# Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study: Implementation and Calibration of the USC-3 Model

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# Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study: Implementation and Calibration of the USC-3 Model

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Prepared for
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# PREFACE

The Manukau Harbour is comprised of tidal creeks, embayments and the central basin. The harbour receives sediment and stormwater chemical contaminant run-off from urban and rural land from a number of subcatchments, which can adversely affect the ecology. State of the environment monitoring in the Pahurehure Inlet showed increasing levels of sediment and stormwater chemical contaminant build up. However, previously little was known about the expected long-term accumulation of sediment and stormwater chemical contaminants in the inlet or adjacent portion of the Manukau Harbour. The South Eastern Manukau Harbour / Pahurehure Inlet Contaminant Study was commissioned to improve understanding of these issues. This study is part of the 10-year Stormwater Action Plan to increase knowledge and improve stormwater management outcomes in the region. The work was undertaken by the National Institute of Water and Atmospheric Research (NIWA).

The scope of the study entailed:

1. field investigation,
2. development of a suite of computer models for
    a. urban and rural catchment sediment and chemical contaminant loads,
    b. harbour hydrodynamics, and
    c. harbour sediment and contaminant dispersion and accumulation,
3. application of the suite of computer models to project the likely fate of sediment, copper and zinc discharged into the central harbour over the 100-year period 2001 to 2100, and
4. conversion of the suite of computer models into a desktop tool that can be readily used to further assess the effects of different stormwater management interventions on sediment and stormwater chemical contaminant accumulation in the central harbour over the 100-year period.

The study is limited to assessment of long-term accumulation of sediment, copper and zinc in large-scale harbour depositional zones. The potential for adverse ecological effects from copper and zinc in the harbour sediments was assessed against sediment quality guidelines for chemical contaminants.

The study and tools developed address large-scale and long timeframes and consequently cannot be used to assess changes and impacts from small subcatchments or landuse developments, for example. Furthermore, the study does not assess ecological effects of discrete storm events or long-term chronic or sub-lethal ecological effects arising from the cocktail of urban contaminants and sediment.

The range of factors and contaminants influencing the ecology means that adverse ecological effects may occur at levels below contaminant guideline values for individual chemical contaminants (i.e., additive effects due to exposure to multiple contaminants may be occurring).

Existing data and data collected for the study were used to calibrate the individual computer models. The combined suite of models was calibrated against historic sediment and copper and zinc accumulation rates, derived from sediment cores collected from the harbour.

Four scenarios were modelled: a baseline scenario and three general stormwater management intervention scenarios.

The baseline scenario assumed current projections (at the time of the study) of

- future population growth,
- future landuse changes,
- expected changes in building roof materials,
- projected vehicle use, and
- existing stormwater treatment.

The three general stormwater management intervention scenarios evaluated were:

1. source control of zinc from industrial areas by painting existing unpainted and poorly painted galvanised steel industrial building roofs;
2. additional stormwater treatment, including:
    - raingardens on roads carrying more than 20,000 vehicles per day and on paved industrial sites,
    - silt fences and hay bales for residential infill building sites and
    - pond / wetland trains treating twenty per cent of catchment area; and
3. combinations of the two previous scenarios.

**International Peer Review Panel**

The study was subject to internal officer and international peer review. The review was undertaken in stages during the study, which allowed incorporation of feedback and completion of a robust study. The review found:

- a state-of-the-art study on par with similar international studies,
- uncertainties that remain about the sediment and contaminant dynamics within tidal creeks / estuaries, and
- inherent uncertainties when projecting out 100 years.

**Key Findings of the Study**

Several key findings can be ascertained from the results and consideration of the study within the context of the wider Stormwater Action Plan aim to improve stormwater outcomes:

- The inner tidal creeks and estuary branches of the Pahurehure Inlet continue to accumulate sediment and contaminants, in particular in the eastern estuary of Pahurehure Inlet (east of the motorway).

- The outer Pahurehure Inlet/Southeastern Manukau bed sediment concentrations of copper and zinc are not expected to reach toxic levels based on current assumptions of future trends in landuse and activities.

