Numerical Modelling of Tidal Dynamic and Water Circulation at the Gold Coast Broadwater, Australia

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ABSTRACT

The development of a vertically averaged numerical model of an estuary in the coastal region of the Pacific Ocean on the east coast of Australia is described. The primary objective of the study is to provide a detailed picture of the tidal characteristics in the study area to enable the simulation of the whole water circulation within the water body. A comprehensive data set is collected as part of this study to understand local dynamics and to calibrate and validate the model. Calibration and validation have been achieved through a comparison of computed tidal harmonics against those derived from harmonic analysis of the measured water level variations. Also a comparison was made between the measured discharges across seven cross sections at critical locations in the study area with the discharge obtained through modelling. Calculations show that tides become mixed, mainly semidiurnal in the estuary. The study shows that for lunar constituents (M2 and S2) dissipation mechanisms are dominant and their amplitudes decrease along the estuary. Solar constituents (O1 and K1) experience an increase in amplitude. However, the net result is a reduction of tidal amplitude, indicating the dominance of dissipation mechanisms.

ADDITIONAL INDEX WORDS: Tide, Circulation, Modelling, Hydrodynamic model

INTRODUCTION

The Gold Coast City Council is examining a number of development proposals and a variety of strategic planning for the Gold Coast, which could potentially have a significant impact on the health of its major estuary, namely Broadwater. This includes development of a cruise ship terminal, desalination plant, water sewage outfall, new industries and also significant land use change within the catchments of the city. A good understanding of change in tidal amplitude and its sensitivity to various development options is crucial for the management of this waterway.

The tidal signal of the Broadwater and as a consequence all the tidally influenced parameters such as water quality and sediment transport regime have already undergone substantial changes during the last three decades due to man-made changes within the catchments and estuarine waterways of the Gold Coast. These changes are expected to continue due to both continued human interference and also accelerated changes in climatic parameters due to global warming.

This study is designed to provide a hydrodynamic model, which can be used as a tool to predict and address the impact of future man-made and natural changes on the health of the tidal waterways of the Gold Coast. The hydrodynamic model will be used to investigate the existing flow pattern and tidal regime within the study area. It will also be used to identify critical spots for more attention during the process of water quality and sediment transport modelling, which will be undertaken in future.

Study Area

Figure 1 shows the extent of the study area. The Broadwater is a semi enclosed water body located on the east coast of Australia and drains freshwater flows from four major river systems of the region (Nerang, Coomera, Logan-Albert, Pimpama) and several smaller creeks into the Pacific Ocean. Geographically the study area is located between (27.68S, 153.13E) and (28.09S, 153.45E).

The Gold Coast Seaway, connected to the Pacific Ocean through a man-made canal (named Gold Coast Seaway) and Jumpinpin Bar opening on the East and connected to Moreton Bay in the north. The boundaries of the study area in the west are inflows from the Coomera, Logan-Albert and Pimpama Rivers and in the south the inflow from the Nerang River.

The Gold Coast Seaway, constructed in 1985 along side with Wave Break Island, replaced a natural shallow opening located approximately 500 metres north of the Gold Coast Seaway at the time of construction. The Gold Coast Seaway has a much higher conveyance compared with the old natural opening at Southport and therefore its construction has had a significant impact on the hydrodynamic and as a result on the sediment transport regime of the Nerang River Estuary.

Jumpinpin Bar was opened in 1896 as a result of successive natural events (and possible human interference). As a result of the creation of this opening Stradbroke Island was divided into two separate islands. The opening of Jumpinpin Bar has had an...
impact on the hydrodynamics of the Broadwater including change in tidal variations in the northern part of the Broadwater.

**METHODOLOGY**

This study starts with the setup of a depth-averaged, two-dimensional numerical hydrodynamic model of the study area. The model is calibrated using field data collected in summer 2004. The model is then validated using a data set collected in 2005. Tidal regime of the study area is obtained through harmonic analysis of the collected data and output of the numerical model. Output of the numerical model is also used to illustrate tide-induced water circulation within the study area and particularly around the Wave Break Island.

**OBSERVATIONS**

The observations used in this study were conducted between November, 2004 and February, 2005 (Mirfenderesk et al., 2004, 2005, 2007). Two separate data sets were collected for calibration and validation of the model. Observed and collected data includes water level, current, and bathymetry of the study area. Water level measurement was conducted at 9 locations using pressure cells and current velocity data was measured along 7 transects lines shown in Figure 1. Tidal measurements were conducted simultaneously at all 9 locations for a period of minimum 35 days.

**MODEL SETUP**

A two dimensional hydrodynamic model was set up to compute the flow velocities and water level variations within the study area using Mike21 package (Danish Institute of Hydraulic). The model area was represented by a 30-metre square grid. The model can be driven by sea level variations specified along the open boundary and wind over model area.

