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Numerical Study of the Hydrodynamics of a Very Shallow Estuarine System - Coombabah Lake, Gold Coast, Australia

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ABSTRACT

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Coastal wetlands and estuaries are important environments providing significant habitats for flora and fauna species - often supporting commercial and recreational fisheries. These systems also act as filters for contaminants and sediments, and the absorption of wave energy. As a consequence of the ecological significance and the potential for anthropogenic disturbances and inputs into Coombabah Lake estuary (Australia), the lake and surrounding wetlands have been the focus of recent scientific study efforts. This estuarine lake (~2 km^2 in size) is a very shallow (mean depth < 1 m) estuarine system that experiences a tidal range of 1.2 m, thus resulting in the continual exposure of large mud flats at low tide. Variations in water column physio-chemical and biological parameters and nutrient concentrations of the benthic sediments have previously been attributed to the hydrodynamic regime, hydrologic events, and sediment sources. In this study, a three-dimensional (3D) hydrodynamic model with unstructured mesh is setup to simulate the hydrodynamic regime and Bottom Boundary Layer (BBL) properties. In particular, the sensitivity of calibration parameters for a very shallow estuarine model is investigated. Model results are verified by recent intensive measurements. The hydrodynamic regime of the lake was found to be favorable for settlement of suspended sediments. The results reveal the necessity to correctly measure and use the appropriate bathymetry and bed roughness conditions in the numerical scheme for very shallow environments.

ADITIONAL INDEX WORDS: *Coastal lake, shallow estuary, hydrodynamic model*

INTRODUCTION

Estuaries are of immense importance to many communities. It has been estimated that 60 to 80 % of the commercial marine fisheries resources depend on estuaries for part of or all of their life cycle (KLEN, 2006). The characteristics of estuarine flow and sediment transport patterns are important as they play a critical role in the functionality and health of these systems. When bottom sediment is resuspended, trace metals, nutrients and organic contaminants are released into the water column, which in turn can limit the amount of light entering the water and reduce water quality (MORRIS and HOWARTH, 1998). Sediment settling can inhibit channel continuity by deposition in navigational areas. If any of these issues creates a significant problem, management strategies must be developed and implemented in order to rectify the situation and/or preserve the environment in a healthy state. These strategies usually involve the development of numerical models that must be based on sound scientific principles. However, many knowledge gaps still exist - resulting in most models relying on the use of approximations when determining boundary conditions and sediment transport dynamics.

The mechanisms that control the transport, resuspension and deposition of the fine suspended sediments or contaminants in tidal estuaries are extremely complex. They are directly influenced by highly variable hydrodynamic conditions near the bed and the characteristics of the transporting materials itself. There have been many investigations of near-bed flows, resuspension and transport of sediments under natural field conditions, with the majority of these have involved non-cohesive sediments [eg (SOULSBY et al., 1994) offshore sites (WILLIAMS et al., 1999; NIKORA et al., 2002) or coastlines dominated by wind wave effects (DAVIES, 1985; CONLEY and GRIFFIN, 2004)]. However, many estuaries have regions dominated by tidal mudflats. A quantitative understanding of sediment/contaminant transport is of fundamental importance for many engineering applications. However, the current theories describing its behaviour require further development (BLACK et al., 2002). This issue is also important for ecological applications because suspended sediments may affect the health of aquatic ecosystems by degrading water clarity, transporting pollutants and smothering of the benthic communities. An accurate hydrodynamic model is a pre-requisite for simulating sediment/contaminant transport in aquatic systems.

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 effort (eg DUNN et al., 2007a, 2007b and 2008; KNIGHT et al., 2008; ALI et al., 2009). DUNN et al. (2007b) have investigated intratidal variability of physio-chemical and biological parameters and attributed the variations to the sources, hydrodynamic regime, freshwater input, and tidal cycles.

