Tauranga Harbour Sediment Study: Implementation and Calibration of the USC-3 Model

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M.O. Green

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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:

Terry Hume

Approved for release by:

David Roper

Formatting checked

Executive Summary

This report describes the implementation and calibration of the USC-3 model in southern Tauranga Harbour.

The model predicts estuarine sedimentation on the planning timescale, which is decades and greater. The model is physically based, and is intended to support decision-making by predicting various changes in the harbour bed sediments associated with catchment development scenarios that will cause changes in sediment runoff from the catchment. The model provides:

- Predictions of sedimentation in different parts of the estuary, which may be compared and used in an assessment of sediment effects.

- Predictions of the change in bed composition over time, which reflects degradation of habitat (e.g., change of sandy substrate to silt), and which may bring associated ecological degradation (e.g., mangrove spread, loss of shellfish beds).

- An explicit analysis of the links between sediment sources in the catchment and sediment sinks in the estuary. This type of analysis effectively links “subestuary effects” to “subcatchment causes”, thus showing where best management practices on the land can be most effectively focused. Without an understanding of the link between source and sink, assessment of sediment sources on the land lacks any effects context.

The implementation of the USC-3 model for southern Tauranga Harbour consisted of defining subestuaries and subcatchments, evaluating the various terms that control sediment transport and deposition inside the harbour, defining the way land-derived sediments are to be fed into the harbour at the subcatchment outlets, and assembling weather time series for driving the model.

Other information required to drive the model, including harbour bed-sediment initial conditions and specifying the way sediment runoff from the land is to be distributed across grainsizes, may vary depending on the particular scenario being addressed. This information is not treated as part of the model implementation. Instead, it is reported with model results in Technical Report E2 of the study (Green, M.O., 2009. Tauranga Harbour Sediment Study: Predictions of Harbour Sedimentation under Future Scenarios. NIWA Client Report HAM2009–078).

Model calibration was achieved by running the model for the 58-year historical period 1943 to 2001, with sediment inputs from the catchment appropriate to that period. The aim of the calibration process was to adjust various terms in the USC-3 model so that hindcasts of sedimentation over the historical period came to match measurements from that same period.

The model was calibrated by reducing the erosion depth for all values of bed-sediment median grainsize by approximately half across the model domain. This resulted in a set of hindcast (1943–2001) annual-average sedimentation rates throughout the model domain that could be interpreted sensibly in broad, physical terms, and that could be reconciled with six reliable measurements of sedimentation rate reported by Hancock et al. (2009). The exceptions were the two subestuaries enclosed by Matakana Island, where the model does not appear to perform very well. The model was calibrated as a whole, against the whole set of sedimentation measurements; in general, it is not possible to calibrate the model subestuary-by-subestuary. The reason is that sediments are exchanged amongst subestuaries, and therefore any particular subestuary cannot be considered in isolation from the rest of the model domain.

Overall, the calibration appears to be satisfactory, and the model can now be used to predict future sedimentation with some confidence.

1. Introduction

1.1 Background

Environment Bay of Plenty (EBOP) seeks to understand sedimentation in Tauranga Harbour in order to understand sediment sources and fate sufficiently to appropriately manage growth and development now and in the future. This will also assist EBOP to adapt management rules and practices appropriately and be able to make 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 sediments. Although these changes are to a large extent driven by historical events when there was little control on 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, including analysis of sediment yields from all sources in the catchment, peak flow monitoring, 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 relative contributions 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 timeframe for predictions is 50 years from the present day (2001).

1.2 Study outline and modules

The study consists of 6 modules:

Module A: Specification of scenarios – Defines landuse and weather information that is required for driving the various models. Three scenarios are defined in terms of landuse, which includes earthworks associated with any development, and weather. The weather is described in terms of magnitude and frequency of storms and wind climate, and needs to be specified to a degree that is sufficient for driving models. The third scenario incorporates anticipated effects of climate change.

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 catchment in order 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 model for prediction of harbour sedimentation over the decadal scale.

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 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 the 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 model for prediction of harbour sedimentation over decadal scales.

Module E: USC-3 model – Uses the USC-3 model to make predictions of sedimentation, bed-sediment composition and linkages between sources and sinks, 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 model hindcasts 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 appropriate? (4) Are there any reversal methods, such as mangrove control and channel dredging, that may be effective in managing sedimentation issues?

1.3 This report

This report, which describes the implementation and calibration of the USC-3 model in southern Tauranga Harbour, is Technical Report E1 of the study and completes Milestone M9.

The implementation of the USC-3 model for southern Tauranga Harbour consists of defining subestuaries and subcatchments, evaluating the various terms that control sediment transport and deposition inside the harbour, defining the way land-derived sediments are to be fed into the harbour at the subcatchment outlets, and assembling weather time series for driving the model.

Other information required to drive the model, including harbour bed-sediment initial conditions and specifying the way sediment runoff from the land is to be distributed across grainsizes, may vary depending on the particular scenario being addressed. This information is not treated as part of the model implementation. Instead, it is reported with model results in Technical Report E2 of the study (Green, M.O., 2009. Tauranga Harbour Sediment Study: Predictions of Harbour Sedimentation under Future Scenarios. NIWA Client Report HAM2009–078).

Model calibration is achieved by running the model for the 58-year historical period 1943 to 2001, with sediment inputs from the catchment appropriate to that period. The aim of the calibration process is to adjust various terms in the USC-3 model so that hindcasts of sedimentation over the historical period come to match observations from that same period.

The calibrated USC-3 model is to be used to predict sedimentation in southern Tauranga Harbour under three future scenarios, described by Parshotam et al. (2008). These are defined in terms of landuse (which includes earthworks associated with any development) and weather. One scenario addresses the potential effects of climate change.

2. Model Overview

2.1 Introduction

The USC-3 ("Urban Stormwater Contaminant") contaminant-accumulation model predicts sedimentation and accumulation of contaminants (including zinc and copper) in the bed sediments of estuaries on the "planning timescale", which is decades and greater. (In this implementation of the model, it will predict sedimentation only.) The model is physically based, and functions as a decision-support scheme.

The model is intended to support decision-making by predicting various changes in the harbour bed sediments associated with catchment development scenarios that will cause changes in sediment runoff from the catchment. The model provides:

- Predictions of sedimentation in different parts of the estuary, which may be compared and used in an assessment of sediment effects.

- Predictions of the change in bed composition over time, which reflects degradation of habitat (e.g., change of sandy substrate to silt), and which may bring associated ecological degradation (e.g., mangrove spread, loss of shellfish beds).

- Predictions of the accumulation of heavy metals in the surface mixed layer of the estuary bed sediments, which may be compared to sediment-quality guidelines to infer associated ecological effects. (This function will not be available in this implementation).

- An explicit analysis of the links between sediment sources in the catchment and sediment sinks in the estuary. This type of analysis effectively links "subestuary effects" to "subcatchment causes", thus showing where best management practices on the land can be most effectively focused. Without an understanding of the link between source and sink, assessment of sediment sources on the land lacks any effects context.

The original USC model was applicable to simple estuaries that consist of a single "settling zone" (where settling of suspended sediments and associated contaminants is enhanced). A small embayment fed by a single tidal creek is an example of where this model would apply. The USC model was initially applied in Lucas and Hellyers Creeks (tidal creeks that drain into the Upper Waitemata Harbour) in the Auckland Region.

The USC-2 model was developed to apply to more complex estuaries consisting of a number of interlinking settling zones and "secondary redistribution areas" (where waves and/or currents mobilise and redisperse sediments and associated contaminants). The secondary redistribution areas were limited to low energy. The USC-2 model was initially applied in the Upper Waitemata Harbour for the Auckland Regional Council.

The USC-3 model was developed for the Central Waitemata Harbour Study for the Auckland Regional Council. It also applies to more complex harbours, although the secondary redistribution areas are no longer limited to low energy.

The USC-3 model subsumes the functions of the two previous versions of the model. Hence, it is the USC-3 model that has been implemented here for the Tauranga Sediment Study.

The USC-3 model in this implementation requires as inputs estimates of future sediment runoff and grainsizes from the land. Patterns of sediment transport and deposition in the harbour, including the way land-derived sediments are discharged and dispersed in the harbour during and following rainstorms, need to be known. Model initial conditions include present-day grainsize distribution of harbour bed sediments. The model is calibrated against annual-average sedimentation rates in the harbour.

2.2 Model overview

Predictions are typically made at the "planning timescale", which is decades and greater. This is much longer than "standard" estuary sediment-transport models.

Predictions are made at the scale of the subestuary, which corresponds to km-scale compartments of the harbour with common depth, exposure and bed-sediment grainsize.

The catchment is divided into subcatchments on a similar scale. Each subcatchment discharges through one outlet to the harbour.

A long-term weather sequence is used to drive the model over time. The weather sequence that drives the model may be constructed randomly or biased to represent worst-case or best-case outcomes. The weather sequence may also reflect the anticipated effects of climate change.

The model simulates the deposition of sediment that occurs under certain conditions (e.g., in sheltered parts of the harbour, or on days when there is no wind), and the erosion of sediment that occurs under other conditions (e.g., in parts of the harbour where there are strong tidal currents or on days when it is windy). It also simulates the dispersal of sediments and contaminants eroded from the land when it rains and discharged (or "injected") into the harbour with freshwater runoff.

Physically-based "rules" are used by the model to simulate the injection into the harbour of land-derived sediments from the catchment when it is raining. The particular rule that is applied depends on the weather and the tide at the time. Sediment is only injected into the harbour when it is raining.

Another set of physically-based rules is used to simulate the erosion, transport and deposition of estuarine sediments inside the estuary by tidal currents and waves. "Estuarine" sediments refers to all of the sediment that is already in the harbour on the day at hand, and includes all of the land-derived sediment that was discharged into the harbour previous to the day at hand.

The model has a mixed timestep, depending on the particular processes being simulated:

- For the injection into the harbour of sediment that is eroded from the land when it rains the model timestep is 2 complete tidal cycles (referred to herein as "one day").

- For the resuspension of estuarine bed sediments by waves and tidal currents the model timestep is also one day.

- Each day an injection and/or resuspension event may occur, or no event may occur. The rainfall, wind and tide range on the day govern whether or not an event occurs. The rainfall, wind and tide range on each day are determined by the long-term weather sequence that drives the model.

- The rainfall, wind and tide range on the day govern the way land-derived sediment is injected into the harbour. At the end of the day on which injection occurs, land-derived sediment may be settled onto the bed in any part of the harbour, may be in suspension in any part of the harbour, or may be lost to "sinks" (areas of the harbour that may accumulate sediment, but which do not erode). The part of the land-derived sediment load that is in suspension at the end of the injection day is further dispersed throughout the harbour on days following the injection day until it is all accounted for by settlement to the bed (in any part of the harbour) and loss to sinks. This may take different lengths of time to achieve, depending on where the dispersal/deposition process begins at the end of the injection day. Hence, the timestep for this process is variable.

- The wind and tide range on the day govern the way estuarine bed sediment is resuspended. At the end of the day on which resuspension occurs, resuspended sediment may be settled onto the bed in any part of the harbour, may be in suspension in any part of the harbour, or may be lost to sinks. The part of the resuspended sediment load that is in suspension at the end of the resuspension day is further dispersed throughout the harbour on days following the resuspension day until it is all accounted for by settlement to the bed (in any part of the harbour) and loss to sinks. This may take different lengths of time to achieve, depending on where the dispersal/deposition process begins at the end of the resuspension day. Hence, the timestep for this process is variable.

- The model builds up the set of predictions by "adding together", over the duration of the simulation, injection and resuspension events and the subsequent dispersal and deposition of injected and resuspended sediment. The simulation duration is typically 50 or 100 years. In essence, the model moves sediment/contaminant from each subcatchment to the various subestuaries each time it rains, and amongst the various subestuaries to account for the action of waves and tidal currents.

A key feature of the model is that the bed sediment in each subestuary is represented as a column comprising a series of layers, which evolves as the simulation proceeds.

The bed sediment evolves in the model by addition of layers when sediment is deposited, and by removal of those same layers when sediment is eroded. At any given time and in any given subestuary, there may be zero layers in the sediment column, in which case the bed sediment consists of "pre-existing" bed sediment only. This corresponds to the initial conditions mentioned above. Layer thicknesses may vary, depending on how they develop during the simulation.

Both land-derived and estuarine sediments may be composed of multiple constituent grainsizes (e.g., clay, silt, fine sand, sand). The proportions of the constituent grainsizes in each layer of the sediment column may vary, depending on how they develop in the simulation. This results in finer or coarser layers as the case may be.

Under some circumstances, the constituent grainsizes in the model interact with each other and under other circumstances they act independently of each other.

For example, the erosion rate is determined by a weighted-mean grainsize of the bed sediment that reflects the combined presence of the constituent grainsizes. This has an important consequence: if the weighted-mean grainsize of the bed sediment increases, it becomes more difficult to erode, and so becomes "armoured" as a whole. This reduces the erosion of all of the constituent grainsizes, including the finer fractions, which otherwise might be very mobile. The bed-sediment weighted-mean grainsize is calculated over the thickness of the bed-sediment "active layer".

In contrast, the individual grainsizes, once released from the bed by erosion and placed in suspension in the water column, are dispersed independently of any other grainsize that may also be in suspension. Dispersion of suspended sediments is in fact very sensitive to grainsize, which has an important consequence: the constituent grainsizes may "unmix" once in suspension and go their separate ways. This can cause some parts of the harbour to, for instance, accumulate finer sediments over time and other parts to accumulate coarser sediments. This is reflected in a progressive fining or coarsening, as the case may be, of the bed sediment. The model accounts for this process.

In some parts of the harbour or under some weather sequences, sediment layers may become permanently sequestered by the addition of subsequent layers of sediment, which raises the level of the bed and results in a positive sedimentation rate. In other parts of the harbour or under other weather sequences, sediment layers may be exhumed, resulting in a net loss of sediment, which gives a negative sedimentation rate. Other parts of the harbour may be purely transportational, meaning that erosion and sedimentation balance, over the long term. However, even in that case, it is possible (with a fortuitous balance) for there to be a progressive coarsening or fining of the bed sediments.

Because model predictions are sensitive to sequences of events (as just described), a series of decade-long simulations is typically run, with each simulation in the series driven by a different, randomly-chosen weather sequence. The predictions from the series of simulations are averaged to yield one average prediction of sedimentation and contaminant accumulation over the decade-long duration. Each weather sequence in the series is constructed so that long-term weather statistics are recovered.

2.3 Comparison with the USC-2 model

The USC-2 model allowed for erosion of bed sediment by waves and currents between rainfall events, but only in a limited way. In effect, only sediment that was deposited in the immediately-previous rainfall event was allowed to be eroded and redispersed/redeposited throughout the harbour in any given between-rainfall period. This had the effect of "ratcheting up" deposition, as sediment deposited during previous events became sequestered, which is appropriate in sheltered basins. This will not be acceptable in the case of open water bodies.

The USC-3 model works differently. It allows erosion of any portion of the bed sediment that has been deposited since the beginning of the simulation, including all of it. The USC-3 model does in fact allow for the net change in bed level over the duration of the simulation to be negative (erosional regime). However, as implemented for this study, this is prevented by not allowing erosion to occur below a certain basement level that is set at the start of the simulation. A subestuary may be purely transportational over the duration of the simulation, meaning that the net change in sediment level can be zero.

3. Model Details

3.1 Characteristics of special subestuaries

3.1.1 Tidal creeks

Sediments may not be resuspended inside those subestuaries designated as tidal creeks. Sediments resuspended elsewhere in the harbour by waves and currents that get deposited inside tidal creeks will therefore be sequestered, which will enhance the accumulation of sediments in the tidal creeks. This is expected, since tidal creeks are sheltered from the waves (in particular) and currents that could otherwise erode them, and thereby reduce accumulation, on a daily basis. Tidal creeks also attenuate (i.e., retain a portion of) the land-derived sediment load that passes through them, carried by freshwater runoff on the way to the main body of the harbour. The attenuated part of the land-derived sediment load deposits in the tidal creek.

3.1.2 Sinks

Sediments deposited in those subestuaries designated as sinks also may not be subsequently removed by resuspension. Unlike tidal creeks, there is no special arrangement for attenuating land-derived sediment loads that pass through sinks.

3.1.3 Deep channels

Sediments are not allowed to erode from or deposit in subestuaries designated as deep channels.

3.2 Resuspension of estuarine bed sediments by waves and currents

3.2.1 Introduction

Every day, estuarine sediments may be resuspended (in the USC-3 model) by tidal currents and waves, and redispersed and redeposited elsewhere in the estuary. “Estuary sediments” here includes all the land-derived sediments injected into the harbour prior to the day at hand.

The USC-3 model predicts this on the basis of the tide range and the wind speed and direction. The tide range controls the strength of tidal currents and possibly the residual circulation patterns. The wind speed and direction control the generation of waves, which are principally responsible for resuspension of bed sediments. In addition, the wind may generate currents that are superimposed on tidal currents and that therefore affect patterns of sediment dispersal.

Daily movement of sediments in the harbour is controlled by *ED50*, *R5*, *R5SUSP* and *RFS*, which are determined by the DHI estuary model suite[1].

- *ED50* is an erosion depth on the resuspension day.
- *R5* and *R5SUSP* describe sediment dispersal and deposition on the resuspension day.
- *RFS* describes sediment dispersal and deposition on the days following the resuspension day.

Table 3.1 summarises the meaning of the terms *ED50*, *R5*, *R5SUSP* and *RFS*. Refer to this table during the following detailed description.

Figure 3.1 shows how *ED50*, *R5*, *R5SUSP* and *RFS* are applied. Refer to this figure during the following detailed description

3.2.2 Details

ED50

In each subestuary in the USC-3 model domain, excluding those subestuaries designated as tidal creeks, sinks and deep channels, tidal currents and waves each day may resuspend sediments to a depth of *ED50*.

ED50 is determined for each subestuary using the DHI model suite for each of a number of bed-sediment weighted-mean grainsizes (termed *D50* in the following) under each of a number of environmental conditions (e.g., tides, winds). A separate DHI simulation is run for each origin subestuary. Each DHI simulation duration is one day (2 complete tidal cycles), and each simulation begins with estuarine sediments in the subestuary at hand stationary (i.e., on the bed).

ED50 is an erosion depth: it is evaluated at the end of each one-day timestep, it is averaged over the subestuary, and it has units of metres. *ED50* may be zero.

[1] The “DHI estuary model suite” comprises the DHI Water and Environment (DHI) MIKE3 FM hydrodynamic model, the DHI MIKE3 MT sediment transport model, and the SWAN wave model.

ED50 = 0 in subestuaries designated as tidal creeks, sinks or deep channels.

R5 and *R5SUSP*

Once eroded from the bed and placed in suspension, each constituent grainsize disperses and settles in the USC-3 model according to its own settling speed and as though it is the only grainsize in suspension. In this way, the various grainsizes in the bed can become "uncoupled" from each other once in suspension.

The fraction of constituent grainsize *iparticle* that is eroded from subestuary *kestorigin* and deposited in subestuary *kestdestination* by the end of the resuspension day is given by $R5_{iparticle,kestorigin,kestdestination}$. The total mass of constituent grainsize *iparticle* that comes to be deposited in subestuary *kestdestination* by the end of the resuspension day is given by:

$$\sum_{kestorigin=1}^{nest}(SEDIMENTMASS_{iparticle,kestorigin} \times R5_{iparticle,kestorigin,kestdestination})$$

where $SEDIMENTMASS_{iparticle,kestorigin}$ is the mass of constituent grainsize *iparticle* that is released by resuspension in origin subestuary *kestorigin* by erosion to a depth of $ED50_{iparticle,kestorigin}$. This is explained in detail in a later section, when the layering of the bed sediment is explained.

