

Hydrodynamic, Water Quality and Sediment Transport Modeling of Estuarine and Coastal Waters on the Gold Coast Australia

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ABSTRACT

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There is an increasing demand for knowledge about hydrodynamic, morphological and water quality processes within the estuarine waterways of the Gold Coast. This study describes the development of a suite of hydrodynamic, sediment transport and water quality models for the Gold Coast tidal waterways. The modeling framework described was developed to provide a strategic understanding of waterway behaviour at a level appropriate for planning and environmental impact assessment in addition to guiding strategic decision making. The model simulations are based on DHI's two-dimensional flexible mesh code, MIKE21 FM. The hydrodynamic equation is linked to a set of transport-dispersion (transport module) equations that are solved using the flow field generated by the hydrodynamic model. This transport module establishes connection between heat, salinity, tracers and turbulence parameters and hydrodynamic. It also provides a base for water quality and sediment transport modeling. Water quality modeling is achieved through development of required process module. Process module is constructed using templates that the ECOLab interface provides. The process module describes the flow of N, P and C between the various trophic forms. The external factors, such as salinity and temperature, which govern the variations of the components in time and space, are made available to processes through a link with the hydrodynamic module. The current induced sediment transport and the associated morphological evolution in the study area were simulated by the sediment transport module of the software. The transport rates and the morphological evolution are calculated on the same flexible mesh that was used for hydrodynamic and water quality modeling. The resulting estuarine model framework has been applied to a number of specific issues such as recycled water discharge and waterway assimilative capacity. Future applications include modeling of extreme events under climate change.

ADDITIONAL INDEX WORDS: *Estuarine modeling, Hydrodynamics, Water Quality, Sediment Transport*

INTRODUCTION

The City of the Gold Coast is positioned in a major coastal growth area on the eastern coast of Australia and has been subject to substantial development stress over the recent years. The inception of the Gold Coast Estuarine Modeling Study (GEMS) was a result of the increasing demand for knowledge about the hydrodynamic (HD), morphological and water quality processes within the complex estuarine system the Gold Coast is built on. GEMS encompassed scientific understanding, predictive modeling and decision-support methodologies. To this end a comprehensive data collection program within the estuarine waterways on the Gold Coast was undertaken in years 2004 and 2005. This exercise was followed by the development of a two-dimensional rectilinear hydrodynamic model of the Broadwater (MIRFENDERESK and TOMLINSON, 2007a). The Broadwater is a coastal water body that drains four major river systems, namely the Nerang, Coomera, Pimpama and Logan-Albert. Broadwater is connected directly to

Pacific Ocean via two tidal openings, namely the Gold Coast Seaway and Jumpinpin. Interaction between the Broadwater and the open ocean through these tidal inlets were studied by MIRFENDERESK and TOMLINSON (2008).

In addition to the Gold Coast Seaway and Jumpinpin, the Broadwater is connected to the Pacific Ocean via Moreton Bay to the north of the Gold Coast, as shown in Figure 1. Due to substantial interaction between these two water bodies, a model that covers both areas was deemed necessary for full and comprehensive simulation of the estuarine waterways of the Gold Coast. The focus of this paper is the development and rationale for the modeling framework to deliver a decision-making tool to the local authority.

STUDY AREA

The MIKE21FM GEMS model covers a region from the Southern Queensland border at the Tweed River to Noosa Head located more than 300 km further north and offshore to

