Science of the Total Environment 407 (2009) 3033–3043

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Extensive drought negates human influence on nutrients and water quality in estuaries

Travis S. Elsdon [a,*], Marthe B.N.A. De Bruin [a,b], Noël J. Diepen [a,b], Bronwyn M. Gillanders [a]

[a] Southern Seas Ecology Laboratories, School of Earth and Environmental Sciences, Darling Building DX 650 418, University of Adelaide, Adelaide, South Australia 5005, Australia
[b] Department of Environment and Applied Science, Hogeschool Zeeland, The Netherlands

ARTICLE INFO

Article history:
Received 1 August 2008
Received in revised form 16 December 2008
Accepted 9 January 2009
Available online 11 February 2009

Keywords:
Flow
Freshwater
Climate change
Nutrients
Drought
Estuary

ABSTRACT

Impacts of land-use on estuarine environmental parameters and nutrients are well documented, but little is known about these characteristics during extensive periods of low water flow (i.e., drought). Droughts are set to increase in frequency and magnitude with climate change, and understanding their influence on ecosystems is imperative. We investigated differences in environmental parameters and nutrients in urban and rural estuaries during a period of prolonged low flow. Sampling was done along each estuary at multiple times to place small-scale variability in the context of land-use differences. No differences were detected between land-use for environmental parameters or nutrients in mean effects or variance structure. Urban estuaries had reduced variation in nutrients over time compared to rural estuaries, which suggested that their concentrations are more stable. Large differences existed within and between individual estuaries, and over time. Low freshwater flow conditions in estuaries provide a glimpse to future climate change impacts of drought, and a baseline upon which pollution and anthropogenic effects can be assessed.

1. Introduction

Estuaries are among the most biologically productive and ecologically important ecosystems (Beck et al., 2001; Edgar et al., 1999; Mártínez et al., 2007). Understanding impacts on them is imperative to their conservation and future management. As transition zones between terrestrial and marine environments, waters entering estuaries are influenced by the lands they run over: agricultural, urban, industrial (McClusky and Elliot, 2004). Instinctively then, differences in land-use types can have dramatic impacts on estuarine environments (Bowden and Valiela, 2001; Dauer et al., 2000), particularly on environmental properties and water column nutrients (Borbor-Cordova et al., 2006; Castro et al., 2007; Mikac et al., 2007). Knowledge of how differences in land-uses alter environmental properties and nutrients comes predominantly from systems with high flows, such as European estuaries. The ecology of many world regions, however, differ substantially from high flow systems, and are characterised by small perennial estuaries that have intermittent to low flows (Mackay and Cyrus, 2001).

Global climate change is set to impact rainfalls, causing increased frequency and severity of low flow in some regions (Esterling et al., 2000; Sheffield and Wood, 2008). Regions most likely affected are those that already have low rainfall and intermittent periods of drought (Easterling et al., 2000; Lioubimtseva, 2004; Sheffield and Wood, 2008). For a majority of systems, determining effects of climate change are difficult (Hulme et al., 1999), however, taking advantage of current weather anomalies to gain insight into future impacts is critical (Ciais et al., 2005). The effect drought has on estuarine waters that flow from different land-use is largely unknown (Burkholder et al., 2006; Mackay and Cyrus, 2001). As freshwater flowing to estuaries originates from runoff, rainfall (Correll et al., 1999), and some permanent groundwater base flow (Valiela et al., 2000), the water quality and ecology of estuaries is likely to be impaired. Yet understanding how environmental properties and nutrients behave in estuaries under drought conditions is imperative to establishing baselines of data upon which anthropogenic impacts can be assessed (Dayton et al., 1998; Edgar et al., 2004; Pauly, 1995).

Land surrounding estuaries is often viewed as fertile alluvial plains for agriculture or in urban areas as conduits for industrial and urban wastes. As such natural waterways are often altered by dredging for shipping and reclamation to obtain greater usable land. Such human activities compromise estuarine ecosystems, and in many cases have caused large scale alterations of the hydrology (Roy et al., 2005; Vaze et al., 2004), environmental parameters, and natural communities via habitat destruction. Nutrients in estuaries are derived from natural ecological events, such as upwelling, litter fall, storm events, and weathering (Valiela et al., 1996), and from human activities, such as sewage outfalls, leaching of nitrogen and phosphorus from cleared land, fertiliser run-off, industrial effluents, and agricultural effluents (Carpenter et al., 1998; Paul and Meyer, 2001). Dissolved nutrient concentrations are often exacerbated in areas of urbanisation (Castro

* Corresponding author. Tel.: +61 8 83037036; fax: +61 8 83034364.
E-mail address: travis.elsdon@adelaide.edu.au (T.S. Elsdon).

0048-9697/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.scitotenv.2009.01.012

Table 1
Tidal conditions at each sampling time over which continuous measurements and discrete samples were taken

Estuaries	Date	Sampling relative to tide	TI (m)	Potential influence of tide in estuary
Onkaparinga	07 May	Within 3 h 25 m of rising tide	1.6 m	Tide influenced
	31 May	Within 3 h 22 m of rising tide	1.7 m	Tide influenced
	15 Jun	Within 4 h 59 m of rising tide	1.4 m	Tide influenced
Inman	04 May	Within 2 h 30 m of rising tide	1.9 m	Sandbar present, minimal tide influence
	30 May	Within 0 h 41 m of rising tide	1.5 m	Sandbar present, minimal tide influence
	21 Jun	Within 5 h 20 m of rising tide	1.3 m	Sandbar present, minimal tide influence
Hindmarsh	03 May	Within 2 h 29 m of rising tide	2.0 m	Sandbar present, minimal tide influence
	01 Jun	Within 0 h 48 m of rising tide	1.5 m	Sandbar present, minimal tide influence
	No third sampling period			
Myponga	02 May	Within 2 h 58 m of rising tide	1.7 m	Sandbar present, minimal tide influence
	29 May	Within 1 h 00 m of rising tide	1.3 m	Sandbar present, minimal tide influence #
	20 Jun	Within 2 h 57 m of rising tide	1.3 m	Sandbar present, minimal tide influence
Bungala	02 May	Within 4 h 06 m of rising tide	1.7 m	Sandbar present, minimal tide influence
	30 May	Within 3 h 03m of rising tide	1.5 m	Sandbar present, minimal tide influence
	21 Jun	Within 4 h 16 m of rising tide	1.3 m	Sandbar present, minimal tide influence
Waitpinga	08 May	No tidal influence	1.7 m	Sandbar, no tide influence
	29 May	No tidal influence	1.3 m	Sandbar, no tide influence
	20 Jun	No tidal influence	1.3 m	Sandbar, no tide influence

TI = tidal influence (maximum−minimum tidal height) in coastal waters outside estuaries. Tidal data were obtained from the Australian Bureau of Meteorology.
Potential influence of tide in estuary: *tide influenced* — regular influx of coastal saltwater twice daily, *sandbar present, minimal tide influence* — presence of a substantial sandbar resulting in only very large tides causing mixing of coastal and estuarine waters, and *sandbar, no tide influence* — sandbar completely isolating estuarine and coastal waters. # saltwater intrusion or re-distribution occurred.

et al., 2007; Mikac et al., 2007), due to increased atmospheric nitrogen and inadequate or leaking sewage systems (Carpenter et al., 1998; Walsh, 2000). Lands with >10% impervious surfaces can have enhanced nutrient concentrations (Hatt et al., 2004). Thus, land-use practices can greatly influence estuaries, because processes occurring in watersheds have flow-on consequences downstream.

Variation in environmental parameters and nutrients in both space and time have been investigated in several studies, mostly from European systems (e.g. Balls, 1994). Temperature, salinity, and nutrient concentrations can vary considerably in time and space (Balls, 1994; Cox et al., 2006; Elsdon and Gillanders, 2006; Seuront et al., 2002). In estuaries open to coastal waters and affected by tidal mixing, small-scale temporal variation can be extremely large (Caffrey et al., 2007), with changes over tidal cycles explaining up to 30% of total variation, which although not as important as diurnal and lunar components (explaining 39 to 75% of variation depending on season), were still significant in magnitude (Caffrey et al., 2007). Changes in environmental parameters and nutrients over larger scales (weeks, months, and seasons) may be linked to seasonal events, such as freshwater inputs from runoff and weather patterns (ArandaCirerol et al., 2006; Cox et al., 2006; Eyre, 1997; Eyre and Pont, 2003; White et al., 2004). Spatial variation of nutrients often follows observed patterns in temperature, light, hydrodynamics, and organic matter (Boyle et al., 2004), and as such fine scale heterogeneity can occur. Such significant variation in nutrient concentrations over short time scales highlights the need to assess impacts of land-use in the context of natural variation.

The lack of data on water quality in small coastal estuaries during extensive drought periods inhibits the formation of general patterns and determining future impacts associated with climate change. We aimed to examine and establish if trends in environmental variables and nutrients exist in estuaries subjected to a six year intensive drought. We hypothesize that estuaries in different land-use will have different environmental properties and nutrients, and that trends exist both spatially along estuaries and temporally within estuaries. Specifically we aimed to examine environmental parameters of temperature, salinity, pH, and oxygen, along with nutrient variables of oxidised nitrogen, orthophosphate, and ammonia.

