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Preliminary Measurements of Turbulence and Environmental Parameters in a Sub-Tropical Estuary of Eastern Australia

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Abstract. In natural systems, mixing is driven by turbulence, but current knowledge is limited in estuarine zones where predictions of contaminant dispersion are often inaccurate. A series of detailed field studies was conducted in a small sub-tropical creek in eastern Australia. Hydrodynamic, physio-chemical and ecological measurements were conducted simultaneously to assess the complexity of the estuarine zone, notably the interactions between turbulence and environment. The measurements were typically performed at high frequency over a tidal cycle. The results provide an original data set to complement long-term monitoring and a basis for a more detailed study of mixing in sub-tropical systems. Unlike many long-term observations, velocity and water quality scalars were measured herein with sufficient spatial and temporal resolutions to determine quantities of interest in the study of turbulence, while ecological indicators were sampled systematically and simultaneously. In particular the results yielded contrasted outcomes, and the finding impacts on the selection process for key water quality indicators.

Key words: ecology, estuary, field experience, tropical stream, turbulence, water quality

1. Introduction

Mixing and dispersion of matter is of considerable importance in estuaries. Applications encompass 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

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environment, and storm-water runoff during flood events. Current knowledge is limited: e.g., the vertical mixing coefficient is often approximated by the depth-averaged momentum exchange coefficient, while transverse mixing and dispersion coefficients are assumed constant over relatively long distances. Both sets of assumptions are questionable. Predictions of contaminant dispersion in estuaries are therefore based upon empirical mixing coefficients that are highly sensitive to the natural system and must be measured in-situ. Experimental findings of mixing coefficients are however accurate only “within a factor of 10” at best and they can rarely be applied to another system [1–3]. Although mixing is driven by turbulence, the interactions between hydrodynamics, water quality and ecology are rarely considered together. There has been some research into pollutant dispersion in individual river catchments, but very little systematic research has been done on turbulent mixing in natural estuarine systems, in particular in sub-tropical zones. One reason for the minimal attention to this problem in the literature is the very complex behaviour of an estuary.

A series of multi-disciplinary field studies were conducted in the estuarine zone of Eprapah Creek, in eastern Australia. The purpose of field works was to undertake an initial assessment of the complexity of a small estuarine system, and the interactions between hydraulic engineering, physio-chemistry and ecology. The results provide new insights into basic mixing processes in sub-tropical estuaries. The experience highlights important issues and practical considerations for further studies.

1.1. CASE STUDY: EPRAPAH CREEK

Eprapah Creek (Longitude 153.30°East, Latitude –27.567°South) is a subtropical stream located in the Redlands Shire close to Brisbane City. Average hydrological conditions are listed in Table I for a 50-year period. Eprapah Creek flows directly to the Moreton Bay at Victoria Point (Figure 1). It is basically 12.6 km long with about 3.8 km of estuarine zone. In the latter, the water depth is typically about 1–2 m mid-stream, the width is about 20–30 m and the tides are semi-diurnal with a range of about 2 m. The catchment ($\sim 39\,\text{km}^2$ area) is mostly urban in the lower reaches and semi-rural/rural residential in the upper reaches. It includes several conservation areas hosting endangered species: e.g., koalas, swamp wallabies, sea eagles.

Water quality and ecology have been closely monitored at Eprapah Creek (Victoria Point QLD) over 30 years by Redland Shire Council, Queensland Environmental Protection Agency (EPA) and local community groups (e.g. [4]). The creek was heavily polluted in 1998 by illegal

Table I. Average hydrological conditions at Redlands station (Long.: 153.250°E, Lat. -27.528°S) for the period 1953–2003 (Reference: Australian Bureau of Meteorology) – Eprapah Creek catchment is located less than 10 km from the Redland meteorological station.

Parameters	Value	Units
Air temperature at 09:00	20.5	°C
Average humidity at 09:00	67	%
Average wind speed at 09:00	8.6	km/h
Average yearly rainfall	1284.3	mm
Maximum monthly rainfall	909.7	mm
Maximum daily rainfall	241.0	mm
Average number of rainy days	116	days/year
Average sunny days	81	days/year
Average number of overcast days	60	days/year

discharges of tributyl-tin (TBT) and chemical residues. Although the estuarine zone includes two environmental parks, there are some marinas and boat yards, and a major sewage plant discharge that affect the natural system [5] (Figure 1). The upstream catchment has been adversely affected by large-scale poultry farms, wineries, land clearance and semi-urban development. Recent works included the constructions of new shopping centres and residential lots less than 500 m from the estuary in 2003–2004.

2. Experimental Methods

The experimental programme was focused on a series of field measurements in this small, but simple sub-tropical estuary system (Figures 1 and 2). During the field investigations, a number of hydrodynamic, physio-chemical and ecological indicators were recorded simultaneously at high-frequency. In all field works, instantaneous velocity and physio-chemical data were measured continuously mid-estuary. In the first three studies, the sampling volumes were located 0.5 m below the free-surface to characterise the properties of the upper flow layers. During the fourth investigations, the sampling volume was located 5.2 cm above the bed in the deep channel section. During the first and fourth field works, physio-chemical and ecological data were further recorded simultaneous at 4 and 3 sites respectively along the estuary.

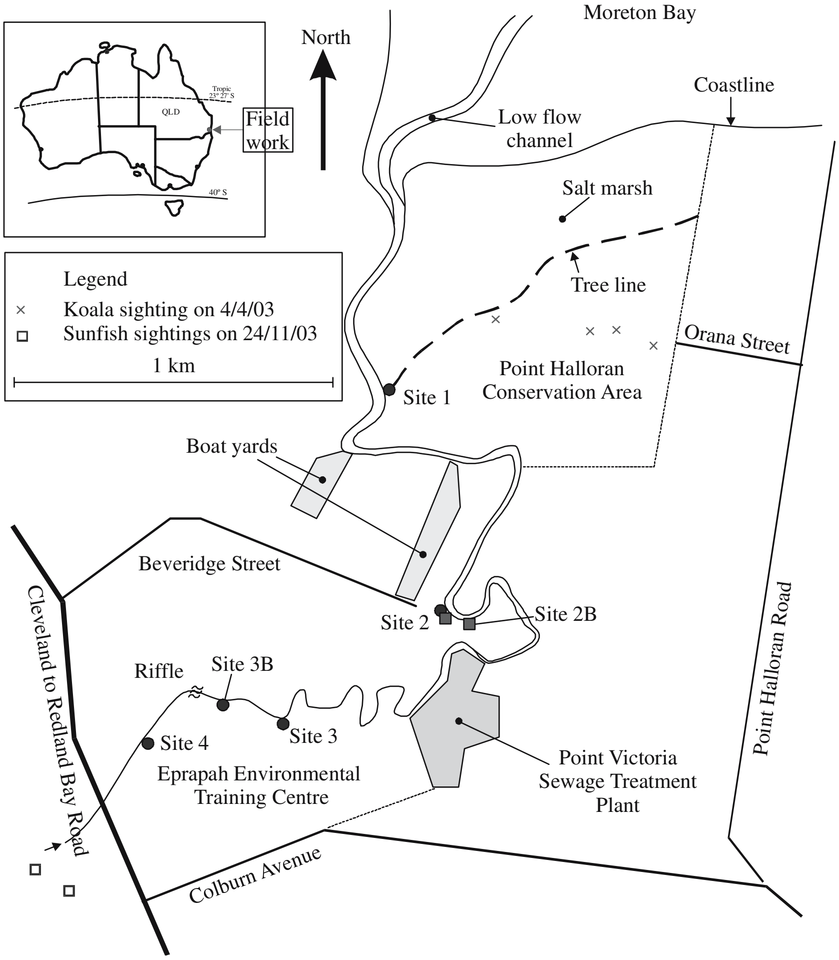

Figure 1. Map of Eprapah Creek estuarine zone. Blue circle: water quality and fish sampling station. Red square: instantaneous velocity and water quality measurement site.