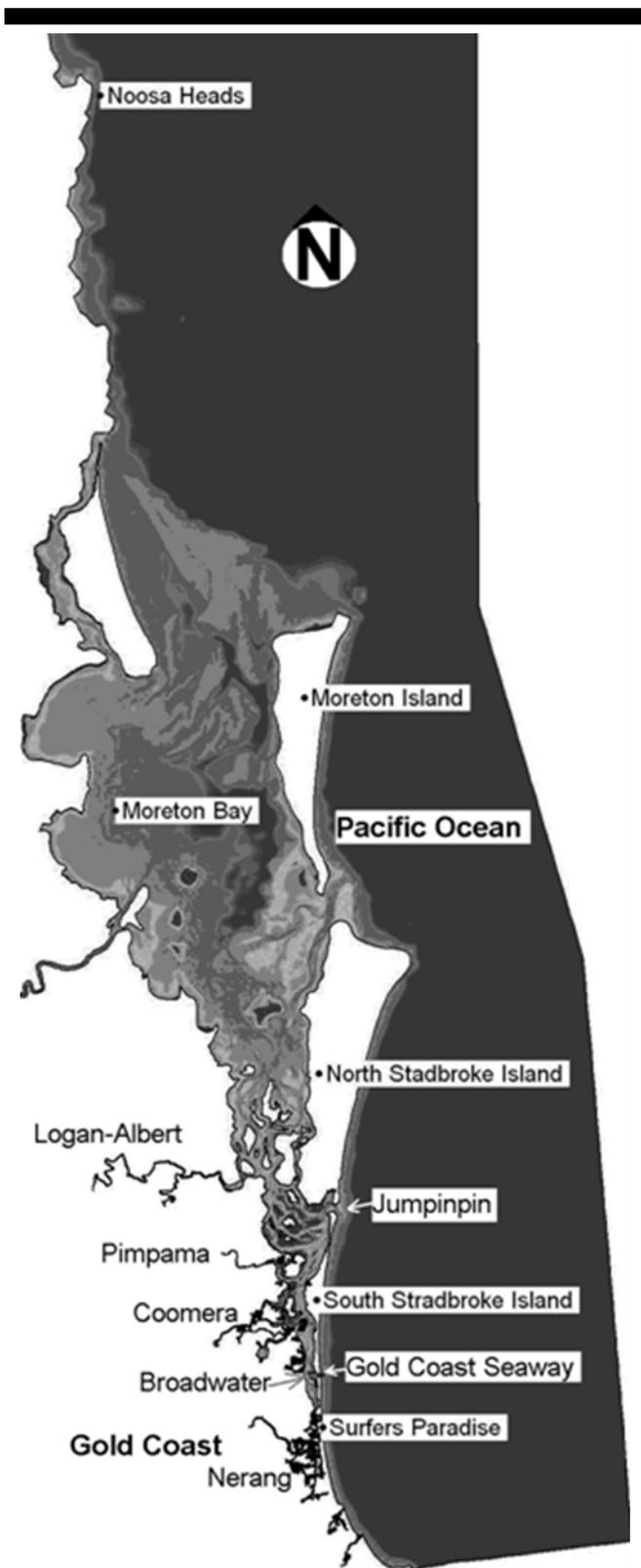


Figure 1. Layout of the study area

approximately the 100 m depth contour. Figure 1 shows the MIKE21FM GEMS model extent. This model covers all tidal waterways on the Gold Coast in a resolution that allows the full

tidal prism to be resolved. The tidal tributaries that are connected to the main Broadwater system, namely the Nerang, Coomera, Pimpama and Logan-Albert, are also defined in an adequately fine resolution to allow for accurate calculation of the tidal prism of the system. The above-mentioned local tributaries can further be separated from the main body of the model for further refinement for more detailed studies. In that case the driving force for these local models is created by extracting tidal or discharge boundaries from the global model.

The coastal and inland areas within the Gold Coast region are both diverse and dynamic. The coastline responds continuously to sediment processes both locally and from the net import of sediments from the Tweed River entrance sand bypass to the south. In the estuarine systems of the Broadwater-Moreton Bay there is a complex interaction between the relatively high tidal amplitudes and the complex couplings through narrow channels between the main water bodies, and through the Seaway and Jumpinpin to the ocean. The large inland waterways influence the overall dynamics of the system primarily by providing storage, but by doing so also add a time-lag to the tidal signal.

METHODOLOGY

This study comprises of the following five steps:

- Collection and sourcing field data;
- Development of a flexi mesh grid representing bathymetry and topography of the study area.
- Development of a suite of hydrodynamic, advection-dispersion, water quality and sediment transport models.
- An initial calibration of the models based on available data,
- Discussion of the initial results of the modeling exercise..