- Zinc source control targeting industrial building roofs produced limited reduction of zinc accumulation rates in the harbour because industrial areas cover only a small proportion of the catchment area and most unpainted galvanised steel roofs are expected to be replaced with other materials within the next 25 to 50 years.

- Given that the modelling approach used large-scale depositional zones and long timeframes, differences can be expected from the modelling projections and stormwater management interventions contained within these reports versus consideration of smaller depositional areas and local interventions. As a consequence, these local situations may merit further investigation and assessment to determine the best manner in which to intervene and make improvements in the short and long terms.

**Research and Investigation Questions**

From consideration of the study and results, the following issues have been identified that require further research and investigation:

- Sediment and chemical contaminant dynamics within tidal creeks.

- The magnitude and particular locations of stormwater management interventions required to arrest sediment, copper and zinc accumulation in tidal creeks and embayments, including possible remediation / restoration opportunities.

- The fate of other contaminants derived from urban sources.

- The chronic / sub-lethal effects of marine animal exposure to the cocktail of urban contaminants and other stressors such sediment deposition, changing sediment particle size distribution and elevated suspended sediment loads.

- Ecosystem health and connectivity issues between tidal creeks and the central basin of the harbour, and the wider Manukau Harbour.

**Technical reports**

The study has produced a series of technical reports:

Technical Report TR2008/049
Southeastern Manukau Harbour / Pahurehure Inlet Harbour Contaminant Study. Landuse Analysis.

Technical Report TR2008/050
Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study. Sediment Load Model Structure, Setup and Input Data.

Technical Report TR2008/051
Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study. Sediment Load Model Evaluation.

Technical Report TR2008/052
Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study. Sediment Load Model Results.

Technical Report TR2008/053
Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study. Predictions of Stormwater Contaminant Loads.

Technical Report TR2008/054
Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study. Harbour Sediments.

Technical Report TR2008/055
Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study. Harbour Hydrodynamics and Sediment Transport Fieldwork.

Technical Report TR2008/056
Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study. Hydrodynamic Wave and Sediment Transport Model Implementation and Calibration.

Technical Report TR2008/057
Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study. Implementation and Calibration of the USC-3 Model.

Technical Report TR2008/058
Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study. Predictions of Sediment, Zinc and Copper Accumulation under Future Development Scenario 1.

Technical Report TR2008/059
Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study. Predictions of Sediment, Zinc and Copper Accumulation under Future Development Scenarios 2, 3 and 4.

Technical Report TR2009/110
Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study. Rainfall Analysis.

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# 1 Executive Summary

The main aim of the Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study is to model contaminant (zinc, copper) and sediment accumulation for the purposes of, amongst other things, identifying significant contaminant sources, and testing efficacy of stormwater treatment options.

This report describes the implementation and calibration of the USC-3 model for the Study. The model, which functions as a decision-support scheme, 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. Because the USC-3 model makes explicit use of estimates of future heavy-metal and sediment loads from the catchment, it is truly a predictive model compared to, say, simply extrapolating past heavy-metal concentrations in harbour bed sediments. Because future sediment and heavy-metal loads will change according to management practice and policy, model predictions can be used to compare performance of competing development scenarios and to evaluate efficacy of zinc source control of industrial areas. In addition, the model tracks the movement of sediments and contaminants, which enables links between sources (on the land) and sinks (in the estuary) to be identified. This facilitates targeting of management intervention.

The model implementation consists of specifying the sediment particle sizes to be addressed in the model, defining subestuaries and subcatchments, specifying the weather time series used to drive the model, defining the way land-derived sediments and associated heavy metals are to be fed into the harbour at the subcatchment outlets, evaluating the various terms that control sediment and associated heavy-metal transport and deposition inside the harbour, and defining the way heavy-metal concentration in the estuarine bed-sediment surface mixed layer is to be evaluated.

The calibration of the model was achieved by running the model for the historical period 1940 to 2001, with sediment and metal (zinc, copper) 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 its hindcasts of the historical period come to match observations from that same period. The terms that may be adjusted are (1) the fraction of the sediment runoff from the land that is treated as sediment washload / slowly-settling, low-density flocs, (2) the areas over which sediments may deposit, (3) the various terms that control sediment and attached metal dispersal and deposition, and (4) the metal retention factor. Adjustments in these terms are made until realistic sediment dispersal patterns, sedimentation rates and metal accumulation rates are simultaneously obtained.

