Sediment Dynamics of a Very Shallow Subtropical Estuarine Lake

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ABSTRACT

Ali, A.; Lemckert, C.J.; Zhang, H., and Dunn, R.J.K., 0000. Sediment dynamics of a very shallow subtropical estuarine lake. *Journal of Coastal Research*, 00(0), 000–000. Coconut Creek (Florida), ISSN 0749-0208.

Estuaries are of immense importance to many communities. The characteristics of estuarine flow and sediment conditions are important, since they play a critical role in the functionality and health of these systems. This study investigated sediment dynamics of a very shallow subtropical estuarine system: Coombabah Lake, southern Moreton Bay (Australia). Total suspended solid concentrations, turbidity, salinity, and tide levels were measured at eight stations within the lake. *In situ* current velocity and meteorological data were also collected during the study period, and data were analysed to determine the dominant sediment dynamic processes within the lake. Sediment transport was simulated using a three-dimensional numerical model to better understand the influence of various physical processes. Influence of sea-level rise on the sedimentary dynamic processes was also examined. Results of the study identified that sediment dynamics were dominated by advection processes driven by the influence of tides, with wind and wave forcing playing minor roles during the study period. Model simulations agreed well with the collected field data. The influence of sea-level rise within the system was predicted to reduce the turbidity of the system, and presumably increase primary productivity.

ADDITIONAL INDEX WORDS: *Sediment dynamics, shallow estuary, subtropical, Coombabah Lake.*

INTRODUCTION

Estuaries are of immense importance to many communities. It has been estimated that 60%–80% of commercial marine fishery resources depend on estuaries for part or all of their life cycle (Klen, 2006). The characteristics of estuarine flow and sediment conditions are important, since they play a critical role in the functionality and health of these systems. Knowledge of suspended sediment dynamics is essential for quantifying fluxes of substances and determining the fate of pollutants (Regnier and Wollast, 1993). Resuspension of bottom sediments has been shown to influence productivity in shallow-water environments (Christiansen *et al.*, 1997; Cloern and Nichols, 1985) through water column enrichment by nutrients originating from the sediment (Kemp and Boynton, 1984; Simon 1989; Tengberg, Almroth, and Hall, 2003) and impacting light availability (Anthony *et al.*, 2004; Lawson *et al.*, 2007; Olesen, 1996). Additionally, resuspension events potentially impact water quality through release of trace metals and

organic contaminants (Liu, Hsu, and Kuo, 2002; Morin and Morse, 1999; van Rijn, 1993). The movement of sediments can cause siltation to occur in estuarine and coastal waters, including harbours and ports, or erosion of estuarine banks, which are mitigated by expensive dredging operations or bank protection measures, respectively (Liu, Hsu, and Kuo, 2002). Sedimentation may also lead to mortality of benthic communities through smothering and burial (Morris and Howarth, 1998; Norkko, Hewitt, and Thrush, 2006).

Therefore, an understanding of the controlling mechanisms and accurate predictions of sediment transport processes in estuarine and coastal waters are of fundamental importance to engineering design awareness and the management of these environments (*e.g.* Bartley *et al.*, 2012; Droppo *et al.*, 2011; Liu, Hsu, and Kuo, 2002; Lopes, Dias, and Dekeyser, 2006; van Maren and Hoekstra, 2004).

Mechanisms controlling the transport, resuspension, and deposition of fine sediments (and sediment-bound contaminants) within tide-dominated estuaries are extremely complex. Numerous investigations of near-bed flows, resuspension, and transportation of sediments under natural field conditions have been undertaken to date, with many involving non-cohesive sediments (*e.g.* Soulsby, Atkins, and Salkield, 1994), offshore sites (*e.g.* Nikora, Goring, and Ross, 2002; Williams *et al.*, 1999), or coastlines dominated by wave actions (*e.g.* Davies, 1985; Zhang and Chan, 2003; Zhang, Sannasiraj and Chan,

DOI: 10.2112/JCOASTRES-D-12-00255.1 received 4 December 2012; accepted in revision 7 April 2013; corrected proofs received 17 July 2013

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Published Pre-print online 2 August 2013.

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2009). Furthermore, since many estuaries have regions dominated by tidal mudflats, considerable efforts have been made to investigate the resuspension mechanisms and transportation processes of cohesive sediments in estuarine settings (e.g. Brand *et al.*, 2010; Giardino *et al.*, 2009; Guan, Wolanski, and Dong, 1998; Hayter and Mehta, 1986; Liu, Hsu, and Kuo, 2002; Uncles and Stephens, 2010).

Surrounded by two environmental reserves (Coomababah Lake Nature Reserve and the Ivan Gibbs Wetland Reserve), Coomababah Lake (Figure 1) is an area of significant international importance under the Ramsar Convention on Wetlands, and it is classified as a fish habitat area within the Moreton Bay Marine Park. The wetland serves as an important wildlife corridor between the Nerang State Forest and the coastline (Frank and Fielding, 2004). Over the past five decades, human activities surrounding Coomababah Lake (including the clearing of land for golf courses and the construction of a sewage treatment plant on the eastern margin of the lake) have significantly altered the catchment and surrounding land use. According to the regional importance of the lake and surrounding wetlands, the region has been the focus of recent scientific efforts (e.g. Ali, Lemckert, and Dunn, 2010; Ali, Zhang, and Lemckert 2009; Dunn *et al.*, 2007a, 2007b, 2008, 2012; Knight *et al.*, 2008), with most efforts being aimed at understanding the physical and biogeochemical processes within the lake. Previously, Ali, Lemckert, and Dunn (2010) quantified salt fluxes of Coomababah Lake and determined the dominant mixing processes of this estuarine system and recommended further modelling studies. Subsequently, Ali, Zhang, and Lemckert (2009) carried out a hydrodynamic modelling study of this shallow intertidal system to understand the hydrodynamics of Coomababah Lake and similar systems; however, knowledge of sediment dynamics within the system is still poor.