2.1. PRESENTATION

Field works took place on four different days (Table II). They involved more than 80 people, including researchers, students, professionals and local community groups for a single-day each time. Tidal and weather conditions are summarised in Table II. Typical sampling locations included Sites 1, 2, 2B, 3, 3B and 4 (Figures 1 and 2) located respectively at AMTD 0.6, 2, 2.1, 3.1, 3.5 and 3.8 km, where AMTD is the Adopted Middle Thread Distance: i.e., the upstream distance from river mouth. Sites 1, 2, 3, 3B and 4 are marked with a blue circle on Figure 1. Hydraulic, physio-chemical and ecological data were recorded from the bank: e.g.,

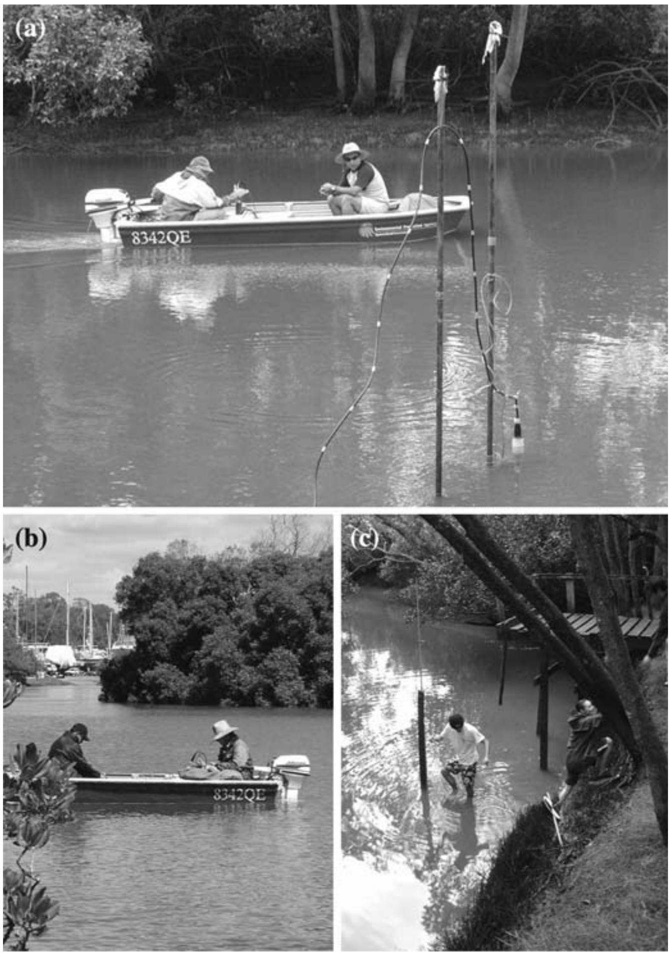

Figure 2. Photographs of field investigations in Eprapah Creek estuary. (a) ADV and YSI6600 probes at Site 2B on 24 November 2003, looking from the left bank. The ADV velocimeter (yellow casing) and YSI6600 probe were held outside of the poles seen in foreground; (b) Site 1 on 2 September 2004 at 12:00 noon (high tide), view from the left bank looking upstream during YSI6920 probe measurements from the boat. Note the boat yard in the background; (c) Site 3 on 2 September 2004 at 06:45 (low tide), looking downstream; (d) Site 3 on 2 September 2004 at 09:30 (flood tide), looking downstream.

water elevations, surface velocity, air and water temperatures, conductivity, pH, dissolved oxygen, turbidity, fish sampling. Most readings were taken every 15–30 min, while bird watching was continuous. Fish sampling was conducted using small bait traps and dip nets designed to catch native fish species (typically less than 10 cm in length). The sampling procedure was developed jointly by the University of Queensland, Waterwatch

Figure 2. Continued.

Queensland, Greening Australia Queensland and Brisbane City Council, and it has been applied throughout the state of Queensland.

Vertical profiles of physio-chemical parameters were conducted in the middle of the creek at several sites. They were performed at high tide and during ebb flow using a water quality probe YSI^{TM}6920 lowered from a boat drifting with the flow (e.g. Figure 2b). Measurements of water temperature, conductivity pH, conductivity, dissolved oxygen content and turbidity were performed every 20–50 cm.

At one site, mid-estuary, a Sontek^{TM} acoustic Doppler velocimeter (ADV) and a water quality probe YSI^{TM}6600 were deployed and data-logged at high-frequency continuously (Table II). The probes were located at Site 2 on 17 July 2003, and Site 2B on 4 April and 24 November 2003, and 2 September 2004. They were installed about the middle of the main channel in a moderate bend to the right when looking downstream (Figure 2). The ADV and YSI6600 probe sensors were positioned 300 mm apart in the same horizontal plane and held by a metallic frame sliding on two poles. The probes were installed outside of the support system to limit the wake effects of the support (Figure 2a). Further details on the experimental procedures are available in Chanson *et al.* [6].

2.2. DATA ACCURACY

For measurements from the bank, the data accuracy was about 1 cm for water level elevation, 0.2–0.5 °C for water temperature, 1–2% for conduc-

Table II. Summary of field conditions and measurements in mid-estuary (Site 2, AMTD 2 km).

	4 April 2003	17 July 2003	24 November 2003	2 September 2004
Tides (Victoria Point)	05:16 (0.67 m) 11:03 (2.22 m) 17:24 (0.57 m) 23:31 (2.41 m)	00:00 (2:63 m) 06:44 (0.60 m) 12:19 (1.92 m) 18:01 (0.59 m)	03:27 (0.21 m) 09:50 (2.74 m) 16:29 (0.46 m) 21:53 (2.11 m)	06:02 (0.40 m) 11:52 (2.21 m) 18:02 (0.56 m) 11:59 (2.29 m)
Study period	06:00–18:00	06:00–14:05	07:00–16:00	06:00–18:00
ADV/YSI6600 record period	10:10–14:05	06:10–14:05	09:18–15:55	07:50–18:00
ADV/YSI6600 sampling volume location	0.5 m beneath free-surface 14.2 m from left bank	0.5 m beneath free-surface 8.0 m from left bank	0.5 m beneath free-surface 10.8 m from left bank	0.0525 m above bed 10.8 m from left bank
Sampling frequencies ADV/YSI6600	25 Hz/0.2 Hz	25 Hz/0.2 Hz	25 Hz/0.5 Hz	25 Hz/0.33 Hz
Sunrise/Sunset times	05:58/17:42	06:36/17:10	04:44/18:22	06:00/17:35
Weather	Sunny (Small storm on 3 April 03 evening)	Overcast	Overcast with few showers	Overcast with few drops (Drought period)

tivity, 0.2–0.5 for pH measurement with pH paper, 5 cm on turbidity Secchi disk length, 10% on the surface velocity and 5–10% on the dissolved oxygen concentration. With the water quality probes YSI6920 and YSI6600, the data accuracy was ±2% of saturation concentration for dissolved oxygen (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. No information was available on the data accuracy on chlorophyll concentrations.

