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Modelling Cohesive Sediment Dynamics in Moreton Bay

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I acknowledge 'the universe' for 'existing', although I may not believe it had such 'intentions' to do so, I appreciate it nonetheless.

I'd like to pass an obligatorily large thank you to my family and friends for supporting me and enduring my differential slide into madness, much alike the settling velocity of a suspended flocculated cohesive sediment falling on smaller particles until it is again lifted by the turbulent eddies of family and friends to carry on its journey.

Abstract

Many ports around the world require maintenance of engineered navigational channels, for the safe passage and berthing of vessels, that suffer from sedimentation. Dredging is often performed on these vital navigational channels, an economically burdening and traditionally ecologically risky operation. Moreton Bay is a subtropical semi-enclosed waterbody of high value on the east coast of Australia that has been impacted by anthropogenic development, particularly through natural vegetation clearing for agriculture. The Port of Brisbane operates and maintains a shipping channel through the bay and into the lower Brisbane river. A trailing suction hopper dredger is utilised to maintain the safe navigational depth of the channel. Much of the fine sediments dredged from the lower Brisbane river section of the channel is placed into a designated placement area nearby. The context of the sediment dynamics of the environment this material is being placed into and surrounding this placement area are not well understood. The sediment bed characteristics around this area of interest is thought to behave cohesively. A three-dimensional numerical model of Moreton Bay was developed using open source Delft3D (Deltares, Delft, The Netherlands) focusing on cohesive sediment transport processes. Calibration and two validation stages were carried out on the modelled hydrodynamics in order to reduce the large range of uncertainty in the sediment transport computations. A subsequent investigation was then undertaken into the relative modelled scales of response and variability surrounding the tidal and wind driven suspension within a defined 10x10 km study area enclosing the Mud Island placement area within Moreton Bay. Following from this, the model was utilised to predict a dredge material placement scenario that would later be monitored. In conducting these investigations, a contextualised understanding of the significance of dredge material placements within the Mud Island placement area was developed, along with further understanding of the dynamics of suspended material around this environment in which dredge material is being placed into. It was found from the modelled scale of response in the study area, that approximately 10% of the total bed disturbance resulting in suspension was directly due to tidal forcing over 2015 and 2016. However, large wind events generating at least 10-fold greater suspended sediment in the study area and occurring less than 10% of the time in 2015 and 2016 would have been the driver of more than 50% of the total amount of bed disturbance resulting in suspension inside the study area. These results are contrasted by the results of both model predictions and field observations of a dredge material placement event in the Mud Island placement area which suggest placement events have a very localised effect on elevated sediment concentrations spanning and lasting less than 1 km and 3 hours in space and time.

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Chapter 1. Introduction

This chapter provides a brief introduction to this thesis. The motivation for undertaking this work is described in the first section. Specific aims for this thesis are specified in the second section. Whilst the structure of the thesis is outlined in the third section.

1.1. Motivation

The location of the study, Moreton Bay, is a very important receiving waterbody to a much larger area of developing catchments with growing populations and a large percentage of agricultural land use. Additional to these pressures, storm severity and frequencies have been and are predicted to increase into the future. A key pollutant associated with these pressures for this system and other similar high value bays around the world are terrestrial fine sediment loads, and the associated heavy metals and nutrients that are introduced. The bay's importance and value lies not only in its economic resource through commercial fishing, tourism, and facilitation of a major shipping channel for the Port of Brisbane, but also as a system of high ecological significance.

The Port of Brisbane's major shipping channel through Moreton Bay services the developing and growing greater Brisbane region and requires annual maintenance dredging for the safe navigation of large cargo and cruise ships. Maintenance dredging of the shipping channel incurs large economical costs, where dredged material is placed back into the bay at the shortest distance away from the shipping channel and therefore cheapest area to zone for spoil placement. The impacts and extent of the effect of these placement events are not well understood in this area, including characteristics of resuspension from the bed and the significance of the wind environment.

1.2. Aims

This thesis aimed to develop a sediment transport model of Moreton Bay to investigate and quantify the scale of the dynamics of muddy sediments both naturally suspending and resulting from placement operations conducted by the Port of Brisbane in the vicinity of Mud Island. Model performance was validated directly against historical and recent observed hydrodynamic and sediment measurements in order to achieve a level of confidence in the outcomes. The key objectives were:

- to estimate the relative scale of bed suspension and the effect/variability caused by the tidal and wind environment in and immediately surrounding the Mud Island placement area; and
- to predict and estimate the contextual impact and extent of dredge material placement in the Mud Island placement area.

1.3. Structure

Chapter 2 provides a general review of previous literature surrounding the study region, including dredging activity and other aquatic ecosystems facing similar challenges and uncertainties. The known relevant physical processes involved in the sediment dynamics studied in this thesis are also discussed.
Chapter 3 is a description of the model development process, including the calibration and validation methods utilised for parametrising and evaluating the performance of the model.

Chapter 4 describes and details the results of an investigation into sediment suspension in the Mud Island study area. The chapter includes an insight into both the tidal and wind-driven suspension around the Mud Island spoil site.
Chapter 5 provides an outline of a study on the placement of dredge material in the Mud Island study area. A predictive model use is described, and an overview of a subsequent event monitoring study and results are provided.
Chapter 6 is a concluding chapter discussing the conclusions of the thesis, limitations of the model and studies, as well as recommendations.

Chapter 2. Literature Review

This chapter gives an overview of the background in previous works related to this thesis and the study region. The first section provides an introduction to the current understanding of the Moreton Bay system. The second section reviews the physical processes to be considered for this study.

2.1. Moreton Bay Study Region

Moreton Bay is a semi-enclosed embayment sheltered largely from the Coral Sea by the barrier islands of Moreton and North Stradbroke (as illustrated in Figure 1). With an average depth that is less than ten metres, ranging to a greatest depth more than forty metres (Beaman, 2010), the 1,493.7 km^2 waterbody receives loading from catchments totalling an area of 22,807 km^2 (Digby et al., 1999). The catchments of this bay have seen one of the fastest growing populations in Australia with projections expecting the population in Brisbane to increase by at least a further 50% by 2036 (QOESR, 2015).

Moreton Bay's catchments have become modified landscapes where greater than 10% is considered urban, and less than 25% is comprised of natural vegetation, with the remaining largest fraction of land used for agricultural purposes (Capelin et al., 1998). Subsequently, high intensity rainfall events in the region have been found to cause a significant degradation in the water quality of the waterways entering the Moreton Bay ecosystem (DERM, 2011; Davies & Eyre, 1998), coinciding with large amounts of fine sediment thought to be caused by runoff and gully erosion (Saxton et al., 2012; Coates-Marnane et al., 2016b). Some of the ecological downstream effects of these arising circumstances has been the subject of much critical research such as studies into the benthic microalgal communities, which can contribute up to 50% of primary productivity in shallow coastal systems such as Moreton Bay, and were found to be significantly negatively affected by catchment development (Grinham, 2007).

The study region is considered a high value ecosystem, hosting migratory birds along the East Asian-Australasian Flyway with identified RAMSAR areas, and is declared as a marine park with habitat protection zones for the large biodiversity that the subtropical bay supports (Neil, 1998). Additional to its vastly cited and recognised ecological value, Moreton Bay also serves the South East Queensland region through purposes ranging from aquaculture and mining operations, to commercial and recreational fishing, as well as tourism especially in the iconic megafauna such as dugongs which are entirely dependent on the primary production of seagrass communities (Skinner et al., 1998). Another key service offered by Moreton Bay is the safe passage of commercial vessels into the Port of Brisbane and the lower Brisbane river. The Port of Brisbane maintains a shipping channel for this purpose that suffers from sedimentation like many others around the world. Maintenance is performed using a suction hopper dredger as pictured in Figure 2.

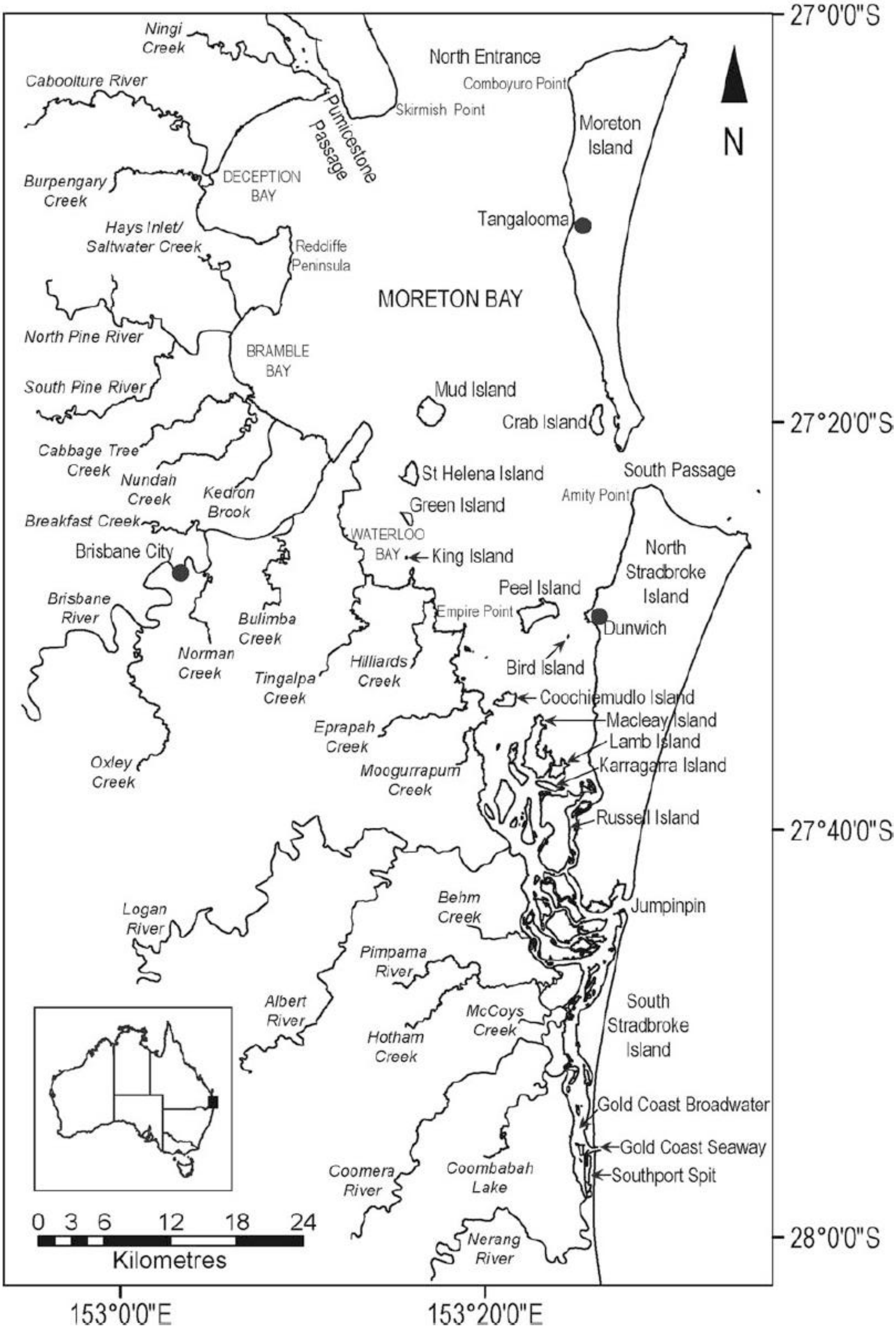

Figure 1: The Moreton Bay estuary illustrating the major river systems draining to the Bay and the major tidal entrances that connect the Bay to the Coral Sea (Gibbes et al., 2014)

Figure 2: Trailing suction hopper dredger (TSHD) Brisbane (Dredging Today, 2015)

The sediment dredged from Moreton Bay and the Brisbane river has been, from historically over the last 100 years to now, used for many purposes onshore, notably including the reclamation of land for the expansion of the Port of Brisbane on Fisherman's Island and 14 million tonnes of sand for the construction of Brisbane Airport. A study of the behaviour of the resulting dredge-generated plume from this sand dredging found a very spatially localised concentration increase of 10-fold and 100-fold near the water surface and bed respectively compared to background conditions lasting less than one hour (Willoughby & Crabb, 1983). However currently and of great relevance to this thesis, much muddy sediment (largely consisting of clay and silt on the Wentworth scale (Wentworth, 1922)) is placed into a designated spoil area between Mud Island and the main shipping channel (connecting the Brisbane river to the Coral Sea through the north entrance of Moreton Bay). The disposal of muddy sediment has been investigated regionally nearby in Townsville, Queensland, specifically offshore disposal at a typical depth of 12 metres by opening trap doors with the hopper dredger both moving and stationary. A mobile disposal method was found to provide some visibly elongated plume dispersal, whilst rough weather characterised by wave-induced turbulence inhibited floc settling and allowed the plume to be transported away from the placement area (Wolanski et al., 1992). The hydrodynamic environment and sediment characteristics are crucial to understanding the underlying sediment dynamics.