In this paper, 10 days of hydrodynamic and suspended sediment field data and a three-dimensional modelling system, MIKE3 FM (DHI, 2008a, 2008b), is used to provide an understanding of the sediment dynamics (more specifically; the primary source, distribution, settling, resuspension, and transport of cohesive sediments) of a shallow intertidal lake system, using Coomababah Lake and the surrounding areas as a case study. The output from the model simulations and field-measured data were compared to evaluate the model reliability. The influence of sea-level rise on the sedimentary process within the shallow intertidal lake system was also examined. Further, the sensitivity of bed roughness on the sedimentary process was additionally examined using the numerical model.

STUDY SITE

Physical and Hydrological Setting of Coomababah Lake

Coomababah Lake is a subtropical estuarine system situated within southern Moreton Bay, Australia, located in the midtidal region of Coomababah Creek. The lake covers $\sim 2 \text{ km}^2$ with an urbanised catchment area of 44 km^2 characterised by residential, commercial, and light industrial developments. Additionally, the lake (Figure 1a) is a shallow body of water characterised by a relatively flat bathymetry (Figure 1b), with a mean depth of $\sim 0.5 \text{ m}$ and is influenced by a predominantly semidiurnal mixed tidal regime with a range of less than 1 m

(Ali, Lemckert, and Dunn, 2010). During periods of low water, large portions of the surface sediments become exposed. Mud ($< 63 \mu\text{m}$) and sands ($> 63 \mu\text{m}$) dominate the southern (landward) and northern (seaward) surface sediments, respectively (Dunn *et al.*, 2007b, 2008). During dry conditions (*i.e.* no influence of rainfall runoff) peak velocities during flood/ebb tides at the creek mouth are $\sim 0.25 \text{ m s}^{-1}$ (Ali, Lemckert, and Dunn, 2010). On the other hand, the peak velocity within the main channel near the lake entrance is $\sim 0.5 \text{ m s}^{-1}$ during the same period because of the differences in the tidal prism and channel geometry. Episodically, large inputs of freshwater from Coomababah Creek occur during periods of heavy rainfall, mostly during summer storm seasons, where rainfall runoff enters the lake through the SW creek entrance (hereafter referred to as the creek mouth), and leave the lake from the NE entrance (hereafter referred to as the lake entrance). Ultimately, Coomababah Creek discharges into the Gold Coast Broadwater, within southern Moreton Bay.

During the study period (1–10 November 2005) freshwater runoff input to the lake *via* Coomababah Creek was $\sim 2.5 \text{ m}^3 \text{ s}^{-1}$.

METHODS

Field and Laboratory Measurements

In situ hydraulic measurements were conducted within Coomababah Lake from 1 to 10 November 2005 during a parallel study investigating the variability of physiochemical parameters and transport of filterable nutrients (see Dunn *et al.*, 2007a). The measurements captured both spring and neap tidal variations. Water depth, salinity, and turbidity were measured simultaneously at eight stations (1–8; Figure 1b) utilising moored conductivity–temperature–depth (CTD) probes (NXIC-CTD; Falmouth Scientific, Inc., Cataumet, Massachusetts, U.S.A.). The CTD sensors were positioned $\sim 15 \text{ cm}$ above the surface sediment and collected data for 3.5 minutes (at a frequency of 10 Hz) every 15 minutes. Station 1 was most influenced by catchment flows (freshwater) in comparison with Station 8, which was most influenced by the tidal (seawater) regime (Ali, Lemckert, and Dunn, 2010; Ali, Zhang, and Lemckert, 2009). Station 8 also represented the deepest point within the lake, followed by Stations 4 and 1, all of which remained submerged for the majority of the study period. Station 5 represented the shallowest sample location followed by Station 7, both of which become exposed during all low tides. Stations 2, 3, and 6 were exposed only during low tide spring conditions.

Current data were collected at Stations 1 and 8 using acoustic Doppler velocimeters (ADV; Vector velocimeter; Nortek AS, Rud, Norway) positioned $\sim 30 \text{ cm}$ above the surface sediment. ADV sensors collected data at burst intervals of 30 minutes, at a frequency of 32 Hz and 4096 samples per burst.

Two water samples and associated turbidity recordings were simultaneously collected at each station daily during high tides. Water samples were collected manually using a sample pole and 500-mL low-density polyethylene (Nalgene) sample bottles at a depth $\sim 30 \text{ cm}$ below the water surface from a small flat-bottom research vessel. Turbidity values were recorded using a hand-held Nephelometer (NEP 160 Turbidity meter, McVan Instruments Pty. Ltd.). The sampling depth at the

Figure 1. (a) Location map of the study site and (b) lake bathymetry with sampling (circle) and model boundary (triangle) locations (AHD = Australian Height Datum).

majority of the stations represented the middepth, since total water depths were ~ 0.5 m. Great care was taken during vessel movement and sample collection to avoid both wave action and propeller induced resuspension of bottom sediments. Wave heights and periods were visually estimated at all stations during water sampling. Additionally, water samples for the determination of total suspended solid (TSS) concentrations were also collected on an hourly basis for 13 hours on 4 November 2005 in order to determine the tidal variations. TSS samples were filtered through preweighed GF/F membranes (47-mm diameter, Millipore), and the membranes air dried to constant weight in desiccators (Balls, 1994).

The bathymetry of the lake was also measured using a hand-held Trimble real time kinetic global positioning system unit (horizontal error < 0.50 m and vertical error < 0.20 m). Bathymetric sample points ranged from spacing of ~ 1.0 m to ~ 100 m within the lake. During the study period, a temporary weather station (WeatherMaster 2000; Envirodata) was also installed on a houseboat anchored within the lake (see Lee, 2006). Meteorological conditions, including air pressure, solar radiation, humidity, rainfall, wind speed, and wind direction, were recorded every 15 minutes during the study period. Daily evaporation was estimated from the collected meteorological data using a modified Penman equation (EnvirodataEasiAccess software).