The error on the instantaneous velocity component was 1% of the measurement range according to the manufacturer. That is, between 0.01 and 0.003 m/s for the velocity ranges used.

2.3. PRACTICAL CONSIDERATIONS

During the first two field studies, a few data samples were not recorded by the YSI6600 probe once every 5 min when the turbidity sensor wiper cleaned the lens. The problem was not critical and did not affect the data accuracy and timing. The problem was resolved in the last field study when data were recorded every 2 s.

Present experience demonstrated recurrent problems with the ADV velocimeter evidenced by high levels of noise and spikes in the three velocity components. In the stream, the velocity fluctuations characterise the combined effects of the Doppler noise, installation vibrations and turbulent velocity fluctuations. Several researchers discussed the inherent noise of an ADV system (e.g. [7, 8]). Spikes may be caused by aliasing of the Doppler signal, and some techniques were proposed to eliminate these [9, 10]. Herein the ADV velocity data were cleaned by removing communication errors, low signal-to-noise ratio data (< 5 dB) and low correlation samples ($<70\%$), and they were "despiked" using a acceleration thresholding method. Yet, during periods of low velocity, the ADV Doppler noise and spikes predominated causing large fluctuations in velocity around zero. This can be observed in Figure 3 in the range 37,500–38,500 s. When the velocity direction is calculated, its fluctuations are even greater because there is no predominant flow direction as shown during the corresponding time in Figure 3. Some problem was also experienced with the vertical velocity component. The writers' experience at Eprapah Creek suggests that classical "despiking" techniques for ADV velocimeter are not sufficient and should be adapted for estuarine field investigations (e.g. [11]). Hence data errors might still exist in the present data sets.

3. Experimental Results

3.1. GENERAL OBSERVATIONS

For all studies, the tidal influence was felt up to 3.5 km upstream of the river mouth (Site 3B) but not at the most upstream site (Site 4, Figure 1), although some saltwater inflow was observed at the latter during king tide in 2002. The Site 4 was basically a freshwater system for each study. For the greatest tidal range (24 November 2003), a very-shallow water zone formed at low tide between Site 2B and the sewage plant: i.e., depth less than 0.3–0.5 m. At very low tides, this "bar" acted as a weir reducing drastically mixing between the upper and lower estuarine zones. During dry periods (e.g. 2 September 2004), the "bar" prevented exchange flows at low tide and early ebb period, and limited the water renewal into the upper estuary.

Physio-chemical observations were conducted systematically from the bank, from a boat mid-stream and with continuous recording 0.5 m

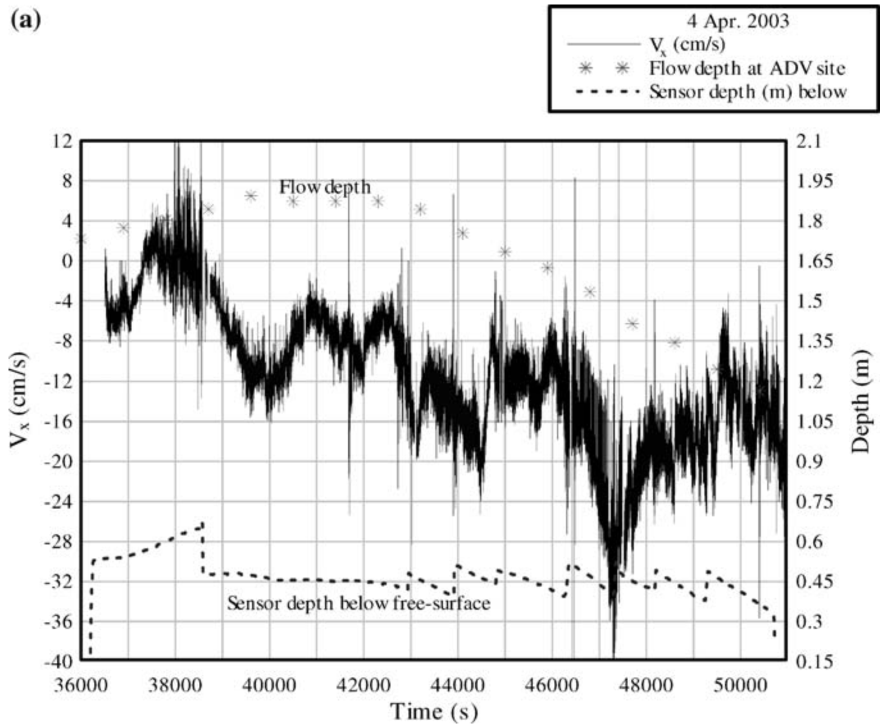

Figure 3. Instantaneous velocity and physio-chemical property fluctuations at Site 2B on 4 April 2003 during high tide and early ebb tide. The horizontal axis is the clock time in seconds with $t = 0$ at 0:00. (a) Streamwise velocity component V_x (in cm/s, positive downstream) [black solid line], measured flow depth at the probe location [red star *], and sensor depth beneath the free-surface [dashed blue line]; (b) Transverse velocity component V_y (in cm/s, positive towards the left bank) [black solid line], and dissolved oxygen DO content in percentage of saturation [solid blue line]; (c) Vertical velocity component V_z (in cm/s, positive upwards) [black solid line], salinity (ppt), temperature (Celsius) [solid blue line].

beneath the free-surface at one site. A statistical summary of basic physio-chemical results recorded at mid-estuary is presented in Table III, including median values, standard deviations, minima and maxima. Water temperature data were affected predominantly by the natural heating of the sun, and by the flood tide bringing in some temperate waters from the Moreton Bay. Dissolved oxygen (DO) measurements showed more oxygenated waters near the river mouth and maxima around high tide. Basically waters rich in dissolved oxygen were brought in by the flood tide while both freshwater runoff and treated effluents tended to be oxygen depleted. Turbidity data indicated consistently a greater water clarity at high tide and at beginning of ebb flow. Secchi disk and YSI probe turbidity data were about constant along the estuarine zone. Water conductivity data followed the tidal