The largest velocities recorded in Moreton Bay occur in the northern entrance and southern passage where the most volumetric oceanic flushing takes place (Church, 1977, 1979). A developed residual clockwise flow is suggested due to an asymmetry in flood and ebb tides through each of the passages, resulting in a nett northerly flow on the western side, and southerly on the eastern side of the bay (Dennison & Abal, 1999). Waverider buoy data measured between 1980 and 1984 found the mean wave height to be 0.3 metres with a period of 3 seconds, and a less than 1% occurrence of waves more than 1 metre or with a period of 9 seconds, owing to a largely wind-driven wave environment (Lawson & Treloar, 1985). Attempts to mathematically model Moreton Bay using both analytical and numerical techniques have been made, with an example being Bailey (2010), whom created a 2-dimensional model to investigate pollutant transport sources from the Brisbane river, concluding that the transport of a conservative pollutant was only significantly altered by applied winds in shallower areas of the bay whereas deeper areas were tidally dominated. Field studies have also proven to be a useful tool for investigation, with an example being You (2005), whom conducted a field study collecting current, wave, and suspended sediment concentrations at a mean depth of 6.1 metres over 3 weeks in Deception Bay of Moreton Bay. You (2005) found the main driving force of fine sediment resuspension from the cohesive bed surrounding the study site to be wind generated waves with a critical orbital velocity on the order of 70 mm/s.

Both the spatially and temporally varying properties of Moreton Bay's sedimentary bed have been studied through independent surveys. A recent comprehensive survey collecting and analysing sediment grab samples throughout the bay found there has been a drastic increase in the distribution of fine sediments since the last comprehensive survey, depicted in Figure 3 (Maxwell, 1970; Lockington et al., 2017a). The mud content related area expansion posited by Lockington et al. (2017a) was mostly in samples taken from shallower and poorer water quality western and southern areas of the bay. Whilst Coates-Marnane et al. (2016a) has taken sediment cores within the bay suggesting that the more recent turbid western bay phenomenon is a combined effect of both an increase in the supply of fine sediment and an effective reduction in depth due to up to a 9-fold increase in accretion over the last 100 years (in comparison to the last 1500 to 3000 years).

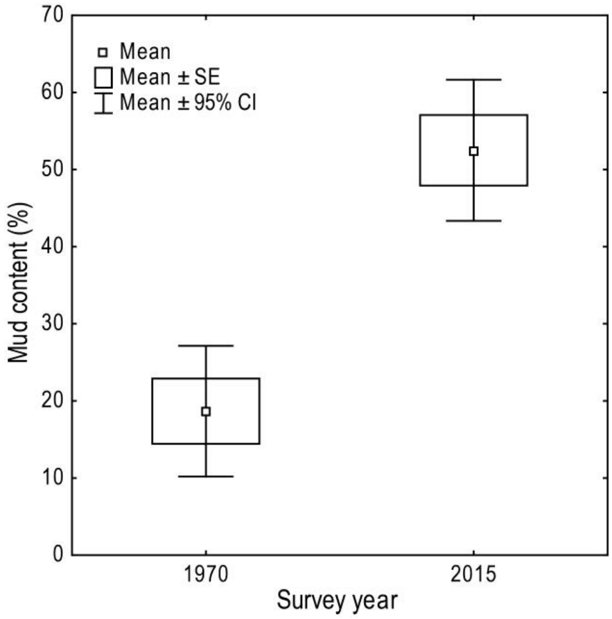

Figure 3: Significant increase in surface sediment mud content from 1970 to 2015 using sites common to both surveys (Lockington et al., 2017a)

The pressures imposed on this study region are similar to those faced by other bays around the world such as San Pablo Bay in California (Jeffe et al., 2007), Fouha Bay in Guam (Wolanski et al., 2003), and Airai Bay in Palau (Golbuu, 2003). Dredge material placement into the water column has also been the subject of other worldly studies into the subject. An extensive study into a recirculation effect at a placement site near the entrance to the Port of Rotterdam, The Netherlands, by Spanhoff et al. (1990) found through the combination of mass balance and modelling techniques that 50-80% of the placed material at this site had transported back to the river outlet over 20 years. Morton et al. (2001) studied a shallow lagoon, Laguna Madre, Texas, with average depths outside of the defined navigation channel of less than one metre. Nearly all placed material in this lagoon was subject to resuspension and transport either back to the channel or dispersed across the lagoon due to local waves and wind-driven currents. Experimental containment designs around high maintenance areas were investigated with some observed benefit over a 2-year period. John et al. (2000) characterised the free fall dumping of bulk loads into three modes dependent on local depth, currents, and sediment type. Wakeman et al. (1975) discussed a turbidity monitoring program performed in San Francisco Bay, USA, measuring the turbidity at different distances from the overflow of a hopper dredger. Whilst turbidity increased in the locality of the vessel, the values found were considered much smaller than turbidity during high run-off and high wind-wave events. A systematic analysis of the stability of disposal sites was performed by Scheffner (1991), and Luger et al. (2002) investigated the optimisation of dredge spoil disposal using a numerical model implemented in Delft3D. A few other studies have also used numerical modelling to study dredge material placement, such as Moritz et al. (1999) and Teeter et al. (1999).

2.2. Physical Processes

A useful tool in modelling coastal environments are the shallow water equations applied and commonly used where the horizontal length scales considered are orders of magnitude larger than the vertical scales of the depth. Three-dimensional shallow water equations are considered here, derived from the more general Navier-Stokes equations for a momentum balance in Figure 4.

$$\frac{\partial \rho u}{\partial t} + u\frac{\partial \rho u}{\partial x} + v\frac{\partial \rho u}{\partial y} + w\frac{\partial \rho u}{\partial z} - f_{cor}\rho v = \left(\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} - \frac{\partial p}{\partial x}\right)$$

$$\frac{\partial \rho v}{\partial t} + u\frac{\partial \rho v}{\partial x} + v\frac{\partial \rho v}{\partial y} + w\frac{\partial \rho v}{\partial z} + f_{cor}\rho u = \left(\frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} - \frac{\partial p}{\partial y}\right)$$

$$\frac{\partial \rho w}{\partial t} + u\frac{\partial \rho w}{\partial x} + v\frac{\partial \rho w}{\partial y} + w\frac{\partial \rho w}{\partial z} = \left(\frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \tau_{zy}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z} - \frac{\partial p}{\partial z}\right) - \rho g$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0$$

Figure 4: 3D shallow water equations where velocities u, v, and w are in respect to directions x, y, and z. ρ is the density of the fluid, σ and τ are the normal and shear stresses due to viscosity, and p is the pressure. f_{cor} is the Coriolis force accounting for a model located on the surface of a rotating Earth-like planet

Further assumptions can and are made, taking incompressible flow and uniform density within a given control volume balance. A given non-trivial wave environment complicates matters as the velocities can then be split into mean, turbulent, and oscillatory components. The equations can then be averaged over the wave motions for wave-related and turbulent Reynolds-stresses. Turbulent motions are assumed to have associated turbulent stresses along a proportional plane relative to the velocity gradient of the plane. There is also some wave-related pressure considered as a time-averaged term (Longuet-Higgins & Stewart, 1962). The resulting horizontal momentum equations consist of inertia, advection, Coriolis, horizontal viscosity, vertical viscosity, pressure gradient, and wave forcing terms. A hydrostatic assumption can then be made, also reducing the vertical momentum balance. The system then becomes determinant by simultaneous methods given known boundary conditions. Figure 5 reproduces the result of this systematic process of reduction to a three-dimensional hydrostatic mathematical model approximating the hydrodynamic environment.

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - f_{cor}v = \frac{\partial}{\partial x}\left(\nu_h \frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu_h \frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial z}\left(\nu_v \frac{\partial u}{\partial z}\right) - \frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{W_x}{\rho}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + f_{cor}u = \frac{\partial}{\partial x}\left(\nu_h \frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu_h \frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial z}\left(\nu_v \frac{\partial v}{\partial z}\right) - \frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{W_y}{\rho}$$

$$\frac{\partial Uh}{\partial x} + \frac{\partial Vh}{\partial x} + \frac{\partial \eta}{\partial t} = 0$$

$$p = p_a + \int_z^{\bar{\eta}} \rho g dz$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

Figure 5: Three-dimensional hydrostatic model including Stokes drift as in Mei (1989)

Authors such as You (2005) have proposed the importance of wind generated waves in the study of sediment dynamics in Moreton Bay. The foundational principle underlying the physical mechanism of wind generated waves is the exchange of momentum between the wind and water interface through resonant means of energy transfer (Phillips, 1957). The growth of wind waves is non-trivial with not only the increase in wave steepness enhancing wind interaction with the water surface as described by Miles (1957), but weak non-linear quadruplet interactions between wave components develop which can have order of magnitude effects on waves with large travel distances (Hasselmann, 1962). At shallower depths, energy loss occurs with wave boundary layer interaction at the bed (Ardhuin et al., 2003). By Holthuijsen (2007), it is useful for spectral analysis of wind waves from time series into spectra describing a frequency domain where wave energy density is considered into a function of frequency.

Some cohesive sediment behaviour is summarised from van Rijn (1993). The defining property of a cohesive bed is its significant cohesive forces due particularly relevantly to ionised particles with organic content, especially when suspended in a saline environment. This cohesive nature results in flocculation of the fine particles, resulting in larger flocs with altered settling velocities. A given sediment bed is thought to behave cohesively or non-cohesively, given a mixture of coarse and fine particles. Laboratory and in-situ experiments have been undertaken to determine the critical particle size distribution characteristics for a cohesively behaving bed. A variety of natural bed core samples roughly classified as silty sand, clayey silt, and silty clay were exposed to successively increased flow in a flume to observe their respective critical shear stresses for erosion. Samples that had greater than 30% mud content exhibited cohesive behaviour (Delft Hydraulics, 1989). An in-situ erosion flume was used by Houwing (2000) to investigate the critical bed shear stress for erosion of mixtures of sand and mud, which also concluded a critical mud content of approximately 30%. Experiments were also undertaken in flumes using both current and wave conditions, showing that the critical wave-related bed shear stress for sand was not affected by mud contents smaller than 30% (Panagiotopoulos et al., 1997).

Chapter 3. Model Development

This chapter provides an overview of the model development process undertaken for this thesis. The first section outlines the overarching system conceptual model. The second section provides a description of the model setup. In the third section, the calibration process is detailed, and the fourth section demonstrates the results of the validation.

3.1. Conceptual Model

The subject of the model development is to approximately represent the environmental system and its associated processes concerning submerged sediment dynamics. A conceptual diagram of some of the key processes affecting sediment dynamics in Moreton Bay is presented in Figure 6. In order to model the sediment dynamics and resolve the aims of this thesis within this bay, a three-dimensional transient model was required to be developed.