To investigate the impact of wind on the results, the model was run with and without wind. The results showed that the impact of wind over the water surface was insignificant compared with the tidal forces and that the hydrodynamics of the Broadwater is dominated by the astronomical tides. The model has open boundaries at the Seaway, Jumpinpin Bar and Moreton Bay. A gauging station at Russell Island provided water level variations on the northern boundary of the model. Two tidal stations were set at the Gold Coast Seaway and at Jumpinpin to provide required eastern boundary conditions. To include these two tidal inlets into the model it was decided to extend the model into the ocean and instead of the measured water level variations to use tidal predictions by Maritime Safety Queensland (MSQ). These tidal predictions are based on long-term water level measurements at Snapper Rock in southern part of the Gold Coast Seaway in the ocean and are valid for the Gold Coast area. MSQ has had an operational tidal station close to Seaway as well. Long-term survey of water level at these two stations has revealed that the residuals resulting from the meteorological conditions have been almost the same at both stations. On this basis meteorological component of water level obtained from the MSQ tide station, which is located close to Seaway, was applied to tidal prediction at the eastern open boundary to create a water level time history. Tidal gauges that were installed at the Seaway and Jumpinpin (as part of this study) were used to ensure the water level variations at the eastern boundary of the model were correct. This provides a driving force for the model as the changes in water level propagate through the entire grid system. Measured water level variations along the northern boundary at Russell Island were applied as the driving force at the northern boundary of the model.

**MODEL CALIBRATION**

Sea surface elevation and horizontal velocity field were simulated for tidal variations within the study area. The model was run for 36 days from 25th December, 2004 to 1st February, 2005. The model was calibrated using tidal harmonics resulted from the observed simultaneous time series of water level variations at six sites and discharges across seven transects at critical locations within the study area. Discharge across these transects was calculated using velocity measurements, which was conducted using Acoustic Current Doppler Profiler (ADCP) over a full tidal cycle. Calibration was achieved through finding the best fit between measured and simulated data by varying the Manning’s roughness coefficient uniformly across the study area. The adopted Manning coefficient for this study is 0.045 for mangroves and 0.025 for sandy areas. In addition, tidal harmonic analysis of the simulated data was performed to obtain the amplitude and phase of the water surface elevation. These outputs were compared with tidal harmonics obtained from the measured water level variations. Table 1 shows a comparison between tidal constituents obtained from measured and modelled time series.
This comparison is made for main tidal constituents O1, K1, M2 and S2. In both cases the results show good agreement between model results and observed values.

On average the difference between the modelled and predicted amplitudes for M2 component is 1.5 cm or less than 2.8%, while for O1, K1 and S2 components the amplitude difference was nearly zero. Similarly the average difference between modelled and predicted phase for M2 component is –2 degree, which is less than 1%. This value is 0.6, 1.5 and –0.7 degrees for the O1, K1 and S2 components respectively. Figure 2 shows the performance of the model in terms of discharge at six ADCP transect locations within the study area (see Figure 1).

The results show a good match between the discharges obtained from model results and the one calculated from the measured velocity across each transect using ADCP. Transect No. 6 in Figure 2 shows an interesting pattern of discharge variations along a relatively narrow waterway within the Broadwater (ADCP transect No. 6 in Figure 2). The measured discharge shows a sharp increase in discharge during flooding tide in this waterway (which is an anabranch of the Broadwater). It also shows a sharp change of direction of flow followed by a gradual reduction of discharge during ebbing flood and then followed by a relatively sharper discharge variation towards the end of ebbing period. The figure shows that the model has produced an excellent simulation of this pattern. In general the match between discharges across the ADCP transects, calculated from the measured velocity and also calculated from the model results are very good.

MODEL VALIDATION

The model is validated against simultaneous water level measurements at nine stations for a period of 28 days during November, 2004. Tidal constituents at the nine control points, calculated from model outputs and measurements, are compared for validation of the model. Table 2 shows the comparison between observed and modelled amplitude and phase variations.

On average the differences between the modelled and predicted amplitudes for M2 component is 1.6 cm or less than 3%, while for O1, K1 and S2 components the amplitude difference was nearly zero. Similarly the average difference between modelled and predicted phase for M2 component is almost zero. This value is 0.9, 1.4 and 3.7 degrees for the O1, K1 and S2 components respectively. The very small differences between tidal constituents during calibration and validation periods can be due to limited length of data collection period and the fact that boundary conditions for these two simulation periods were based on measurements at different months.

