Journal of Coastal Research	26	3	436–443	West Palm Beach, Florida	May 2010

Salt Fluxes within a Very Shallow Subtropical Estuary

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ABSTRACT

ALI, A.; LEMCKERT, C.J., and DUNN, R.J.K., 2010. Salt fluxes within a very shallow subtropical estuary. *Journal of Coastal Research,* 26(3), 436–443. West Palm Beach (Florida), ISSN 0749-0208.

This article describes the transport processes and net salt flux within a shallow estuarine system, with particular reference to the Coombabah Lake–Creek system in Queensland, Australia. Observations of currents and salinity at two locations within Coombabah Lake provided a basis for assessing the relative importance of various transport processes within a very shallow (water depth <1 m) subtropical estuary. The instantaneous velocity and salinity data were decomposed into time-averaged means and time-varying components and were used to quantify the salt flux components attributed to various physical processes. In this study, advection by residual flow, which contributed 65% of the total salt flux, was identified as the dominant process in transporting salt. The advective flux also determined the direction of the net salt flux within this shallow estuarine system. This study concludes that the net salt flux varies spatially and temporarily with hydromorphological and meteorological conditions.

ADDITIONAL INDEX WORDS: *Salt flux, shallow estuary, subtropical, Coombabah Lake.*

INTRODUCTION

Coastal wetlands and estuaries are important environments, providing significant habitats for flora and fauna species, often supporting commercial and recreational fisheries (Stumpf and Haines, 1998). Furthermore, these systems act as filters against contaminants and sediments (Faulkner, 2004), absorb wave energy, and also provide cultural and recreational benefits (Lee *et al.,* 2006b).

To quantify the water circulation and mixing processes within estuarine systems, it is often convenient to study salinity distribution patterns because salinity is typically considered as a conservative tracer (Dyer, 1997). The behaviour of salts within the water column provides a basis for predicting transport of other soluble conservative substances. Salt is transported downstream by freshwater flow (which enters the estuary through rivers, creeks and groundwater systems) and is mixed back upstream against this seaward flow. The overall landward mixing (termed *dispersion* rather than *diffusion*) is produced primarily by the effects of tides, winds, and gravitational circulation (Hunkins, 1981).

To date, a significant number of studies have been undertaken to determine salt fluxes within estuarine systems characterised by very low to high rates of freshwater discharge (2.3 to 3750 m^3/s) and varying water depths ranging from 3 to 24 m (*e.g.,* Bowden, 1963; David and Kjerfve, 1998; Hunkins, 1981; Kjerfve, 1986; Lewis and Lewis, 1983; Miranda and Kjerfve, 1998; Park and James, 1990; Pritchard, 1954; Restrepo and Kjerfve, 2002; Uncles and Jordan, 1979). However, the quantification of salt fluxes within very shallow estuaries is limited (*e.g.,* Sylaios *et al.,* 2006).

Previous studies have shown a high degree of variability in salt fluxes within estuarine environments as summarised in Table 1. Bowden (1963) calculated the fluxes for four periods (twice at a single station and once at an additional two stations) along and across the Mersey Estuary, with the results indicating a net salt flux consistently directed upstream. Bowden (1963) claimed the discrepancies between salt fluxes were due to variations of velocity across the estuary. Uncles and Jordan (1979) described the residual transport of water as the dominant mechanism for residual transport of salt, observed opposite fluxes seaward during the neap tide phase at one station, and reported fluxes in a landward direction twice the magnitude at another station during spring tides within the deep Severn Estuary (England). However, the latter station was located in a complex topographic region 17.2 km upstream from the previous downstream station. Uncles and Jordan (1979) termed the spring-neap variations in salinity as significant compared with that resulting from time-varying freshwater inputs. Hunkins (1981), Lewis and Lewis (1983), David and Kjerfve (1998), and Miranda and Kjerfve (1998) also observed the residual transport of water as the principal factor in determining the net salt flux. More interestingly, Lewis and Lewis (1983) identified a net salt flux landward at downstream stations and seaward at upstream stations within the Tees Estuary (England). Kjerfve (1986)

DOI: 10.2112/08-1118.1 received 18 August 2008; accepted in revision 16 December 2008.

Table 1. *Previously reported salt fluxes per unit width (positive seaward and negative landward) divided by mean water depth.*[1,2]