2. Materials and methods

2.1. Study area

Estuarine sampling was done between May and June 2007 (Austral fall or autumn)(Table 1). During the periods of November 2001 to October 2007, the Australian Bureau of Meteorology reported a drought with rainfalls approximately 20% below long-term averages (AGBM, 2007). Our sampling was done at the end of this period of low rainfall. We examined environmental parameters in six estuaries at three sampling periods (see below), three of which feed into Gulf St Vincent (Onkaparinga, Myponga, Bungala estuaries), and three feed directly into the Southern Ocean (Hindmarsh, Inman, and Waitpinga estuary) (Fig. 1). All estuaries were located within the Mount Lofty Ranges, South Australia. The climate of Mount Lofty Ranges is typically

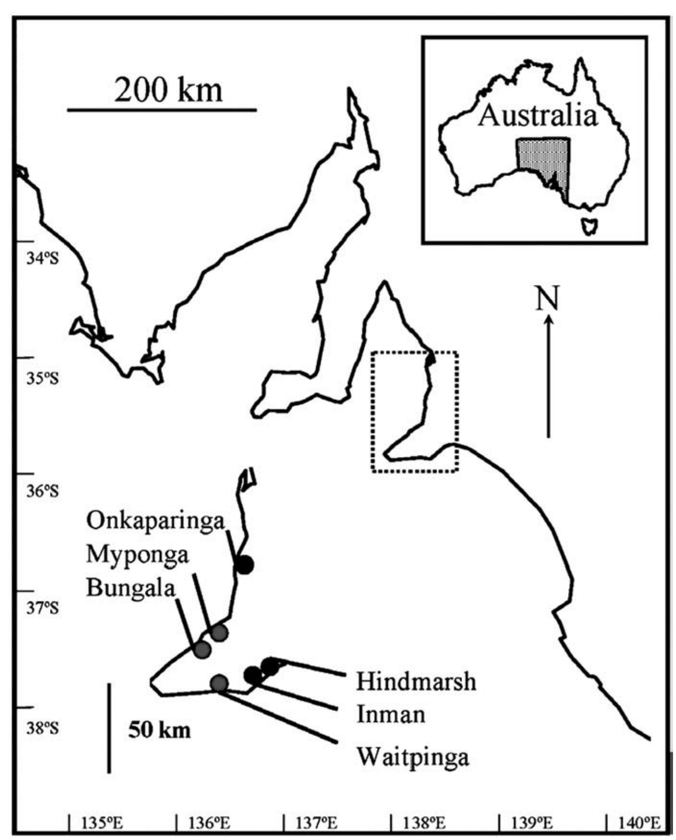

Fig. 1. Locations of the study area in South Australia. Black circles = urban estuaries, grey circles = rural estuaries.

Mediterranean, with hot and dry summers and mild and wetter winters.

Of the estuaries sampled, three can be considered rural (Myponga, Bungala, Waitpinga) and three urban (Onkaparinga, Inman, and Hindmarsh) based on their surrounding land-use. Urban estuaries receive contamination via storm water entering directly from the catchment. Onkaparinga receives waste waters from a former sewage treatment plant in the upper catchment. Land-use upstream of the wastewater plant is a mixture of grazing, dairy farming, rural residential, horticulture and viticulture, with small patches of native vegetation (Liddicoat et al., 2004). Adjacent to the estuary land-use is primarily residential housing, commercial services, and conservation lands. Land-use in the catchments of the Inman and the Hindmarsh is predominantly irrigated and non-irrigated grazing, dairy farming, horticulture, with small patches of forestry and nature conservation (Liddicoat et al., 2004). Both the Inman and Hindmarsh estuaries have adjacent residential and some light commercial or industrial land-use. The Inman received waste water from a local sewage treatment plant, until 2005 (Liddicoat et al., 2004).

Rural estuaries had catchments dominated by agricultural practices, primarily stock grazing, and have a lack of riparian vegetation buffering the watercourses. Estuaries of Myponga, Bungala, and Waitpinga, all on the lower Fleurieu Peninsula, have land-use dominated by grazing of dairy cattle, with around 50% improved pasture and remnant patches of native vegetation (Liddicoat et al., 2004). Septic tank leakage is a potential source of nutrient and pathogen pollution to these water courses.

2.2. Sampling of environmental data

Environmental parameters (temperature, salinity, pH, dissolved oxygen, chlorophyll *a*, and alkalinity) and nutrients (oxidised nitrogen, orthophosphate, and ammonia) were sampled along the length of each estuary (estuarine position) at three random times during autumn. This sampling design therefore provided tests of differences due to land-use (urban vs rural), estuaries (3 estuaries in each land-use), position within each estuary (positions one through seven, fresh to marine respectively), and temporal stability of patterns (three random times during May to June).

During the course of sampling estuaries had the potential to be open to either Gulf St Vincent or the Southern Ocean, however, unlike estuaries dominated by coastal waters (i.e. tidal creeks, tide-dominated estuaries) the estuaries we sampled are largely flow through sand dunes or sandy beaches, dropping in height, before mixing with coastal waters. As such, most of the estuaries have little to no influence from daily tidal cycles, because most they were either closed at the mouth by a dominant sandbar (i.e. Inman, Bungala, Waitpinga, Hindmarsh, Myponga) or had only small amounts of water exchange over their sandbars by waves at extremely high tides (i.e. Hindmarsh, Myponga) (Table 1). We did not preclude estuaries with closed mouths from our sampling (Wiatpinga), because low flow naturally results in the closure of estuarine mouths in temperate Australia, and the effects mouth closure may have on water quality and nutrients are indicative of drought conditions. Only Onkaparinga received daily and regular tidal flushing, and at this estuary sampling was done on the rising tide within sampling commencing and finishing within 2 h of the high tide for each sampling time. We considered differences in salinity, environmental properties, and nutrients that occurred with sampling time to reflect larger changes (estuarine freshwater intrusion and large tides) rather than small scale temporal variability.

Temperature, salinity, pH, and dissolved oxygen were obtained using an YSI sonde (model 6600) at a depth between 15 and 40 cm with a recording interval of 2 or 5 s. At each site, 25 replicate measurements (comprising of unique data points) of environmental variables were recorded on the YSI sonde (n=25 replicates). Nutrients were sampled in duplicate at each sampling time and position (n=2 replicates). A

Table 2

ANOVA comparing temporal and spatial patterns in environmental variables and nutrients

		T °C	Sal	pH	O_2 mg L^{-1}		$NO^-_{2/3}$ mg N L^{-1}	PO^{3-}_4 mg P L^{-1}	NH_3 mg N L^{-1}		Chl *a*	Alk mg $CaCO_3$ L^{-1}
Test 1	*df*	MS†	MS†	MS†	MS†	*df*	MS†	MS†	MS†	*df*	MS†	MS†
Time=T	2	19.07**	184.45	0.41**	71.15	2	0.07	0.01	0.14**	2	0.96	0.18
Land use=L (No test)	1	0.09	160.10	0.29	73.76	1	0.68	0.00	0.19	1	6.53	3.14
Estuary=E (L)	2	0.78	128.9	0.42**	58.18	2	0.91	0.03	0.02	2	12.41	0.11
Position=P (No test)	2	0.21	33.23	0.03	2.49	2	0.06	0.00	0.02	2	2.51	0.28
T×L	2	0.29	25.55	0.05	40.08	2	0.23	0.01	0.03	2	1.31	0.31
T×E (L)	4	0.53***	33.32***	0.03***	601.38***	4	0.15***	0.01	0.01***	4	5.28***	0.20***
T×P	12	0.16	8.68	0.01	5.48	12	0.02	0.00	0.01	4	3.17	0.15
L×P (No test)	6	0.22	4.04	0.02	3.66	6	0.01	0.01	0.02	2	9.82	0.20
P×E (L)	12	0.15	2.75	0.02	4.62	12	0.02	0.01	0.01	4	4.45	0.09
T×L×P	12	0.22	7.43	0.01	2.79	12	0.02	0.00	0.01	4	4.58	0.03
P×T×E (L)	24	0.19***	6.70***	0.02***	3.71***	24	0.03***	0.00	0.01***	8	3.67***	0.05***
Error	2016	0.00	0.05	0.00	0.02	84	0.00	0.00	0.00	36	0.30	0.01

		T °C	Sal	pH	O_2 mg L^{-1}		$NO^-_{2/3}$ mg N L^{-1}	PO^{3-}_4 mg P L^{-1}	NH_3 mg N L^{-1}
Test 2	*df*	MS†	MS†	MS†	MS†	*df*	MS†	MS†	MS†
Time=T	1	19.16**	9.93	0.01	5.34	1	0.01	0.00	0.02
Land use=L (No test)	1	0.43	112.05	0.59	114.21	1	0.09	0.03	0.89
Estuary=E (L)	4	0.76	61.06	0.32*	35.15	4	0.33	0.03	0.12
Position=P (No test)	6	0.12	29.57	0.06	7.32	6	0.05	0.01	0.03
T×L	1	0.23	22.16	0.02	79.27	1	0.09	0.01	0.11
T×E (L)	4	0.37***	30.87***	0.04***	57.98***	4	0.07***	0.01	0.34***
T×P	6	0.09	5.07	0.01	7.36	6	0.01	0.01	0.00
L×P (No test)	6	0.24	1.97	0.03	7.08	6	0.01	0.01	0.03
P×E (L)	24	0.12	4.37	0.01	3.09	24	0.02	0.00	0.01
T×L×P	6	0.12	4.81	0.00	4.04	6	0.02	0.00	0.00
P×T×E (L)	24	0.15***	2.94***	0.01***	3.33***	24	0.01***	0.00	0.01***
Error	2016	0.00	0.03	0.00	0.02	84	0.00	0.00	0.00

Test 1 has three times and two estuaries. Test 2 has two times and three estuaries. Chlorophyll *a* and Alkalinity were analysed using Test 1 only.

T=temperature, Sal=salinity, O_2=dissolved oxygen, $NO^-_{2/3}$=oxidised nitrogen, PO^{3-}_4=orthophosphate, NH_3=ammonia, Chl *a*=chlorophyll *a*, Alk=alkalinity. df=degrees of freedom, MS=mean squares estimate. *p<0.05, **p<0.01, ***p<0.001. Cochran's test of homogeneity was used, tests that were significant † were ln(x+1) transformed, for tests that remained significant, alpha was judged at α=0.01.