The fraction of constituent grainsize *iparticle* that is eroded from subestuary *kestorigin* and that remains in suspension in subestuary *kestdestination* at the end of the resuspension day is given by $R5SUSP_{iparticle,kestorigin,kestdestination}$. The total mass of constituent grainsize iparticle that is in suspension in subestuary *kestdestination* at the end of the resuspension day is given by:

$$\sum_{kestorigin=1}^{nest}(SEDIMENTMASS_{iparticle,kestorigin} \times R5SUSP_{iparticle,kestorigin,kestdestination})$$

If *kestdestination* corresponds to a deep channel, then *R5* is forced to 0, since sediments are not allowed to settle to the bed in deep channels.

R5 and *R5SUSP* between them account for all of the sediment that is resuspended in each origin subestuary. That is:

$$\sum_{kestdestination=1}^{nest}(R5_{iparticle,kestorigin,kestdestination} + R5SUSP_{iparticle,kestorigin,kestdestination}) = 1$$

For every combination of origin subestuary and destination subestuary, *R5* and *R5SUSP* are determined using the DHI model suite for each of a number of constituent grainsizes under each of a number of environmental conditions (e.g., tides, winds). A separate DHI simulation is run for each origin subestuary. Each DHI simulation duration is one day (2 complete tidal cycles), and each simulation begins with estuarine sediments in the subestuary at hand stationary (i.e., on the bed).

R5 is evaluated at the end of each one-day timestep. It is averaged over the subestuary, and is dimensionless. *R5* may vary according to grainsize, which permits different grainsizes to disperse independently around the harbour, once released by erosion from the bed sediment.

R5SUSP is evaluated at the end of each one-day timestep. It is averaged over the subestuary, and is dimensionless. *R5SUSP* may vary according to grainsize, which permits different grainsizes to disperse independently around the harbour.

RFS

The term *RFS* governs the fate of sediment that remains in suspension at the end of the resuspension day.

For every combination of origin subestuary and destination subestuary, *RFS* is determined using the DHI model suite for each of a number of constituent grainsizes under each of a number of environmental conditions (e.g., tides, winds). A separate DHI simulation is run for each origin subestuary. Each DHI simulation begins with a unit load of estuarine sediment in suspension in the origin subestuary at hand. Each simulation is run until all of the suspended sediment is accounted for by settlement to the bed (anywhere in the harbour) or loss to a sink.

RFS is averaged over the subestuary, and is dimensionless. *RFS* may vary according to grainsize, which permits different grainsizes to disperse independently around the harbour.

$RFS_{iparticle,kestorigin,kestdestination}$ is the fraction of constituent grainsize *iparticle* that is in suspension in origin subestuary *kestorigin* at the end of the resuspension day and that ultimately gets deposited in destination subestuary *kestdestination*.

Following the application of *RFS* in the USC-3 model, all of the estuarine sediment that was eroded from the bed of each origin subestuary (which cannot include subestuaries designated as tidal creeks, sinks or deep channels) on resuspension day is deposited in a destination subestuary (which can be the same as the origin subestuary, but which cannot be a deep channel).

Following the application of *RFS*, the total mass of estuarine sediment of constituent grainsize *iparticle* deposited in subestuary *kestdestination* is given by:

$$\sum_{kestorigin=1}^{nest}(SEDIMENTMASS_{iparticle,kestorigin} \times R5_{iparticle,kestorigin,kestdestination}) +$$

$$\sum_{kestorigin=1}^{nest}(SEDIMENTMASS_{iparticle,kestorigin} \times R5SUSP_{iparticle,kestorigin,kestdestination} \times$$

$$RFS_{iparticle,kestorigin,kestdestination})$$

3.3 Injection into the harbour of sediments when it rains

3.3.1 Introduction

During and in the immediate aftermath of rainstorms, sediment is eroded from the land.

The USC-3 model does three things each time the long-term weather sequence presents a day on which rainfall occurs. (1) Land-derived sediment loads for that day are evaluated at the base of each subcatchment (BOC). (2) Land-derived sediment loads for that day are evaluated at the edge of the main body of the harbour (EMB). For some outlets, BOC is the same as EMB. For others, sediments have to be transferred through tidal creeks to get to EMB. (3) The sediment loads are discharged from EMB into the main body of the harbour, and dispersed and deposited.

3.3.2 Land-derived sediment loads at BOC

$LANDSEDIMENT\underline{BOC}MASS_{jcatch,iparticle}$ is the sediment load at the base of subcatchment *jcatch* split amongst constituent grainsizes. These loads will vary by rainfall. Here, "BOC" means at the base of the subcatchment.

For the implementation of the USC-3 model in southern Tauranga Harbour, the GLEAMS-TAU model (Parshotam et al., 2009; Elliott et al., 2009) is used to predict sediment runoff from the land. This is presented by the GLEAMS-TAU model as daily sediment loads for each subcatchment split by constituent grainsize. The exact way these are prepared for input into the USC-3 model is described in the next chapter.

3.3.3 Transfer of land-derived sediment loads to EMB

Subcatchment outlets may discharge along the fringes of the main body of the harbour or they may discharge into freshwater creeks. Freshwater creeks may, in turn, drain into the main body of the harbour through relatively extensive tidal creeks, or they may, in effect, discharge directly along the fringes of the main body.

Sediments that pass through tidal creeks that drain into the main body of the harbour may be subjected to flocculation. If the flocs or aggregates so formed are relatively dense, these may settle in the tidal creek before reaching the estuary main body. This results in a so-called “attenuation” – or reduction – of the sediment loads between BOC and EMB. The degree of attenuation depends on the hydrodynamics of the tidal creek, which is largely dependent on the interaction between the freshwater discharge from the land and the saline water. In the extreme case, the freshwater discharge may be so large, under very heavy rainfall, that the tidal creek acts a simple extension of the freshwater drainage network, jetting the sediment load directly into the main body of the estuary.

The aim, then, in this step is to convert $LANDSEDIMENT\underline{BOC}MASS_{jcatch,iparticle}$ into $LANDSEDIMENT\underline{EMB}MASS_{jcatch,iparticle}$. The particular scheme used to accomplish these conversions depends on where the outfall discharges, as follows:

Outfalls that discharge into freshwater creeks that in turn discharge directly into the main body of the harbour

In this case, there is no load attenuation and so $LANDSEDIMENT\underline{BOC}MASS_{jcatch,iparticle} = LANDSEDIMENT\underline{EMB}MASS_{jcatch,\ iparticle}$.

Outfalls that discharge directly into the main body of the harbour

As above, there is no load attenuation and so $LANDSEDIMENT\underline{BOC}MASS_{jcatch,iparticle} = LANDSEDIMENT\underline{EMB}MASS_{jcatch,\ iparticle}$.

Outfalls that discharge into the main body through a tidal creek

The attenuation of the land-derived sediment loads in the tidal creek is now accounted for by applying the factor $RTC_{subestuary,jcatch,iparticle}$, where *subestuary* refers to a subestuary that has been designated as a tidal creek and *jcatch* refers to the subcatchment that discharges into that tidal-creek subestuary.

Table 3.2 summarises the meaning of the term *RTC*. Refer to this table during the following detailed description.

RTC is the fraction of sediment load $LANDSEDIMENT\underline{BOC}MASS_{jcatch,iparticle}$ presented at the base of the subcatchment that passes through the tidal creek and emerges at the edge of the main body of the estuary. *RTC* is dimensionless. Hence:

$LANDSEDIMENT\underline{EMB}MASS_{jcatch,iparticle} = LANDSEDIMENT\underline{BOC}MASS_{jcatch,iparticle} \times RTC_{subestuary,jcatch,iparticle}$.

Note that *RTC* may vary by constituent grainsize, reflecting the influence of particle size on particle dynamics, and by rainfall, reflecting the influence of freshwater discharge on tidal-creek dynamics.

Note that the portion of the sediment load that does not escape from the tidal creeks (i.e., $LANDSEDIMENT\underline{BOC}MASS_{jcatch,iparticle} \times [1-RTC_{subestuary,jcatch,iparticle}]$) is accumulated on the bed of the tidal creek.

3.3.4 Dispersal inside the harbour of sediment loads presented to EMB

Dispersal of land-derived sediments in the harbour on the day they are injected into the harbour (with the freshwater runoff) is accomplished using *R*, *RSUSP* and *RFS*, which are determined by the DHI estuary model suite.

R and *RSUSP* describe sediment dispersal and deposition on the injection day.

RFS describes sediment dispersal and deposition on the days following the injection day.

Table 3.3 summarises the meaning of the terms *R*, *RSUSP* and *RFS*.

Figure 3.2 shows how *R*, *RSUSP* and *RFS* are applied. This also shows the role of *RTC*. Refer to this figure during the following detailed description.

$R_{jcatch,kest,iparticle}$ is the fraction of the land-derived sediment load of constituent grainsize *iparticle* from subcatchment *jcatch* that is presented at EMB and that gets deposited in subestuary *kest* at the end of the injection day.

$RSUSP_{catch,kest,iparticle}$ is the fraction of the land-derived sediment load of constituent grainsize *iparticle* from subcatchment *jcatch* that is presented at EMB and that remains in suspension in subestuary *kest* at the end of the injection day.

The total mass of constituent grainsize *iparticle* injected into the harbour from all subcatchments that comes to be deposited in subestuary *kest* by the end of the injection day is given by:

$$\sum_{jcatch=1}^{ncatch}(LANDSEDIMENTEMBMASS_{jcatch,iparticle} \times R_{jcatch,kest,iparticle})$$

The total mass of constituent grainsize *iparticle* injected into the harbour from all subcatchments that remains in suspension in subestuary *kest* at the end of the injection day is given by:

$$\sum_{jcatch=1}^{ncatch}(LANDSEDIMENTEMBMASS_{jcatch,iparticle} \times RSUSP_{jcatch,kest,iparticle})$$

If *kest* corresponds to a deep channel, $R = 0$ and $RSUSP = 1$, since sediments are not allowed to settle to the bed in deep channels.

R and *RSUSP* between them account for all of the land-derived sediment that is injected into the harbour on injection day. That is:

$$\sum_{kestdestination=1}^{nest}(R_{jcatch,kest,iparticle} + RSUSP_{jcatch,kest,iparticle}) = 1$$

For every subcatchment, *R* and *RSUSP* are determined using the DHI model suite for each of a number of constituent grainsizes under each of a number of environmental conditions (e.g., tides, winds, freshwater discharge). A separate simulation is run for each subcatchment. Each DHI simulation duration is one day (2 complete tidal cycles).

R and *RSUSP* are evaluated at the end of each injection day. They are both averaged over the subestuary and they are both dimensionless. Both *R* and *RSUSP* may vary according to grainsize, which permits different grainsizes to disperse independently around the harbour.

The term *RFS* governs the fate of land-derived sediment that remains in suspension at the end of the injection day. This is the same *RFS* that governs the fate of sediment that remains in suspension at the end of the resuspension day.

Following the application of *RFS* in the USC-3 model, all of the land-derived sediment that was injected from each subcatchment on injection day is deposited in a subestuary (this cannot be a deep channel).

Following the application of *RFS*, the total mass of land-derived sediment of constituent grainsize *iparticle* deposited in subestuary *kestdestination* is given by:

$$\sum_{jcatch=1}^{ncatch}(LANDSEDIMENTEMBMASS_{jcatch,iparticle} \times R_{jcatch,kest,iparticle} \times RFS_{iparticle,kestorigin,kestdestination})$$

3.4 Building the bed-sediment column

In this section, the development of the bed-sediment column is described.

3.4.1 Days it is not raining

If it is not raining on the day at hand, then only any resuspension of estuarine bed sediments by waves and currents is accounted for.

Firstly, the D_{50} grainsize of the bed-sediment active layer is calculated in each subestuary. For homogenous bed sediment (i.e., just one layer), D_{50} is given by:

$$D_{50} = \sum_{iparticle=1}^{nparticle} F_{iparticle} \times D_{iparticle}$$

where $F_{iparticle}$ is the fraction of grainsize *iparticle* in the bed sediment, $D_{iparticle}$ is the diameter of grainsize *iparticle*, and there are *nparticle* constituent grainsizes in the bed sediment.

The same equation for D_{50} holds when the bed sediment is layered but, in order to facilitate calculation, $F_{iparticle}$ is replaced by $FAL_{iparticle}$, which is the fraction of grainsize *iparticle* in the active layer of the bed sediment:

$$FAL_{iparticle} = SEDIMENTMASSAL_{iparticle} / SEDIMENTMASSAL$$

Here, *SEDIMENTMASSAL* is the total mass of sediment (i.e., all grainsizes) in the active layer:

$$SEDIMENTMASSAL = \sum_{iparticle=1}^{nparticle} SEDIMENTMASSAL_{iparticle}$$

and $SEDIMENTMASSAL_{iparticle}$ is the mass of grainsize *iparticle* in the active layer:

$$SEDIMENTMASSAL_{iparticle} = \sum_{ilayer=1}^{nlayersactive} SEDIMENTMASS_{ilayer,iparticle}$$

Here there are *nlayersactive* sediment layers in the active layer and $SEDIMENTMASS_{ilayer,iparticle}$ is the mass of grainsize *iparticle* in layer *ilayer* of the bed sediment:

$$SEDIMENTMASS_{ilayer,iparticle} = F_{ilayer,iparticle} \times SEDIMENTMASS_{ilayer}$$

and $F_{ilayer,iparticle}$ is the fraction of grainsize *iparticle* in layer *ilayer* of the bed sediment.

The erosion depth in each subestuary is found by going into the *ED50* lookup table at the value of D_{50} for the subestuary at hand. *ED50* is selected from the lookup table at the closest value of D_{50} in the table. Through the selection of *ED50* from the lookup table, erosion is made to occur when and where the bed shear stress due to the combined wave and current flow exceeds the critical shear stress for initiation of motion, τ_{critical}. Through D_{50}, the different particle sizes that may constitute the bed sediment interact to govern erosion.

ED50 is converted to a mass of sediment to be eroded from the bed. The mass of sediment eroded from the bed corresponding to *ED50* is given by $SEDIMENTMASS = \rho_{\text{settled}} \times A \times ED50$, where ρ_{settled} is the bulk density of the bed sediment and A is the area of the subestuary in question.

Layers are removed from the sediment column to supply the erosion. A certain number of layers of bed sediment will be released from the bed by the erosion. The mass of sediment contained in each sediment layer is given by $SEDIMENTMASS_{ilayer} = \rho_{\text{settled}} \times A \times THICK_{ilayer}$, where $THICK_{ilayer}$ is the thickness of sediment layer *ilayer*. Hence, *nlayerseroded* sediment layers will be eroded, where:

$$\sum_{ilayer=1}^{nlayerseroded} SEDIMENTMASS_{ilayer} = SEDIMENTMASS$$

The active layer may embrace many layers in the bed sediment, which will have resulted from previous sedimentation/erosion episodes. Erosion is therefore affected by the history of events, in the sense that sediment layers build up over time, and D_{50} takes into account the layering of the bed sediment.

The mass of sediment corresponding to *ED50* is partitioned amongst the constituent grainsizes according to the percentage of each constituent grainsize in the bed sediment. If erosion removes a number of sediment layers from the bed and each layer has a different grainsize composition, then partitioning of the eroded sediment amongst the constituent grainsizes takes into account that layering, as follows:

$$SEDIMENTMASS_{iparticle} = \sum_{ilayer=1}^{nlayerseroded} F_{ilayer,iparticle} \times SEDIMENTMASS_{ilayer}$$

where $SEDIMENTMASS_{iparticle}$ is the mass of sediment assigned to constituent grainsize *iparticle*. Note that:

$$\sum_{iparticle=1}^{nparticle} SEDIMENTMASS_{iparticle} = SEDIMENTMASS$$

For each subestuary, sediment eroded from all the other subestuaries is deposited on the bed using the terms *R5, R5SUSP* and *RFS*, as described previously. The mass to be deposited is converted to a thickness and deposited in a single layer. The proportioning of the deposited-layer thickness amongst the grainsizes is identical to the proportioning of the deposited mass amongst the grainsizes.

3.4.2 Days it is raining

If it is raining on the day at hand, then any resuspension of estuarine bed sediments by waves and currents is accounted for first. Then any injection of land-derived sediments into the harbour is accounted for.

The resuspension of estuarine bed sediments by waves and currents is accounted for as described above, to the point where all the resuspended estuarine sediment has been deposited on the estuary bed (i.e., *RFS* has been applied).

The next steps deal with injection of land-derived sediments into the harbour.

The mass of land-derived sediment of each constituent grainsize *iparticle* that is presented to the edge of the main body of the harbour and that now gets dispersed and deposited in the harbour is given by $LANDSEDIMENT\underline{EMB}MASS_{jcatch,iparticle}$. These loads may already have been attenuated if they passed through a tidal creek on their way from the base of the subcatchment to the edge of the main body of the harbour. Any such attenuation is achieved by applying the term *RTC* as previously described.

The total mass of land-derived sediment that is deposited in each subestuary is determined. This is accomplished by applying the terms *R*, *RSUSP* and *RFS*, as described previously, to $LANDSEDIMENT\underline{EMB}MASS_{jcatch,iparticle}$. The mass to be deposited is converted to a thickness and deposited in a single layer. The proportioning of the deposited-layer thickness amongst the grainsizes is identical to the proportioning of the deposited mass amongst the grainsizes.

Both the injection of land-derived sediments on the day it was raining and the resuspension of estuarine bed sediments, also on the day it was raining, have now been accounted for.

Table 3.1: Summary of the meaning of the terms *ED50*, *R5*, *R5SUSP* and *RFS*.

Term	Applies to	Describes	Varies with	Specified for	Applied at	Special conditions
ED50	Estuary bed sediment	Erosion	Weighted-mean grainsize of bed sediment (D_{50})	Every subestuary	End of resuspension day	Zero in tidal creeks, sinks, deep channels
R5	Estuary bed sediment	Dispersal	Size of constituent particle (D_{con})	Every origin subestuary $\mapsto$ destination subestuary combination	End of resuspension day	Cannot deposit sediment in deep channel
R5SUSP	Estuary bed sediment	Dispersal	Size of constituent particle (D_{con})	Every origin subestuary $\mapsto$ destination subestuary combination	End of resuspension day	All sediment in deep channels is left in suspension
RFS	Estuary bed sediment that is left in suspension by *R5SUSP*	Dispersal	Size of constituent particle (D_{con})	Every origin subestuary $\mapsto$ destination subestuary combination	Until all sediment left in suspension at end of resuspension day deposits or is lost to sink	Cannot deposit sediment in deep channel

Table 3.2: Summary of the meaning of the term *RTC*.

Term	Applies to	Describes	Varies with	Specified for	Applied at
RTC	Land-derived sediment	Attenuation of sediment load in tidal creek	Size of constituent particle (D_{con})	Every sub-catchment that discharges into a subestuary that is defined as a tidal creek	End of injection day

Table 3.3: Summary of the meaning of the terms *R*, *RSUSP* and *RFS*.

