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Spatial variation in physio-chemistry in a small river estuary

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Understanding of riverine and estuarine mixing processes remains limited, and predictions are highly sensitive to specific features of natural systems. One reason for this is the very complex variations of hydrodynamic and physio-chemical properties with the tidal phase. This study presents the results of two field works during which a range of flow and chemical parameters were recorded simultaneously at several locations along a small sub-tropical estuary. The studies were conducted in contrasting (wet and dry) conditions. Field measurements indicated that the hydrodynamics and water conductivity were dominated by tidal forcing and, to a lesser extent, by freshwater inputs. There were generally significantly greater differences between longitudinal sites than between vertical depths, although some marked differences were observed between the upper and lower estuarine zones. The comparative results between wet and dry field studies illustrated some marked stratification in wet weather along the whole of the estuary, implying that the surface samples were not representative of the average water column properties. Overall, the complexity of the hydrodynamics and water quality has some impact on water quality modelling of the system.

1. INTRODUCTION

While there is some knowledge of the mixing of matter in rivers, understanding of estuarine processes remains limited despite relevant applications including sediment transport, smothering of seagrass and coral, release of organic and nutrient-rich wastewater into ecosystems (including from treated sewage effluent), toxicant release and fate within the environment, and stormwater runoff during flood events.[1,2] It is acknowledged that mixing in natural waterways is a turbulent process, but predictions of contaminant dispersion in estuaries are highly sensitive to specific features of the natural system and must rely on exhaustive field data for accurate calibration and validation.[3,4] One reason for the minimal coverage of this problem in the literature is the very complex variations of hydrodynamic and physio-chemical properties with tidal phase.

Two series of field investigations were conducted in a small sub-tropical estuary in eastern Australia (Fig. 1) where water quality and ecology have been closely monitored for over 30 years.[5–7] The purpose of the field works was to record a range of flow and chemical parameters simultaneously and to gain some understanding of the interactions between tidal flows and physio-chemistry over a 12 h period, including the effects of sampling location and timing on the physio-chemistry. This was achieved by sampling simultaneously at several locations using comparable instrumentation. The results provide a better understanding of spatial variations in estuarine water properties, while the experience highlights important issues and practical considerations for water quality monitoring in a small estuary.

2. STUDY LOCATION AND FIELD INVESTIGATIONS

The experimental programme was focused on two series of field measurements in a small sub-tropical estuary. Eprapah Creek (long. 153·30°, lat. –27·567°) is a small stream located close to Brisbane city in Queensland, Australia. It is 12·6 km long with about 3·8 km of estuarine zone (Fig. 1) and the creek flows directly into Moreton Bay at Victoria Point. The catchment (area ~39 km^2) is mostly urban in the lower reaches and semi-rural to rural-residential in the upper reaches. The average annual rainfall in the catchment was 1284 mm over the last 50 years, with a maximum recorded daily rainfall of 241 mm and maximum monthly rainfall of 910 mm. The furthest upstream extent of the estuary is 3·5–3·8 km from the river mouth depending on tide conditions; this corresponds to sites 3B to 4 in Fig. 1. In the estuarine zone, the water depth is on average about 1–2 m mid-stream, the width is about 20–30 m and the tides are semi-diurnal with a typical range of about 1·5–2·5 m.

The estuary zone includes several conservation areas for wildlife. For example, sun fish, koalas, swamp wallabies, sea eagles and other wildlife were seen during each field study. The estuary also includes boat yards and a major sewage plant discharge[8,9] (Fig. 1). The plant discharged treated wastewater to the estuary at 2·7 km adopted middle thread distance (AMTD) on a continuous basis. The plant involved secondary-level treatment with chlorine disinfection. Typical daily flows were 5–7 Ml per day. The effluent conductivity was below 5 mS/cm and the outflow had a common diurnal fluctuation with peak flows/loads in the early morning and evening (personal communication with Jeff Bailey, treatment plant manager).

Field works took place on two different days with similar tidal conditions in autumn and spring (Table 1). During each investigation, a number of hydrodynamic and physio-chemical parameters were recorded simultaneously at several longitudinal locations for a 12 h period. The same measurement technique,

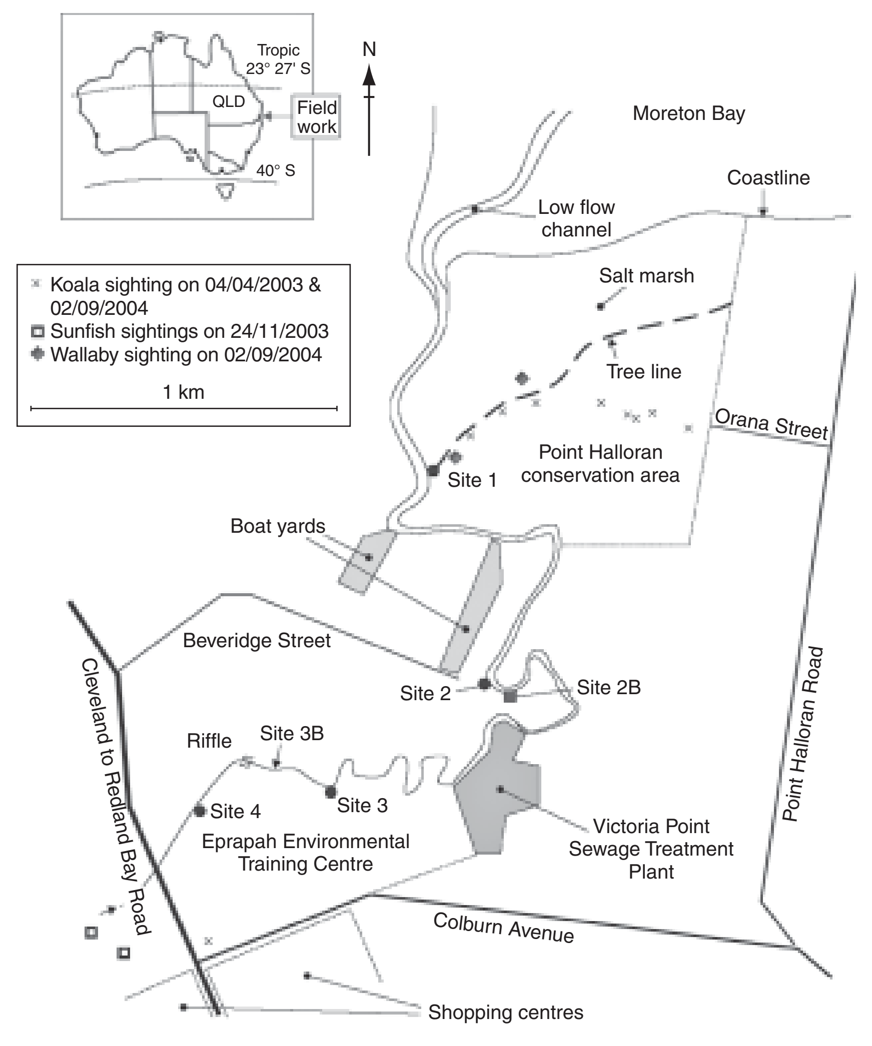

Fig. 1. Map of Eprapah Creek estuary. Circles represent surface sampling sites conducted from the bank; the square is instantaneous physio-chemical measurement site (YSI6600 probe)

instrumentation and sites were used in both studies. There was, however, a major difference between the two studies. On 4 April 2003 (study 1), some freshwater runoff was observed in the morning following a short but intense storm on the previous evening. On 2 September 2004 (study 2), the data were affected by an ongoing drought; rainfall of less than 40 mm over the previous four months (May–August 2004) was recorded, compared with an average of 322 mm for the same period over the past 50 years.