Study Site	Spring/ Neap	Freshwater Flow m³/s	Mean Depth m	$\langle h\rangle\langle\bar{u}\rangle\langle\bar{s}\rangle$ Flux 1 ppt cm/s	$\langle hu_T s_T\rangle$ Flux 2 ppt cm/s	$\langle\bar{u}\rangle\langle h_T s_T\rangle$ Flux 3 ppt cm/s	$\langle\bar{s}\rangle\langle h_T u_T\rangle$ Flux 4 ppt cm/s	$\langle h\bar{u}'\bar{s}'\rangle$ Flux 5 ppt cm/s	$\langle F\rangle$ Net Flux ppt cm/s	Reference
Mersey estuary–Narrows at Station A	Neap	41.05	20.4	6.34	−6.95	—	—	−2.36	−2.97	Bowden (1963)
Mersey estuary–Narrows at Station A	Spring	18.02	20.4	2.63	−0.44	—	—	−3.04	−0.85	Bowden (1963)
Mersey estuary–Narrows at Station C	Neap	66.70	20.4	10.00	−12.27	—	—	−3.22	−5.49	Bowden (1963)
Mersey estuary–Narrows at Station D	Spring	42.90	20.4	6.00	−14.40	—	—	−5.15	−13.65	Bowden (1963)
Severn Estuary–Station A	Preneap	154.00	19.4	100.00	3.20	—	—	−0.24	102.96	Uncles and Jordan (1979)
Severn Estuary–Station B	Prespring	105.00	14.7	−190.00	−7.40	—	—	−0.43	−197.83	Uncles and Jordan (1979)
Hudson Estuary–The Narrows 1	—	238.00	~24.0	42.65	8.22	—	−19.12	−11.02	20.73	Calculated from Hunkins (1981)
Hudson Estuary–The Narrows 2	—	845.00	~24.0	78.12	9.25	—	−7.47	−57.03	22.87	Calculated from Hunkins (1981)
Hudson Estuary–Yokkers	—	182.00	~10.0	36.22	8.78	—	−20.18	−8.68	16.14	Calculated from Hunkins (1981)
Tees Estuary–Station 1	Neap	3.20	~18.0	−79.10	−0.90	0.00	0.00	−0.90	−80.90	Lewis and Lewis (1983)
Tees Estuary–Station 1	Spring	4.20	~18.0	−268.40	−0.90	−0.10	0.00	−0.30	−269.40	Lewis and Lewis (1983)
Tees Estuary–Station 8	Neap	3.20	~5.0	93.70	−43.90	5.30	2.00	−6.60	50.50	Lewis and Lewis (1983)
Tees Estuary–Station 8	Spring	4.20	~5.0	246.20	−98.60	80.10	0.70	−0.80	227.60	Lewis and Lewis (1983)
North Inlet–Flood channel	—	1.00–5.00	~3.0	−19.20	−315.00	0.20	6.40	−0.10	−327.70	Kjerfve (1986)
North Inlet–Mid channel	—	1.00–5.00	~3.0	68.40	−234.70	0.30	−24.30	−0.10	−190.70	Kjerfve (1986)
North Inlet–Ebb channel	—	1.00–5.00	~3.0	288.30	−127.20	0.00	−24.20	−0.70	136.20	Kjerfve (1986)
Tyne Estuary–Station 1	—	73.10	4.7	23.70	0.60	−5.20	2.40	0.20	21.70	Park and James (1990)
Tyne Estuary–Station 4	—	2.30	11.4	−0.30	−5.10	0.00	2.80	0.40	−2.20	Park and James (1990)
Laguna de Terminos–Carmen Inlet	—	—	6.4	367.19	26.56	0.00	3.13	0.00	396.88	Calculated from David and Kjerfve (1998)
Laguna de Terminos–Puerto Real Inlet	—	—	5.0	328.00	−10.00	0.00	156.00	4.00	474.00	Calculated from David and Kjerfve (1998)
Bertioga Channel	Neap	~10.00	5.5	108.53	−9.64	0.55	−2.91	−32.18	64.35	Calculated from Miranda and Kjerfve (1998)
Bertioga Channel	Spring	~10.00	5.7	66.18	−7.27	0.37	−4.73	−7.27	47.28	Calculated from Miranda and Kjerfve (1998)
San Juan River delta—San Juan	—	2450.00	7.0	135.50	−3.20	3.80	−1.10	−5.30	129.90	Restrepo and Kjerfve (2002)
San Juan River delta–Chavica	—	2450.00	6.0	119.10	−138.20	10.50	−17.50	−2.60	−28.70	Restrepo and Kjerfve (2002)
San Juan River delta–Charambira	—	2450.00	9.0	635.20	22.90	4.50	18.30	−4.30	676.80	Restrepo and Kjerfve (2002)
San Juan River delta–San Juan	—	3750.00	7.0	4.50	−111.10	0.00	−10.90	−16.40	−133.80	Restrepo and Kjerfve (2002)
San Juan River delta–Chavica	—	3750.00	6.0	139.70	−250.30	16.50	−10.80	−0.80	−105.80	Restrepo and Kjerfve (2002)
San Juan River delta–Charambira	—	3750.00	9.0	111.20	−17.10	0.20	−1.70	−32.60	50.90	Restrepo and Kjerfve (2002)
Vassova lagoon–Entrance canal	Spring	0.94	0.75	−0.03	−0.03	—	—	—	−0.06	Sylaios et al. (2006)
Vassova lagoon–Entrance canal	Neap	0.94	0.72	−0.29	−0.02	—	—	—	−0.31	Sylaios et al. (2006)
Coombabah Lake–Station A	Spring	—	1.12	166.58	−27.86	4.04	−46.09	—	37.68	Present study
Coombabah Lake–Station A	Neap	—	1.30	116.29	−9.38	1.52	−30.81	—	77.62	Present study
Coombabah Lake–Station B	Spring	—	0.62	48.67	−10.64	3.09	22.88	—	64.01	Present study
Coombabah Lake–Station B	Neap	—	0.74	76.75	−9.08	3.60	−5.47	—	65.80	Present study

[1] Flux 1 represents the advective salt flux because of water discharge and change in storage volume during the tidal cycle; Flux 2 represents the sloshing effect—the tidal dispersion via triple correlation between tidal depth change, tidal current, and tidal salinity, usually directed upstream; Flux 3 represents the cross-correlation between tide and salinity—maximum (and positive) when tide and salinity are in phase, and minimum (and negative) when they are out of phase; Flux 4 represents the Stokes' drift dispersion; and Flux 5 represents the salt dispersion because of mean shear produced by gravitational circulation.

[2] — indicates data were not available.