Numerical Model

A three-dimensional flexible mesh modelling system, MIKE3 FM (DHI, 2008a), was used to simulate the sediment dynamics within Coombabah Lake. A horizontally unstructured grid was used, with larger cells within flat areas and smaller cells within narrow channels. Grid cells were triangular in shape, ranging

in size from ~ 400 m² to ~ 1800 m², and totalled 1548 within the grid domain. A vertically structured bottom-fitted sigma grid system was used with eight layers of different thickness, with thicker layers near the water surface and thinner layers near the bottom. The top three layers were equally spaced, with each layer thickness 0.2 times the total water depth; the next three layers were equally spaced, with each layer thickness 0.1 times the total water depth; and the bottom two layers were also equally spaced, with each layer thickness 0.05 times the total water depth. The hydrodynamic model is based on the solution of the three-dimensional incompressible Reynolds averaged Navier-Stokes equations, subject to the assumptions of Boussinesq and hydrostatic pressure (DHI, 2008a). MIKE3 FM uses a standard advection-diffusion equation for simulating transport of scalar quantities (e.g. salinity, suspended sediment).

The bed shear stress $\bar{\tau}_b = (\tau_{bx}, \tau_{by})$ was determined by a quadratic friction law:

$$\frac{\bar{\tau}_b}{\rho_0} = c_f \bar{u}_f |\bar{u}_f| \quad (1)$$

where x and y are horizontal coordinates; c_f is the drag coefficient; $\bar{u}_f = (u_f, v_f)$ is the flow velocity at a distance Δz_b above the bed; and the drag coefficient is

$$c_f = \left(\frac{\kappa}{\ln \left(\frac{\Delta z_b}{z_0} \right)} \right)^2 \quad (2)$$

where $\kappa = 0.4$ is the von Kármán constant; $z_0 = k_s/30$ is the bed roughness length scale; and k_s is the roughness height.

Deposition occurs when the computed bed shear stress is less than the critical bed shear stress for deposition (a predefined

value). Alternatively, erosion occurs when the computed bed shear stress is greater than the bed shear stress for erosion (another predefined value).

A sediment transport model was set up for Coombabah Lake utilising the calibrated hydrodynamic model of Ali, Zhang, and Lemckert (2009). The hydrodynamic model was calibrated against water levels and velocities measured at Stations 1 and 8. Bathymetric correction, bed roughness, and eddy viscosity were tuned in the calibration processes.

The bed sediments may potentially be resuspended by surface shear stress in shallow lake systems. Measured wind data was utilised for the simulation of surface shear stresses. Sediment transport modelling depends to a greater extent on the bed shear stress and the bed roughness (Whitehouse *et al.*, 2000). In most cases, numerical models (*e.g.* MIKE3, ECOMSED) simulate bed shear stress from near-bed velocities and bed roughness using Equations (1) and (2). In the present study, site-specific bed shear stress and bed roughness data collected by Ali, Zhang, and Lemckert (2009) from the Coombabah lake–creek system using a traversing system developed by Ali and Lemckert (2009) were used as the boundary conditions. Sediments start to move when simulated bed shear is greater than a predefined critical bed shear stress and begin to settle down when simulated bed shear stress is less than a predefined critical bed shear stress. Critical bed shear stresses for erosion and deposition differ based on bed composition and depositional history. In contrast to other hydraulic parameters (*e.g.* water depth and flow velocity), bed roughness within the lake was quite homogenous (Ali, Zhang, and Lemckert, 2009). Since the model utilised a homogeneous and measured bed roughness, it was not changed during the sediment transport model calibration. However, sensitivity of bed roughness on sediment concentration was investigated.

Tide levels were predicted utilising astronomical tidal constituents estimated by Ali, Lemckert, and Dunn (2010); thus, predicted tide levels were applied as open boundary conditions. Measured time series of precipitation, evaporation, and wind were applied as other forces in the model. A source point was also added at the creek mouth (see Figure 1b; Easting 534285 m, Northing 6911760 m) to represent the freshwater flow upstream of Coombabah Creek. Flow of the source was estimated from the measured velocity at Station 1 multiplied by the mean depth and width of the creek.

The sediment transport model was utilised to simulate cohesive sediment only. Constant sediment concentrations were used at the open boundary and at the source point. A constant bed roughness height (k_s) of 0.1 m obtained from the hydrodynamic model calibration of Ali, Zhang, and Lemckert (2009) was utilised in the sediment transport model.

Tide levels used as downstream boundary condition were raised by up to 0.5 m with 0.1-m increments to quantify the impact of various sea-level rises on the behaviour of this shallow estuarine lake. These levels were chosen because they represent a realistic predicted rise in levels for the next 50 years, which is at the lower end of expected sea-level changes (Cooper and Lemckert, 2012). TSS concentrations within the lake for various sea-level rises were analysed to quantify the impact of increased water depth on TSS concentrations from similar sources.

Figure 2. Measured hydraulic and water quality data: (a) water depth, (b) flow velocity, (c) salinity, and (d) turbidity.