Data Collection

Required data for this study were sourced as follows:

- Sedimentological data was collected as part of this study. This included sediment samples and turbidity measurements. Sediment samples were collected using a grab-sampler at 104 locations across the study area. The collected samples were sieved to determine grain size distributions of the bed sediment within the study area. Turbidity data were collected at 87 locations across the study area.
- Hydrographic data was sourced from earlier studies (MIRFENDERESK and TOMLINSON, 2006, 2007a, 2008, 2009). These include simultaneous water level measurements at 34 stations and current measurements at 14 locations across the study area.
- Given the vast extent of the study area, the strategy for water quality data collection was focused on collection of two types of data sets. The first data set is less comprehensive but covers most of the study area, aimed at providing a global view of water quality status of the study area. It includes measurements of parameters such as Conductivity, Salinity, Dissolved Oxygen, Temperature, Turbidity, Secchi, PH, Chl-a, NH₄, NO₂, Total N, Organic N, PO₄, and total P on monthly basis. The second data set was comprehensive but only focused on one river system to enable an understanding of governing processes in a representative estuary to be gained. The first data set was sourced from the Ecosystem Health Monitoring Program (EHMP) that is run by Queensland Government in partnership with local Governments within the study area. The second data set was sourced from the Gold Coast City

Council. This data set covers time history of water quality data at 10 stations at the Pimpama River Estuary for a period of 12 Months. This data set also includes information on seagrass, Mangrove & salt-marsh distribution, Macro-invertebrates survey and sediment biogeochemistry data.

Grid Generation

The grid generation process in MIKE21FM is performed automatically; however the user can influence the size of the mesh and its resolution at various locations across the model area by introducing break lines and setting maximum grid size parameters. The Broadwater system is an extremely complex area with many narrow estuaries, man-made canals, deep dredged channels and mangrove lined banks requiring all channels however shallow, narrow, deep or wide to be resolved as finely as possible, allowing for a complete understanding and true representation of the system dynamics. With a need to have models with realistic and acceptable run times there are many areas that have a mesh resolution that could be considered relatively coarse. These areas were manually investigated and modified as part of the mesh development process and preliminary calibration to make sure they represented the detailed DTM as best as they could. In this model the study area is represented by a flexi-mesh comprising of 293764 triangular elements. The resolution of elements has been progressively increased from the open ocean boundary towards the narrow tidal waterways. The area inside the Broadwater, the tidal entrance and the ebb shoal outside of the tidal inlet were represented with adequately fine elements to account for complex flow pattern and bathymetric variability in these areas. A five meter Digital Elevation Model was sourced from an earlier study (MIRFENDERESK and TOMLINSON, 2007a); and used for the generation of a mesh of the study area.

Hydrodynamic Modeling

Numerical modelling was conducted using DHI MIKE software. Mike21FM simulates unsteady flow taking into account bathymetry and external forcing such as wind, tidal elevations, currents and other hydrographic conditions. The code is based on the numerical solution of the two dimensional incompressible Reynolds averaged Navier-Stokes equations invoking the assumptions of Boussinesq and of hydrostatic pressure. The model solves the momentum and depth average continuity equations and the flexi mesh enables a fair description of the details and channels throughout the estuary.

In this model turbulence is modelled using an eddy viscosity concept. Given the chosen spatial resolution, the small scale turbulence is approximated by a sub-grid scale model proposed by Smagorinsky (DHI manual 2008). Smagorinsky (1963) proposed to express sub-grid scale transport by an effective eddy viscosity related to a characteristic length scale. The sub grid scale eddy viscosity is given by

$$A = c_s^2 l^2 \sqrt{2S_{ij}S_{ij}} \quad (1)$$

where c_s is a constant, l is a characteristic length and the deformation rate is given by

$$S_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (i, j = 1, 2) \quad (2)$$

The bottom shear stress is determined by a quadratic friction law

$$\frac{\bar{\tau}_b}{\rho_0} = c_f \bar{u}_b |\bar{u}_b| \quad (3)$$

where c_f is the drag coefficient and $\bar{u}_b = (u_b, v_b)$ is the flow velocity above the bottom. In this model setup u_b is the depth-averaged velocity and the drag coefficient is determined from the Manning number, M .