2.1. Sampling sites and measurement techniques

Measurements were conducted at several sampling sites located in conservation zones (Table 2, Figs 1 and 2). Table 2 lists all the sampling sites; their locations are shown in Fig. 1 where circles represent surface sampling and the square represents self-logging probes. At several sites (sites 1, 2, 3 and 4), surface sampling was performed simultaneously from the banks between 6:00 and 18:00 (Table 2). Measurements taken included surface velocity, air and water temperatures, pH, turbidity (Secchi disk) and dissolved oxygen (DO). Temperatures were measured with an alcohol thermometer. The water conductivity was recorded using an Oakton ECTest High+ Thermometer/conductivity meter. pH measurements were conducted with Macherey–Nagel pH paper. The DO content was measured with a Hach test kit using a modified Winkler method. Readings were taken every 15 to 30 min. The full data set of the first study is reported by Chanson *et al.*[7]

During both studies, the maximum extent of the tides corresponded to site 3B. Site 4 was a freshwater system that is only subjected to some saltwater intrusion once or twice per

	Date	Tides*		Air temp.: °C†	Water temp. °C†	Conductivity: mS/cm†	DO: mg/l†	pH†	Turbidity: m (Secchi)†	Remarks
		Time	Height: m							
Study 1	4 Apr 2003	05:16 11:03 17:24 23:31	0·67 2·22 0·57 2·41	22·2	23·5	29·6	4·3	6·7	0·7	Short intense rainstorm on 3 April 2003
Study 2	2 Sept 2004	06:02 11:52 18:02 23:59	0·40 2·21 0·56 2·29	17·4	17·14	49·1	5·5	6·7	0·6	After a six-month drought

*Height above lowest astronomical tide at the river mouth
†Average reading measured mid-estuary between 06:00 and 18:00

Table 1. Field study conditions at Eprapah Creek in 2003 and 2004

Site	AMTD: km*	Primary sampling technique	Remarks
1	1·0	Surface sampling (from right bank)	From 06:00 to 18:00 every 15–30 min
2	2·0	Surface sampling (from left bank)	From 06:00 to 18:00 every 15–30 min
2B	2·1	Continuous sampling every 5 s, 0·5 m below surface, 14·2 m from left bank Continuous sampling every 3 s, 0·06 m above bed, 10·8 m from left bank	On 04/04/2003 from 10:00 to 14:00 On 02/09/2004 from 7:30 to 18:00
3	3·1	Surface sampling (from right bank)	From 06:00 to 18:00 every 15–30 min
4	3·9	Surface sampling (from right bank)	Freshwater site; sampled on 04/04/2003 only from 06:00 to 18:00 every 15–30 min

*AMTD: adopted middle thread distance measured upstream from river mouth and positive upstream

Table 2. Summary of sampling sites and techniques

year during the largest spring tides. In the second study, surface sampling was restricted to sites 1, 2 and 3.

In addition, a number of vertical profiles of physio-chemical parameters were obtained from a boat several times at each site. These were performed using a YSI physio-chemical probe lowered from a boat drifting with the flow; measurements of temperature, pH, conductivity, DO content and turbidity were performed every 20 to 50 cm after waiting at least 2 min for each parameter to stabilise (longer times were required at the

