MODELLING THE MORPHOLOGICAL RESPONSE OF AN EBB TIDAL DELTA TO STORM WAVE FORCING

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The Nerang river outlet - located on the Australian east coast - was stabilised with two entrance jetties in 1986. The entrance, now known as the Gold Coast Seaway, has been the subject of growing concern about the ongoing growth of the ebb tidal delta. Historical analysis of surveying data confirmed the gradual growth of ebb tidal delta, although a sand bypassing system was implemented upstream when the entrance was stabilised. The dredging of the Seaway ebb delta is inevitable to keep the navigation channel open and safe. However, the dredging operation is both time and budget consuming and therefore having a more accurate model which can predict the pattern of morphological changes precisely seems essential. A coupled wave, flow and sediment transport model was developed using MIKE 21 Coupled Model to investigate the sediment transport pattern mainly in the area of the ebb-tidal delta and its linkage with littoral drift in the adjacent open coast. The hydrodynamics of the model were calibrated and verified against current measurements inside the Seaway and offshore wave data obtained from the Gold Coast Wave Rider Buoy. The pattern of the simulated morphological changes was qualitatively similar to that of the observations, and the model's results show that the storm waves forcing govern the growth of the ebb-tidal delta, and also leads to severe bathymetry changes along the adjacent ocean beaches. The model was found to underestimated the volume of sediment transport in the domain and so further model sensitivity analysis is ongoing in an effort to reach to a quantitatively calibrated morphological model.

Keywords: ebb-tidal delta; coupled modelling; sediment transport

INTRODUCTION

Tidal inlets are natural or artificial openings along coastlines where seawater penetrates land and provides a connection between the ocean and bays, lagoons, marshes and tidal creek systems (Fontolan et al. 2007). Coastal engineers and scientists are often faced with the need to predict the morphological evolution of these estuaries and tidal inlets. This is because morphological changes can have important effects in coastal environments, especially in estuaries which are areas of high commercial, recreational and ecological interest (Moore et al. 2009).

Various modelling approaches have been used to simulate the morphological evolution of tidal inlets. Some of them only applied tidal regime forcing in the model mainly to verify the empirical theories and also explain those theories further with the developed models (van Leeuwen et al. 2003; Dissanayake et al. 2009; Van der Wegen et al. 2010). Some others, such as Van der Vegt et al. (2006) tried to explain the equilibrium of a tide dominated tidal inlet by the balance of sediment transport between wave and tide forces in the inlet, only by adding the frontal waves to the hydrodynamic forces of the model. Eventually, some process-based morphodynamic models were developed and applied for tidal inlets under combined forces of tide and waves, but still some simplifications were applied. For example Tung et al. (2009) and Tung (2011) applied process-based morphological modelling under different wave and tide conditions for an idealized tidal inlet; and for running the model in a reasonable time, morphological factor was used.

Gold Coast is one of the fastest growing cities in Australia, hence there is a need to fully understand and predict changes that may adversely affect the dynamics of the Gold Coast estuarine system (Davies 2008). One of the most commercially significant parts of the waterways of the Gold Coast is the Gold Coast Seaway, which was named after stabilisation of Nerang river outlet in order to maintain a safe navigable channel. Although Gold Coast Seaway was stabilised and a sand bypassing system was developed to bypass the longshore sediment transport, growth of the ebb tidal delta in the mouth of the inlet seems to be continuing. Therefore, dredging operations need to be carried out in the area to keep the navigating channel open and safe, which is both time consuming and costly. Thus, understanding the processes involved in sediment transport in the area, and as a result morphological evolution in the mouth of the inlet is essential to make informed coastal management decisions. The main purpose of this study was to develop a calibrated and verified process-based model which can

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simulate the morphological evolution of the Gold Coast Seaway ebb-tidal delta under the actual wave and current condition.

STUDY AREA SETTING AND HISTORY

The Gold Coast Seaway is a trained tidal inlet which is located on the Australian East coast at a longitude of 27°56'10S and a latitude of 153°25'60E and links an intra-coastal waterway known as The Broadwater with the Pacific Ocean (Figure 2). It was created by stabilisation of Nerang River entrance in 1986 with two training walls, and to reduce wave penetration and protect the western shore of the Broadwater a new artificial island, known as Wave Break Island, was created at the same time. The tidal cycle in the area is a semi-diurnal cycle which is varying from 0.2 to 2 m with a mean of 1 m. Wave forcing in the entrance region includes three swell regimes which have a dominant influence on coastal dynamics of the region (Allen and Callaghan 1999). The first regime is S to SE swells in winter and spring, the second regime is NE to E high energy swells generated by Tropical Cyclones from November to April, and the third swell regime is NE to SE, generated by East Coast Lows from March to July.