Term	Applies to	Describes	Varies with	Specified for	Applied at	Special conditions
R	Land-derived sediment	Dispersal	Size of constituent particle (D_{con})	Every origin subestuary $\mapsto$ destination subestuary combination	End of injection day	Cannot deposit sediment in deep channel
RSUSP	Land-derived sediment	Dispersal	Size of constituent particle (D_{con})	Every origin subestuary $\mapsto$ destination subestuary combination	End of injection day	All sediment in deep channels is left in suspension
RFS	Land-derived sediment that is left in suspension by *RSUSP*	Dispersal	Size of constituent particle (D_{con})	Every origin subestuary $\mapsto$ destination subestuary combination	Until all sediment left in suspension at end of injection day deposits or is lost to sink	Cannot deposit sediment in deep channel

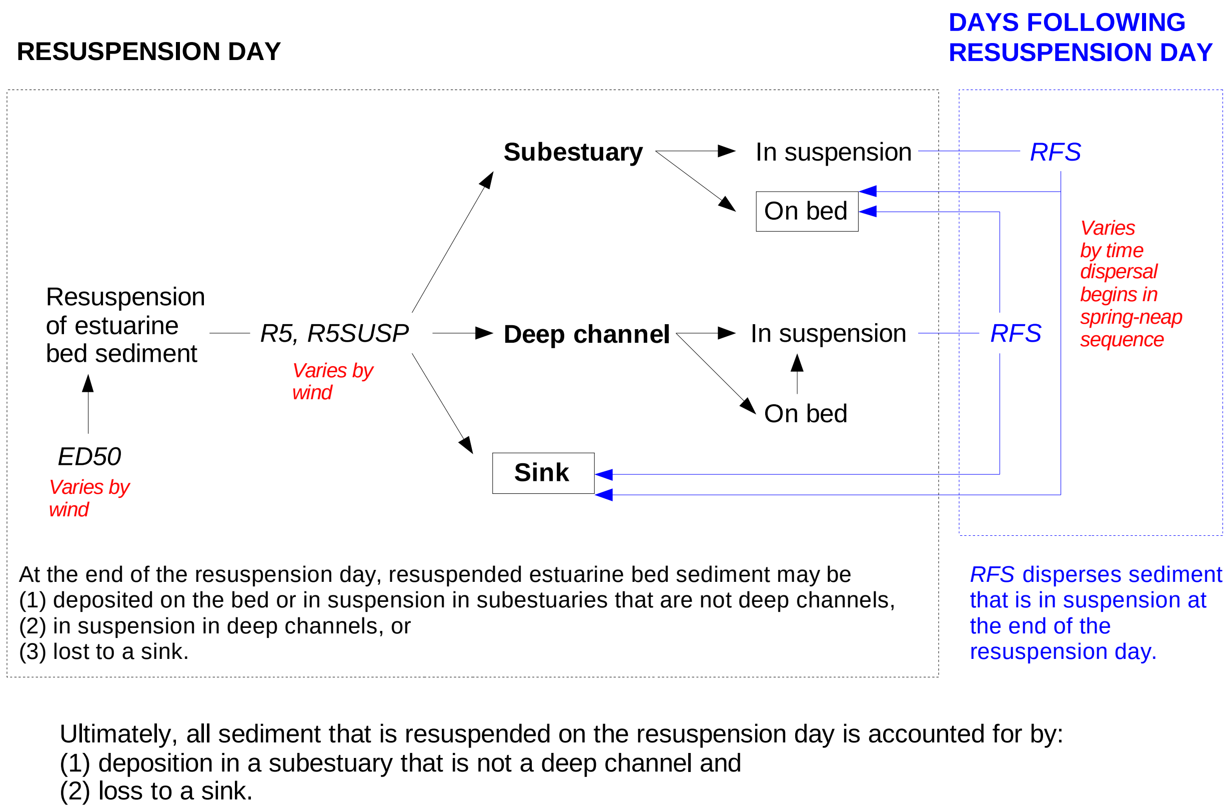


Figure 3.1: Summary of the way the terms *ED50*, *R5*, *R5SUSP* and *RFS* are applied.

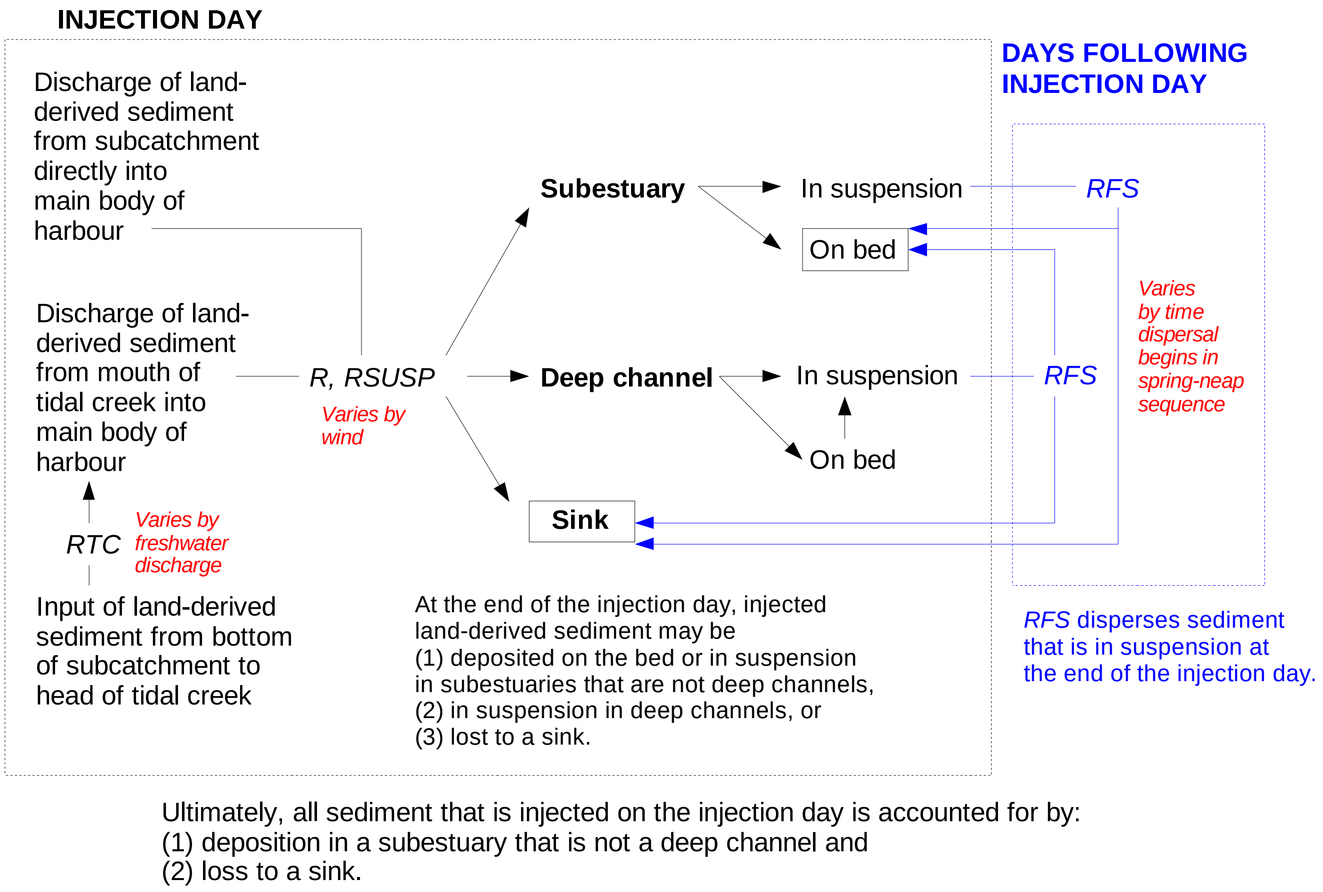


Figure 3.2: Summary of the way the terms *RTC, R, RSUSP and RFS* are applied.

4. Model Implementation

The implementation of the USC-3 model for southern Tauranga Harbour consists of defining subestuaries and subcatchments, evaluating the various terms that control sediment transport and deposition inside the harbour, defining the way land-derived sediments are to be fed into the harbour at the subcatchment outlets, and assembling weather time series for driving the model.

4.1 Subestuaries

- Sediments deposited in tidal creeks may not be subsequently removed by resuspension, and land-derived sediments that pass through tidal creeks are attenuated. For this implementation, there are no tidal creeks.

- Sediments deposited in sinks are removed from the model. Predictions of sedimentation are not made for sinks.

- Sediment is not allowed to deposit in or erode from deep channels. Predictions of sediment accumulation are not made in deep channels.

The original subdivision of southern Tauranga Harbour into subestuaries for the purposes of application of the USC-3 model has been described by Hancock et al. (2009). This original subdivision, which was conceived early in the study, was subsequently modified following a detailed reconnaissance of the harbour in February, 2009. The modified subestuaries are shown in Figure 4.1, and further information is given in Table 4.1. These modified subestuary definitions are used from this point. Refer to Appendix 1 for further information on how original subestuary definitions were modified.

- Subestuary 16–MHR is the middle-harbour sandbanks.

- Subestuary 15–AGR is the embayment at the mouth of the Aongatete River. Sediment discharged from the river is prograding into the embayment, and being colonised by mangroves.

- Subestuary 14–WNR is a dual embayment at the mouth of the Wainui River. The inner embayment is largely choked with mangroves. The outer embayment features complicated sandbanks and islands.

- Subestuary 13–PAH is a sheltered embayment accessed from Pahoia Beach Road. The inner part of the embayment is largely occupied by a centrally-located stand of mangroves, but the mouth of the embayment is open.

- Subestuary 12–WAI is at the mouth of the Waipapa River. There is a depositional lobe associated with the river, and the inner reaches are filled with mangroves.

- Subestuary 23-OMO is the open intertidal flats between the mouth of the Waipapa River and the western shore of Omokoroa Peninsula.

- Subestuary 24–OMI is the sandbank between the eastern shore of Omokoroa Peninsula and the western shore of Motuhoa Island.

- Subestuary 22–MOT is a mid-harbour sandbank that lies to the east of Motuhoa Island.

- Subestuary 11–MGO is Mangawhai Bay Outer, which runs along the east of Omokoroa Peninsula. This is open and flat, and exposed to winds and strong tidal currents.

- Subestuary 20–MGI is Mangawhai Bay Inner. This is enclosed by the East Coast Main Trunk rail line embankment, and is virtually disconnected from the adjoining outer embayment (i.e., 11–MGO, to the east of the rail line). It is an effective sediment trap.

- Subestuary 10–TPO (Te Puna Outer) is partially enclosed by a spit complex at the mouth, and is being colonised by mangroves.

- Subestuary 26–TPI (Te Puna Inner) is the inner pocket of Te Puna estuary that is enclosed by the East Coast Main Trunk rail line embankment. The pocket is reached via Jess Road. It is virtually disconnected from its adjoining outer embayment (to the east of the rail line), and is an effective sediment trap.

- Subestuary 9–WKA is Waikaraka estuary. Like 10–TPO, it is partially enclosed by a spit complex at the mouth, and is being colonised by mangroves.

- Subestuary 21–OIK is a mid-harbour sandbank that lies off Oikimoke Point.

- Subestuary 8–WAR is at the mouth of the Wairoa River. This is an area of extensive, exposed sandflats.

- Subestuary 25–MAT is a small embayment near the mouth of the Wairoa River, formed by the Matua peninsula. It is open but fringed with mangroves.

- Subestuary 7–WKE is Waikareao estuary, which receives runoff from Kopurererua Stream.

- Subestuary 4–WMA is Waimapu estuary, which receives runoff from Waimapu Stream and which is enclosed at the mouth by the SH2 embankment.

- Subestuary 5–TAC is the intertidal flats that run along the Tauranga City foreshore.

- Subestuary 6–WPB is Waipu Bay, which lies across the main channel from the Tauranga City foreshore.

- Subestuary 3–WEL is Welcome Bay. This is fringed by mangroves.

- Subestuary 2–RNC is the central reaches of Rangataua Bay. This receives runoff from a number of streams (including Waitao) and is fringed by mangroves.

- Subestuary 1–SPE is the northeastern intertidal flats of Rangataua Bay, adjacent to the speedway. This is fringed by mangroves, which are thick in places.

- Subestuary 19–HCK is Hunters Creek, which penetrates the southern end of Matakana Island.

- Subestuary 18–RGI lies on the opposite (western) side of Rangiwaea Island from Hunters Creek.

- Subestuary 17–MKI is the intertidal flats that run along the western, central section of Matakana Island.

- Subestuary 27–SPO is the South Pacific Ocean, which is a sink. This designation as a sink is based on the assumption that the bulk of any sediment transported through the mouth of the harbour is dispersed widely. By virtue of its designation as a sink, the offshore region is also prevented from eroding and supplying sediment to southern Tauranga Harbour.

- Subestuaries 28–DCS, 29–DCC and 30–DCN are deep, subtidal channels that convey rapid currents. They can neither accumulate sediment nor supply sediment to the rest of the model domain below the initial "basement" level.

4.2 Subcatchments

The subdivision of the catchment surrounding southern Tauranga Harbour into subcatchments for the purposes of application of the USC-3 model is shown in Table 4.2 and Figure 4.2. Note that the subcatchments used in this report differ from the subcatchment codes used in the GLEAMS-TAU modelling reports (Parshotam et al., 2009; Elliott et al., 2009) by a value of 100. That is, for example, subcatchment 2 in Parshotam et al. (2009) and Elliott et al. (2009) is subcatchment 102 in this report. This change has been made to more readily distinguish between subestuaries and subcatchments.

4.3 Sediment transport in the harbour

Sediment transport in the harbour is evaluated using the DHI estuary model suite, which comprises the DHI Water and Environment (DHI) MIKE3 FM hydrodynamic model, the DHI MIKE3 MT sediment flocculation/transport model, and the SWAN wave model. Together, these simulate tidal propagation within the harbour, tide- and wind-driven currents, freshwater mixing, waves, and sediment flocculation, transport and deposition. SWAN uses the water levels and current fields predicted by the MIKE3 FM model in predicting wind-generated waves. The predicted wave heights, periods and directions are in turn used to quantify wave-induced bed shear stress, which then transports sediments in the MIKE3 MT model.

The DHI model implementation and calibration for Tauranga Harbour are described in Pritchard and Gorman (2009).

The DHI model suite is used to create a library or database of sediment-transport patterns in the harbour, which the USC-3 model then looks up as it does its calculations.

For creating that library, the calibrated MIKE3 MT model was used to simulate the resuspension, transport and redeposition of four sediment grainsizes: 4, 12, 40 and 125 μm. These grainsizes represent: sediment washload / slowly-settling, low-density sediment flocs; fine silt; coarse silt; and fine sand, respectively.

Fall speeds of 0.0001 m/s, 0.001 m/s and 0.01 m/s were assigned to the 12, 40 and 125 μm fractions, respectively. These are Stokes fall speeds assuming sediment density of 2.65 g/m^3 (quartz). Hence, the 12, 40 and 125 μm fractions are implied to be, as a result, in an unaggregated state.

The fall speed for the 4 μm fraction was set at 0.00001 m/s to represent sediment washload and slowly-settling, low-density sediment flocs. 4 μm is a nominal size for this fraction.

4.3.1 Resuspension of estuarine bed sediments by waves and currents

***ED50* (erosion depth on the resuspension day)**

The DHI model suite was used to determine *ED50* for each of four D_{50} grainsizes (4, 12, 40 and 125 μm) and three winds that apply on days it is not raining (calm, NW wind at 6.34 m/s, ENE wind at 6.35 m/s) and five winds that apply on days it is raining (for rainfall 0.9–50 mm: calm, NW wind at 6.34 m/s, ENE wind at 6.35 m/s) (for rainfall > 50 mm: NE wind at 7.12 m/s, SE wind at 7.23 m/s). Wind was chosen to vary because it is the primary control on waves, which in turn control resuspension of bed sediment.

The simulation duration in every case was 1 day (one complete tidal cycle). The tide range for each simulation was fixed (average range).

ED50 for each wind was calculated together with *R5* and *R5SUSP* for the same wind from the one DHI model run. How this was done is described in the next section.

An example of *ED50* by the end of the resuspension day is shown in Figure 4.3 (subestuary 24–OMI, sandbank east of Omokoroa Peninsula). The bed sediment with the smallest median grainsize apparently erodes more than the bed sediments with larger median grainsize. This makes sense, but it is important to realise that *ED50* is really a potential erosion depth, not an actual one. This is because (described in next section) *ED50* is calculated using the DHI model on a subestuary-by-subestuary basis, with the whole harbour apart from the subestuary in question being “concreted”. The actual erosion depth in any given subestuary arises from the combination of erosion in the subestuary in question and deposition of sediment from all other subestuaries in the harbour. It is because the latter is turned off in the DHI model runs used to determine *ED50* that *ED50* so calculated is not actual. (Of course deposition is accounted for in the USC-3 model.) Figure 4.3 shows that winds at the site in question have an effect on *ED50* by the end of the resuspension day, but the particular wind direction does not.

Figure 4.4 compares *ED50* by the end of the resuspension day at an exposed site (subestuary 24–OMI, sandbank east of Omokoroa Peninsula) with *ED50* at a sheltered site (subestuary 3–WEL, Welcome Bay). There is virtually no resuspension of bed sediment at the sheltered site.

ED50 was determined for each of four D_{50} grainsizes: 4, 12, 40 and 125 µm, which, in effect, creates a lookup table of values that is used by the USC-3 model. When bed-sediment erosion is applied in the USC-3 model, the bed-sediment D_{50} in the subestuary in question is first calculated, and then the lookup table of erosion depths is selected from at the closest corresponding value.

_R5_ and _R5SUSP_ (describe sediment dispersal and deposition on the resuspension day)

The DHI model suite was used to determine *R5* and *R5SUSP* for each of the four D_{con} constituent grainsizes (4, 12, 40 and 125 µm, where 4 µm represents washload / low-density, slowly-settling sediment flocs) and three winds that apply on days it is not raining (calm, NW wind at 6.34 m/s, ENE wind at 6.35 m/s) and five winds that apply on days it is raining (for rainfall 0.9–50 mm: calm, NW wind at 6.34 m/s, ENE wind at 6.35 m/s) (for rainfall > 50 mm: NE wind at 7.12 m/s, SE wind at 7.23 m/s). As mentioned previously, wind was chosen to vary because it is the primary control on waves, which in turn control resuspension of bed sediment.

For each combination of sediment, environmental condition and “origin” subestuary, a separate DHI model run was required.

For each model run, all subestuaries except the origin subestuary were “concreted”. That is, only the bed sediment in the estuary in question was allowed to erode. (If the DHI model were able to simultaneously track sediments from different origin areas in the harbour then this would not be necessary.) The DHI model was run for two complete tidal cycles. Model runs started at high tide and ended at high tide. High tide corresponds approximately to slackwater.

An example of *R5* and *R5SUSP* at the end of the resuspension day is shown in Figure 4.5. Sediment resuspended from subestuary 2–RNC (Rangataua Bay) is seen to spread into the northern sector of Rangataua Bay (1–SPW), Welcome Bay (3–WEL) and beyond (the foreshore along Tauranga City [5–TAC] and Waipu Bay [6–WPB]). Sediment is left in suspension in the deep channels inside harbour, but no sediment is lost outside the harbour mouth by the end of the resuspension day. The different wind directions do not seem to have much effect on the dispersal patterns, presumably because the origin subestuary is more-or-less equally exposed to all wind directions, and no significant residual circulation is set up by the wind.

Note:

- The amount of sediment resuspended in each origin subestuary is given by *ED50*.

- If the destination subestuary corresponds to a deep channel, then *R5* is forced to 0, since sediments are not allowed to settle to the bed in deep channels.