The metal retention factor *MRF*, which is the fraction of the metal load emanating from each subcatchment that is attached to the corresponding sediment particulate load, is the key calibration parameter. This term is used to reduce the concentration at which metals are delivered to the harbour in the model, and is chosen to yield a time-rate-of-change of metal concentrations over the historical period that ends in target concentrations being achieved. The physical interpretation is that (1 – *MRF* ) represents the proportion of the metal load emanating from the catchment that gets lost

to a dissolved phase and which does not accumulate (by definition) in the estuary bed sediments, and/or (1 – *MRF* ) represents the proportion of the metal load emanating from the catchment that gets attached to very fine particles that never settle and so do not accumulate in the bed of the harbour. The calibrated value of *MRF* was very similar to that arrived at in the calibration of the USC-3 model of the Central Waitemata Harbour, and that value furthermore has some experimental basis. Therefore, the calibration is not implausible.

To demonstrate the performance of the calibrated model, hindcast sediment and metal dispersal patterns are shown and interpreted, hindcast sedimentation rates are compared to measured sedimentation rates, and hindcast metal (zinc and copper) accumulation is compared to measured metal concentrations in estuary bed sediments.

The USC-3 model is ready to make predictions for future catchment development scenarios.

# 2 Introduction

The main aim of the Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study is to model contaminant (zinc, copper) and sediment accumulation for the purposes of, amongst other things, identifying significant contaminant sources, and testing efficacy of stormwater treatment options.

Specifically, the model will be used to:

- predict the accumulation of sediment, zinc and copper in the bed sediments of Pahurehure Inlet (as defined in Figure 1 of the RFP);
- quantify the contributions of these contaminants from the various outfalls throughout the catchment;
- test the effects of stormwater treatment and zinc source control of industrial areas.

The following model predictions for each "inlet compartment" (which are to be decided in consultation with the ARC) are required:

(A) Trends over the period 1950 to 2100 of sediment deposition and copper and zinc concentrations for probable future population growth and urban development in the Pahurehure catchment consistent with the Regional Growth Strategy, without either zinc source control of industrial areas or additional stormwater treatment.

(B) As for (A), but with zinc source control of industrial areas and without additional stormwater treatment.

(C) As for (A), but with additional realistic stormwater treatment and without zinc source control of industrial areas.

(D) As for (A), but with zinc source control of industrial areas and additional realistic stormwater treatment.

(E) For (A) to (D), the mass load contributions of sediment, copper and zinc from each subcatchment.

(F) The year when sediment-quality guidelines (TEL, ERL, PEL and ERM) will be exceeded.

## 2.1 Model suite

The Study centres on the application of a suite of models that are linked to each other:

- The GLEAMS sediment-generation model, which predicts sediment erosion from the land and transport down the stream channel network  Predictions of sediment supply are necessary because, ultimately, sediment eroded from the land dilutes the concentration of contaminants in the bed sediments of the harbour, making them less harmful to biota.

- The Contaminant Load Model (CLM)- a contaminant/sediment-generation model, which predicts sediment and contaminant concentrations (including zinc, copper) in stormwater at a point source, in urban streams, or at end-of-pipe where stormwater discharges into the receiving environment. Note the main distinction between the use of GLEAMS and CLM for estimating sediment generation in this study is that the former is largely used for rural areas and the latter for urban areas. Further details are given in Moores and Timperley (2008).

- The USC-3 (Urban Stormwater Contaminant) contaminant/sediment accumulation model, which predicts sedimentation and accumulation of contaminants (including zinc, copper) in the bed sediments of the estuary. Underlying the USC-3 model is yet another suite of models: the **DHI** Water and Environment **MIKE3 FM HD** hydrodynamic model, the **DHI MIKE3 FM MT** (mud) sediment transport model, and the **SWAN** wave model (Holthuijsen et al. 1993), which simulate harbour hydrodynamics and sediment transport. Combined, these three models can be used to simulate tidal propagation, tide- and wind-driven currents, freshwater mixing, waves, and sediment transport and deposition within a harbour."