Sediment along the Gold Coast consists of well sorted fine sand, d_{50}=220μm with a grading coefficient of about 1.25. The longshore drift along the Gold Coast is estimated to be about 500,000 m^3/year toward the north, which is compromising of 650,000 m^3/year toward the north and 150,000 m^3/year toward the south (Turner et al. 2006). The dominant northwards longshore drift meant that, prior to the construction of the entrance training walls in 1986, the Nerang River Inlet was migrating northward (WRL and GCCM 1998). The dynamic ebb-tidal delta was a dangerous obstacle which resulted in numerous boating accidents; Therefore, the entrance did not provide safe access to the ocean. By the early 1980's, the boating activity increased vastly due to the rapid growth of the Gold Coast into the nation's premier resort area and so it was then decided to train the Nerang River entrance to provide a safe navigation channel (Sennes et al. 2007). According to the Delft Hydraulics report (Delft 1970), because of the large magnitude of the northerly longshore drift on the Gold Coast, any scheme to stabilise the entrance would require implementing an artificial sand bypassing system across the entrance. Hence, a bypassing plant was implemented and completed in 1986 (Sennes et al. 2007).

Following the construction of the Seaway and its associated bypassing system there have been significant changes to the overall dynamics of sediment movement in the region. Sedigh et al. (2012) analysed historical survey data of the Gold Coast Seaway region for the period 2004 to 2011 and found that the ebb-tidal delta was growing at an approximate average rate of 7550 m^3 /month despite the on-going artificial bypassing of sand from upstream to downstream (Figure 1). This growth is causing problems for the navigation and dredging is periodically planned to maintain accessibility of the channel. The system is still in a transitional state as a new dynamic equilibrium is yet to be established and dredging activities act to slow down the process of reaching an equilibrium. Numerical simulation of the morphodynamics of the inlet region can help achieve a better understanding of the morphodynamics of the system and thus assist in making better informed coastal management decisions. For instance, examining ways that sediment trapping in the ebb-tidal delta could be reduced,and the estimation of optimum dredging frequency, location and quantity of.
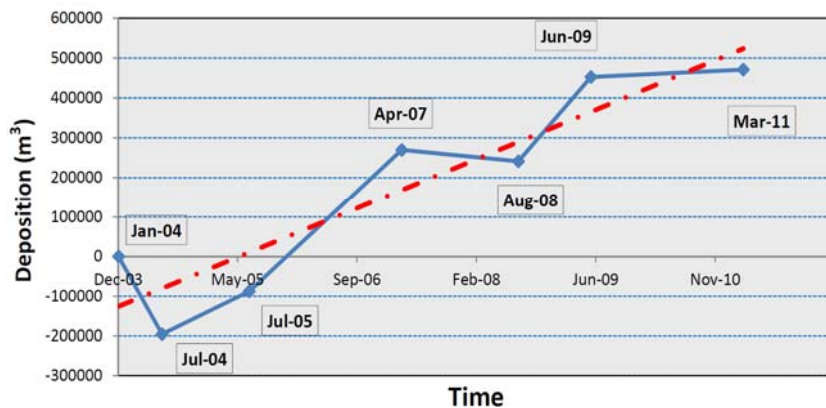

Figure 1. Volume of deposition in ebb-tidal delta (Sedigh et al. 2012)

NUMERICAL MODELLING

The first step in understanding the morphodynamical behaviour of the system is to investigate the sediment transport processes and mechanisms. In this regard, a numerical model, using MIKE 21/3 Coupled model, was developed to simulate the morphodynamics of the tidal inlet. The hydrodynamics component of the model was first calibrated against observations and then applied to investigate the sediment exchange in the Gold Coast Seaway inlet region and open coast, and the pattern of morphological changes in the Gold Coast Seaway ebb-tidal delta.

In this study all of the simulations are performed in 2DH (Depth Averaged) due to two main reasons. First, the computational time was a constraint in this study and using a 3D simulation would increase the simulations time significantly. Second, it has been shown in several studies that 2DH models are capable of simulating and reproducing the behaviour of tidal inlets (Bertin et al. 2009b; Bruneau et al. 2011; Tung 2011).