- Sediment may deposit in the same subestuary from which it is resuspended, but this is not reflected in values for *R5*. Instead, *ED50* naturally accounts for this. As a result, $R5_{kestorigin,kestdestination}$ = 0 when *kestorigin* = *kestdestination*. *R5SUSPkestorigin,kestdestination* may be nonzero when *kestorigin* = *kestdestination*.

***R* and *RSUSP* (describe sediment dispersal and deposition on the injection day)**

The DHI model suite was used to determine *R* and *RSUSP* for each of the four D_{con} constituent grainsizes (4, 12, 40 and 125 μm, where 4 μm represents washload / low-density, slowly-settling sediment flocs) and the five winds that apply on days when it is raining (for rainfall 0.9–50 mm: calm, NW wind at 6.34 m/s, ENE wind at 6.35 m/s) (for rainfall > 50 mm: NE wind at 7.12 m/s, SE wind at 7.23 m/s).

For each combination of sediment, environmental condition and origin subcatchment, a separate DHI model run was required.

For each model run, a unit load of suspended sediment was injected in suspension over 24 hours at the subcatchment outfall in question. The injection point was the element in the harbour model closest to the subcatchment outlet. The injected sediment was tracked as the simulation proceeded. All subestuaries in the harbour were "concreted". That is, bed sediment in subestuaries was not allowed to erode. However, land-derived sediment was able to settle and be resuspended from subestuaries, as dictated by the hydrodynamics. The DHI model was run for two complete tidal cycles. Model runs started at high tide and ended at high tide. High tide corresponds approximately to slackwater.

An example of *R* and *RSUSP* by the end of the injection day is shown in Figure 4.6, for land-derived sediment from Matua subcatchment (116–MAT) discharged initially into the Matua subestuary (25–MAT). Most of the sediment is retained in Matua subestuary, but some escapes into the adjacent subestuary at the mouth of the Wairoa River (8–WAR) and beyond into the deep channels. The finer grainsizes escape into the wider harbour, and the coarser grainsizes are retained near the point of discharge. Neither wind direction nor rainfall seem to have much of an effect on the dispersal patterns.

4.3.2 Dispersal of sediment on days following resuspension / injection day

***RFS* (describes sediment dispersal and deposition on the days following the resuspension day)**

The DHI model suite was used to determine *RFS* for each of the four D_{con} constituent grainsizes (4, 12, 40 and 125 μm, where 4 μm represents washload / low-density, slowly-settling sediment flocs) and three tide-range sequences. Tide range was chosen to vary because this has the greatest effect on sediment dispersal over the longer term (i.e., more than one day). Tide range was varied by varying the starting point in the spring-neap cycle (spring–mean–neap…, neap–mean–spring…, mean–spring–mean….).

For each combination of sediment, environmental condition and origin subestuary, a separate DHI model run was required.

A unit load (1000 kg) of sediment was placed in suspension in the origin subestuary at hand at the start of each model run, and tracked until “equilibrium” was attained. This was defined as the time when all (99%) of the suspended sediment could be accounted for by settlement to the bed (anywhere in the harbour where deposition is permitted) or loss to a sink.

At the end of each model run, a sediment budget is constructed, and *RFS* calculated accordingly.

Figure 4.7 shows a comparison between *R5* at the end of the resuspension day and *R5* at equilibrium (i.e., after applying *RFS*) for estuarine sediment resuspended from subestuary 2–RNC (Rangataua Bay). (Note that after application of *RFS* no sediment is left suspended anywhere in the model domain. Hence, there is no sediment in the deep channels, since sediment in deep channels can only be in suspension.) On the days following the resuspension day, sediment that was in the deep channels at the end of the resuspension day is lost outside the harbour mouth. Furthermore, more of the finest grainsize is lost to offshore compared to the coarser grainsizes. This result is typical of sediment resuspended from every subestuary.

Figure 4.8 shows a comparison between *R* at the end of the injection day and *R* at equilibrium (i.e., after applying *RFS*) for land-derived sediment injected from the Matua subcatchment (116–MAT). (Note that after application of *RFS* no sediment is left suspended anywhere in the model domain. Hence, there is no sediment in the deep channels, since sediment in deep channels can only be in suspension.) Similar to *R5*, most of the sediment in the deep channels at the end of the injection day ends up being lost outside the harbour mouth, with more of the finer grainsizes being lost.

4.4 Evaluation of land-derived sediment loads at BOC

The GLEAMS-TAU model provides daily land-derived sediment loads at the base of each subcatchment.

Even though the daily GLEAMS-TAU timestep matches the one-day timestep in the USC-3 model associated with injection of land-derived material into the harbour, there is still some manipulation required to assemble these loads for input into the USC-3 model.

Catchment landuse in both the 55-year future period (2001–2055, which is the period of interest as far as management decisions and policy formulation are concerned) and the 58-year historical period (1943–2001, which is the period for calibrating and validating the USC-3 model) is typically fixed in 10-year blocks for input into the GLEAMS-TAU model. For example, in the future period, landuse may be fixed in each of four 10-year blocks with (for example):

- block 1 representing the period 2001–2010;
- block 2 representing the period 2011–2020;
- block 3 representing the period 2021–2030;
- block 4 representing the period 2031–2040.

The final block, block 5, represents the 15-year period 2041–2055.

The landuse specified in each of these future-period blocks of course reflects proposed development scenarios being considered in the study. (The landuse specified in blocks that span the historical period are based on actual landuse for those times.) In each block, the landuse is fixed.

GLEAMS-TAU is run separately for each block, driven by a (say, for the purposes of this explanation) 50-year daily rainfall time series to create a corresponding 50-year daily sediment runoff time series from each subcatchment. The 50-year rainfall series used to drive the GLEAMS-TAU simulations may be from the past 50 years, on the assumption that future weather will not be that much different to past weather. Alternatively, the 50-year rainfall series may be adjusted to reflect the anticipated changes in climate in future years.

The GLEAMS-TAU model runs are then subsampled to create daily sediment loads from each subcatchment, as follows.

To create the daily sediment loads needed by the USC-3 model for the period 2001–2010, 5 × 2-year sub-blocks are randomly selected from the 50-year GLEAMS-TAU sediment runoff time series from block 1. The selected sub-blocks are placed back-to-back to provide the daily inputs for the 10-year period 2001–2010. This procedure is repeated, randomly selecting 5 × 2-year sub-blocks from each block of GLEAMS-TAU data, until the 55-year daily time series needed to drive the USC-3 model is created.

The advantage to this block-sampling scheme, which is significant, is that the effects on sediment generation of antecedent rainfall and rainfall intensity on the day of generation, both of which can create large variability in the response of the catchment to rainfall, can be captured. For example, sediment yield (sediment generation per unit rainfall) may be higher under intense rainfall after an extended period of dry weather compared to less intense rainfall when the ground is partly saturated. These effects are captured in GLEAMS-TAU, and they get transferred to the USC-3 model by using sequences of GLEAMS-TAU output to drive the USC-3 model. This was not the case in the previous version of the USC model (USC-2), which assigned a fixed sediment runoff to events covering a range of rainfalls.

Extreme sediment-generation events are captured in the 50-year series produced by GLEAMS-TAU (this is the reason GLEAMS-TAU is run for 50 years, even though the landuse typically spans less than that period), but they are not necessarily captured in the USC-3 model by the scheme described this far. To ensure that extreme sediment-generation events do get captured in the USC-3 model, it is run in a "Monte Carlo package". Specifically, the USC-3 model is run *N* times to create *N* sets of predictions for the 55-year future period, where *N* is of the order 10^2. The *N* sets of predictions are averaged to give one set of "average" predictions for the future period, and it is these average predictions that are delivered to the user. Each of the *N* runs of the model is driven by a different time series of sediment runoff from rural sources, randomly constructed as just described. The set of *N* simulations, constructed in this way, will properly account for extreme events, so long as *N* is "large".

4.5 Evaluation of weather time series

The particular sediment dispersal patterns (as represented by *ED50*, *R*, *R5* and *RFS*) that the USC-3 model applies on a daily basis as it does its calculations are determined on the basis of a daily weather time series, which comprises daily rainfall, wind speed and wind direction. That is, a daily weather time series for the period of interest is required to drive the USC-3 model.

The daily rainfall is determined as a by-product of the same block-sampling scheme used to create the daily sediment runoff from the GLEAMS-TAU model output. In effect, each time a daily GLEAMS-TAU sediment runoff is picked out by the sampling scheme, the corresponding daily rainfall is also picked out.

The daily wind (speed and direction) is determined by random sampling from a distribution of winds. The particular winds applied in the DHI model suite to generate the library of sediment-transport patterns in the harbour have already been mentioned. The following probabilities are applied to these winds to form the distribution of winds which is interrogated by the random sampling:

- Days it is not raining:
    - calm – 0.90,
    - NW wind at 6.34 m/s – 0.05,
    - ENE wind at 6.35 m/s – 0.05.
- Days it is raining, and rainfall 0.9–50 mm:
    - calm – 0.85,

    - NW wind at 6.34 m/s – 0.08,
    - ENE wind at 6.35 m/s – 0.07.
- Days it is raining and rainfall > 50 mm:
    - NE wind at 7.12 m/s – 0.5,
    - SE wind at 7.23 m/s – 0.5.

Table 4.1: Characteristics of (modified) subestuaries for the purposes of application of the USC-3 model. The area shown in the table is the total subestuary area.

Code	Subestuary	Area (m^2)	Sink	Tidal Creek	Deep Channel
1 – SPW	Speedway	2,300,000			
2 – RNC	Rangataua Bay	5,000,000			
3 – WEL	Welcome Bay	1,500,000			
4 – WMA	Waimapu	1,500,000			
5 – TAC	Tauranga City foreshore	3,600,000			
6 – WPB	Waipu Bay	3,200,000			
7 – WKE	Waikareao	2,600,000			
8 – WAR	Mouth of Wairoa River	3,234,013			
9 – WKA	Waikaraka	800,000			
10 – TPO	Te Puna (outer)	829,639			
11 – MGO	Mangawhai Bay (outer)	1,926,783			
12 – WAI	Mouth of Waipapa River	1,400,000			
13 – PAH	Pahoia Beach Road	1,300,000			
14 – WNR	Mouth of Wainui River	3,600,000			
15 – AGR	Mouth of Aongatete River	3,400,000			
16 – MHR	Middle-harbour sandbanks	16,400,000			
17 – MKI	Matakana Island	4,800,000			
18 – RGI	Rangiwaea Island	2,400,000			
19 – HCK	Hunters Creek	6,300,000			
20 – MGI	Mangawhai Bay (inner)	473,217			
21 – OIK	Oikimoke Point	3,500,000			
22 – MOT	Sandbank east of Motuhoa Island	1,900,000			
23 – OMO	West of Omokoroa Peninsula	2,600,000			
24 – OMI	Sandbank east of Omokoroa Peninsula	900,000			
25 – MAT	Matua	700,000			
26 – TPI	Te Puna (inner)	770,361			
27 – SPO	Ocean	n/a	✓		
28 – DCS	Deep channel south	n/a			✓
29 – DCC	Deep channel central	n/a			✓
30 – DCN	Deep channel north	n/a			✓

Table 4.2: Division of the catchment into subcatchments for the purposes of application of the USC-3 model. The subcatchment codes shown in this figure are taken from the GLEAMS-TAU modelling reports (Parshotam et al., 2009; Elliott et al., 2009) and they differ from the subcatchment codes used in this report by a value of 100. That is, for example, subcatchment 2 in Parshotam et al. (2009) and Elliott et al. (2009) is subcatchment 102 in this report. This change has been made to more readily distinguish between subestuaries and subcatchments

Code	Subcatchment
101 – MKE	Matakana 1
102 – MMI	Mount Maunganui
103 – PAP	Papamoa
104 – WTO	Waitao
105 – KMK	Kaitemako
106 – WMP	Waimapu
107 – KOP	Kopurererua
108 – WAR	Wairoa
109 – OTU	Oturu
110 – TPU	Te Puna
111 – MGW	Mangawhai
112 – WAI	Waipapa
113 – APA	Apata
114 – WNR	Wainui
115 – AGR	Aongatete
116 – MAT	Matua
117 – MKW	Matakana 2

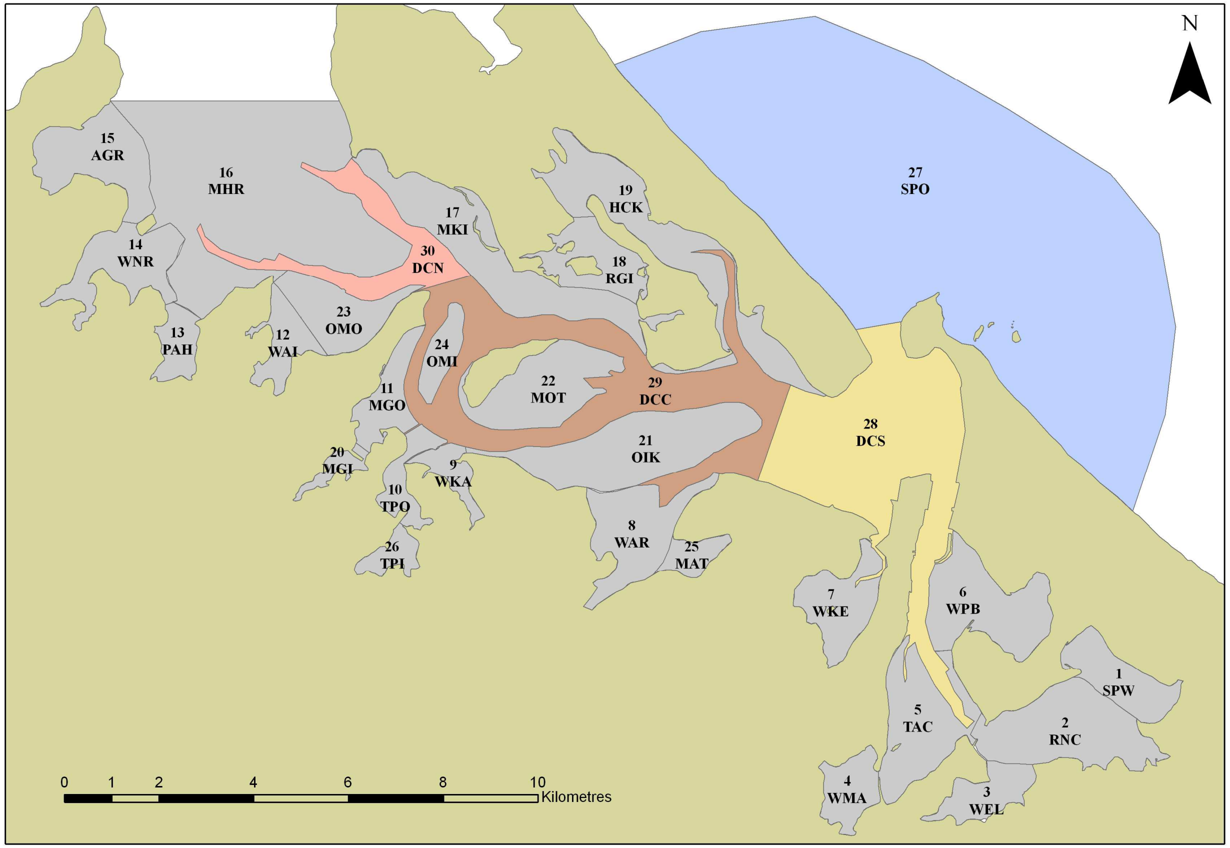


Figure 4.1: Modified subdivision of the harbour into subestuaries for the purposes of application of the USC-3 model.

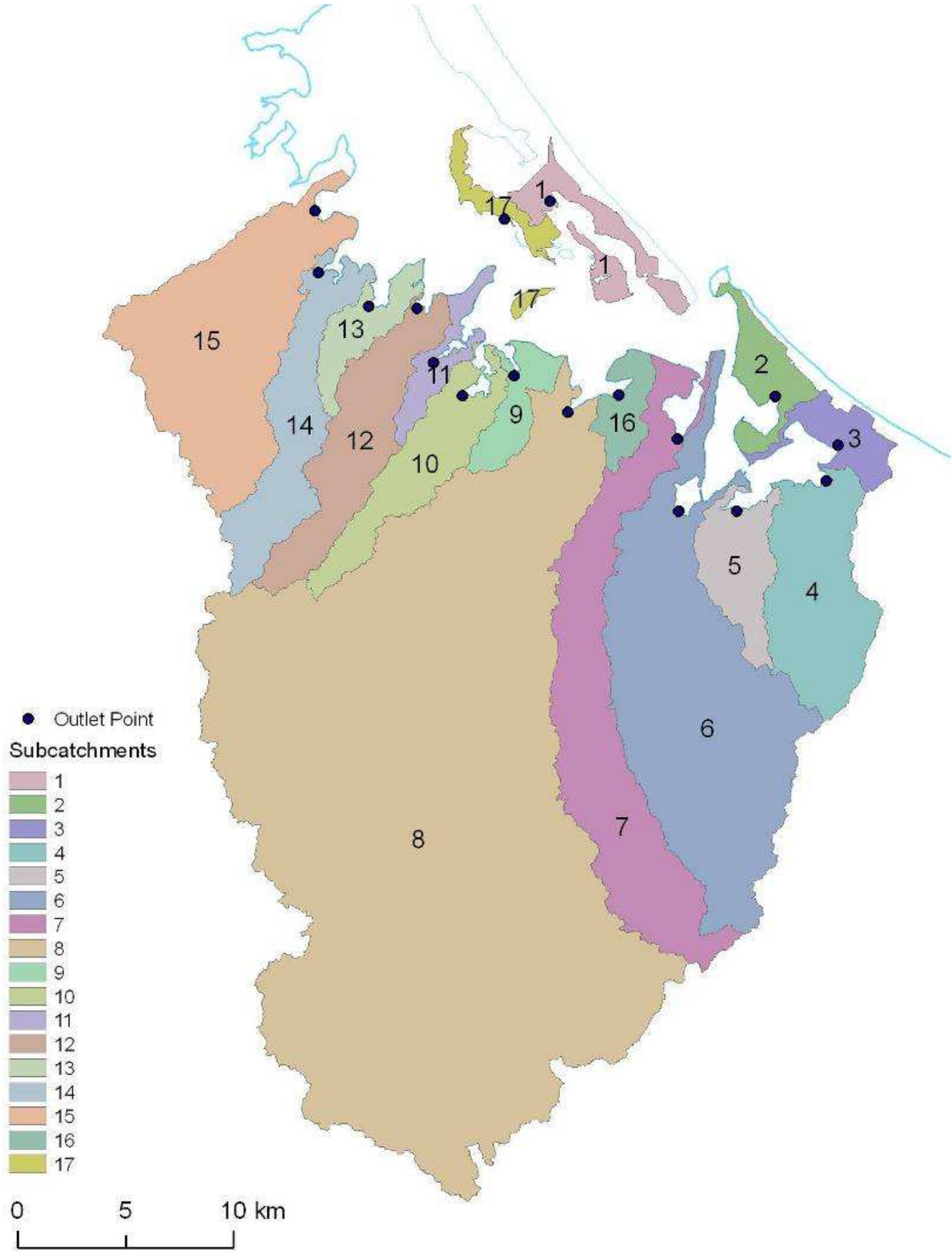


Figure 4.2: Division of the catchment of southern Tauranga Harbour into subcatchments for the purposes of application of the USC-3 model. The subcatchment codes shown in this figure are taken from the GLEAMS-TAU modelling reports (Parshotam et al., 2009; Elliott et al., 2009) and they differ from the subcatchment codes used in this report by a value of 100. That is, for example, subcatchment 2 in Parshotam et al. (2009) and Elliott et al. (2009) is subcatchment 102 in this report. This change has been made to more readily distinguish between subestuaries and subcatchments.

