Tauranga Harbour Sediment Study: Hydrodynamic and Sediment Transport Modelling

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Tauranga Harbour Sediment Study: Hydrodynamic and Sediment Transport Modelling

Mark Pritchard
Richard Gorman

NIWA contact/Corresponding author

Terry Hume

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National Institute of Water & Atmospheric Research Ltd
Gate 10, Silverdale Road, Hamilton
P O Box 11115, Hamilton, New Zealand
Phone +64-7-856 7026, Fax +64-7-856 0151
www.niwa.co.nz

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Reviewed by: Scott Stephens
Approved for release by: Terry Hume
Executive Summary

EBOP contracted NIWA to conduct the Tauranga Harbour Sediment Study to: (1) assess the relative contributions of catchment sediment sources surrounding the southern Tauranga Harbour, 2) assess the characteristics of significant sediment sources from the catchment and (3) investigate the fate (dispersal and deposition) of catchment sediments throughout Tauranga Harbour.

This report is Technical Report D1 of the Tauranga Harbour Sediment Study. Herein we report on the implementation and calibration of numerical models used in the study: an estuarine hydrodynamic model, a wave model, and a sediment-transport model. Together these simulated the dispersal of contaminants and sediments by physical processes such as tidal currents and waves.

The models used in the study were the DHI Water and Environment MIKE3 FM HD hydrodynamic model, the DHI MIKE3 FM MT (mud) sediment transport model, and the SWAN wave model.

The Tauranga Harbour model bathymetric mesh was produced from a combination of a previously calibrated 2-dimensional model mesh and LIDAR survey data supplied by EBOP that provided extra information on the intertidal mud flats and in the tidal creeks.

The implementation and calibration of the MIKE3 FM model was based on information contained in archive reports, journal articles and available data sets. Available time series of observed water levels, and currents were used to calibrate the hydrodynamic model. No measured wave statistics or time series data of suspended sediment concentration was available for calibrating the SWAN or MT models.

The calibrated hydrodynamic model provided good predictions of water surface elevations and semi-diurnal tidal currents inside the harbour. The effects of wind driven currents in the harbour were negligible in scale as compared to the tide.

The modelled salinity was compared to a number of CTD casts recorded during a small survey of the harbour in 1999. The modelled salinity showed consistency with the CTD where the water column was well mixed and of lower salinity than the ocean. Stratification was slightly stronger in the Western Channel as a result of the freshwater outflow from the Wairoa River.

Sediment dynamics in the harbour were simulated using the MIKE3 FM MT model. The fate (transport and resuspension) of four sediment size classes (4, 12, 40 and 125µm) from the major freshwater sources were traced in the harbour. The model was set up using literature derived values and empirical constants that describe sediment settling, deposition, and erosion in the model domain. An example of the results is presented from the simulations that show the predicted SSC and deposition in the harbour from the major freshwater and sediment sources.
The model was used to simulate 380 different scenarios to provide the USC-3 sedimentation model with lookup tables that describe sediment transport in Tauranga Harbour under various wave fields, winds, source inflow rates and tides.
1. Introduction

1.1 Background

Environment Bay of Plenty (EBOP) seeks to understand patterns of sediment supply, dispersal and deposition in Tauranga Harbour. EBOP wishes to sufficiently understand sedimentation\(^1\) in the harbour to appropriately manage growth and development of the surrounding catchment both now and in the future, and to adapt management rules and practices appropriately. Knowledge of harbour sedimentation will facilitate decisions concerning development of the harbour and catchment with full understanding of likely sedimentation effects. This need stems from section 5 of the Tauranga Harbour Integrated Management Study (THIMS), which describes the many effects of sedimentation in the harbour. Although these changes are to a large extent driven by historical events when there was little control on catchment development, there is increasing public concern about sediment-related issues, and these are expected to escalate as the catchment continues to develop and climate change becomes increasingly felt. The THIMS recommended a review of the drivers and consequences of sedimentation in the harbour, including analysis of sediment yields from all sources in the catchment, peak flow monitoring in source streams, projection of sediment yields under proposed development scenarios, assessment of sediment effects in the harbour including cumulative effects, analysis of current best practices, and recommendations on how to address the findings, including appropriate policy.

EBOP contracted NIWA to conduct the Tauranga Harbour Sediment Study. The study began in April 2007 and is scheduled to run for 3 years. The main aim of the study is to develop a model or models to be used to: (1) assess the relative contributions of sediment to the harbour of the various sediment sources in the catchment surrounding Tauranga Harbour, (2) assess the characteristics of significant sediment sources, and (3) investigate the fate (dispersal and deposition) of catchment sediments in Tauranga Harbour. The project area is defined as the southern harbour, extending from Matahui Point to the harbour entrance at Mount Maunganui. The time frame for predictions is 2001–2050.

1.2 Study outline and modules

The study consists of 6 modules:

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1 Sediment is defined as unaggregated particles derived from a land catchment and transported into the harbour from a freshwater source.

2 "Sedimentation" for the purposes of the study is defined as temporal and spatially-variable erosion/deposition of sediment in the harbour.
Module A: Specification of scenarios used to drive the models – Defines land use e.g., earthworks that are associated with rural and urban development; the weather in terms of the magnitude and frequency of storms; and finally the anticipated effects of climate on weather and sea level rise.

Module B: Catchment sediment modelling - (1) Uses the GLEAMS model to predict time series of daily sediment yields from each subcatchment under each scenario. (2) Summarises these predictions to identify principal sources of sediment in the subcatchment; to compare sources of sediment under present-day landuse and under future development scenarios; and to assess sediment characteristics of significant sources. (3) Provides sediment loads to the USC-3 sedimentation model for extrapolation of harbour sedimentation over decadal scales.

Module C: Harbour bed sediments - (1) Develops a description of the harbour bed sediments to provide sediment grainsize and composition information required for running the harbour sediment-transport model and for initialising the USC-3 sedimentation model. (2) Provides information on sedimentation rates over the past 50 years for end-of-chain model validation.

Module D: Harbour modelling - (1) Uses the DHI FM (Flexible Mesh) hydrodynamic and sediment models and SWAN wave model to develop predictions of sediment dispersal and deposition at the “snapshot” or event scale, including during and between rainstorms and under a range of wind conditions. (2) Provides these event predictions to the USC-3 sedimentation model for extrapolation of harbour sedimentation over decadal scales.

Module E: USC-3 model - Uses the USC-3 sedimentation model to make predictions of sedimentation, bed-sediment composition and linkages between sources and sinks at decadal scales, based on division of the catchment into subcatchments and the estuary into subestuaries. An end-of-chain model validation will consist of comparing USC-3 sedimentation model predictions of annual-average sedimentation rate to measurements, where the measurements derive from Module C.

Module F: Assessment of predictions for management – Assesses and synthesises information developed in the modelling components of the study using an expert panel approach. It will address matters including: (1) Which catchments are more important as priority areas for focusing resources to reduce sedimentation in the harbour? (2) What are the likely effects of existing and future urban development on the harbour? (3) How can the appropriate regulatory agencies (EBOP, WBPDC and TCC) most effectively address sedimentation issues, and what management intervention could be

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2 An end-of-chain model validation will consist of comparing USC-3 model predictions of annual-average sedimentation rate to measurements, where the measurements derive from Module C.
1.3 This report

This report is Technical Report D1 of the Tauranga Harbour Sediment Study and completes Module D and Milestone 7 (as agreed with the client). It documents the implementation, calibration and validation of the harbour hydrodynamic model, the wave model and the sediment-transport model to meet the requirements of the USC-3 model. The particular models used in the study were the: DHI Water and Environment MIKE3 FM HD hydrodynamic model, the DHI MIKE3 FM MT (mud) sediment transport model (http://www.dhigroup.com), and the SWAN wave model (Holthuijsen et al. 1993). Combined, these can be used to simulate tidal propagation, tide- and wind-driven currents, freshwater mixing, waves, and sediment transport and deposition within a harbour.

These combined model outputs underpin the predicted distribution of suspended sediment and sediment deposition in the seabed in the harbour. These predictions are then used in the USC-3 model in Module E of the study.