The aim of this study was to set up a three-dimensional model and to simulate the hydrodynamic regime, in particular the BBL hydrodynamic properties in order to develop a better understanding of the sediment/contaminant transport processes

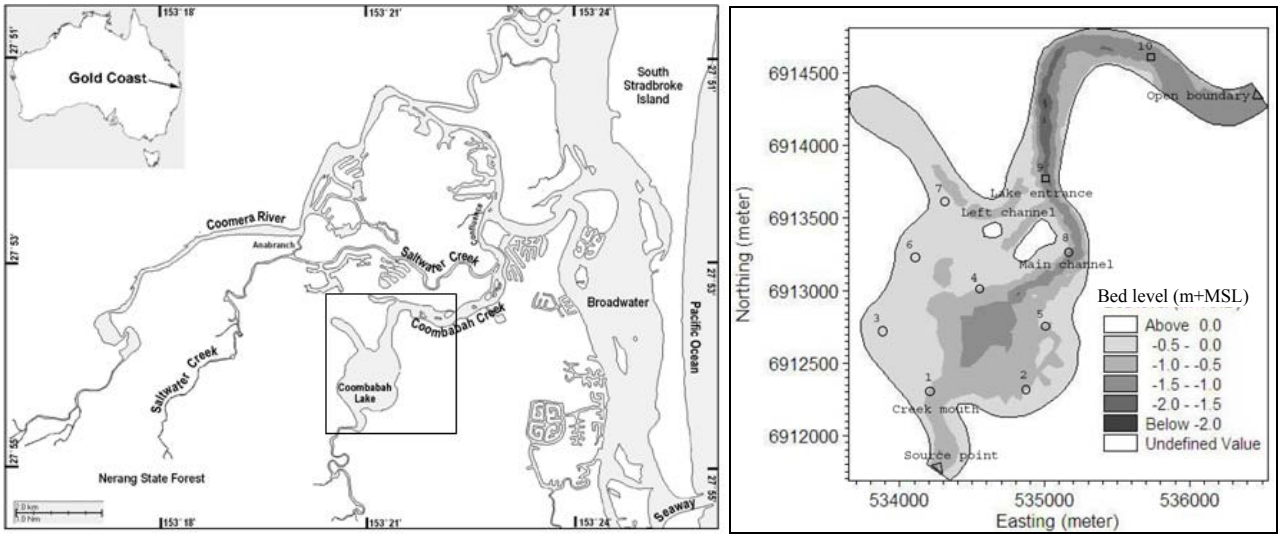

Figure 1. Location map of study site (left) and bathymetry of Coombabah Lake including measurement stations (right)

within Coombabah Lake, Gold Coast, Australia. The sensitivity of calibration parameters of a very shallow estuarine model is investigated and discussed. The model is verified by intensive measurements made within the lake system itself.

STUDY SITE

Coombabah Lake is a sub-tropical estuarine system situated in southern Moreton Bay, south-east Queensland (Australia) (Figure 1), one of the fastest growing regions in the developed world (SKINNER et al., 1998). The lake covers ~ 2 km^2 (GHD, 2003) with an urbanised catchment area of 44 km^2 characterized by residential, commercial and light industrial developments. The lake (Figure 1) is a shallow body of water characterized by fine sediments (DUNN et al., 2007a, 2008) and located in the mid-tidal region of Coombabah Creek. The creek enters into the lake at 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 (DUNN et al., 2007b). With the exception of shallow channels, Coombabah Lake is characterised by a relatively flat bathymetry (Figure 1), with mean 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 and recognized fish and migratory bird habitat. DUNN et al. (2008) carried out bed material analysis of the lake and concluded that the lake was dominated by mud (< 63μm) in the southern (landward) and sand (> 63μm) in the northern (seaward) regions.