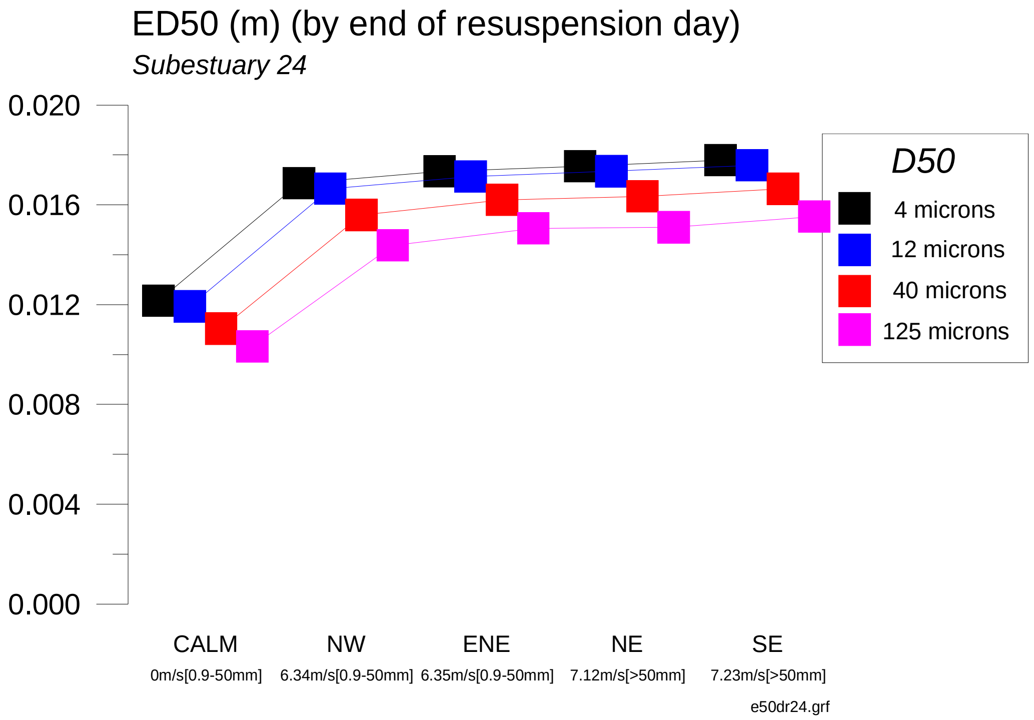
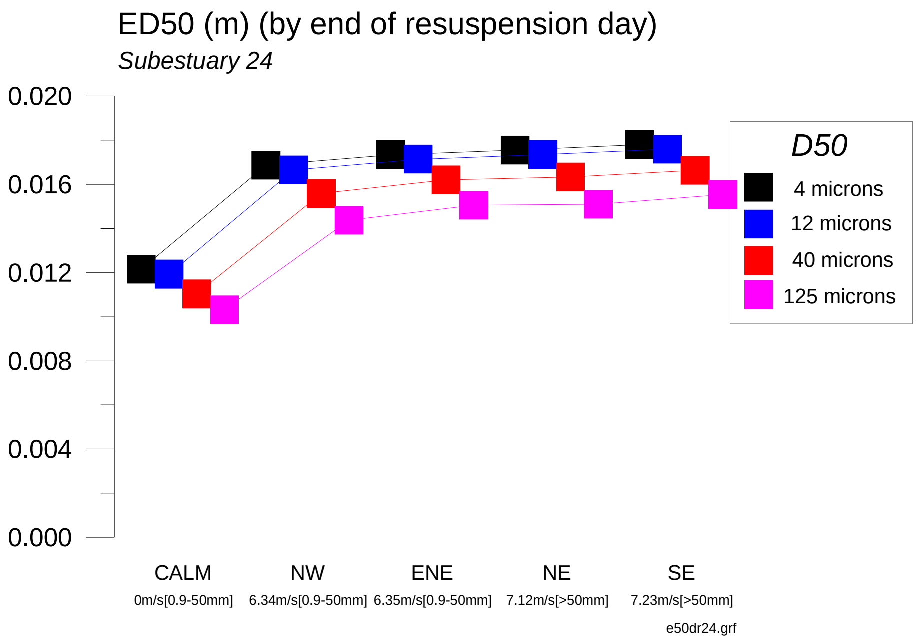


Figure 4.3: *ED50*, subestuary 24–OMI (sandbank east of Omokoroa Peninsula) by the end of the resuspension day.



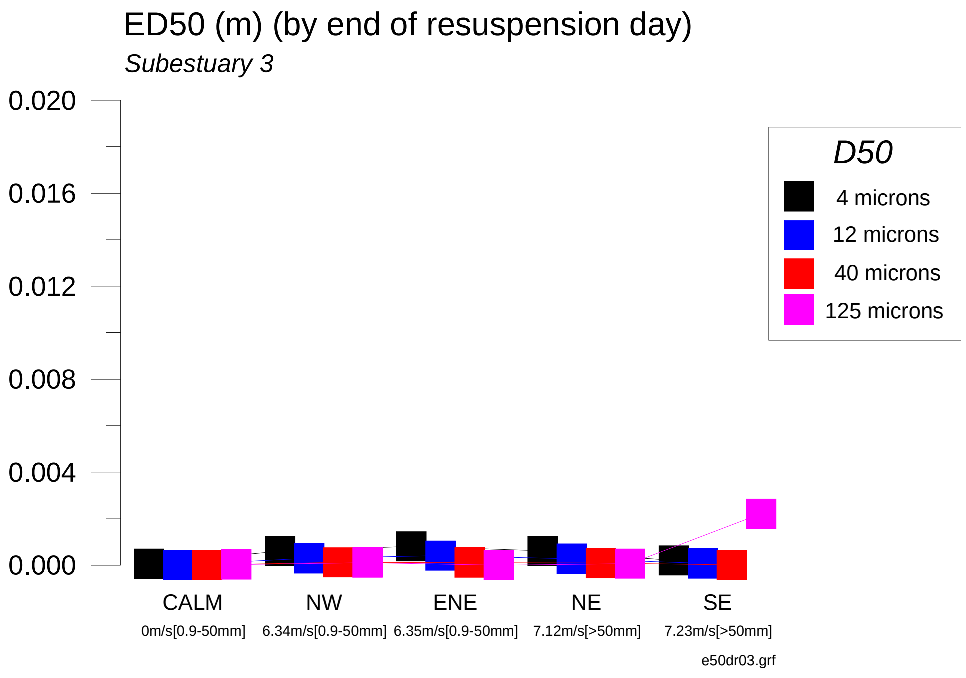


Figure 4.4: Comparison of *ED50* by the end of the resuspension day at an exposed site (subestuary 24–OMI, sandbank east of Omokoroa Peninsula) and a sheltered site (subestuary 3–WEL, Welcome Bay).

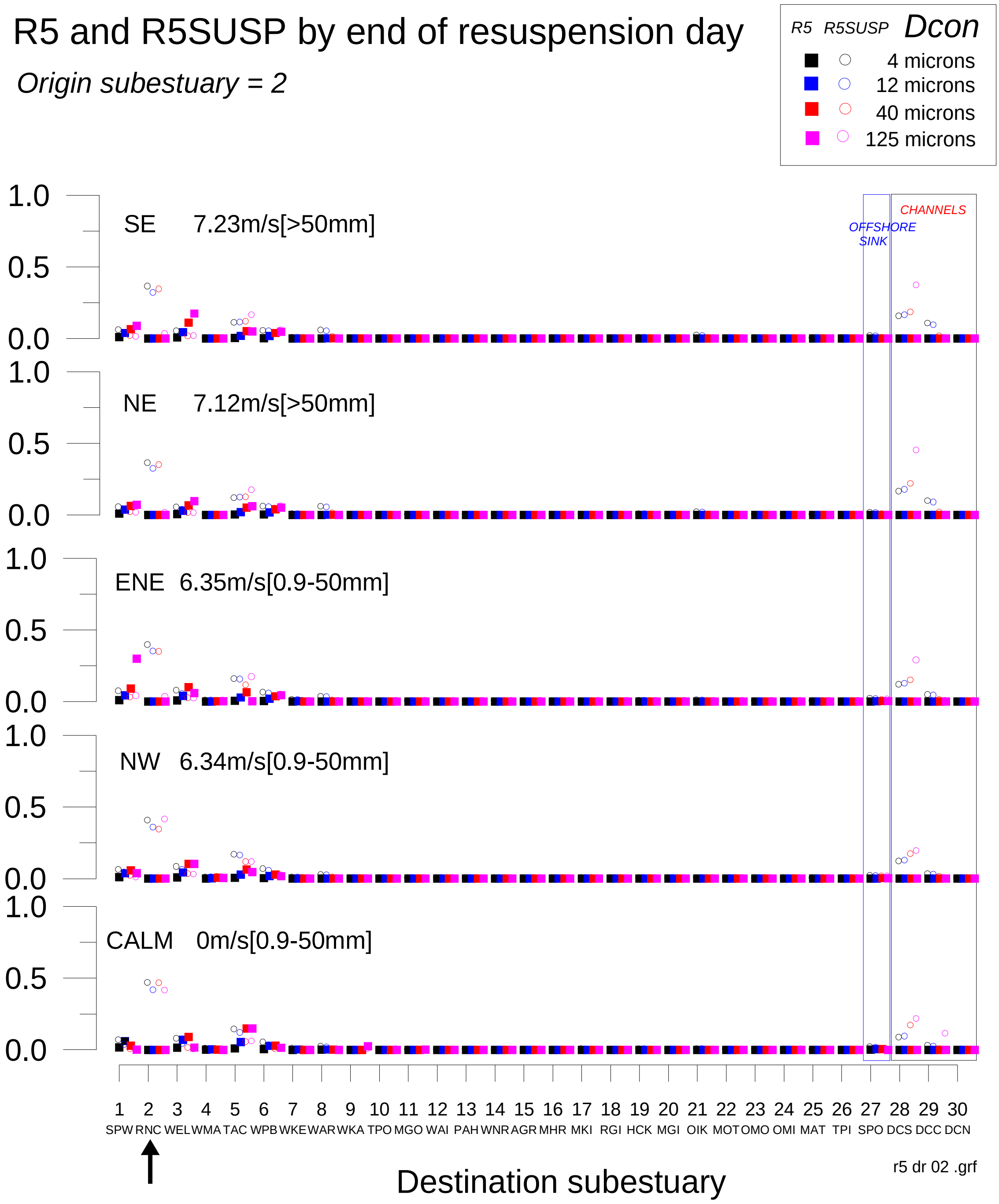


Figure 4.5: *R5* and *R5SUSP* (dimensionless) showing the dispersal of estuarine bed sediment resuspended from subestuary 2–RNC (Rangataua Bay – shown the arrow) by the end of the resuspension day.

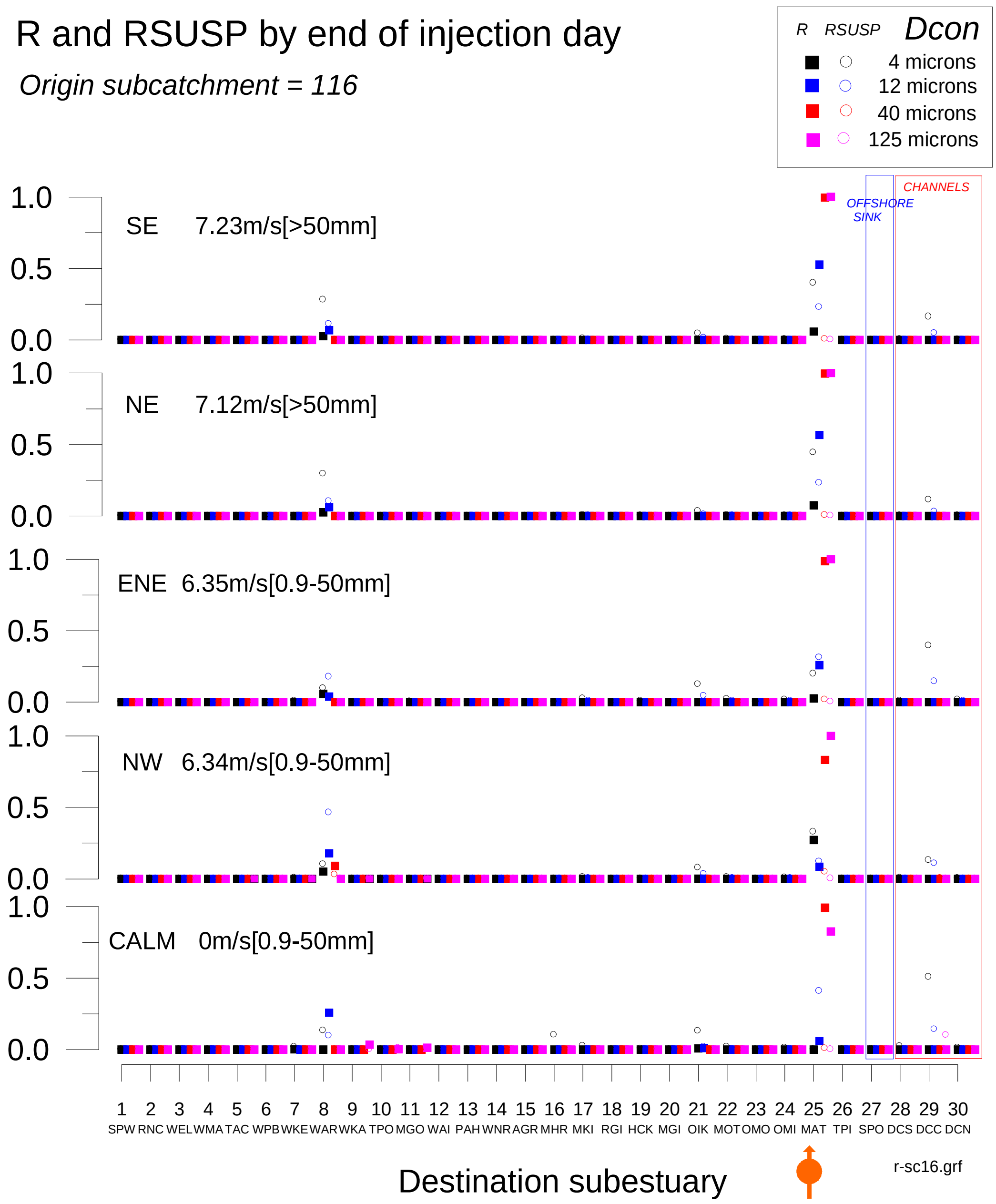


Figure 4.6: *R* and *RSUSP* (dimensionless) showing the dispersal of land-derived sediment injected from subcatchment 116 (Matua – shown the arrow) by the end of the injection day.

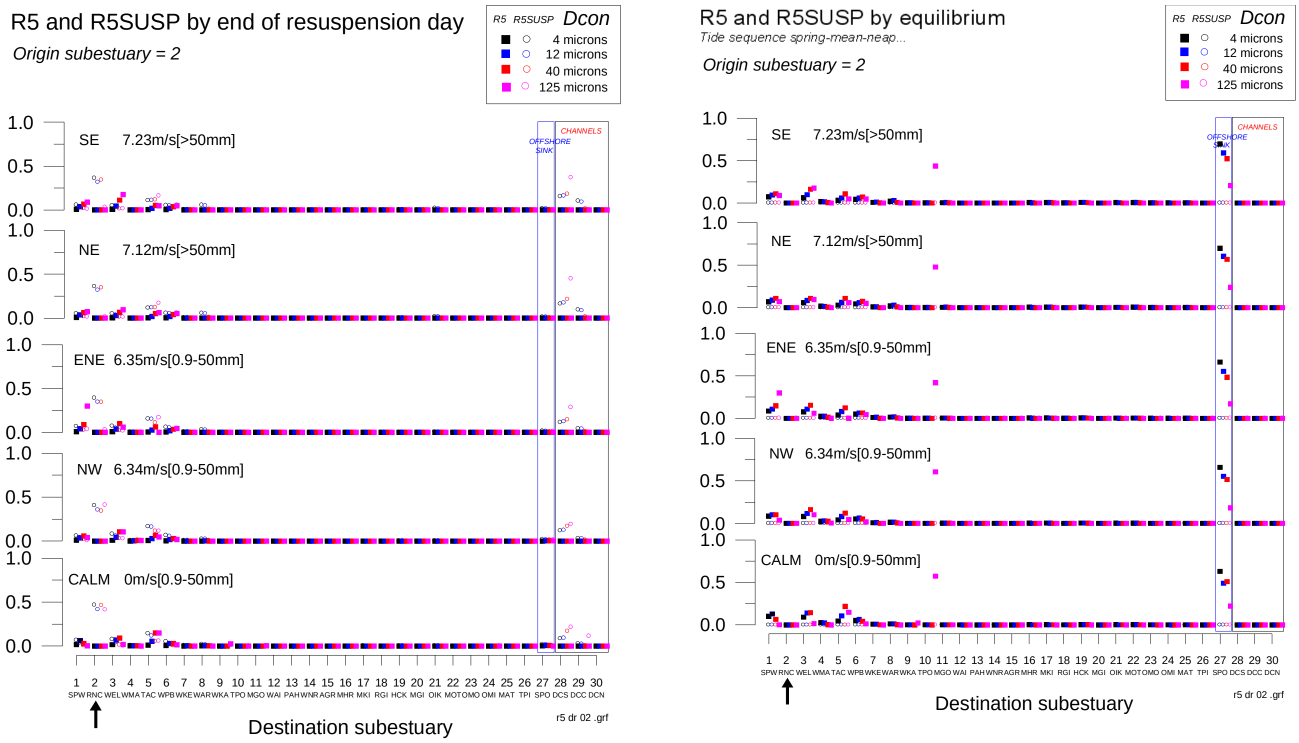


Figure 4.7: Comparison between *R5* at the end of the resuspension day and *R5* at equilibrium (i.e., after applying RFS) for estuarine sediment eroded from the Rangatua Bay (2–RNC) subestuary.