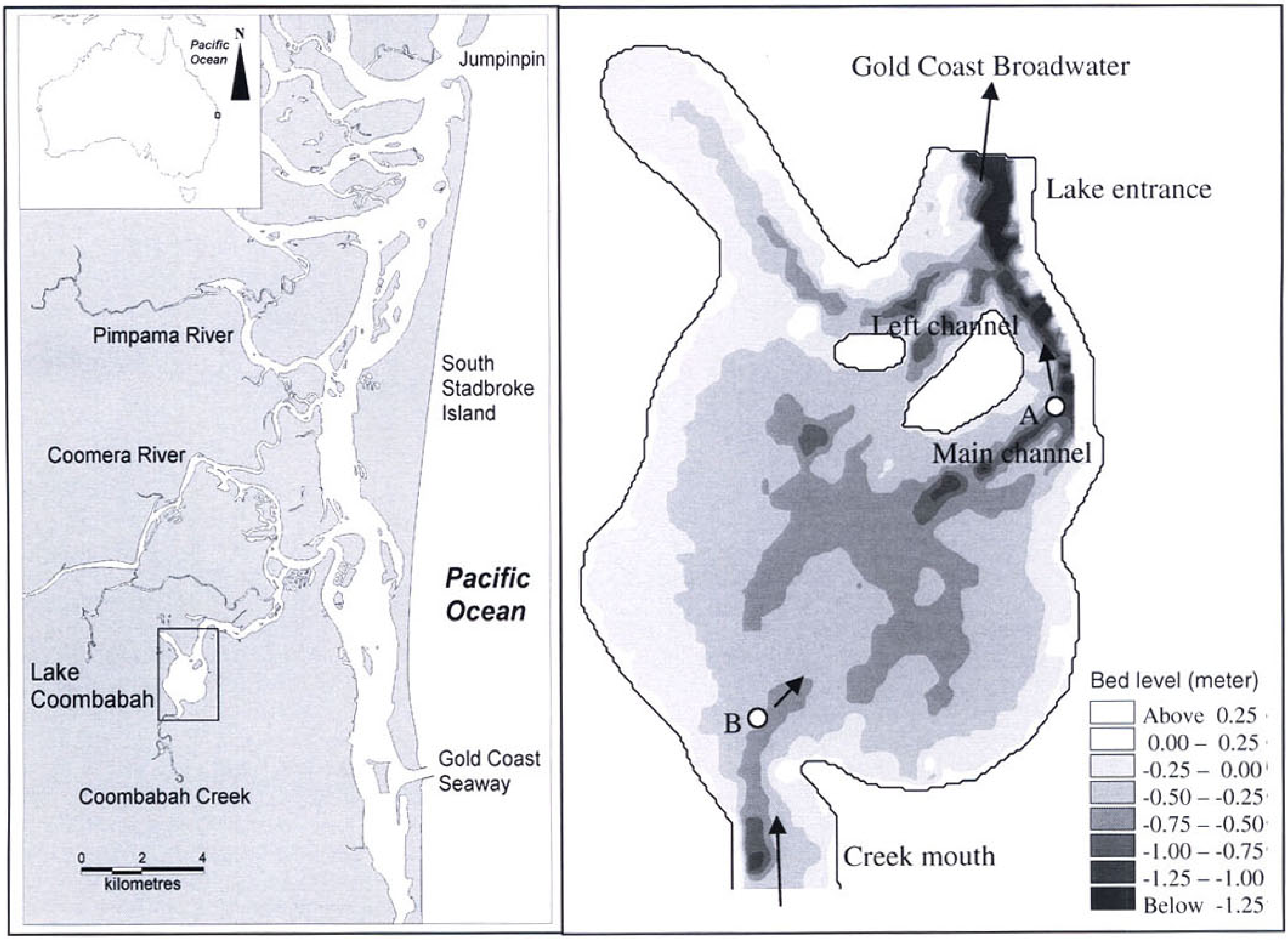

Figure 1. Location map of the study site, Coombabah Lake (southern Moreton Bay, Australia).

found seaward transport through ebb channels and landward transport through mid and flood channels within the North Sea Inlet, South Carolina (United States). Park and James (1990) also observed a net seaward transport near the head and landward transport near the mouth of the Tyne Estuary (England). Restrepo and Kjerfve (2002) investigated salt fluxes through three distributaries within the San Juan River Delta (Columbia) and found advection and tidal pumping were the dominant processes in salt transport. Moreover, they observed net seaward flux in one distributary, whereas net landward flux was evident in another distributary in the same estuary. Sylaios et al. (2006) also identified advection as the main mechanism for salt transport, which was consistently landward in direction. Additionally, Sylaios et al. (2006) observed that tidal pumping was an order of magnitude smaller than advection. Although the net flux was landward most of the time, forcing salt into the Vassova Lagoon (Greece), magnitudes were highly variable and changed frequently with meteorological and tidal conditions. Overall, none of the estuaries investigated was observed to exist under a steady condition (*i.e.,* negligible net salt flux). Instead, net salt fluxes varied both spatially and temporarily with changing hydromorphological and meteorological conditions (see Table 1), thus warranting further studies in identifying the controlling mechanisms within particular systems.

This study is the first to quantify salt fluxes within the shallow Coombabah Lake–Creek system, providing an initial understanding of the system's physical processes, assisting future management decisions in this ecologically and economically significant region. Furthermore, this study contributes to a greater understanding of the physical processes occurring within shallow estuarine systems.

METHODS

Study Site

Coombabah Creek is a subtropical estuarine system situated in southern Moreton Bay, south-east Queensland (Australia) (see Figure 1), one of the fastest growing regions in the developed world (Skinner, Gillam, and Rohlin, 1998). The creek is a 17 km long, moderately impacted (Cox and Moss, 1999; Lee *et al.,* 2006a) tidal creek that flows through Coombabah Lake. The creek enters the lake at the south-west side (hereby referred to as the *creek mouth*) and leaves the same from the north-east side (hereby referred to as the *lake entrance*). Ultimately, Coombabah Creek discharges into the Gold Coast Broadwater, within southern Moreton Bay. Thus, the creek mouth has a greater influence on the freshwater flow entering the lake system than the lake entrance, which is dominated by the inflow of seawater.

The lake covers ~2 km^2 (GHD, 2003), with an urbanised catchment area of 44 km^2, characterised by residential, commercial, and light industrial developments. The lake is a shallow body of water characterised by fine sediments (Dunn *et al.,* 2007b) and is located in the midtidal region of Coombabah Creek, with urban development positioned to the east and along the southern and western shorelines.

With the exception of shallow channels, Coombabah Lake is characterised by a relatively flat bathymetry (Lee *et al.,* 2006a), with depths from 0 to ~1 m. During periods of low water, large portions of the benthic lake sediments become exposed. Episodically large inputs of freshwater occur during periods of heavy rainfall, predominantly during summer periods. Despite its modest dimensions, Coombabah Lake is ecologically significant, being a valuable fish and migratory bird habitat. Additionally, the lake system is unique within southern Moreton Bay because it behaves as an inverse estuary during summer periods, when evaporation exceeds typical freshwater inflows (Benfer, King, and Lemckert, 2007).