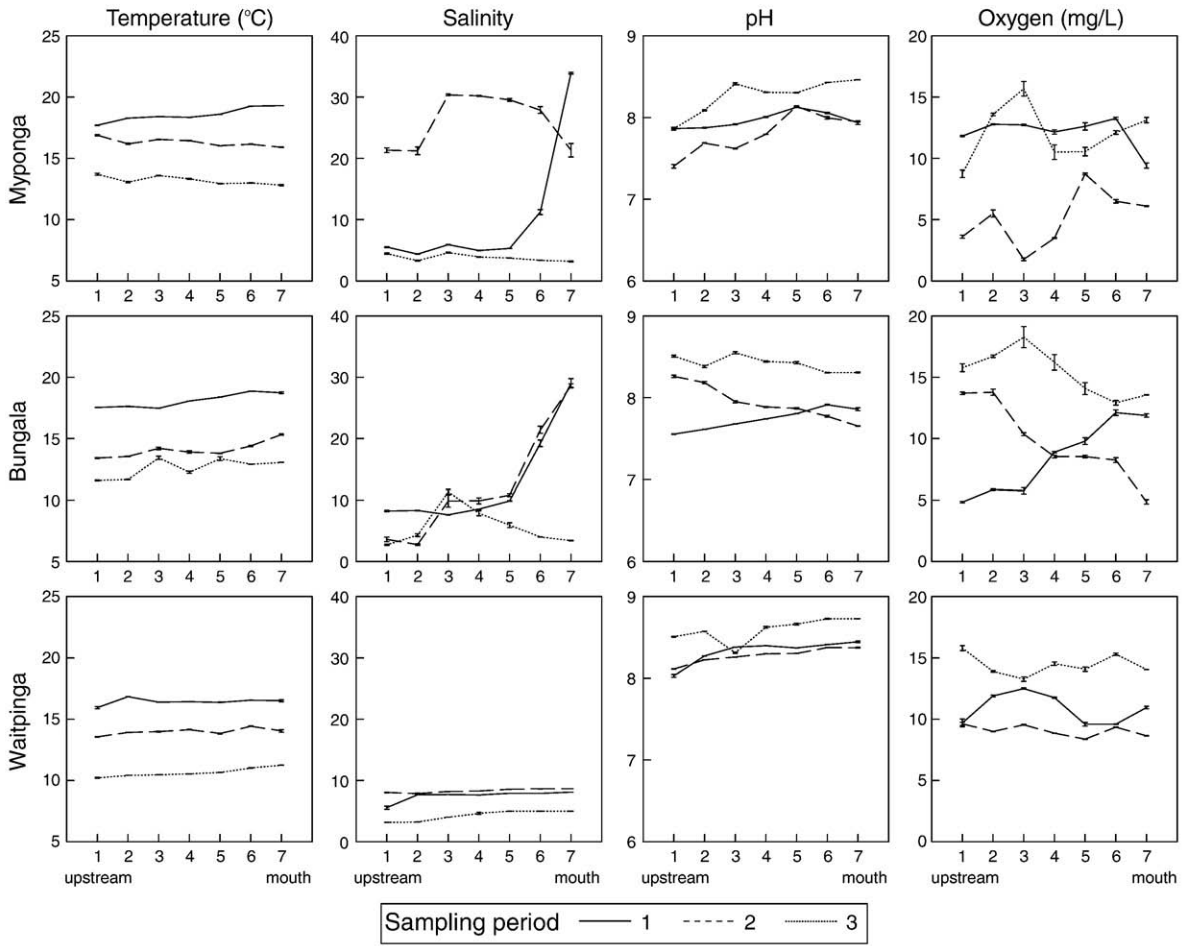

Fig. 2. Graphs of temperature (°C), salinity, pH and dissolved oxygen (mg L^{-1})(means±s.e.) at spatial scales of positions along the rural estuaries over three sample periods during May–June 2007.

greater number of replicate samples were not collected, due primarily to the large numbers of samples taken over the course of the study. For each nutrient sample, water was collected using a new sterilized 25 ml syringe, which was submerged to the depth of the syringe, thus, ensuring all samples were collected at a depth of 10 cm. Duplicate samples were collected within 50 cm of each other. The syringed water was then immediately filtered through a 0.45 µm membrane filter into a 15 ml polypropylene screw top vial. Samples were stored on ice in the field, and immediately frozen at −20 °C until analysis. Prior to samples being analysed they were defrosted (within 2 h of analysis) and placed in racks on the auto analyser stage. Nutrients were analysed using an Automated Ion Analyser (QuickChem 8500 FIA), using standard methods of nitrite/nitrate ($NO^{-}_{2/3}$; QuickChem® Method 31-107-04-1-A), orthophosphate (PO_4^{3-}; Method 31-115-01-1-I), and ammonia (NH_3; Method 31-107-06-1-B).

Chlorophyll *a* was sampled at three positions within the estuary: the first, fourth, and seventh sites. At each position, 2×1 L water samples were taken to determine chlorophyll *a* (n=2 per position). The water was filtered through a Whatman GF/C filter and the filter stored frozen for the analysis of chlorophyll *a* (Wetzel, 1983). Chlorophyll *a* was determined by resuspending GF/C filters in 10 ml of 100% ethanol at 70 °C for 5 min and sonicating for 30 s. Samples were cooled rapidly in ice and analysed using a spectrophotometer at 665 and 750 nm, using a blank of 100% ethanol. Chlorophyll *a* was determined using equations from Golterman et al. (1978). Alkalinity was determined from duplicate (n=2) water samples using a Hanna test kit (HI 3811 Alkalinity Test Kit).

2.3. Data analysis

Univariate analysis of variance was used to determine if environmental parameters and nutrients differed spatially and temporally. Due to missing nutrient data in Hindmarsh river at one time, two separate analyses were done to achieve balanced designs for time and estuary tests and to facilitate interpretations of these effects. The first (Test 1) compared three sampling times and two estuaries within each land-use, the second (Test 2) compared two sampling times and three estuaries. Chlorophyll *a* and alkalinity were analysed using Test 1.

Scales of Time, Land-use (urban vs rural), Estuary (estuaries in each Land-use), and Position (in each estuary) were examined using a four factor ANOVA. Time was random, Land-use was orthogonal to time and fixed, Estuary was nested within land-use and was random, and Position was orthogonal to estuary and was fixed. Separate analyses were done for each environmental parameter and nutrient. Where significant differences were detected (e.g., $p<0.05$, or $p<0.01$ if heterogeneous), means were compared using Student–Newman–Keuls (SNK) tests, to determine where these differences occurred (Underwood, 1997).

To determine if variation around mean values of environmental parameters and nutrients differ between land-use, ANOVAs comparing standard deviations of Positions were done (Benedetti-Cecchi, 2003). Standard deviation was calculated for each position, and the seven estimates for each estuary (each estimate being a position) were compared among Time, Land-use, and Estuary.

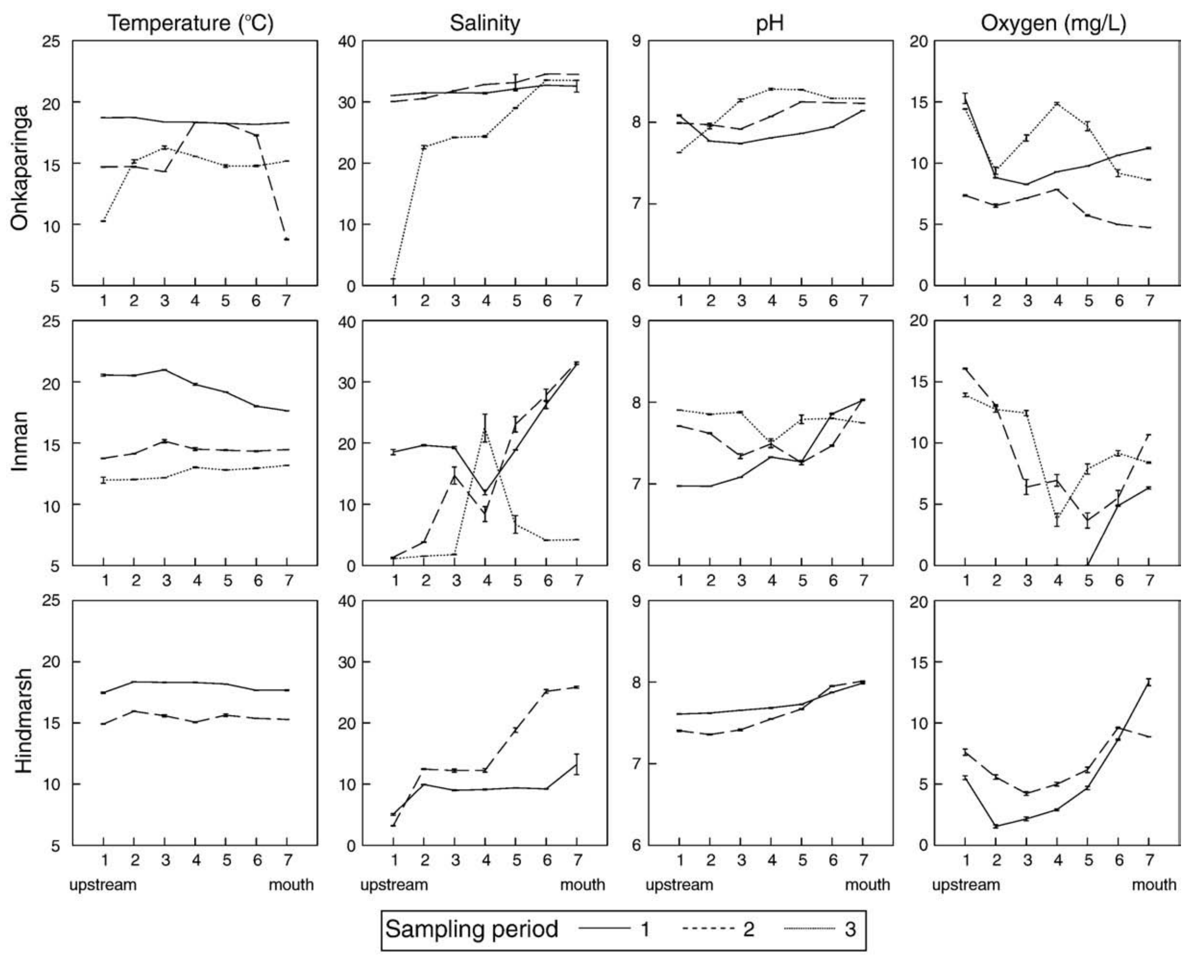

Fig. 3. Graphs of temperature (°C), salinity, pH and dissolved oxygen (mg L^{-1})(means ± s.e.) at spatial scales of positions along the urban estuaries over three sample periods during May–June 2007.