Calibration was achieved by varying roughness values. The calibration was performed against water level and discharge measurements at 34 and 14 locations inside Broadwater, respectively. The discharge is calculated using the velocity data that was collected by an ADCP in January 2005. The model is forced at offshore ocean boundaries with a spatially and time varying tidal signal generated using the DHI global tide model allowing the model to perform in a more natural manner in terms of the interconnections within the system. This approach is important when looking at water quality and sediment transport issues as the whole region is able to freely exchange water.

Advection Dispersion Modeling

The advection-dispersion module of the model simulates the movement of dissolved or suspended solids and substances. Given the nature of the study area, it is expected to have two different driving forces behind mixing processes.

- Turbulence dominated mixing processes at upper reaches of the rivers where tidal flux is not strong and
- Tidal-flux dominated mixing processes at lower reaches of the rivers and within the Broadwater and Moreton Bay, where tidal fluxes are strong.

On this basis calibration of the advection and dispersion performance of the model was undertaken using two sets of data at two different locations.

The first data set was obtained through monitoring the dilution and movement of a tracer dye (Rhodamine WT), introduced into the water column during a number of experiments at a number of locations in the Broadwater (MIRFENDERESK et al 2007b). Monitoring and tracking of the dye plume was achieved using marker drogues and a DGPS fixed survey vessel recording rhodamine concentrations. The second data set was obtained in the Pimpama River estuary using a different methodology, based on the recovery of the estuary from a deluge of freshwater inflow following a flooding event. This methodology involved:

- Collection of salinity data for a freshwater flush through the system (this occurred during February 2004) to measure salinity spatial gradients dissipation over time;
- Estimation of inflow volumes during the freshwater inflow event; and
- Calibration of the advection and dispersion parameters in the model using salinity data and inflow volume estimates.

A flow proportioning factor of 50 with maximum range of $5\text{m}^2/\text{s}$ to $50\text{m}^2/\text{s}$ gave the best replication of the salinity behavior of the estuary.

Water Quality Modeling

The condition of the estuarine system on the Gold Coast can be generally divided into three sections: the Broadwater, the lower reaches of the tidal river systems and upper reaches of the rivers. Some of these areas, in particular in the Logan-Albert and Pimpama estuaries have poor water quality and suffer from reduced biodiversity. Nutrient over-enrichment from urbanization or agricultural activities is considered as a threat to the ecology of the Gold Coast estuarine waterways.

One of the main purposes of the water quality modeling is to simulate the nutrient (N and P) cycle in the estuarine system and hence to develop a tool that allows testing new ideas for management of the health of the estuarine waterways on the Gold Coast. The extent of the water quality model is similar to that of the hydrodynamic model but the focus of the model is on the Gold Coast. The model development is a work in progress, given the large size of the area that is covered by the model. The study has taken an estuary by estuary calibration approach; the first estuary being the Pimpama River Estuary.

The water quality model is structured based on the standard Eutrophication module of the DHI's ECO Lab Modeling system with some modifications reflecting the important pathway for cycling of nutrients via N-Fixation and Denitrification as shown in Figure 3. The spatial characteristics of the sediments were described by incorporating the sediment biofacies mapping into the model. Calibration of the model parameters was undertaken using the water quality, sediment biogeochemistry, seagrass and mangrove data available for the study area. Upstream boundary of estuary was sourced from the output of the EMSS ("Environmental Management Support System") model (Chiew, Scanlon, 2002). This model provides estimates of pollutant loads (Total Nitrogen (TN), Total Phosphorous (TP), Total Suspended Solids (TSS) and E-coli.).