As a consequence of the ecological significance and the potential for anthropogenic disturbances and inputs into Coombabah Lake, the lake and surrounding wetlands have been the focus of recent scientific efforts (*e.g.,* Burton *et al.,* 2008; Dunn *et al.,* 2007a, 2007b, 2008; Frank and Fielding, 2004; Hollingsworth and Connolly, 2006; Knight *et al.,* 2008).

Field Measurement and Data Processing

The data collection program was conducted from November 1, 2005, to November 10, 2005. A submersible sensor base was positioned at two individual sample locations characterised by differing salinity concentrations within Coombabah Lake, referred to as Station A (near the lake entrance) and Station B (near the creek mouth) (see Figure 1). The stationed instrument packages consisted of a conductivity, temperature, and depth probe (NXIC-CTD; Falmouth Scientific, Inc., Cataumet, Massachusetts) and a high resolution three-dimensional acoustic Doppler velocimeter (Vector velocimeter; Nortek AS, Rud, Norway). High-frequency conductivity, temperature, and depth data were collected from 15 cm above the bed using time-averaged data (3.5 min bursts at frequency of 10 Hz) obtained every 15 minutes. Acoustic Doppler velocimeter data were obtained from 30 cm above the bed at burst intervals of 30 minutes, at a frequency of 32 Hz and 4096 samples per burst.

Meteorological conditions, namely air pressure, solar radiation, humidity, rainfall, and wind speed and direction within the lake environment, were recorded every 15 minutes during the study period using a data logging weather station (WeatherMaster 2000; Environdata, Warwick, Australia). Daily evaporation was estimated from the meteorological data collected using a modified Penman equation (EasiAccess software; Environdata).

Additionally, before the deployment of Stations A and B, water level data from Coombabah Lake were obtained during the period between September 13, 2004, to December 20, 2004, by using a submersible tide gauge (XR-420-TG; Richard Brancker Research Ltd., Ottawa, Canada). The dominant tidal constituents for the area were obtained using this collected data.

Quantification of Salt Fluxes

Total salt flux within an estuarine system is typically determined using velocity and salinity concentrations at several water depths along a vertical section measured at different locations across the section (*e.g.,* Bowden, 1963; Fischer, 1972; Sylaios *et al.,* 2006). However, observations of currents and salinity collected at one location along the cross-section of a main channel within an estuarine system may also provide a valid experimental approach when assessing the relative importance of different transport processes (*e.g.,* Lewis and Lewis, 1983; Pritchard, 1954; Restrepo and Kjerfve, 2002; Simpson, Vennel, and Souza, 2001; Uncles and Jordan, 1979; Uncles, Elliott, and Weston, 1985). The longitudinal salt flux within estuarine systems can be decomposed into components attributed to different physical processes (Table 1) (Bowden, 1967; Dyer 1997; Hunkins, 1981; Kjerfve, 1986; Pritchard, 1954; Restrepo and Kjerfve, 2002). In general, the net salt flux per unit width perpendicular to the main flow (F) may be calculated as the following (Bowden, 1963; Dyer, 1997; Kjerfve, 1986; Restrepo and Kjerfve, 2002):

$$F = \int_0^h (us)\, dz \tag{1}$$

where F represents the net flux (ppt m^2/s); $u(z)$ represents the observed velocity (m/s); $s(z)$ represents the observed salinity (ppt); z represents the vertical coordinate; and h represents water depth (m). The instantaneous velocity and salinity can be decomposed as $u = \bar{u} + u'$ and $s = \bar{s} + s'$, where the primed quantities represent deviations from the depth-averaged means, $\bar{u}$ and $\bar{s}$. The depth-averaged means may be decomposed into time-averaged means and time-varying components, $\bar{u} = \langle\bar{u}\rangle + u_T$ and $\bar{s} = \langle\bar{s}\rangle + s_T$, such that

$$u = \langle\bar{u}\rangle + u_T + u' \tag{2}$$

$$s = \langle\bar{s}\rangle + s_T + s' \tag{3}$$

where angle brackets are net, or time-averaged, over at least one complete tidal cycle. By substituting Equations (2) and (3) into Equation (1), the net flux can be decomposed into the following terms (Restrepo and Kjerfve, 2002):

$$\langle F\rangle = \langle h\rangle\langle\bar{u}\rangle\langle\bar{s}\rangle + \langle hu_Ts_T\rangle + \langle\bar{u}\rangle\langle h_Ts_T\rangle + \langle\bar{s}\rangle\langle h_Tu_T\rangle + \langle h\bar{u}'\bar{s}'\rangle \tag{4}$$

which, for simplicity, can be written as

$$\text{Net flux} = \text{Flux 1} + \text{Flux 2} + \text{Flux 3} + \text{Flux 4} + \text{Flux 5} \tag{5}$$

An estuary is considered to be at steady state when the net salt flux over a complete tidal cycle is zero, with the advective