1.4 The DHI MIKE3 FM HD and MT Model

Tauranga Harbour was modelled using the DHI MIKE3 FM HD hydrodynamic and MT (mud) sediment transport modelling suite. The finite element, 3-dimensional sigma coordinate (multi-layer) semi-implicit model finds numerical solutions for the Navier-Stokes equations for momentum whilst conserving mass through the principle of continuity. Physical processes in the model can be parameterised / simulated through specifying for example, eddy scales, turbulent closure schemes, surface and bottom boundary conditions, salinity/temperature structure and the earth’s rotational effects. The model open boundary is initialised and forced using tidal data. Inputs of freshwater are input at source locations, which allow variation in seawater density to be included in model solutions. The finite element grid and baroclinic capability, plus the inclusion of a wetting and drying scheme makes the model ideal for simulating time/spatially varying gravity, density and tidally driven flows in coastal regions with complex shoreline and/or embayment’s.

The MIKE3 FM HD model can be forced at boundaries by both oceanic/estuarine tides and freshwater sources. These two forcing mechanisms produce the essential boundary physics required to simulate barotropic (tides and surface pressure gradients) and baroclinic (internal pressure gradients driven by horizontal and vertical density differences) in the model domain. The effects of geostrophy, i.e., currents produced by
the force balance between pressure gradients and the earth’s rotation, are negligible for the size of domain under consideration for this study.

Sediment transport in the MIKE3 FM MT model is simulated through the application of the advection-diffusion (transport) equation. In addition to estuarine dynamics, the effects of localised surface gravity wave fields on sediment erosion, deposition, re-suspension and transport are also computed and included into final model predictions.

Particles of a specified size may be introduced into the model scheme as a sediment flux associated with each specific freshwater discharge into the model domain. The total sediment load can then be split into specific size ranges, each with a specified Stokes settling velocity and critical depositional/erosion shear stress. The modelled estuarine hydrodynamics and application of the advection-diffusion scheme then transport this sediment flux around the model domain.

Localised model morphological evolution is based on deposition and erosion of sediments transported in the model domain i.e., bed levels are updated at each time step. This causes change and feedback in the modelled hydrodynamic and transport equations through both continuity and dynamical constraints (see Appendix 1).

1.5 The SWAN wave model

The SWAN wave model is a spectral wave model particularly suited to shallow-water applications in coastal and estuarine environments. It describes the sea state in terms of the amount of energy associated with each wave frequency and propagation direction. The model computes the evolution of the wave spectrum by accounting for the input, transfer and loss of energy through various physical processes.

In addition to specified wind fields, the SWAN model uses the water levels and current fields predicted by the MIKE3 FM HD model in predicting the wind-generated waves in the MIKE3 FM model domain. The predicted wave heights, periods and directions are then imported back into the MIKE3 FM model. These predictions are used to quantify wave-induced bed shear stress, which then contributes to sediment transport in the MIKE3 FM MT model (see Appendix 1).
2. Study requirements and model development

Delivery of catchment sediment into Tauranga Harbour is very dependent on tidal creek dynamics, so these narrow channels required a fine model mesh. The model mesh was also required to resolve and separate the harbour’s main sub-tidal channels from the intertidal areas so that flooding and drying was well represented. This becomes particularly important when considering the resuspension and transport of intertidal bed sediments.

The initial step in setting up the model of Tauranga Harbour was to identify the main freshwater and sediment sources into the model domain. These outlets were identified following consultation with the EBOP and are shown Figure 1 and tabulated in Table 1.

![Figure 1: Schematic regional overview of catchments (shaded areas) and catchment outlet locations (dots) used in the Tauranga Harbour sediment study.](image-url)
Table 1: Subcatchment names, outlet identification (ID) codes and area.

<table>
<thead>
<tr>
<th>Subcatchment name</th>
<th>Outlet ID</th>
<th>Area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matakana</td>
<td>1</td>
<td>1409</td>
</tr>
<tr>
<td>Mt Maunganui</td>
<td>2</td>
<td>1299</td>
</tr>
<tr>
<td>Papamoa</td>
<td>3</td>
<td>1182</td>
</tr>
<tr>
<td>Waitao</td>
<td>4</td>
<td>4332</td>
</tr>
<tr>
<td>Kaitemako</td>
<td>5</td>
<td>1989</td>
</tr>
<tr>
<td>Waimapu</td>
<td>6</td>
<td>11824</td>
</tr>
<tr>
<td>Kopurererua</td>
<td>7</td>
<td>7879</td>
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<td>Wairoa</td>
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<td>46534</td>
</tr>
<tr>
<td>Oturu</td>
<td>9</td>
<td>1158</td>
</tr>
<tr>
<td>Te Puna</td>
<td>10</td>
<td>2799</td>
</tr>
<tr>
<td>Mangawhai</td>
<td>11</td>
<td>957</td>
</tr>
<tr>
<td>Waipapa</td>
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<td>3680</td>
</tr>
<tr>
<td>Apata</td>
<td>13</td>
<td>1240</td>
</tr>
<tr>
<td>Wainui</td>
<td>14</td>
<td>3523</td>
</tr>
<tr>
<td>Aongatete Bellevue</td>
<td>15</td>
<td>7854</td>
</tr>
<tr>
<td>Bellevue</td>
<td>16</td>
<td>950</td>
</tr>
<tr>
<td>Matakana 2</td>
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</tr>
<tr>
<td>Total catchment</td>
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</tr>
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</table>

2.1 Model mesh development

The model MIKE3 FM mesh was developed after consultation with EBOP who along with NIWA defined and agreed the geographical regions of interest, the subcatchments, the subestuaries and the freshwater/sediment source input sites.

The foundation of the present model grid was based on NIWA archive bathymetry and Port Company sounding data shown in Figure 2. This bathymetric data was then combined with high resolution Light Detection and Ranging imagery (LIDAR) data.

LIDAR is an aircraft based remote sensing instrument used to collect highly accurate ground levels (relative to local chart datum). The regional coverage of the LIDAR image tiles are shown in Figure 3. Each of the Tauranga Harbour LIDAR image tiles consisted of approximately 1 point per 2 m² with height accuracy mostly ±0.25 m. These data were then processed into a series of mosaic images that were then further post-processed into bathymetric data that was then incorporated into the model mesh.
The processing of the raw LIDAR data to Chart Datum and into a format readable by the MIKE3 FM models was carried out as outlined in Appendix 2. This data was especially useful for increasing the resolution of the tidal creeks and mudflats. However, the channelised region of the estuary that remained flooded at times of low water was not penetrable by the LIDAR instrumentation. Therefore, as no additional bathymetric survey work was conducted by NIWA for the project, the bathymetry in the inner and upper regions of creeks and tidal channels in the inlet were left to be resolved from archive aerial photography. This did leave some uncertainty on the shape, cross-section and depth of some of the creeks and channels. The resultant model mesh produced from all the available data is shown in Figure 4.

For the purpose of USC-3 sedimentation modelling, the model domain was then divided into a number of subestuaries based on source locations, sub-tidal channels and sinks. This was not implemented until the post-processing stage of the MIKE3 FM model runs. Ultimately, the SSC and sediment deposition in each subestuary at the ‘end’ of a scenario run was included in a lookup table utilized by the USC-3 sedimentation model. The boundaries and details of each subestuary domain are shown in Figure 5 and Table 2.
Figure 2: Tauranga Harbour showing the location of Port Company soundings used in model mesh construction as areas of blue shading.
Figure 3: Arial photography of Tauranga Harbour showing limits of LIDAR coverage used in model mesh construction as blue lines. Freshwater and sediment source inputs are shown in red.
Figure 4: Final model grid produced for the MIKE3 FM model from a combination of archive data, Port Company surveys and LIDAR flights. Depths are shown in model mesh with respect to lowest astronomical tide (LAT). Blue circles indicate the freshwater and sediment source inputs.
Table 2: Subestuary element information. Code = Subestuary code number No of Elements = Number of model mesh elements in the subestuary; Area = Sum of all element surface areas contained in subestuary; Sink = Subestuary defined as a sediment sink only in the USC-3 model; Source = Source of freshwater and sediment; Deep Channel = Subestuary where sediment may remain in suspension once it has been flushed from a source.

