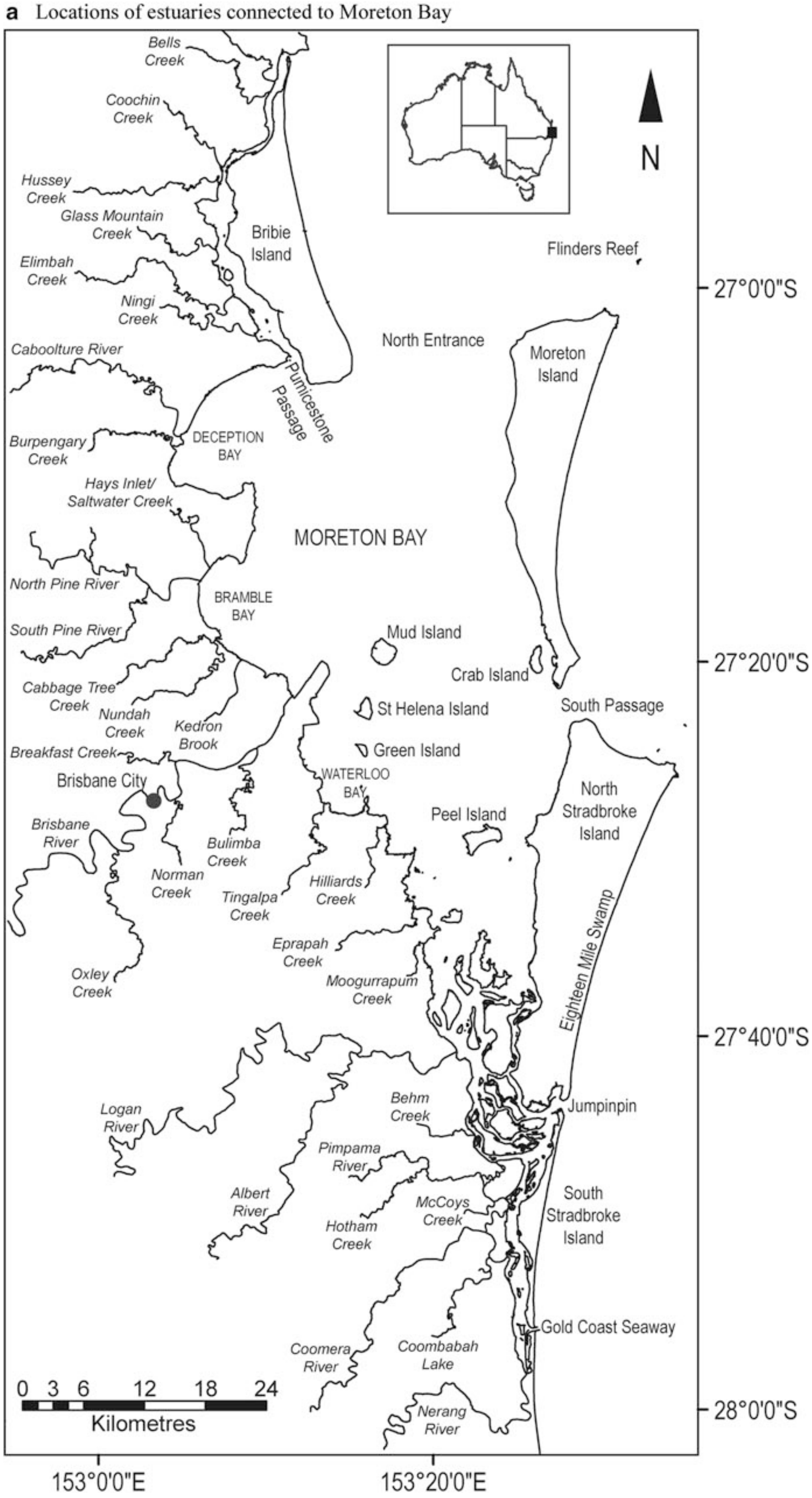

a Locations of estuaries connected to Moreton Bay

Fig. 1 Estuaries of South-East Queensland and Moreton Bay. (**a**) Locations of estuaries connected to Moreton Bay. (**b**) Sketch of Moreton Bay catchments and main water storages looking West

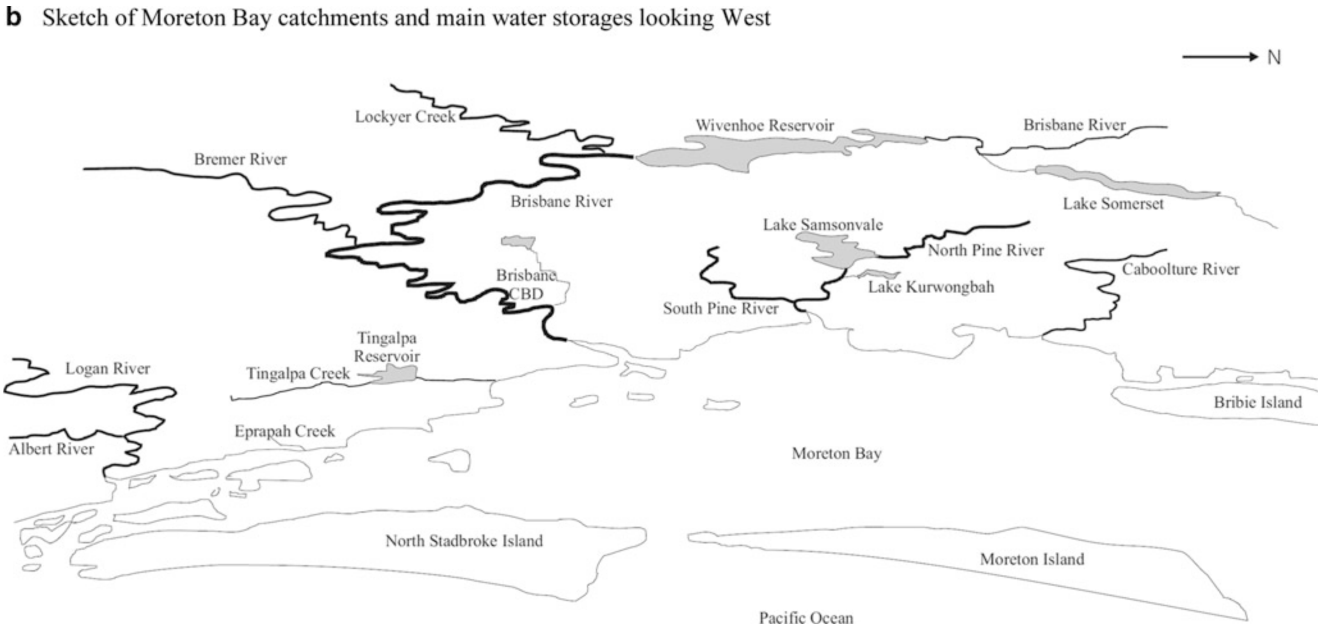


Fig. 1 (continued)

Fig. 2 Photographs of peri-urban estuaries of South-East Queensland – (**a**) Brisbane River in Brisbane (Courtesy of Brisbane Marketing). (**b**) Nudgee Creek on 2 May 2010. (**c**) Trawler in Cabbage Tree Creek on 12 Feb. 2003. (**d**) Field measurements in the upper estuarine zone (AMTD 3.1 km) of Eprapah Creek in June 2006

Figure 3 shows some salinity contours in a large river (Brisbane River) and a small system (Eprapah Creek) as functions of the average middle thread distance (AMTD) measured from the river mouth. Figure 3 highlights the contrasted salinity distributions during drought and shortly after a major event. This dual mode has shaped the sediment processing, water quality and ecosystem health dynamics of the region's estuaries. While some medium to large estuaries

Table 1 Summary of physical classification of South-East Queensland estuaries (After Digby et al. 1998)