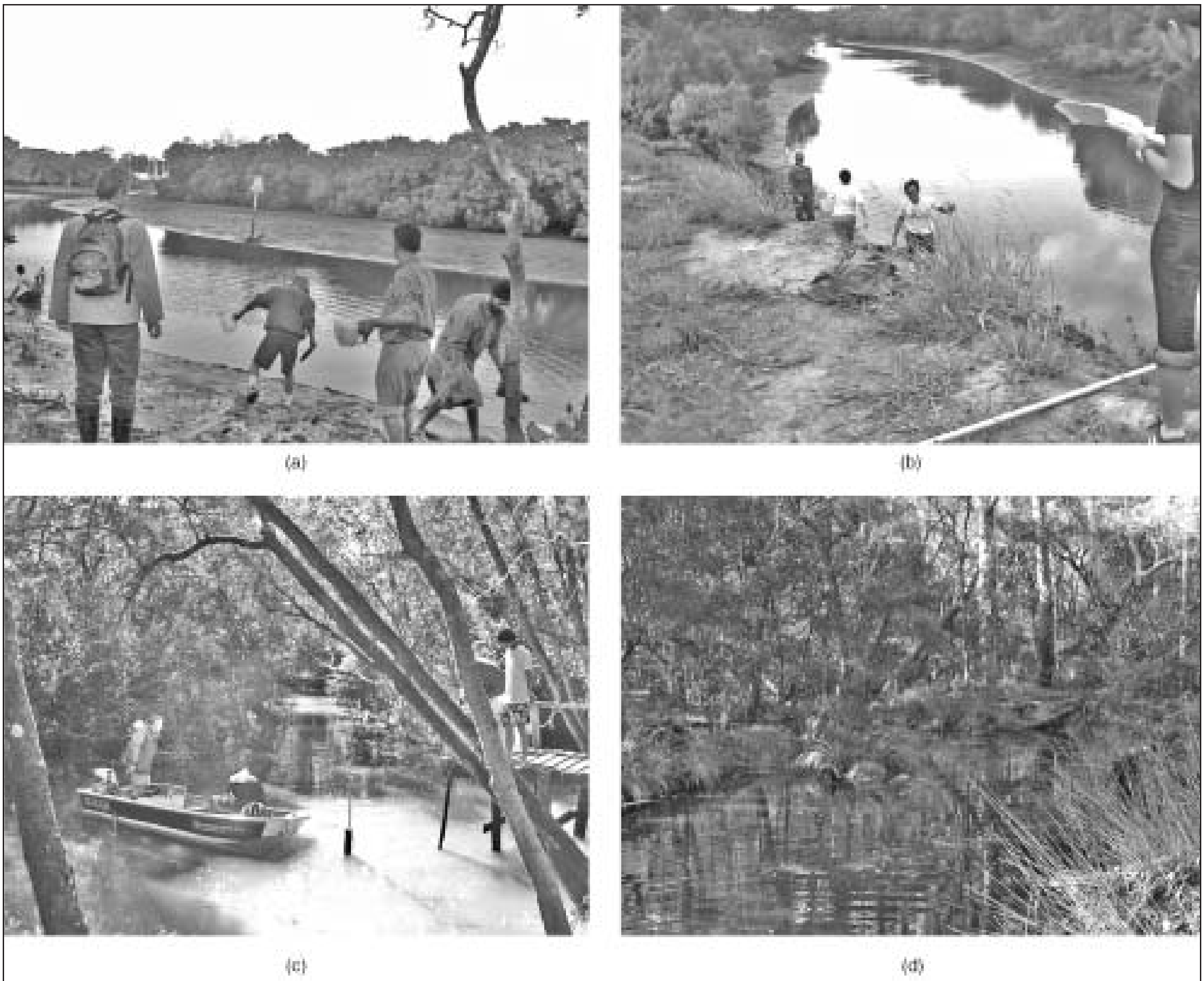

Fig. 2. Surface sampling sites. (a) Site 1 on 2 September 2004 (study 2) at sunrise and low tide, looking upstream with marinas in background. (b) Site 2 on 4 April 2003 (study 1) looking downstream, early mid-morning (courtesy of CIVL4140 Group 2, 2003/1). (c) Site 3 on 2 September 2004 (study 2) around 09:30 during end of flood tide; students interacting with EPA scientific officers conducting a vertical profile of physio-chemistry measurements. (d) Site 4 on 4 April 2003 (study 1) looking downstream

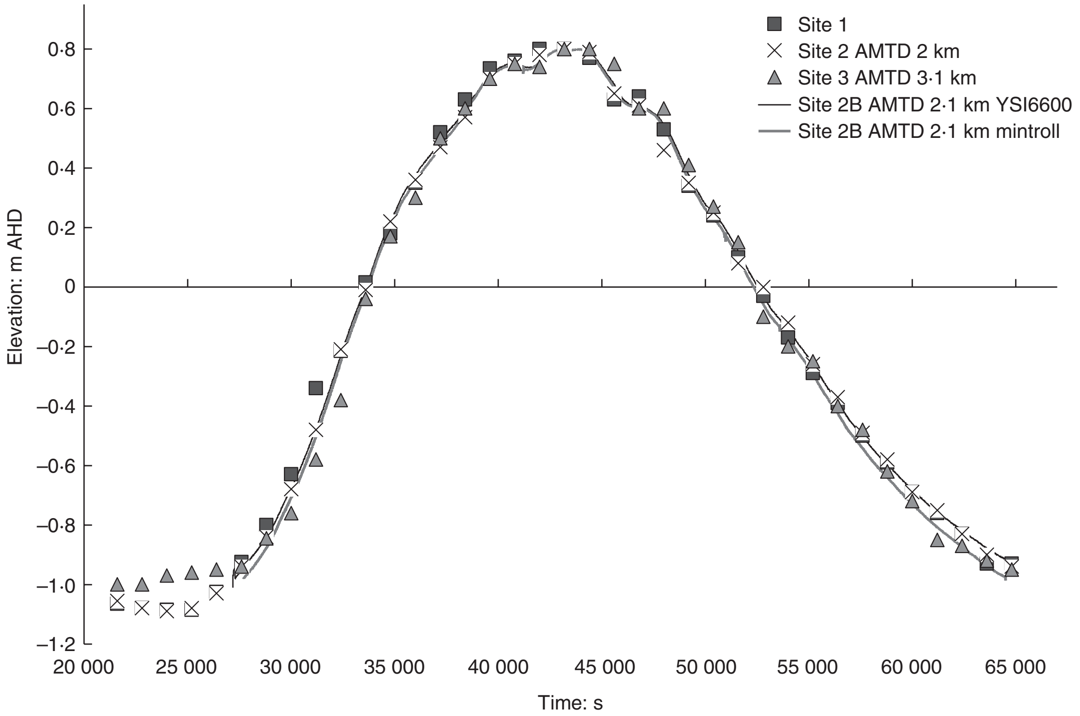

Fig. 3. Time variations in water elevations on 2 September 2004 (study 2) at four sampling sites—comparison between manual readings (sites 1, 2 and 3) and self-logging probes (YSI6600 and mini-Troll pressure gauge)

interface of the salt wedge). Most vertical profiles were performed around mid-tides and high water conditions. No measurement could be conducted at low tides in the upper estuary.

Furthermore, a YSI6600 physio-chemical probe was deployed and data-logged continuously mid-estuary at 0·2 Hz and 0·5 Hz for study 1 and study 2, respectively (Table 2). The probe was installed at site 2B, approximately in the middle of the channel in a moderate bend to the right when looking downstream. The position of the probe sensors are detailed in Table 2.

2.2. Data accuracy

Surface sampling at sites 1, 2, 3 and 4 was conducted with a data accuracy of about 1 cm for water level elevation, 0·2–0·5°C for water temperature, 1–2% for conductivity, 0·2–0·5 for pH measurement with pH paper, 5 cm for turbidity Secchi disk length, 10% for surface velocity and 5–10% on DO concentration.[7] For the vertical profiles (YSI6920 water quality probe), the accuracy was ±2% of saturation concentration for DO, ±0·5% for conductivity, ±0·15°C for temperature, ±0·2 unit for pH, ±0·02 m for depth, ±1% of reading for salinity and ±5% for turbidity. For continuous sampling (YSI6600 water quality probe), the accuracy data was ±2% of saturation concentration for DO, ±0·5% for conductivity, ±0·15°C for temperature, ±0·2 unit for pH, ±0·02 m for depth, ±1% of reading for salinity and ±5% for turbidity.

3. FIELD OBSERVATIONS

Water level observations consistently showed maxima and minima slightly after the reference high and low tides (Victoria Point). This is a typical feature of an estuarine system where information on tide reversal must travel upstream.[4,10,11] Fig. 3 shows the measured water elevations during study 2. The findings were consistent for all field studies. The water levels in the estuary were dominated by tidal forcing and the tidal effects were felt up to 3·3–3·5 km upstream of the river mouth (site 3B, Fig. 1). This is seen in Fig. 3 with little difference in water levels between all three sites (sites 1, 2 and 3). During the flood tide ($t = 30\,000–35\,000$ s), the water level rose more quickly next to the river mouth than at the upstream sites, and the time lag corresponded to about the time required for the tidal wave to propagate upstream into the estuary channel. Note that the water depth at the upstream site 3 was less than 0·5 m at low tide and the flow conditions were then affected by bottom shear. Site 4 was a freshwater system for both studies and the water level there was thus unaltered by the tide.