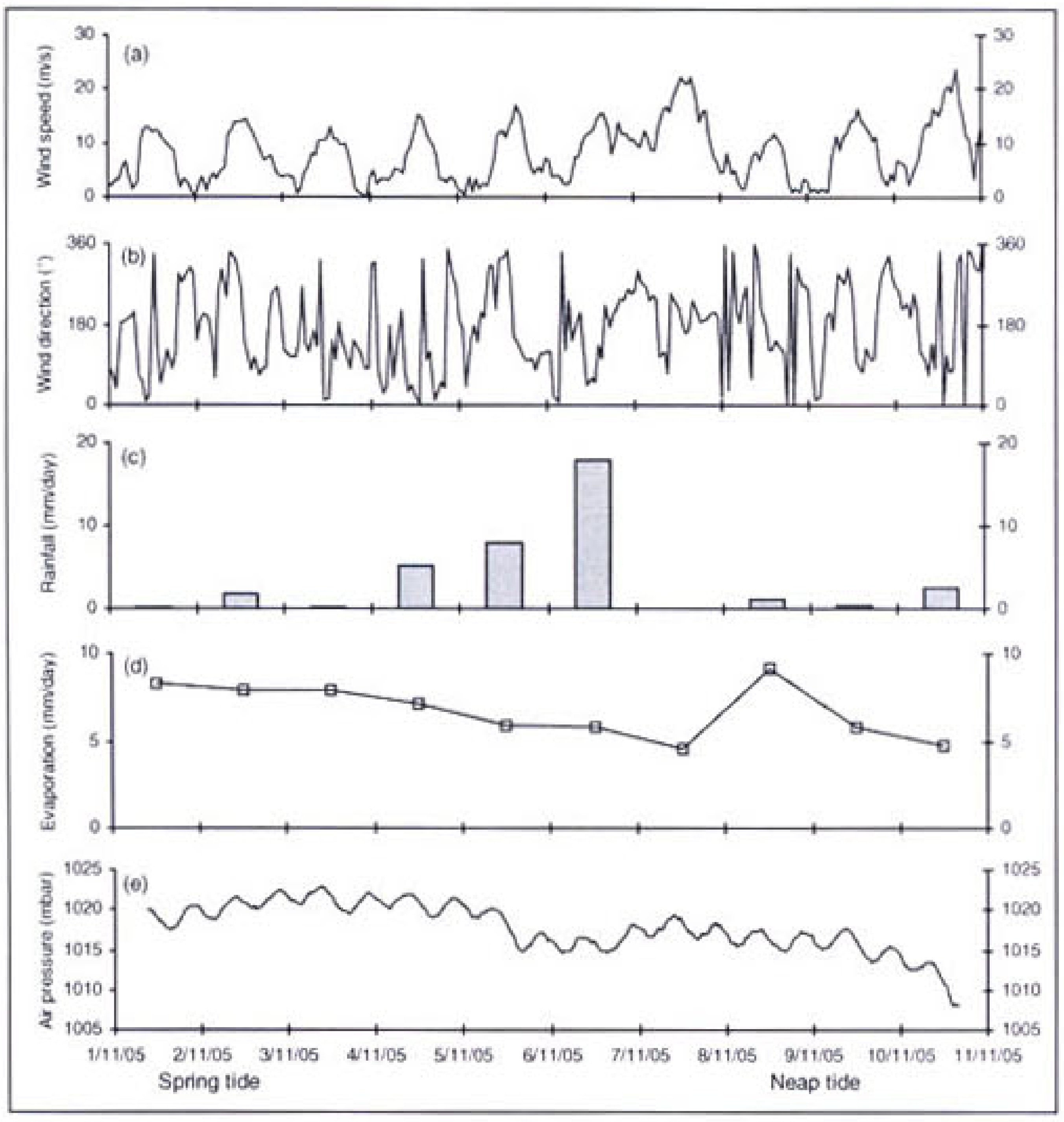

Figure 2. Meteorological data collected on site: (a) wind speed, (b) wind direction, (c) rainfall, (d) evaporation, and (e) air pressure.