<table>
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<th>Subestuary</th>
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<th>Area (km²)</th>
<th>Sink</th>
<th>Source</th>
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<td><strong>1</strong></td>
<td><strong>26</strong></td>
<td><strong>3</strong></td>
</tr>
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</table>
Figure 5: Subestuaries defined from regional catchments and source outlets for application of the USC-3 sedimentation model. Subestuary size and classification are shown in Table 2.
3. Model setup and calibration

3.1 Modelling rationale and approach

The 3 models described in Section 1 were used under a series of ‘event’ driven scenarios based on freshwater (baseline, median and high rainfall) and sediment source discharge rate, tidal range and wind (wave) driven forcing. This series of scenarios would require 380 model simulations to meet the demands of the follow up USC-3 sedimentation modelling study. Sediment was treated under a nominal load that was later scaled on the basis of the Gleams model output. The results from these 380 event driven scenarios were then included in a series of look up tables that contain suspended sediment mass and bed deposition mass for each of the modelled grainsize fractions for each of the subestuaries in the model domain. The look up tables were then utilised by the USC-3 sedimentation model.

The look up tables are constructed from model runs that simulate:

- Initial distribution of catchment derived sediments from a source following a rainfall event. Simulations are initiated by a combination of:
  
  i. 2-M$_2$ tidal cycles;
  
  ii. 4-wind speeds and directions;
  
  iii. High and median rainfall driven freshwater discharge rates.

- Determination or bed erosion depth and redistribution of bed sediments for both wet and dry conditions in each subestuary. Simulations are initiated by a combination of:
  
  i. High, median rainfall and baseline (dry conditions) freshwater discharge rates;
  
  ii. 2-M$_2$ tidal cycles;
  
  iii. 4-wind speeds and directions plus calm conditions.

- Determination of longer term redistribution of sediments that are in suspension in each subestuary and deep channel. Simulations were run under calm only conditions and were initiated by a combination of:
i. Nominal suspended load in the water column;

ii. Spring to neap tides (7-days);

iii. Neap to spring tides (7-days);

iv. Mean to spring to mean tides (7-days).

3.2 Processes included in the model

The Tauranga harbour model includes the effects of local tides, freshwater (salinity), winds and the impact of waves on currents predicted by the SWAN model. The predicted hydrodynamics from the MIKE3 FM HD model then drive the MT sediment transport module that provides the results for the USC-3 simulations. A more comprehensive description of where the forcing for each respective process is derived or data sourced from is included in the following sections.

3.3 Available calibration data

This Tauranga Harbour Sediment Study did not incorporate a study-specific field program. Therefore, archive data made available from various sources were used to calibrate the harbour hydrodynamic model through a series of hindcast simulations. There was no data to calibrate the SWAN and MIKE3 FM MT sediment transport models.

The Department of Earth and Ocean Sciences and Department of Biological Sciences, University of Waikato kindly provided the primary source of data used in the hydrodynamic calibration. These data comprised of several current meter records, tide gauge records plus a series of CTD surveys (see Section 3.8) in regions of the harbour. Unfortunately, the current and tide time series and CTD survey data were not coincident. Therefore, two separate series of model runs were required to calibrate the hydrodynamic model: one series for sea level elevations and currents; the other for the salinity calibration. Figure 6 shows the mooring positions and Table 3 gives a brief summary of the data sources.
Figure 6: Position of current meter and tide gauge moorings used to calibrate the hydrodynamic model, overlaid on the model domain.
Table 3: Descriptive summary of the instruments, data sources and deployment periods used in the calibration of the Tauranga Harbour hydrodynamic model.

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Instrument Type</th>
<th>Easting (NZTM)</th>
<th>Northing (NZTM)</th>
<th>Deployment date/duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM2</td>
<td>S4</td>
<td>1879426</td>
<td>5832650</td>
<td>06-05-2006/29-days</td>
</tr>
<tr>
<td>CM3</td>
<td>S4</td>
<td>1878483</td>
<td>5832783</td>
<td>06-05-2006/29-days</td>
</tr>
<tr>
<td>CM5</td>
<td>FSI</td>
<td>1878087</td>
<td>5828747</td>
<td>06-05-2006/29-days</td>
</tr>
<tr>
<td>A2</td>
<td>Aanderaa TG</td>
<td>1876549</td>
<td>5829399</td>
<td>18-11-1998/29-days</td>
</tr>
</tbody>
</table>

3.4 Calibration parameters

The MIKE3 FM was calibrated by achieving a ‘best fit’ between the model and coincident observations. These observations were confined to a limited time series of tidal level, current meter and hydrographic measurements collected during 1999 and 2006. No times series of wave statistics or sediment dynamics were available for this study.

Parameters that were ‘adjusted’ in the model to achieve a best fit between modelled and observed values were the:

- Smagorinsky eddy coefficient: Simulates horizontal shear in the model and causes change in the amplitude of surface elevations and the magnitude of current speeds.

- $k$-$\epsilon$ Vertical turbulence closure: Controls mixing in the vertical and impacts on vertical stratification in the model due to freshwater inputs.

- Bed roughness ($z_0$): Controls the phase (timing) of sinusoidal signals as for example, tidal elevations and currents.

The measure of the ‘goodness of fit’ between observed and predicted was then estimated through the:

- Root mean square error (RMSE) – A measure of the difference in the variance between the observed and predicted signal.

- Cross-correlation – A coefficient that describes the strength in the phase relationship (timing) between two oscillating signals. 0-1, with 0 being weak and 1 being strong.
• Bias: The residual offset between two time series. ± bias indicates a positive/negative offset in time series data.

3.5 Offshore tidal boundary conditions

Tidal forcing at the models offshore oceanic boundary was extracted from the pressure transducer record fitted to CM3 (see Figure 6). Mean water depth was subtracted from the record to provide a surface elevation forcing condition. For later scenario simulations used to produce the USC-3 lookup table results, least squares harmonic analysis was used to the extract semi-diurnal tidal constituents used to synthesise different tidal scenarios.

3.6 Calibration of water surface elevation

Figure 7a to Figure 7e shows a series of model - data/synthesised comparisons for five separate sites in the model domain (see Figure 6). Three site comparisons were with actual data the other (A2) was synthesised through least squares tidal harmonic analysis from another record. The simulations ran from 6th May - 6th June 2006 concurrent with the 3 current meter moorings.
Figure 7a: Observed and predicted tidal elevations at site CM2 for the period 6th May- 6th June 2006.

Figure 7b: Observed and predicted tidal elevations at site CM3 for the period 6th May- 6th June 2006.
**Figure 7c:** Observed and predicted tidal elevations at site CM5 for the period 6th May-6th June 2006.

**Figure 7d:** Harmonic synthesised and predicted tidal elevations at site A2 for the period 6th May-6th June 2006.

Bed roughness $z_0$ through the model domain was left set at default 0.05m to achieve the best fit between measured and predicted water surface elevations.

**Table 4:** Summary analysis of the comparison between observed and predicted sea surface elevations at the 2 coastal and 2 harbour calibration sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>RMSE (m)</th>
<th>Cross-Correlation</th>
<th>Bias (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM2</td>
<td>0.02</td>
<td>0.96</td>
<td>0</td>
</tr>
<tr>
<td>CM3</td>
<td>0.03</td>
<td>0.96</td>
<td>0</td>
</tr>
<tr>
<td>CM5</td>
<td>0.02</td>
<td>0.97</td>
<td>-0.03</td>
</tr>
</tbody>
</table>
The modelled elevations were compared to the observed through RMSE, cross-correlation (cross-covariance analysis) and bias between the two time series. Table 4 shows that the RMSE error between the observed and predicted tidal amplitudes at all four sites was exceptionally small. Furthermore, analysis of the phase difference between the two signals was very small as ratified through the high cross-correlation between the two time series (Emery and Thompson, 2001). The bias or difference in the residual offset between the predicted was also in order on only a few cm at all sites. Most of the discrepancy between the signals would be caused by deviations in bathymetry and localised bed roughness effects that cannot not be accounted for in the model grid.

The largest deviation in elevations was at the A2 site. This was attributed to using harmonic predictions in the comparison as opposed to actual observations since the measured time series were too short to resolve all of the harmonic components required to produce water levels. Localised discrepancies in bathymetry would also contribute to a deviation.

### 3.7 Calibration of currents

Currents in the model were calibrated by adjusting model parameters to attain the best fit between observed and modelled currents at the three current meter mooring sites shown in Figure 6 and described in Table 3. The best overall fit between observed and model predictions was obtained by using a Smagorinsky horizontal eddy viscosity coefficient of 0.28 for the horizontal eddy viscosity formulation, with a lower bound of $1.8e-006m^2/s$ and an upper bound of $10m^2/s$.