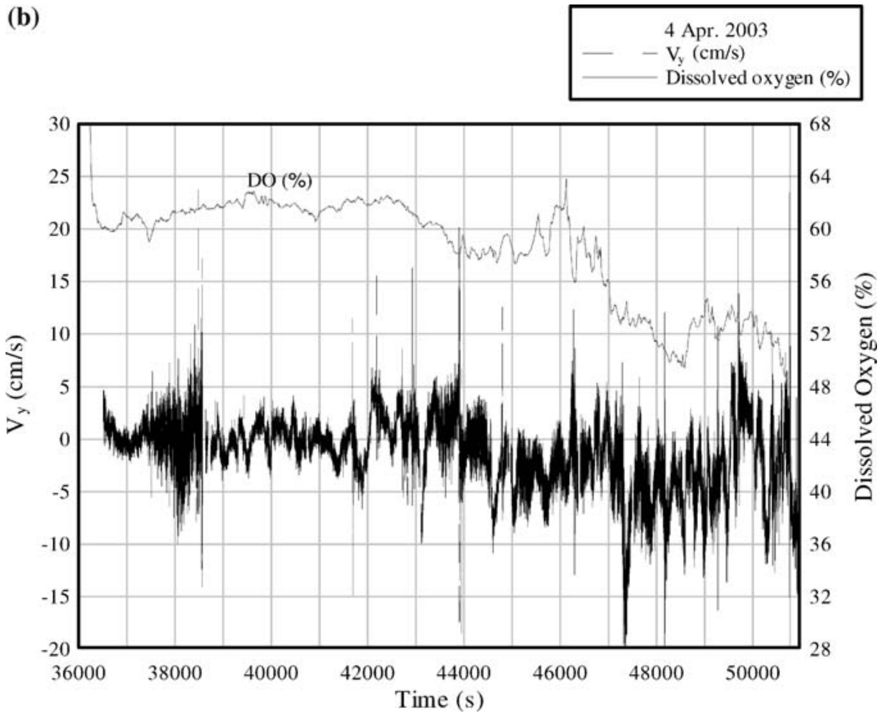

Figure 3. Continued.

cycle with an influx of saltwater during the flood flow and a reflux during the ebb in the inter-tidal zone, with an overall decrease in time-average salinity with increasing distance from the river mouth. A decrease in pH with increasing distance from the river mouth was observed consistently observed, suggesting slightly acidic waters in the upstream reach.

Vertical profiles of physio-chemical parameters showed that the distributions of water temperature, dissolved oxygen content, turbidity and pH were reasonably uniform at high tide and in the early ebb flow for all two studies. Conductivity data showed however some flow stratification with a fresh water lens above a saltwater wedge. The stratification was possibly the strongest on 4 April 2003 and caused by some freshwater runoff caused by a storm on the evening before.

3.2. SHORT-TERM FLUCTUATIONS OF VELOCITY AND PHYSIO-CHEMICAL PARAMETERS

Short-term fluctuations in velocity and physio-chemical parameters were systematically investigated mid-estuary (AMTD 2 km). Turbulent velocity records, measured with the velocimeter, suggested distinct periods: i.e., a

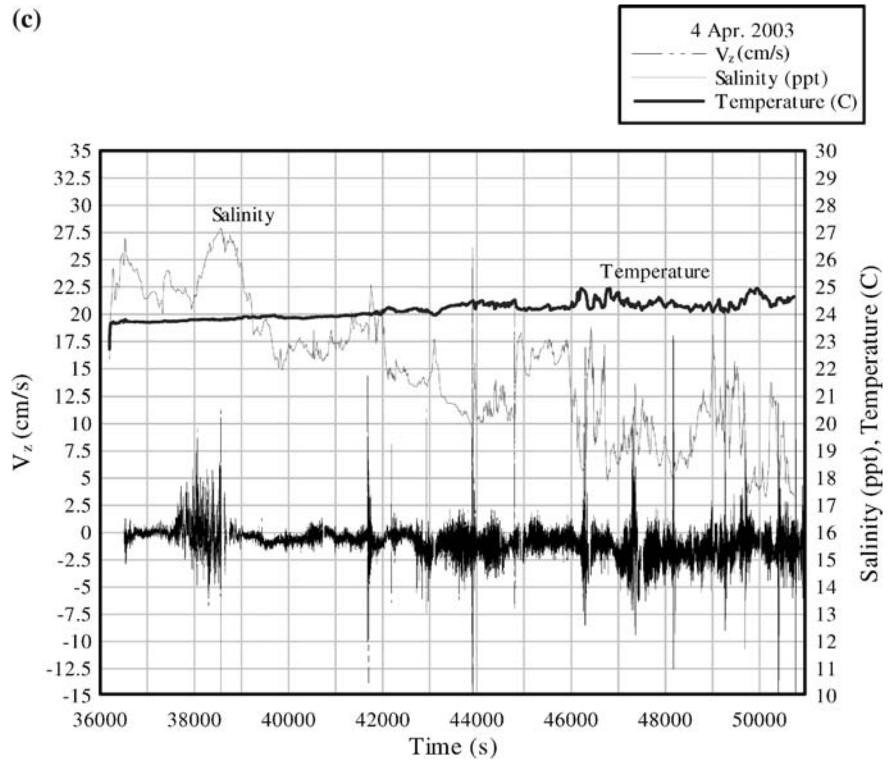

Figure 3. Continued.

slack time around high and low tides, and some strong flushing during the flood tide (17 July 2003) and ebb tides (4 April 2003, 24 November 2003 & 2 September 2004). Around high and low tides, the velocity magnitudes were small (i.e. less than 10 cm/s), and the velocity direction was highly fluctuating. The velocity magnitude increased with time after slack, and the strongest currents were observed during mid-ebb tides (4 April 2003, 24 November 2003 & 2 September 2004) with instantaneous velocities of about 0.2–0.35 m/s. Detailed records showed consistently significant time fluctuations of both velocity magnitude and direction, with fluctuations in instantaneous velocity directions of typically 20–30°. Instantaneous water quality results showed relatively small fluctuations of physio-chemical parameters with time. These fluctuations were at least one order of magnitude smaller than observed turbulent velocity fluctuations. The findings might suggest that the estuary was reasonably well-mixed in terms of temperature, pH, DO and turbidity, although the turbulence was possibly not homogeneous in the waterway.

Figure 3 presents instantaneous velocity and water quality data recorded at high frequency on 4 April 2003. For these data, the surveyed cross-section

Table III. Physio-chemical measurements mid-estuary (AMTD 2 km).

	4 April 2003	17 July 2003	24 November 2003	2 September 2004
Water temp. (°C): median	24.15	17.5	25.6	17.2
Standard deviation	0.296	0.910	0.349	0.554
Skewness	0.376	0.743	−0.410	0.108
Kurtosis	−0.451	−0.593	−1.209	−1.32
Range [Min-Max]	[23.7–25.0]	[15.7–19.9]	[24.7–26.0]	[16.35–18.1]
Air temp. (°C): mean	22.2	17.2	–	–
Range [Min–Max]	[15.5–29]	[10.5–21.5]	[19–29]	[9.5–22]
Conductivity (mS/cm): median	35.1	37.7	50.3	49.34
Standard deviation	3.42	4.64	4.52	4.19
Skewness	0.091	−0.083	−0.225	−0.477
Kurtosis	−0.782	−1.670	−1.509	−1.168
Range [Min–Max]	[28.1–42.3]	[26.8–43.6]	[42.7–55.1]	[41.0–53.57]
DO (% sat): median	0.602	0.86	0.815	0.694
Standard deviation	0.0392	0.098	0.0228	0.1824
Skewness	−0.865	−0.392	−0.205	−0.22
Kurtosis	−0.703	−1.515	−1.231	−1.239
Range [Min-Max]	[0.49–0.645]	[0.66–0.94]	[0.762–0.848]	[0.343–0.955]
pH: median	7.51	7.45	7.77	7.37
Standard deviation	0.181	0.253	0.232	0.323
Skewness	−0.123	−0.061	−0.118	−0.251
Kurtosis	−1.097	−1.695	−1.600	−1.295
Range [Min–Max]	[7.15–7.83]	[6.6–7.77]	[7.40–8.04]	[6.68–7.79]
Turbidity (NTU): median	9.5	9.8	18.8	21.1
Standard deviation	1.17	5.88	6.74	14.0
Skewness	0.604	*10.69?*	0.404	28.7
Kurtosis	1.952	*124.5?*	−0.741	*1487?*

of the estuary is presented in Figure 4, where the free-surface and sensor location at high tide are shown. Figure 3 presents instantaneous velocity components V_x, V_y and V_z, with V_x the streamwise velocity component positive downstream, V_y the transverse velocity component positive towards the left bank and V_z the vertical velocity component positive upwards. In Figure 3a, the right vertical axis corresponds to the measured water flow depth and the

Table III. Continued.