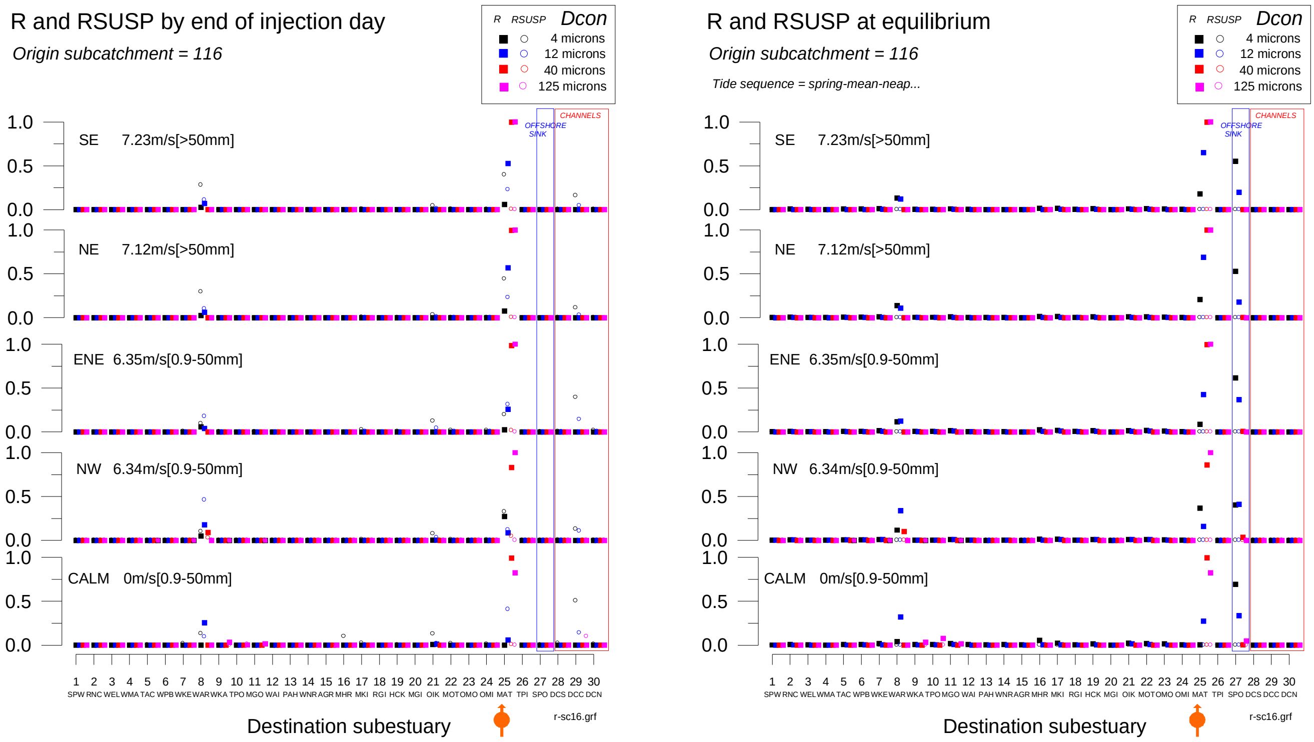


Figure 4.8: Comparison between *R* at the end of the injection day and *R* at equilibrium (i.e., after applying *RFS*) for land-derived sediment injected from subcatchment 116 (Matua – shown by the arrow).

5. Model Calibration

The USC-3 model was run for the 58-year historical period 1943 to 2001, with sediment inputs from the catchment appropriate to that period. The aim of the calibration process was to adjust various terms in the USC-3 model so that its hindcasts ("backward-looking predictions") during the historical period came to match observations from that same period.

For model calibration, the USC-3 model was run in a Monte Carlo package, which consisted of 100 individual USC-3 model runs. The average of the 100 individual model outputs was used in the calibration process.

5.1 Sediment inputs

The block-sampling scheme described in the previous section was applied to the 2001 GLEAMS-TAU model output[2] to produce the daily land-derived sediment loads at the base of each subcatchment for the 58-year historical period (1943–2001).

The split of the GLEAMS-TAU sediment loads by constituent grainsize was based on analysis of samples that were collected from a range of locations in the Kopurererua catchment during a heavy rainfall event on 30–31 July 2008. The sampling locations are shown in Figure 5.1 and Table 5.1. The samples were collected by EBoP using a sample pole to submerge the bottle at a near-surface and a mid-stream (mid-flow) location. As the depth was shallow at all the sites, even in the rain events, this provides a sample representative of the main channel flow. Samples were selected for analysis to represent the upper and lower parts of the catchment and both the rising

[2] The GLEAMS-TAU hindcast sediment loads to the harbour for the historical landuse coverages (1943, 1959, 1973) were significantly different from the 2001 loads (up to 50%). This result was considered to be unrealistic, given the fairly small changes in landuse in the catchment overall. Upon further analysis, it was found that the change in hindcast sediment load was related more to changes in the method of mapping landuse than to actual landuse change. For example, the landuse maps in 1943 have a coarse spatial resolution compared with the 2001 landuse, which introduces artifacts, and the landuse categories for the 1973 landuse data did not translate well to the categories used in 2001. These differences in sediment runoff associated with differences in landuse representation had the potential to result in unrealistic trends in sediment loading to the harbour, and consequent artifacts in the trends of sediment deposition rates. Rather than risk these artifacts, a decision was made to use just the 2001 landuse for hindcasting. This is unlikely to result in significant errors, as the overall change in landuse in the catchment has been modest. While some scrub land has been converted to pasture, and some pasture landuse has been converted to pine plantations, the overall change in the degree of vegetation cover has not been great. Moreover, it was found in simulations of future landuse, that urbanisation makes only a small contribution to the overall sediment load to the harbour; historical urbanisation would also probably have made only a relatively small contribution. For these reasons, it was considered more suitable to use the sediment loads from 2001 for the hindcast simulations.

and falling stages of the hydrograph (Figure 5.2). The samples were analysed to determine particle size distribution using an ANKERSMID EyeTech laser particle sizer. This instrument uses a laser, camera and image analysis to measure and count particles as suspended sediments are pumped through a continuous flow cell. In this way, many particles are counted and robust grainsize statistics are provided. Samples were counted for 300 seconds after disaggregation by ultrasound. Mean grainsize by volume was determined for each sample, as well as the percentage distribution in the grainsize classes <8 μm, 8–25 μm, 25–100 μm and >100 μm. (The volume measurement provides the statistic that is most similar to the particle size that would be achieved by sieving, and is the statistic that is most relevant for use in erosion/deposition mass-balance models). The results are shown in Table 5.1 and Figure 5.3. The average particle-size distribution was found to be 18.6% / 17.5% / 49.9% / 14.0% in the classes <8 μm, 8–25 μm, 25–100 μm and >100 μm, respectively.

The split of the GLEAMS-TAU sediment loads at the base of each subcatchment by constituent grainsize was based on this average distribution as follows.

For every subcatchment except 108–WAR (Wairoa), 107–KOP (Kopurererua) and 106–WMP (Waimapu), the average Kopurererua distribution in the size classes <8 μm and 8–25 μm was equated with the constituent grainsizes 4 μm and 12 μm, respectively. Then, the average Kopurererua distributions in the size classes 25–100 μm and >100 μm were added together and the sum was equated with the constituent grainsize 40 μm. The 125 μm constituent grainsize was set to zero. This results in splitting the GLEAMS-TAU sediment loads at the base of every subcatchment except 108–WAR, 107–KOP and 106–WMP into 18.8% / 17.5% / 63.9% / 0% for the 4, 12, 40 and 125 μm constituent grainsizes. The three constituent grainsizes 4, 12 and 40 μm will be referred to collectively throughout the remainder of this report just as "fine sediment". The sediment runoff from every subcatchment except 108–WAR, 107–KOP and 106–WMP therefore consists exclusively of "fine sediment". This will make the interpretation of results considerably simpler.

Bell et al. (2006) reported bedload as a percentage of suspended sediment as being 45% for five divisions of the catchment that drains to Tauranga Harbour. That is, bedload is 31% of the total load. The Kopurererua sampling is biased towards the suspended-sediment load, and the GLEAMS-TAU model does not treat bedload at all. Following Bell et al., a method was developed to include a bedload component in the sediment runoff from just the three largest subcatchments (108–WAR, 107–KOP and 106–WMP). The GLEAMS-TAU loads at the base of each of these subcatchments is assumed to be just the load in suspension. Following Bell et al., the total load is then given by $1.45 \times G$, where G represents the GLEAMS-TAU (suspended) load, and $0.45 \times G$ is the bedload. Hence, the bedload is 0.45/1.45 = 0.31 of the total load; the suspended load is 1.00/1.45 = 0.69 of the total load; and the bedload is 0.45/1.00 = 0.45 of the suspended load. Based on this calculation, 1.00×*G* is assigned to the three constituent grainsizes 4, 12 and 40 μm ("fine sediment", travelling in suspension) as before, and 0.45×*G* is assigned to the 125 μm constituent grainsize ("coarse sediment", travelling as bedload). This gives a total sediment runoff of 1.45×*G* (sum of suspended load and bedload) for 108–WAR, 107–KOP and 106–WMP.

Figure 5.4 shows daily sediment runoff (sum of all grainsizes) versus daily rainfall constructed from one example time series constructed as just described, which demonstrates variability in response of the catchment to rainfall, which is captured in the model.

Table 5.2 show the annual-average fine-sediment runoff from each subcatchment. The largest sediment runoff is from the Wairoa River subcatchment (108–WAR) and the smallest is from Matakana 1 (101–MKE). Generally, more sediment comes from the larger subcatchments. In addition, more sediment comes from the subcatchments that discharge to the western shoreline of the harbour (which are steeper) compared to the subcatchments that discharge to the eastern shoreline (which are flatter).

Table 5.3 shows the annual-average coarse-sediment runoff from each subcatchment. As explained previously, coarse sediment is presumed to originate only from the three largest subcatchments (108–WAR, 107–KOP and 106–WMP). Furthermore, the coarse sediment runoff is contrived so that it constitutes about 31% of the total sediment load from those subcatchments.

Figure 5.5 shows the annual fine-sediment runoff from each subcatchment for each year in the historical period 1943–2001. This is the annual runoff averaged over all USC-3 model runs in the Monte Carlo package.

5.2 Grainsize composition of subestuary bed sediments

The grainsize composition of the surface mixed layer in each subestuary in the USC-3 model domain needs to be specified for the start of the historical period to initialise the model. With no information on past conditions available, the present-day grainsize composition, described by Hancock et al. (2009) was applied.

Hancock et al. (2009) provided information on mean grainsize and mean bed-sediment composition across three size classes from surface-sediment samples reported in various literature sources: <63 μm ("mud"), 63–200 μm ("sand") and >200 μm ("gravel"). These classes were dictated largely by the way grainsize information was presented in the various source reports that the information was extracted from, and the classes do not align very tidily with the constituent grainsizes used in this study. Hence, some simplifications were required, as follows.

The measured (i.e., the mean result reported by Hancock et al. from the literature) >200 μm fraction was assigned to a 500 μm constituent grainsize in the model bed sediment. This constituent is not allowed to move in the model, and is included to match the model bed-sediment D_{50} to the measured bed-sediment D_{50}. The measured 63–200 μm fraction was assigned to the 125 μm constituent grainsize in the model. The measured 25–63 μm fraction was divided evenly between the 12 and 40 μm constituent grainsizes in the model. Hence, as a result of this scheme, the 4 μm constituent grainsize, which represents slowly-settling, low-density sediment flocs, is not present initially in the model bed sediment. However, a part of the GLEAMS-TAU sediment runoff is assigned to the 4 μm constituent grainsize, so this grainsize may accumulate in the estuarine bed sediment as the simulation proceeds. However, in practice, this was found not to occur, as this fraction is widely dispersed, and typically is lost to the coastal ocean.

5.3 Results

Although it is possible to adjust more in the calibration process, just one parameter needed to be adjusted in this case to achieve calibration. This was the erosion depth (*ED50*), which was reduced for all values of D_{50} by approximately half across the model domain to achieve a reasonably good match between the set of measured annual-average sedimentation rates and the set of hindcast (1943–2001) annual-average sedimentation rates. There were six reliable measurements of sedimentation rate, from Hancock et al. (2009), available to use in the calibration process. Five of these measurements were derived from radioisotopic dating of sediment cores, and the sixth derived from a study of organochlorine contaminants. It is important to note that the model as a whole is calibrated in this way, against the whole set of sedimentation measurements; in general, it is not possible to calibrate the model subestuary-by-subestuary. The reason is that sediments are exchanged amongst subestuaries, and therefore any particular subestuary cannot be considered in isolation from the rest of the model domain.

The fine-sediment sedimentation rates hindcast by the calibrated model are shown in Figure 5.6 and the coarse-sediment sedimentation rates are shown in Figure 5.7. A brief discussion of these follows. A more comprehensive discussion and analysis requires taking account of sediment-transport pathways, sediment runoff from the land, and proportion of the sediment runoff that gets lost to the coastal ocean, amongst other things. A comprehensive analysis, including the influence of all of these factors, will be given with the model results in Technical Report E2 of the study (Green, M.O., 2009. Tauranga Harbour Sediment Study: Predictions of Harbour Sedimentation under Future Scenarios. NIWA Client Report HAM2009–078).

The following comments relate to hindcast fine-sediment sedimentation rates shown in Figure 5.6:

- Hindcast fine-sediment sedimentation in the central reaches of the harbour to the north of the harbour mouth is zero (region bounded by the yellow line in Figure 5.6, which encompasses 8–WAR, 21–OIK, 22–MOT, 24–OMI, 23–OMO, 16–MHR and 17–MKI). These reaches are scoured by tidal currents and are exposed to locally-generated windwaves that frequently resuspend bed sediments. This prevents the accumulation of fine sediments, and the seabed in these areas is typically hard-packed, clean, rippled sand. The hindcast sedimentation rate of zero in 8–WAR is consistent with Hancock et al.'s (2009) conclusion that the core data from 8–WAR indicate "a highly wave-exposed intertidal flat, with negligible long-term accumulation of fine sediments". The core data from 23–OMO are also consistent with an exposed area where, according to Hancock et al. "long-term accumulation of fine sediments is negligible".

- The hindcast fine-sediment sedimentation rate in subestuary 11–MGO is small. The seabed in this area is also hard-packed sand and it is exposed to winds and strong tidal currents. Hence, it is functionally similar to the central reaches of the harbour (region bounded by dashed yellow line in Figure 5.6 to indicate that similarity).

- Hindcast fine-sediment sedimentation in the central reach of the harbour to the south of the harbour inlet (5–TAC) is also zero. This area is swept by strong tidal currents and the seabed is sandy. The long axis of this area presents a long fetch to northeasterly winds, which generate waves that scour the bed of fine sediments.

- Hindcast fine-sediment sedimentation in 6–WPB is very small. This is close to the mouth of the harbour, which favours loss of fine sediment to the coastal ocean, and it drains a catchment (102–MMI) with a very small sediment yield.

- Both 4–WMA and 7–WKE (bounded by the light cyan line in Figure 5.6) have, on the face of it, surprisingly low hindcast sedimentation rates given that they are virtually impounded and that the sediment runoff from the respective adjacent subcatchments is quite high. However, the respective catchments are also quite large, which means that freshwater runoff will be large and therefore capable of flushing the embayments[3]. Furthermore, both embayments are close to the mouth of the harbour, which favours loss of fine sediment to the coastal ocean. In both 4–WMA and 7–WKE, the hindcast fine-sediment sedimentation rate is similar to Hancock et al.'s reported measured sedimentation rate.

- Hindcast fine-sediment sedimentation in the central, more exposed reaches of Rangataua Bay (2–RNC) is smaller than in the more sheltered fringes, which have experienced rapid mangrove spread in recent years (1–SPW and 3–WEL) (region bounded by red line in Figure 5.6). Rangataua Bay drains subcatchment 104–WTO, which has a high sediment runoff.

- The four northernmost subestuaries in the model (15–AGR, 14–WNR, 13–PAH and 12–WAI, region bounded by pink line in Figure 5.6) have similar hindcast sedimentation rates, which are high compared to elsewhere in the model domain. In each case they deposit sediment mainly from the adjacent subcatchment, as a group they are far from the mouth of the harbour, and tidal currents in this central part of the harbour are relatively weak, all of which favour retention of fine sediment. The measured sedimentation rate reported by Hancock et al. in this region (1.6 mm/year) is similar to but somewhat smaller than the hindcast sedimentation rate in the closest subestuary (2.4 mm/year in 14–WNR). However, Hancock et al.'s core was taken near the boundary of 14–WNR and 16–MHR, where the sedimentation rate can be expected to be smaller. Hancock et al. note that where the core was taken, the radioisotope profiles are "consistent with a wave-exposed intertidal flat environment".

- The hindcast fine-sediment sedimentation rate in 20–MGI is similar to that in the four northernmost subestuaries. However, this subestuary is virtually enclosed by the East Coast Main Trunk rail line and so it is not functionally similar to that group of subestuaries. Subestuary 26–TPI is also enclosed by the rail line, and this subestuary features the highest hindcast sedimentation rate. (These subestuaries are bounded by the orange line in Figure 5.6).

[3] Hancock et al. (2009) suggested that sedimentation in 4–WMA is caused by low sediment inputs from the catchment and energetic wave resuspension of bed sediments. However, the GLEAMS-TAU hindcasts do not support the former claim (subcatchment 106, which drains into subestuary 4–WMA, has the second-largest sediment runoff of all subcatchments in the historical period), and the embayment is small and enclosed, which will limit the growth of waves.

- Subestuary 10–TPO and 9–WKA (bounded by the blue line in Figure 5.6) are both partially enclosed by a spit complex at the mouth, are both small, and both drain small catchments. The hindcast fine-sediment sedimentation rate is intermediate between the sedimentation rate in the respective impounded headwaters and the sedimentation rate in the central reaches.

- The hindcast fine-sediment sedimentation rate in the two subestuaries enclosed by Matakana Island (18–RGI and 19–HCK, region bounded by black line in Figure 5.6) is small. The sediment runoff from the respective adjacent subcatchments (117 and 101) is small. Hancock et al.'s core data indicate a sedimentation rate of 1.3 mm/year, which is much larger than the hindcast fine-sediment sedimentation rate. A possible explanation is that the core was taken in a localised depositional sink, although care was taken in the sampling to avoid that situation. A more likely conclusion is that the model is not performing well in this area.

The hindcast coarse-sediment sedimentation rates are shown in Figure 5.7. Coarse sediment was only discharged from the three largest subcatchments in the model domain (108–WAR, 107–KOP and 106–WMP), and it was found that the coarse sediment so discharged was not dispersed in the model to other subestuaries beyond the subestuary at the base of each respective subcatchment, although a small fraction of the coarse sediment runoff did escape to the coastal ocean. Hindcast coarse-sediment sedimentation rates are shown in Figure 5.7:

- The hindcast coarse-sediment sedimentation rate was 3.2 mm/year in subestuary 8–WAR at the mouth of the Wairoa River, and 2.4 mm/year in subestuary 25–MAT, which is immediately adjacent. Hancock et al. were not able to establish a sedimentation rate there (although they did conclude that fine sediments do not accumulate in this region, which is consistent with the hindcast fine-sediment sedimentation rate of zero). Given that this part of the harbour is the principal coarse-sediment depositional lobe associated with the Wairoa River the hindcast coarse-sediment sedimentation rate does not seem unreasonable.

- The hindcast coarse-sediment sedimentation rate was 3.7 mm/year in 4–WMA. This is much greater than Hancock et al.'s measured value of 0.8 mm/year. However, Hancock et al. did note that their dating was applied to a "low-density mud layer", and so their result can be interpreted as a fine-sediment sedimentation rate. If that is the case, then it is pleasing that the hindcast fine-sediment sedimentation of 1.1 mm/year is similar to Hancock et al.'s measured value of 0.8 mm/year.

- The hindcast coarse-sediment sedimentation rate was 1.0 mm/year in 7–WKE, which is the Waikareo estuary at the mouth of the Kopurererua River. Added to the hindcast fine-sediment rate of 0.9 mm/year, this gives a total hindcast sedimentation rate of nearly 2 mm/year, which is twice the measured value reported by Hancock et al. The measured rate reported by Hancock et al. in 107–WKE was derived by Burggraaf et al. (1994) by analysis of DDT measurements, and should apply to the total (sum of fine and coarse sediment). Hence, the model is overpredicting the total (fine plus coarse) sedimentation rate by about a factor of two. It may be that the coarse-sediment runoff from the Kopurererua subcatchment is being over-estimated in the model.