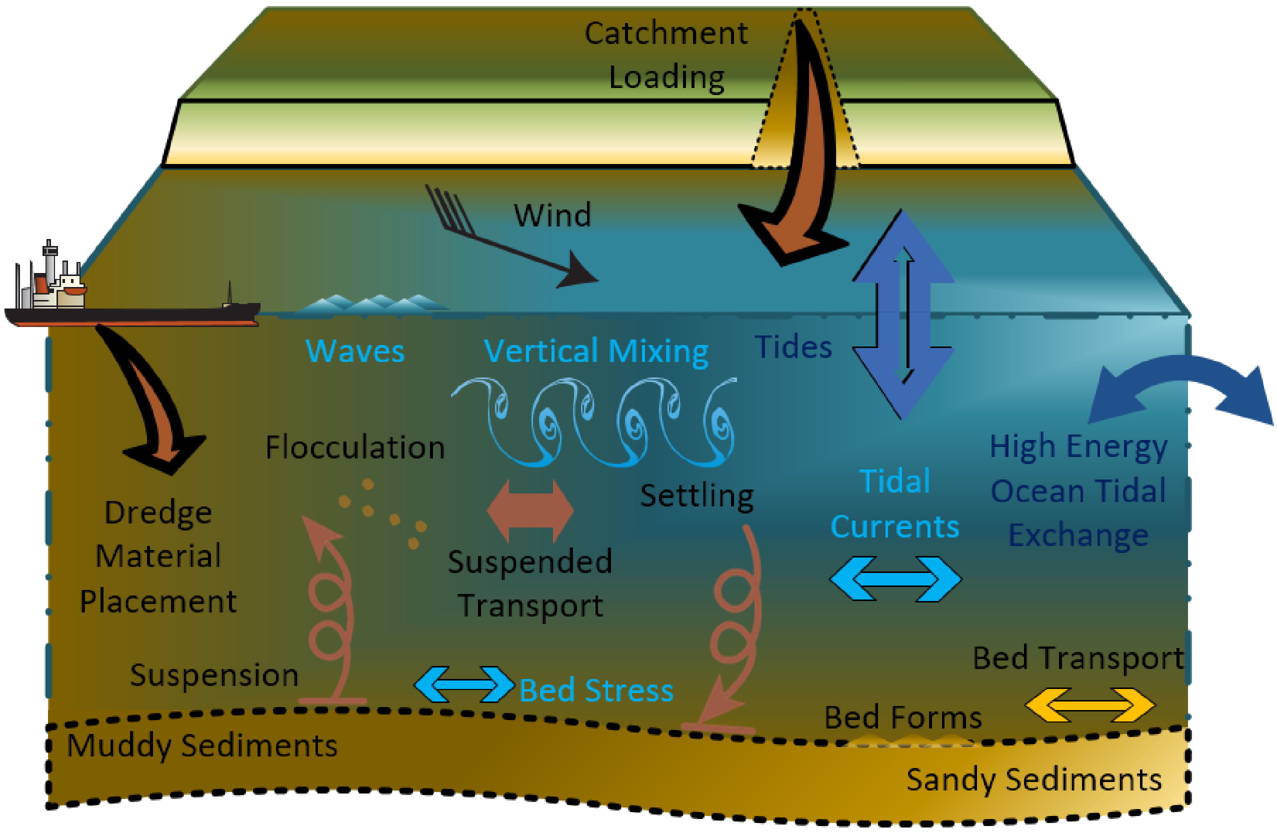

Figure 6: Moreton Bay sediment dynamics conceptual model

3.2. Model Setup

A model was developed using open source Delft3D-FLOW, which underwent six primary iterations, each with their own respective branches. The latest iteration used for all results presented in this thesis utilised an unrotated regular rectangular computational grid domain, maximising orthogonality and having a maximal resolution of 100 metres inside Moreton Bay. The hydrodynamic and morphologic grids are four-fold less fine in the Coral Sea to the east, totalling 344,776 grid elements. The total domain extent is presented by the red boundary in Figure 7, along with the 100-metre resolution bathymetric dataset provided by Beaman

(2010), and categorised sediment grab samples from Lockington et al. (2017a) using the 30% mud threshold for cohesive behaving beds estimated by van Rijn (2012). The bathymetric data was modified in Pumicestone passage and the lower Brisbane river for the purposes of numerical modelling, with the port extension excluded from the model domain by no-flow boundaries. The bathymetry has also been modified through smoothing of steep gradients in the Coral Sea near the open boundaries to maintain numerical stability.

The model makes use of an Arakawa C-grid structure (depicted in Figure 8), and has a total of five σ-coordinate layers (presented in Figure 9) with greater spatial resolve near the bed boundary and the water surface where the largest gradient rates are expected with bed interactions and water surface wind shearing. Greater computational expense is taken to minimise truncation errors resulting from the σ-coordinate system. The three-dimensional shallow water equations are solved using a finite difference alternate direction-implicit scheme by cyclic reduction. Transport of constituents such as suspended sediments are solved using three-dimensional advection-dispersion mass balance in finite control volumes by taking Generalised Lagrangian Mean (GLM) velocities (Delft3D-FLOW, 2013).

The model is forced by water level boundaries immediately outside the computational domain in the Coral Sea. Two to three sets of more than twenty astronomical constituents from tidal analysis are linearly varied and used to determine the water levels along these open boundaries. Normal advection gradient components are ignored along these open boundaries due to the formation of an artificial boundary layer common in numerical implementations of coastal boundaries (Delft3D-FLOW, 2013). Wind forcing was carried out through a uniform one minute frequency wind field from the Inner Beacon weather station managed by the Bureau of Meteorology (BOM), and in the case of forecasting utilised predictions from the European Centre for Medium Range Weather Forecasts (ECMRWF). Predictions of the bedform roughness are made using van Rijn (2004) determined by the composition of the bed (D50% and D90% particle sizes by volume) and the current hydrodynamic environment every simulated ten minutes.

From the categorised georeferenced sediment grab samples depicted in Figure 7, the sediment bed of each model grid cell was defined based on the nearest neighbour interpolation approach (with some artefact correction). Non-cohesive bed and suspended load transport is computed in components according to van Rijn (1993), whilst the mass flux of cohesive sediment between the bed-water interface is calculated by Partheniades (1965).

The developed Delft3D-FLOW model is coupled every simulated ten minutes with a simultaneously developed Delft3D-WAVE model computing wave spectra with a stationary third generation SWAN model (SWAN, 2006). A simplistic diagram of the model coupling is provided in Figure 10. The WAVE computational domain was developed in a nested configuration with a coarser domain covering the extent of the FLOW domain at a 4-fold decrease in spatial resolution, whilst a finer grid at the maximum resolution of 100 metres (equal to the FLOW domain) covers the Mud Island study area for this thesis. The nested WAVE domain configuration is illustrated in Figure 11. Wind forcing from the FLOW model is communicated to the WAVE model for use in computing the wave spectra.

Delft3D tagged version 6.02.09.6864 (Deltares, Delft, The Netherlands) was compiled onto UQ’s Research Computing Centre’s (RCC) Tinaroo High Performance Computing (HPC) cluster. The coupled model was typically run using MPI on a single node with 2 Intel Xeon E5-2680V3 2.5 Ghz processors and 120 GB of RAM (only 16 GB required).

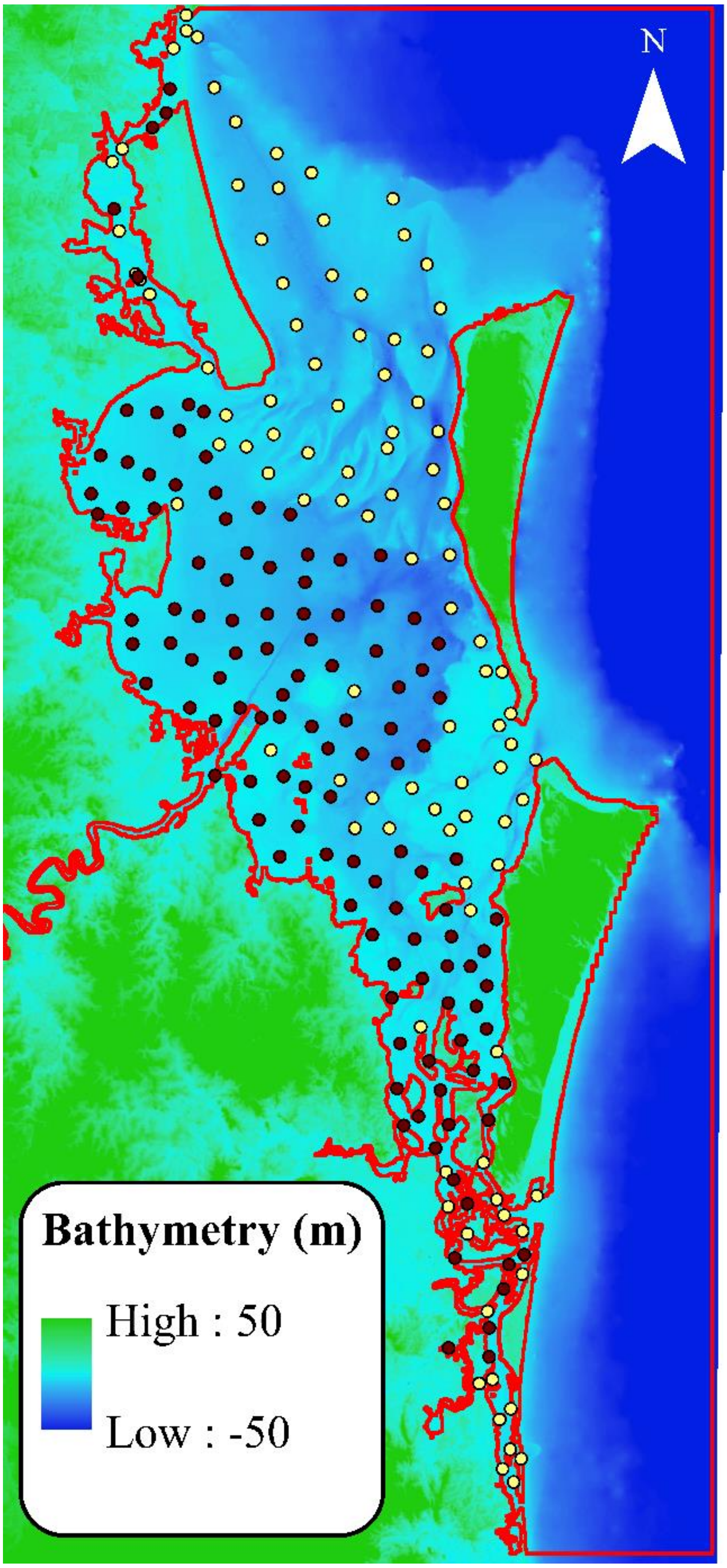

Figure 7: Model domain indicated by red line, brown markers indicate samples with >30% mud content cohesive beds, and yellow markers indicate otherwise non-cohesive beds as sampled by Lockington et al. (2017a) and categorised by van Rijn (2012), bathymetry provided by Beaman (2010)