## 2.2 This report

This report describes the implementation and calibration of the USC-3 model for the Southeastern Manukau / Pahurehure Inlet Contaminant Study. The model, which functions as a decision-support scheme, 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. The USC-3 model was first developed for the Central Waitemata Harbour Contaminant Study. The development is described in detail by Green (2007); much of the information in that report is reproduced herein for the sake of completeness.

The model implementation consists of specifying the sediment particle sizes to be addressed in the model, defining subestuaries and subcatchments, specifying the weather time series used to drive the model, defining the way land-derived sediments and associated heavy metals are to be fed into the harbour at the subcatchment outlets, evaluating the various terms that control sediment and associated heavy-metal transport and deposition inside the harbour, and defining the way heavy-metal concentration in the estuarine bed-sediment surface mixed layer is to be evaluated. Other information required to drive the model, including harbour bed-sediment initial conditions (e.g.,particle size, metal concentration in the surface mixed layer, subcatchment sediment and metal loads), varies depending on the particular scenario being addressed. This information is not treated as part of the model implementation; instead, it is reported where the scenario model runs are reported.

Model calibration is achieved by running the model for the historical period 1940 to 2001, with sediment and metal 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 sediment/metal dispersal, sedimentation, and zinc and copper accumulation over the historical period come to match observations from that same period.

# 3 Model Description and Overview

## 3.1 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. 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 and contaminant loads in the 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.
- 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 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 environments. 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. 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 Southeastern Manukau Harbour / Pahurehure Inlet.

The USC-3 model requires as inputs estimates of future heavy-metal loads from the land, estimates of future sediment loads and particle sizes from the land, and estimates of the natural metal concentrations on catchment soils. Parameters required by the model include bed-sediment mixing depth in the harbour and bed-sediment active layer thickness in the harbour. 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 particle size distribution of harbour bed sediments and present-day metal concentrations on harbour bed sediments. Assumptions need to be made regarding the association of heavy metals with sediment particulate matter. The model is calibrated against annual-average sedimentation rates in the harbour and metal concentrations in harbour bed sediments.

Because the model makes explicit use of estimates of future heavy-metal and sediment loads from the catchment, it is truly a predictive model compared to, say, simply extrapolating past heavy-metal concentrations in harbour bed sediments. Because future sediment and heavy-metal loads will change according to management practice and policy, model predictions can be used to compare performance of competing development scenarios and to evaluate efficacy of zinc source control of industrial areas.

In addition, the model tracks the movement of sediments and contaminants, which enables links between sources (on the land) and sinks (in the estuary) to be identified. This facilitates targeting of management intervention.

## 3.2 Model overview

The USC-3 model makes predictions of sedimentation, change in bed-sediment composition and accumulation of heavy metals in the surface mixed layer of estuary bed sediments over a 100-year timeframe, given sediment and heavy-metal inputs from the surrounding catchment on that same timeframe.

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 particle size.

The catchment is divided into subcatchments on a similar scale to the subestuaries. 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 and contaminants from the catchment when it is raining. The particular rule that is applied depends on the weather and the tide at the time. Sediment/contaminant 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 and associated contaminants inside the estuary by tidal currents and waves. "Estuarine" sediments and contaminants refers to all of the sediment and contaminant that is already in the harbour on the day at hand, and includes all of the land-derived sediment and contaminant 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 two 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 is 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. 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 simply moves sediment/contaminant between the various subcatchments and various subestuaries each time it rains, and between the various subestuaries to account for the action of waves of tidal currents.

Mass is conserved in the model.

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 sediment column holds both sediments and contaminants.

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 particle sizes (e.g., clay, silt, fine sand, sand). The proportions of the constituent particle sizes 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 particle sizes 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 particle size of the bed sediment that reflects the combined presence of the constituent particle sizes. This has an important consequence: if the weighted-mean particle size of the bed sediment increases, it becomes more difficult to erode, and so becomes "armoured" as a whole. This reduces the erosion of <u>all</u> of the constituent particle sizes, including the finer fractions, which otherwise might be very mobile. The bed-sediment weighted-mean particle size is calculated over the thickness of the bed-sediment "active layer".