Estuary Name	Latitude [°South]	Longitude [°East]	Classification[b]	Catchment area [km^2]	Water area [km^2]	Perimeter [km]	Maximum length [km]	Maximum width [km]	Entrance width [km]
Pumicestone Passage	−27.08	153.151	TD	702	49.88	154.0	36.16	2.8	2.27
Caboolture River	−27.15	153.044	RD	354	1.77	20	7.85	0.36	0.37
Burpengary Creek	−27.16	153.040	TD	108	0.41	8.98	2.92	0.62	0.62
[a]Hays Inelt/Saltwater Creek	−27.26	153.071	TD	74.35	2.67	11.11	3.86	1.25	1.25
Pine River	−27.28	153.063	TD	806	4.043	44.41	12.61	0.66	0.51
Nundah/Cabbage Tree Creek	−27.33	153.088	TD	131	0.41	15.02	3.11	0.17	0.14
Nudgee Creek	−27.34	153.094	TD	1.7	0.09	6.224	3.32	0.13	0.13
Brisbane Airport Floodway/ Kedron Brook	−27.35	153.111	TD	40	0.84	13.71	6.37	0.36	0.25
Brisbane River	−27.37	153.166	RD	13,643	18.67	123.54	45.88	1.34	1.75
Tingalpa Creek	−27.47	153.200	RD	150	0.9	11.96	5.13	0.6	4.1
Hilliards Creek	−27.49	153.266	TD	62	0.35	4.93	1.64	0.52	0.16
Eprapah Creek	−27.56	153.294	TD	31	0.08	3.62	1.61	0.14	0.042
[a]Moogurrapum Creek	−27.59	153.302	TD	15.1	0.06	4.17	2.05	0.13	0.13
Logan-Albert River	−27.69	153.349	RD	3,822	5.01	53.71	21.81	0.79	0.32
[a]Behm Creek	−27.76	153.360	TD	29.81	0.25	13.54	6.75	0.14	0.14
Pimpama River	−27.82	153.396	RD	[a]171	1.76	20.92	7.64	0.36	0.21
[a]McCoys Creek	−27.82	153.378	TD	14.2	0.17	10.11	4.94	0.16	0.16
Coomera River	−27.83	153.396	RD	[a]489	3.62	45.29	16.68	0.36	0.23
Coombabah Lake	−27.87	153.400	TD	[a]44	4.647	34.62	9.37	1.47	0.47
Nerang River	−27.98	153.424	RD	[a]498	4.0	47.31	20.71	0.48	0.3

Notes:

[a]Indicates data not included in Digby et al. (1998). Data based on analysis of a combination of geo-referenced aerial photography, topographic maps and digital elevation models

[b]Classification refers to tidally dominated (TD) or river dominated (RD) estuary

Table 2 Average hydrological conditions of the Brisbane River estuary and Eprapah Creek

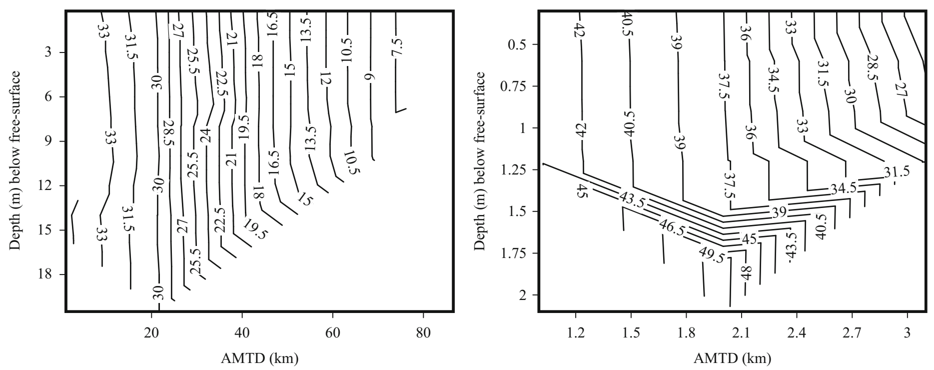
Hydrological characteristic	Units	Brisbane River mouth	Brisbane River upper estuary	Eprapah Creek
Station name		Brisbane Airport	Ipswich	Redlands
Station reference number		040842	040101	040265
Period		1994–2012	1913–1994	1953–2010
Air temperature at 09:00	Celsius	21.7	20.7	21.4
Average humidity at 09:00	%	65	66	69
Average wind speed at 09:00	km/h	15.4	5.6	8.4
Average yearly rainfall	mm	1013.5	877.8	1269.7
Maximum monthly rainfall	mm	577.2	780	909.7
Maximum daily rainfall	mm	168.4	340	241
Average clear days	days/year	133.4	84.8	82.1
Average number of cloudy days	days/year	98.9	76	59.9

Reference: Australian Bureau of Meteorology

Notes: Brisbane Airport is located next to the Brisbane River mouth; Ipswich is located less than 7 km from the Brisbane River upper estuarine zone; Eprapah Creek catchment is located less than 10 km from the Redlands meteorological station

listed in Table 1 are characterised as river-dominated estuaries, the riverine influence on hydrodynamics and water quality occurs during large rainfall events of relatively short duration. With their relatively small catchment area, whilst being tide dominated for much of the year, the majority of the smaller estuaries, can experience significant catchment flows over relatively short time scales (hours) during rainfall events. These events can significantly alter the channel hydrodynamic, sediment dynamics, water quality and ecosystem health characteristics of these small estuaries for short periods (<48 h) (Fig. 3b). This rapid response, the small spatial scales and associated logistical ease of operating in such systems makes them attractive for use as a ‘natural laboratory’ to investigate the influence of rain events on estuarine processes.

a Salinity distributions during a drought - Left: Brisbane River on 14 June 2007 after a 7-year long drought; Right: Eprapah Creek on 2 September 2004 during mid-flood tide after a 4-month long dry period



b Salinity distributions shortly after a flood event - Left: Brisbane River on 24 January 2011 after the 12-14 January 2011 flood; Right: Eprapah Creek on 28 August 2006 about 4 hours after a short rain storm in the early morning

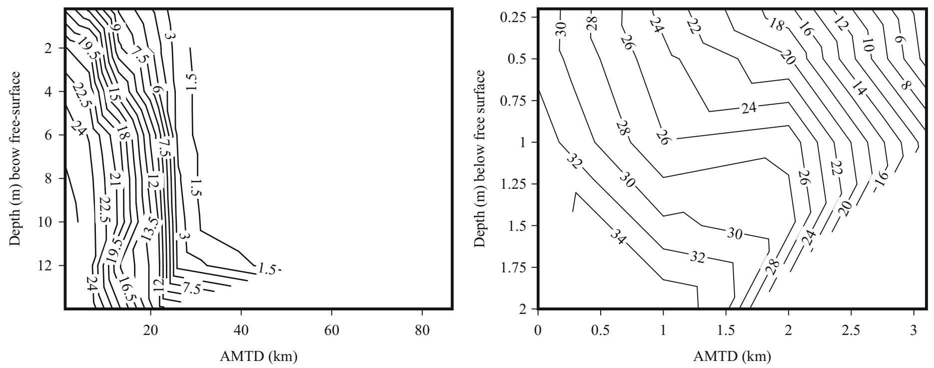


Fig. 3 Salinity distributions in the Brisbane River (*Left*) and Eprapah Creek (*Right*) during wet events and droughts as functions of the average middle thread distance (AMTD), measured from the river mouth. (**a**) Salinity distributions during a drought – *Left*: Brisbane River on 14 June 2007 after a 7-year long drought; *Right*: Eprapah Creek on 2 September 2004 during mid-flood tide after a 4-month long dry period. (**b**) Salinity distributions shortly after a flood event – *Left*: Brisbane River on 24 January 2011 after the 12–14 January 2011 flood; *Right*: Eprapah Creek on 28 August 2006 about 4 h after a short rain storm in the early morning

In many ways, the small estuarine systems have the potential to provide information for a better understanding in medium and large estuarine processes, provided that appropriate methods are available to upscale the physical data.