Water quality observations were conducted systematically from the bank, from a boat mid-stream and with some continuous recording at one site (Table 2). Figs 4–6 show time variations of several physio-chemical parameters at all sites for both field studies. The observations showed similar general trends. The data indicated an increase in water temperature near the middle of the day as surface waters were heated by the sun (Figs 4(a) and 6(a)). For comparison, Fig. 5 shows measured air and water temperatures mid-estuary (AMTD 2 km) during study 1. The flood tide also brought in some temperate waters from the Moreton Bay (Figs 4(a) and 6(a)).

The conductivity data followed the tidal cycle with an influx of saltwater during the flood flow and a reflux during the ebb. This is shown for the sampling sites 1 and 2 in Figs 4(b) and 6(b). The results suggested little difference between these two sites located 1 km apart. In the upper estuary (site 3), however, the conductivity data derived from surface sampling systematically showed some anomaly. The conductivity readings were lowest at high tide and largest at low tide, in contrast to

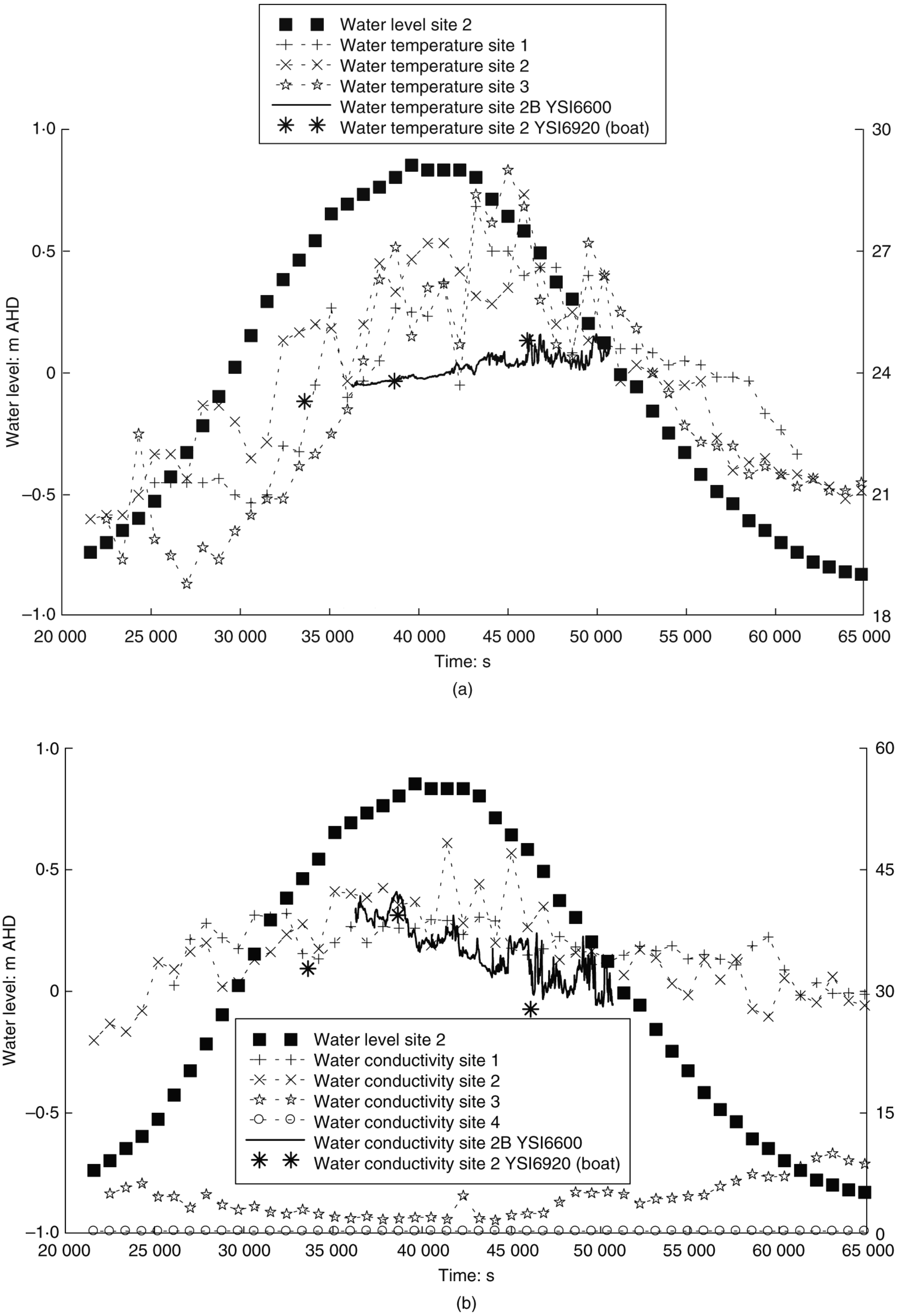

Fig. 4. Time variations in (a) water temperature and (b) water conductivity on 4 April 2003 (study 1) at five sampling sites—comparison between manual readings from the bank (sites 1, 2, 3 and 4), self-logging probe data (YSI6600 located 0·5 m below free surface, site 2B), surface measurements from a boat (YSI6920, site 2) and measured water elevations at site 2

all other sampling sites (Figs 4(b) and 6(b)). This is believed to be specific to the shallow-water upper estuary system. At low tides, the water depth was less than 0·5 m. Boundary shear induced strong vertical mixing and the physio-chemistry was quasi-homogeneous. At high tide, some stratification was observed (Fig. 7) and surface sampling recorded the properties of the freshwater lens.

Dissolved oxygen contents were maximum around high tide, and downstream waters were more oxygenated than the waters at upstream sites (Fig. 6(c)). Variations in DO were a combination of several factors, including photosynthesis, flood tide and sewage release. Generally, the present observations tend to support suggestions that the flood tide brought in waters rich in oxygen, while runoff waters, sewage effluent release and