In contrast, the individual particle sizes, once released from the bed by erosion and placed in suspension in the water column, are dispersed independently of any other particle size that may also be in suspension. Dispersion of suspended sediments is in fact very sensitive to particle size, which has an important consequence: the constituent particle sizes 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 100-year simulations is 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 contaminant accumulation over the 100-year duration. Each weather sequence in the series is constructed so that long-term weather statistics are recovered.

Heavy metals are "attached" to sediments. Hence, heavy metals are discharged into the estuary when it rains together with the land-derived sediments that are eroded from the catchment. Heavy metals are also eroded, transported and deposited inside the estuary together with the estuarine sediments. Heavy metals are accumulated in the sediment layers that form in the harbour by deposition, and they are placed in suspension in the water column when sediment layers are eroded.

Heavy metals may be differently associated with the different constituent sediment particle sizes. Typically, heavy metals are preferentially attached to fine sediment particles. This means that where fine particles accumulate in the harbour, so too will the attached heavy metals accumulate. On the other hand, there may be certain parts of the harbour where heavy metals are not able to accumulate. Bands of fine sediment in the sediment column may also be accompanied by higher concentrations of heavy metals, and vice versa.

The principal model output is the change through time of the concentration of heavy metal in the surface mixed layer of the estuary bed sediments, which can be compared with sediment-quality guidelines to determine ecological effects.

Concentration of heavy metals in the surface mixed layer is evaluated in the model by taking account of mixing of the bed sediment, which has the effect of reducing extreme concentration gradients in the bed sediment that would otherwise occur in the absence of mixing.

Mixing of the bed sediment is caused by bioturbation and/or disturbance by waves and currents. Any number of layers in the sediment column that have been deposited since the beginning of the simulation may be included in the mixed layer Mixing may also extend down into the pre-existing bed sediment (i.e., the bed sediment as specified by the model initial conditions).

### 3.2.1 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 / contaminant 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 is not acceptable in the case of more 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.

# 4 Model Details

## 4.1 Characteristics of special subestuaries

### 4.1.1 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 and contaminants 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.

### 4.1.2 Sinks

Sediments and contaminants 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.

### 4.1.3 Deep channels

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

## 4.2 Resuspension of estuarine bed sediments by waves and currents

### 4.2.1 Introduction

Every day, estuarine sediments and their associated contaminants 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 and attached contaminants 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 4.1 summarises the meaning of the terms *ED50*, *R5*, *R5SUSP* and *RFS*. Refer to this table during the following detailed description.

Figure 4.1 shows how *ED50*, *R5*, *R5SUSP* and *RFS* are applied. Refer to this figure during the following detailed description.