A more detailed scrutiny of this idea of small estuaries as 'natural laboratories' is presented by exploring the characteristics of the Eprapah Creek estuary and the up-scaling to the larger Brisbane River estuary. The Eprapah Creek estuary is located in Victoria Point, Redland Bay (Table 1, Fig. 2d). The catchment area is 39 km^2 and Eprapah Creek flows eastwards, emptying into Moreton Bay North-West of Victoria Point. The waterway is 12.6 km long and about 4 km of the creek is tidal. Eprapah Creek has two small tributaries, Little Eprapah Creek and Sandy Creek, located in the west of the catchment and discharging into the main channel at the middle of the catchment (Redlands Shire Council 2012). The Brisbane River estuary extends from the river mouth approximately 86.6 km upstream to Colleges Crossing as well as the 22 km of the Bremer River upstream from its junction with the Brisbane River (Table 1, Fig. 2a). Many small tributaries enter this complex tidal estuary including Bulimba, Oxley, Norman and Breakfast Creeks. These tributaries drain urban, industrial and semi-rural catchments (Connell and Miller 1998). Both Eprapah Creek and the Brisbane River lower estuary were adversely affected by severe pollution in the late 1990s (Appendix II). A summary of a landmark court case is presented in Appendix II.

Turbulent Mixing and Sediments, Water Quality and Ecology

For the last decade, a series of turbulence, suspended sediment and water quality measurements were conducted in the estuarine zone of Eprapah Creek (Fig. 2d). The physical

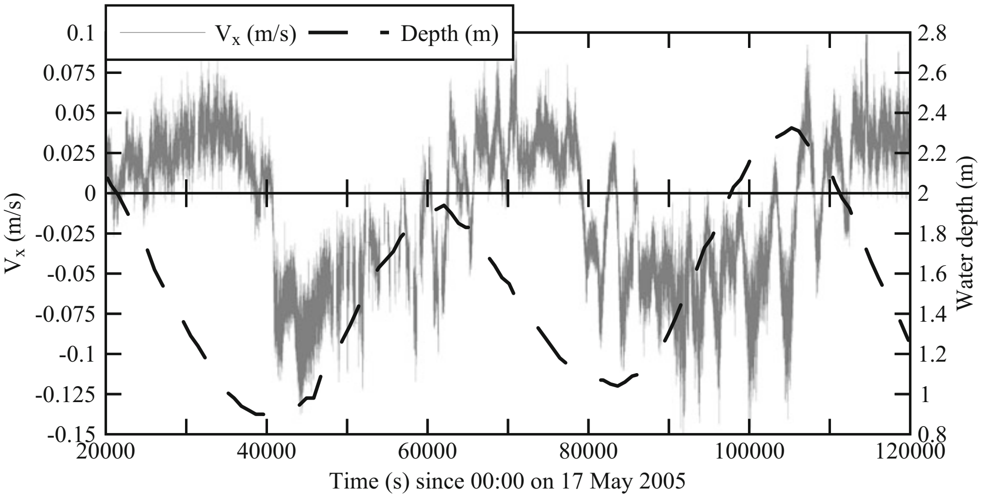


Fig. 4 Water depth and longitudinal velocity in the mid-estuarine zone (AMTD 2.1 km) of Eprapah Creek at 0.2 m above the bed under neap tide conditions on 17 May 2005 – The velocity data were sampled continuously at 25 Hz

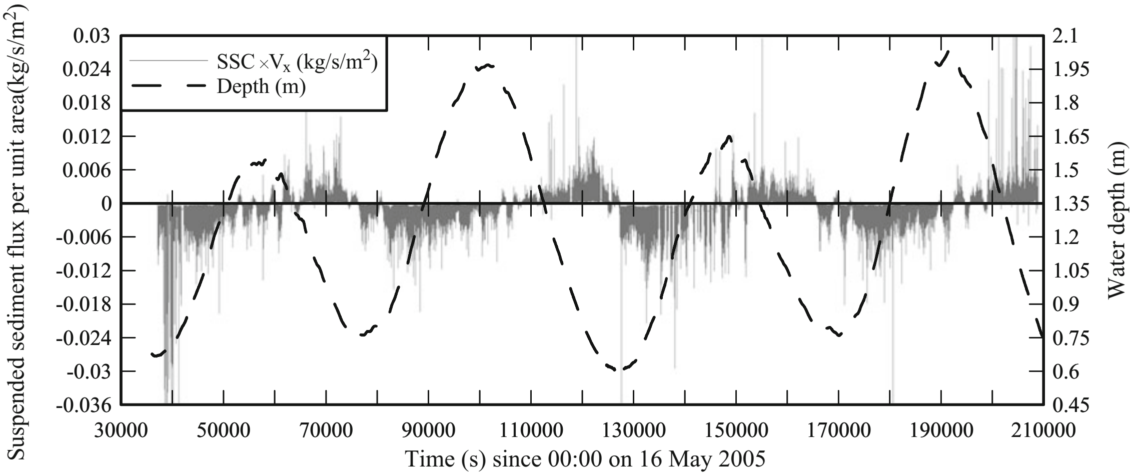
studies were performed with state-of-the-art instrumentation to characterise the spatial and temporal variations in mixing properties as functions the tidal and hydrological conditions, including during tide dominated periods and rainfall events. The continuous turbulent velocity sampling at high frequency allows a detailed characterisation of the turbulence field in estuarine systems and its variations during the tidal cycle. Figures 4 and 5 illustrate some results in terms of the water depth, velocity and suspended sediment flux. A brief summary follows.

The bulk flow parameters vary in time with periods comparable to tidal cycles and other large-scale processes. The turbulent properties depend upon the instantaneous local flow properties; they are little affected by the flow history, but their structure and temporal variability are influenced by a variety of parameters including the tidal conditions and bathymetry. A striking feature of the data sets is the large fluctuations in all turbulent properties and suspended sediment flux during the tidal cycle including during slack periods, with some basic differences between neap and spring tide turbulence (Figs. 4 and 5) (Trevethan et al. 2008a). The upper estuarine region of this elongated tidal creek is drastically less mixed than the lower zone during tide dominated periods with some adverse impact on the water quality and ecological indicators (Trevethan et al. 2007). During rainfall events, the estuarine processes are dominated by the significant flushing associated with a strong vertical stratification of the water column, while the depth-averaged salinity data exhibit a dome-shaped intrusion curve (Chanson 2008). The field observations show some significant three-dimensional effects associated with strong secondary currents including transverse shear events (Trevethan et al. 2008b). Short-lived and highly energetic turbulent events, called bursting, play a major role in terms of sediment scour, scalar transport and accretion as well as contaminant mixing and dispersion (Trevethan and Chanson 2010).

Overall the turbulent flow properties are highly fluctuating and a large number of parameters are required simultaneously to characterise the turbulent mixing and its properties' variations with time. In plain terms, the turbulent mixing "does not slack". The mixing properties are not constant and differ between fluid, scalar and sediments. This result has fundamental implications in terms of predictive models: current numerical data are outdated and the predictive models are outclassed by recent development in computational fluid dynamics (CFD) albeit their implementation is not trivial. The mixing properties should not be assumed constant in a shallow estuary, and some similar findings are reported in a number of shallow estuarine systems of Australia and Japan with comparable hydrological and tidal conditions (Chanson and Trevethan 2010).