RESULTS AND DISCUSSION

Field Observations

A mixed tidal pattern was observed within the depth, velocity, and salinity data, with higher velocity and salinity values occurring during spring tides at both Stations 1 and 8 (Figure 2a–c). However, an unusual tidal phenomenon was observed within Coombabah lake system during the study period. Lower tidal ranges occurred during spring tide conditions compared with the greater tidal ranges observed during neap tide conditions. The spring semidiurnal tide also changed to a mixed type during neap tide conditions. Moreover, the high water level during the neap tide period was higher than the high water level during the spring tide period. Mean water depth and salinity values were greater during neap tide conditions in comparison with the spring tide conditions (Figures 3a–b). Potential explanations of these peculiarities are twofold. Firstly, the presence of a low air pressure system that developed in the region during the neap tidal period resulted in an increase in water level of ~5 cm, and secondly, the occurrence of a recorded rainfall event within the lake catchment contributed increased freshwater flow into the shallow lake (see Figure 4). However, the actual rate of freshwater inflow into the lake is unknown. The observed increasing salinity trend was due to the added storage from the seaward, indicating the quantity of freshwater input was relatively small. Salinity of the lake followed the tide with high salinity during high tides and low salinity during low tides (Figure 2c). Alternatively, turbidity values were lower during high tides and higher during low tides (Figure 2d). The higher water depth due to the low atmospheric pressure and high catchment runoff activated higher tidal energy in the lake system. The observed turbidity at Station 1 was much higher (almost four times) than the turbidity observed at Station 8. On the other hand, salinity and flow velocity at Station 1 were

Figure 3. Tidally averaged hydraulic and water quality data: (a) water depth, (b) salinity, and (c) turbidity.

lower than that of Station 8, suggesting most of the suspended sediments within the lake are catchment borne and enter the lake through the upper Coombabah Creek with catchment runoff. The turbid lake water mixes with relatively clear sea water during flood tides and propagates seaward during the ebb tide (*i.e.* relatively clear seawater pushes back turbid lake waters and reduces suspended sediment concentration during the flood tide). Observed sediment data reveals that advection is the dominant process of transporting sediment within Coombabah Lake. Ali, Lemckert, and Dunn (2010) previously identified advection as the dominant process of transporting salinity within Coombabah Lake. Mitchell *et al.* (2008) also

Figure 4. On-site meteorological conditions: (a) wind speed, (b) wind direction, (c) rainfall, and (d) air pressure.

Figure 5. Measured TSS concentrations (duplicate water samples) and total water depth at Station 4.

identified advection *via* tide as the dominating factor of solute transport in a similar case study in the United Kingdom. In contrast to water depth and salinity, mean turbidity at Station 1 was increased during spring tide and low during neap tide periods (Figure 3). The opposite trend was observed at Station 8, where low turbidity values during spring tide and high turbidity values during neap tides were observed. The large tidal range during neap tide increased mixing and flushing capacities of the lake and therefore reduced the turbidity at Station 1 compared with the spring tide periods. Station 8 experienced increased turbidity during neap tide periods due to a high mixing rate. Being located in a subtropical region, Coombabah Lake system experiences similar hydrometeorological conditions time and again.

Wind conditions during the field campaign were generally moderate but highly variable, ranging from 2 to 20 km h⁻¹ with a mean wind speed of 7 km h⁻¹ directed from the S or SE (blowing from the creek mouth to the lake entrance) (Figures 4a and b), which is the dominant wind direction for coastal SE Queensland during this seasonal period. Light rainfall was recorded every day except on 7 November 2005. Rainfall increased gradually from 0.5 mm day⁻¹ on 1 November 2005 to 18 mm day⁻¹ (the maximum) on 6 November 2005. Additionally, air pressure also lowered by ~5 mbar during this period. In general, waves were small with approximate heights and periods of 0.2 m and 2 s, respectively.

Observed TSS concentrations within the lake varied temporally and spatially. TSS concentrations were elevated during the spring tide period and reduced during the neap tide period (Figure 5). Concentrations gradually reduced by 50% (from 0.30 kg m⁻³ to 0.15 kg m⁻³) during the study period (Figure 5). This resulted from the large tidal range during the neap tide period, increasing the mixing and flushing capacity of the lake, thus reducing the TSS concentration within the lake. Additionally, increased water depths during the neap tide reduced the wave-induced resuspension of bed sediments that also favoured the sediment settling process.

Variations of approximately 0.05 kg m⁻³ were observed between the duplicate TSS samples collected from the same

sites and sample depth within a short time period (*e.g.* minutes apart) (Figure 5). This variation is presumably a result of the variability of TSS concentrations within the dynamic environment and (to a much lesser extent) possible uncertainties in sampling and analysis processes.

Mean TSS concentrations over the study period at Stations 1, 2, 3, 4, 5, 6, 7, and 8 were 0.236, 0.230, 0.281, 0.215, 0.228, 0.261, 0.266, and 0.166 kg m^{-3} , respectively. Mean TSS concentrations revealed the landward and shallower stations experienced higher TSS concentration compared with the seaward and relatively deep stations. The highest mean TSS concentration was observed at Station 3, and the lowest at Station 8. Being located near the sediment source (creek mouth), Station 1 experienced a greater TSS concentration compared with other deeper stations. Increased TSS concentrations at the shallower stations presumably resulted from sediment resuspension caused by wind and wave activity.

Model Calibration

The sediment transport model was calibrated against TSS concentrations measured from 1 to 10 November 2005. Critical bed shear stresses, dispersion coefficients, and sediment boundary conditions were adjusted during the calibration processes. Through a calibration process, this study selected the value of critical bed shear stresses for erosion and deposition as 0.4 N m^{-2} and 0.1 N m^{-2} , respectively. The selected bed shear stress values are within the range observed in mud-dominated estuarine systems (Araújo, Teixeira, and Teixeira, 2008; Tolhurst *et al.*, 1999; Verney *et al.*, 2006). Horizontal and vertical dispersion parameters were also refined during the calibration process, and a horizontal dispersion coefficient of $1 \text{ m}^2 \text{ s}^{-1}$ was selected as a constant over time and space. The vertical eddy viscosity selected from the hydrodynamic model calibration was used as the vertical dispersion coefficient with a scaling factor of 1. Owing to the lack of observed data, constant TSS concentrations (which were determined through a trial-and-error method), were used at the source point and open boundary. Generally, estuarine systems carry catchment runoff during ebb tides and seawater during flood tides. Maximum TSS concentrations were observed during the ebb tide and minimum TSS concentrations during the flood tide (Figure 6b) periods. The maximum and minimum observed TSS concentrations were 0.4 kg m^{-3} and 0.1 kg m^{-3} at Station 8 (near the lake entrance), respectively. Thus a TSS concentration of 0.4 kg m^{-3} at the upstream source point and 0.1 kg m^{-3} at the downstream open boundary were used in the model and provided improved results. The TSS concentration used at the upstream source point was higher than the observed TSS concentration due to the concentration gradient occurring in a seaward-to-landward direction.