Table 5.1: Locations where suspended-sediment samples were taken by EBoP in the Kopurererua catchment during a heavy rainfall event on 30–31 July 2008, together with mean grainsize and particle-size distribution of the samples.

Sample #	Location	Time	Stage	Mean grainsize (µm)	<8 µm (%)	8–25 µm (%)	25–100 µm (%)	>100 µm (%)
4514	SH2	13:25	rising	78	7.1	7.5	55.7	29.7
4515	SH2	22:35	peak	69	8.9	9.1	63.2	18.8
4432	SH29	09:10	rising	33	20.2	21.2	58.6	0.0
4435	SH29	19:25	rising	51	18.7	14.6	52.6	14.1
4437	SH29	23:40	peak	11	55.2	30.3	14.5	0.0
4509	SH29	11:25	late falling	53	13.6	17.5	54.9	14.0
4519	Keenan Rd	12:27	rising	83	11.4	13.5	40.1	35.0
4523	Taumata Rd	12:00	rising	37	13.5	27.2	59.3	0.0
AVERAGE				**52**	**18.6**	**17.6**	**49.9**	**14.0**

Table 5.2: Annual-average fine-sediment runoff, averaged over all the USC-3 model runs in the Monte Carlo package. The left panel shows subcatchments in numerical order; the right panel shows subcatchments ranked by sediment runoff.

Subcatchment	Historical (kg)
101	64,652
102	559,785
103	561,634
104	10,520,966
105	2,070,604
106	18,021,912
107	8,522,896
108	54,260,163
109	457,565
110	6,085,202
111	1,259,846
112	6,311,340
113	4,922,580
114	9,734,132
115	7,116,097
116	267,445
117	318,869

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Subcatchment	Historical (kg)
108	54,260,163
106	18,021,912
104	10,520,966
114	9,734,132
107	8,522,896
115	7,116,097
112	6,311,340
110	6,085,202
113	4,922,580
105	2,070,604
111	1,259,846
103	561,634
102	559,785
109	457,565
117	318,869
116	267,445
101	64,652

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Table 5.3: Annual-average coarse-sediment runoff, averaged over all the USC-3 model runs in the Monte Carlo package.

Subcatchment	Historical (kg)
101	-
102	-
103	-
104	-
105	-
106	8,000,348
107	3,748,525
108	23,882,625
109	-
110	-
111	-
112	-
113	-
114	-
115	-
116	-
117	-

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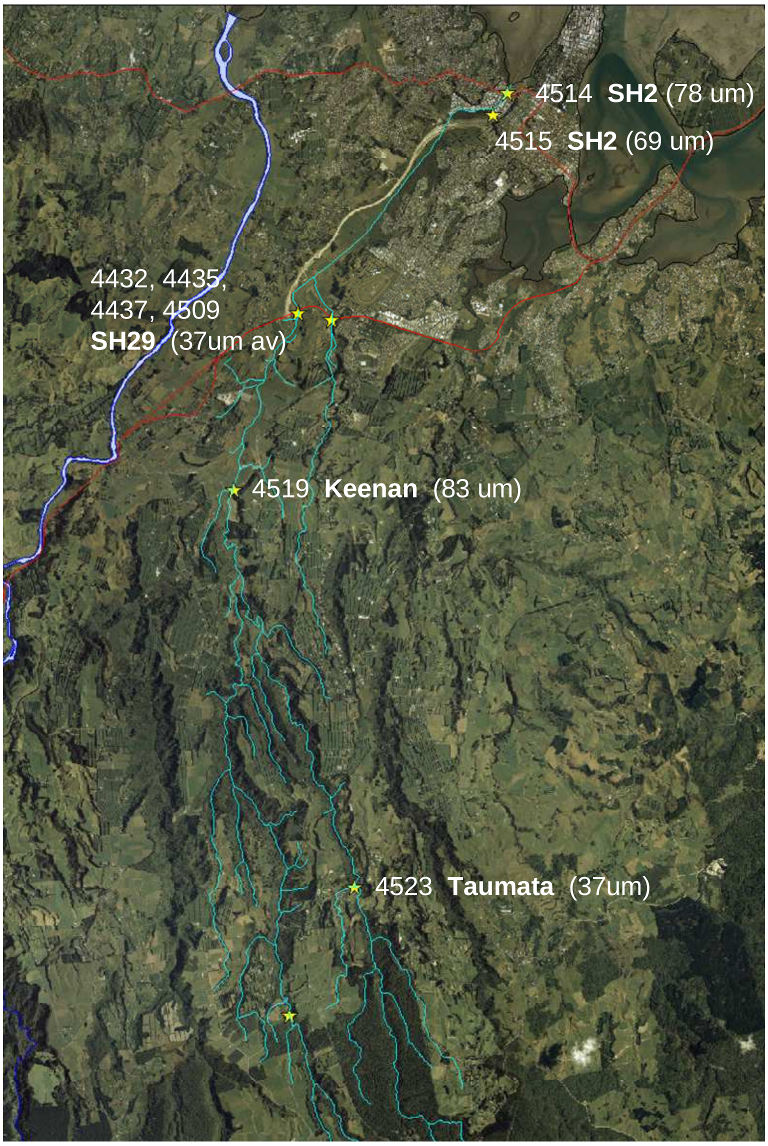


Figure 5.1: Locations where suspended-sediment samples were taken by EBoP in the Kopurererua catchment during a heavy rainfall event on 30–31 July 2008 (yellow stars), and mean grainsize (um = microns) of the samples.

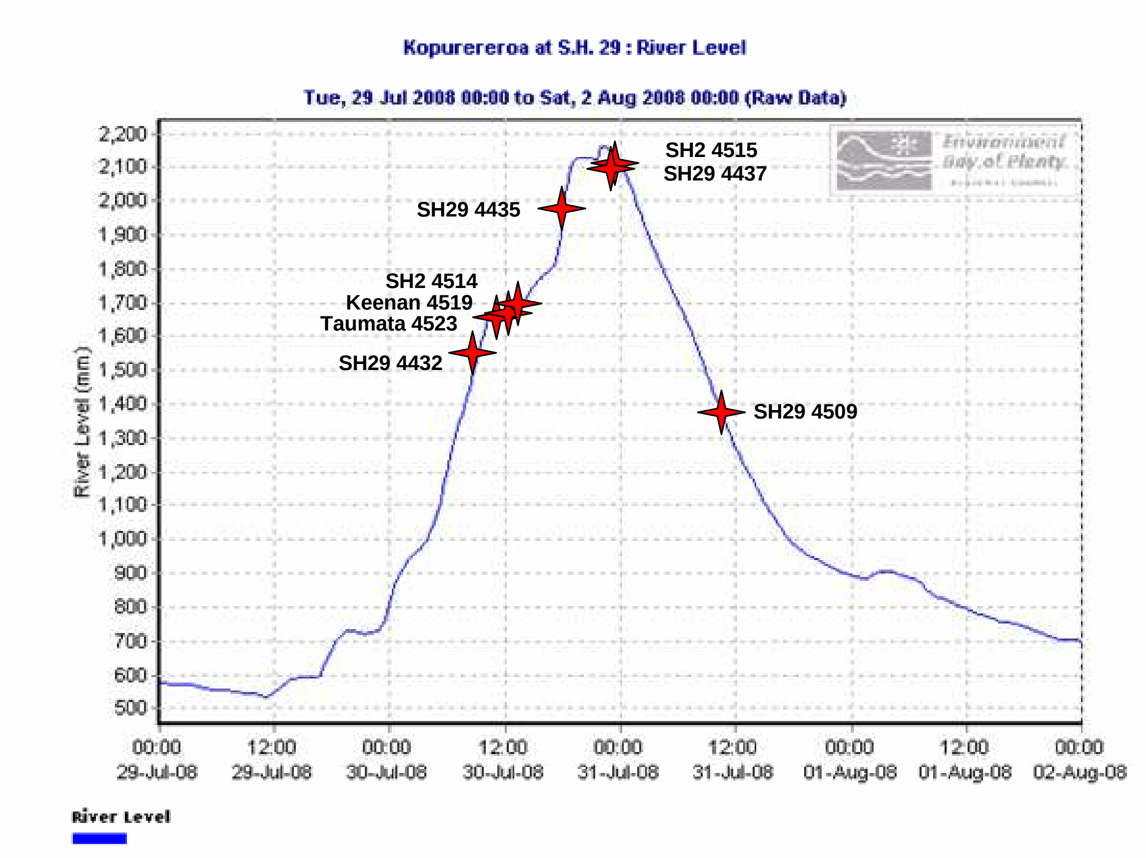
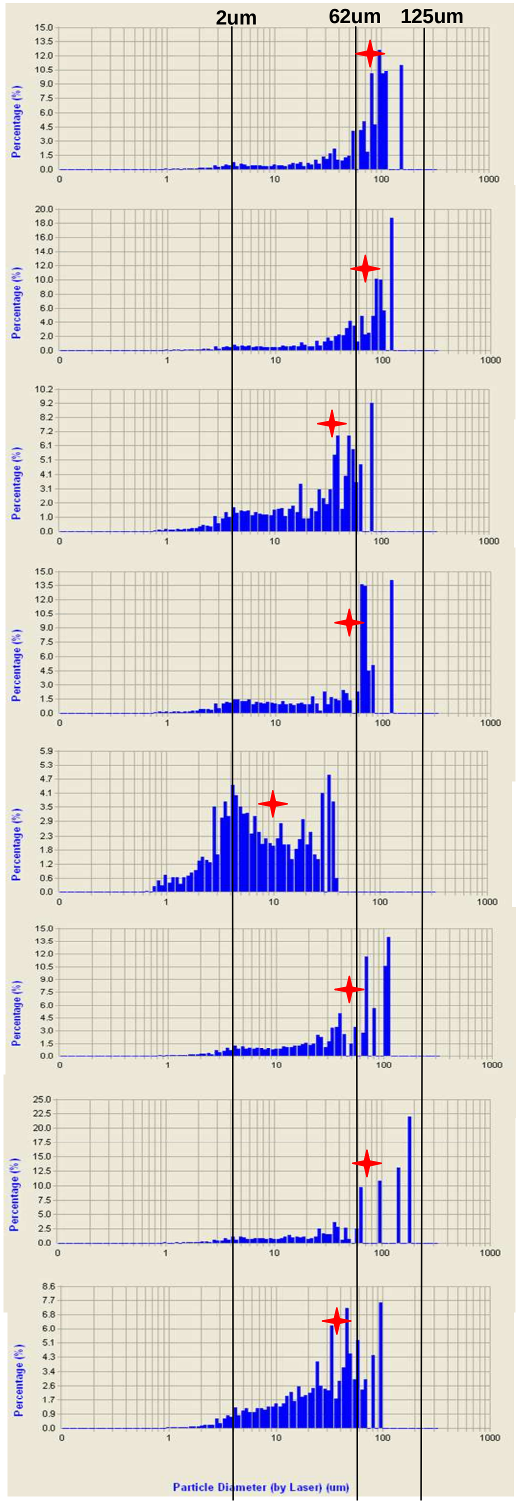


Figure 5.2: Timing of sampling in the Kopurererua catchment with respect to the flood hydrograph at SH29 flow station.



Sample #	Site	Mean grain size (microns)
4514	SH2	79
4515	SH2	69
4432	SH29	33
4435	SH29	51
4437	SH29	11
4509	SH29	53
4519	Keenan	83
4523	Taumata	37

Figure 5.3: Grainsize distributions of Kopurererua samples. The red stars indicate the mean size of the particles in each sample.

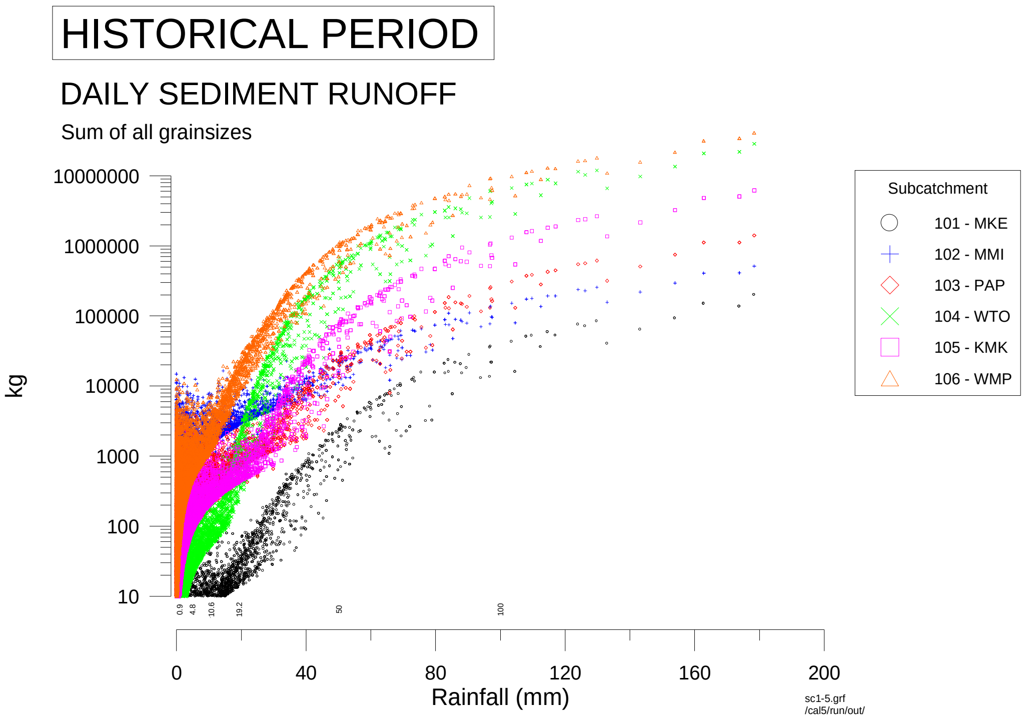


Figure 5.4: Daily sediment runoff (sum of all grainsizes) versus daily rainfall, assembled from an example 58-year historical-period time series of daily sediment runoff constructed to drive the USC-3 model.

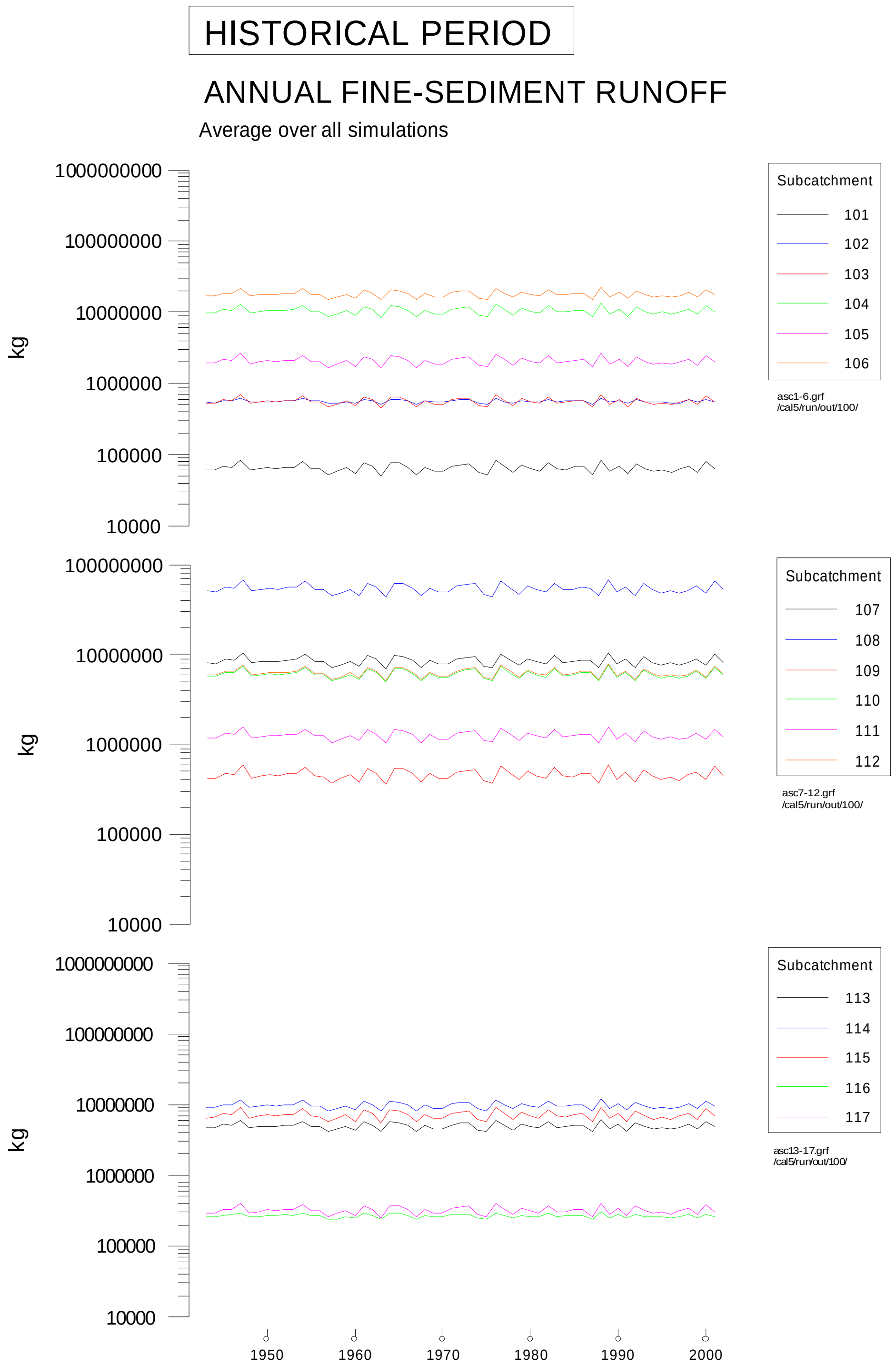


Figure 5.5: Annual fine-sediment runoff from each subcatchment for each year in the historical period. This is the average over all USC-3 model runs in the Monte Carlo package.