TIDAL DATA ANALYSIS

To quantify the tidal characteristics of the Broadwater, a frequency domain analysis is carried out for measured tidal time series. The purpose of tidal analysis is to determine the amplitude and phase of the individual cosine waves each of which represents a tidal constituent. Tidal harmonic analysis of the tide gauges data is carried out using Mike21 package (Danish Hydraulic Institute). Tidal characteristics of the study area is identified as mixed predominantly semi diurnal using the form number as defined by (Pugh, 2004):

\[ N = \frac{(O_1 + K_1)}{(M_2 + S_2)} \]  

(1)

Form number is defined as the ratio between main diurnal and main semidiurnal components of tide. The form number at various locations at Broadwater is different, varying between 0.3 and 0.6.
A form number between 0.25 and 1.5 is regarded as mixed predominantly semidiurnal. On this basis the general tidal regime in the study area can be classified as predominantly semidiurnal.

**DISCUSSION**

Discharge at the Gold Coast Seaway can reach up to 4100 m$^3$/s during spring tide and close to 1600 m$^3$/s during neap tide. Approximately 70% of this discharge comes from the northern channel (Figure 3) and 30% from the southern channel. Contribution of the Nerang system to the discharge at the Seaway is slightly more than 16%. Model results show that 14% of the discharge at the Seaway is coming from north but not flowing into the Seaway through the northern channel. This flow goes through the channels to the west and then to the south of Wave Break Island and then joins to the flow through the main southern channel. In general, both simulation results and measurements show that the northern dredged channel conveys much more flow than the southern channel during both ebb and flood tides.

Harmonic analysis of the current velocity within the study area shows the existence of a residual current around the Wave Break Island. The magnitude of this residual current is approximately 0.06 m/sec.

Many sections of the Gold Coast City have been built at low-lying areas and are flood prone. The slightest change in tail water due to tidal regime change can have significant impact on the depth and extent of inundation within the city. The tidal amplitude variations within the Broadwater are the result of a balance between two opposing forces. On one side tidal amplitudes tend to increase due to the shoaling effect and on the other hand tend to decrease due to intensive dissipation due to bottom friction and head loss at the two main entrances of the system, i.e. Seaway and Jumpinpin Bar. In general, from the model results and observations it can be seen that head loss associated with Seaway and Jumpinpin openings accounts for almost 10 to 15 cm reduction in tidal amplitude.

Simulation results show an insignificant reduction in the tidal range between the Seaway and the Nerang mouth. The reason for little attenuation is that the dredged southern navigation channel, which extends from the Seaway to the Nerang River, provides a smooth path for tidal flow to and from the Nerang River. Both measurements and model results show that there is a reduction in tidal variation along the northern channel. The sand banks to the north and west of Wave Break Island provide a significant restriction to the flows to and from the northern part of the Broadwater. It can be seen that tidal range at Runaway Bay is reduced to approximately 87% of that immediately inside the Seaway entrance. Model results and also current measurements, indicate higher velocity and higher current through the northern channel than through the southern channel. Figure 4 shows that the time of the strongest ebb current through the Seaway is approximately four to five hours after the low tide and similarly the strongest flood flow is approximately three hours after the high tide.

Both measurements and the results of the numerical model show that semidiurnal components are more affected than the diurnal components at the Broadwater system, mainly due to their different frequencies. Figure 5 shows a significant reduction in M2 and S2 components along the northern channel from the Seaway to the Runaway Bay. Diurnal components O1 and K1 show an opposite trend and increase from the Seaway to Runaway Bay. The reduction of the lunar components is less along the southern channel from the Seaway to the Mouth of the Nerang River. Similar to the behaviour in northern channel, solar components O1 and K1 show an increase along the southern channel. Similar studies in coastal lagoons show the same trend with respect to the behaviour of the lunar and solar components of the tide. (Byun et al., 2004).

**SUMMARY AND CONCLUSION**

A combination of field measurements and numerical modelling has been used to understand tidal dynamics of the Broadwater and to provide a tool for predicting tidal variations within the Broadwater. The major hydrodynamic features are identified and reproduced with reasonable accuracy by a depth averaged two-dimensional model. Spatial and temporal comparison between the measured water level and discharge with model results
demonstrate good performance of the hydrodynamic model.

Simulation results (Figure 3) show that ebb tide flowing from north to south enters the Seaway in three different ways: 1) Directly through the northern channel close to South Stradbroke Island, 2) southward through the channel along the western edge of Wave Break island and into the southern channel via a channel located along the southern edge of the Wave Break Island. 3) Southward through a channel along mainland and into the northern channel via a channel along the northern edge of the Wave Break Island. During flood tide, the flow pattern is almost the same as that of ebb flow but the flow directions are reversed. Model results indicate the existence of a residual current around the Wave Break Island.

Tidal regime in the study area is mixed predominantly semidiurnal. Tidal analysis of the measured data and model results show a reduction of amplitude of main lunar components against an increase of amplitude of main solar components of the tide, as it progresses upstream of the estuary.

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LITERATURE CITED


Figure 4. Discharge-water level variations at Seaway

Figure 5. Variation of lunar and solar tidal constituents along the southern and northern channels to the Seaway