Sediment Transport Modeling

The purpose of the sediment transport modeling at this stage is to gain some understanding on the rate of bed level changes within the natural and man-made canals and waterways as a result of tidal flow. The sediment transport module of the DHI's MIKE21fm model coupled with the above-mentioned hydrodynamics model

has been used for the simulation of sand transport in this study. The model uses a spatially varying bed material map (as explained in data collection section). Engleund and Hansen total load transport formulation resolving both bed load and suspended load formulations has been used as the transport theory. In this theory the dimensionless rate of total-load transport Φ_t is calculated as:

$$\Phi_t = 0.1 \frac{C^2}{2g} \theta^{2.5} \quad (4)$$

With C = Chezy's number and

$$\Phi_t = \frac{q_t}{\sqrt{(s-1)gd^3}} \quad (5)$$

With q_t = the total load sediment transport and g = gravitational acceleration. The dimensionless bed shear stress θ is defined as

$$\theta = \frac{U_f}{\sqrt{(s-1)gd}} \quad (6)$$

Where U_f is the shear velocity related to total friction, d is the grain diameter; and s is the relative density of the bed material.

Equilibrium conditions have been used on the boundaries, meaning that no excess sediment will enter or leave area. The model is run with morphology at every time step causing the bathymetry to be updated dynamically.

RESULTS

From a sediment transport point of view, the study is still in progress. Initial results of the modeling indicate that the estuarine waterways on the Gold Coast are still re-adjusting to the latest

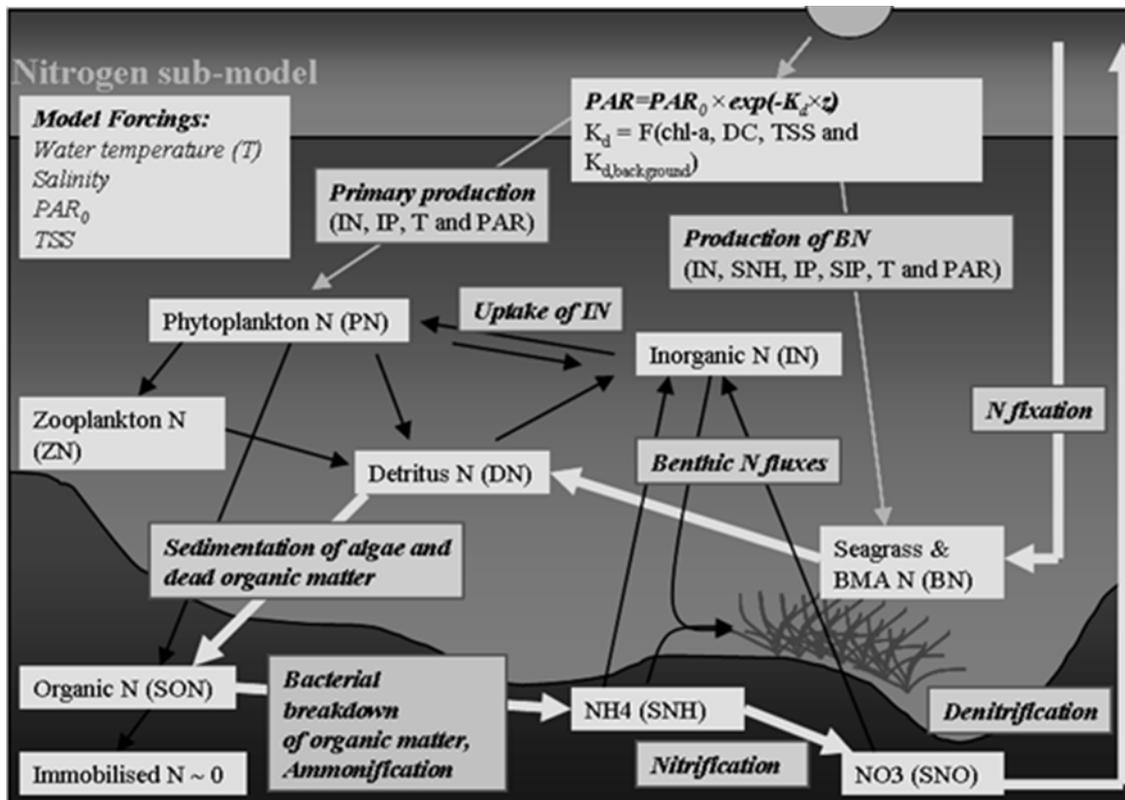


Figure 2. The important pathway for cycling of nutrients via N-Fixation and Denitrification (shown by white thick arrows).

developments within the study area. These developments range from stabilization of the Nerang River Tidal entrance (Gold Coast Seaway) to moderate modifications and realignment of the man-made and natural waterways.