Magnitude of effects (ω^2) were estimated for both Rural and Urban land-use (see Vaughan and Corballis, 1969). Magnitude of effects is equivalent to r^2 values in regressions, such that they represent strengths of effects (or fit) explained by spatial and temporal scales (Graham and Edwards, 2001). To compare the amount of variation explained by spatial and temporal scales (as opposed to error), we summed ω^2 of significant terms; this was done for each land-use.

3. Results

3.1. Environmental parameters and nutrients

No differences were detected between rural and urban land-use (Table 2). This was evident by the lack of interactions involving land-use as a factor (i.e., Time × Land-use × Position and Time × Land-use tests). Environmental parameters and nutrients within estuaries were, however, highly variable within estuaries over time (Position × Time × Estuary (Location) interaction)(Table 2). This interaction was detected for all environmental parameters, as well as $NO^{-}_{2/3}$ and NH_3. No differences were detected in PO_4^{3-} at any spatial or temporal scale (Table 2).

Temperature varied along each estuary with sampling time (Figs. 2 and 3), although not all positions differed for all estuaries. There were no consistent trends of increasing or decreasing temperature along estuaries. Salinity differed among position within estuaries, but again not all positions differed in all estuaries (Figs. 2 and 3, Table 2). Two exceptions were at sampling times 1 and 2 in Waitpinga (salinity between ~7.62 and 8.65) and Onkaparinga at sampling times 1 and 2 (salinity between ~30.05 and 34.50). Salinity increased towards the estuary mouth for some estuaries on some sampling times (e.g., Hindmarsh, Figs. 2 and 3). In Myponga, the second sampling time had increased salinity, which matched that detected during the first sampling at the mouth site, suggesting that this water body had been pushed up into the estuary due to storm surge or a similar mechanism (Fig. 2). pH differed significantly among most positions within estuaries, however, the magnitude of change differed with estuaries (Figs. 2 and 3, Table 2). There were no consistent trends of increasing or decreasing pH along estuaries, and pH ranged from 6.9 to 8.7. Water pH was within the bounds of good levels for all estuaries and all sampling periods (Table 3). Dissolved oxygen levels differed among sampling positions and estuaries for each sampling time (Figs. 2 and 3, Table 2). During the

Table 3
Trigger values for water quality indicators for pH, oxygen, chlorophyll *a*, nitrate and nitrite, ammonia, and orthophosphate (ANZECC, 2000)

		Environmental variable	
		Dissolved oxygen	Chlorophyll *a*
Indicator level	pH	(mg L^{-1})	(mg L^{-1})
Good	6.5–9	>6	<1
Moderate	n/a	5–6	1–10
Poor	<6.5, >9	<5	>10

	Nitrate + Nitrite as oxidised nitrogen (mg N L^{-1})	Ammonia (mg N L^{-1})	Orthophosphate (mg P L^{-1})
Good	<0.1	<0.05	0.005–0.015
Moderate	0.1–1.0	0.05–0.5	n/a
Poor	>1.0	>0.5	n/a

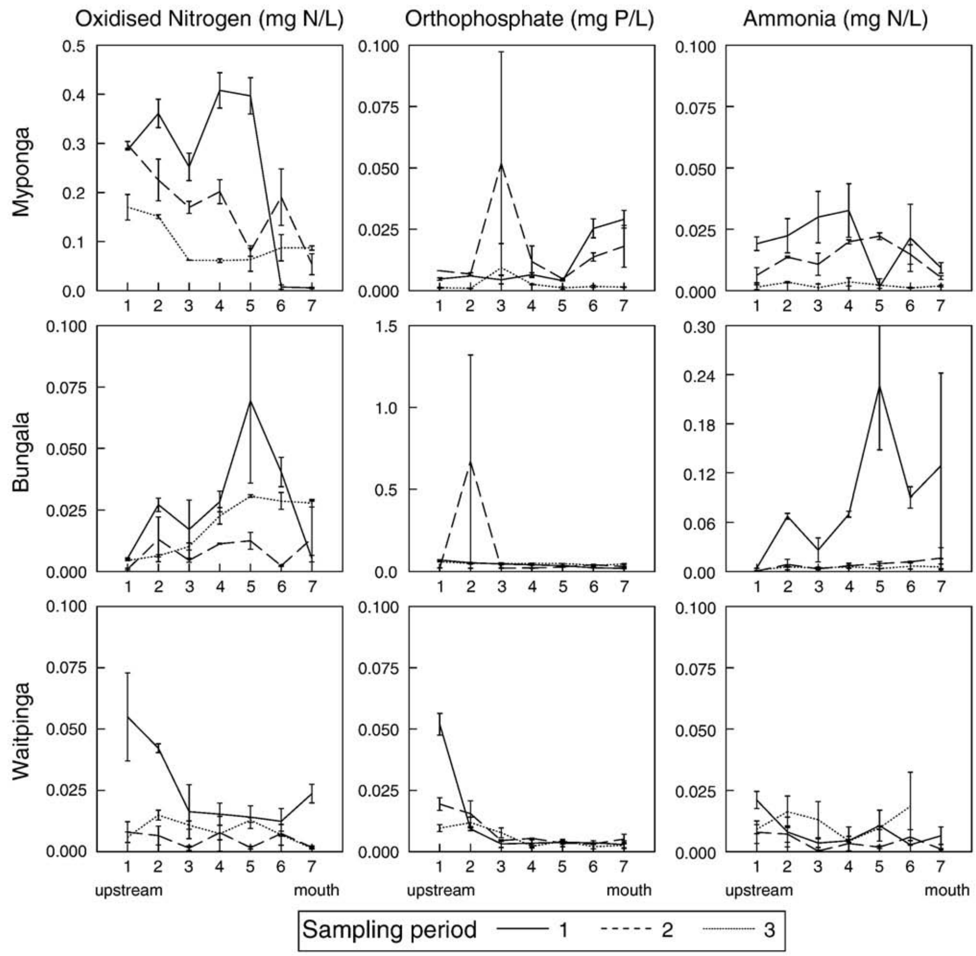

Fig. 4. Graphs of oxidised nitrogen (mg N L^{-1}), orthophosphate (mg P L^{-1}) and ammonia (mg N L^{-1})(means ± s.e.) at spatial scales of positions along the rural estuaries over three sample periods during May–June 2007. Note *y*-axis varies among plots.

second sampling time no difference was found along the length of the Waitpinga (between 8.37 and 9.62 mg L^{-1}) (Fig. 2, Table 2). During the first sampling period, oxygen in Inman estuary was zero in the upper five positions, corresponding to anoxic waters, and increased towards the estuary mouth (to between 4.88 and 6.33 mg L^{-1}), whereas on subsequent samplings oxygen was considerably higher, and more similar to other estuaries (Figs. 2 and 3, Table 2). In the Hindmarsh, oxygen levels were poor in the upper and middle part, although the second sampling period had moderate to good levels (Table 3). During the second sampling period, the water had a very bad odour and enriched tannin colour (the banks are tea-tree lined, genus *Melaleuca*, and tannin colour is normal) and dead fish were found. Based on oxygen values, water quality in the upper parts of Bungala and Myponga would be classified as poor (Table 3). Oxygen values in the Inman were extremely low (zero) during the first sampling periods, suggesting very poor water quality.

Nitrate and nitrite ($NO^{-}_{2/3}$) concentrations differed with estuarine position for most estuaries and times, however, some estuaries, for example Waitpinga, had homogeneous concentrations, hence driving the interaction between Position, Time, and Estuary (SNK tests, Figs. 4 and 5, Table 2). Ammonium concentrations were homogeneous among and within rural estuaries with the exception of Bungala for the first sampling time (Figs. 4 and 5, Table 2). Ammonia within urban estuaries was largely constant along estuaries, with the exception of Onkaparinga (times 1 and 2), Inman (time 1), and Hindmarsh (time 2)(SNK tests, Fig. 5).

Based on recommended levels of nutrients in estuarine and stream waters several of the estuaries would be classified poor (Table 3). For oxidised nitrogen, Inman had nitrogen indicative of poor water quality, but this was only for one sampling position at one time. Oxidised nitrogen in Myponga and Onkaparinga in the upper and middle part was above 0.1 mg N L^{-1}, which indicated moderate water quality. Ammonia concentrations were good to moderate for all estuaries except 1 site at Onkaparinga and Hindmarsh during the third sampling period, when concentrations could be classified as poor. Classifications for orthophosphate are either good or poor based on a cut off of 0.015 mg L^{-1} (below being poor, above being good, Table 3). Phosphate concentrations in all estuaries were classified as poor for some sampling periods and positions. Bungala and Hindmarsh had poor water quality for all positions and sampling times.

Chlorophyll *a* concentrations differed along estuaries, except for Inman and Myponga when concentrations were more similar (SNK tests, Fig. 6, Table 2). There were no general trends of increasing or decreasing chlorophyll *a* concentrations along estuaries. Chlorophyll *a* concentration was generally considered good, however, Onkaparinga can be considered poor and Waitpinga and Hindmarsh considered moderate (Table 3). Differences in alkalinity among estuarine positions were detected in the Myponga and Bungala for the first and second sampling times, and also Inman for the first sampling. For all other estuaries and sampling times there were no differences (SNK tests, Fig. 7, Table 2).