Simulated and observed TSS concentrations of the entire study period matched reasonably well (Figure 6a) compared with the complexity of the sediment transport model. The model produced excellent results during the neap tide period; however, simulated TSS concentrations were lower than those observed during the spring tide period. This underestimation may have resulted from the contribution of marine-borne noncohesive sediment (potentially transported into the lake by strong spring tidal current) to the collected field samples, which

Figure 6. Comparison of simulated and observed TSS: (a) entire study period and (b) one tidal cycle.

has not been considered in this modelling exercise. Additionally, there was a slight phase difference between the simulated and observed TSS concentrations near the spring tide period (Figure 6b), although the magnitudes were quite similar. The variability of TSS concentrations during tidal cycles can be driven by resuspension (Uncles and Stephens, 1998) and advection (van Maren and Hoekstra, 2004) processes, or a combination of both (Pritchard, 2005). Subsequently, this study undertook a modelling investigation to determine the dominant process occurring within this shallow estuarine lake.

Simulation Results

The numerical model described previously was utilised to characterise the dynamics of cohesive sediments within the lake in order to assess the contribution of the main forces: tides, runoff, waves, and winds. The sensitivity of bed roughness on the sediment transport was also investigated. Simulation results demonstrated that the TSS concentrations during the ebb tide period (Figures 7b, d, and f) were much higher than those during the flood tide period (Figures 7a, c, and e). The model replicated the observed TSS concentration distribution reasonably well. TSS concentrations mapped during the flood tide period showed high concentrations (0.45 kg m^{-3}) at the shallow landward stations and low concentrations (0.15 kg m^{-3}) at the relatively deeper seaward stations, which is in agreement with the field observations. TSS concentrations near the eastern and western edges of the lake were increased during high tide periods. Observed salinity was also low at

Figure 7. Simulated TSS concentrations: (a, b) with no waves and winds; (c, d) with waves; and (e, f) with winds (left panel during flood tides and right panel during ebb tides).

these shallow areas during high tides. Therefore, these areas experience relatively low mixing regimes with seawater and consequently low flushing by tidal flows. Simulated velocity distribution during flood and ebb tides (Figure 8) also supports

it. On the other hand, seawater carrying low suspended sediment loads mixes with sediment-laden catchment runoff within the channels, ultimately flushing these out of the system during ebb tides.

Figure 8. Simulated velocity distributions during (a) flood and (b) ebb tides.

Higher TSS concentrations moved seaward during ebb tides. The highest concentration zone was formed around the creek mouth and extended up to the middle region of the lake (Figure 7b). Therefore, the region of highest suspended sediments—the turbidity maxima—could be formed within the creek further upstream of the lake, which moves back and forth under tidal influence. Model results support that advection is the main process of sediment transport within Coombabah Lake, which is driven by the tidal regime. This model produced similar results under both spring and neap tide conditions. Modelling results also revealed catchment runoff was the main source of TSS during this study period.

Figure 9. Simulated TSS concentrations at Station 4 without and with wave and wind activity included.

A constant wave of 0.2 m height and 2 s period directed from the SE was estimated and used in the sediment transport model, which identified that only 5% of the TSS load was borne from the bed, resulting from resuspension by waves during low tides (Figures 7d and 9). Although wave action is important in the mixing and sediment transport processes of shallow-water environments (Zhang *et al.*, 2004), no significant influence of waves on TSS concentrations was observed during high tides within Coombabah Lake for the conditions encountered. The waves were small due to limited fetch, and their influence diminished before reaching the bed sediments during high tides. Resuspension of sediment by waves occurred during low tides only.

Similar to the waves, wind-induced currents and turbulences also increased TSS concentrations during low tides (Figures 7f and 9). The effect was more influential during stronger wind speeds and reduced during weaker winds, as previously reported by Dunn *et al.* (2007a). The spatial distribution of TSS concentrations during low tide periods changed quite significantly due to wind forcing (Figure 7f). During SE winds, the highest TSS concentration zone was enlarged and extended, approaching the lake entrance. On average, wind-generated currents increased the TSS concentration by 7% within the lake system. However, TSS concentrations at Station 4 were increased by ~25% during neap tides (Figure 9) as a result of extension of the high turbidity zone pushed by the SE wind. Although wind and wave actions have a minor effect on TSS concentrations during high tide, the inclusion of these forces provided improved and more representative results. However, very strong wind influences the TSS concentration during both high and low tides. Doubling the wind speed increased the TSS concentration within the lake by approximately three times the observed typical concentrations.

Figure 10. Simulated TSS concentration for various bed roughness values.

The sensitivity of bed roughness to sediment concentrations (Figure 10) revealed the TSS concentration changed by 7% for a corresponding change in bed roughness by 50%. Moreover, bed roughness was not influential during high tides ($<1\%$).