**Table 4.1:**

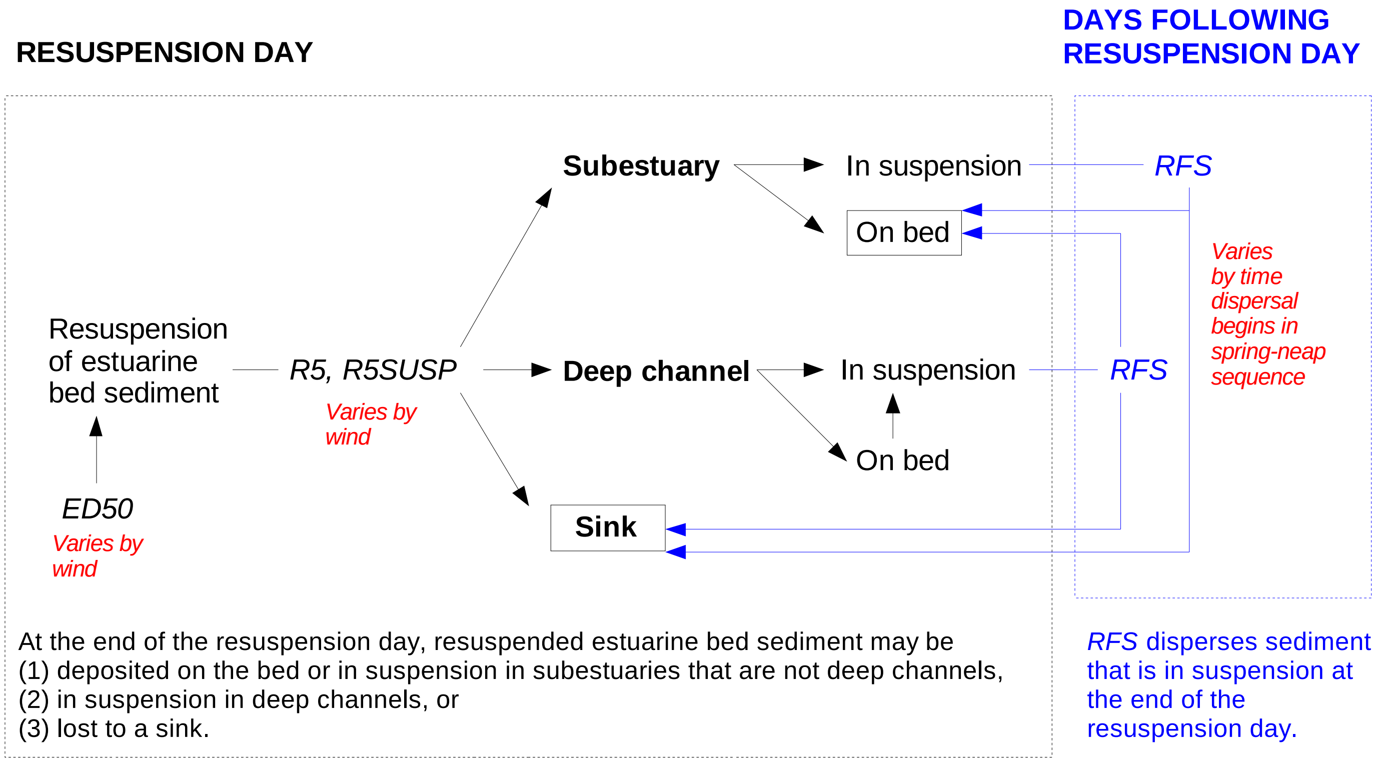
Summary of the meaning of the terms *ED50*, *R5*, *R5SUSP* and *RFS*.

| Term | Applies to | Describes | Varies with | Specified for | Applied at | Special conditions |
|---|---|---|---|---|---|---|
| *ED50* | Estuary bed sediment | Erosion | Weighted-mean particle size 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 ↦ 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 ↦ 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 ↦ destination subestuary combination | Until all sediment left in suspension at end of resuspension day deposits or is lost to sink | |

[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.

**Figure 4.1:**

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




Ultimately, all sediment that is resuspended on the resuspension day is accounted for by:
(1) deposition in a subestuary that is not a deep channel and
(2) loss to a sink.

### 4.2.2 Details

#### 4.2.2.1 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 particle sizes (termed $D_{50}$ 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 (two 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.
- *ED50* = 0 in subestuaries designated as tidal creeks, sinks or deep channels.

#### 4.2.2.2 R5 and R5SUSP

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

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

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

- 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 particle sizes 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 (two 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 particle size, which permits different particle sizes 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 particle size, which permits different particle sizes to disperse independently around the harbour.

#### 4.2.2.3 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 particle sizes 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 particle size, which permits different particle sizes to disperse independently around the harbour.

$RFS_{iparticle,kestorigin,kestdestination}$ is the fraction of constituent particle size *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 particle size *iparticle* deposited in subestuary *kestdestination* is given by:

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

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

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

#### 4.2.2.4 Heavy metals

The same terms *R5*, *R5SUSP* and *RFS* govern the movements of heavy metals associated with estuarine sediments by tidal currents and waves.