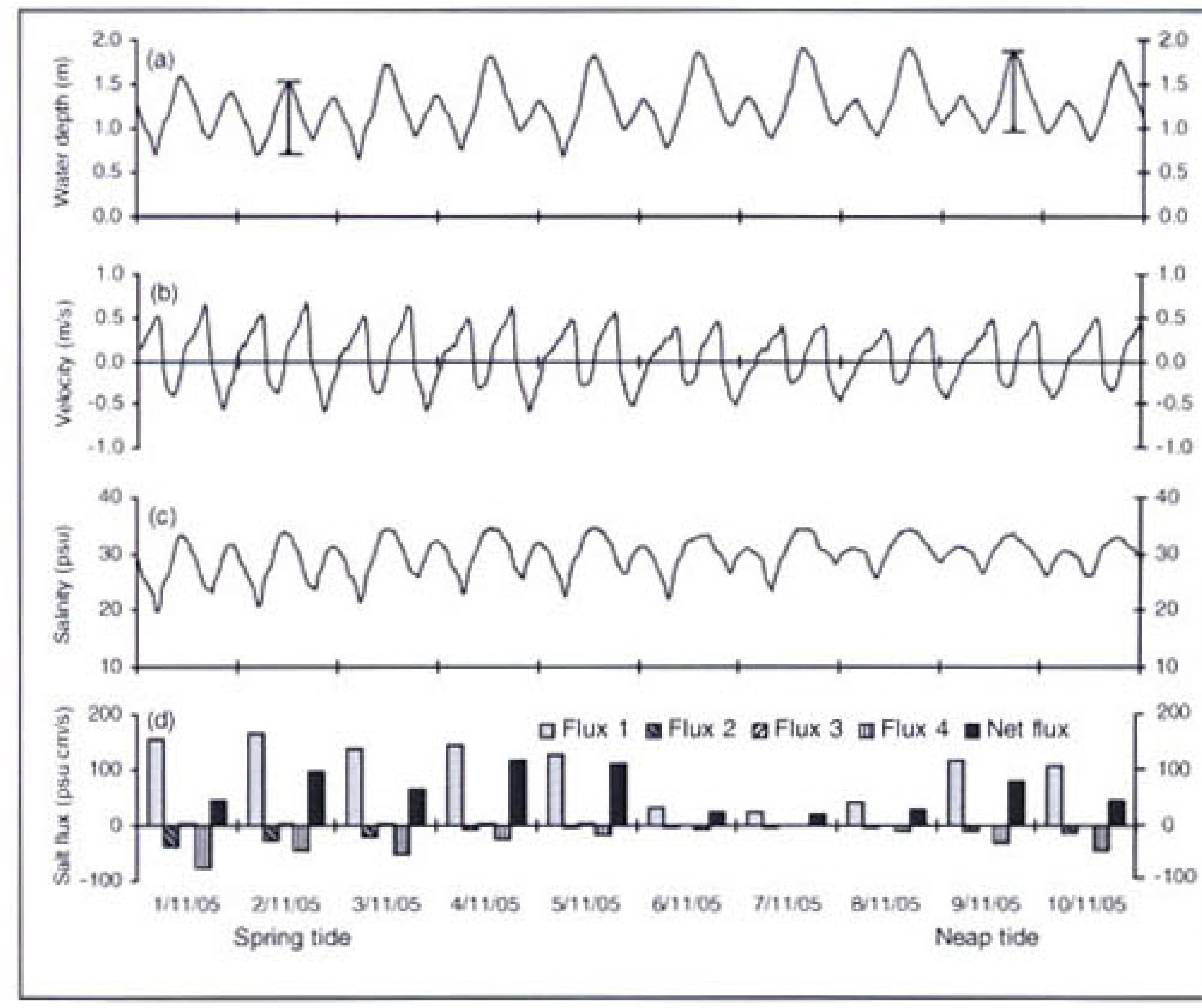

Figure 3. Hydraulic data collected at Station A: (a) water depth, (b) water velocity, (c) salinity, and (d) computed salt fluxes.

and dispersive modes of transport balancing the exchange. Salt fluxes within the lake were calculated for a full tidal cycle (24.5 h) using Equation (4). Because of the very shallow and vertically well-mixed nature of the lake (Benfer, King, and Lemckert, 2007; Dunn *et al.,* 2007a), gravitational circulation within the lake was considered negligible and therefore Flux 5, $\langle h\bar{u}'\bar{s}' \rangle$, in Equation (4) was considered insignificant.

RESULTS AND DISCUSSION

Hydrometeorological Properties

Astronomical tidal constituents were obtained from water level data collected in 2004. The semidiurnal constituents M_2, S_2, K_2, L_2, and N_2 of Coombabah Lake were 0.37 m, 0.02 m, 0.03 m, 0.09 m, and 0.06 m in amplitude with phase lags of 243°, 226°, 121°, 322°, and 161°, respectively. The diurnal constituents K_1, O_1, Q_1, and S_1 were 0.19 m, 0.11 m, 0.03 m, and 0.10 m in amplitude with phase lags of 195°, 99°, 356°, and 131°, respectively. Astronomical tidal constituents were assumed to be the same after 1 year (during this study) because no major changes in geometry and bathymetry of the lake channel system occurred during this period. The lake experiences a mixed tidal regime, mainly of a semidiurnal nature, with a form number of 0.66.

Wind conditions during the 2005 study period were generally moderate but highly variable, ranging from 2 to 20 km/h (see Figure 2a), with the average wind speed at 7 m/s and directed from south or south-east (blowing from the creek mouth to the lake entrance, see Figure 2b). Light rainfall was recorded every day except on November 7, 2005 (see Figure 2c). Rainfall increased gradually from 0.5 mm/d on November 1, 2005 to 18 mm/d (the maximum) on November 6, 2005. Evaporation varied between 5 and 10 mm/d (see Figure 2d), which is greater than the annual regional average (3.5 mm/d) and even greater than the monthly average for the same periods in other years (5 mm/d) recorded by the Australian Bureau of Meteorology (2007). Air pressure also dropped by approximately 5 millibars during the study period (Figure 2e).

Water depth, velocity, salinity, and the computed salt flux components at Station A are presented in Figures 3a–d. A mixed tidal pattern was observed in water depth, velocity, and salinity data, with higher velocity and salinity ranges occurring during spring tides. The opposite trend was observed in the case of the tidal range, where lower ranges occurred during spring tide conditions, compared with the greater ranges observed during neap tide conditions. The spring semidiurnal tide also changed to a mixed type during neap tide conditions. Mean water depth and salinity were greater during neap tide conditions in comparison to the spring tide conditions. Potential explanations for the observed greater water depth during the sampled neap tidal condition were twofold. First, the presence of low air pressure that developed in the region during the neap tidal period resulted in an increase in water level by ~5 cm, and second, a recorded rainfall event within the lake catchment contributed increased freshwater flow into the shallow lake. However, the actual rate of freshwater flow is unknown. The increasing salinity trend was due to the added storage from the seawater, indicating the quantity of freshwater input was relatively small.

Salt Fluxes

At Station A, Flux 1 (advective flux) was the dominant flux, which was directed down the estuary (seaward) at a rate of 155 psu cm/s on November 1, 2005, and reached its maximum