Interestingly, although total water flow was distributed by 60% and 40% between the main channel and left channel (Figure 1) (Ali, Zhang, and Lemckert, 2009), respectively, sediment discharge was distributed the other way. TSS was distributed as 43% and 57% between the main channel and left channel, respectively. TSS concentrations were always higher in the left channel than the main channel, which caused higher sediment discharges through the left channel than the main channel. This occurrence has also been observed within a similar subtropical estuary in Bangladesh (Ali, Mynett, and Azam, 2007). Although flood tides have a higher sediment carrying capacity, in this instance flood tides carried less sediment, since the main sediment source is located upstream. However, the flood tide may potentially transport higher quantities of noncohesive sediment (which has not been considered in this modelling exercise).

Influence of Sea-Level Rise

The simulated results revealed that in the event of an increase in the regional sea level, a reduction in TSS concentration would typically occur, potentially providing a positive influence on water column (*i.e.* phytoplankton) and benthic (*i.e.* algae and macrophytes) productivity within the shallow lake environment. The predicted mean TSS concentrations corresponding to hypothetical increases in sea level for the lake over the 10-day simulation period are presented in Table 1. The results from the simulation show a predicted reduction of TSS concentrations on the order of 10%, corresponding to an increase in sea level by 0.2 m. A general reduction in TSS concentrations would improve water clarity, increasing the photic depth. Increased irradiance within the water column would presumably benefit primary productivity (MacIntyre, 1993; Underwood and Kromkamp, 1999) within the shallow intertidal lake by providing increased light during periods of high water.

Table 1. Predicted lake-wide mean TSS concentrations during the 10-day simulation period for various sea-level rises.

Sea-level rise (m)	Mean TSS concentration (kg m^{-3})	Reduction in TSS concentration (%)
0.0	0.266	0.0
0.1	0.249	6.9
0.2	0.240	10.7
0.3	0.236	12.7
0.4	0.234	13.6
0.5	0.233	13.9

TSS concentrations within the lake were reduced by the simulated rise in sea level due to the intrusion of relatively clear water from the sea. In general, estuarine lake systems receive pollutants from upstream catchments, which are generally diluted by downstream sea waters. In contrast, the lake would be negatively affected where pollutant sources have been identified downstream of the lake system (Dunn *et al.*, 2007a; GHD, 2003). This study considered no change in upstream conditions as a result of the sea-level rise. Furthermore, the model was not extended beyond the lake system and did not include the surrounding mangrove environments.

CONCLUSIONS

Intratidal variations of sediment concentrations are relatively higher than subtidal variations within Coombabah Lake. Shallow landward zones of the lake experience low flushing, and therefore retain greater suspended sediment concentrations compared with the more well-defined central channels. In contrast to the general tendency, the lake experienced increased mixing as well as increased flushing during the neap tide period than the spring tide period as a result of higher tidal range (*i.e.* higher energy) during the neap tide period. Catchment runoff was determined as the main source of cohesive sediment input for the lake system. During the study period, wind-generated currents contributed 7% of the sediment resuspension within the lake. Alternatively, wave action contributed 5% of sediment resuspension but was limited to periods of low tide. Waves were considered not important in this shallow lake system due to the limited fetch and young nature of the waves. Sediment dynamics of this subtropical estuarine lake system are dominated by advection processes driven by tides rather than by local resuspension and weak mixing processes. Sea-level rise was predicted to have a positive impact on the productivity of shallow estuarine lake systems by reducing turbidity and thus improving the water quality where a pollutant source is not located downstream of the lake.

ACKNOWLEDGMENTS

The authors would like to acknowledge DHI Water and Environment, Denmark, for their assistance in providing the MIKE modelling system for this study. The authors would also like to acknowledge the financial assistance of the Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management, Australia. Acknowledgments are made to P. Williams, N. Benfer, and the Griffith School of

Engineering laboratory technicians (Griffith University, Gold Coast Campus) for their assistance with field work.