In order to reach a better calibration and verification for hydrodynamics of the model whilst minimizing the computation time as much as possible, a total of three numerical models were developed which includes a regional HD model, a regional SW model, and a local HD-SW-ST model. The first two were developed to extract more precise boundary conditions for the local higher resolution morphological model.

Regional HD Model

The regional HD model and its boundary limits were extended so that it includes a reasonable area for accounting the tidal lags in the results (Figure 2). The water levels at the boundaries were assigned from the global tidal prediction of MIKE which is based on TOPEX/POSEIDON altimetry data and represents the major diurnal (K1, O1, P1 and Q1) and semidiurnal tidal constituents (M2, S2, N2 and K2) with a spatial resolution of 0.25 × 0.25 degrees (DHI 2009b).
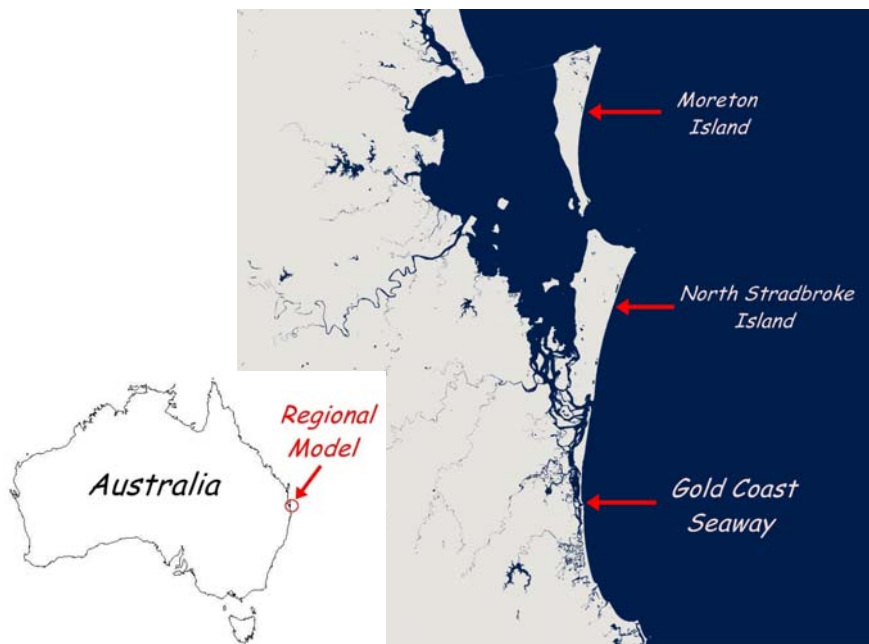
Figure 2. Map of the Regional Model area in the east Coast of Australia

A variety of data sources were used to create the bathymetry of the regional and finally the local model. A part of data was provided by the Gold Coast City Council for the Gold Coast Estuarine Modelling Study (GEMS), which included two data sets from May 2008 and October 2007. For the bathymetry of the local model the same set of data used, and the bathymetry of the seaway area was updated with available surveying data from Queensland Transport close to the time that the model was set up to run. Moreover, since none of the above mentioned data include the bathymetry of the berm, the bathymetry of the areas close to the coastline edges were extracted and interpolated from available ETA lines survey data from Gold Coast City Council.

The best calibration for the final local hydrodynamic model was achieved when most of the model area was assumed to have bed resistance equivalent to manning number of 40 m $^{1/3}$/s. The water levels