METHODS

Field Measurement

A field measurement campaign was conducted within Coombabah Lake from 1 to 10 November 2005. Tide levels were measured at eight stations (1-8) distributed over the entire lake (Figure 1) utilizing CTDs (NXIC-CTD; Falmouth Scientific, Inc.). Velocities were also measured at 30 cm above the bed at Stations 1 and 8 using Nortek ADVs (Vector velocimeter; Nortek AS). Station 1 had the maximum influence of freshwater flow; on the other hand, Station 8 had the maximum tidal influence. Station 8 also represents the deepest point within the lake followed by Station 4 and Station 1, which remain under water almost all the time. On the other hand, Station 5 represents the shallowest point followed by Station 7, which become dry during all low tides. Stations 2, 3 and 6 become dry only during spring tide lows. Bathymetry of the lake was measured by high accuracy (horizontal error < 0.50 m and vertical error < 0.20 m) hand-held GPS. However, the GPS was fitted on a pole and the bed level was measured from a boat. Therefore, the vertical error can be up to 0.50 m. Bathymetric points were very dense (spacing about 1.0 m) in steep areas and sparse (spacing about 100 m) in flat areas. A temporary weather station was also installed on a houseboat anchored within the lake during the study.

Another field study was conducted on 13 November 2007 to estimate bed shear stress and bed roughness within Coombabah Lake. A new traversing system was utilized to measure vertical velocity profiles at Stations 1, 4, 8, 9 and 10 during an ebb tide. The velocity and elevation data were fitted into the Prandtls Logarithmic velocity profile (PRANDTL, 1926). Shear velocity (u_*) and bed roughness height (z_0) were estimated from the best fit curve. Subsequently, the shear velocity and roughness height were utilized to calculate bed shear stress ($\tau_b=\rho u_*^2$, where ρ is the density of water) and roughness length ($k_s=30z_0$) respectively. Thus calculated bed roughness lengths were utilized in calibration and bed shear stresses were utilized in verification of the model.

Numerical Model

A three-dimensional flexible mesh modeling system MIKE3 FM (DHI, 2008) was employed to simulate hydrodynamic properties with particular emphasis upon the investigation of the BBL. A horizontally unstructured grid was used with larger cells within flat areas and smaller cells within narrow channels. The cells were triangular in shape with approximately 1800 m^2 for the largest and approximately 400 m^2 for the smallest sizes amounting to 1548 cells in total. A vertically structured bottom-fitted sigma grid system was used with eight layers of variable thickness. The layers were thinner near the bottom for comparison with the observed data. Predicted tide levels with seasonal correction 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 (Easting 534285 m, Northing 6911760 m) to represent the flow from the upstream of Coombabah Creek. Flow of the source was estimated from the measured velocity at Station 1 multiplied by average depth and width of the creek.

RESULTS AND DISCUSSION

Field Data

The lake experiences a mixed tidal regime, mainly of a semidiurnal nature. During the 2005 study, wind conditions were generally moderate but highly variable, ranging from 2 to 20 km/h with the average wind speed of 7 km/h and directed from south or south-east (blowing from the creek mouth to the lake entrance (ALI et al., 2009). Light rainfall was recorded every day except on 7 November. Rainfall increased gradually from 0.5 mm/day on 1 of November to 18 mm/day (the maximum) on 6 of November. Evaporation varied between 5 and 10 mm/day, which is greater than the annual regional average (3.5 mm/day), and even greater than the monthly average for the same periods in other years (5 mm/day) recorded by the AUSTRALIAN BUREAU OF METEOROLOGY (2007). Air pressure was dropped by approximately five milibar (mbar) during this period.

Bed shear stresses and bed roughness heights observed within Coombabah Lake-Creek system are presented in Table 1. Observed data shows bed shear stresses within the lake are significantly (by more than an order) less than that of the creek. Bed shear stresses within the lake increased almost geometrically along the main flow path landward to seaward from 0.02 N/m^2 to 0.12 N/m^2. The bed shear stresses within the creek also varied along the reach, high (0.78 N/m^2) at the lower reach near model open boundary and low (0.55 N/m^2) at the upper reach near lake entrance. The variations in bed shear stresses were expected since it depends on the flow velocity which is low in the upper reach and high in the lower reach within a tidal estuary if cross-sectional areas are the same. On the other hand, bed roughness was very similar all around the lake and the creek, though the bed materials are different (DUNN et al., 2008). The roughness length (k_s) varied slightly, between 0.10 m and 0.13 m.