Detailed data similar to those presented in Figs. 4 and 5 are unavailable for most estuaries of South East Queensland, especially the larger estuaries. There is a critical need for further expert monitoring during non flood events as well as during major flood events. This situation is highlighted by a lack of basic data on flow and mixing for the estuary of the Brisbane River. The most recent data was collected in 1998, consisting of limited drogue and tracer experiments (McAllister and Patterson 1999). These data showed a reasonably long tidal excursion (4–8 km per tidal cycle) and significant mixing. To the authors' knowledge, there has been no detailed physical investigation in the estuarine zone, with an acute absence of high frequency long-duration data sets. Collection of such data in a large estuarine system like the Brisbane River is challenging, especially during flood events with a high risk of equipment loss (Brown and Chanson 2012). Without such data, it is nearly impossible to up-scale detailed physical data collected in small systems to larger estuaries without adverse scaling effects. As a result the ability to understand the underlying hydrodynamic processes driving higher order processes such as sediment transport, mixing of chemicals and ecosystem processes will continue to be limited.

a Mid-estuarine zone data on 16-18 May 2005 - Suspended sediment flux data sampled continuously at 25 Hz



b Upper estuarine zone data on 5-6 June 2006 - Suspended sediment flux data sampled continuously at 50 Hz

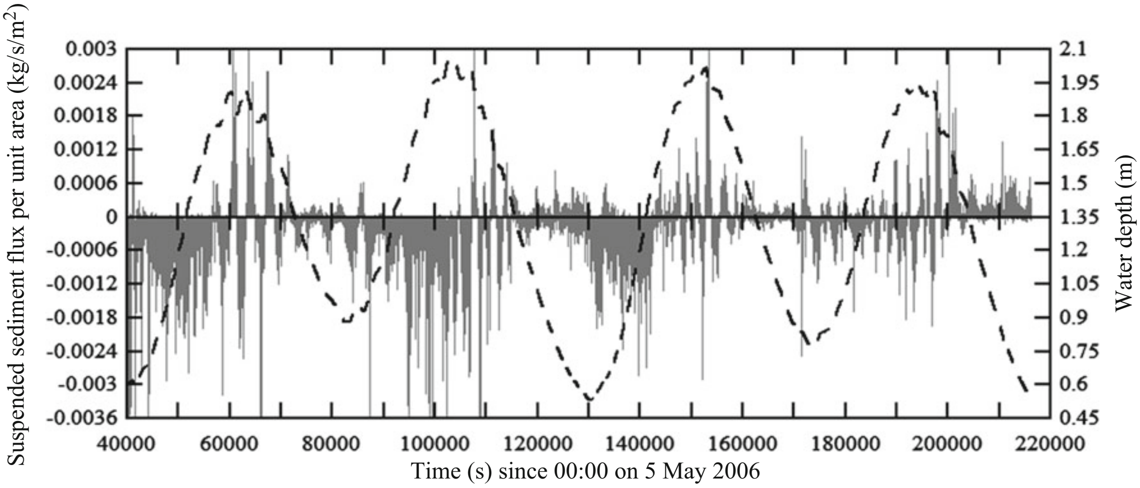


Fig. 5 Water depth and suspended sediment flux per unit area in the mid-estuarine zone (AMTD 2.1 km) and upper estuarine zone (AMTD 3.1 km) of Eprapah Creek at 0.2 m above the bed under neap tide conditions – Note the differences in *vertical* axes scaling between Fig. 5a, b. (**a**) Mid-estuarine zone data on 16–18 May 2005 – Suspended sediment flux data sampled continuously at 25 Hz. (**b**) Upper estuarine zone data on 5–6 June 2006 – Suspended sediment flux data sampled continuously at 50 Hz

Anthropological Influences: Resources, Pressures, Impacts, and Remediation

The condition of South-East Queensland estuaries has been classified as 'modified' or 'extensively modified' because of the impacts of sewage treatment plant discharges, dams and weirs, wetland loss, urbanisation, dredging and entrance modification (Digby et al. 1998). These impacts are a consequence of catchment modifications which have occurred in four distinct phases: (1) natural catchment condition, (2) Aboriginal landscape modification, (3) European agricultural development and associated vegetation clearing, and (4) catchment urbanisation. Prior to European influence, there was some evidence of landscape modification by the local Aboriginal people. Forest burning or 'firestick farming' practices are thought to have led to increased erosion rates and associated sediment delivery to waterways (Hall 1990; Neil 1998). Quantifying the extent of this landscape modification is challenging; however the extent of modification from a 'natural' state is thought to be in the order of 10 % (Neil 1998). Following European settlement about 200 years ago, the landscape was modified by a combination of timber operations and vegetation removal to develop livestock grazing land. This led to a further increase in sediment and nutrient loading to the estuaries, as well as some modifications of the hydrology and hydrodynamics. It is estimated that the catchment sediment yield likely increased by a factor of 2–5 (Neil 1998). Following land transformations associated with agricultural use, a progressive urbanisation of the catchments took place. This influenced the region's estuaries in a range of ways including (a) increased wastewater discharges, (b) altered hydrological performances with more rapid transition of runoff, coupled with increased sediment and chemical runoff, (c) altered regional hydrodynamics and sediment transport processes as a result of construction of large-scale dams for water supply and flood mitigation purposes, and (d) channel modification to support growing fishing and shipping industries as well as a significant recreational boating activities.

Initial management interventions to improve the estuarine ecosystem health generally focused on upgrades to sewage treatment plants (STPs) and industrial point source discharges (SEQHWP 2007). These actions reduced nutrient loads, especially nitrogen, released to estuarine waterway, and in turn resulted in a decline in the occurrence of phytoplankton blooms in many estuaries (SEQHWP 2007). A reduction of the rates of sediment and nutrient (nitrogen and phosphorous) transport from upland catchments to the region's estuaries has been the focus of more recent management interventions (SEQHWP 2007). The retention and restoration of vegetation in riparian zones across large parts of the catchment has been identified as an important component of the management response because of their sediment and nutrient trapping capacity (SEQHWP 2007). The large spatial scales, capital cost and long time frames for realisation of benefits makes such riparian management action challenging. Another intervention was the establishment of the Moreton Bay Marine Park in 1993 to protect the unique values and high biodiversity of the Bay and its associated estuaries. The marine park covers 3,400 km^2, stretching 125 km from Caloundra to the Gold Coast and encompassing most tidal areas of the Bay, including many river estuaries. The landward boundary is generally the line of highest astronomical tide. The majority of the region's estuaries are located within the general use zones: i.e., zones in which boating and both recreational and commercial fishing are permitted (QDERM 2010) – these general use areas having a different level of protection than those designated for habitat protection, conservation and national marine park zones.

A subtle yet distinct difference between the Brisbane River and Eprapah Creek is observed in terms of urbanisation. Within the Brisbane River catchment, urbanisation has been predominantly focused on the coastal/estuarine flood plain regions with urbanisation of riparian zones being a dominant feature (Fig. 2a). In the Eprapah Creek catchment, much of the lower coastal region has been maintained in a vegetated state through the creation of conservation areas. There is little urbanisation in the riparian areas of the Eprapah Creek estuary (Fig. 2d) – a key feature of many peri-urban estuaries (Fig. 2b). This condition (i.e. urban development in the catchment coupled with maintenance of functioning near-natural riparian zones) is often identified as the desirable future state of a catchment landscape for the improvement of water quality (SEQHWP 2007). Both catchments are characterised by a mix of urban and agricultural land uses in the upper catchment areas. On a regional scale it is estimated that between 30 and 65 % of pre-European vegetation cover has been removed by agricultural and urban/industrial development activities (Catterall et al. 1996; DERM 2010). In the Eprapah Creek catchment it is thought that approximately 40 % pre-European vegetation has been cleared for agricultural and urban development (Redlands Shire Council 2012). Another key difference in anthropological influences of the Brisbane River and Eprapah Creek is the extent of dredging. The Brisbane River has undergone significant dredging over an extended period of time (Dobson 1990) while this has been much more restricted at Eprapah Creek. The environment of the Brisbane River was significantly altered by channel dredging which extended the tidal zone from 16 km to in excess of 85 km upstream (Holland et al. 2002). Large increases in flow velocity and turbidity levels, and consequent changes in the fauna and flora, have occurred. The river has had a number of dredging phases, commencing with the opening of the Brisbane River bar in 1862 and dredging to allow shipping to access the dry dock and working docks, then located at the site of the current Southbank Parklands opposite of the Central Business District (CBD) (McLeod 1978). The modern Port of Brisbane Pty Ltd (PBPL) is now responsible for all dredging in the Brisbane River, from Point Cartwright in the north to Hamilton, about 15 km upstream of the river mouth. This includes 90 km of shipping channel and the dredging occurs to a maximum depth of 16.5 m below mean sea level (MSL). Dredging in the Brisbane River and Moreton Bay is now continuously undertaken for: (a) the maintenance of shipping channels servicing the Port of Brisbane, and (b) the reclamation of land using the dredge spoil. At Eprapah Creek, dredging occurred in the last decades at a much smaller scale. Privately owned marinas developed two channels approximately 200 m long, 15 m wide and 2 m deep, connecting the shipping yards to the main channel about 1 km upstream of the river mouth. To the best of the authors' knowledge, the dredging was not carried further into the main channel, although accurate records of such activity are difficult to trace. Personal communications with the current shipyard operators confirmed that both channels have experienced noticeable silting up in recent years to a point where they are serviceable only during high tide, impacting on the operation of the marinas.