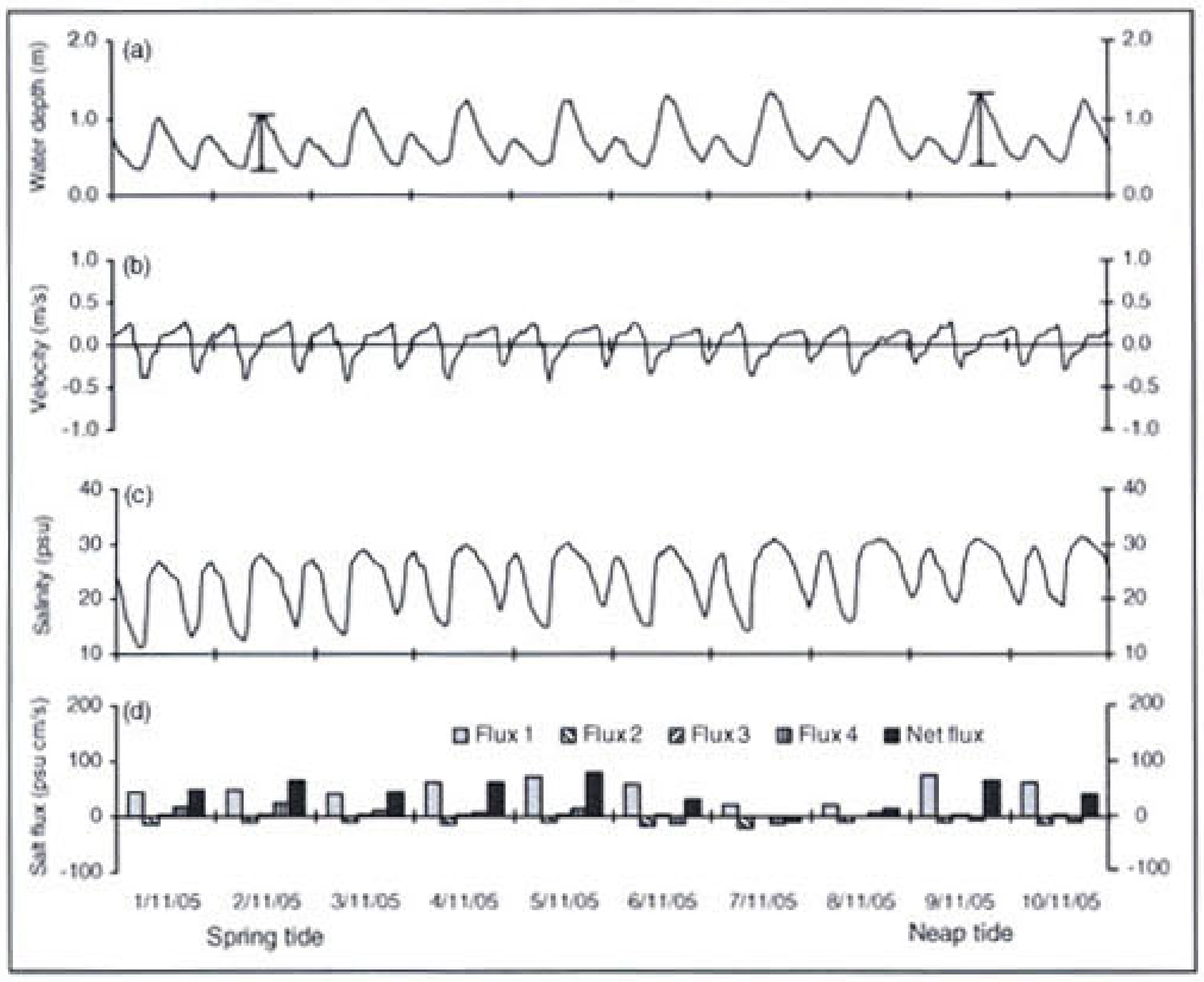

Figure 4. Hydraulic data collected at Station B: (a) water depth, (b) water velocity, (c) salinity, and (d) computed salt fluxes.

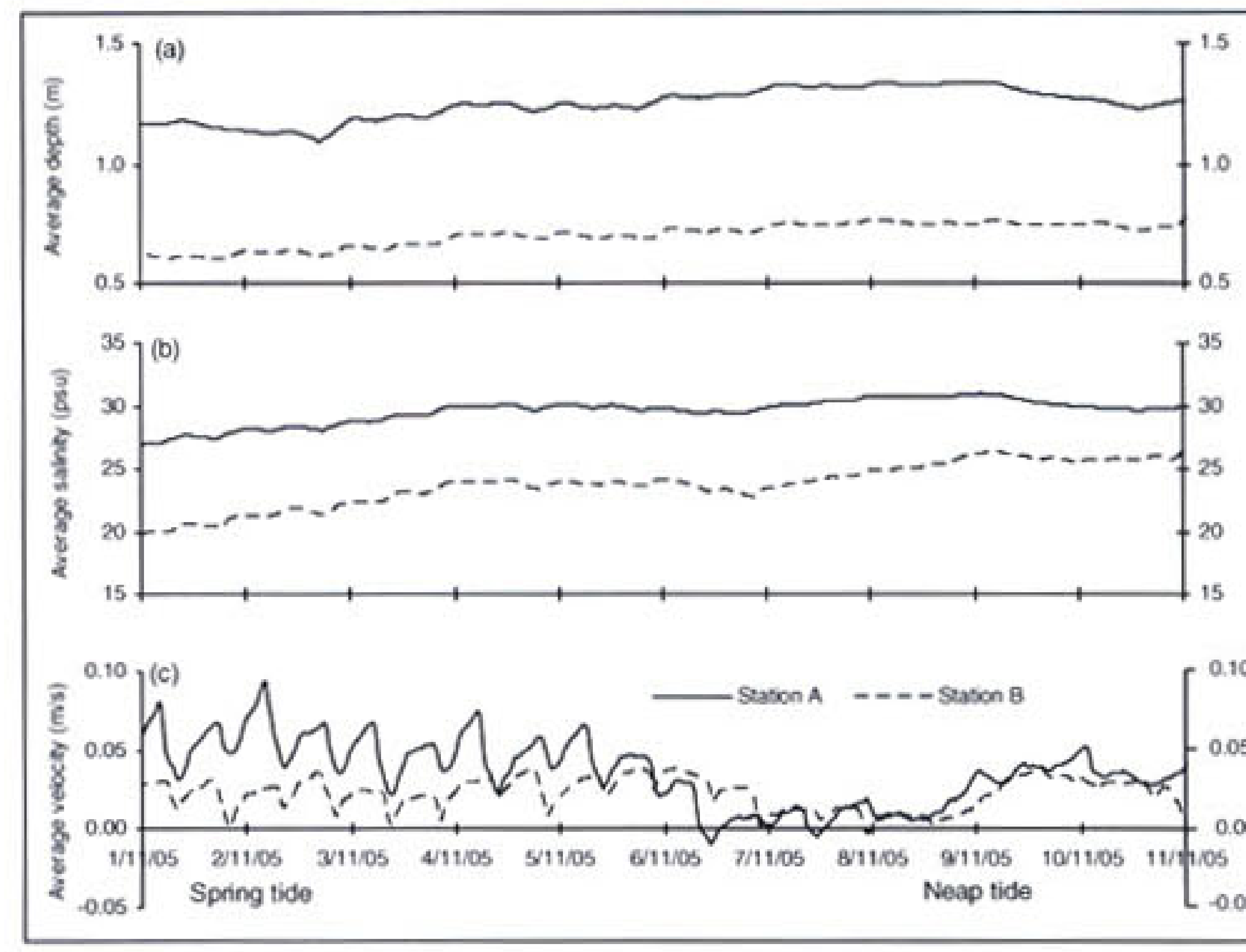

Figure 5. Average hydraulic data at both Stations A and B: (a) water depth, (b) salinity, and (c) water velocity.