The vertical turbulence closure in the MIKE3 FM model is based on a standard $k$-$\varepsilon$ model, with a buoyancy extension (e.g., Rodi, 1980, 1984). This closure model uses transport equations for the turbulent kinetic energy (TKE), $k$, and the dissipation of TKE, $\varepsilon$, to describe the turbulence. Details of all the constants and coefficients used in the turbulence module are shown Table A1.

Figures 8a–c show comparisons between the observed and modelled current vectors: $u$ (East-West component); $v$ (North-South component) spanning the 2006 current meter deployment record. All calibration simulations were run for 30-days; roughly encompassing complete spring-neap tidal cycle.
Figure 8a: Observed and predicted currents at site CM2 (harbour entrance) between 6th May - 6th June 2006.
**Figure 8b:** Observed and predicted currents at site CM3 (harbour entrance) 6th May- 6th June 2006.

![Figure 8b](image)

**Figure 8c:** Observed and predicted currents at site CM5 (inside harbour entrance) 6th May- 6th June 2006.

**Table 5:** Summary analysis of the comparison between observed and predicted current vectors at the 2 coastal and 1 harbour calibration site.

<table>
<thead>
<tr>
<th>Site</th>
<th>$u$ RMSE (m/s)</th>
<th>$v$ RMSE (m/s)</th>
<th>$u$ Cross-Correlation</th>
<th>$v$ Cross-Correlation</th>
<th>$u$ Bias (m/s)</th>
<th>$v$ Bias (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM2</td>
<td>0.09</td>
<td>0.14</td>
<td>0.45</td>
<td>0.8</td>
<td>0.06</td>
<td>-0.07</td>
</tr>
<tr>
<td>CM3</td>
<td>0.12</td>
<td>0.09</td>
<td>0.54</td>
<td>0.76</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>CM5</td>
<td>0.08</td>
<td>0.08</td>
<td>0.95</td>
<td>0.84</td>
<td>0.03</td>
<td>-0.04</td>
</tr>
</tbody>
</table>

Visual comparison of the time series indicate that outside the harbour entrance, the modelled currents do not reproduce all of the variability in the measured data. At both
the CM2 and CM3 sites there are significant bias (see Table 5), with the measured data having a residual drift to the North-West (see Figure 9)

The phase relationship between the modelled and observed currents was correlated, albeit moderate at the two outer entrance mooring sites (CM2 and CM3). RMSE values of $O(0.12 \text{ m/s})$ and biases of approximately $0.07 \text{ m/s}$ also indicated deviations between the observed and modelled values at the outer sites. This suggested a clear residual deviation in the observed amplitudes of both the $u$ and $v$ vector components of flow from that predicted by the model. This was further investigated by subtracting a fitted tide computed by harmonic analysis of the observed current meter data from the actual current data at the two mooring sites, to obtain the non-tidal (residual) component of current flow.

![Graph showing the progressive vector diagrams](image)

**Figure 9:** Progressive vector diagrams for tidally filtered non-tidal (residual) current meter data collected at sites CM2 and CM3 between 6th May-6th June 2006. Dashed line indicates a North-West direction

Figure 9 illustrates the magnitude and direction of the ‘tidally filtered’ residual currents as progressive vector diagrams. The residual current at site CM2 has a North-West directed alongshore residual flow of approximately 0.07 m/s. The residual current at site CM3 has a West-North-West directed alongshore residual flow of approximately 0.11 m/s.
There are two reasons that we expect the model to be at variance to the current-meter measurements outside the harbour entrance. The first is that the bathymetry in this region is evolving dynamically in response to strong ebb- and flood-tidal currents that flush the entrance and due to wave-driven littoral currents that move sand into the entrance. Thus the measured bathymetry used to make the model grid is likely to be different to that present when the current-meters were deployed. Since the bathymetry has a strong steering effect on the flood-ebb currents in this area, differences in bathymetry would cause differences in current flow. The second reason is that the model is forced at the open boundary only by the astronomical tides and incorporates no large-scale non-tidal oceanographic flows. Other current-meter deployments along the Bay of Plenty open coast have shown that non-tidal residual currents flow along the coast, often for several days before reversing (e.g., Bell, 1985; Senior et al. 2004). These currents are large-scale oceanographic flows related to weather systems passing across New Zealand generating coastally-trapped-waves and they can be relatively strong on the open coast compared to the tides.

The visual comparison of currents shown in Figure 8c and the goodness of fit statistics presented in Table 5 for the inner harbour current meter mooring (CM5) demonstrate reasonable agreement with the observations.

Tables 6a-6c show the results from a least squares tidal harmonic analysis (Pawlowicz et al. 2002) of both modelled and observed current phase and amplitude for each of the 3 current meter sites. Current amplitude was defined in terms of the ellipse major amplitude (maximum tidal current along the principal axis of the current) and ellipse inclination (peak tidal current direction relative to True North), and ellipse phase (time of the peak tidal current relative to NZST). Only tidal constituents with signal to noise ratios (SNR) > 10 are reported (there are many other tidal constituents that could not be resolved because the record durations were too short). However, the $M_2$ component, which is the dominant tidal component around the New Zealand coast, was adequately resolved.
Table 6a: Comparison of measured and predicted tidal current ellipses at site CM2 (Harbour outer entrance).

<table>
<thead>
<tr>
<th>Location</th>
<th>Observed</th>
<th>Modelled</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amplitude</td>
<td>Inclination</td>
<td>Phase</td>
</tr>
<tr>
<td></td>
<td>(m/s)</td>
<td>(° True)</td>
<td>(° NZST)</td>
</tr>
<tr>
<td>M2 Principle Lunar</td>
<td>0.26</td>
<td>93</td>
<td>315</td>
</tr>
<tr>
<td>S2 Principle Solar</td>
<td>0.05</td>
<td>104</td>
<td>24</td>
</tr>
<tr>
<td>M4 Quarter SD</td>
<td>0.11</td>
<td>83</td>
<td>278</td>
</tr>
</tbody>
</table>

Table 6b: Comparison of measured and predicted tidal current ellipses at site CM3 (Harbour outer entrance).

<table>
<thead>
<tr>
<th>Location</th>
<th>Observed</th>
<th>Modelled</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amplitude</td>
<td>Inclination</td>
<td>Phase</td>
</tr>
<tr>
<td></td>
<td>(m/s)</td>
<td>(° True)</td>
<td>(° NZST)</td>
</tr>
<tr>
<td>M2 Principle Lunar</td>
<td>0.17</td>
<td>123</td>
<td>334</td>
</tr>
<tr>
<td>S2 Principle Solar</td>
<td>0.03</td>
<td>107</td>
<td>90</td>
</tr>
<tr>
<td>M4 Quarter SD</td>
<td>0.05</td>
<td>124</td>
<td>337</td>
</tr>
</tbody>
</table>

Table 6c: Comparison of measured and predicted tidal current ellipses at site CM5 (Harbour inner entrance).

<table>
<thead>
<tr>
<th>Location</th>
<th>Observed</th>
<th>Modelled</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amplitude</td>
<td>Inclination</td>
<td>Phase</td>
</tr>
<tr>
<td></td>
<td>(m/s)</td>
<td>(° True)</td>
<td>(° NZST)</td>
</tr>
<tr>
<td>N2</td>
<td>0.11</td>
<td>13</td>
<td>279</td>
</tr>
<tr>
<td>M2 Principle Lunar</td>
<td>0.71</td>
<td>17</td>
<td>316</td>
</tr>
<tr>
<td>S2 Principle Solar</td>
<td>0.17</td>
<td>16</td>
<td>36</td>
</tr>
<tr>
<td>K2</td>
<td>0.08</td>
<td>18</td>
<td>346</td>
</tr>
<tr>
<td>M4 Quarter SD</td>
<td>0.07</td>
<td>34</td>
<td>271</td>
</tr>
</tbody>
</table>
The principle lunar ($M_2$) provided the major astronomical forcing of currents at each respective site, as expected.