of the northern and southern rivers at the boundaries, as well as the North, South and East boundaries of the local model, as shown in Figure 3, were extracted from the results of regional HD model.
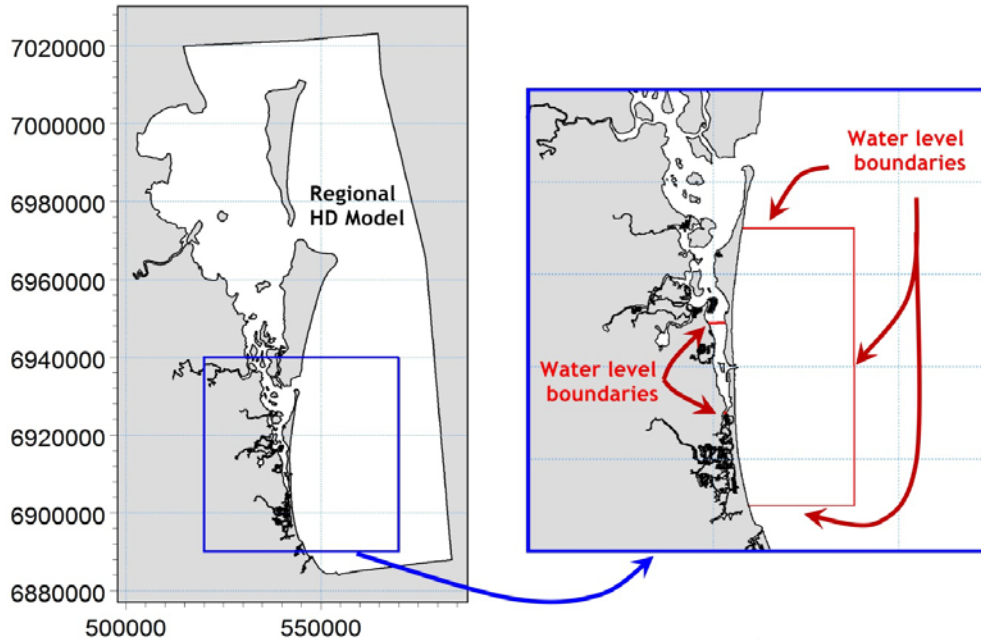

Figure 3. Locations of the water level boundary outputs from the Regional HD model for the local HD Model (Red lines in the right image are the boundaries of the Local HD model)

Regional Wave Model

Two wave models were used to simulate the wave condition in the area. The larger scale wave model, which was called the "Regional wave model", covered the area from northern extremity of the North Stradbroke Island to the north and Point Danger (Tweed River Entrance) to the south; with an offshore width of about 39 km at the Gold Coast Seaway (Figure 4).
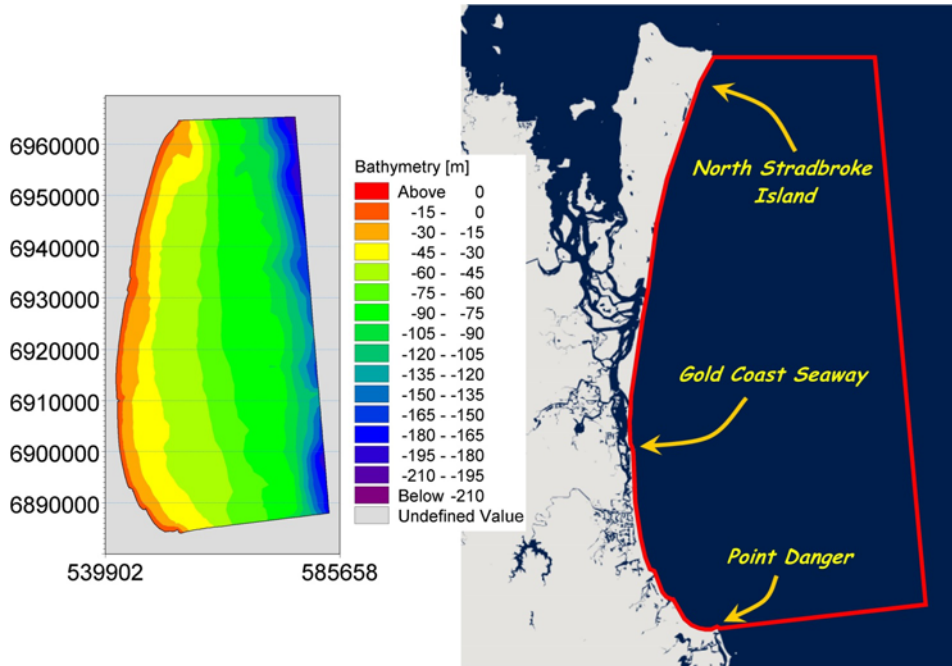

Figure 4. Regional Wave model domain and Bathymetry

The results provided by the regional wave model were used as the boundary conditions for the local model. Sensitivity analysis of the final local model results, based on the choice of wave boundary condition for regional wave model, was conducted then. Different wave boundary conditions applied on the boundaries included ECMWF, WWIII and Brisbane buoy wave data measurements. The final local model results for all of the above mentioned wave boundary conditions were acceptable. However the best results were obtained using Brisbane Buoy measured as the boundaries of the regional wave model.