Bed shear stresses and bed roughness lengths were measured during ebb tide because of field constraint. The lake is very shallow and did not allow our boat to move freely for more than an hour. Therefore, the traverser was moved to Station 1 during flood tide and started measurement immediately after starting of the ebb tide to avoid the boat to be stranded. However, bed shear stresses and bed roughness lengths were assumed to be very much similar during flood and ebb tides when there is no rainfall.

Model Calibration

The model was calibrated against water levels and velocities measured from 1-10 November 2005. Bathymetric correction, bed roughness and eddy viscosity were tuned in the calibration processes. Correlation coefficients between simulated and measured water levels and velocities were used as model performance indicators. To examine the sensitivity to possible errors in the measured bathymetric levels the lake bathymetry was artificially lowered from 0 to 0.25 m in 0.05 m interments. The correlation coefficients between observed and simulated time series data were compared. The highest correlation was observed to occur when the bed was lowered by 0.15 m with respect to the measured elevation (Figure 2). However, a ±0.20 m error in bathymetric measurements is usual (CHIA-CHYANG and HSING-WEI, 2003). Water levels at Stations 3 and 4, and velocity at Station 8 showed continuous improvement up to the maximum (0.25 m) lowering. In contrast, water level at Station 7 slightly deteriorated when bed level was lowered. The average correlation coefficient improved by 0.06 for a bed level lowering by 0.15 m. This shows how critical it is to get the Digital Elevation Model (DEM) correct for such shallow systems. Deeper systems are certainly not as sensitive to such elevation errors due to a greater volume/depth ratio.

The model was also tested against a series of bed roughness values. A range of roughness length from 0.02 m to 0.20 m (constant over entire model domain) was utilized in the calibration process. It was found to be the second most sensitive calibration parameter to the model. The observed roughness length 0.10 m (constant over the entire model domain) provided the best result. A bed roughness map generated based on the grain size distribution (0.06 m for muddy area and 0.12 m for the sandy area) was also tested and found the results quite similar to the constant roughness 0.06 m. However, almost all the measurement stations were located within muddy areas where the roughness did not vary on the roughness map. Similarly, the model was tested with various eddy viscosities and was found relatively less sensitive to it. The correlation coefficient changed by 0.02 when the eddy coefficient was changed by an order of 2. Finally, the k-ε eddy formula was selected with default values (DHI, 2008) of various parameters. Therefore, numerical models of shallow estuaries are highly sensitive to bathymetric accuracy followed by bed roughness and eddy viscosity.

Simulated water levels and velocities at Station 1 are compared with the measured data on Figure 3. Quite good agreement was observed between simulated and measured water levels. However, the simulated velocity was slightly low during both flooding and ebbing tides. Very low bed roughness (0.02 m) slightly improved velocity calibration but significantly deteriorated water level calibration. In general, the model reproduced the prototype quite well.

Table 1: Observed bed shear stress and bed roughness length

Station	Bed shear stress, τ_b (N/m^2)	Roughness length, k_s (m)
1	0.02	0.11
4	0.06	0.13
8	0.12	0.12
9	0.55	0.11
10	0.78	0.10

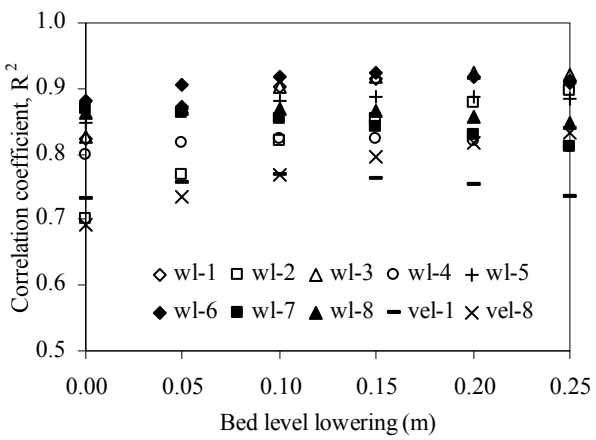

Figure 2. Correlation coefficients between observed and simulated water levels and velocities for various bed level lowering.