Overall, the observed and modelled phase, and inclination for the $M_2$ constituent are in generally good agreement. The largest inclination phase discrepancies between observed and predicted values occur in the $M_4$ quarter diurnal constituent. This is caused by the non-linearity of the tide in shallow waters and slight discrepancies in model and real bathymetry. Table 6c shows the predicted tidal ellipse properties for the major semi-diurnal components of the astronomical tide at the current-meter site (CM5) inside the harbour are in excellent agreement with those resolved from the observations.

### 3.8 Salinity

Calibration of the model for salinity was restricted by lack of moored time series salinity data in the model domain. Therefore, our best effort towards salinity validation in the model focused on comparing model outputs to a series of CTD casts taken in a small time window. These CTD casts were made during a survey of the inner harbour by University of Waikato during 1999 (Conrad Pilditch, pers. comm.). The geographical positions of the CTD casts are shown in Figure 10.

As for the hydrodynamic calibrations a hindcast simulation was produced for a period when salinity data was available: 3rd–11th February 1999. The model was initially spun up for the 14-day period prior to the CTD survey using a synthesised tidal boundary condition produced from a tidal harmonic analysis of water level depths recorded at the CM2 current meter site (see Figure 6). Source inflow rates were based on background flows derived from the WRENZ (Water Resource Environmental Database New Zealand).

Salinity profiles from the model were then extracted from grid cells at positions and times corresponding to the respective CTD cast. Figure 11 shows the timing of the CTD casts with respect to the stage of the tide. Most of the casts used in the comparison were recorded at times close to high and low water levels.

The CTD observations at all three CTD station sites suggested a weakly stratified water column. Near surface salinities were in $O(0.25$ PSU) less than those measured in the lower water column. Such a weak salinity stratification is difficult to resolve using numerical models.

The CTD casts show mostly vertically well-mixed salinity profiles, and that salinities are significantly lower than the ocean outside the harbour indicating that freshwater
inputs to the harbour are being mixed vertically throughout the water column with only weak vertical gradients. Stratification was slightly stronger in the Western Channel as a result of the outflow from the Wairoa River, the major freshwater source, but even this is weak, and would be difficult to reproduce with a numerical model. The model doesn’t quite get this fine-scale detail right because the vertical grid layers are too coarse, but it does simulate the approximate amount of freshwater being mixed throughout the water column.

Figure 10: Position of CTD stations and SWAN site comparison with respect to the model domain used to calibrate salinity in the hydrodynamic model.
Figure 11: Timing of CTD casts used in for salinity calibration with respect to stage of tide for 3rd—11th February 1999. Colouring of marker corresponds to CTD casts presented in Figure 12 for the 3 CTD station sites.

Figure 12a: Observed (solid line) and predicted (stippled line) vertical profiles of salinity vs depth for the Omokoroa station during the survey period 3rd—11th February 1999.
**Figure 12b:** Observed (solid line) and predicted (stippled line) vertical profiles of salinity vs depth for the Motuhoa station during the survey period 3rd—11th February 1999.

**Figure 12c:** Observed (solid line) and predicted (stippled line) vertical profiles of salinity vs depth for the Western station during the survey period 3rd—11th February 1999.
3.9 SWAN model application to Tauranga Harbour

A SWAN wave model domain covered the southerly section of Tauranga Harbour utilising the same grid (mesh) as used for MIKE3 FM HD and MT models. The spectral grid had 32 discrete frequencies logarithmically placed between 0.10 Hz and 2.00 Hz, and 24 direction bins at 15° increments. All other model settings were SWAN defaults as described in the manual (Holthuijzen et al. 2000).

3.10 SWAN wave model description

The SWAN model (Booij et al. 1999; Ris et al. 1999) is a spectral wave model particularly intended for shallow-water applications in coastal and estuarine environments. It describes the sea state at each time (t) and position (x, y) within a defined region in terms of the amount of energy associated with each wave frequency (f) and propagation direction (θ). The model computes the evolution of the wave spectrum \( F(f, \theta) \) by accounting for the input, transfer and loss of energy through various physical processes. These processes include:

- wave generation by wind stress;
- wave propagation;
- refraction by the seabed and/or currents;
- transfer of energy between interacting waves of different frequencies and directions (a nonlinear effect);
- dissipation by white-capping;
- depth-induced breaking;
- bottom friction.

The model takes inputs specifying relevant environmental conditions, including:

- wind speed and direction;
- water depth;
- current speed and direction;
• incident wave conditions at the domain boundary.

In the most general case, the above parameters can be given as a function of position \((x, y)\) and time \((t)\), although sometimes a “stationary” simulation is done, where the equilibrium sea state is computed assuming time-invariant conditions.

### 3.11 SWAN model results

Several SWAN model simulations were set up and forced from a series of selected wind fields and hydrodynamics \((u, v, \text{depth})\).

The wind speed and directions used to force the SWAN model simulations are shown in Table 7. The direction selected for each of the four scenarios’ (these are later used in the USC-3 model) was based on the harbour exposure to wind.

Although New Zealand North Island is exposed to a predominantly South-Westerly wind, Tauranga Harbour falls in the lee of the Kaimais mountain range. Therefore, the majority of localised wind waves in the harbour are generated from North-North-East (NNE), North-East (NE) and South-East (SE) winds. These components of wind direction are approximately orthogonal to the longitudinal axis of the harbour. Therefore, for completeness, a North-West (NW) component that represents a wind blowing down the longitudinal axis of the harbour was also included. Mean wind speeds for these directions were then extracted from the analysis of meteorological data (wind speed and direction) collected at Tauranga Airport between 1991-2008.

| Table 5: Wind scenario values used in SWAN simulations for Tauranga harbour. |
|---------------------------------|-----------------|------------------|
| **Scenario and Direction**      | **Wind Direction (met convention)** | **Wind Speed (m/s)** |
| W1                              | NE              | 6.32             |
| W2                              | SE              | 6.4              |
| W3                              | NW              | 6.34             |
| W4                              | ENE             | 6.35             |

SWAN model tidal hydrodynamics were forced by depth averaged currents and water depths from the calibrated MIKE3 FM model for the 2006 calibration period. The SWAN model was run for 24 hours (after initial spin up), the period required of the MIKE3 FM MT model to produce wave inclusive scenario simulations for the USC-3 model. No actual field data (wave statistics) were available for a direct comparison with SWAN model output.
Example of the results produced from the SWAN simulations are shown in Figures 13a–d for an exposed site in Subestuary 30 (deep channel) and Figures 14a–d for an enclosed site in Subestuary 8. The Figures plot time series of wave statistics for the 4 different wind scenarios shown in Table 5. Results from the simulations were then assimilated into the MIKE 3–FM model to synthesize the effect of surface wave dynamics on sediment transport in the MT module.

**Figure 13a:** Results from SWAN model simulations for wind scenario W1 (NE winds) for the enclosed basin (SE-8) and exposed deep channel (SE-8) sites. Figure includes plots of: significant wave height (Hs); peak wave period (Tpeak); mean wave period (Tmean); wave orbital velocity (**** at the seabed?) (Urms); mean depth (Hmean).
Figure 13b: Results from SWAN model simulations for wind scenario W2 (SE winds) for the enclosed basin (SE-8) and exposed deep channel (SE-30) sites. Figure includes plots of: significant wave height ($H_s$); peak wave period ($T_{peak}$); mean wave period ($T_{mean}$); wave orbital velocity ($U_{rms}$); mean depth ($H_{mean}$).

Figure 13c: Results from SWAN model simulations for wind scenario W3 (NW winds) for the enclosed basin (SE-8) and exposed deep channel (SE-30) site. Figure includes plots of: significant wave height ($H_s$); peak wave period ($T_{peak}$); mean wave period ($T_{mean}$); wave orbital velocity ($U_{rms}$); mean depth ($H_{mean}$).
Figure 13d: Results from SWAN model simulations for wind scenario W4 (ENE winds) for the enclosed basin (SE-8) and exposed deep channel (SE-30) site. Figure includes plots of: significant wave height (Hs); peak wave period (Tpeak); mean wave period (Tmean); wave orbital velocity (Urms); mean depth (Hmean).