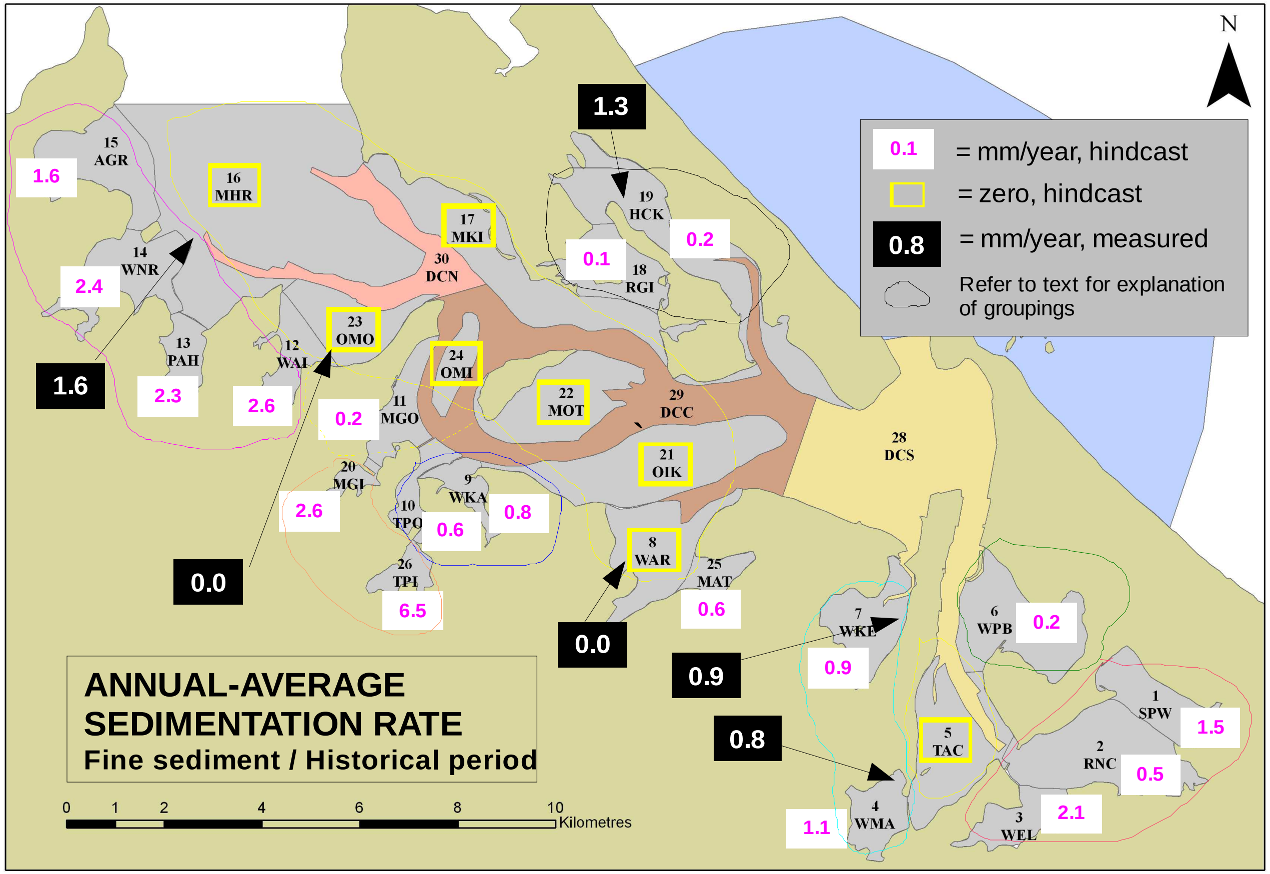


Figure 5.6: Hindcast (by the calibrated USC-3 model) fine-sediment sedimentation rate and measured sedimentation rate (Hancock et al. 2009). The hindcast is the average over all USC-3 model runs in the Monte Carlo package.

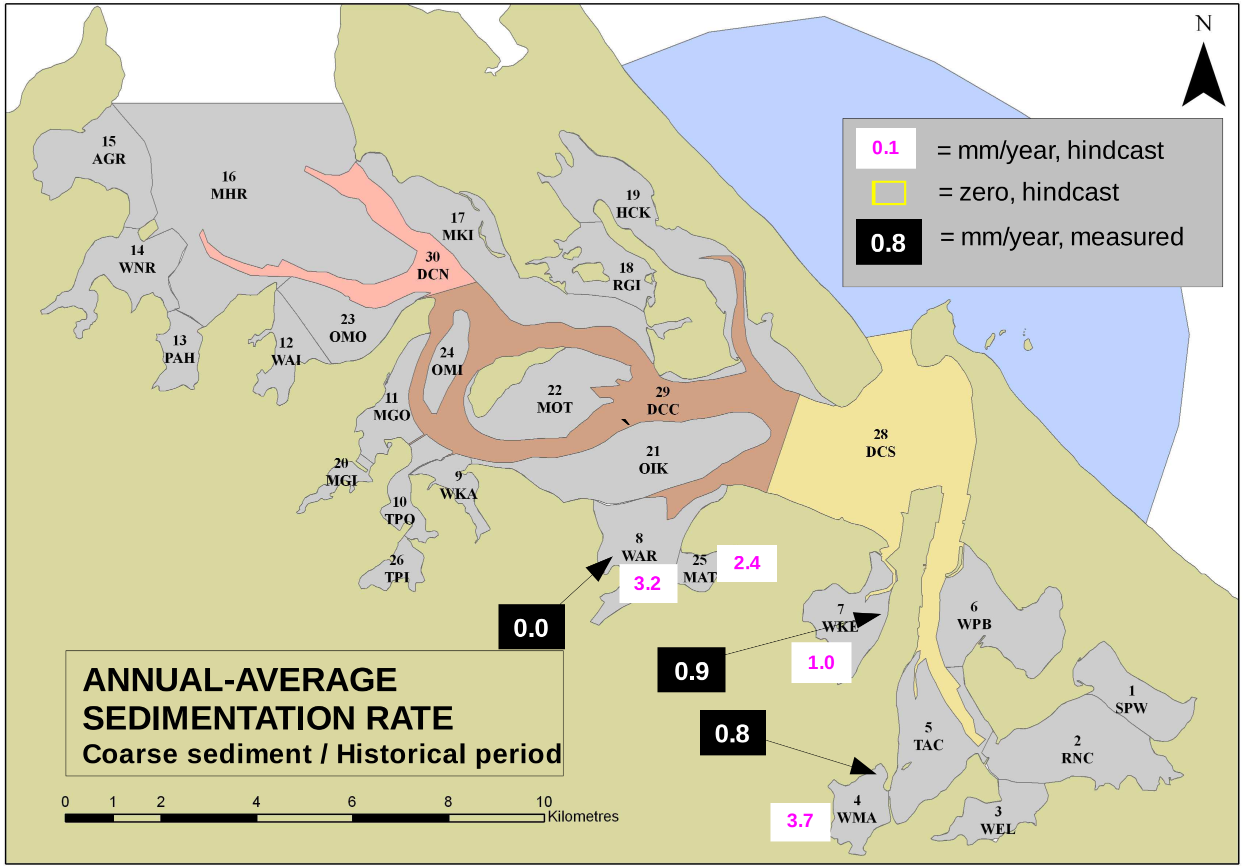


Figure 5.7: Hindcast (by the calibrated USC-3 model) coarse-sediment sedimentation rate and measured sedimentation rate (Hancock et al. 2009). The hindcast is the average over all USC-3 model runs in the Monte Carlo package.

6. Conclusions

The USC-3 model has been implemented for southern Tauranga Harbour and calibrated by reducing the erosion depth for all values of bed-sediment median grainsize by approximately half across the model domain. This resulted in a set of hindcast (1943–2001) annual-average sedimentation rates throughout the model domain that could be interpreted sensibly in broad, physical terms, and that could be reconciled with six reliable measurements of sedimentation rate reported by Hancock et al. (2009). The exceptions were the two subestuaries enclosed by Matakana Island, where the model does not appear to perform very well. The model was calibrated as a whole, against the whole set of sedimentation measurements; in general, it is not possible to calibrate the model subestuary-by-subestuary. The reason is that sediments are exchanged amongst subestuaries, and therefore any particular subestuary cannot be considered in isolation from the rest of the model domain.

Measurements of sedimentation reported by Hancock et al. (2009) confirm the model hindcasts of zero fine-sediment sedimentation in the central reaches of the harbour, including at the mouth of the Wairoa River. However, coarse sediment is hindcast to accumulate in this region, which is the principal coarse-sediment depositional lobe of the Wairoa River. Measured sedimentation is consistent with hindcasts of fine-sediment sedimentation in the vicinity of the four northernmost subestuaries in the model domain. Measured sedimentation in the Waimapu embayment in the south is consistent with hindcasts, assuming that the measurement is of fine-sediment accumulation only, which seems to be the case. The hindcast in the Waikareao embayment is less easy to reconcile with measurement, where the hindcast total (fine plus coarse sediment) sedimentation rate is too large by a factor of two. It may be that the coarse-sediment runoff from the Kopurererua subcatchment is being over-estimated.

Overall, the calibration appears to be satisfactory, and the model can now be used to predict future sedimentation with some confidence.

7. References

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Appendix 1 – Changes Made to Subestuary Definitions

The original subdivision of southern Tauranga Harbour into subestuaries for the purposes of application of the USC-3 model is shown in Figure A1.1, and described further in Hancock et al. (2009).

- Subestuary 16–MHR is the middle-harbour sandbanks.

- Subestuary 15–AGR is the embayment at the mouth of the Aongatete River. Sediment discharged from the river is prograding into the embayment, and being colonised by mangroves.

- Subestuary 14–WNR is a dual embayment at the mouth of the Wainui River. The inner embayment is largely choked with mangroves. The outer embayment features complicated sandbanks and islands.

- Subestuary 13–PAH is a sheltered embayment accessed from Pahoia Beach Road. The inner part of the embayment is largely occupied by a centrally-located stand of mangroves, but the mouth of the embayment is open.

- Subestuary 12–WAI is at the mouth of the Waipapa River. There is a depositional lobe associated with the river, and the inner reaches are filled with mangroves.

- Subestuary 23-OMO is the open intertidal flats between the mouth of the Waipapa River and the western shore of Omokoroa Peninsula.

- Subestuary 24–OMI is the sandbank between the eastern shore of Omokoroa Peninsula and the western shore of Motuhoa Island.

- Subestuary 22–MOT is a mid-harbour sandbank that lies to the east of Motuhoa Island.

- Subestuary 11 is Mangawhai Bay, which runs along the east of Omokoroa Peninsula. Mostly this is open and flat, but it also includes a very sheltered pocket, almost completely closed off from the main embayment by the East Coast Main Trunk rail line embankment.

- Subestuary 10 is Te Puna estuary. It also includes a very sheltered pocket that is almost completely closed off from the main embayment by the East Coast Main Trunk rail line embankment. The pocket is reached via Jess Road. The embayment seaward of the enclosed pocket is partially enclosed by a spit complex at the mouth, and is being colonised by mangroves.

- Subestuary 9–WKA is Waikaraka estuary. It is also partially enclosed by a spit complex at the mouth, and is being colonised by mangroves.

- Subestuary 21–OIK is a mid-harbour sandbank that lies off Oikimoke Point.

- Subestuary 8–WAR is at the mouth of the Wairoa River. This is an area of extensive, exposed sandflats, which extends all the way along the Otumoetai Peninsula.

- Subestuary 25–MAT is a small embayment near the mouth of the Wairoa River, formed by the Matua peninsula. It is open but fringed with mangroves.

- Subestuary 7–WKE is Waikareao estuary, which receives runoff from Kopurererua Stream.

- Subestuary 4–WMA is Waimapu estuary, which receives runoff from Waimapu Stream and which is enclosed at the mouth by the SH2 embankment.

- Subestuary 5–TAC is the intertidal flats that run along the Tauranga City foreshore.

- Subestuary 6–WPB is Waipu Bay, which lies across the main channel from the Tauranga City foreshore.

- Subestuary 26 is a very small pocket at the southern end of the Tauranga City foreshore, adjacent to the eastern side of the SH2 embankment.

- Subestuary 3–WEL is Welcome Bay. This is fringed by mangroves.

- Subestuary 2–RNC is the central reaches of Rangataua Bay. This receives runoff from a number of streams (including Waitao) and is fringed by mangroves.

- Subestuary 1–SPE is the northeastern intertidal flats of Rangataua Bay, adjacent to the speedway. This is fringed by mangroves, which are thick in places.

- Subestuary 20 is a sandbank in the middle of the harbour throat.

- Subestuary 19–HCK is Hunters Creek, which penetrates the southern end of Matakana Island.

- Subestuary 18–RGI lies on the opposite (western) side of Rangiwaea Island from Hunters Creek.

- Subestuary 17–MKI is the intertidal flats that run along the western, central section of Matakana Island.

- Subestuary 27–SPO is the South Pacific Ocean, which is a sink. This designation as a sink is based on the assumption that the bulk of any sediment transported through the mouth of the harbour is dispersed widely. By virtue of its designation as a sink, the offshore region is also prevented from eroding and supplying sediment to southern Tauranga Harbour.

- Subestuaries 28–DCS, 29–DCC and 30–DCN, which are deep, subtidal channels that convey rapid currents, are designated in the model as deep channels.

This original subdivision, which was conceived early in the study, was subsequently modified following a detailed reconnaissance of the harbour in February, 2009. The modified subestuaries are shown in Figure A1.2.

The following notes explain the motivations for the changes made to the subestuaries:

- The inner pocket of Mangawhai Bay (subestuary 11) that is enclosed by the East Coast Main Trunk rail line embankment is virtually disconnected from the outer embayment (to the east of the rail line). Furthermore, the pocket is an effective sediment trap, but the outer embayment is exposed to winds and strong tidal currents. Hence, it makes sense to divide subestuary 11 into two subestuaries, where the rail line crosses.

- The inner pocket of Te Puna estuary (subestuary 10) that is enclosed by the East Coast Main Trunk rail line embankment is also virtually disconnected from its adjoining outer embayment (to the east of the rail line). This pocket is also an effective sediment trap, but the outer embayment will be more active. Hence, it makes sense to divide subestuary 10 into two subestuaries, where the rail line crosses.

- Subestuary 26 is too small relative to the size of the other subestuaries, and is not distinguished in any significant way from subestuary 5–TAC. Subestuary 26 can therefore be disposed of.

- Subestuary 20 is in an energetic part of the harbour where deposition, especially of fine sediments, will be zero. Subestuary 20 can therefore be added to a deep channel.

- The part of subestuary 8–WAR that extends along the Otumoetai Peninsula is more exposed, and quite far removed from the mouth of the Wairoa River.

Given these motivations, the following changes were made:

- Original subestuary 20 was added to subestuary 28–DCS, which is a deep channel.

- Original subestuary 26 was merged with original subestuary 5–TAC.

- Original subestuary 11 (Mangawhai Bay) was divided in two at the rail line and the inner pocket thus divided off (to the west of the rail line) was designated as subestuary 20–MGI (Mangawhai Bay “inner”). The outer part (to the east of the rail line) is subestuary 11–MGO (Mangawhai Bay “outer”).

- Original subestuary 10 (Te Puna) was divided in two at the rail line and the inner pocket thus divided off (to the west of the rail line) was designated as subestuary 26–TPI (Te Puna “inner”). The outer part (to the east of the rail line) is subestuary 10–TPO (Te Puna “outer”).

- The part of subestuary 8–WAR that extends along the Otumoetai Peninsula was removed and added to the adjacent deep channel 28–DCS.

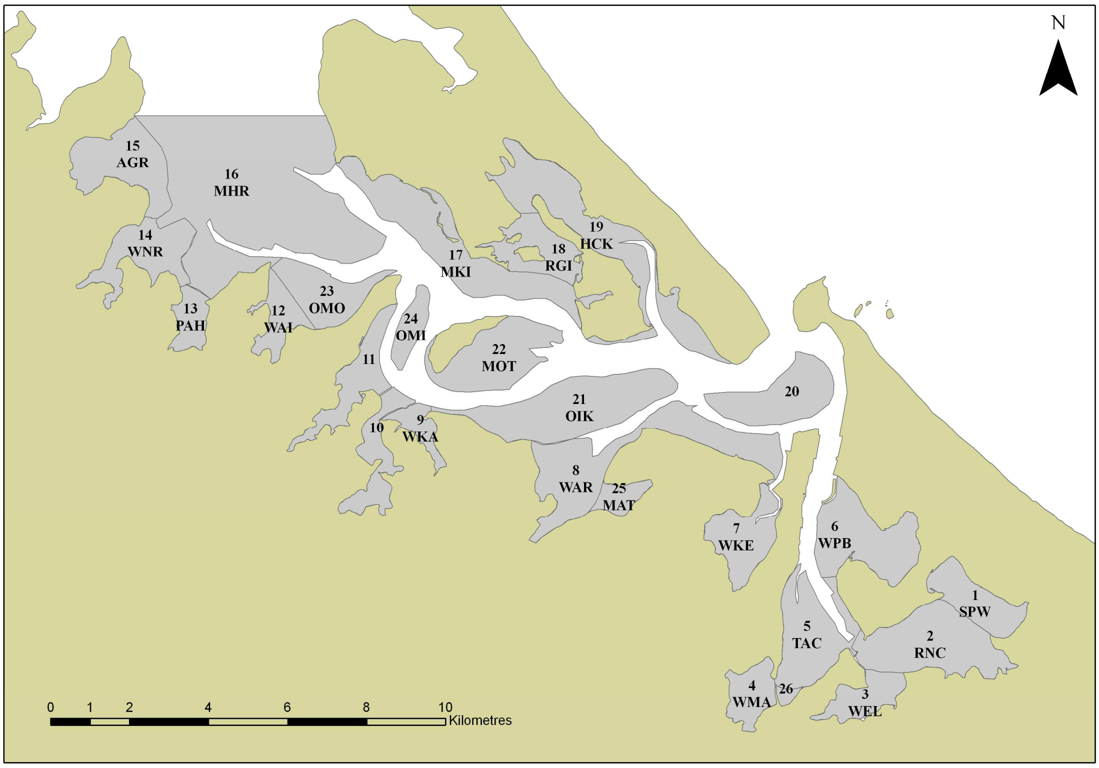

Figure A1.1: Original subdivision of the harbour into subestuaries for the purposes of application of the USC-3 model (after Hancock et al., 2009).

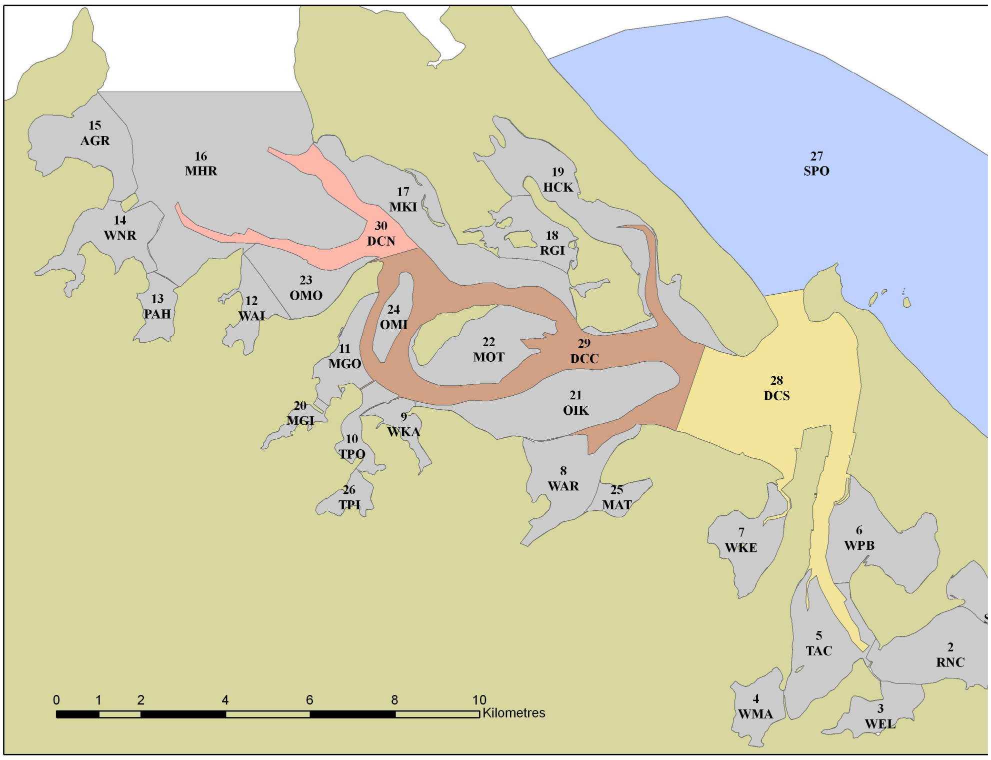

Figure A1.2: Modified subdivision of the harbour into subestuaries for the purposes of application of the USC-3 model.