3.2. Variation in environmental variables and nutrients

Differences between land-use may be detected as differences in means or differences in the variance associated with those means (i.e., means do not change, but variation is different between land-use).

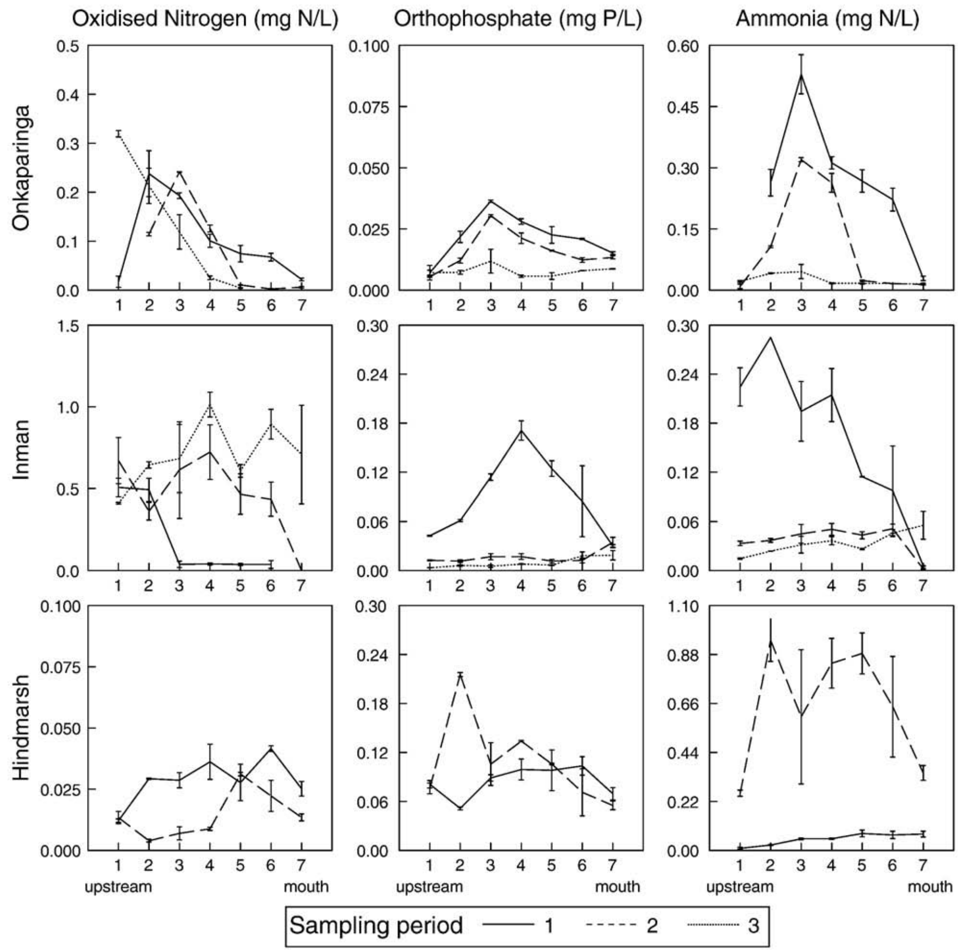

Fig. 5. Graphs of oxidised nitrogen (mg N L^{-1}), orthophosphate (mg P L^{-1}) and ammonia (mg N L^{-1})(means ± s.e.) at spatial scales of positions along the rural estuaries over three sample periods during May–June 2007. Note *y*-axis varies among plots.

Variation in data around means did not differ with Land-use (nonsignificant Time × Land-use interaction, Table 4). Significant differences in variation were detected for sampling Time for temperature, salinity, and NH_3 (test 1) and temperature (test 2) (Table 4). For temperature, variance was greatest during times 2 and 3, for salinity, variance was greatest during time 2, and for $NO_{2/3}^{-}$ variation was greatest during time 1. A significant difference in variation was detected for Estuary for salinity (test 1)(Table 4), with variation being greatest during time 2. An increase in variation with Time and Estuary suggests that the parameters had greater variation along estuaries and among estuaries during these periods.

Significant differences were detected with interactions between Time and Estuary for oxygen, $NO_{2/3}^{-}$, and NH_3 (Table 4). For each variable, the interaction of Time and Estuary was caused by differences at only one sampling time, however, there was inconsistency among which time that was (e.g., times 1 and 2 for $NO_{2/3}^{-}$, time 2 for oxygen and NH_3). The interaction between Time and Estuary suggests that parameters were more variable at certain times of sampling, but differences were dependent on the estuary sampled.

3.3. Magnitude of effects (ω^2)

Magnitude of effects were calculated for each of urban and rural land-use. For all environmental parameters, significant differences were detected with interactions of Estuary and Time, and Estuary and Time and Position (Table 5). For nutrients, significant differences were detected in rural land-use, similar to those found for environmental parameters. For urban land use, the only significant nutrient affect was $NO_{2/3}^{-}$ (Table 5). Given that tests in urban and rural land-use were based on identical designs, the sum of significant interaction terms was used to compare between land-use. For seven of the nine tests, the variation in rural land-use was greater than that in urban land-use (exceptions: salinity and chlorophyll *a*), which suggested that in rural estuaries, environmental parameters and nutrients are more dynamic and change more than in urban estuaries.

4. Discussion

4.1. Land-use differences during a drought period

We found no differences in environmental parameters or nutrients between urban and rural estuaries based on statistical analyses of replicate data (means) and standard deviations (variance) for each position. Rural estuaries did, however, have stronger patterns of change that urban estuaries (based on variance components), suggesting that these estuaries were more dynamic in environmental parameters and nutrients.

Urban and rural land-use types were chosen to represent differences in water and nutrient diffuse sources. Pollutant yields within each land-use were largely dependent on management practices (i.e., farming and agriculture) and hydrological responses (i.e., river flow), which generally differ among catchments of different land-use (Castro et al., 2007; Vaze et al., 2004). Differences among land-use likely reflected runoff and water yields of catchments (Correll et al., 1999; Wilkinson et al., 2005) with sealed urban surfaces having high runoff (Hatt et al., 2004) and therefore greater concentrations of nutrients directly entering estuaries compared to rural land-use where nutrients are buffered by riparian vegetation. The similarities in environmental parameters and nutrients we detected between land-use were surprising (based on means and standard deviations), although as stated previously, our data indicated that rural estuaries were more dynamic in change compared to urban estuaries. We had anticipated detecting differences among rural and urban estuaries because previous studies have shown this in the systems we examined (e.g., N and P in freshwater streams with different land use)(Liddicoat et al., 2004). However, similarities in phosphorus concentrations between grazed, forested, and urban lands have been detected in several studies (Mikac et al., 2007; Wood, 1986), and our results concur with those findings.

We detected minimal differences in water quality between land-use during a period of extensive drought, as characterised by an on average 20% reduction of rainfall from late 2001 to late 2007 (AGBM, 2007). During periods of reduced rainfall, little freshwater would enter streams, let alone influence estuarine processes (Burkholder et al., 2006). This was evident in our study, as freshwater entering the estuaries we sampled altered salinity in the headwater areas with only modest mixing down the estuary, hence mean differences were not apparent between rural and urban estuaries. Thus the waters we sampled were not subjected to large influences from land-use (i.e., recent runoff events) but had undergone complexing and uptake of nutrients (Hubertz et al., 2005). The small amount of land use influence on water quality and nutrients, was however, picked up by differences in variation among the rural and urban estuaries (based on

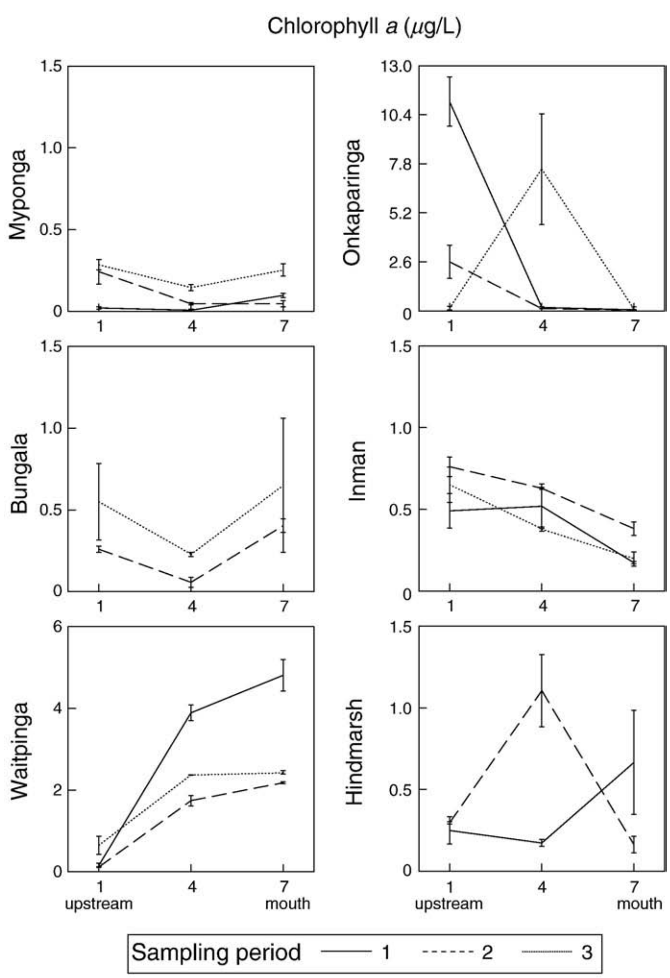

Fig. 6. Graphs of chlorophyll *a* (mg L^{-1}) at spatial scales of positions along the rural estuaries over three sample periods during May–June 2007. Note *y*-axis varies.