Using the same terms *R5*, *R5SUSP* and *RFS* to describe the dispersal of both sediments and heavy metals following erosion of the bed sediment has the effect of “locking” the heavy metals to the sediments. Thus, as different sediment particle sizes disperse independently around the harbour in the USC-3 model, so the heavy metals associated with the different particle sizes also disperse.

## 4.3 Injection into the harbour of sediments and contaminants when it rains

### 4.3.1 Introduction

During and in the immediate aftermath of rainstorms, sediment is eroded from the land, and heavy metals such as zinc and copper, are scoured and flushed from various reservoirs and sources. There are two types of source: natural and anthropogenic. Natural metals derive from the soils of both rural and urban areas. Anthropogenic metals derive from human activity in urban areas.

The heavy metals (both natural and anthropogenic) released by rainfall travel down through the stream-channel and stormwater networks, initially in solution, but increasingly in suspension, attached to particulate suspended sediments in the stormwater. Sediments and contaminants that find their way into the main body of the harbour will be dispersed and deposited by waves and currents.

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 and contaminant loads for that day are evaluated at the base of the catchment (BOC). (2) Land-derived sediment and contaminant loads for that day are evaluated at the edge of the main body of the harbour (EMB). For some stormwater outfalls, BOC is the same as EMB. For others, sediments and heavy metals have to be transferred through tidal creeks to get to EMB. During this step, heavy metals get attached to sediment particulate matter. (3) The sediment loads with heavy metals attached are discharged from EMB into the main body of the harbour, and dispersed and deposited.

### 4.3.2 Land-derived sediment and contaminant loads at BOC

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

- For the implementation of the USC-3 model in Southeastern Manukau Harbour / Pahurehure Inlet, the GLEAMS model is used to predict sediment runoff from rural areas. Hence, for this implementation, "GLEAMS sediments" is synonymous with "sediments from sources in rural areas". Note that GLEAMS provides daily sediment loads for each subcatchment split by constituent particle size. The exact way these are prepared for input into the USC-3 model is described in the next chapter.
- Also for this implementation, the CLM contaminant-generation model is used to predict sediment from urban areas. Hence "CLM sediments" is synonymous with "sediments from sources in urban areas". Note that the CLM provides annual sediment loads, also split by constituent particle size. The exact way these are prepared for input into the USC-3 model is described in the next chapter.

The corresponding heavy metal load from each subcatchment on the day at hand is $LANDHEAVYMETAL\underline{BOC}MASS_{jcatch}$. Again, "*BOC*" means at the base of the subcatchment.

- The CLM contaminant-generation model provides annual anthropogenic (urban) heavy-metal loads for each subcatchment, split by constituent sediment particle size that carries the load.
- Natural heavy-metal loads, which get added to anthropogenic loads to form total loads, are calculated by multiplying the total (rural plus urban) sediment load by the concentration at which natural heavy metals are carried on soils. This is described in detail in the next chapter.

### 4.3.3 Transfer of land-derived sediment and contaminant loads to EMB

Stormwater outfalls 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.

The way heavy metals become attached to land-derived particulate sediments depends on the route they take to the harbour.

For instance, geochemical processes in tidal creeks associated with the mixing between fresh and saline water may accelerate the attachment of zinc to sediment particulate matter. On the other hand, zinc may remain primarily in the dissolved phase – with very little attachment to sediment – in stormwater that discharges directly along the fringes of the main body of the harbour.

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 will also result in sequestration in the bed sediment within the tidal creek of any attached heavy metals. This results in a so-called “attenuation” – or reduction – of the sediment and contaminant 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/contaminant load directly into the main body of the estuary.

The aim, then, in this step is to convert (1) $LANDSEDIMENT\underline{BOC}MASS_{jcatch,iparticle}$ into $LANDSEDIMENT\underline{EMB}MASS_{jcatch,\ iparticle}$ and (2) $LANDHEAVYMETAL\underline{BOC}MASS_{jcatch}$ into $LANDHEAVYMETAL\underline{EMB}MASS_{jcatch,\ iparticle}$ The second conversion will also deal with the attachment of heavy metals to sediment particulate matter. The particular scheme used to accomplish these conversions depends on where the outfall discharges, as follows.