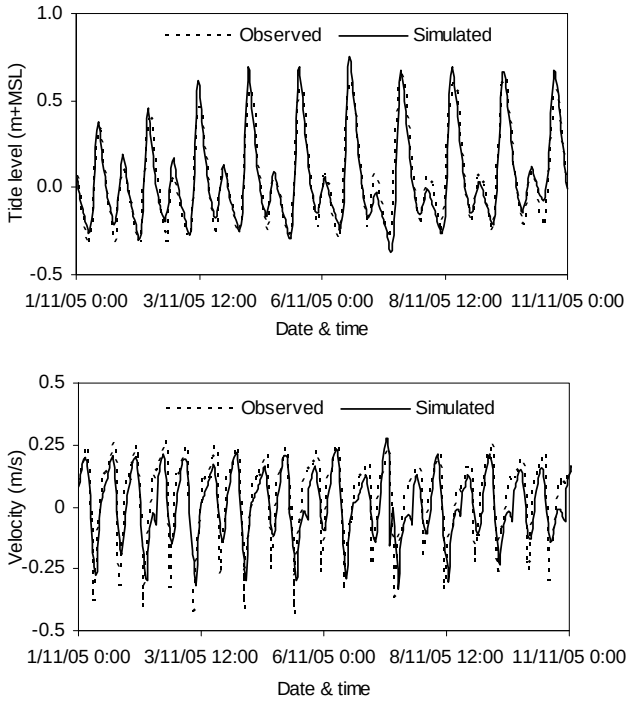

Figure 3. Comparison of tide level (top) and velocity (bottom) at Station 1

Simulation Results

The numerical model described previously was utilized to analyze the hydrodynamic regime of the lake particularly the flow distribution within the lake. A snapshot of velocity vectors (Figure 4) shows a number of eddy circulations were generated at the onset of flood tide. Figure 4 shows the flood tide already travelled up to the middle of the lake through the left channel while the main channel experiencing ebb tides. More importantly, an eddy around the large island reveals the existence of flood and ebb dominated channels within the lake. The flow distribution between the main channel and the left channel near the lake entrance are plotted on Figure 5 to compare their conveyance capacities. Simulated results reveal the total flow is distributed by 60% and 40% between main channel and left channel, respectively. Figure 5 also demonstrates that the ebb tide takes longer time than the

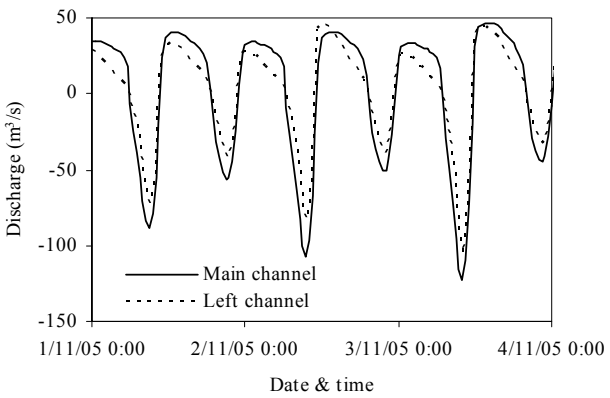

Figure 5. Simulated flow through bifurcation channels at Lake entrance (positive seaward)