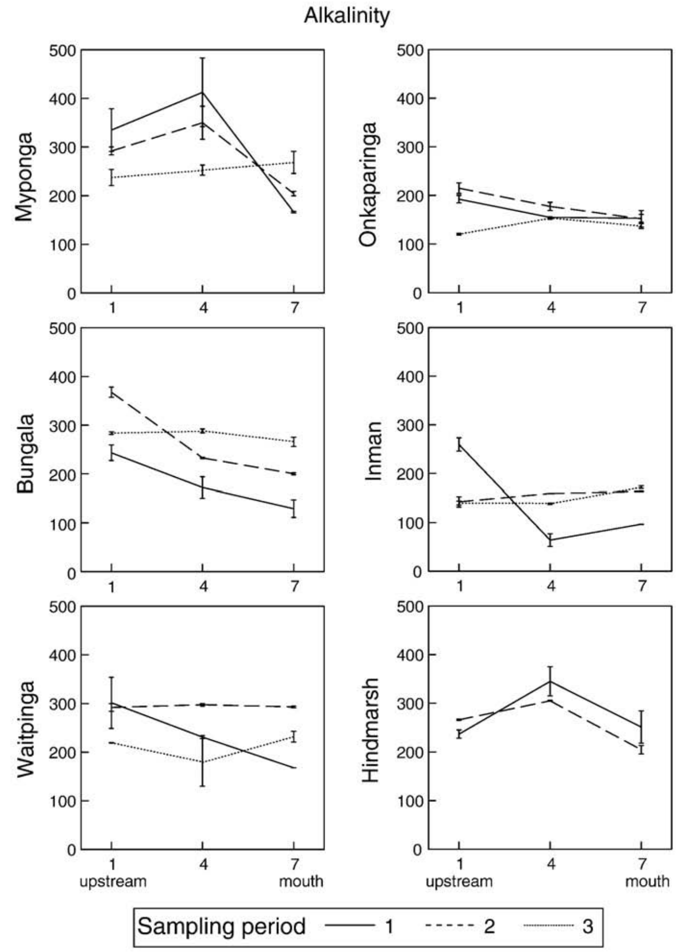

Fig. 7. Graphs of alkalinity (mg $CaCO_3$ L^{-1})(means±s.e.) at spatial scales of positions along the rural estuaries over three sample periods during May–June 2007.

variance components), which suggested that rural estuaries experienced more change over time, but these effects were not great enough to influence mean values. Nevertheless, the variance components provide a means to discriminate between land use systems. A reduction in total nitrogen and phosphorus in estuaries during a drought period in North Carolina has been observed (Burkholder et al., 2006). Their data characterises a lack of peak nutrient inputs during winter, which are apparent in years preceding the drought. In contrast, the estimates of nutrients in the Mount Lofty estuaries (Wood, 1986), where differences in land-use were detected, were taken in freshwater streams where land runoff is more likely to directly result in elevated nutrients.

A majority of our knowledge of estuarine processes and water quality come from estuaries of high flow or large perennial systems (Balls, 1994; Castro et al., 2007) — a stark contrast to drought stricken and small ephemeral estuaries on Australia's southern coast. Estuaries that are subjected to lengthy periods of drought, such as those in Australia, Africa, Mediterranean Middle East, and the Americas, may not conform to generalised and assumed patterns (Mackay and Cyrus, 2001). Climate change is projected to increase the frequency of drought events in many regions of the world (Sheffield and Wood, 2008). In Australia, it is predicted that rainfalls will be 15% and 45% less than the current long-term average by 2030 and 2070 respectively (Bardsley, 2006; Suppiah et al., 2006), which represents a rainfall reduction in close proximity to the conditions we sampled. By documenting patterns of water quality under these conditions we can establish baseline data similar to the predicted conditions of the future (Dayton et al., 1998; Edgar et al., 2004) to which additional

Table 4
ANOVA comparing variance structure among times and spatial scales

		T °C	Sal	pH	O_2 mg L^{-1}		$NO^-_{2/3}$ mg N L^{-1}	PO_4^{3-} mg P L^{-1}	NH_3 mg N L^{-1}		Chl *a*	Alk mg $CaCO_3$ L^{-1}
Test 1	*df*	MS†	MS†	MS†	MS†	*df*	MS†	MS†	MS†	*df*	MS†	MS†
Time=T	2	0.16*	1.56*	0.01	1.62	2	0.01	0.01	0.01*	2	2.14	1.20
Land use=L (No test)	1	0.00	0.04	0.00	0.71	1	0.04	0.01	0.00	1	2.45	1.47
Estuary (L)=E	2	0.06	1.69*	0.01	0.31	2	0.05	0.00	0.00	2	5.03	3.04
T×L	2	0.01	0.38	0.00	0.20	2	0.01	0.01	0.00	2	0.08	0.94
T×E (L)	4	0.02	0.20	0.00	0.33	4	0.01	0.00	0.00	4	1.58	1.75
Error	72	0.02	0.39	0.00	0.16	72	0.00	0.01	0.00	24	1.85	1.17

		T °C	Sal	pH	O_2 mg L^{-1}		$NO^-_{2/3}$ mg N L^{-1}	PO_4^{3-} mg P L^{-1}	NH_3 mg N L^{-1}
Test 2	*df*	MS†	MS†	MS†	MS†	*df*	MS†	MS†	MS†
Time=T	1	0.16*	1.66	0.01	0.11	1	0.01	0.00	0.00
Land use=L (No test)	1	0.00	0.19	0.00	0.02	1	0.01	0.00	0.02
Estuary (L)=E	4	0.04	1.54	0.00	0.32	4	0.02	0.00	0.01
T×L	1	0.01	0.28	0.00	0.45	1	0.01	0.01	0.01
T×E (L)	4	0.01	0.39	0.00	0.42**	4	0.01***	0.00	0.02***
Error	72	0.01	0.34	0.00	0.09	72	0.00	0.01	0.00

Test 1 has three times and two estuaries. Test 2 has two times and three estuaries. Chlorophyll *a* and Alkalinity were analysed using Test 1 only.
T=temperature, Sal=salinity, O_2=dissolved oxygen, $NO^-_{2/3}$=oxidised nitrogen, PO_4^{3-}=orthophosphate, NH_3=ammonia, Chl *a*=chlorophyll *a*, Alk=alkalinity. *df*=degrees of freedom, MS=mean squares estimate. **p*<0.05, ***p*<0.01, ****p*<0.001. Cochran's test of homogeneity was used, tests that were significant † were ln(x+1) transformed, for tests that remained significant, alpha was judged at α=0.01.

change (i.e., pollution outfalls, anthropogenic impacts) can be assessed (see Hulme et al., 1999).

4.2. Environmental parameters

Water temperature is greatly influenced by air temperature and rainfall. During our sampling, freshwater flows from rainfall increased slightly (BOM), which corresponded to slight decreases in water temperature. In Onkaparinga, temperature did not decrease between samplings, perhaps because this estuary is open to the sea and is more influenced by sea temperatures and tides. This pattern is consistent with a previous study at Onkaparinga, which found large effects of tides and days on water temperature (Elsdon and Gillanders, 2006).

Salinity differed considerably among estuaries, but there was a general trend for a typical estuarine gradient from fresh to estuarine to marine water, caused by the small amounts of baseflow or runoff. Consistency of this pattern was dependent on sampling times, and was influenced largely by limited fresh water flow. Those estuaries that had little to no saltwater intrusion by tidal exchanges: Myponga, Bungala, Inman, Waitpinga, and Hindmarsh had patterns consistent with freshwater filling the estuary and being mixed slightly with salt water. In Myponga, there was some evidence of saltwater intrusion up the estuary for the second sampling time, with this likely to have occurred when storm surge forced saltwater that was present at the mouth up into the estuary. This saltwater was then later pushed back over the sandbar by freshwater before the third sampling time. Onkaparinga was the exception to this, due largely to 100% tidal flushing of the 4 km section near the mouth (Wilkinson et al., 2005). Longitudinal patterns are common in shallower estuaries where advection and diffusive mixing of fresh and marine waters occur (Roy et al., 2001) rather than wind driven mixing that leads to greater homogenisation of salinity throughout the estuarine body (Ward and Montague, 1996). Thus, strong patterns in salinity along small estuaries appeared to be maintained over the sampling periods.

Table 5
Components of variation associated with Analyses of Variance, comparing between rural and urban estuaries

Source of variation		Temperature		Salinity		pH		Oxygen			Chlorophyll *a*		Alkalinity	
	df	Rural ω^2	Urban ω^2	Rural ω^2	Urban ω^2	Rural ω^2	Urban ω^2	Rural ω^2	Urban ω^2	*df*	Rural ω^2	Urban ω^2	Rural ω^2	Urban ω^2
Estuary=E	1	0.00	5.23	48.49	0.00	52.45*	0.00	0.00	0.00	1	10.39	7.45	0.00	0.00
Time=T	2	63.28	84.61	14.44	25.94	12.31	47.62	0.00	19.45	2	0.00	0.00	8.62	0.00
Position=P (No test)	6	–	–	–	–	–	–	–	–	2	–	–	–	–
E×T	2	10.43***	5.70***	3.15***	34.86***	1.60***	17.32***	61.66***	38.72***	2	6.67*	48.72***	56.82***	15.88*
E×P	6	0.00	1.04	0.00	0.00	0.00	8.25	5.57	0.00	2	0.00	2.37	1.24	18.57
T×P	12	0.00	0.19	0.00	13.77	0.00	0.00	0.00	0.00	4	0.00	3.28	0.00	19.95
E×T×P	12	25.45***	2.42***	29.52***	22.68***	30.97***	25.06***	27.03***	34.27***	4	74.57***	36.31***	25.96***	23.71*
Error	1008	0.85	0.81	4.39	2.75	2.66	1.75	5.73	7.56	18	8.38	1.88	7.35	21.89
Exp. variation		35.88 >8.11		32.67 <57.55		85.02 >42.39		88.70 >72.98			81.23 <85.03		82.78 >39.59	

		$NO^-_{2/3}$		PO_4^{3-}		NH_3	
	df	Rural ω^2	Urban ω^2	Rural ω^2	Urban ω^2	Rural ω^2	Urban ω^2
Estuary=E	1	37.44	52.35	1.83	6.64	3.26	0.00
Time=T	2	0.00	1.51	17.20	0.98	39.46	12.22
Position=P (No test)	6	–	–	–	–	–	–
E×T	2	27.29***	11.52	47.25***	0.00	5.32***	27.07
E×P	6	0.00	7.82	0.00	1.49	12.99	0.00
T×P	12	0.00	2.85	4.82	0.00	4.27	0.00
E×T×P	12	23.82***	20.63***	22.48***	0.00	30.72***	23.92
Error	42	11.45	3.32	6.42	90.89	3.98	36.79
Exp. variation		51.11> 20.63		69.72> 0.00		36.04> 0.00	

Shown are estimates of variance components (ω^2) and associated significant sources of variation.
$NO^-_{2/3}$=oxidised nitrogen, PO_4^{3-}=orthophosphate, NH_3=ammonia. **p*<0.05, ***p*<0.01, ****p*<0.001.