Local Model Set up

The domain of the local model is shown in Figure 5. The mesh sizes in the Gold Coast Seaway as well as those of the area of the ebb-delta were reduced in order to have more precise predictions of hydrodynamics and morphological changes. The minimum and maximum element lengths were about 15 m and 1 km, respectively. Bed resistance in HD model was used as the calibration factor for hydrodynamic calibration, and finally it was set to a manning number of 40 $m^{1/3}$/s for the whole domain.
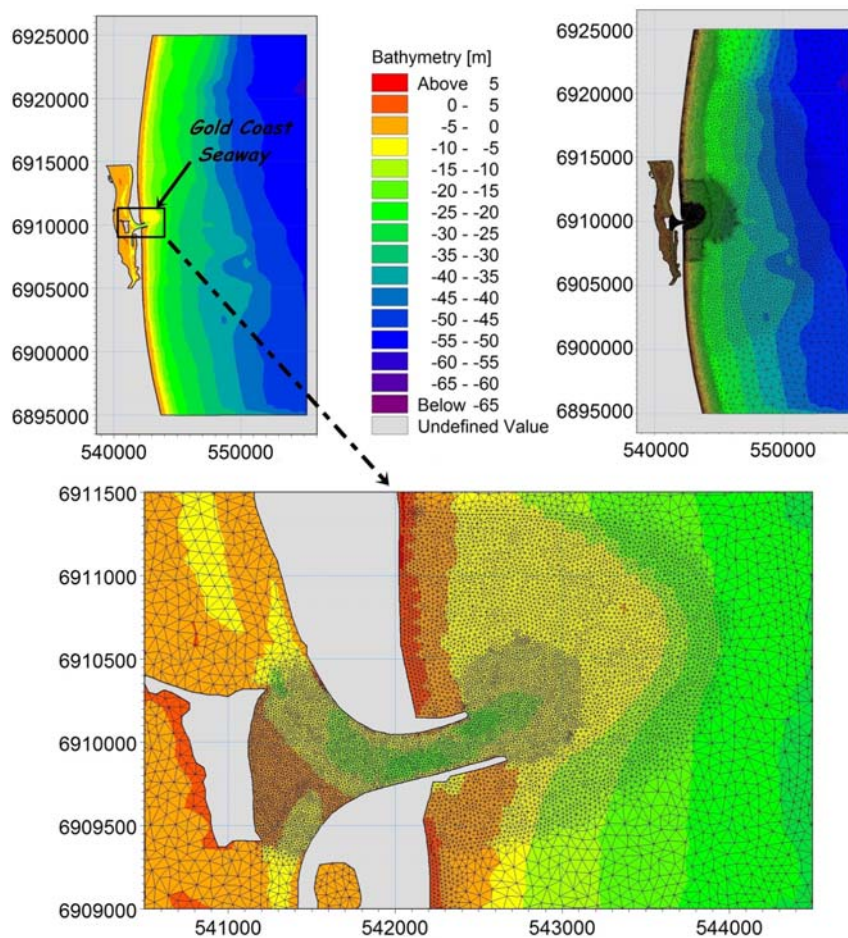

Figure 5. Local HD Model Domain and mesh

According to the measurements and previous studies, median diameter of the sand in the area was set to d_{50}=220μm (Splinter et al. 2012). The grading coefficient of the sand was calculated based on the results of sieve analysis of sand samples from the region, and set to 1.25 in the model. For erosion of the coastlines, an angle of repose needs to be defined, which was set to 50 degree based on the analysis of ETA line survey data from GCCC in several sections in different times. Wave breaking factor, $\gamma = H_b/h_b$, was assumed to be constant through the whole region and equal to the default value of 0.8, although previous research and measurement in the area confirmed that Gamma is variable and has a decreasing trend in the offshore direction (Jafari 2013). This will be used as one of the calibration

factors for sediment transport and morphological changes in the area in the following stages of the research.

The research area morphological evolution depends on both current and waves. Hence, the module that was selected for sediment transport modelling was "Combined Wave and Current". In this case sediment transport rates are derived by linear interpolation of pre-generated sediment transport table which is based on a quasi three-dimensional sediment transport model (STPQ3D) (DHI 2009a). In the STPQ3D model, the bed load transport model of Engelund and Fredsøe (1976) is used, where the bed load transport is calculated from the instantaneous Shield's parameter. For the generation of the sediment transport tables, the critical Shield's parameter based on the properties of seawater and sediment in the area was set to 0.045, this was the minimum allowable critical Shields parameter in the model. Water temperature was assigned 20°C based on the average measured seawater temperature in the area. According to sensitivity analysis of the sediment transport rate, the semi-empirical wave theory of Doering and Bowen (1995) which is valid in all water depths and breaking and non-breaking waves was chosen for the generation of sediment transport table.