The SWAN simulation results in Figures 13a–d show that the simulated wave activity at both enclosed and exposed sites in response to the four wind scenarios is limited to short-period wind-sea chop of height up to ~0.2 m. Short period (Tmean < 2 s), small amplitude (Hs < 0.2m) are suggested to dominate the predicted wave field at both sites. However, the wind-waves can generate significant near-bed orbital velocities (Urms) in shallow water, as can be seen at SE-8 (Urms ~0.1 m/s, Figures 13a,c). When exposed to a wind blowing across the harbour, the generated wind-waves create orbital velocities at the seabed that can entrain sediment into the water column for transport by tidal currents. For deep areas of the harbour, for areas on the upwind side of the harbour, or when wind speeds are low, wave activity is minimal and wave orbital velocities are insufficient to entrain sediments into the water column.
4. **Suspended sediment transport**

The MIKE3 FM MT sediment transport model as described in Appendix 1 requires information about for example, sediment particle size and fall velocity, critical thresholds for deposition and erosion of the particles. A study by Green and Coco (2007) indicate that sediment coarser than fine sand is not likely to be mobilised in any significant way by waves and currents in enclosed harbours. Hence, any sediment coarser than fine sand is considered here to be “relict”, and does not contribute to the suspended-sediment load in the model. This is not to say that coarser sediment will never be moved; wave and current conditions will at times cause the re-suspension and transport of sand-sized material even in relatively sheltered areas of the harbour, while sand transport will be a regular occurrence in exposed areas with fast tidal currents, such as near the inlet throat. However, the great majority of sediment transport in relatively sheltered areas of the harbour will be of the finer sediment fractions, and that is the focus of this study. Therefore, particle grainsizes of 4, 12, 40 and 125 µm were used in the sediment transport model, corresponding to the very fine silt to very fine sand sediment fraction.

4.1 **MT module setup**

Based on the chosen size distribution, the Stokes fall speed assuming sediment density of 2650 kg/m$^3$ (quartz) was assigned to each grainsize: 0.00001 m/s, 0.0001 m/s, 0.001 m/s and 0.01 m/s respectively, for the 4, 12, 40 and 125 µm fractions based on Stokes fall velocity.

The analysis of the available archive data on Tauranga Harbour bed sediment composition is shown in Figure 15. The results suggested the highest mud (<63 µm) concentrations were confined to subestuaries on the North-West of the harbour model domain.
Figure 15: Regional map of Tauranga Harbour showing bed sediment size composition. Subestuary number (bold); mean grain size (mm); % mud content; sorting parameter. See Hancock et al. (2009) for further details.
However, by area these subestuaries (19.4 km$^2$) accounted for <15 % of the total model (125 km$^2$) domain area. Furthermore, the MIKE3 FM MT module can be set in either no-flocculation or flocculation mode. Mud formed only a minor fraction of the total sediment deposits in the whole of the harbour domain; and the transport of multiple particle size classes can only be simulated by the MT module of the MIKE3 modelling suite. Therefore, no flocculation was included in the model setup.

The MT model was set up using literature based values for sediment erosion and deposition as there were no field (time series) data. The critical bed shear stress for erosion $\tau_{e}$ is suggested to be set for cohesive type sediments at 0.15 N/m$^2$ for freshly deposited sediments (Whitehouse et al. 2000). Therefore, the $\tau_{e}$ for the whole of the model domain was set to 0.15 N/m$^2$. The critical bed shear stress for deposition was set at $\tau_{d} = \tau_{e}/2$ for each of the four-sediment grainsizes (Whitehouse et al. 2000).

Bed erosion rate ($E$) in the MT module was modelled through a soft bed parameterization (see Appendix 1) to simulate mainly freshly deposited sediment (Parchure and Mehta, 1985). The erosion coefficient $\alpha$ and an excess bed shear stress ($\tau_b - \tau_{ce}$) evolve the erosion rate exponentially and are ultimately based on the modeled current speeds and drag at the bed. Thus sediment transport depends on current speed multiplied by a high power. This becomes especially important during spring tides as the bed shear stress increases due to an increase in the magnitude of tidal currents, and so considerably more sediment transport occurs during spring tides than at neaps.

Figure 16 illustrates an example of published erosion rates (Van Rijn, 1989; Houwing, 1999; Whitehouse, 2000; Andersen and Pejrup, 2001; Wang, 2003) for similar physical settings and grainsizes used in this study. The $\alpha$ and $E_I$ values were set at $E_I = 0.00005$ kgm$^{-2}$s$^{-1}$ and $\alpha = 8.3$ in our model. These values were set to reflect the higher side of published values. The intention here, as no data was available, was to lean towards a worst case scenario. A potentially higher incidence of sediment re-suspension and remobilisation due to higher rates of erosion at higher values of excess bed shear stress would for USC-3 modelling produce a cautionary (slightly high) result for transport and deposition of sediments around the harbour.
Figure 16: Comparison of 5 published erosion rates and the erosion rate (Mike MT) used in the MIKE3 FM MT model setup for Tauranga Harbour.

4.2 MT model scenario setup

The MT model was set up to provide a series of look up tables that contain suspended sediment mass and bed deposition mass for each of the modelled grainsize fractions for each of the subestuaries in the model domain. Each value in a table is derived from a specific model scenario. Each model scenario is based on combinations of sediment discharged from a specific source identified in Table 1 with a:

1. A specific tide i.e., either a 2-cycle semi-diurnal tide for wave inclusive runs or 7-day spring to neap, neap to spring or mean-spring-mean tides for non-wave inclusive runs.

2. A specific wind wave event using SWAN simulations that were driven by wind speed and direction as shown in Table 7.

3. A specific discharge rate from each source that is derived from the WRENZ database. These coincided to a baseline flow, median flow and high flow.

4. A nominal sediment load of 1000 kg/m$^3$ which is injected at the specific source under investigation over one M$_2$ tidal cycle. The actual flux was dependent on the freshwater discharge rate at the source.
No times series data of SSC was available to this study hence the MT model could not be calibrated. Therefore, for this study our approach was to couple a calibrated hydrodynamic model coupled with a ‘literature parameterised’ and ‘expert implemented’ MT sediment transport model. All results from scenario simulations were checked to see if they produced physically credible results in response to each specific forcing scenario.

4.3 Examples of MT model simulations

For demonstration purposes, an example MT simulation and a description of the results is presented in the following sections.

The MIKE3 FM MT model was spun up for the 14-days that preceded the analysed and presented results. The hydrodynamic model that drives the MT model was forced with baseline source flow rate from all sources, a sediment flux for 4 µm (very fine silt) injected at the Wairoa River (Source 8), no winds (SWAN modelling presented in earlier sections showed wave activity was small) and tidal elevations as recorded at site CM3 at the entrance of the harbour for the 2006 calibration period. The model was then run for a further month and results extracted from the model.

The results from model predictions for salinity illustrated in Figure 17a show a brackish water plume that emanates from the source and spreads out into the harbour. Figures 17b–c shows an example of the modelled sediment dispersal from the Waroa River through a 2-dimensional snapshot of SSC (4µm size fraction) and bed deposition. The area of dispersal and spreading of the predicted SSC and resultant bed deposition was clearly related to the area of brackish water spreading and dispersion.
Figure 17a: Example of salinity distribution in Tauranga Harbour after receiving a freshwater inflow from the Wairoa River (Source 8) based on median freshwater source discharge rates.
Figure 17b: Example of net bed deposition (4µm particle size) in Tauranga Harbour after receiving a sediment flux from the Wairoa River (Source 8) at median freshwater source discharge rates.
Figure 17c: Example of net bed deposition (4µm particle size) in Tauranga Harbour after receiving a sediment flux from the Wairoa River (Source 8) at median freshwater source discharge rates.
Figure 18: Localised example of modelled bed shear stress ($\tau_b$); total SSC ($\Sigma$SSC) and bed deposition rate for Subestuary 8 (Wairoa River) in Tauranga Harbour.

A localised example of sediment dynamics is shown Figure 18. The figure shows that the model simulates the periodic (tidally modulated) changes in bed shear stress both at semi-diurnal and fortnightly (due to the spring-neap tidal cycle) time scales. The modelled sediment time series shows how both transport and deposition is oscillatory and coincident with changes in the magnitude of bed shear stress through tidal forcing.