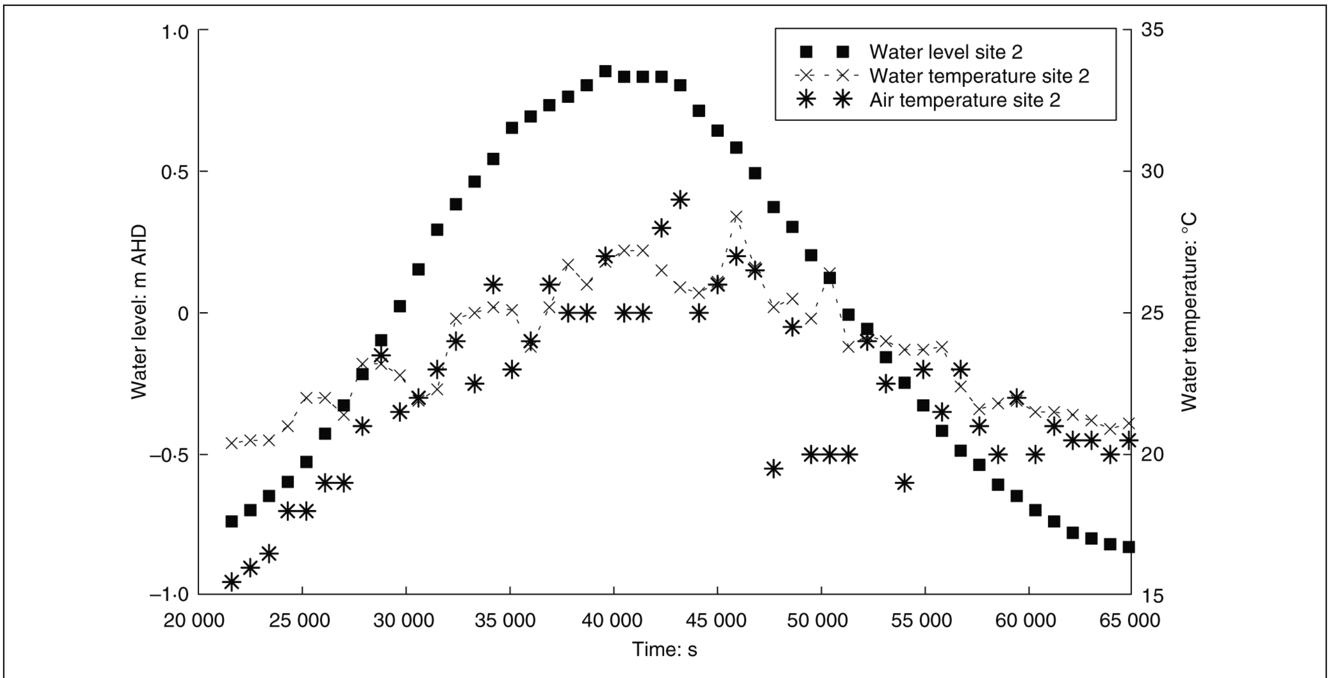

Fig. 5. Time variations in air and water temperature on 4 April 2003 (study 1), mid-estuary (site 2, manual readings from bank)

poor flushing of the upper estuarine zone yielded oxygen-starved upstream waters (e.g. Fig. 6(c), site 3, AMTD 3·1 km).

The pH data must be considered with care (Fig. 6(d)). Surface sampling from the bank was performed using pH paper—the readings may be affected by human errors including poor readability in low light periods at the start and end of each study. However, all data suggested a decrease in pH levels with increasing distance from the river mouth for both studies (Fig. 6(d)). On 4 April 2003, it is suggested that the freshwater runoff contributed to low upstream pH levels.

Turbidity data showed greater water clarity at high tide and at the beginning of ebb flow (Figs 6(e) and 6(f)). This was possibly a consequence of zero mean flow associated with lower turbulence levels during these periods that would favour sedimentation and deposition of suspended matters. Fig. 6(e) shows Secchi disk readings and Fig. 6(f) shows turbidity readings in NTU. Fig. 6(f) shows that bottom and surface readings were very close, but it should be noted that the turbidity levels in NTU were relatively low generally.

Vertical profiles showed that the distributions of water temperature, DO content, turbidity and pH were reasonably uniform at high tide and in the early ebb flow for both studies. Conductivity data showed, however, a stratification of the flow with a freshwater lens above a saltwater wedge (Fig. 7). The stratification was possibly the strongest on 4 April 2003 because of substantial freshwater runoff. Fig. 7 shows vertical distributions of conductivity at about the same tide phase during the ebb tide.

3.1. Comments

Water conductivity was mainly affected by tidal influences and freshwater inputs from the catchment and from the sewage discharge. The interpretation of the changes of other physical chemical indicators such as temperature, DO, pH and turbidity was challenging because they were influenced by other factors that cannot easily be isolated. For example, the DO concentrations were affected by oxygen-consuming bacteria in the water column and sediment, algal primary production and respiration, and oxygen transfer with the atmosphere. Nonetheless, the results provided some insight into the potential variability of these indicators between sites and within the water column.

In the present study, the results showed only relatively small differences between surface and bottom sampling during study 2 (dry weather data), despite noise in the measurements. On occasions, there was a lag time with the sampling location closer to the bottom, suggesting different movement and possibly biological processes. Furthermore, there were generally significantly greater differences between longitudinal sites than between vertical depths. The measurements were focused largely on the higher part of the tide and further work would be required to verify these conclusions over several tidal cycles and during night time conditions.

An additional unknown was the influence of the sewage effluent discharge, particularly at low tides. Further work could involve tracking the fate of the current STP effluent (e.g. tracer studies) and conducting similar studies on sub-tropical estuaries without sewage treatment discharges.

4. DISCUSSION

One aim of this work was to investigate the effect of sampling location and timing on physio-chemistry samples. This was scrutinised by simultaneous sampling at several locations using comparable, preferably identical, metrology. The results provided some indication of the effect of tide phase on sampling results for similar small sub-tropical estuaries. At Eprapah Creek, the water level was little affected by longitudinal location