Current calibration data was obtained from two vertically oriented ADCPs (Stuart et al. 2010). The seabed ADCP was mounted at 27.9341° S and 153.4254° E, and the pipeline ADCP was located on the sand bypassing pipeline at 27.9352° S and 153.4257° E, both recording velocity profiles every 30 minutes. In this study, Pipeline ADCP data was used for the calibration and verification purposes. The results of the wave model were obtained for the location of the offshore wave buoy, Gold Coast Buoy, which is currently located at 27° 57.950'S and 153° 26.570'E (Figure 6). The water depth at the Gold Coast Buoy location is approximately 18 metres.

The chosen morphological simulation period was from August 2008 till June 2009 as it encompassed the measured hydraulic flow data time in the seaway and that a significant amount of morphological change occurred in response to two severe storms.

Figure 6. Locations of The Gold Coast Seaway ADCPs and Gold Coast Buoy

RESULTS

Hydrodynamics

Calibrated flow and wave models were verified against measured Pipeline ADCP data in May 2009, and Gold Coast Buoy data in Dec 2007 to Jan 2008, as shown in Figure 7. According to the figures, the model results have a close agreement with the measurement. Agreement between the model and observed flow parameters at Pipeline ADCP during 20 days in May 2009, and for Gold Coast buoy 30 days data in 2007 to 2008, were assessed by using the accuracy metrics such as Bias, R^2, RMSE and NRMSE as shown in Table 1 and Table 2. The metrics for both flow within the Seaway and wave parameters offshore, represent a good verification of the model versus the measurement.
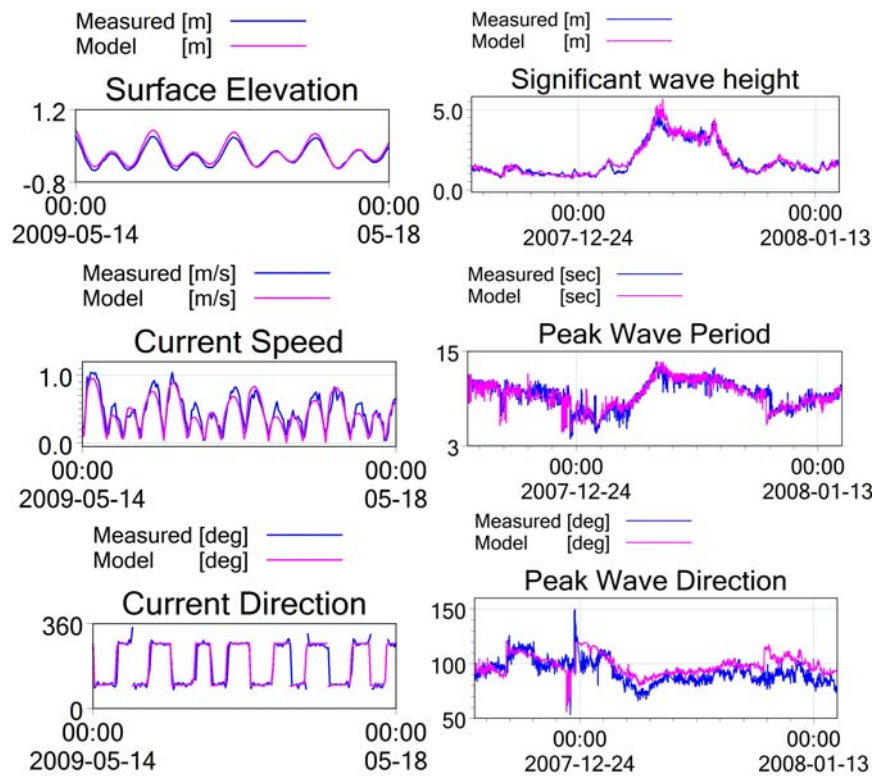
Figure 7. Comparison of hydrodynamics model results and measurements