Oxygen levels were related to changes in salinity, with freshwater increasing oxygen during the third sample time, compared to the first two samplings. Low oxygen in the upper parts of the Bungala were likely related to reduced water flow and an abundance of decaying vegetation and organic material, which can cause oxygen depletion (Balls, 1994; Dauer et al., 2000). Low oxygen in Inman was also associated with decaying organic matter, and potentially with past inputs of secondary treated waste from the former Victor Harbor waste water treatment plant (Liddicoat et al., 2004). Although the water treatment plant is no longer disposing water into Inman estuary, a flux of high nutrients from benthic sediments is likely to still occur.

Alkalinity remained relatively stable across sampling locations and times, as would be expected given that very little change was detected in pH. High pH was detected for most estuaries during the third sampling time. These patterns may represent primary production from algae blooms or rainfall diluting water bacteria levels increasing pH levels (Rasmussen et al., 1983). For example, Waitpinga had quite high pH values when compared to the other estuaries, and this estuary also contained a large biomass of algal mats. Changes in chlorophyll *a* that were detected in estuaries most likely represent changes in phytoplankton abundance, distribution, or composition (Paerl et al., 2005). Large changes both within an estuary (longitudinal distribution) and among sampling times (temporal changes) were detected, which suggested the phytoplankton community responded to hydrological changes (Cox et al., 2006; Paerl et al., 2005). Several estuaries showed patterns of chlorophyll *a* increasing (Waitpinga) or decreasing (Inman), indicative of either growth or decline in phytoplankton abundance or changes in species composition over time.

4.3. Nutrients

Our data may suggest that regardless of land-use, chemical and biological processes that act within estuaries may have resulted in similarities in environmental processes, and in particular nutrients (Balls, 1994). For example, similar concentrations of nutrients were detected among urban and rural estuaries, however, urban estuaries, such as Inman and Hindmarsh, had high levels of algal growth and consequently low oxygen. Large algae growth is likely to have resulted from nutrient uptake, thus, depleting ambient nutrient concentrations (Bowden and Valiela, 2001). Thus, while different nutrient concentrations may be washed into estuaries, over time these nutrients have resulted in biological productivity (Bowden and Valiela, 2001; Dauer et al., 2000). With subsequent influxes of freshwater being minimal, nutrient concentrations within the estuaries remained relatively unchanged over time.

Poor water quality in estuaries is likely to reflect inputs from land runoff. Two urban sites, Inman and Onkaparinga, have had extensive modification and past effluent treatment plants located on or near them. Inman had the highest $NO_{2/3}^-$ levels, which could be caused by residual input of secondary treated waste from the Victor Harbor Waste Water Treatment Plant (WWTP)(Liddicoat et al., 2004). Although the WWTP is no longer discharging directly into the estuary, over 30 years of constant nutrient inputs (between 1972 and November 2005) are likely to be causing a significant fluxing of nutrients from benthic sediments (Cook et al., 2004; Howarth, 1988). Alternatively, high ammonia could be due to its release from decaying organic matter, and being unable to convert to $NO_{2/3}^-$ by bacteria, because of the low oxygen levels (Hubertz et al., 2005). It is likely that a combination of nutrient flux from sediment and low oxygen were responsible for the high nutrients detected in Inman at concentrations consistent to those reported prior to the cessation of direct discharge from the WWTP (EPA, 2008; Wilkinson et al., 2005; Wood, 1986). Similar to the Inman estuary, the Onkaparinga drains a significant watershed either direct or via wetlands (Wilkinson et al., 2005), and has, in the past, received seepage from the Christie Beach WWTP via sludge lagoons located in the estuaries wetlands (Wilkinson et al., 2005). These lagoons leak ammonia through groundwater into the estuary similar to those at Inman (Liddicoat et al., 2004), although in the current sampling ammonium values were not abnormally high.

The large differences we detected among duplicate water samples for some days may be indicative of small scale patchiness within water bodies (Seymour et al., 2007). The discrepancies were unlikely to represent analytical or sampling errors, because they were isolated to only one chemistry and adjacent samples during the analysis were not inflated in nutrients (i.e. oxidised nitrogen — ruling out field and instrument inaccuracy). We therefore interpreted these discrepancies as legitimate data points, but would recommend a greater number of samples to help elucidate either nutrient patchiness in estuaries or reduce variance in estimates of nutrients at particular sites and times.

5. Conclusion

Large difference in nutrients and environmental parameters were detected among sampling times. Such large differences over small temporal scales could considerably alter interpretations of general patterns, and therefore the ability to determine future impacts of climate change. For example, if we only sampled the second time at Hindmarsh estuary, when nutrients were high, water was extremely tannin and odorous, and dead fish were present, then water quality would be assessed as catastrophically poor (Breitburg, 2002), yet this was not representative of the long term trends for that estuary (Wood, 1986). Our ability to deduce that water quality in the Hindmarsh was not catastrophically poor was achieved by re-sampling on additional times, and therefore deducing that water quality was dynamic and establishing a more true representation of the estuaries condition.

Our sampling was done over a two month period because we aimed at addressing hypotheses about differences among urban and rural habitats, and not necessarily to establish a long term dataset. We did this because to establish long term datasets to detect an impact may take years, during which the environmental stressor (drought) may be alleviated. So that our hypothesis was not tested at just one time, we sampled estuaries on three occasions, and determined that irrespective of temporal change, land use influences were minimal. Moreover, the study was done during the wetter season, when land use affects on environmental variables should be most apparent, yet we failed to detect any differences. The application of either long term monitoring or monitoring to capturing time-variant processes would of course require a different sampling designs that captures variation over small scales and expresses it relative to variation at larger scales (Caffrey et al., 2007; Vaughan and Corballis, 1969). In complex environments, such as estuaries and coastal areas, this may be achieved by sampling over tidal cycles on replicate days, and repeating this at monthly or seasonal intervals. In doing so, variation at small scales would be captured and compared at scales relevant to larger processes (i.e. monthly, seasonal, or annual differences).

Generalizations about differences between rural and urban land-use are potentially difficult for estuaries given large variability. Individual estuaries have specific combinations of land-use, runoff, and biological and chemical processes that may not group according to rural and urban land-use categories. Our study indicated that during drought periods when freshwater flow into estuaries was low there were no differences between urban and rural estuaries. Instead, changes in environmental parameters and nutrients within estuaries and over time were stronger than any differences among land-use. Understanding the response of temperate estuaries to drought conditions is imperative to successfully monitoring change and impacts of future climate stressors.

Acknowledgements

We thank Ruan Gannon and Bayden Russell for field assistance. Funding was provided from the Australian Research Council. The research formed part of a water management degree for Marthe De Bruin and Noël Diepens at Hogeschool Zeeland, the Netherlands. Travis Elsdon received support by an ARC postdoctoral fellowship.

References

AGBM. Six years of widespread drought in southern and eastern Australia November 2001–October 2007. Special climate statement 14. Australian Government Bureau of Meteorology, Melbourne; 2007. 6 pp.

ArandaCirerol N, Herrera-Silveria JA, Comín FA. Nutrient water quality in a tropical coastal zone with groundwater discharge, northwest Yucatán, Mexico. Est. Coast. Shelf Sci. 2006;68:445–54.

Balls PW. Nutrient inputs to estuaries from Nine Scottish east coast rivers; influence of estuarine processes on inputs to the North Sea. Est. Coast. Shelf Sci. 1994;39:329–52.

Bardsley D. There's a change on the way — an initial integrated assessment of projected climate change impacts and adaptation options for Natural Resource Management in the Adelaide and Mt Lofty Ranges region. Department of Water, Land and Biodiversity Conservation, Government of South Australia, Australia, Adelaide; 2006. 70 pp.

Beck MW, Heck KL, Able KW, Childers DL, Eggleston DB, Gillanders BM, et al. The identification, conservation, and management of estuarine and marine nurseries for fish and invertebrates. BioScience 2001;51:633–41.

Benedetti-Cecchi L. The importance of the variance around the mean effect size of ecological processes. Ecology 2003;84:2335–46.

Borbor-Cordova MJ, Boyer EW, McDowell WH, Hall CA. Nitrogen and phosphorus budgets for a tropical watershed impacted by agricultural land use: Guayas, Ecuador. Biogeochemistry 2006;79:135–61.

Bowden JL, Valiela I. The ecological effects of urbanization of coastal watersheds: historical increases in nitrogen loads and eutrophication of Waquoit Bay estuaries. Can. J. Fish. Aquat. Sci. 2001;58:1489–500.

Boyle KA, Kamer K, Fong P. Spatial and temporal patterns in sediment and water column nutrients in a eutrophic southern California estuary. Estuaries 2004;27:378–88.

Breitburg D. Effects of hypoxia, and the balance between hypoxia and enrichment, on coastal fishes and fisheries. Estuaries 2002;25:767–81.