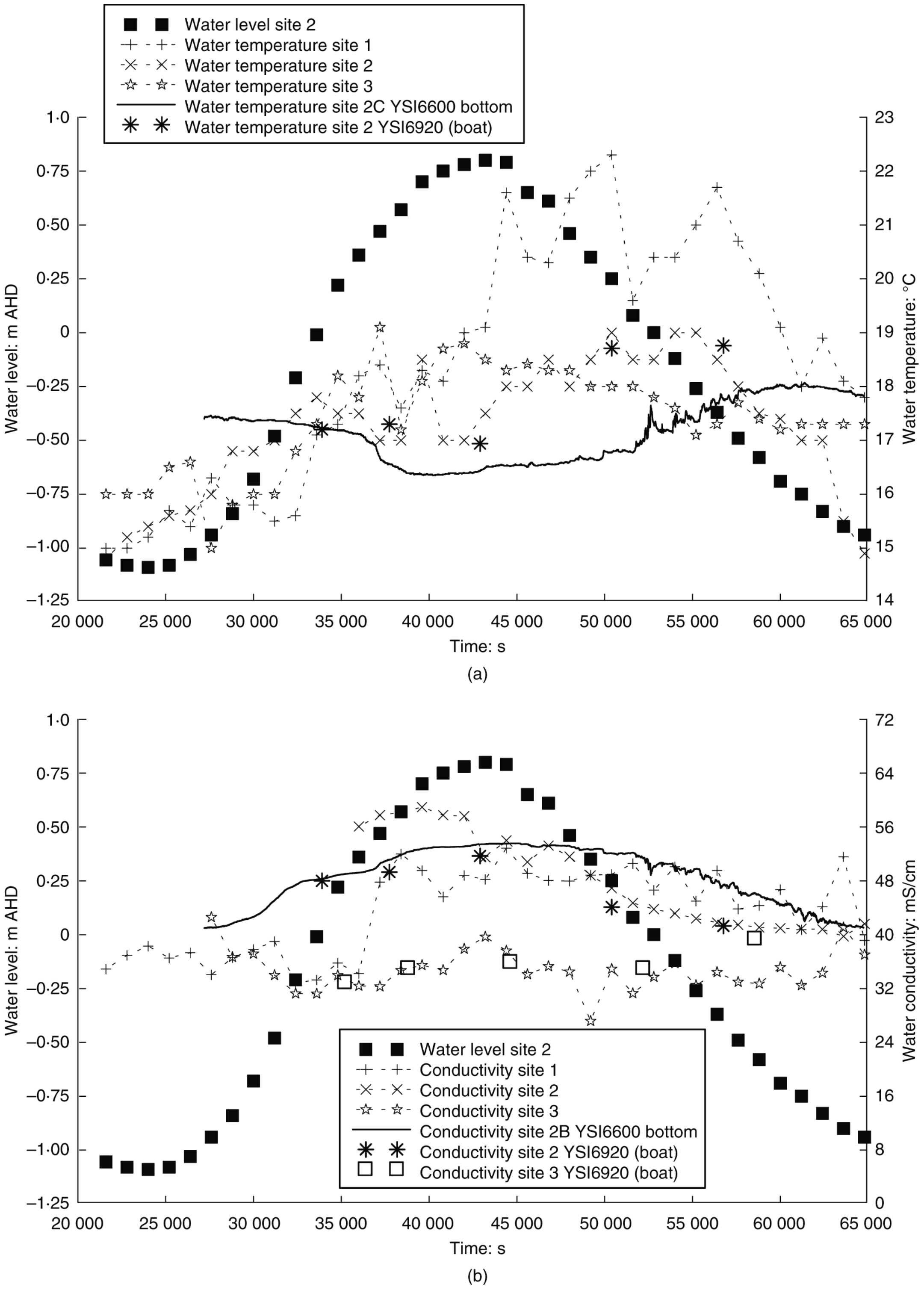

Fig. 6. Time variations in water properties on 2 September 2004 (study 2) at four sampling sites. Comparison between manual readings from the bank (sites 1, 2 and 3), self-logging probe data (YSI6600 located 0·1 m above the bed, site 2B), surface measurements from a boat (YSI6920, sites 2 and 3) and measured water elevations at site 2. (a) Water temperature, (b) water conductivity, (c) DO content, (d) pH, (e) turbidity (Secchi disk) and (f) turbidity (NTU) near the bottom (YSI6600 probe) and next to the surface (YSI6920 probe)

and sampling time. This is seen in Fig. 3 and it is relatively typical of small estuaries dominated by tidal forcing.

In terms of water temperature, some anomaly was noted during the second field study at site 1 around 13:00 and 14:30 ($t = 47\,000$ and $52\,000$ s, Fig. 6(a)). Some rapid drops in air temperature were caused by dark clouds, strong winds and brief showers. These induced a brief lowering of surface water temperature at that site (AMTD 1 km). These atmospheric events were observed first hand by one author. These isolated events emphasised the impact of climatic conditions, even brief change, on field data.

At site 3, the conductivity data derived from surface sampling showed systematically anomalous trends. The conductivity results contrasted with other sampling site data, and this is

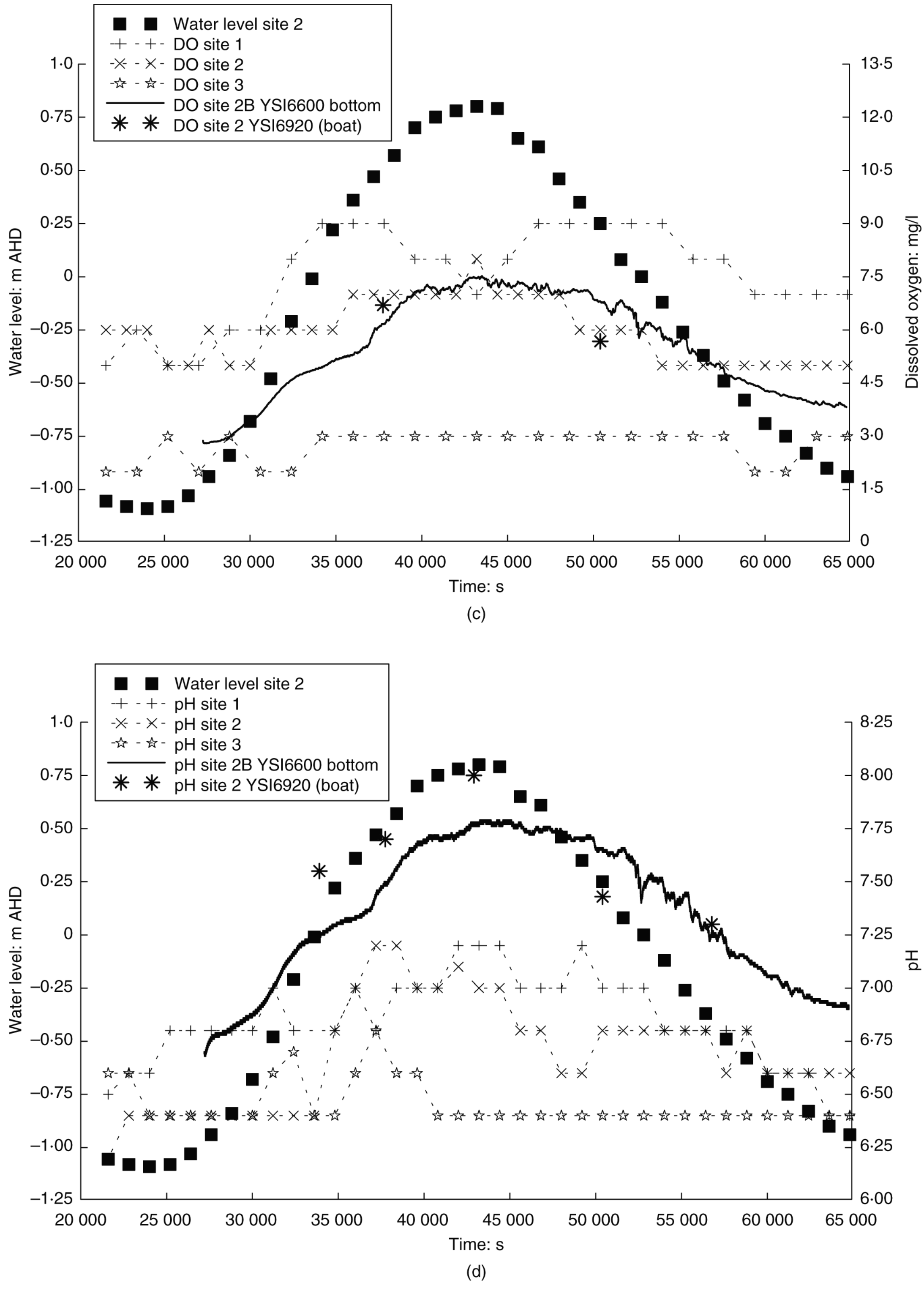

Fig. 6. Continued

believed to be typical of upstream shallow-water sites. As such, the finding had direct implications in terms of monitoring. That is, the water column of the upper estuary could be well mixed at low tides with shallow water and stratified at high tides.