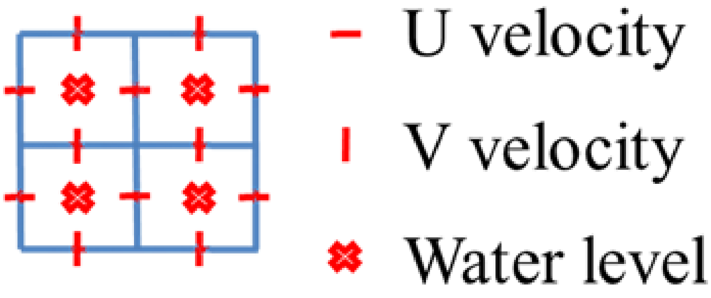

Figure 8: Section of Arakawa C-grid

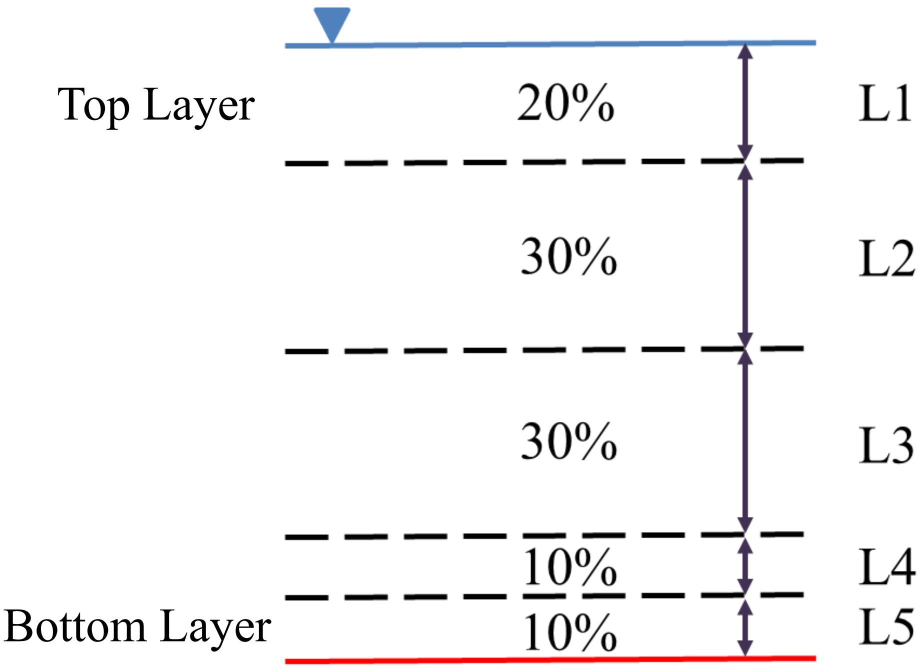

Figure 9: σ-coordinate layer thicknesses (red line sediment surface, blue line water surface)

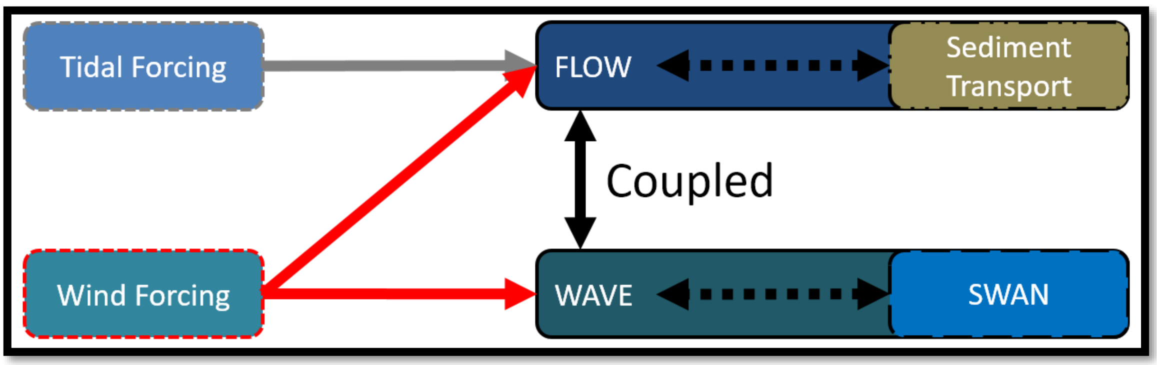

Figure 10: Simplistic coupled model schematic

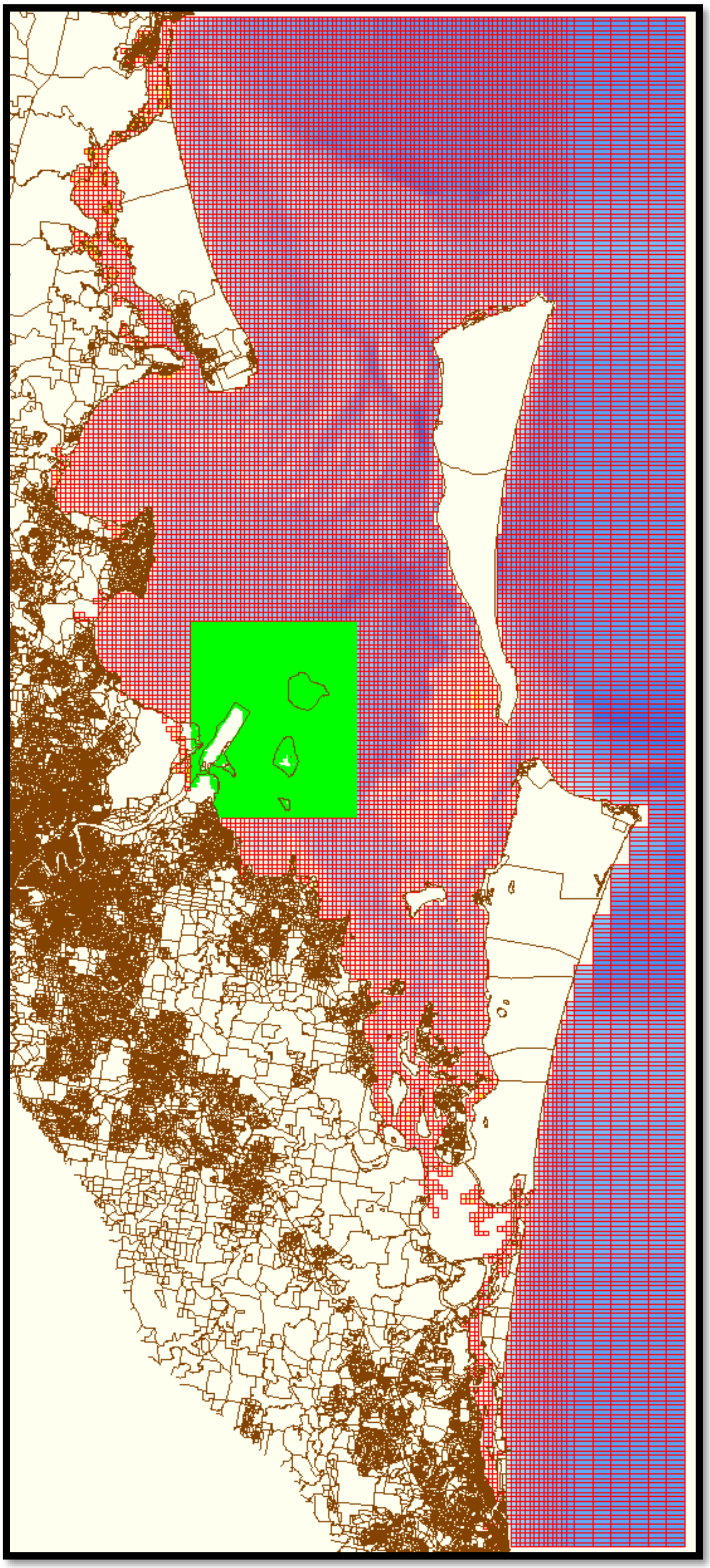

Figure 11: Delft3D-WAVE nested computational domains, red grid illustrating regional coarser grid, green grid illustrating finer local grid

3.3. Calibration

Parallel long-term deployments of Acoustic Doppler Current Profilers (ADCPs) were undertaken in 2015. The corresponding 35 day overlapping deployment window was used for the purposes of calibrating and validating the hydrodynamic predictions of the model developed in this thesis. Model performance was determined using indicators posited by Moriasi et al. (2015), primarily weighted towards the predictive performance of the model compared against near-bed layers of the water column measured by the ADCP deployed in the Mud Island study area. A following independent deployment shifted spatially and over a different observation season was undertaken during this thesis to form the basis of a second validation period. The ADCP deployments are illustrated in Figure 12 with the primary evaluative sites for each respective period underlined.

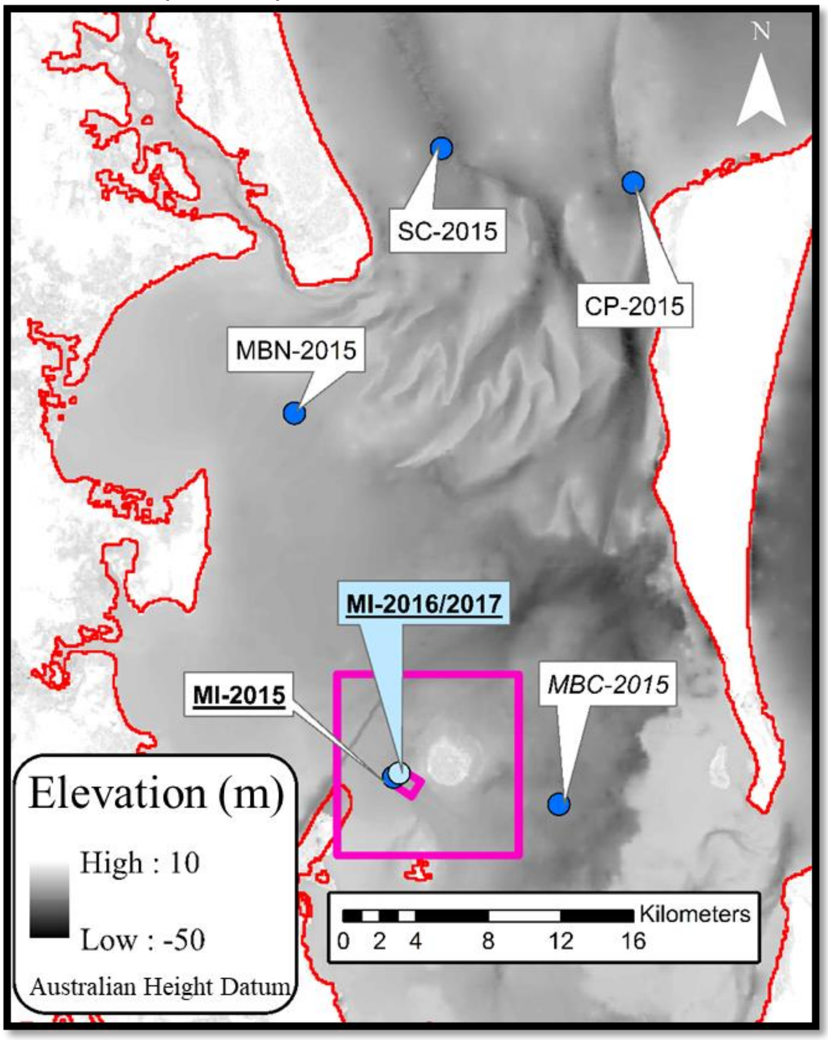

Figure 12: ADCP deployments used in calibration and validation stages of the model development, model domain indicated by red lines, and elevations provided by Beaman (2010), defined 10x10 km study area identified by pink boundary with dredge material placement area inset

An approximate week-long period was subsampled from the parallel deployment window for calibration purposes. Calibration was performed in a successive parameter sensitivity and optimisation method. It is noted that a longer calibration period would be preferred, however the shorter period allowed more parameter calibration in the given time allocation of the thesis work. As this thesis focus is on the Mud Island placement area, the primary model performance against the ADCP deployments in this area is presented.

Bed roughness was the first parameter to be calibrated, with uniform variations, roughness maps based on the sediment distribution sampled by Lockington et al. (2017a), and uniform variations with bedform roughness prediction trialled. Figure 13 and Figure 14 present some calibration performance from this successive process.