REFERENCES

- Ali, A. and Lemckert, C.J., 2009. A traversing system to measure bottom boundary layer hydraulic properties. *Estuarine, Coastal and Shelf Science*, 83, 425–433.
- Ali, A.; Lemckert, C.J., and Dunn, R.J.K., 2010. Salt fluxes in a very shallow sub-tropical estuary. *Journal of Coastal Research*, 26(3), 436–443.
- Ali, A.; Mynett, A.E., and Azam, M.H., 2007. Sediment dynamics in the Meghna estuary, Bangladesh: a model study. *Journal of Waterway, Port, Coastal and Ocean Engineering*, 133(4), 255–263.
- Ali, A.; Zhang, H., and Lemckert, C.J., 2009. Numerical study of the hydrodynamics of a very shallow estuarine system—Coomabab Lake, Gold Coast, Australia. In: da Silva, C.P. (ed.), *Proceedings of the International Coastal Symposium (Portugal 2009)*. Journal of Coastal Research, Special Issue No. 56, pp. 922–926.
- Anthony, K.R.N.; Ridd, P.V.; Orpin, A.R.; Larcombe, P., and Lough, J., 2004. Temporal variation of light availability in coastal benthic habitats: effects of clouds, turbidity, and tides. *Limnology and Oceanography*, 49(6), 2201–2211.
- Araújo, M.A.V.C.; Teixeira, J.C.F., and Teixeira, S.F.C.F., 2008. Application of laser anemometry for measuring critical bed shear stress of sediment core samples. *Continental Shelf Research*, 28, 2718–2724.
- Balls, P.W., 1994. Nutrient inputs to estuaries from nine Scottish east coast rivers: influence of estuarine processes on inputs to the North Sea. *Estuarine, Coastal and Shelf Science*, 39, 329–352.
- Bartley, R.; Speirs, W.J.; Ellis, T.W., and Waters, D.K., 2012. A review of sediment and nutrient concentration data from Australia for use in catchment water quality models. *Marine Pollution Bulletin*, 65(4–9), 101–116.
- Brand, A.; Lacy, J.R.; Hsu, K.; Hoover, D.; Gladding, S., and Stacey, M.T., 2010. Wind-enhanced resuspension in the shallow waters of South San Francisco Bay: mechanisms and potential implications for cohesive sediment transport. *Journal of Geophysical Research*, 115, C11024.
- Christiansen, C.; Gertz, F.; Laima, M.J.C.; Lund-Hansen, L.C.; Vang, T., and Jørgensen C., 1997. Nutrient (P, N) dynamics in the south-western Kattegat, Scandinavia: sedimentation and resuspension effects. *Environmental Geology*, 29, 66–77.
- Cloern, J.E. and Nichols, F.H., 1985. Time scales and mechanisms of estuarine variability, a synthesis from studies of San Francisco Bay. *Hydrobiologia*, 129, 229–237.
- Cooper, J.A.G. and Lemckert, C.J., 2012. Extreme sea level rise and adaptation options for coastal resort cities: a qualitative assessment from the Gold Coast, Australia. *Ocean and Coastal Management*, 64, 1–12.
- Davies, A.G., 1985. Field observations of the threshold of sediment motion by wave action. *Sedimentology*, 32(5), 685–704.
- DHI (Danish Hydraulic Institute), 2008a. Scientific documentation, MIKE 21 & MIKE 3 flow model FM, hydrodynamic and transport module. Horsholm, Denmark: DHI Water and Environment, 52pp.
- DHI, 2008b. User Guide, MIKE3 Flow Model, Mud Transport Module. Horsholm, Denmark: DHI Water and Environment, 88pp.
- Droppe, I.G.; Krishnappan, B.G.; Liss, S.N.; Marvin, C., and Biberhofer, J., 2011. Modelling sediment-microbial dynamics in the South Nation River, Ontario, Canada: towards the prediction of aquatic and human health risk. *Water Research*, 45(12), 3797–3809.
- Dunn, R.J.K.; Ali, A.; Lemckert, C.J.; Teasdale, P.R., and Welsh, D.T., 2007a. Short-term variability of physico-chemical parameters and the estimated transport of filterable nutrients and chlorophyll-a in the urbanised Coombabah Lake and Coombabah Creek system, southern Moreton Bay, Australia. In: Lemckert, C. (ed.), *International Coastal Symposium 2007 Proceedings (Gold Coast, Queensland, Australia)*. Journal of Coastal Research, Special Issue No. 50, pp. 1062–1068.
- Dunn, R.J.K.; Lemckert, C.J.; Teasdale, P.R., and Welsh, D.T., 2007b. Distribution of nutrients in surface and sub-surface sediments of Coombabah Lake, southern Moreton Bay (Australia). *Marine Pollution Bulletin*, 54, 606–614.
- Dunn, R.J.K.; Welsh, D.T.; Jordan, M.A.; Waltham, N.J.; Lemckert, C.J., and Teasdale, P.R., 2012. Benthic metabolism and nitrogen dynamics in a sub-tropical coastal lagoon: microphytobenthos stimulate nitrification and nitrate reduction through photosynthetic oxygen evolution. *Estuarine, Coastal and Shelf Science*, 113, 272–282.
- Dunn, R.J.K.; Welsh, D.T.; Teasdale, P.R.; Lee, S.Y.; Lemckert, C.J., and Meziane, T., 2008. Investigating the distribution and sources of organic matter in surface sediment of Coombabah Lake (Australia) using elemental, isotopic and fatty acid biomarkers. *Continental Shelf Research*, 28(18), 2535–2549.
- Frank, T.D. and Fielding, C.R., 2004. Sedimentology and geochemistry of an urban coastal lake system: Coombabah Lake Nature Reserve, Gold Coast, Queensland. *Australian Journal of Earth Sciences*, 51, 261–271.
- Giardino, A.; Ibrahim, E.; Adam, S.; Toorman, E.A., and Monbaliu, J., 2009. Hydrodynamics and cohesive sediment transport in the IJzer estuary, Belgium: case study. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 135, 176–184.
- Guan, W.B.; Wolanski, E. and Dong, L.X., 1998. Cohesive sediment transport in the Jiaojiang River estuary, China. *Estuarine, Coastal and Shelf Science*, 46, 861–871.
- Gutteridge, Haskins and Davey (GHD) Pty. Ltd., 2003. *Coombah Creek Environmental Inventory*. Brisbane, Australia: GHD, 439p.
- Hayter, E.J. and Mehta, A.J., 1986. Modelling cohesive sediment transport in estuarial waters. *Applied Mathematical Modelling*, 10, 294–303.
- Kemp, M.W. and Boynton, W.R., 1984. Spatial and temporal coupling of nutrient inputs to estuarine primary production: the role of particulate transport and decomposition. *Bulletin of Marine Science*, 35, 522–535.
- Klen, T., 2006. *Estuaries, an Introduction to Marine Biology and Oceanography*. <http://darter.ocps.net/classroom/klenk/Festuary.htm>.
- Knight, J.M.; Dale, P.E.R.; Dunn, R.J.K.; Broadbent, G.J., and Lemckert, C.J., 2008. Patterns of tidal flooding within a mangrove forest: Coombabah Lake, Southeast Queensland, Australia. *Estuarine Coastal and Shelf Science*, 76, 580–593.
- Lawson, S.E.; Wiberg, P.L.; McGlathery, K.J., and Fugate, D.C., 2007. Wind-driven sediment suspension controls light availability in a shallow coastal lagoon. *Estuaries and Coasts*, 30, 102–112.
- Lee, S.Y., 2006. Impact of urbanisation on coastal wetlands: a case study of Coombabah Lake, South-east Queensland. Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management, *Technical Report 54*, 219p.
- Liu, W.-C.; Hsu, M.-H., and Kuo, A.Y., 2002. Modelling of hydrodynamics and cohesive sediment transport in Tanshui River estuarine system, Taiwan. *Marine Pollution Bulletin*, 44, 1076–1088.
- Lopes, J.F.; Dias, J.M., and Dekeyser, I., 2006. Numerical modeling of cohesive sediments transport in the Ria de Aveiro lagoon, Portugal. *Journal of Hydrology*, 319, 176–198.
- MacIntyre, S., 1993. Vertical mixing in a shallow eutrophic lake: possible consequences of the light climate of phytoplankton. *Limnology and Oceanography*, 38, 798–817.
- Mitchell, S.B.; Burgess, H.M.; Pope, D.J., and Theodoridou, A., 2008. Field studies of velocity, salinity and suspended solids concentration in a shallow tidal channel near tidal flap gates. *Estuarine, Coastal and Shelf Science*, 78, 385–395.
- Morin, J. and Morse, J.W., 1999. Ammonium release from resuspended sediments in the Laguna Madre estuary. *Marine Chemistry*, 65, 97–110.
- Morris, A.W. and Howarth, M.J., 1998. Bed stress induced sediment resuspension. *Continental Shelf Research*, 18, 1203–1213.
- Nikora, V.; Goring, D., and Ross, A., 2002. The structure and dynamics of the thin near-bed layer in a complex marine environment: a case study in Beatrix Bay, New Zealand. *Estuarine, Coastal and Shelf Science*, 54(5), 915–926.
- Norkko, J.; Hewitt, J.E., and Thrush, S.F., 2006. Effects of increased sedimentation on the physiology of two estuarine soft-sediment