Table 1. Accuracy metrics of 20 days in May 2009

	Surface Elevation	Current speed	Current Direction
Bias	0.01 (m)	-0.1 (m/s)	-0.21 (Deg)
R	0.97	0.88	0.9
RMSE	0.1	0.18	37.57
NRMSE (%)	7.02	12.98	10.88

Table 2. Accuracy metrics of one month simulation from December 2007 to January 2008

	Significant wave height	Peak wave period	Peak wave direction
Bias	0.05 (m)	-0.10 (s)	6.65 (deg)
R	0.97	0.88	0.57
RMSE	0.25	0.84	12.32
SI (%)	14.03	8.82	13.33

Morphodynamics

Simulation of a ten-month period from August 2008 to June 2009, which included two severe storms, was initially conducted with default values for all model parameters assumed. It was found that the majority of the morphological changes of the ebb delta in that period were in response to the severe storm East Coast Low (ECL) in May 2009. Based on this, all further simulations were run for only the period covering the ECL (19 to 25 May 2009) so as to reduce simulation run times. The morphological changes that resulted from the simulation of the East Coast Low storm in May 2009 with the measured and calculated values for model parameters, as described in local model set up section, were compared with the difference between two hydrographical surveys in August 2008 and June 2009. This comparison showed an approximately similar pattern, although both the ten-month period run and six-day run, for May 2009, underestimate the morphological changes (Figure 8).
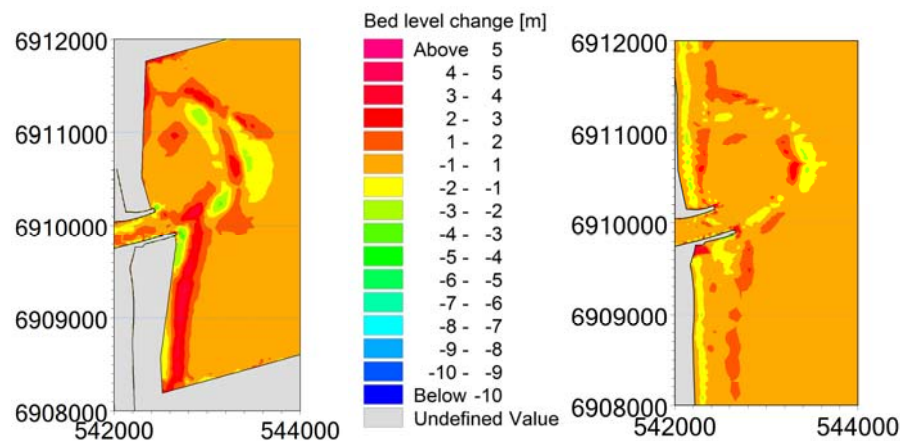
Figure 8. Left: Actual bed level Change from August 2008 to June 2009
Right: Simulated bed level Change for ECL May 2009

The numerical model showed that during storms which are mostly from the south-east in this case, cross-shore currents erode a significant amount of sand from the coastline and deposit it offshore. One hypothesis is that the longshore currents due to the storms transport a portion of the eroded sand northward to the inlet mouth which eventually results in growth of the ebb delta. The validity of this hypothesis needs to be investigated further when a fully calibrated morphological changes model is developed. To improve the morphological model simulation, the sensitivity of the model to different parameters was investigated. For instance, it was found that the model results are very sensitive to sediment grain size in the area; choice of wave breaking parameters and also to the wave theory that is applied in calculation of orbital velocity required for the generation of sediment transport tables. The next step of this study is the calibration and detailed descriptions of the bed evolution in the Gold Coast Seaway region, specifically in its ebb-tidal delta.

SUMMARY AND CONCLUSION

To explore the reasons of continuing growth of ebb-tidal delta in the Gold Coast Seaway mouth, a depth averaged coupled wave, flow and sediment transport model was developed using MIKE 21/3 Coupled Model. The model's hydrodynamics module was calibrated and verified versus field measurement data using current and wave measurements. The results of the sediment transport model with morphological update for ten-month simulation from August 2008 to June 2009 was found to be very similar to those of six-day model of East Coast Low storm. The pattern of the simulated morphological changes was qualitatively similar to that of the observations, although both simulations underestimate the bathymetry changes throughout the domain. Since the model results showed that most of morphological evolution in the ebb-tidal delta happens during the storm, all future simulations were run for only the period covering the ECL storm to reduce simulation run times. To reach to a quantitatively calibrated morphological model, further model sensitivity analysis is continuing.

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