	4 April 2003	17 July 2003	24 November 2003	2 September 2003
Range [Min–Max]	[5.8–14.8]	[7.2–*90.8?*]	[7.1–43]	[17.2–*864?*]
Turbidity (m Secchi): mean	0.68	0.84	–	0.5
Range [Min–Max]	[0.53–1.0]	[0.5–1.2]	–	[0.3–0.8]

Notes:

1- Statistics: median, standard deviation, skewness, kurtosis. Extreme values in brackets [ ].
2- Skewness is the Fisher skewness. Zero means a Gaussian/normal distribution.
3- Kurtosis is the Fisher kurtosis or kurtosis excess. Zero means a Gaussian/normal distribution.
4- Skewness and kurtosis are dimensionless.
5- Italic data: erroneous data caused by deposit on the turbidity sensor lens.
6- All data were recorded with the YSI660 probe but air temperatures and Secchi disk readings.

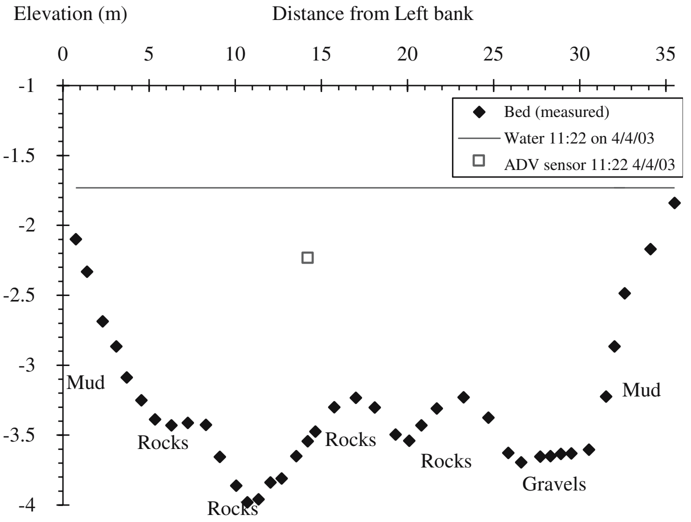

Figure 4. Channel cross-section at Site 2B looking downstream. The water free-surface and velocimeter sensor locations are shown for the 4 April 2004 at high tide (11:22).

sensor distance below free-surface. For the latter data, the vertical see-saw steps were manual vertical displacements of the velocimeter and water quality probes. In Figure 3b and c, the right vertical axis corresponds to dissolved oxygen contents (Figure 3b), and salinity and temperature (Figure 3c).

In natural systems, the flow motion is characterised by unpredictable behaviour, strong mixing properties and broad spectrum of length scales

(Nezu and Nakagawa 1993). There is however some coherence caused by bursting phenomena and large-scale vortical motion. The present data set highlighted large fluctuations of instantaneous velocity direction which are characteristics of the passage of coherent vortical structures (Figure 3). Indeed, in the present study, the probability distribution functions of the velocity direction were approximately Gaussian which was consistent with random turbulent processes. Continuous measurements showed further some important fluctuations in instantaneous velocity and physio-chemical parameters caused by navigation (e.g. Figure 2 Top & 5a). Boat passages were typically associated with large fluctuations in velocity for a few seconds, followed by a longer period, lasting for several minutes, of fluctuations in both velocity and water quality parameters. Figure 5b and c illustrate the effects of a small boat travelling upstream at low speed during the ebb tide (Figure 5a). In Figure 5b, the data are presented in terms of velocity magnitude $|V|$ and direction θ. During the event, the velocity magnitude increased sharply when the wake reached the probe sensors while the velocity direction changed markedly. These large fluctuations were followed by a longer period of fluctuations in velocity magnitude and direction. Overall, while the data implied some mixing induced by wake waves and propeller motion, there were longer-lasting interactions between boat-induced turbulence and secondary circulation in the river. These might explain the long periods of important fluctuations in turbidity, conductivity and temperature following each boat passage.

A statistical analysis of instantaneous physio-chemical records was performed in terms of the auto-correlation and cross-correlation functions. A comparison of the auto-correlation with a time delay T gives a measure of the rate of change of a given quantity. In this study, the relevant time scales $T_{0.5}$ were typically about 1–4 min for all physio-chemical parameters and flow periods, where $T_{0.5}$ is the time delay for which the normalised auto-correlation coefficient was 0.5. $T_{0.5}$ must be a significant time scale for river mixing processes, and it was observed that $T_{0.5}$ was reduced following the passage of boats with outboard motor. The results showed further strong correlations between pH and conductivity that were consistent with both variables being related to ion concentration in water. pH data lagged typically by about 5–10 s behind conductivity data. Possible explanations might include mixing processes or difference in sensor response time.

3.3. FISH SAMPLING AND BIRD OBSERVATIONS

During each field work, more than 50 birds corresponding to more than 10 species were sighted at each site (Table IV). Results must be considered with care since flocks of birds were seen and accounted for up to one third of the total number of sightings. Overall bird sightings showed a strong