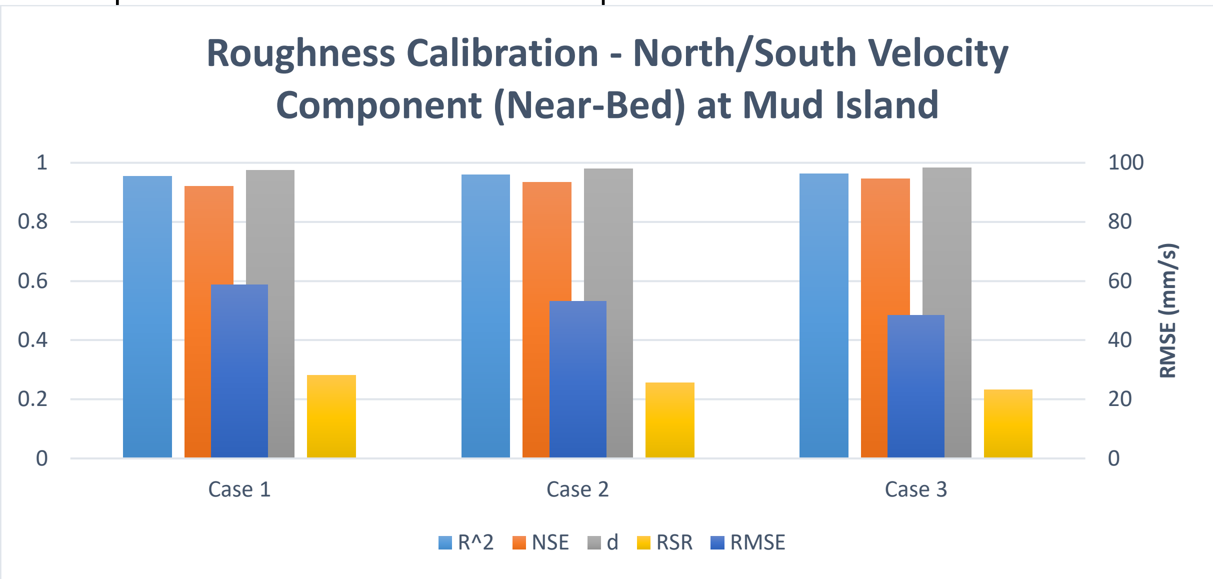

Figure 13: Roughness successive calibration at Mud Island ADCP deployment for north/south velocity components

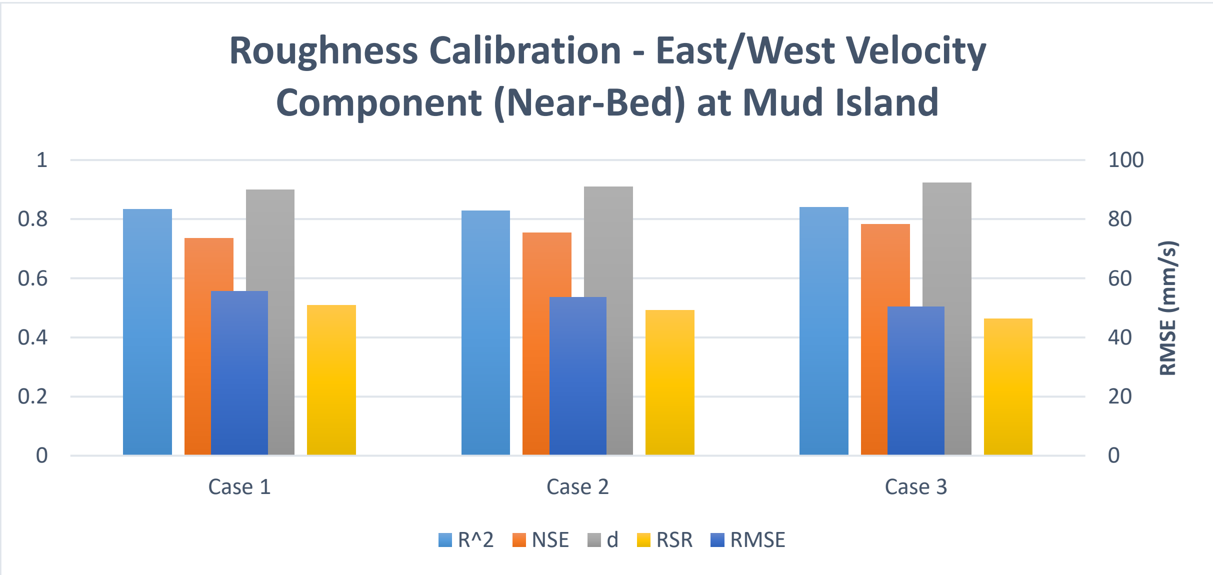

Figure 14: Roughness successive calibration at Mud Island ADCP deployment for east/west velocity components

A summary of calibrated parameters is listed with attached comments on relative value:

Bed Roughness Calibration: Uniform *with Bedform Roughness Prediction* ***- Fair Sensitivity***
Wave Bed Stress Formulation: *Van Rijn (2004)* ***– High Sensitivity***
Turbulence Model: *k-ε Second-order Turbulence Closure Model* ***– Low Sensitivity***
Horizontal Large Eddy Simulation: *Slope in log-log Spectrum of 1.666666* ***– High Value***
Dimensional Number of 2
Prandtl-Schmidt Number of 0.7
Spatial Low-pass Filter Coefficient of 0.3333333
No High-pass Filtering

3.4. Validation

Validation Period 1

The first validation period for the model covered the spring-neap period immediately following the calibration period. Overall performance objectives for the model were to represent the general flow behaviour of the Mud Island study area. Figure 15, Figure 16, and Table 1 demonstrate the model's performance within the Mud Island study area. The most significant of the two velocity components analysed compared very favourably with observations, whilst the east/west component was not as well represented by the model. However, the validation results of this period were deemed sufficient for the purposes of this study.

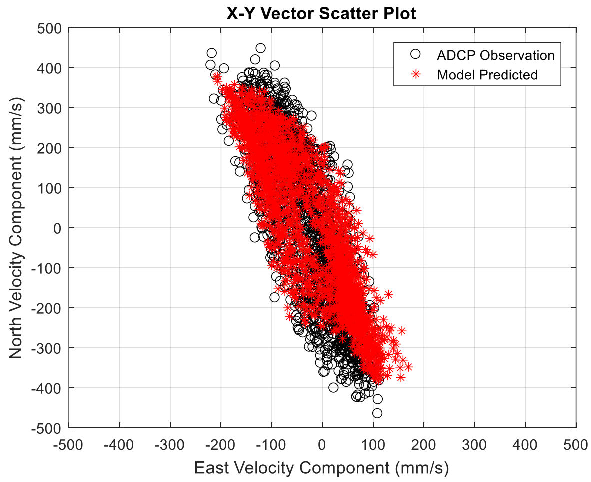

Figure 15: X-Y vector scatter plot of observed and predicted velocities just over 1 m above the bed at the Mud Island ADCP deployment site for validation period 1

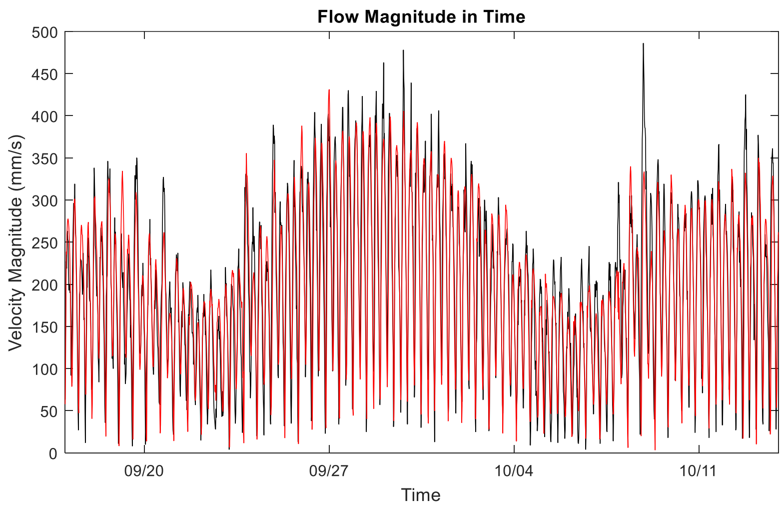

Figure 16: Flow magnitude plot over validation period 1, ADCP observations in black, model predictions in red

Table 1: Model performance evaluation for validation period 1 in Mud Island study area near-bed

Performance Measure	North/South	East/West
R^2 - Coefficient of Determination	0.95	0.81
NSE - Nashe-Sutcliffe Efficiency	0.95	0.67
d - Index of Agreement	0.99	0.93
RMSE (mm/s) - Root Mean Square Error	45.72	37.60
RSR - Standard Deviation Ratio	0.22	0.57

The ADCP deployed in the Mud Island study area was also estimating the significant wave height every hour, and this is plotted against the model predictions every twenty minutes for the validation period in Figure 17.

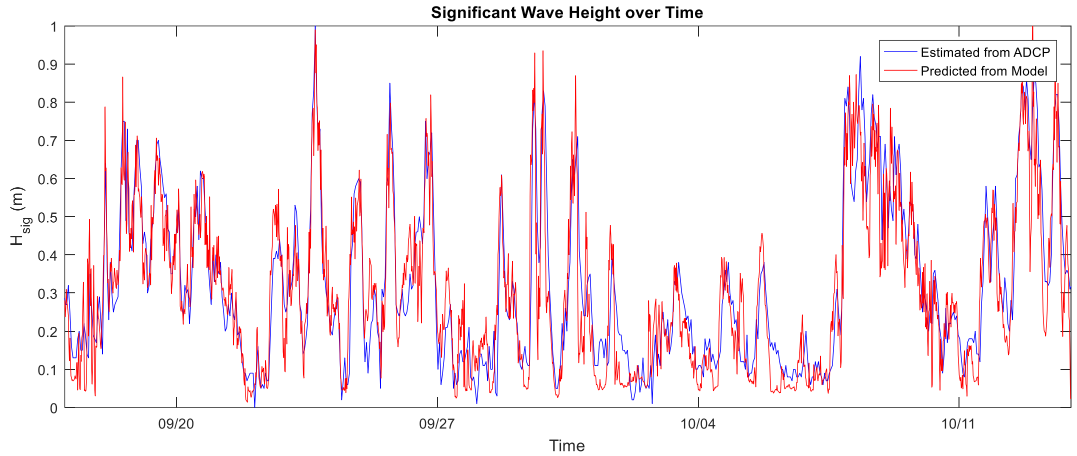

Figure 17: Significant wave height plotted over validation period 1, hourly ADCP estimations in blue, 20-minute frequency model predictions in red

Validation Period 2

The second validation period for the model covered from the 26th of November 2016, to the 13th of January 2017. Although the second validation site is merely 200 metres north east of the 2015 Mud Island ADCP deployment, a noticeable difference in the measured currents was observed. As shown in Figure 18, Figure 19, and Table 2, the model performed adequately at reproducing the general hydrodynamics of the site. Noticeable disparities between the predicted and observed velocities occurred during two separate wind events in excess of 80 km/h from the south easterly direction. The resulting measurements from these events found significantly magnified ebb currents corresponding to the direction of the wind that the model could not reproduce. However, a wind event of similar magnitude from the north also occurred during this period and did not result in poor model predictions.