The conflict of use between the marinas serving a sector of the community, and the environmental and community access aspects of Eprapah Creek is a microcosm of many issues for the wider management of South East Queensland

Fig. 6 Mixing and dispersion experiments in the wake of an outboard motor in Eprapah Creek (AMTD 2 km)

estuaries. Navigation is a typical example of human interaction with estuaries (Fig. 2a, c). The activity may be for recreational, primary production and transportation. Adverse effects of navigation are especially important when the system has low flushing potential. Impacts of navigation are ubiquitous, often accepted uncritically until serious impacts occur. These include noise, wave erosion of banks and wake/propeller emission of chemicals. The latter includes the emissions of inboard and outboard engines, emissions of oils, antifouling and waste disposal (Kelly et al 2004). The small scale mixing caused by navigation was recently tested by measuring the mixing and dispersion from an outboard motor in a small peri-urban waterway (Eprapah Creek) (Fig. 6). Organic dye was used as a surrogate for exhaust emissions, and dye concentrations were measured with an array of concentration probes stationed in the creek. The results highlighted very significant mixing in-homogeneity, challenging the many conventional modelling approaches.

Summary and Discussion: What Sort of Peri-Urban Estuary Do We Want for 2050 and Beyond?

Defining a future vision for an estuary is a vital and complex task. In the absence of clearly defined description of the desired future state of the system, it is challenging to identify the types of actions required to reach the future state. Key indicators are required to quantify the estuary state and to allow progress towards achieving a given vision. A common approach includes bio-physical measures: e.g., targets for dissolved concentrations of chemicals, suspended sediment concentrations, bio-diversity measurements, measures of the spatial area of a given ecosystem type. While such bio-physical indicators form the basis of 'visions' outlined in many natural resource management plans, there is a growing recognition of the importance of developing system-specific social (e.g. length of access time, number of visits, number of complaints) and economic (e.g. fisheries productivity, revenue from tourism) indicators. As an illustration, Fig. 2a presents some recreational activity on the Brisbane River, while Fig. 2b, c show respectively some residential development and fishing activity in two smaller estuaries. In South-East Queensland, a range of planning and management processes have been undertaken to scope the desired future condition of the region's estuaries. A central element has been the definition of resource condition targets (RCTs) for each estuarine system. The RCTs use a combination of environmental values and specific water quality objectives to classify the current and future state of the waterways, as documented in the South East Queensland Healthy Waterways Strategy 2007–2012 (SEQHWP 2007). This document sets a 2026 timeline and the current set of targets is designed to halt the current decline in water quality and ecosystem health. While this is an important first step in any natural resource management process, the relatively short timeframe (15–20 years) prevents largely the examination of possible long-term (>20 years) future states. A further interesting theme of past commentary on management approaches was the idea of management of 100–1,000 year planning horizons (Davie et al. 1990; Tibbetts et al. 1998). While there are very practical reasons for using the current short timeframes, the process of framing and examining potential future states over longer time periods is likely to be informative. This is particularly true in light of the design life of most infrastructure associated with the management actions adopted to halt the decline of the waterway state: e.g., wastewater treatment plant upgrades, incorporation of water sensitive urban design elements in stormwater drainage systems, restoration of riparian zones. These have a 25–100 year design life. It can be argued that any investment decision in relation to estuary management actions should consider a time-line that at least encompasses the entire lifecycle of the associated infrastructure. If a longer time-line is adopted in relation to the future of the estuaries, the desired outcomes might move beyond 'halting the decline' to a number of different potential future states ranging from some sub-optimal condition to the 'best attainable condition' for the system (Fig. 7). Figure 7 presents a conceptual diagram illustrating different phases of a natural resource management cycle. The future condition depends on the relationship between the system's minimal viable condition and condition at which the system is stabilised. If some minimum viable level is not crossed, the system can regenerate to a range of states (outcomes A, B, C) representing maintenance of the stable condition (outcome C), restoration of the reference condition (outcome B) and even a state of enhanced resource condition compared to the reference condition (outcome A). If the minimum viable level is crossed (e.g. a threshold level is reached), the system may enter an alternative stable state (outcome D).

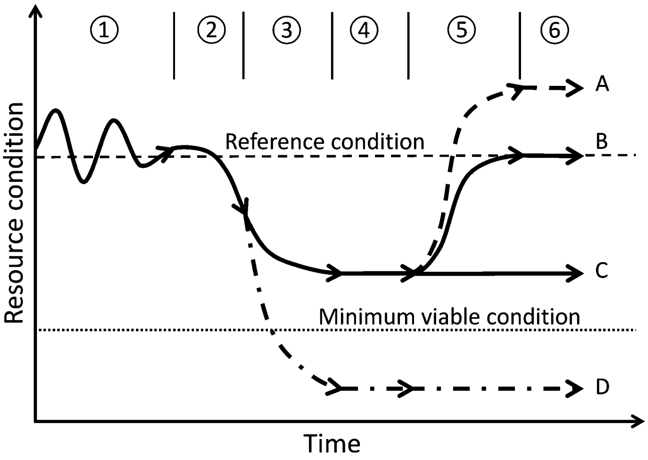


Fig. 7 Conceptual diagram illustrating the different phases of a natural resource management cycle: ① Historical condition with natural fluctuations (often used to define a historical reference condition);② Observation of resource condition decline; ③ Management intervention to halt the decline; ④ System stabilisation; ⑤ Regeneration (augmented regeneration or natural system resilience); and ⑥ Future condition

There are some notable examples of the potential for both planned and unplanned ecosystem restoration to levels equivalent or exceeding those of pre-development conditions. The history of the Sumitomo Copper Mine and associated forestry operations in Besshi, Japan provides an illustration of a long timeframe mining operation commenced around 1690 and completed in 1973, investment in technological advancements and environmental regulation (Nishimura 1989). The transition to different forms of land use, establishment of conservation zones and ecosystem resilience transformed a once barren landscape devoid of most vegetation into a vibrant forest ecosystem that has been sustainably managed for wood production over the past 100 years (Aomame 2007) (outcome A, Fig. 7). The Landes Forest in South-western France is another example of a large-scale ecosystem restoration project that commenced in the mid-nineteenth century and sought to establish a large-scale (~10,000 km^2) pine forest to address severe soil erosion issues developed from centuries of pastoral activities (IFN 2003). In France, another large-scale project was the 'Restauration des Terrains en Montagne' (RTM) conducted in mountain areas during the nineteenth century (~3,000 km^2), with very successful outcomes in terms of drastic soil erosion reduction (Brugnot and Cassayre 2002; Antoine et al. 1995), and later emulated effectively in Japan (Nakao 1993). The challenges associated with more recent large-scale ecosystem restoration efforts are daunting particularly with the issue of transformation from a degraded to a 'netpositive' state. They have been documented for a number of systems including the California Bay Delta, Chesapeake Bay and Mississippi River (Doyle and Drew 2008). The more recent restoration efforts have not had the benefit of longer timeframes associated with the preceding examples, perhaps suggesting that the combination of long timeframes, the transition to different forms of land use, establishment of conservation zones and ecosystem resilience are particularly important factors to consider.