The effect of tidal bed stress on SSC and deposition is further shown in Figure 19 which illustrates the dimensionless SSC and deposition rates (both normalised by maximum value) vs bed shear stress. The model demonstrated that sediment was being deposited until the bed shear stress exceeded the critical threshold for deposition ($\tau_{cd} = 0.075$ N/m$^2$) for the sediment fraction (4 $\mu$m). When bed shear stress was high the sediment remained in suspension. This process plays the predominant role in the transport of sediments at both initial (source) and subsequent larger harbour domain scales. The inclusion of the SWAN simulations into the model (wave orbital velocities) made little difference $O(6\%)$ to the SSC levels at source and open and exposed sites.
4.4 Summary

The observed and predicted sea surface elevation phase relationship inside the model domain was in good agreement. However, there was some disparity between absolute amplitudes. This was probably caused by the localised non-resolved variations in bed roughness and bathymetry in the model. Nevertheless, the RMSE of tidal elevations was small as compared to the total amplitude of the tide at all 4 of the measured sites. The bias in observed and predicted series was through slight localised discrepancies in bathymetry. Overall, the modelled sea surface elevations were in good agreement with the observations.

The statistical and tidal elliptical properties for the major semi-diurnal currents resolvable from the observations and model showed forcing constituents were in agreement within the harbour. The modelled predicted the correct phasing amplitude, and direction of currents at the calibration site (CM5).

However, the predicted currents outside the harbour entrance (CM2 and CM3) showed a greater disparity with those observed at mooring sites. The observed tidal phase showed a weaker correlation with those observed and the model under predicted peaks in the current vectors at both mooring sites. Statistical analysis of the predicted and observed currents using both RMSE and bias gave values ranged from 0.09 – 0.19 m/s.
and 0.02 – 0.07 m/s respectively. A de-tided progressive vector analysis of the currents at these sites showed a continual Northerly directed drift at both sites. This is attributed to forcing the model with astronomical tides that do not include the effects of unresolved coastal processes such as coastally trapped waves as commonly observed on the East coast of New Zealand. These differences are further compounded by localised changes in bathymetry due to the continual evolution of the near shore seabed due to wave-driven littoral currents that move sand into the entrance.

Paucity of salinity data limited the salinity calibration of the model to a basic inter-comparison of CTD casts at three separate harbour sites against hind-cast model predictions for the corresponding time and place of a CTD cast. Since these results were based on predicted (un-gauged) freshwater source inflow rates for many of the sources the results were highly encouraging. The observed salinity profiles showed lower salinities to the North-East of the harbour (Omokoroa) with weak near surface stratification at depths < 1.5 m. The modelled values of salinity matched the observed values within approximately 0.25 PSU. However, the simulations did not resolve the observed weak stratification for these two sites.

The SWAN model of the region driven by the MIKE3 FM HD model and localised wind fields produced the wave parameters to be include in subsequent MIKE3 FM MT simulations of the harbour. Predicted wave fields for the four wind scenarios of the harbour suggested that in both enclosed (SE-8) and open water (SE-30) sites, wave period was short and wave heights small (<0.2m) and wave orbital velocities weak. Wave orbital velocities did increase in shallow areas at the enclosed site (SE-8) when subjected to North-Easterly and North-Westerly winds through set up in the basin.

The MIKE3 FM MT model was set up using literature based values for empirical coefficients and constants. The results suggested that SSC, and sediment deposition were strongly linked to source outflow rates and the tide. The model indicated that sediment injected at a freshwater source was dispersed and transported by freshwater spreading out from a source and by tidally generated bed shear stress. Furthermore, the model was shown to conform to the specific threshold criterions specified for a specific particulate size. The particles settled and deposited when shear stress was below critical threshold criterions and remained in suspension when shear stresses exceeded the threshold criterions.

The model represented the main (tidally driven) sediment transport processes. It correctly represented the timing of SSC peaks associated with peak tidal flows and also reproduced the spring–ebb tidal modulation.
The model was then used to simulate 380 different scenarios to provide the USC-3 sedimentation model with lookup tables that describe sediment transport in Tauranga Harbour under various wave fields, winds, source inflow rates and tides.

5. Acknowledgements

We thank the Port of Tauranga for bathymetric soundings data, Stephen Park and his colleagues for LIDAR data and extracting survey and sediment data from EBOP records for our use. Cliff Hart, Nicole Hancock and Sanjay Wadhwa assisted with the hydrodynamic, bathymetric, sediment data and GIS work. University of Waikato staff Terry Healy, Conrad Pilditch, Debra Stokes, Kyle Spiers for providing hydrodynamic and sediment data from their records. We thank Scott Stephens and Terry Hume for reviewing the report.
6. References


Green, M.O.; Coco, G. (2007). Sediment transport on an estuarine intertidal flat: measurements and conceptual model of waves, rainfall and exchanges with a tidal creek. Estuarine, Coastal and Shelf Science 72: 553-569.


7. **Appendix 1: Formulation of processes simulated by the MIKE3 models**

This section outlines the methods used by the MIKE3 FM HD and MT models to simulate tidal propagation within the harbour, tide- and wind-driven currents, freshwater mixing and sediment transport.

7.1 **Bed shear stress**

MIKE3 FM HD uses a quadratic friction law to define the bed shear stress due to the current:

$$\frac{\tau_b}{\rho_0} = c_f \bar{u} \left| \bar{u} \right|$$

where $c_f$ is the drag coefficient, $\bar{u}$ is the time-averaged current speed at a distance $\Delta z_b$ above the bed, and $\rho_0$ is the density of water. The drag coefficient is defined in terms of a logarithmic profile between the seabed and the point $\Delta z_b$ above the seabed:

$$c_f = \frac{1}{\left(\frac{1}{\kappa} \ln \left(\frac{\Delta z_b}{z_0}\right)\right)^2}$$

where $\kappa=0.4$ is von Karman’s constant and $z_0$ is the bed roughness length, which is typically varied to calibrate the model.

The enhancement of the current-related bed shear stress by any waves that may be present is increased for use in the calculation of sediment transport. The method used is a parameterisation of Fredsøe’s (1984) method, which was derived by Soulsby et al. (1993). The mean and maximum combined wave-current bed shear stresses are given as follows:

$$\frac{\tau_{wc,mean}}{\tau_c + \tau_w} = \frac{\tau_c}{\tau_c + \tau_w} \left(1 + b \left(\frac{\tau_c}{\tau_c + \tau_w}\right)^p \left(1 - \frac{\tau_c}{\tau_c + \tau_w}\right)^q\right)$$

$$\frac{\tau_{wc,max}}{\tau_c + \tau_w} = \left(\frac{\tau_c}{\tau_c + \tau_w}\right)^m \left(1 - \frac{\tau_c}{\tau_c + \tau_w}\right)^n$$

where $b$, $p$, $q$, $a$, $m$, $n$ constants:

$$a = a1 + a2 \cos \gamma i + (a3 + a4 \cos \gamma i) \log 10(r)$$

$$b = b1 + b2 \cos \gamma j + (b3 + b4 \cos \gamma j) \log 10(r)$$
\[ m = m_1 + m_2 \cos \gamma_i + (m_3 + m_4 \cos \gamma_i) \log_{10}(r) \]
\[ n = n_1 + n_2 \cos \gamma_i + (n_3 + n_4 \cos \gamma_i) \log_{10}(r) \]
\[ p = p_1 + p_2 \cos \gamma_j + (p_3 + p_4 \cos \gamma_j) \log_{10}(r) \]
\[ q = q_1 + q_2 \cos \gamma_j + (q_3 + q_4 \cos \gamma_j) \log_{10}(r) \]

and \( a_1, a_2, \) etc. are given in the table below, \( \gamma \) is the angle between the waves and currents with \( I = 0.8, j = 3.0 \) and \( r = 2 f_w/f_c \).