- bivalves, *Austrovenus stutchburyi* and *Paphies australis*. *Journal of Experimental Marine Biology and Ecology*, 333, 12–26.
- Olesen, B., 1996. Regulation of light attenuation and eelgrass *Zostera marina* depth distribution in a Danish embayment. *Marine Ecology Progress Series*, 134, 187–194.
- Pritchard, D., 2005. Suspended sediment transport along an idealised tidal embayment: settling lag, residual transport and the interpretation of tidal signals. *Ocean Dynamics*, 55, 124–136.
- Regnier, P. and Wollast, R., 1993. Distribution of trace metals in suspended matter of the Scheldt estuary. *Marine Chemistry*, 43, 3–19.
- Simon, N.S., 1989. Nitrogen cycling between sediment and the shallow-water column in the transition zone of the Potomac river and estuary II. The role of wind-driven resuspension and adsorbed ammonium. *Estuarine, Coastal and Shelf Science*, 28, 531–547.
- Soulsby, R.L.; Atkins, R., and Salkield, A.P., 1994. Observations of the turbulent structure of a suspension of sand in a tidal current. *Continental Shelf Research*, 14(4), 429–435.
- Tengberg, A.; Almroth, E., and Hall, P., 2003. Resuspension and its effects on organic carbon recycling and nutrient exchange in coastal sediments: in situ measurements using new experimental technology. *Journal of Experimental Marine Biology and Ecology*, 285, 119–142.
- Tolhurst, T.J.; Black, K.S.; Shayler, S.A.; Mather, S.; Black, I.; Baker, K., and Paterson, D.M., 1999. Measuring the in situ Erosion Shear Stress of Intertidal sediments with the Cohesive Strength Meter (CSM). *Estuarine, Coastal and Shelf Science*, 49, 281–294.
- Uncles, R.J. and Stephens, J.A., 1998. Sediment transport in the Humber-Ouse Estuary, UK, during May 1994. In: *Proceedings of the 8th International Biennial Conference on Physics of Estuaries and Coastal Seas* (Balkema, Rotterdam, the Netherlands), pp. 73–82.
- Uncles, R.J. and Stephens, J.A., 2010. Turbidity and sediment transport in a muddy sub-estuary. *Estuarine, Coastal and Shelf Science*, 87, 213–224.
- Underwood, G.J.C. and Kromkamp, J., 1999. Primary production by phytoplankton and microphyto benthos in estuaries. *Advances in Ecological Research*, 29, 93–153.
- van Maren, D.S. and Hoekstra, P., 2004. Seasonal variation of hydrodynamics and sediment dynamics in a shallow subtropical estuary: the Ba Lat River, Vietnam. *Estuarine, Coastal and Shelf Science*, 60, 529–540.
- van Rijn, L.C., 1993. *Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas*. Amsterdam, the Netherlands: Aqua, 650p.
- Verney, R.; Brun-Cottan, J.-C.; Lafite, R.; Deloffre, J., and Taylor, J.A., 2006. Tidally-induced shear stress variability above intertidal mudflats in the macrotidal Seine estuary. *Estuaries and Coasts*, 29(4), 653–664.
- Whitehouse, R.; Soulsby, R.L.; Roberts, W., and Mitchener, H., 2000. *Dynamics of Estuarine Muds*. London: Telford, 210pp.
- Williams, J.J.; Rose, C.P.; Thorne, P.D.; O'Connor, B.A.; Humphery, J.D.; Hardcastle, P.J.; Moores, S.P.; Cooke, J.A., and Wilson, D.J., 1999. Field observations and predictions of bed shear stresses and vertical suspended sediment concentration profiles in wave-current conditions. *Continental Shelf Research*, 19(4), 507–536.
- Zhang, H. and Chan, E.S., 2003. Modeling of the turbulence in the water column under breaking wind waves. *Journal of Oceanography*, 59(3), 331–341.
- Zhang, H.; Madsen, O.S.; Sannasiraj, S.A., and Chan, E.S., 2004. Hydrodynamic model with wave-current interaction in coastal regions. *Estuarine, Coastal and Shelf Science*, 61, 317–324.
- Zhang, H.; Sannasiraj, S.A., and Chan, E.S., 2009. Wind wave effects on hydrodynamic modeling of ocean circulation in the South China Sea. *The Open Civil Engineering Journal*, 3, 48–61.