4.1. Differences between the two field studies

Comparative results of the two field studies illustrated a few differences (Figs 4, 6 and 7). The second study was conducted at the start of spring, with temperatures on average cooler than those during the first study (conducted in autumn). However, the primary difference was the extreme and opposite hydrology of the catchment, that is some freshwater runoff during the first study after an overnight short but intense rainstorm and a long-lasting very dry period during the second study.

Conductivity data clearly showed the effect of freshwater runoff in the first study (Figs 4(b), 6(b), 7). This is best seen in Fig. 7, which shows readings taken about 2 h after the high tide for each study. In the upper estuary (site 3), the water conductivity was negligible during study 1 (Fig. 4(b)), while it was

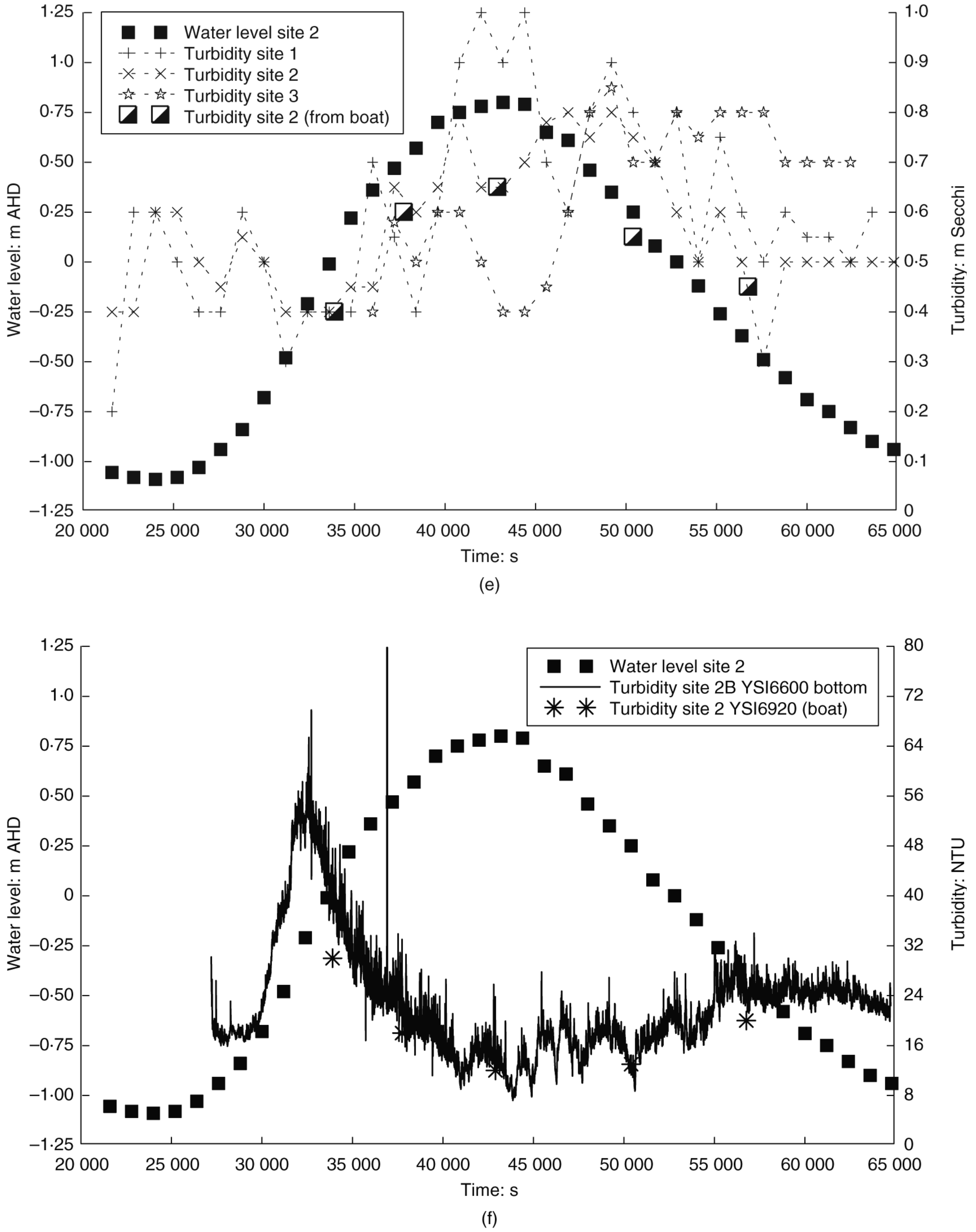

Fig. 6. Continued

systematically above 25 mS/cm during study 2. This was checked by two independent techniques—surface sampling from the bank and surface sampling from a boat (Fig. 6(b)). On 4 April 2003 (study 1), the effect of freshwater runoff was strongest in the upper estuary (AMTD ⩾ 2 km) with very low surface water conductivity readings and stronger stratification at sites 2 and 3 (Figs 4(b) and 7(a)). During the second study, stratification was weaker mid-estuary (site 2) and nil at the downstream site (site 1).

The dry weather results (Fig. 7(b)) showed some measurable difference in conductivity across the depth. Greater effects were seen at the upstream sites (a difference of 10 mS/cm). The downstream site showed a relatively uniform profile. In comparison, the wet weather profiles (study 2) showed greater differences in conductivity across the depth and hence stratification. The upper sites were most strongly influenced by the catchment runoff and the data showed conductivities closer to freshwater at the surface. Below 1·0 m depth, the conductivity levels for all three sites were more uniform with depth and closer to the conductivity of seawater. These results suggest that this estuary—in both dry and wet conditions—is strongly influenced by freshwater inputs that resulted in relatively poor vertical mixing. The influence of freshwater runoff was seen mostly in the surface layers, particularly in the upper 1 m of the water column in the upper and mid-estuary (sites 2, 3B and 3).