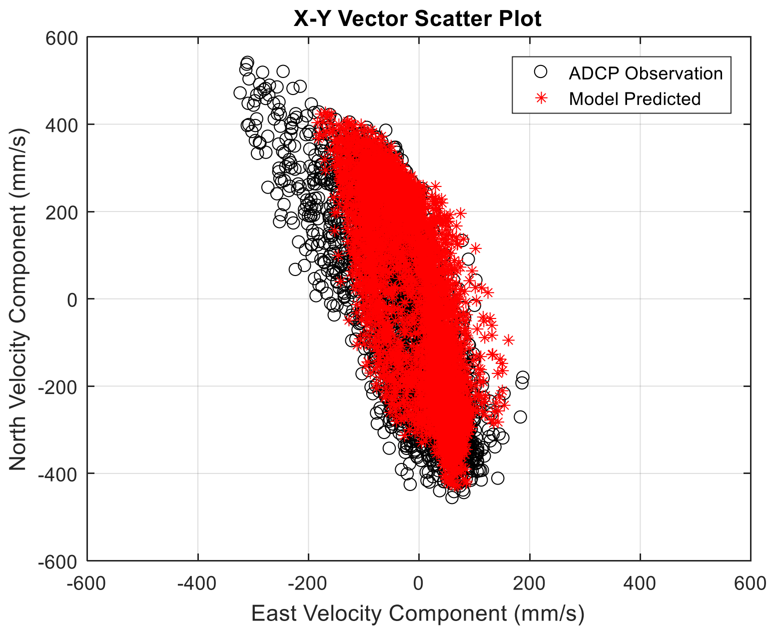

Figure 18: X-Y vector scatter plot of observed and predicted velocities just over 1 m above the bed at the Mud Island ADCP deployment site for validation period 2

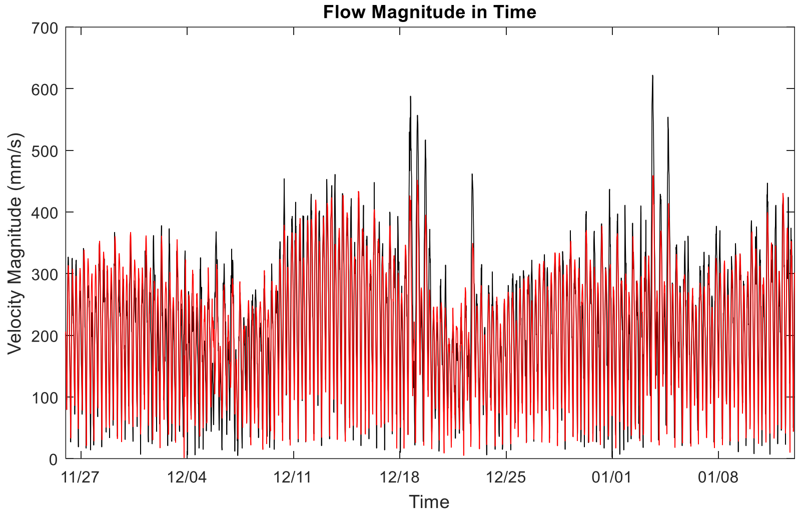

Figure 19: Flow magnitude plot over validation period 2, ADCP observations in black, model predictions in red

Table 2: Model performance evaluation for validation period 2 in Mud Island study area near-bed

Performance Measure	North/South	East/West
R^2 - Coefficient of Determination	0.93	0.77
NSE - Nashe-Sutcliffe Efficiency	0.93	0.70
d - Index of Agreement	0.98	0.91
RMSE (mm/s) - Root Mean Square Error	59.68	41.64
RSR - Standard Deviation Ratio	0.27	0.53

Chapter 4. Mud Island Sediment Dynamics Case Study

This chapter presents a case study of the dynamics of sediment suspension in the Mud Island study area. The first section details the experimental design. In the second section, the tidal driven effects of sediment suspension in the area are investigated. The scale of the effect of wind on sediment suspension in the study area is explored in the third section.

4.1. Study Design

In order to investigate the suspension behaviour of material in the study area, a clearly defined bounded area of 10x10 km was determined to encapsulate the Mud Island spoil grounds and surrounding area (See Figure 20). Due to the complexities involved in the tidal currents with sediment transport in space and time, an extensive property of the study area was used to gauge the relative scales of response from the model. The total dry weight of suspended sediment was integrated across the study area and time averaged. A tidal only baseline condition was first run for the considered high tidal energy period of January 2017 to gauge the effective scale and variability of suspended sediment in the area contributed by the tide alone. To test the area's relative suspended sediment response to wind forcing, the model was run again over the baseline period for eight wind directions. Each wind direction was applied with a day-long averaging period for each trialled wind speed up to 50.4 km/h with a buffer period between each wind application for the system to return to tidal baseline conditions. A subtractive baseline process was then utilised between the wind applied model datasets and the baseline tidal dataset to separate the amount of suspended material in the area that would not have otherwise been there without the applied wind. One-minute frequency wind observations over 2015 and 2016 from the Inner Beacon weather station in the middle of the bay managed by the Bureau of Meteorology were then analysed. The wind observations were combined to determine which of these modelled environmental conditions would have been the most significant contributing component to the total bed disturbance resulting in suspension in the area given the scale of response of the model.

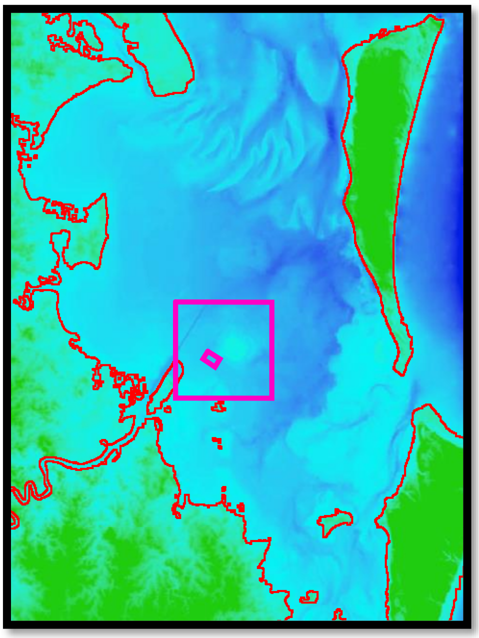

Figure 20: Defined 10x10 km Mud Island study area with outer boundary indicated in pink, and inset pink boundary indicating placement area, red line indicating domain boundary

4.2. Tidal-driven Effects

Figure 21 shows the resulting variability and scale of response of the baseline tidal only suspension in the study area over the days of the trialled spring-neap period.

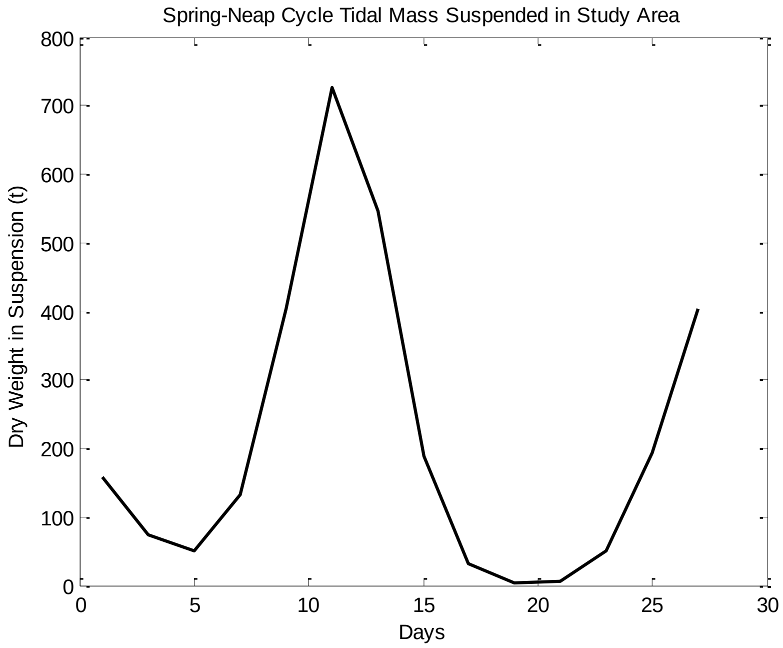

Figure 21: Tidal-driven total dry weight of sediment in suspension inside study area over spring-neap period of January 2017

4.3. Wind Condition Effects

Figure 23 shows the modelled spatial distribution of significant wave height at 50.4 km/h with the suggested relative wind direction scaling factors from the suspended sediment wind enhancement presented in Figure 22. The relative wind direction scaling resulted from the wind enhancement response curves from each wind direction belonging approximately to the same family of exponential curves, barring the north westerly wind direction.

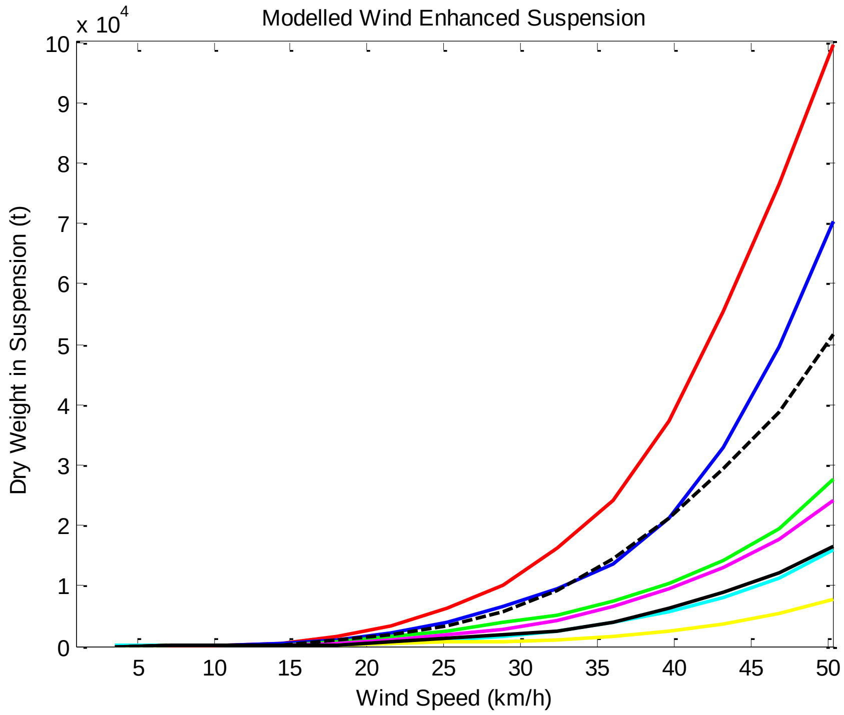

Figure 22: Wind-driven total dry weight of suspended sediment enhancement inside study area, red indicating northerly, dark blue indicating north easterly, green indicating easterly, magenta indicating south easterly, cyan indicating southerly, yellow indicating south westerly, solid black indicating westerly, dashed black indicating north westerly

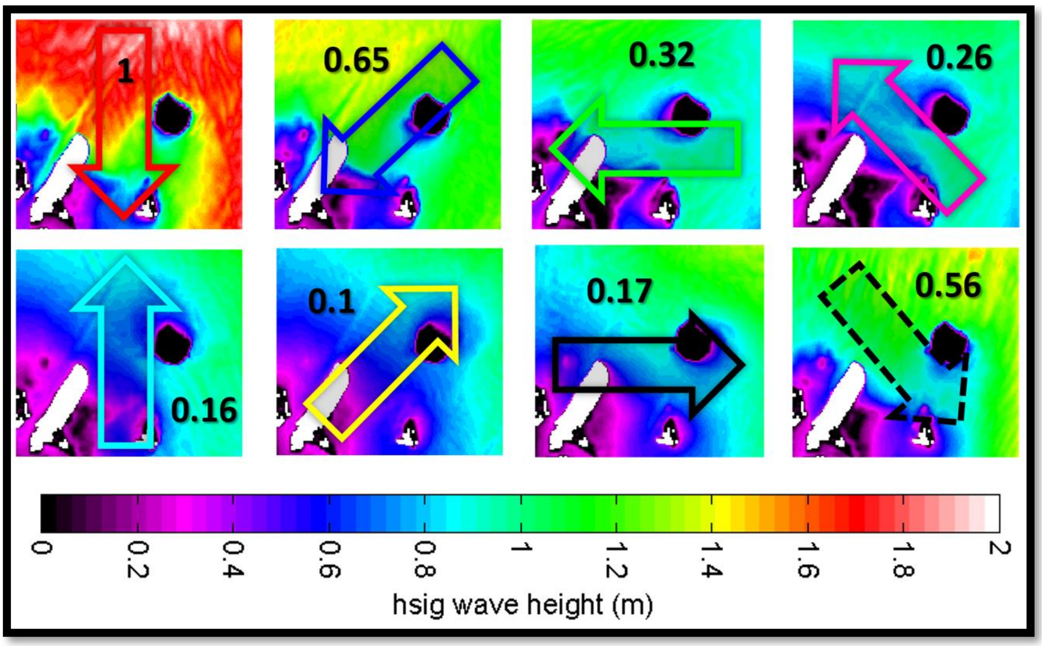

Figure 23: Modelled significant wave heights at 50.4 km/h winds from indicated directions, annotated with effective wind direction total suspended sediment in study area response scaling

A wind rose classifying the observed wind from 2015 and 2016 into wind bands of interest to the wind enhancement of sediment suspension in the study area is presented in Figure 24. The lowest wind speed magnitude range is where the scale of model response due to wind was dominated by the effect of wind shear on the water surface altering the magnitude of the tidal currents. The model response in this wind band is characterised by an insignificant scale of variable positive and negative effects on the total amount of sediment suspended. The lighter blue wind band is where the effect of the wind becomes significant on the scale of the tidal suspension, and the dominant effect of the wind transitions to wave bed-shear stresses in shallower areas. Combining the frequency of occurrence of these two wind bands, these conditions occurred nearly half the time. In the green wind speed range, the enhancement of the total amount of sediment suspended due to the added wind forcing starts to dominate the total amount suspended compared to tidal only conditions depending on the prevailing wind direction. The green wind speed range was also found to occur nearly half the time, reinforcing the importance of wind direction in this study area. The orange wind speed range is where the wind effects on the total amount suspended were found to be the most significant cause of suspension in the area, regardless of wind direction. Lastly, the red wind speed band occurring less than 1% of the time was outside the tested range of wind speeds, and subsequently these events may be underestimated in the following analysis.