From hydrodynamics point of view the volume of Broadwater varies between 30 giga liter (GL) during low tide and more than 50 GL during high tide. Flux through the Gold Coast Seaway can be close to 60 GL during high tide and close to 40 GL during smaller diurnal tides. Tidal regime at the Broadwater and its associated waterways are mixed predominantly semi diurnal.

There is a 2 hour time lag between high tide at the Gold Coast Seaway and Jumpinin and that in Moreton Bay. Given the connectivity of the Broadwater to Moreton Bay via a number of narrow channels, the northern part of the Broadwater is partly dominated by a delayed tide in Moreton Bay, whereas the southern section of the Broadwater follows tidal wave propagating through the Gold Coast Seaway. As a result of the time lag there is 1.5 hours lag between high water and slack water at the Gold Coast Seaway, meaning that discharge through the seaway approaches zero approximately 1.5 hours after high water.

The Broadwater system is mainly a marine system with salinity of 33 ppt. the level of salinity reduces at the upper reaches of the river system. The study has found that the Broadwater area is in a relatively good ecological condition. Hydrodynamic modeling results indicate that up to 100 GL of water can be exchanged between the Broadwater and the Pacific Ocean through the Gold Coast Sea way every day. Given such a high degree of tidal exchange the good ecological condition is regarded as relatively sustainable and therefore the Broadwater is expected to show some resilience against minor to moderate changes in catchment conditions or the addition of wastewater discharges. Such assimilative capacity has not been observed at the upper reaches of the estuarine waterways associated with the Broadwater, partly due to weaker tidal exchange and greater influence from catchments runoff.

Detailed water quality study so far has been focused on the Pimpama estuary. The findings of the study suggest that the system is Nitrogen limited. This finding is consistent with earlier studies undertaken by Herbert (1999) for general coastal marine ecosystems. Primary sources of productions are identified as Phytoplankton, sea grasses in the Benthic Zone and Benthic Micro-Algae (BMA). Nitrogen fixation is recognized as the most important driver of the system.

The system is highly sensitive to Dissolved Inorganic Nutrients (DIN). Currently DIN is controlled by a natural De-nitrification process that successively reduces the amount of fixed nitrate (NO_3) and nitrite (NO_2) to primary gaseous dinitrogen (N_2). This natural process can be compromised if the bed sediment oxygen level reduces below a critical level required for Nitrification, as the sediment oxygen pool controls the nitrification process. Over-enrichment of the estuary for instance because of waste discharge, could potentially disrupt the coupled nitrification-denitrification processes and can lead to eutrophication of the estuary. Over enrichment can result in rapid growth of pelagic macroalgae and phytoplankton which in turn, suppresses benthic plant growth by reducing light availability. Organic matter produced in the water column sinks to the sediment surface where it decomposes and consumes the oxygen supplies. This will cut the required oxygen for nitrification process and then force a cycling of N in the system by the NH_4 fluxing back out into the water column instead. This will cause a cycling of nutrients and eventually a build up within the system that could lead to entropic condition. Modeling indicates that catchment runoff dominates water quality in the upper reaches of the estuary.

DISCUSSION

The modeling framework described above was developed to provide a strategic understanding of waterway behaviour at a level appropriate for planning and environmental impact assessment in addition to guiding strategic decision making. The modelling approach adopted was to provide boundary conditions and broad scale parameters which would be universally accepted and which could provide the baseline for more detailed site specific studies as part of environmental investigation or for assessment of particular proposals for development or other activities that would be required to be undertaken by consultants. Overall, the GEMS studies and modelling activities have been undertaken in a research-oriented collaborative partnership which has yielded outstanding cost-effective outcomes.

To date GEMS has been applied to the dispersion of recycled water discharges; the impact of catchment pollutant loads on waterways; the stability of the main tidal connections to the Pacific Ocean – The Seaway and Jumpinin, and the extent of foreshore erosion and channel stability in response to dredging or waterway development. Future applications include modeling of extreme events under climate change.

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