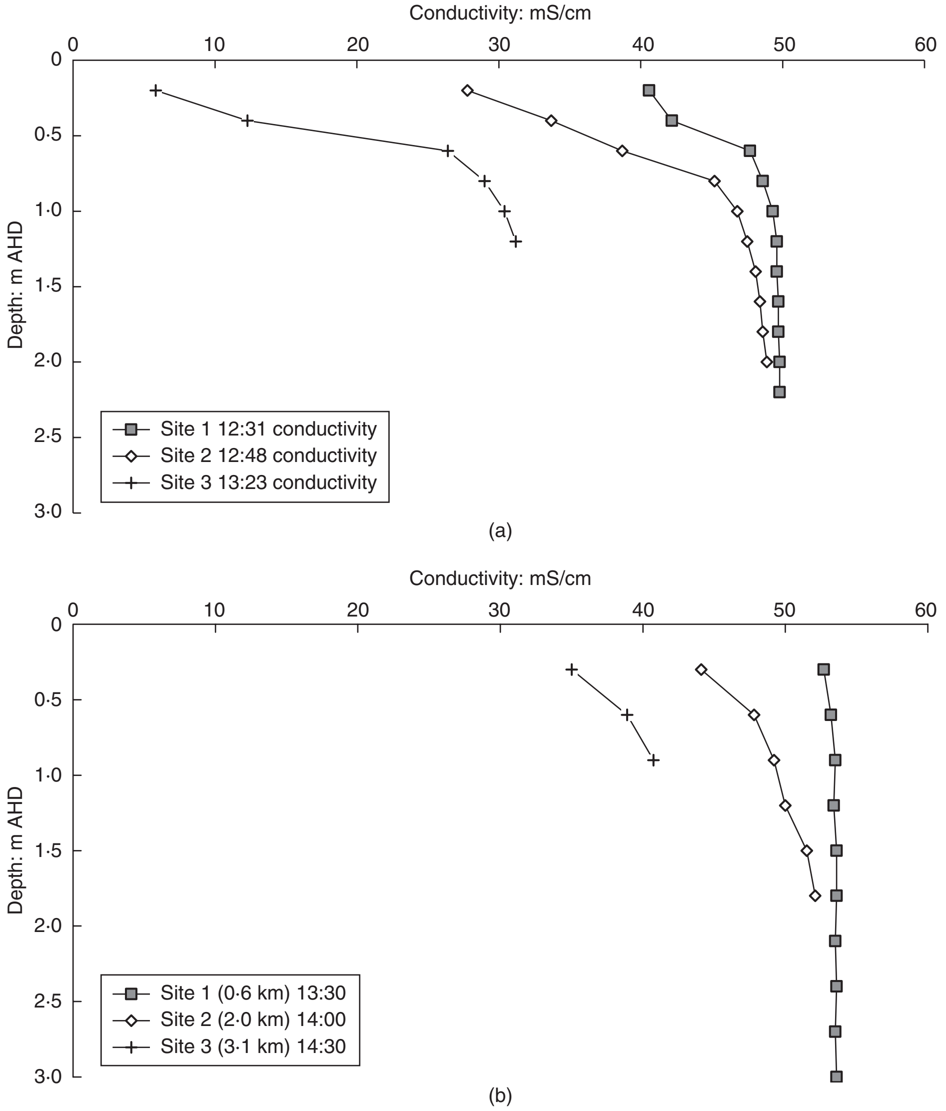

Fig. 7. Vertical profiles of water conductivity during the ebb tide: (a) 4 April 2003 (study 1); (b) 2 September 2004 (study 2)

Continuous monitoring data suggested that the differences were small in dry weather. Little comparison was available for wet weather, where the effects are likely to be much more significant.

4.2. Implication for long-term monitoring

Most ambient water quality monitoring programmes involve sample collection just below the surface (within the top 0·3 m). The results of this study show that surface measurements may not be representative of the whole vertical profile of an estuary in either dry or wet periods. The adequacy of surface sampling would depend on sampling location along the estuary. In dry weather, the estuary is better mixed, particularly at lower sites. During wet weather, surface sampling may result in the sampling of catchment runoff rather than the condition of the estuary. If the purpose of monitoring is an assessment of ecological health, it could be argued that measurements should focus on locations where organisms live—this could be part or all of the water column. Ideally, multiple samples should be taken across the profile when the system is not homogenous, although this would significantly increase the costs of such monitoring programmes. If a single sample is taken, the current information tends to suggest that measurements at a depth of around 1 m or half of the water column depth may provide a more representative sampling depth location for a small sub-tropical estuary.

A further challenge of water quality monitoring is obtaining a representative 'snap shot' of the estuary despite changing tidal conditions during sampling and the time required to relocate (often taking 30–60 min per vertical profile). One approach may consist of using some specific vertical elevation(s) as a representative marker of tidal effects during sampling. If a relationship could be developed between some elevation and the influences on the indicators (e.g. conductivity), the results could be adjusted to gain a better picture of water quality at a single point in time.

Another important influence on estuary water quality appeared to be the freshwater inputs on mixing. The effects of catchment runoff (or rainfall) should be considered when designing and implementing monitoring programmes. A quantification of these effects at Eprapah Creek would involve further work and tracer studies; some numerical modelling might also assist.

The effect of shallow-water areas appears to be an important issue in smaller estuaries, having a potentially significant effect. The results also suggested that variability (short term) caused by sample locations close to shore could be significant. It is likely that sampling in the centre of the stream would be preferable (e.g. from a boat).

4.3. Implications for modelling

The results of this study have a number of implications for water quality modelling of small estuary systems. The hydrodynamics must consider the typically poor vertical mixing in such systems. The use of one-dimensional depth- and width-averaged models would seem inappropriate, particularly if calibrated and validated with surface-based water quality samples. A two-dimensional width-averaged model would more likely simulate the vertical profiles but would require significant water quality data across the vertical profile of the system to validate its reliability.

However, the ability of a numerical model to simulate upper estuary processes is doubtful given the observed anomalies. Continuous monitoring of catchment inputs (e.g. STP flows, surface runoff) would be required at the same frequency as the model simulation steps. The practicalities and costs of measurements may mean that this is not possible.

5. SUMMARY

This study presents the results of two field works during which a range of flow and chemical parameters were recorded simultaneously at several locations along a small sub-tropical estuary. The work was focused on an understanding of the interactions between tidal flows and physio-chemistry for 12 h periods. The two studies were conducted in contrasting conditions: wet and dry.

The field measurements indicated that hydrodynamics and water conductivity were dominated by tidal forcing and, to a lesser extent, by freshwater runoff. There were generally significantly greater differences between longitudinal sites than between vertical depths. Some marked differences were, however, observed between the upper and lower estuarine zones. In the upper estuary, the water depths were shallow at low tides (less than 0·5 m). The boundary shear induced some strong vertical mixing and the water column was well mixed at low tides, although some stratification was observed at high tides.

Comparative results between wet and dry field studies illustrated some key differences. In the wet weather (study 1), some marked stratification was observed along the whole estuary. The surface samples were not representative of the average water column properties. The vertical profiles suggested that samples taken at about mid-depth were a better proxy of the entire column.

The complexity of the hydrodynamics and water quality of the estuarine zone has some impact on the water quality modelling of the system. Clearly, one-dimensional or even two-dimensional models are unlikely to simulate upper estuary processes. The experience of this work has highlighted some important issues and practical considerations for water quality monitoring in a small estuary.

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