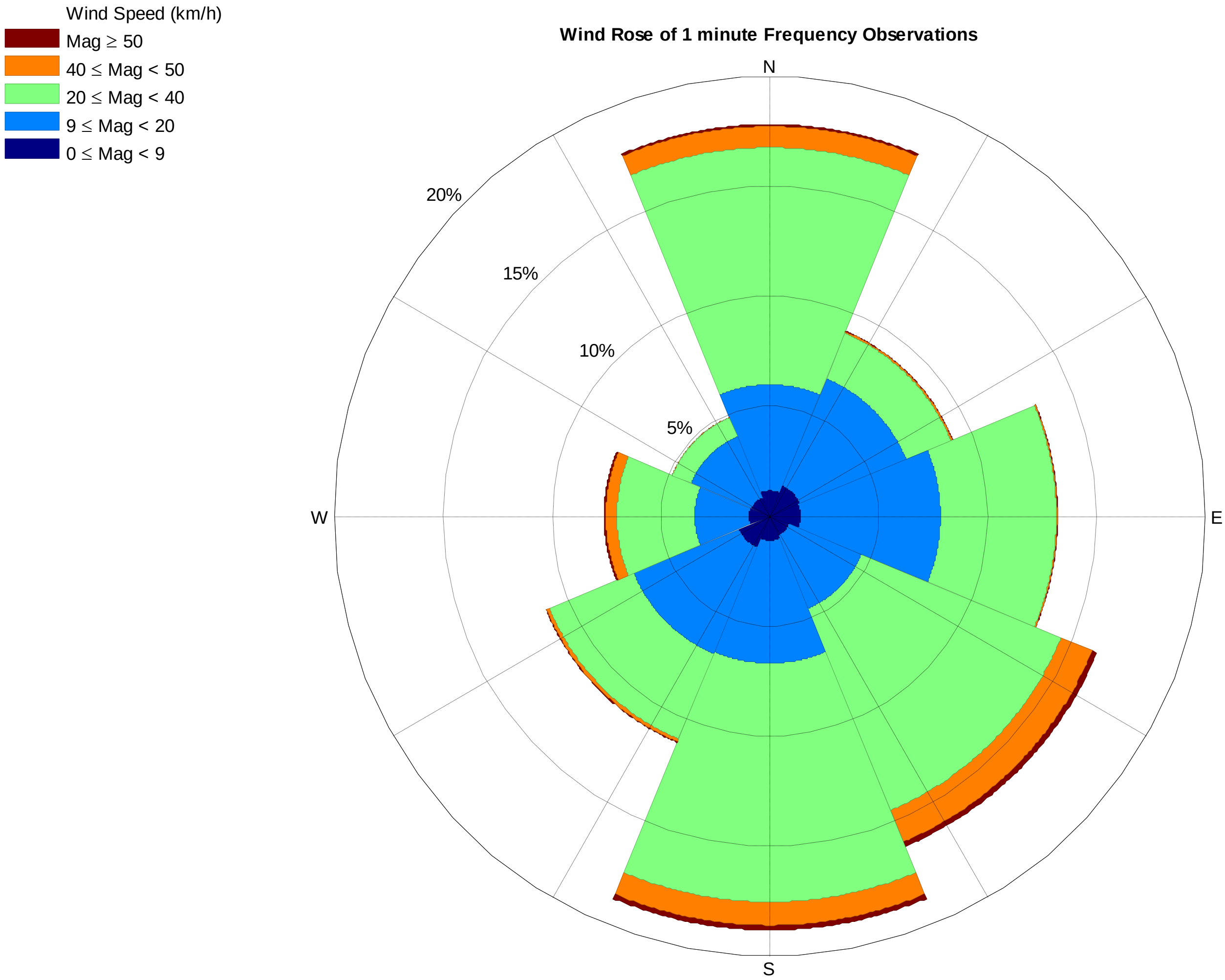

Figure 24: Wind rose of one minute frequency observations from Inner Beacon weather station over 2015 and 2016 managed by the Bureau of Meteorology (BOM), wind speeds binned into model wind speed response ranges

The wind observations analysed were mapped and weighted to their corresponding scale of response from the model to investigate the relative contributions and importance of these wind factors based on their actual occurrences over 2015 and 2016. Figure 25 presents the resulting wind sediment suspension contribution rose for the study area. It should be noted that the lowest wind speed band has been taken out of this plot due to its insignificant effect on the scale of the system considered. Most of the time it was found from the scale of responses in the model, that the wind would not be dominating the total amount of sediment suspended in the area. However, from the highest three suspension bands with more than 10-fold the suspended sediment due to tide alone at a given time, this model predicts that even with the less than 10% occurrence of these conditions, the majority of bed disturbance resulting in suspension in the study area over 2015 and 2016 would have been during these wind conditions. Table 3 splits the relative contributions into wind direction and tidal components with their frequency of observation. Northerly winds were found to have a very high weighting at nearly 50% of the total (with only 16.4% occurrence), however the tide occurring 100% of the time found itself solely responsible for approximately 10% of the total suspended material in the study area. It then follows that without wind, the study area would experience an approximately 10-fold decrease in the total amount of suspended sediment.

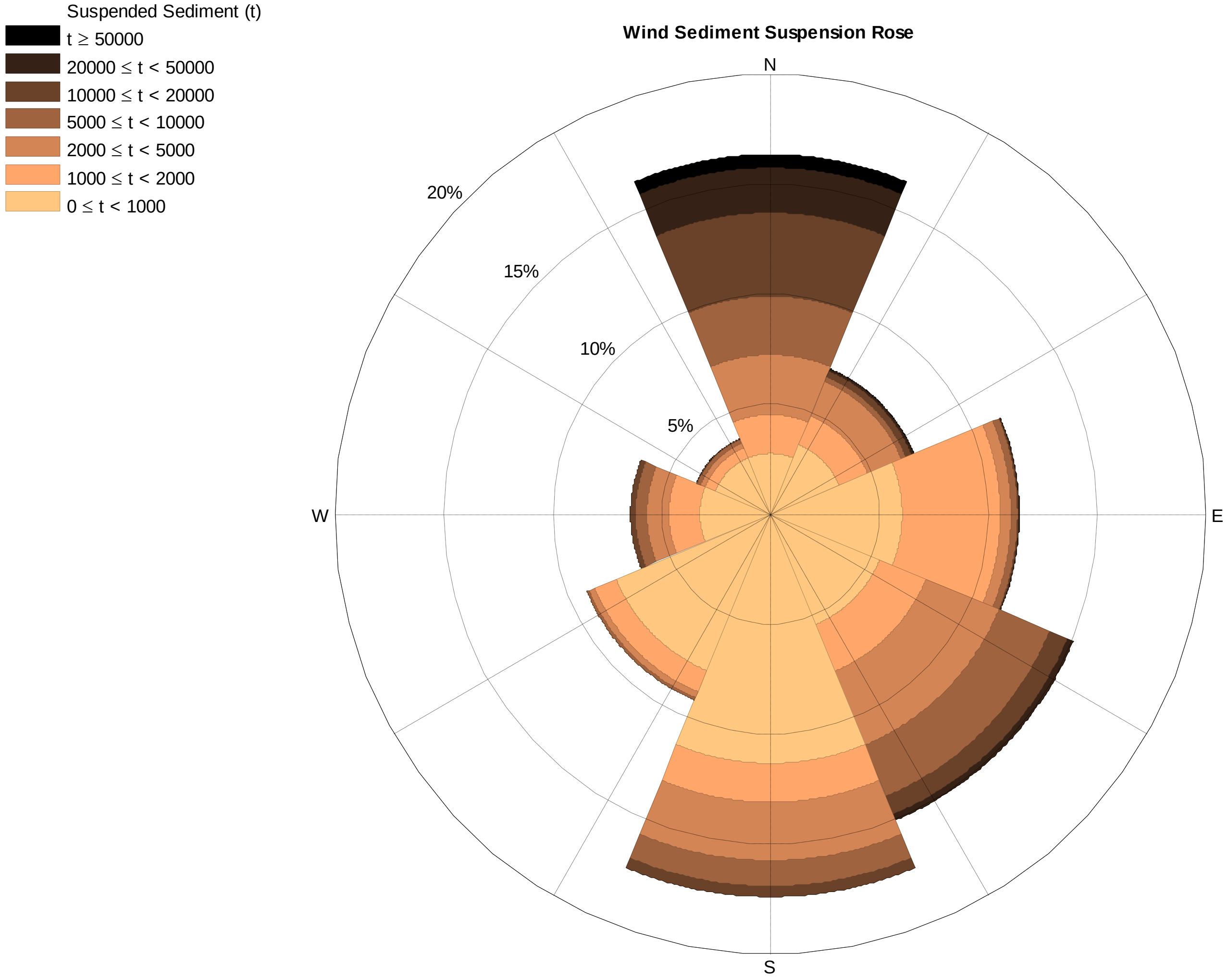

Figure 25: Wind sediment suspension contribution rose generated by combination of total suspended sediment in study area modelled response and one minute frequency observations from Inner Beacon weather station over 2015 and 2016 managed by the Bureau of Meteorology (BOM)

Table 3: Suspended sediment contribution breakdown from 2015 and 2016 one-minute frequency wind observations at Inner Beacon weather station managed by the Bureau of Meteorology

Factor	Suspended Sediment	Occurrence
N Wind	48.2%	16.4%
NE Wind	5.1%	7.2%
E Wind	4.0%	11.4%
SE Wind	15.4%	15.1%
S Wind	8.4%	17.4%
SW Wind	3.7%	9.1%
W Wind	3.7%	6.4%
NW Wind	1.3%	3.7%
Tidal	10.2%	100.00%

It is worth noting that north westerly winds were found to be both the least occurring and result in the least total bed disturbance causing suspension in the study area. This may be related to why this wind direction does not exhibit an exponential response from the same family of exponential curves exhibited by the other wind directions.

Chapter 5. Mud Island Dredge Material Placement Study

This chapter describes a dredge material placement event predicted by the model and used to inform a subsequent monitoring strategy. The first section describes the event and the preparations undertaken for monitoring design. The second section highlights some of the results of the dredge material placement event, comparing the model predictions to observations.

5.1. Monitoring Design

In the design of a monitoring strategy for a dredge material placement event on the 13th of February 2017, a few requirements and limitations were identified. The model developed in this thesis was run in a predictive mode using wind predictions from the European Centre for Medium Range Weather Forecasts (ECMRWF) model. An estimated 3000 m^3 typically loaded trailing suction hopper dredger load was discharged into the second layer of the water column (approximately accounting for the draft of the vessel) at an estimated time of 11am with an assumed 70% water content. The key outputs of the predictive model were the predicted background suspension, plume trajectory, and the relative scale of plume dilution in space and time.

It was determined that it would be necessary to take water column profiles using a CTD (current, temperature, and depth) logging instrument (RBRconcerto, RBR Ltd., Ottawa, Canada) prior to the placement event in order to gauge the background suspended sediment causing turbidity. Profiles were taken tracking the dredge placement plume, which was predicted to only locally, within 1 km, remain above background concentrations in space and time. A following profile would then be taken hours after to confirm if the predicted dredge placement plume had settled out and dispersed from the area.