value of 165 psu cm/s on November 2, 2005. Following this period, the advective flux began to decline gradually until November 5, 2005 (with an abrupt reduction to 30 psu cm/s from 130 psu cm/s), then remained low for 3 days with only minor fluctuations. It then increased to 115 psu cm/s, followed by a declining trend. Flux 2 (tidal dispersion) followed the same trend as Flux 1 but was directed up estuary (landward) (Figure 3d). The tidal dispersion value during November 1, 2005, was 40 psu cm/s and gradually reduced to 3 psu cm/s during November 6, 2005. This value continued for 3 days with little variation, followed by an increasing trend. Flux 3 (the cross-correlation between tide and salinity) was the smallest contributor to the net salt flux among the four salt flux components and was always directed seaward following the same trend of Flux 1 (Figure 3d). Flux 4 (the Stokes' drift dispersion) was directed upstream and was approximately 100% greater than Flux 2. Overall, Fluxes 1 and 3 contributed to the seaward (downstream) salt flux, whereas Fluxes 2 and 4 contributed to the landward (upstream) salt flux. Therefore, Stoke's drift was the main operator in dispersing salt within the water column of Coombabah Lake. However, Flux 1 was the principal contributor, determining the direction of the net salt flux. Overall, Fluxes 1 and 3 contributed 98% and 2%, respectively, to the seaward salt flux, whereas Fluxes 2 and 4 contributed 30% and 70%, respectively, to the landward salt flux.

Water depth, velocity, and salinity data at Station B showed similar characteristics to that of Station A (Figures 4a–c). Fluxes 1 and 3 at this station (Figure 4d) are also directed seaward (similar to Station A). However, Flux 3 contributed approximately 6% of the total seaward flux (two times more than that of Station A). In contrast to Station A, a gradual increase of the Flux 1 value from 40 to 70 psu cm/s was observed from the beginning of the study until November 5, 2005, then gradually reduced to a minimum value of 20 psu cm/s in 2 days, where it remained relatively constant for the next day, before a further increase to the same order. Moreover, it was approximately half that of Station A (except on November 6, 2005), although Station B was located near the mouth of the creek where predominantly freshwater enters the lake. Unlike Station A, Flux 2 at Station B was almost constant, with a slightly higher value on November 6, 2005; and Flux 4 was directed seaward during the first half of the study period. The net salt flux at this station was also directed seaward during the study period, with an average value of approximately 50 psu cm/s, with the exception of November 7, 2005, when it was directed landward with a value of 10 psu cm/s.

Overall, salt fluxes at both stations followed very similar trends (net seaward flux), with the highest fluxes occurring during the spring tide period, and the lowest, before the neap tide period. Moreover, the advective flux was always dominant and determined the direction of the net flux at both stations.

No direct relations between salt fluxes and spring-neap tidal variations were observed during this study. Variations of advective, as well as net salt flux at Station B, were, therefore, likely the result of rainfall events because it followed the same trend of rainfall recorded at the study site. Greater advective values correlated with greater recorded rainfall events and, similarly, lower values with reduced rainfall events. However, rainfall within different areas of the catchment might be different from that measured on-site, which caused a time lag/lead between rainfall peaks and salt flux peaks.

Water depth and salinity were lower during spring tide and higher during neap tide conditions (see Figure 5). The higher depth during neap tide phase (Figure 5a) conditions resulted from higher storage of seawater in addition to the freshwater from the catchments because advective fluxes within the lake were reduced during this period. Furthermore, increasing water depth within the lake aided in diffusion of salts and, thus, reduction in variation of salt concentrations within the lake during the neap tide phase (Figure 5b). However, the advective flux was directly related to the net velocity (Figure 5c), which controlled the direction of the net salt flux.

The advective flux at Station A was consistently greater in comparison to Station B, with the exception of November 7, 2005, when it was reduced to half that of Station B. An investigation of the data revealed the possibility of the occurrence of horizontal circulation within the lake as a result of a distinct ebb-flood channel system (Ahnert, 1960; Nguyen *et al.,* 2008). Circulation within the lake was generally anticlockwise and opposed by the strong southerly winds that occurred during the study period. The left channel of the lake, on the western side of the large island, (see Figure 1), is a flood-dominated channel; on the other hand, the eastern, curved main channel is an ebb-dominated channel. Therefore, net transport of salt through the left channel was landward, whereas that through the main channel was seaward, creating an anticlockwise horizontal circulation (see Figure 1). The circulation could be augmented by a wind-induced setup. This circulation increased advective flux at Station A, in addition to increasing the net storage of the lake. There are no data from the left channel because it was believed to be shallow and unimportant at the onset of the study.

The salinity difference between Stations A and B was 7 psu during the spring tide phase, which was reduced to 4 psu during the neap tide phase (see Figure 5b). On average, the dilution was observed to be 25% during this study period, which also supports the dominance of advective flux caused by freshwater flow.

CONCLUSIONS

Similar to previously reported studies, residual water transport within the shallow waters of Coombabah Lake was identified as the dominant factor influencing residual salt transport. Furthermore, this study indicates the net salt flux alternates frequently in contrast to the steady state condition. Future investigations in the form of continuous long-term studies are required to determine when the net salt flux would change in direction at any particular lake location. Additionally, this study has identified that advective flux was of primary importance in the movement of salts within Coombabah Lake (contributing 65% of the total salt flux in this shallow subtropical estuary) and that the lake was characterised by greater average water depth during neap tide phases, which aids in the diffusion of salts, with a 25% dilution occurring within the lake system. The lake was not an inverse type of estuary during this study because of freshwater input. Future modelling studies of the lake will be required to investigate the existence of any horizontal circulation.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial assistance of the Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management. Acknowledgments are also made to Nathan Benfer and Peta Williams (Griffith University) for their assistance with fieldwork. The authors extend their acknowledgement to anonymous reviewers for their insightful comments.

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