While a 'best attainable' or optimal condition will require some definition in terms of bio-physical conditions, it will also be influenced by socio-economic factors, particularly a level of investments in terms of both economic provisions and management/lifestyle/cultural changes, that the community must be prepared to contribute. Because of their spatial characteristics and associated features, small peri-urban estuary systems offer a unique opportunity to experiment with the various management options to achieve a range of future states: e.g. catchment land use management, stormwater management, fisheries management, management of recreational activities, morphological modification. The inherent bio-physical limits will largely define the optimal state of the system with any given state/condition subsequently refined by subsequent socio-economic considerations. The future vision for the region's estuaries in the bio-physical system might be defined in terms of bio-diversity enhancement, improved ecosystem processing or stronger system resilience. In a socio-economic context a net positive gain might encompass elements such as greater fisheries productivity and enhanced recreational and/or aesthetic values. Conversely the current degradation of South-East Queensland's peri-urban estuaries may have resulted in the crossing of a threshold line that will cause the system to enter an alternative state of lower resource condition from which recovery to a pre-development reference state is not achievable (outcome D, Fig. 7). The development of more detailed visions of the future of South-East Queensland's peri-urban estuaries will involve interactions between the various stakeholders: i.e., community, industry, government agencies and the research community. This process will require a solid understanding of the bio-physical function and capacity of these periurban systems to identify the range of bio-physically feasible scenarios, and there is a critical need to quantify the various factors that will ensure the long term sustainability of the estuary's intended use.

Our current state of knowledge of peri-urban estuaries, and all estuaries more generally, presents a challenge to describe and quantify the key biophysical processes operating in these systems in sufficient detail to accurately characterise the system resilience, minimum viable condition and critical threshold levels. A desirable position does warrant sufficient information and tools to answer adequately key questions about the potential bio-physical states in which these peri-urban estuaries can exist. The understanding and predictive capacity is a necessary starting point for an effective long-term planning process that is able to attract investment to allow the desired future state of these systems to be reached.

Clearly an improved understanding of turbulent mixing and sediment dynamics is needed to provide the basis of improved understanding of higher order estuarine processes such as the transport and fate of chemicals, both natural chemical cycling and pollutant chemicals, as well as the structure and function of biological communities. The latters are often strongly influenced by the light, salinity and dissolved oxygen environments which are in turn directly related to turbulent mixing and sediment dynamics. Such an understanding will necessitate an investment in high quality process measurements (e.g. Fig. 2d) to support the development of useful predictive modelling tools. Given the current trends towards a science- and evidence-based approach to management, there will be an increased reliance on predictive models to better understand and explore the range of possible future states of the region's estuaries. These models must be based on accurate simulation of the hydrodynamics of surface water flows within an estuary. Current approaches to the simulation of estuarine flows typically adopt a very simplified representation of the three-dimensional (3D) flow dynamics. The approaches are based on the equations of momentum, continuity and conservation of heat and salt. At present they usually employ the Boussinesq approximation, neglecting the non-hydrostatic pressure terms, and in some instances replacing the standard vertical turbulent diffusion equation with a simplified mixed layer model. These approaches typically use a time averaged turbulent closure scheme (e.g. eddy viscosity model, Reynolds stress model) to simulate the turbulent processes. The recent measurements in Eprapah Creek system suggest that the simplistic representation of turbulent mixing, and particularly vertical mixing, in these types of models does not provide the level of details required for long term predictions of mixing and sediment dynamics as well as the higher order estuarine processes, without significant undesirable implications. A shift toward computational fluid dynamics (CFD) using the direct Navier–Stokes (DNS) and large eddy simulation (LES) approaches would offer massive advantages in terms of simulation accuracy. Current disadvantages of these modelling approaches for estuarine systems include the computation resources required to complete a simulation and the level of information necessary to describe the system boundary conditions: e.g., morphology and small scale bed roughness, flow vectors and distribution of sediment and dissolved chemicals. For example, a DNS approach requires the model domain to be discretised by a grid with sufficient resolution to capture the length scales associated with the key estuarine processes, bound by the Bachelor scale in the order of 10^{-5} m (Appendix I). Using a rough approach (Nezu and Nakagawa 1993), a model domain with a grid small enough to capture processes at the Bachelor scale would require about 10^{20} and 10^{23} mesh points for Eprapah Creek and the Brisbane River respectively, numbers that are currently unfeasible for routine simulation. The number of operations required for DNS is proportional to $Re^{9/4}$ where Re is the Reynolds number (Lesieur 1997), while the number of operations for LES approach scales as $Re^{3/2}$: for example, $Re \sim 10^6$ and 10^7 for respectively Eprapah Creek and Brisbane River estuarine zones during dry periods. Altogether the LES approach may be comparatively more efficient for the larger estuarine system models. However both DNS and LES approaches can only be used to investigate turbulence processes in simple geometries with flows corresponding to relatively low Reynolds numbers ($\sim 10^5$ for DNS) today (Reynolds 1990). The adoption of simplified CFD approaches, employing various non-dynamic turbulent closures, would reduce the need for such fine scale mesh geometries but would also introduce the same issues experienced by the current 3D models.

As concluding remarks, we explored the potential for some smaller peri-urban estuaries to be used as 'natural laboratories' to gain some much needed information on the estuarine processes. While these small estuaries offer significantly advantages in terms of logistics of field measurement programs, the dynamic similarity is presently limited by a critical and accute absence of detailed physical investigations in larger estuarine systems during non flood events as well as during major flood events. Nonetheless it is suggested that the interactions between the various stakeholders (i.e. community, industry, government agencies, research institutions) are likely to define the vision for the future of South-East Queensland's peri-urban estuaries. A longer term view must be adopted, including some systematic in-depth physical data collection in larger estuaries. In a broader context, there is a trend towards public management intervention to better manage the estuarine systems of South-East Queensland. While this trend has a basis in the region's broader legal framework and has some benefits, there are other community-based and privately-based approaches that might also be employed.

Acknowledgements The authors acknowledge the Queensland Government Department of Natural Resources and Mines for access to some data, as well as Dr Alistair Grinham (The University of Queensland) for assistance with some illustration. H. Chanson acknowledges the support of the Australian Research Council (Grants LP0347242 & LP110100431).