5.2. Dredge Material Placement Event

Recent sediment coring in the Mud Island placement area found a non-trivial sedimentation history (Lockington et al., 2017b), and combined with frequent material placement occurrence at the time, the consolidation history of the bed was considered a high source of uncertainty for the sediment bed properties in the model. Another uncertainty of high significance is the flocculation and settling behaviour of the suspended sediment. As a result of these uncertainties, the critical shear stress for erosion and equilibrium flocculation settling velocity were independently varied to upper and lower expected bounds to obtain a range of expected concentrations (extreme combinations not considered). The monitoring event took place on a high tide and during the low wind speed transition period between a strong northerly to a strong south easterly. Due to the timing of placement with the tide, the model predicted an initial south easterly plume movement followed by a tracking back towards the north. Figure 26 shows the predicted background concentrations for a location 1 km north of the approximated placement location where the plume was predicted to leave the 1 km radius of the placement site at background concentration 3 hours later (shown in Figure 27).

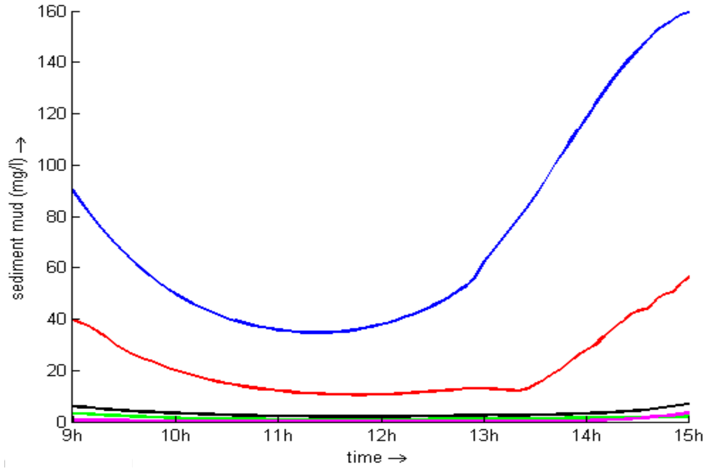

Figure 26: Background suspended sediment 1 km north of predicted placement plotted over hours on 13th January 2017, black indicates baseline parameters, red indicates reduced critical shear stress to 0.2 N/m², while green indicates an increase to 0.5 N/m² with uncertainty ranges from Winterwerp (1989), purple indicates an increased settling velocity of 0.9 mm/s, while blue indicates a decreased settling velocity of 0.1 mm/s with uncertainty ranges from van Rijn (1993)

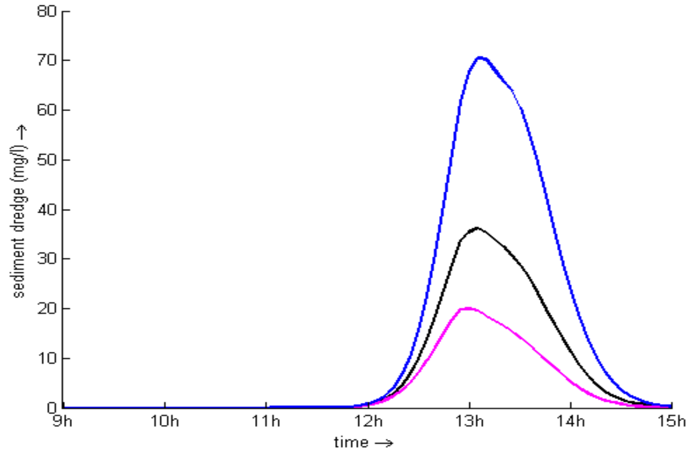

Figure 27: Dredge material placement plume 1 km north of predicted placement plotted over hours on 13th January 2017, black indicates baseline parameters, red indicates reduced critical shear stress to 0.2 N/m², while green indicates an increase to 0.5 N/m² with uncertainty ranges from Winterwerp (1989), however they do not alter the plume dynamics significantly, purple indicates an increased settling velocity of 0.9 mm/s, while blue indicates a decreased settling velocity of 0.1 mm/s indicates an increased settling velocity of 0.9 mm/s, while blue indicates a decreased settling velocity of 0.1 mm/s with uncertainty ranges from van Rijn (1993)

Nephelometric Turbidity Units (NTU) were used as a relative scalable proxy to sediment concentration. In general with the same sediment within the operational limits of the same instrument, increased sediment concentrations should observe increased NTU. Profiles were taken prior to the placement operation, in the dredge plume at the time of placement, and after the predicted timescale of the plume detection limit (post). Table 4 summarises these field measurements with model predictions.

Table 4: Summary of measured and predicted midwater observations of the dredge material placement event on the 13th February 2017

Time on 13th February 2017	RBR Midwater	Modelled Range	Notes
9:26am (Prior)	7.5 NTU	80 mg/l	Typical background range for both
10:47am (Placement)	40 NTU	1000 mg/l	High spatial concentration gradients in dredge plume at time of placement
2:18pm (Post)	10 NTU	120 mg/l	Typical background range for both

The behaviour of the plume as predicted by the model between placement and post-placement measurements is not resolved by these observations. However, the model does contribute to the argument of the spatial and temporal locality of the high concentration placement plume. Figure 28 depicts the predicted spatial dredge material concentration and extent suspended in the third layer of the model (illustrated in Figure 9) at the approximate time of post-placement sampling.

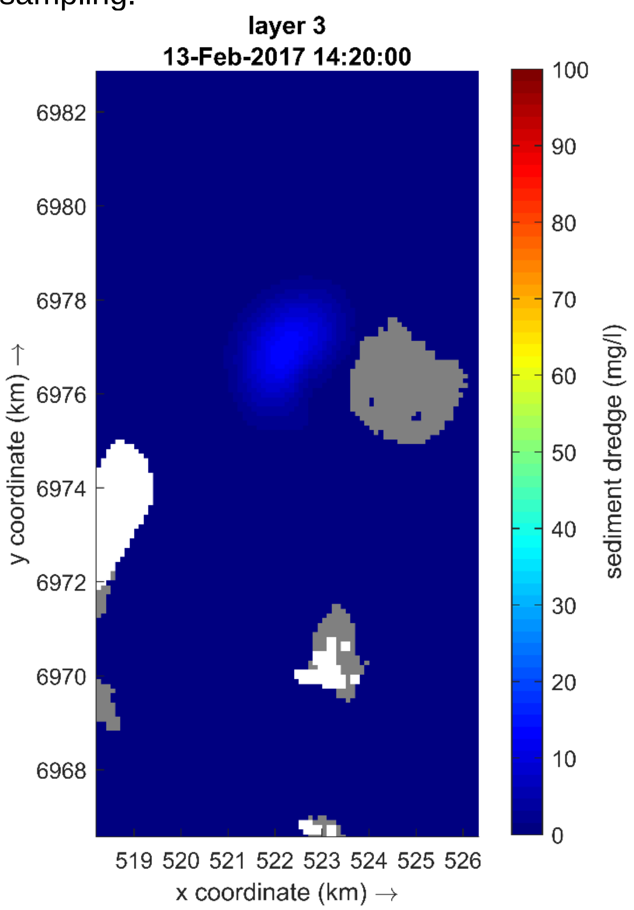

Figure 28: Dredge material placement plume 3 hours and 20 minutes after placement in the model prediction with concentration scaled to the range of predicted background suspension in the locality of the plume

Chapter 6. Conclusions

This chapter discusses the conclusions of this thesis. The first section draws the conclusions from the previous chapters. In the second section, limitations surrounding the scope of this thesis are outlined. The third section suggests recommendations for further work related to this thesis.

6.1. Conclusions

To conclude this thesis, a three-dimensional numerical open source coupled Delft3D model of sediment dynamics in Moreton Bay was developed. An extensive process of calibration and two-part validation was undertaken to establish a relatively high level of confidence in the representation of the hydrodynamic environment around the Mud Island placement and surrounding study area. Hydrodynamic model performance was primarily assessed by the overall representation of the velocities just over one metre above the bed, whilst a limited comparison of the overall behaviour and response of the sediment dynamics in the midwater column was compared from the prediction of a recent dredge material placement monitoring event.

An investigation into the scale and variability of the effect of the hydrodynamic environment factors of tidal and wind forcing in the defined 10x10 km Mud Island study area was performed utilising the developed model. The effect of the tidal environment was tested and then subsequently used as a baseline over a selected high energy spring-neap period. The scale, estimated by the model of total dry weight suspended over the study area varied over the spring-neap period across the full range below 1000 tonnes. A careful experimental procedure was implemented to find the enhancement of this extensive total suspension property due to differing wind speeds up to 50.4 km/h and eight uniformly spaced wind directions. The results of this procedure found an exponential response in this parameter of total suspended sediment enhancement to increasing wind speed. The wind direction was then found to play an effective scaling role, as each of the wind direction suspension enhancement curves belonged approximately to the same family of exponential curves. In light of this significant suspension enhancement in the higher wind speeds tested, an analysis of wind observations over 2015 and 2016 was undertaken to estimate the effective scale of its effect over this extended time period dataset. The ultimate result was that although the tidal component occurred all the time, according to the modelled scale of response it would only have contributed approximately 10% of the total bed disturbance resulting in suspension in the study area. Whereas the highest suspension events occurring less than 10% of the considered period, would have been responsible for most of the total bed disturbance resulting in suspension in the study area over the two years considered.

A study of an isolated dredge material placement event in the Mud Island study area was attempted. The developed model was used in a predictive mode to predict the background suspension, plume trajectory, and the relative scale of plume dilution in space and time for application in the planning for the monitoring of the material placement event. The subsequent conclusions from the results of the dredge material placement field monitoring agreed with the conclusions drawn from the model. Dredge material placement was found to generate a localised detectable plume in space and time, however the plume was found to be not distinguishable from background conditions within 1 km and 3 hours of the placement.

6.2. Limitations

Several processes were not directly considered or addressed by the model. These were processes of bioturbation, differential settling, flocculated particle shearing, variation in thermal energy over space and time, seagrass bed stabilisation and other effects. Although catchment loading through sediment and freshwater input loading from the five major rivers discharging into Moreton Bay is possible in the current model implementation, it is not considered in this thesis due being outside the scope and significant inflows not occurring during the time periods considered. It should be noted that further extensions of this model could be developed to include heat fluxes and biogeochemical processes as a result of the modularity of the open source Delft3D platform. Moreover, areas of fluid mud may be present at times within Moreton Bay, and modelling the behaviour of fluid mud also requires further extension of the model. Limitations of the model were also in the binary classification of mud and sand sediments, whilst the reality of the boundary between their respective distributions is unclear. Compounding this limitation was the identified gap in knowledge of the vertical extent of cohesive sediment and three-dimensional spatial variability in consolidation history. Some of the limitations of the study in Chapter 4 were the application of an analysis of wind observations from a nearby weather station which may not be entirely representative of the winds that occurred in the Mud Island study area, as well as the limitations in the uncertainties of the model discussed. Chapter 5 had limitations surrounding the discrete point measurements of turbidity in time and space, and an undisclosed observation error range. The predictive model was only able to use estimates of the placement time, location, and placement load, and so with the localised spatial and temporal observed and predicted behaviour of the plume, direct comparisons were not considered meaningful.

6.3. Recommendations for Future Studies

Other than addressing the limitations in the previous section, some recommendations for further work are noted. Relative scale of responses in the Mud Island study area are reported from the model results. Sediment properties are based on literature and local expert knowledge of Moreton Bay and the study area. Whilst the relative scales of responses of the system to its environmental conditions are useful for both general understanding and management implications, an accurate estimate of the total sediments suspended locally in the placement area would be useful for further contextualising and understanding the placement of dredge material in this area. Although the model can provide estimates of this, further study needs to be undertaken into characterising the spatial and temporal varying properties of the sediment bed. Further field monitoring should be performed, especially during high wind events in order to calibrate the physical sediment characteristics, and validate the sediment dynamics of the model. From Chapter 4, further work into this type of analysis could be performed on other areas of interest around the bay for other research purposes. In terms of Chapter 5, the results found that the model may be suitable for use in further research into dredge material placement management and monitoring. The placement event considered occurred during slack tide, and further research should be undertaken into the difference between placement operations at different tide stages.

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