<table>
<thead>
<tr>
<th></th>
<th>( a )</th>
<th>( m )</th>
<th>( n )</th>
<th>( b )</th>
<th>( p )</th>
<th>( q )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.06</td>
<td>0.67</td>
<td>0.75</td>
<td>0.29</td>
<td>-0.77</td>
<td>0.91</td>
</tr>
<tr>
<td>2</td>
<td>1.70</td>
<td>-0.29</td>
<td>-0.27</td>
<td>0.55</td>
<td>0.10</td>
<td>0.25</td>
</tr>
<tr>
<td>3</td>
<td>-0.29</td>
<td>0.09</td>
<td>0.11</td>
<td>-0.10</td>
<td>0.27</td>
<td>0.50</td>
</tr>
<tr>
<td>4</td>
<td>0.29</td>
<td>0.42</td>
<td>-0.02</td>
<td>-0.14</td>
<td>0.14</td>
<td>0.45</td>
</tr>
</tbody>
</table>

\( f_w \) is the pure-wave wave friction factor, given by (Swart, 1974) as:

\[ f_w = \exp\left(5.213 \left( \frac{a}{k} \right)^{-0.194} \right) - 5.977 \]

where \( k \) is the bed roughness and \( a \) is the wave-orbital semi-excursion at the bed. Also, \( f_c \) is the pure-current friction factor, given by the logarithmic resistance law:

\[ f_c = 2 \left(2.5 \ln \left( \frac{30h}{k} \right) \right)^2 \]

where \( h \) is the water depth.

### 7.2 Currents

The influence of the wind on currents is treated in terms of the wind-induced shear stress that acts on the sea surface:

\[ \tau_w = \rho_a c_d \left| u_w \right| u_w \]

where \( \rho_a \) is the density of air, \( c_d \) is the drag coefficient and \( u_w \) is the wind speed 10m above the sea surface. The model is typically calibrated by adjusting \( c_d \).
The turbulent transfer of momentum by eddies gives rise to an internal fluid friction which is resolved in the horizontal and vertical dimensions by use of an eddy viscosity formulation.

In the vertical, the eddy viscosity is derived from $k$-$\varepsilon$ formulation where eddy viscosity is determined from the $k$ or production term and $\varepsilon$ the dissipation term (Rodi, 1980, 1984). The turbulence module is parameterised through a series of empirical coefficients.

For the horizontal eddy viscosity, the Smagorinsky formulation was applied, which gives the sub grid-scale eddy viscosity as:

$$ A = c_s^2 l^2 \sqrt{2S_{ij}S_{ij}} $$

where $c_s$ is a constant, $l$ is the characteristic length (approximated by the minimum edge length for each element) and the deformation rate ($S_{ij}$) is given by

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

Using this formulation, the model can be calibrated by adjusting the constant $c_s$ and by defining the upper and lower limits of the horizontal eddy viscosity.

7.3 Salinity

In baroclinic mode MIKE3 FM HD requires coefficients for vertical and horizontal dispersion. These can be constant or they can be proportionally scaled to the eddy viscosity. For the implementation of the model here a scaled dispersion coefficient was used.

7.4 Sediment transport

MIKE3 FM MT can simulate the erosion, transport and deposition of up to 8 different grainsize fractions. For each grainsize a fall velocity ($w_s$) is assigned.

7.4.1 Deposition

Deposition of sediment onto the bed is deemed to occur when and where the bed shear stress ($\tau_b$) is smaller than the critical bed shear stress for deposition ($\tau_{cd}$). A separate $\tau_{cd}$ is assigned to each grainsize.
The deposition rate \( (\text{kg.m}^{-2}.\text{s}^{-1}) \) is given separately for each grainsize by:

\[
D = w_s p_d c_b
\]

where \( p_d \) is the probability ramp function for deposition defined as:

\[
p_d = \max(0, \min(1, 1 - \frac{\tau_d}{\tau_{cd}}))
\]

and \( c_b \) is the near-bed suspended-sediment concentration for the grainsize at hand.

MIKE3 FM MT gives two choices for determining \( c_b \): the Teeter formulation and the Rouse formulation. The Teeter formulation was chosen for implementation here, which is:

\[
c_b = c \left(1 + \frac{p_e}{1.25 + 4.75 p_e^{3.5}}\right)
\]

where \( p_e \) is the Peclet number, defined as:

\[
p_e = 6\frac{w_s}{\kappa U_f}
\]

and \( U_f \) is the friction velocity.

The calibration process involves selecting the fall velocity and the critical bed shear stress for deposition (\( \tau_{cd} \)) for each grainsize.

### 7.4.2 Erosion

Erosion of bed material takes place when and where the bed shear stress exceeds the critical shear stress for erosion (\( \tau_{ce} \)). A single value of \( \tau_{ce} \) is assigned for the bed sediment as a whole.

The erosion rate (\( \text{kg/[m}^2\text{s}] \)) is specified for the bed as a whole as:

\[
E = E_i \exp(\alpha(\tau_{b} - \tau_{ce}))
\]

where \( \alpha \) is a power term and \( E_i \) is the “initial” erosion rate. The total mass of sediment eroded from the bed (which is governed by \( E \)) is then distributed amongst the constituent grainsizes by the proportions of the constituent grainsizes in the bed sediment. For example, if constituent grain size #1 makes up 50% of the bed sediment by mass then 50% of the sediment eroded by \( E \) will be assigned that grainsize.
The calibration process involves selecting one value each for $\tau_c$, $\alpha$ and $E_i$.

### Table A1: List of specific calibration parameters and calibrated as implemented in the DHI MIKE3 FM HD and MT model for Tauranga Harbour.

<table>
<thead>
<tr>
<th>DHI MIKE3 FM</th>
<th>Parameter</th>
<th>Variable used in model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model stability</strong></td>
<td>Model Spin up Time</td>
<td>14 days</td>
</tr>
<tr>
<td><strong>Offshore tidal boundary</strong></td>
<td>Harmonic Tidal constituents</td>
<td>$M_2$, $S_2$, $K_2$, $K_1$, $O_1$, $P_1$, $Q_1$, $2N_2$, $M_4$, $N_4$, $L_2$, $T_2$</td>
</tr>
<tr>
<td><strong>Bed roughness</strong></td>
<td>$Z_0$</td>
<td>0.05</td>
</tr>
<tr>
<td><strong>Horizontal Mixing</strong></td>
<td>Smagorinsky coefficient</td>
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</tr>
<tr>
<td>Lower limit</td>
<td>$N_{x,y}$</td>
<td>1.8e-006 m$^2$/s</td>
</tr>
<tr>
<td>Upper limit</td>
<td>$N_{x,y}$</td>
<td>10 m$^2$/s</td>
</tr>
<tr>
<td><strong>Vertical Mixing</strong></td>
<td>$C_p$</td>
<td>0.09</td>
</tr>
<tr>
<td>$k$-$\varepsilon$ formulation</td>
<td>$C_1$</td>
<td>1.44</td>
</tr>
<tr>
<td></td>
<td>$C_2$</td>
<td>1.92</td>
</tr>
<tr>
<td></td>
<td>$C_3$</td>
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</tr>
<tr>
<td></td>
<td>$\sigma_t$</td>
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<tr>
<td><strong>Salinity scaling factor</strong></td>
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<td><strong>Wind drag coefficient</strong></td>
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</tr>
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<td><strong>Particle Settling Velocity</strong></td>
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<tr>
<td></td>
<td>$12 \mu m$</td>
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<td>$40 \mu m$</td>
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<tr>
<td></td>
<td>$125 \mu m$</td>
<td>1.4e-2 m/s</td>
</tr>
<tr>
<td><strong>Bed Erosion Rate</strong></td>
<td>$E_1$</td>
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<tr>
<td></td>
<td>$\alpha$</td>
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<tr>
<td><strong>Sediment Deposition Threshold</strong></td>
<td>$\tau_{cd}$ (4$\mu$m)</td>
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<td>$\tau_{cd}$ (12$\mu$m)</td>
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<td>$\tau_{cd}$ (40$\mu$m)</td>
<td>0.15 N/m$^2$</td>
</tr>
<tr>
<td></td>
<td>$\tau_{cd}$ (125$\mu$m)</td>
<td>0.15 N/m$^2$</td>
</tr>
</tbody>
</table>
8. Appendix 2: LIDAR data processing

The LIDAR data were supplied to NIWA in a raster (*.las) format, which, once imported into LASEdit software can be viewed, post processed and output into an *.xyz (ascii readable format). These data were then converted from NZTM, corrected to local chart datum and converted to WGS84 co-ordinates and saved in a binary Matlab format for further post processing.

Several hundred binary files were then put through a data reduction routine to make the size of data importable to the DHI MIKE ZERO grid generation tool. Each data file (tile) was concatenated and interpolated onto a regular grid of a sub-region of the area. Then each sub-region was concatenated again and interpolated onto a regular grid of the whole region. In this way LIDAR bathymetry can easily be reprocessed using Matlab files if higher/lower spatial resolution is required.