Appendices

Appendix I: Kolmogorov and Batchelor Scales

Motions in a turbulent flow exist over a broad range of length and time scales (Roberts and Webster 2002). The length scales are linked to the motion of fluctuating eddies in turbulent flows. The largest scales are bounded by the geometric dimensions of the flow, for instance the depth and width of the channel. The large scales are referred to as the integral length and time scales. Observations indicate that eddies lose most kinetic energy after one or two overturns. The rate of energy transferred from the largest eddies is proportional to their energy times their rotational frequency. The kinetic energy is proportional to the velocity squared, in this case the fluctuating velocity v, that is ascribed by the velocity standard deviation. The rotational frequency is proportional to the standard deviation of the velocity divided by the integral length scale. Thus, the rate of dissipation ε is of the order:

$$\varepsilon \sim v^3/l$$

where l is the integral length scale. The rate of dissipation is independent of the viscosity of the fluid and only depends on the large-scale motion. In contrast, the scale at which the dissipation occurs is strongly dependent on the fluid viscosity. These arguments allow an estimate of this dissipation scale, known as the Kolmogorov microscale η, by combining the dissipation rate and kinematic viscosity ν based upon dimensional considerations:

$$\eta \sim \left(\nu^3/\varepsilon\right)^{1/4}$$

Similarly, the time and velocity scales of the smallest eddies may be derived:

$$\tau \sim (\nu/\varepsilon)^{1/2}$$

$$u \sim (\nu\varepsilon)^{1/4}$$

An analogous length scale may be introduced for the range over which molecular diffusion acts on a scalar quantity. This length scale is referred to as the Batchelor scale L_B and it is proportional to the square root of the ratio of the molecular diffusivity D_m to the strain rate γ of the smallest velocity scales:

$$L_B \sim (D_m/\gamma)^{1/2}$$

The strain rate γ of the smallest scales is proportional to the ratio of Kolmogorov velocity to length scales:

$$\gamma \sim u/\eta \sim \varepsilon^{1/2}/\nu$$

Thus, the Batchelor length scale L_B can be recast into a form that includes both the molecular diffusivity of the scalar and kinematic viscosity of the fluid:

$$L_B \sim \left(\nu^2 {D_m}^2/\varepsilon\right)^{1/4}$$

A further dimensionless number is the Schmidt number Sc defined as the square of the ratio of Kolmogorov to Batchelor length scales:

$$Sc = \eta/L_B \approx \nu/D_m$$

In the estuarine zone of Eprapah Creek, a typical mean velocity is 0.2 m/s with a fluctuating velocity v about 30 % of the mean, while an integral length scale is roughly half the channel depth, i.e. $l \approx 1$ m. Water at 20 Celsius has a kinematic viscosity of 1×10^{-6} m^2/s. Therefore, the Kolmogorov length and time scales are about 0.2 mm and 0.07 s respectively. Assuming a diffusivity $D_m \approx 1 \times 10^{-9}$ m^2/s for a typical chemical dye tracer, the Batchelor scale is 0.009 mm, or 32 times smaller than the Kolmogorov microscale. Thus, one would expect a much finer structure of the concentration field than the velocity field. Corresponding values for the Brisbane River are $v = 0.3$ m/s and $l = 5$ m yielding Kolmogorov length and time scales of 0.12 mm and 0.014 s, respectively. The relatively small difference in terms of scales between the two estuaries is because the increase in Kolmogorov length and time scales caused by the larger channel depth is countered by the reducing effect of the increase in mean velocity.

Appendix II: Pollution of Brisbane River and Eprapah Creek: 2001 Court Case

R v Hobson, Moore & Universal Abrasives Pty Ltd (2001) District Court Queensland, Forno DCJ, 15 June 2001, 1606/01.

R v Moore, 1 Qd R 205 (QCA, 2001).

R. v Moore – [2003] 1 Qd R 205, Court of Appeal, Williams JA, Jones J, Douglas J [2001] QCA 431 [C.A. 162/2001] 5, 12 October 2001

Queensland Court decision (2000) R. v Hobson & Moore & Universal Abrasives Pty Ltd.

In EPA v Universal Abrasives Pty Ltd and Moore and Hobson (Brisbane District Court, 2001), a company and two directors were charged with offences under the environmental protection (EP) Act in relation to the disposal of spent abrasive blasting product from a ship cleaning business in Brisbane. On 28 September 1998, the company released liquid waste containing high concentrations of heavy metals including lead, zinc, copper, arsenic, chromium, cadmium, selenium and biocide tributyltin (TBT) to a stormwater drain connected to the Brisbane River at Bulimba. The discharge was analysed and found to contain 2,700,000 μg/L TBT: that is, more than a million times the ANZECC limit of 2 μg/L. The company had also stored abrasive blasting material adjacent to the stormwater drain in a manner contravening its licence conditions. In addition, the same abrasive blasting material was stored in a manner that had the potential to cause serious environmental harm to a mangrove estuary at Eprapah Creek, Thornlands. The company failed to carry out environmental protection orders to clean up the affected sites.

The company and directors pleaded not guilty to causing serious environmental harm and to other offences, but were found guilty by a jury. That was the company and directors; second conviction under the EP Act, and the trial judge found that they showed no remorse. The company was fined $375,000. One director was given a suspended sentence of 9 months imprisonment (suspended for 3 years from sentences totalling 3 years to be served concurrently) and was fined $50,000. The other director was sentenced to 18 months actual imprisonment (based on sentences totalling 7.5 years to be served concurrently) and fined $100,000. In EPA v Moore [2001] QCA 431, the Queensland Court of Appeal rejected an appeal against one of the sentences.

References

Allen CR, Gunderson LH (2011) Pathology and failure in the design and implementation of adaptive management. J Environ Manage 92:1379–1384

Antoine P, Giraud A, Meunier M, Van Asch T (1995) Geological and geotechnical properties of the "Terres Noires" in southeastern France: weathering, erosion, solid transport and instability. Eng Geol 40:223–234

Aomame R (2007) The continuous pursuit of sustainable forest management & living in harmony with nature – Sumitomo Forestry Co., Ltd. Toward a sustainable Japan–corporations at work article series no.62, Japan for Sustainability. Available at: http://www.japanfs.org/en_/business/corporations62.html. Accessed 19 Oct 2012

Batchelor GK (1959) Small-scale variations of convected quantities like temperature in turbulent fluid. J Fluid Mech 5:113–133

Bilger RW, Atkinson MJ (1992) Anomalous mass transfer of phosphate on coral reef flats. Limnol Oceanogr 37:261–272

BOM (2009) Average annual rainfall map (1961–1990). Commonwealth of Australia, Bureau of Meteorology. Available: http://www.bom.gov.au/jsp/ncc/climate_averages/rainfall/index.jsp?period=an#maps. Accessed 1 Sept 2012

Bradshaw P (1971) An introduction to turbulence and its measurement, The commonwealth and international library of science and technology engineering and liberal studies, thermodynamics and fluid mechanics division. Pergamon Press, Oxford, 218 pp

Bradshaw P (1976) Turbulence, vol 12, Topics in applied physics. Springer, Berlin, 335 pp

Brown R, Chanson H (2012) Suspended sediment properties and suspended sediment flux estimates in an urban environment during a major flood event. Water Resour Res, AGU, vol. 48, Paper W11523, p.15. doi: 10.1029/2012WR012381

Brugnot G, Cassayre Y (2002) De la politique française de restauration des terrains en montagne à la prévention des risques naturels. (From the French politics of highland restoration to the prevention of natural hazards). In: Proceedings of the workshop Les pouvoirs publics face aux risques naturels dans l'histoire, Grenoble, MSH Alpes Publication, 22–23 Mar 2001, 11 pp (in French)

Catterall CP, Storey R, Kingston M (1996) Assessment and analysis of deforestation patterns in the SEQ 2001 area 1820-1987-1994: final report. Faculty of Environmental Sciences, Griffith University, Brisbane, 65 pp

Chanson H (1999) The hydraulics of open channel flow: an introduction. Edward Arnold, London, 512 pp

Chanson H (2008) Field observations in a small subtropical estuary during and after a rainstorm event. Estuar Coast Shelf Sci 80 (1):114–120. doi:10.1016/j.ecss.2008.07.013

Chanson H (2009) Applied hydrodynamics: an introduction to ideal and real fluid flows. CRC Press/Taylor & Francis Group, Leiden, 478 pp

Chanson H, Trevethan M (2010) Chapter 4: Turbulence, turbulent mixing and diffusion in shallow-water estuaries. In: Lang PR, Lombargo FS (eds) Atmospheric turbulence, meteorological modeling and aerodynamics. Nova Science Publishers, Hauppauge, pp 167–204

Connell D, Miller G (1998) Moreton Bay catchment: water quality of catchment rivers and water storage. In: Tibbetts IR, Hall NJ, Dennison WC (eds) Moreton Bay and catchment. School of Marine Science, The University of Queensland, Brisbane, pp 153–164