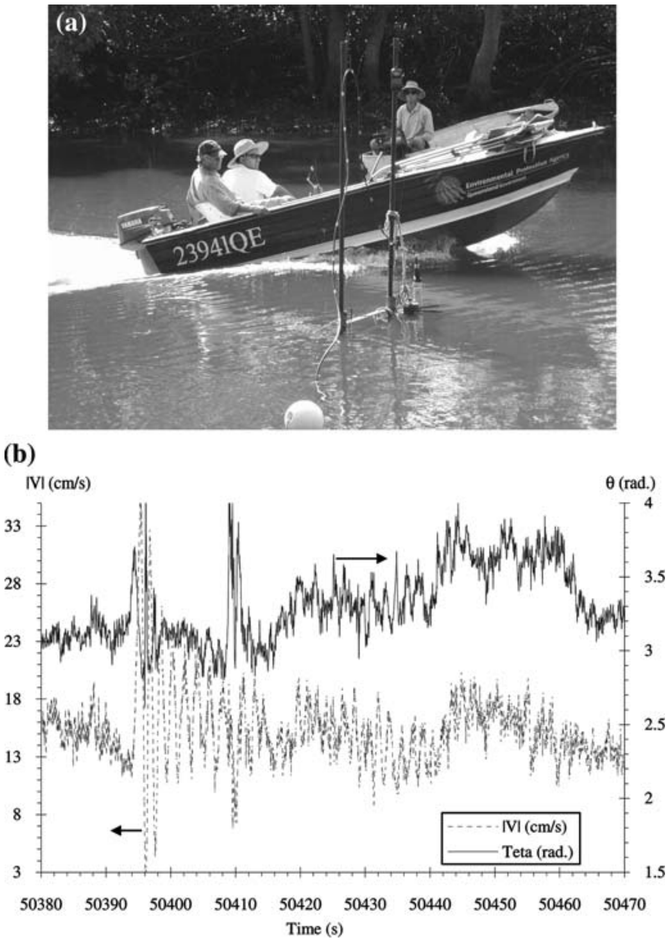

Figure 5. Effect of boat passage on velocity and physio-chemical parameters in mid-estuary at Eprapah Creek (AMTD 2 km, surface sampling) during the ebb tide on 4 April 2003. (a) Photograph of the boat passage, viewed from the left bank with the top of the ADV and YS6600 probes visible; (b) Short term fluctuations of the velocity magnitude $|V|$ and direction θ (in radian) immediately after boat passage. $\theta = 0$ in the upstream direction; (c) Fluctuations of water temperature (Celsius), conductivity (mS/cm), turbidity (NTU) and pH.

activity at all sites, particularly in the morning between 7:00 and 10:00. Yet, on 4 April 2003, there was always a minimum of five bird species seen every hour of day between 6:00 and 18:00 at each Site. This suggests a fair diversity of the bird population in the Eprapah Creek estuarine zone. For comparison, two previous studies [12, 13] reported respectively 120 and 70 bird species in Eprapah Creek estuarine zone. Present findings (Table IV) suggested that the bird population was diverse and active. However the surveys were limited and it is difficult to make any definite conclusion.

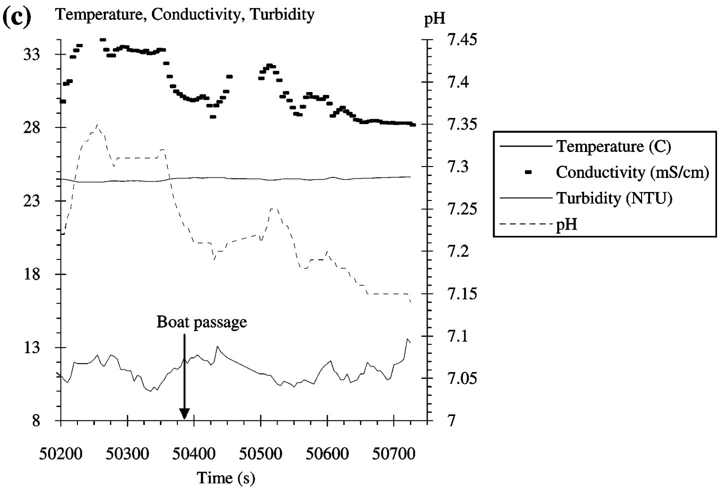

Figure 5. Continued.

Fish sampling was conducted intensively on 4 April 2003 and 2 September 2004. The results presented different trends. On 4 April 2003, more than 400 fish were caught altogether corresponding to 21 species. The largest numbers of fish were caught between 10:00 and 17:00. It is most likely that the combination of flood flow with higher dissolved oxygen contents and sun light induced significant fish activities during the period 10:00–16:00. At the most upstream site (Site 4, freshwater pool), 98.6% of catches were mosquito fish (*Gambusia affinis*), an exotic species tolerant to environmental extremes. This might suggest that native species had difficulties in reduced dissolved oxygen conditions, although native fish activity was present. Empire gudgeon (*Hypseleotris compressa*), Firetail gudgeon (*Hypseleotris galii*), Flat headed gudgeon (*Philypnodon grandiceps*) and Pacific blue-eye (*Pseudomugil signifier*) were caught on 4 April 2003 at Sites 3 and 4, while Sun fish were observed just upstream of Site 4 on 24 November 2003. A very-large amount of macro invertebrates and crustaceans were also observed: e.g., shrimps, prawns, Fiddler crabs, mud crabs.

On 2 September 2004, the data indicated a near-total disappearance of exotic fish, particularly in the upper estuary. Overall a lesser number of fish were caught and most were saltwater species. It is believed that the results are closely linked to an on-going drought period. For the period May–August 2004, the measured rainfall was les than 40 mm compared to the 50-year average rain of 322 mm, for the same period. Native fish species are traditionally more resistant to such long dry periods.

During all field works, recirculation zones were observed in the outer bends of the river. Mid-estuary, toad fish (*Tetractenos hamiltoni*) were seen

Table IV. Fish sampling and bird observations about mid-estuary of Eprapah Creek.

Observations	4 April 2003	17 July 2003	24 November 2003	2 September 2004	Remarks
Nb of bird sightings	189 (496)	200 – 300	293	67 (330)	Site 2 (All sites)
Nb of bird specie sighting	27 (72)	28	38	17 (59)	Site 2 (All sites)
Nb of fish catch	111(437)	185	–	21 (> 50)	Site 2 (All sites)
Nb of fish specie catch	8 (21)	5	–	3 (8)	Site 2 (All sites)
Nb of fish sighting in recirculation zones	–	–	> 500	> 10	Site 2, outer bend
Nb of fish specie sighting in recirculation zones	–	> 2	> 7	> 2	Site 2, outer bend
Nb macro-inver-tebrate & crustacean	> 300	–	–	> 80	All sites

Summary of field observations.
Note: Numbers in brackets correspond to the combined results of three sites on 4 April 2003 (Sites 1, 2, 3 & 4) and to three sites on 2 September 2004 (Sites 1, 2 & 3).

utilising these recirculation regions for feeding, and detailed observations on 24 November 2003 are summarised in Table IV. The findings confirm the existence of an outer bank secondary current cell in river bends, discussed more broadly by Ref. [14] . Present observations showed that recirculation zones varied in space and in time with the tide, but they were always present. Toad fish behaviour allowed a nice characterisation of such zones where turbulent velocity measurement is nearly impossible. The occurrence of recirculation regions is important since outer bend cells contribute to a reduction in bend scouring. They are “dead zones” which are thought to explain long tails of tracer observed in natural rivers. Their existence implies that the turbulence is not homogeneous across the river, and that the time taken for contaminant particles to penetrate the entire flow may be significantly enhanced (e.g. [3, 15]).

4. Discussion

Long-term monitoring data of physio-chemical parameters are presented in Figure 6 for the period 1996–2004 (e.g. [4]). Each data point corresponds to a single water sampling, taken once a month, during day time from a boat drifting with the current, at approximately 0.2 m below the free-surface. The data were recorded at high tide and early ebb flow mid-estuary in front of Site 2 (AMTD 2 km). Monthly monitoring data (Figure 6) illustrated some yearly trends: e.g., in terms of water temperature (Figure 6a). The estuary salinity and conductivity were high during dry periods, but dropped sharply during and immediately after rainfall periods (e.g. mid 1996, mid 1999, early 2003 & early 2004 in Figure 6b). This aspect was not investigated during the present works.