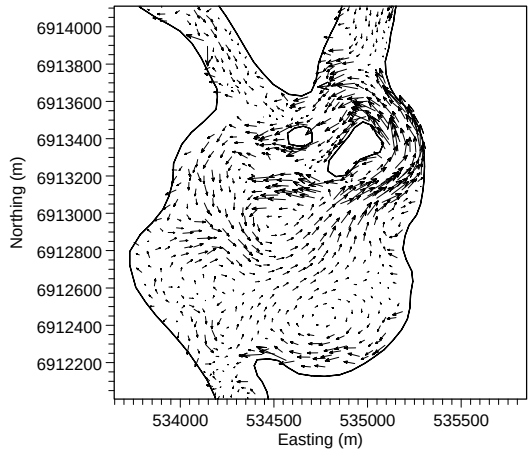

Figure 4. Simulated flow field at the onsets of flood tide

flood tide. On the other hand, the flood flow is stronger than the ebb flow. As a result, the flood tide can carry relatively more and heavier sediments than the ebb tide. The strong flood tide brings marine borne sediments (especially sand) into the lake entrance.

The three-dimensional model facilitated estimation of bottom boundary layer properties such as bed shear stress and Turbulent Kinetic Energy (TKE). Simulated bed shear stresses (Figure 6) matched quite well with observed value. Figure 6 shows bed shear stresses around the mud dominated inner lake areas are an order of magnitude lower than that of the sand dominated lake entrance. Therefore, the hydrodynamic regime of the lake is conducive for the catchment generated suspended sediments to settle on the lake bed. The model replicated vertical TKE profile reasonably well except a region around mid-depth (Figure 7) where simulated value is approximately 50% higher than the observed value. However, the observed value may contain approximately 30% errors in it (GARCIA et al., 2006). Moreover, the model itself inherits a number of uncertainties (HUANG et al., 2001).

CONCLUSIONS

Both observed and simulated velocity supports the classical tidal pumping of sediments landward within Coombabah Lake. The hydrodynamic regime of the lake is also conducive for the catchment generated suspended sediments to settle within the lake. Similar to YANG and KHANGAONKAR (2008), this study found an

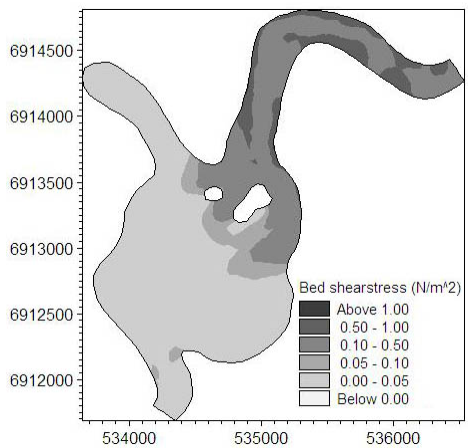

Figure 6. Simulated bed shear stress at ebb tide

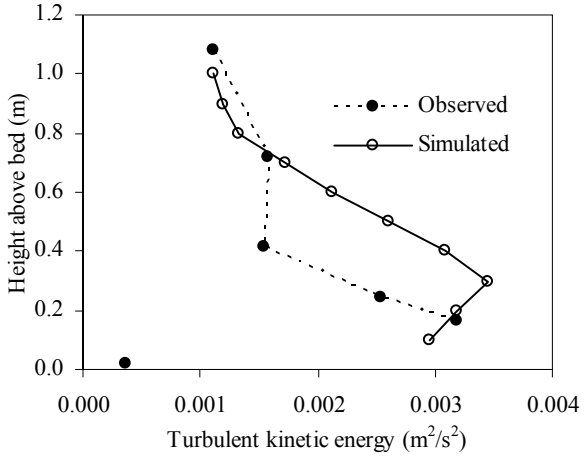

Figure 7: Observed and simulated turbulent kinetic energy

accurate bathymetry is the most important parameter for modeling hydrodynamics particularly within shallow estuaries. Bed roughness was found as the second most important parameter in the modeling exercise for this region.

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