Davie P, Stock E, Choy DL (1990) The Brisbane River a source book for the future. The Australian Littoral Society Inc. in association with the Queensland Museum, Brisbane, 427 pp

Davies PL, Eyre BD (1998) Nutrient and suspended sediment input to Moreton Bay – the role of episodic events and estuarine processes. In: Tibbetts IR, Hall NJ, Dennison WC (eds) Moreton Bay and catchment. School of Marine Science, The University of Queensland, Brisbane, pp 545–552

Dennison WC, Abal EG (1999) Moreton Bay study: a scientific basis of the Healthy Waterway Campaign. SE Qld Regional Water Quality Management Strategy, Brisbane, 246 pp

DERM (2010) Land cover change in Queensland 2008–09: a Statewide Landcover and Trees Study (SLATS) report, 2011. Department of Environment and Resource Management (DERM), Brisbane, 100 pp

DERM (2011) South East Queensland event monitoring summary (6th–16th January 2011) preliminary suspended solids loads calculations. South East Queensland event monitoring program summary report, Department of Environment and Resource Management (DERM), Brisbane, 4 pp

Digby MJ, Saenger P, Whelan MB, McConchie D, Eyre B, Holmes N, Bucher D (1998) A physical classification of Australian estuaries. Report prepared for the Urban Water Research Association of Australia by the Centre for Coastal Management, Report no 9, LWRRDC occasional paper 16/99, Southern Cross University, Lismore

Dobson J (1990) Physical/engineering aspects of the estuary. In: Davie P, Stock E, Choy DL (eds) The Brisbane River a source-book for the future. Australian Littoral Society/Queensland Museum, Brisbane, pp 203–211

Doyle M, Drew CA (2008) Large-scale ecosystem restoration: five case studies from the United States. Island Press, Washington, DC, 344 pp

Dyer KR (1973) Estuaries. A physical introduction. Wiley, London, 140 pp

Dyer KR (1997) Estuaries. A physical introduction, 2nd edn. Wiley, New York, 195 pp

Event Monitoring Group (2011) South East Queensland event monitoring summary (6th–16th January 2011). Preliminary suspended sediment solid loads calculations. South East Queensland event monitoring (Water quality and aquatic ecosystem heath), Queensland Department of Environment and Resource Management, Australia, 4 pp

Fischer HB, List EJ, Koh RCY, Imberger J, Brooks NH (1979) Mixing in inland and coastal waters. Academic, New York, 483 pp

Graf WH (1971) Hydraulics of sediment transport. McGraw-Hill, New York, 513 pp

Hall HJ (1990) 20 000 years of human impact on the Brisbane River and environs. In: Davie P, Stock E, Choy DL (eds) The Brisbane River a source-book for the future. Australian Littoral Society/Queensland Museum, Brisbane, pp 175–182

Hinze JO (1975) Turbulence, 2nd edn. McGraw-Hill Publisher, New York, 790 pp

Holland I, Maxwell P, Grice A (2002) Chapter 12: Tidal Brisbane River. In: Abal E, Moore K, Gibbes B, Dennison WC (eds) State of south-east Queensland waterways report 2001. Moreton Bay Waterways and Catchments Partnership, Brisbane, pp 75–82

IFN (2003) Massif des lands de Gasogne 1998-1999-2000 + Résultats après la tempête du 27/12/1999 – Résultats et commentaires. Inventaire Forestier National (IFN), République Française, Ministère de l'agriculture, de l'alimentation, de la pêche, et des affaires rurales, France, 72 pp

Kelly CA, Ayoko GA, Brown RJ, Swaroop CR (2004) Underwater emissions from a two-stroke outboard engine: a comparison between an EAL and an equivalent mineral lubricant. Mater Design 26(7):609–617

Lesieur M (1997) Turbulence in fluids, 3rd edn. Kluwer Academic, Dordrecht, 515 pp

Lewis R (1997) Dispersion in estuaries and coastal waters. Wiley, Chichester, 312 pp

McAllister T, Patterson D (1999) Task hydrodynamics: exchange and mixing (HD). Final report for the South East Queensland Regional Water Quality Management Strategy, WBM Oceanics, Brisbane

McLeod R (1978) A short history of the dredging of the Brisbane River, 1860 to 1910. J R Hist Soc Qld 10(3):137–148

Nakao T (1993) Research and practice of hydraulic engineering in Japan. J Hydrosci Hydraul Eng Jpn, Special issue SI-4 River Engineering

Neil DT (1998) Moreton Bay and its catchment: seascape and landscape, development and degradation. In: Tibbetts IR, Hall NJ, Dennison WC (eds) Moreton Bay and catchment. School of Marine Science, The University of Queensland, Brisbane, pp 3–54

Nezu I, Nakagawa H (1993) Turbulence in open-channel flows, IAHR monograph series. Balkema Publisher, Rotterdam, 281 pp

Nielsen P (1992) Coastal bottom boundary layers and sediment transport, vol 4, Advanced series on ocean engineering. World Scientific, Singapore, 324 pp

Nishimura H (1989) How to conquer air pollution: a Japanese experience. Elsevier, Amsterdam, 301 pp

QDERM (2010) Moreton Bay Marine Park map. Queensland Department of Environment and Heritage Management QDERM, Brisbane. Available at: http://www.nprsr.qld.gov.au/parks/moreton-bay/zoning/pdf/map3-zoningplus.pdf. Accessed 19 Oct 2012

QOESR (2011) Queensland government population projections: local government areas report. Queensland Office of Economic and Statistical Research QOESR, Brisbane. Available at: http://www.oesr.qld.gov.au/products/publications/qld-govt-pop-proj-lga/index.php. Accessed 19 Oct 2012

Redlands Shire Council (undated) Eprapah creek waterway management plan – final. Redlands Shire Council. Available at: http://web01.redland.qld.gov.au/robo/plans/Eprapah_Creek_WMP/Eprapah_Creek_Waterway_Management_Plan.htm. Accessed 19 Aug 2012

Reynolds WC (1990) The potential and limitations of direct and large eddy simulations, in whither turbulence? turbulence at the crossroads. Lect Notes Phys 357:313–343

Roberts PJW, Webster DR (2002) Turbulent diffusion. In: Shen HH, Cheng AHD, Wang KH, Teng MH, Liu CCK (eds) Environmental fluid mechanics: theories and applications. ASCE, Reston, pp 7–45

Savenije HHG (2005) Salinity and tides in alluvial estuaries. Elsevier, Amsterdam, 194 pp

SEQHWP (2007) South East Queensland healthy waterways strategy 2007–2012. South East Queensland Healthy Waterways Partnership, Brisbane. (www.healthywaterways.org). Accessed 12 Oct 2012

Tennekes H, Lumley JL (1972) A first course in turbulence. MIT Press, Cambridge, MA, 300 pp

Tibbetts IR, Hall NJ, Dennison WC (1998) Moreton Bay and catchment. School of Marine Science, The University of Queensland, Brisbane, 645 pp

Trevethan M, Chanson H (2010) Turbulence and turbulent flux events in a small estuary. Environ Fluid Mech 10(3):345–368. doi:10.1007/s10652-009-9134-7

Trevethan M, Chanson H, Takeuchi M (2007) Continuous high-frequency turbulence and sediment concentration measurements in an upper estuary. Estuar Coast Shelf Sci 73(1–2):341–350. doi:10.1016/j.ecss.2007.01.014

Trevethan M, Chanson H, Brown R (2008a) Turbulent measurements in a small subtropical estuary with semi-diurnal tides. J Hydraul Eng ASCE 134(11):1665–1670. doi:10.1061/(ASCE)0733-9429(2008)134:11(1665)

Trevethan M, Chanson H, Brown R (2008b) Turbulence characteristics of a small subtropical estuary during and after some moderate rainfall. Estuar Coast Shelf Sci 79(4):661–670. doi:10.1016/j.ecss.2008.06.006