Present data recorded at high frequency, for several hours on each day, are compared with the monthly monitoring data in Figure 6. The comparison highlights very-large daily fluctuations in physio-chemical properties. Such a comparison illustrates the difficulty to detect hourly, daily and weekly fluctuations in physio-chemical properties of water with a monthly monitoring programme. Its supports further the complementary nature of both long-term monitoring over several years and high-frequency data sampling over a few hours. Indeed the latter data sets (Present study) highlighted large daily fluctuations in water temperature, salinity, turbidity, DO and pH that suggested strong on-going mixing. Furthermore the present results identified the need for careful design of collection of meta-data (e.g. tide time, water height) for monthly monitoring.

Overall this series of detailed field measurements provided a broad range of simultaneous data collected at relatively high frequency. The results showed consistently contrasted outcomes in terms of natural system health. Fish sampling and bird observations suggested a dynamic but highly diverse eco-system (Table IV). Velocity measurements indicated high turbulence levels and a strong flushing process in the estuary. For example, at mid-tide, the discharge was estimated to be about 6 – 8 m^3/s mid-estuary, while the residual circulation induced by the longitudinal salinity gradient yielded residual velocities of more than 1 cm/s. But other results highlighted poor physio-chemical properties in the upstream reach of the estuary. Serious concerns included low dissolved oxygen and pH levels (Sites 3 and 4), surface slicks (Sites 2 and 3), large numbers of exotic fish (e.g. Site 4) competing with native fish species, and surface runoff (e.g. construction sites, shopping centres) in the upper estuarine zone. Indeed the Australian and New Zealand guidelines for fresh and marine waters [16] specified standards for recreational estuarine water quality that included pH within a 7–8.5 range, dissolved oxygen contents between 80% and 110%, and absence of oil and petrochemical surface film. All present results seemed to

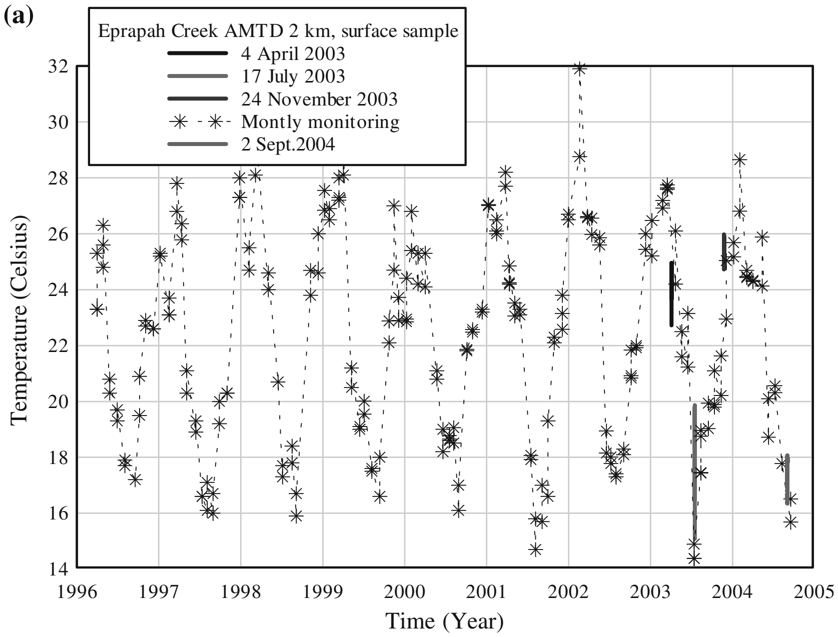

Figure 6. Long-term monitoring of physio-chemical properties mid-estuary at Eprapah Creek (AMTD 2 km, surface sampling). Comparison between monthly monitoring data (symbol *, Queensland Environmental Protection Agency) and detailed field observations with the YSI6600 probe (thick lines). Note that connecting lines for long-term monitoring data are shown for clarity only. (a) Water temperature (Celsius) at 0.2 m below the free-surface at AMTD 2 km (Site 2). Comparison between monthly monitoring and detailed field observations (YSI6600 data); (b) Water conductivity (mS/cm) at 0.2 m below the free-surface at AMTD 2 km (Site 2). Comparison between monthly monitoring, detailed field observations (YSI6600 data), and monthly rainfall data (Cleveland Station, Redlands QLD); (c) Dissolved oxygen concentration (% saturation) at 0.2 m below the free-surface at AMTD 2 km (Site 2). Comparison between monthly monitoring and detailed field observations (YSI6600 data).

demonstrate on-going pollution in the estuary. The findings impact on the selection of a limited number of “key indicators”, which cannot describe the complexity of sub-tropical estuaries.

Additionally, field works provided unique personal experiences to all parties involved, and facilitated interactions between groups with different background and interests. Key interactions included exchanges between university and local community, between government institutions and universities, between professionals and academics, between technical and academic staff. Field works contributed further to the students’ personal development. Field studies complemented traditional lectures and tutorials, and anonymous student feedback demonstrated a very-strong student

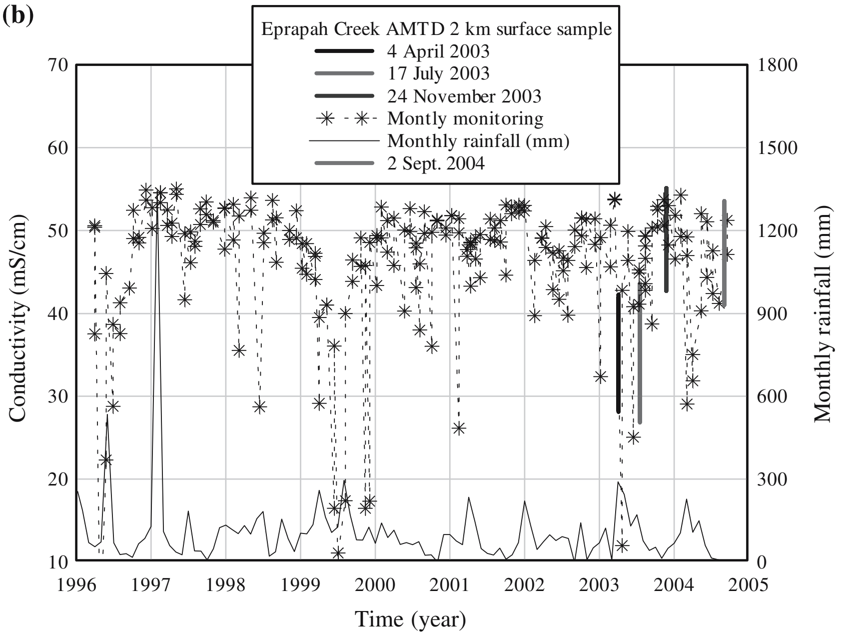

Figure 6. Continued.

interest [17]. Personal student comments supported their enhanced motivation. An international student was very surprised to see a snake passing right in front of her during a wildlife survey; a first-class honours female student discovered the intricacies of practical works in harsh sub-tropical conditions with no fresh water on site: "*it was as much a matter to mix with the environment as to study river mixing*". Group work contributed to new friendships and openings: e.g., between civil and environmental students, between Australian and international students, between students and professionals involved in the study. Such personal experiences were at least as important as the academic experience, and we should not be complaisant with university management and administration clerks to cut costs by eliminating field studies from university curricula.