Burkholder JM, Dickey DA, Kinder CA, Reed RE, Mallin MA, McIver MR, et al. Comprehensive trend analysis of nutrients and related variables in a large eutrophic estuary: a decadal study of anthropogenic and climatic influences. Limnol. Oceanogr. 2006;51:463–87.

Caffrey JM, Chapin TP, Jannasch HW, Haskins JC. High nutrient pulses, tidal mixing and biological response in a small California estuary: variability in nutrient concentrations from decadal to hourly time scales. Est. Coast. Shelf Sci. 2007;71:368–80.

Carpenter SR, Caraco NF, Correll DL, Howarth RW, Sharpley AN, Smith VH. Nonpoint pollution of surface waters with phosphorous and nitrogen. Ecol. Appl. 1998;8:559–68.

Castro P, Valiela I, Freitas H. Eutrophication in Portuguese estuaires evidenced by δ15N of macrophytes. Mar. Ecol. Prog. Ser. 2007;351:43–51.

Ciais P, Reichstein M, Viovy N, Granier A, Ogée J, Allard V, et al. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 2005;437:529–33.

Cook PLM, Eyre BD, Leeming R, Bultler ECV. Benthic fluxes of nitrogen in the tidal reaches of a turbid, high-nutrient sub-tropical river. Est. Coast. Shelf Sci. 2004;59:675–85.

Correll DL, Jordan TE, Weller DE. Effects of interannual variation of precipitation on stream discharge from Rhode River subwatersheds. J. Am. Water Resour. Assoc. 1999;35:73–82.

Cox EF, Ribes M, Kinzie RAI. Temporal and spatial scaling of planktonic responses to nutrient inputs into a subtropical embayment. Mar. Ecol. Prog. Ser. 2006;324:19–35.

Dauer DM, Ranasinghe JA, Weisberg SB. Relationships between benthic community condition, water quality, sediment quality, nutrient loads, and land use patterns in Chesapeake Bay. Estuaries 2000;23:80–96.

Dayton PK, Tegner MJ, Edwards PB, Riser KL. Sliding baselines, ghosts, and reduced expectations in kelp forest communities. Ecol. Appl. 1998;8:309–22.

Easterling DR, Meehl GA, Parmesan C, Changnon SA, Karl TR, Mearns LO. Climate extremes: observations, modelling, and impacts. Science 2000;289:2068–74.

Edgar GJ, Barrett NS, Graddon DJ, Last PR. The conservation significance of estuaries: a classification of Tasmanian estuaries using ecological, physical and demographic attributes as a case study. Biol. Cons. 1999;92:383–97.

Edgar GJ, Bustamante RH, Fariña JM, Calvopiña M, Martínez C, Toral-Grande MV. Bias in evaluating the effects of marine protected areas: the importance of baseline data for the Galapagos Marine Reserve. Environ. Conserv. 2004;31:212–8.

Elsdon TS, Gillanders BM. Temporal variability of elemental concentrations in coastal and estuarine waters. Est. Coast. Shelf Sci. 2006;66:147–56.

EPA. EPA(SA) Water quality. Government of South Australia. Adelaide: Environmental Protection Authority; 2008. pp.

Esterling DR, Meehl GA, Parmesan G, Changnon SA, Karl TR, Mearns LO. Cimate extremes: observations, modeling, and impacts. Science 2000;289:2068–74.

Eyre B. Water quality changes in an episodically flushed sub-tropical Australian estuary: a 50 year perspective. Mar. Chem. 1997;59:177–87.

Eyre BD, Pont D. Intra- and inter-annual variability in the different forms of diffuse nitrogen and phosphorus delivered to seven sub-tropical east Australian estuaries. Est. Coast. Shelf Sci. 2003;57:137–48.

Golterman HL, Clymo RS, Ohnstad MAM. Methods for physical and chemical analysis of fresh waters. Oxford: Blackwell Scientific; 1978. 213 pp.

Graham MH, Edwards MS. Statistical significance versus fit: estimating the importance of individual factors in ecological analysis of variance. Oikos 2001;93:505–13.

Hatt BE, Fletcher TD, Walsh CJ, Taylor SL. The influence of urban density and drainage infrastructure on the concentrations and loads of pollutants in small streams. Environ. Man. 2004;34:112–24.

Howarth RW. Nutrient limitation of net primary production in marine ecosystems. Annu. Rev. Ecol. Syst. 1988;19:89-110.

Hubertz J, Huang X, Kolluru V, Edinger J. Physical processes affecting estuarine health. In: Bortone SA, editor. Estuarine indicators. New York: CRC Press; 2005. 19–33 pp.

Hulme M, Barrow EM, Arnell NW, Harrison PA, Johns TC, Downing TE. Relative impacts of human-induced climate change and natural climate variability. Nature 1999;397:688–91.

Liddicoat C, New B, Herrmann T. Salinity and water quality management in the Inman River, Waitpinga, and Coolawanga Creek catchments. South Australian Department of Water, Land and Biodiversity Conservation, Adelaide; 2004. 175 pp.

Lioubimtseva E. Climate change in arid environments: revisiting the past to understand the future. Prog. Phys. Geogr. 2004;28:502–30.

Mackay CF, Cyrus DP. Is freshwater quality adequately defined by physico-chemical components? Results from two drought-affected estuaries on the east coast of South Africa. Mar. Freshw. Res. 2001;52:267–81.

Mártínez ML, Intralawan A, Vazquez G, Pérez-Maqueo P, Sutton P, Landgrave R. The coast of our world: ecological, economic and social importance. Ecol. Econ. 2007;63:254–72.

McClusky DS, Elliot M. The estuarine ecosystem. Vol Third Edition. Oxford: Oxford University Press; 2004. pp.

Mikac KM, Maher WA, Jones AR. Do physicochemical sediment variables and their soft sediment macrofauna differ among microsize coastal lagoons with forested and urbanised catchments? Est. Coast. Shelf Sci. 2007;72:308–18.

Paerl HW, Dyble J, Pinckney JL, Valdes LM, Millie DF, Moisander PH, et al. Using microalgal indicators to assess human- and climate-induced ecological changes in estuaries. In: Bortone SA, editor. Estuarine indicators. New York: CRC Press; 2005. 145–174 pp.

Paul MJ, Meyer JL. Streams in the urban landscape. Annu. Rev. Ecol. Syst. 2001;32:333–65.

Pauly D. Anecdotes and the shifting base-line syndrome of fisheries. Trends Ecol. Evol. 1995;10:430.

Rasmussen MB, Henriksen K, Jensen A. Possible causes of temporal fluctuations in primary production of the microphytobenthos in the Danish Wadden Sea. Mar. Biol. 1983;73:109–14.

Roy PS, WIlliams RJ, Jones AR, Yassini I, Gibbs PJ, Coates B, et al. Structure and function of South-east Australian estuaries. Est. Coast. Shelf Sci. 2001;53:351–84.

Roy AH, Freeman MC, Freeman BJ, Wenger SJ, Ensign WE, Meyer JL. Investigating hydrologic alteration as a mechanism of fish assemblage shifts in urbanizing streams. J. N. Am. Benthol. Soc. 2005;24:656–78.

Seuront L, Gentilomme V, Lagadeuc Y. Small-scale nutrient patches in tidally mixed coastal waters. Mar. Ecol. Prog. Ser. 2002;232:29–44.

Seymour JR, Seuront L, Mitchell JG. Microscale gradients of planktonic microbial communities above the sediment surface in a mangrove estuary. Est. Coast. Shelf Sci. 2007;73:651–66.

Sheffield J, Wood EF. Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. Clim. Dyn. 2008;31:79-105.

Suppiah R, Preston B, Whetton PH, McInnes KL, Jones RN, Macadam I, et al. Climate change under enhanced greenhouse conditions in South Australia. CSIRO Marine and Atmospheric Research, Adelaide; 2006. 64 pp.

Underwood AJ. Experiments in ecology: their logical design and interpretation using analysis of variance. Cambridge: Cambridge University Press; 1997. 504 pp.

Valiela I, Peckol P, D'Avanzo C, Lajtha K, Kremer J, Rockwell GW, et al. Hurricane Bob on Cape Cod. (environmental damage assessment). Am. Scientist 1996;84:154–65.

Valiela I, Geist M, McClelland J, Tomasky G. Nitrogen loading from watersheds to estuaries: verification of the Waquoit Bay nitrogen loading model. Biogeochemistry 2000;49:277–93.

Vaughan GM, Corballis MC. Beyond tests of significance: estimating strength of effects in selected ANOVA designs. Psychol. Bull. 1969;72:204–13.

Vaze J, Barnett P, Beale G, Dawes W, Evans R, Tuteka NK, et al. Modelling the effects of land-use change on water and salt delivery from a catchment affected by dryland salinity in south-east Australia. Hydrol. Process. 2004;18:1613–37.

Walsh CJ. Urban impacts on the ecology of receiving waters: a framework for assessment, conservation and restoration. Hydrobiologia 2000;431:107–14.

Ward GHJ, Montague CL. Estuaries. In: Mays LW, editor. Water resources handbook. New York: McGraw-Hill; 1996. 12.1–12.114 pp.

Wetzel RG. Limnology. Vol 2nd. New York: Saunders College Publishing; 1983. 767 pp.

White DL, Porter DE, Leqitus AJ. Spatial and temporal analyses of water quality and phytoplankton biomass in an urbanized versus a relatively pristine salt marsh estuary. J. Exp. Mar. Biol. Ecol. 2004;298:255–73.

Wilkinson J, White N, Smythe L, Hutson J, Bestland E, Simmons C, et al. Volumes of inputs, their concentrations and loads received by Adelaide metropolitan coastal waters. Adelaide Coastal Waters Steering Committee, Flinders Centre for Coastal and Catchment Environments, Adelaide; 2005. 83 pp.

Wood C. Mt Lofty ranges watershed — impact of land use on water quality and implications for reservoir water quality management. Engineering and Water Supply Department, Adelaide; 1986. 33 pp.