5. Conclusion

The results and outcomes of this series of preliminary field studies in a subtropical estuary are three-fold. First these investigations provided unique snapshots of a small estuarine system. The single-day studies complemented long-term monitoring, and results should not be extrapolated without care and caution. The works provided a broad range of simultaneous data encompassing hydrodynamics, water quality and ecology, and they

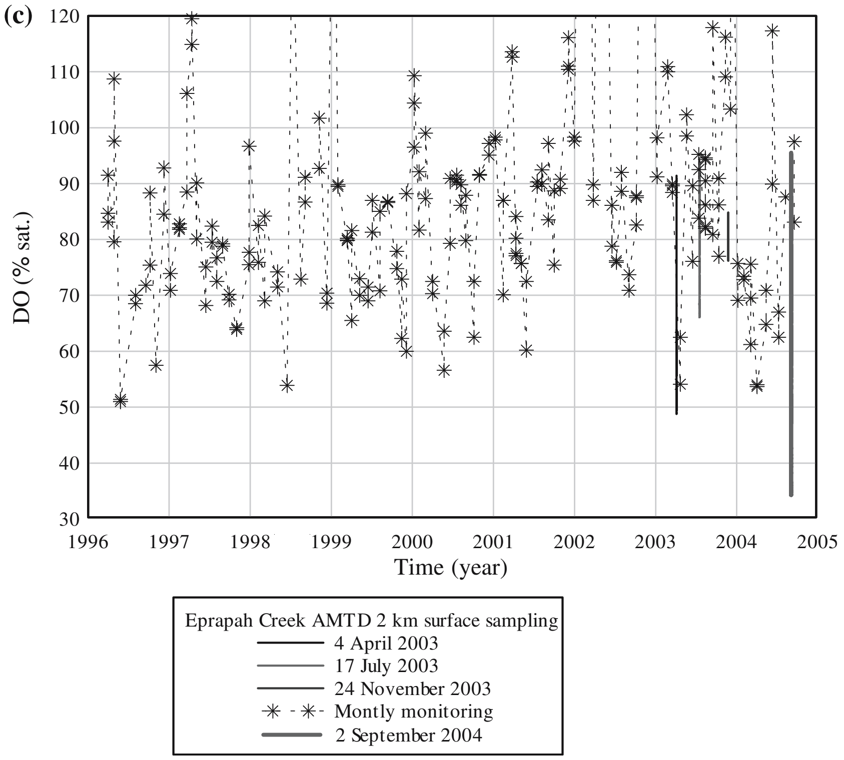

Figure 6. Continued.

constitute the first comprehensive hydrodynamic survey of a sub-tropical system. It is the opinion of the writers that the methodology sets new standards for multidisciplinary, cross-institutional, comprehensive field studies. Second the measurements highlighted contrasted outcomes. While some results were positive, others demonstrated on-going pollution. How can we define accurately "key water quality indicators" to describe the diversity of sub-tropical estuaries? Third the field works provided unique personal experiences and fostered interactions between academics, professionals, local community groups and students. Field studies complemented traditional lectures, and such personal experiences are at least as important as the academic experience.

The experience gained at Eprapah Creek brings new lights into the complexity of the estuarine system, but also thought-provoking outcomes. It is clear that basic mixing processes are driven by turbulence. However its impact on a natural system cannot be comprehended without simultaneous measurements of hydrodynamic, physio-chemical and ecological parameters, implying substantial instrumentation, broad-based expertise and human resources. Genuine inter-disciplinary research is essential.

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References

1. Ippen, A.T.: 1966, *Estuary and Coastal Hydrodynamics*, McGraw-Hill, New York, USA.
2. Fischer, H.B., List, E.J., Koh, R.C.Y., Imberger, J. and Brooks, N.H.: 1979, *Mixing in Inland and Coastal Waters*, Academic Press, New York, USA.
3. Chanson, H.: 2004a, *Environmental Hydraulics of Open Channel Flows*, Elsevier-Butterworth-Heinemann, Oxford, UK, 483p.
4. Óbrien, E. and Fearon, R.: 2001, *South-East Queensland Monitoring Program. Redland Shire Waterways: Water Quality Study 1999*, Environmental Technical Report No. 43, Queensland Environmental Protection Agency, 50p.
5. Jones, A.B., Prange, J. and Dennison, W.C.: 1999, *An Assessment of the Ecological Health of Eprapah Creek*, Report, Marine Botany, Univ. of Queensland, Brisbane, Australia, 23p.
6. Chanson, H., Brown, R., Ferris, J. and Warburton, K.: 2003, *A Hydraulic, Environmental and Ecological Assessment of a Sub-tropical Stream in Eastern Australia: Eprapah Creek, Victoria Point QLD on 4 April 2003*, Report No. CH52/03, Dept. of Civil Engineering, University of Queensland, Australia, June, 189p.
7. Lemmin, U., and Lhermitte, R.: 1999, ADV measurements of turbulence: Can we improve their interpretation? Discussion, *J. Hyd. Engrg.*, ASCE, **125**(6), 987–988.
8. Chanson, H., Aoki, S. and Maruyama, M.: 2002, Unsteady two-dimensional orifice flow: A large-size experimental investigation, *J. Hyd. Res.*, IAHR, **40**(1), 63–71.
9. Mclelland, S.J. and Nicholas, A.P.: 2000, A new method for evaluating errors in high-frequency ADV measurements, *Hydrolo. Process.*, **14**, 351–366.
10. Goring, D.G. and Nikora, V.I. (2002). Despiking acoustic doppler velocimeter data, *J. Hyd. Engrg.*, ASCE, **128**(1), 117–126. Discussion: **129**(6) 484–489.
11. Chanson, H., Trevethan, M. and Aoki, S.: 2005, *Acoustic Doppler Velocimetry (ADV) in a Small Estuarine System. Field Experience and "Despiking"*, Proc. 31th Biennial IAHR Congress, Seoul, Korea, Theme E2, Paper 0161, 10p.
12. Cooper, V.: 1978, *Bird of Eprapah*, Scout Association of Australia, Kelvin Grove Qld, Australia, 46p.
13. Melzer, R. and Moriarty, C.: 1996 *lora and Fauna of Eprapah Creek*, Eprapah Creek Catchment Landare Association, Victoria Point Qld, Australia, 56p.
14. Blankaert, K. and Graf, W.H.: 2001, Mean flow and turbulence in open-channel bend. *J. Hyd. Engrg.*, ASCE, **127**(10), 835–847.
15. Valentine, E.M. and Wood, I.R.: 1979, Experiments in longitudinal dispersion with dead zones, *J. Hyd. Div.*, ASCE, **105**(HY9), 999–1016.

16. Anzecc: 2000, *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*. Australian and New Zealand Environment and Conservation Council (ANZECC) and Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ), Paper No. 4, October 2000.
17. Chanson, H.: 2004b, Enhancing students' motivation in the undergraduate teaching of hydraulic engineering: The role of field works, *J. Prof. Issues Eng Educ. Practice*, ASCE, **130**(4) 259–268.