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

<u>Conversion 1</u>. In this case, there is no load attenuation and so $LANDSEDIMENT\underline{BOC}MASS_{jcatch,iparticle} = LANDSEDIMENT\underline{EMB}MASS_{jcatch,\ iparticle}$.

<u>Conversion 2</u>. $LANDHEAVYMETAL\underline{BOC}MASS_{jcatch}$ is converted to $LANDHEAVYMETAL\underline{EMB}MASS_{jcatch,\ iparticle}$ by using a set of attachment factors:

$LANDHEAVYMETAL\underline{EMB}MASS_{jcatch,\ iparticle} = LANDHEAVYMETAL\underline{BOC}MASS_{jcatch} \times ATTACH_{jcatch,iparticle}$.

The attachment factors partition the heavy-metal load amongst the various constituent particle sizes, which has the effect of locking the heavy metals to particulate sediment. The amount of heavy metal remaining in the dissolved phase at EMB is given by:

$$(1-\sum_{iparticle=1}^{nparticle} ATTACH_{jcatch,iparticle})LANDHEAVYMETALBOCMASS_{jcatch,iparticle}$$

Any heavy metal that remains in the dissolved fraction at EMB is lost from the (model) system. That is, the USC-3 model does not treat any dissolved metals in the harbour.

#### 4.3.3.2 Outfalls that discharge directly into the main body of the harbour

Conversion 1. As above, there is no load attenuation and so $LANDSEDIMENT\underline{BOC}MASS_{jcatch,iparticle} = LANDSEDIMENT\underline{EMB}MASS_{jcatch,\ iparticle}$.

Conversion 2. As above, $LANDHEAVYMETAL\underline{BOC}MASS_{jcatch}$ is converted to $LANDHEAVYMETAL\underline{EMB}MASS_{jcatch,\ iparticle}$ by using a set of attachment factors. Again, some portion of the heavy-metal load may remain in the dissolved phase at EMB, which will be lost from the (model) system.

#### 4.3.3.3 Outfalls that discharge into the main body through a tidal creek

Conversion 1. 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 4.2 summarises the meaning of the term *RTC*. Refer to this table during the following detailed description.

**Table 4.2:**

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*) | Every sub-catchment that discharges into a subestuary that is defined as a tidal creek | End of injection day |

*RTC* is the fraction of sediment load $LANDSEDIMENT\underline{BOC}MASS_{jcatch,iparticle}$ presented at the base of the catchment 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 particle size, reflecting the influence of particle size on particle dynamics, and by rainfall, reflecting the influence of freshwater discharge on tidal-creek dynamics.

Conversion 2. $LANDHEAVYMETAL\underline{BOC}MASS_{jcatch}$ is converted to $LANDHEAVYMETAL\underline{BOC}MASS_{jcatch,\ iparticle}$ using a set of attachment factors as above. Also as above, some fraction of the heavy-metal load may not become attached to particulate matter, which results in loss from the (model) system. Note that the attachment factors here yield the heavy-metal attached to particle sizes at BOC, not EMB (which was the case previously). $LANDHEAVYMETAL\underline{BOC}MASS_{jcatch,\ iparticle}$ so created is then transferred through the tidal creek by using the same value of *RTC* that was used to transfer sediment through the tidal creek:

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

Note that the portion of the sediment and heavy-metal loads that do not escape from the tidal creeks (i.e., $LANDSEDIMENT\underline{BOC}MASS_{jcatch,iparticle} \times (1-RTC_{subestuary,jcatch,iparticle})$ and $LANDHEAVYMETAL\underline{BOC}MASS_{jcatch,iparticle} \times (1-RTC_{subestuary,jcatch,iparticle})$, respectively) are accumulated on the bed of the tidal creek.

### 4.3.4 Dispersal inside the harbour of sediment and contaminant loads presented to EMB

Dispersal of land-derived sediments and contaminants 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 4.3 summarises the meaning of the terms *R, RSUSP* and *RFS*.

Figure 4.2 shows how *R, RSUSP* and *RFS* are applied. This also shows the role of *RTC*. Refer to this figure during the following detailed description.

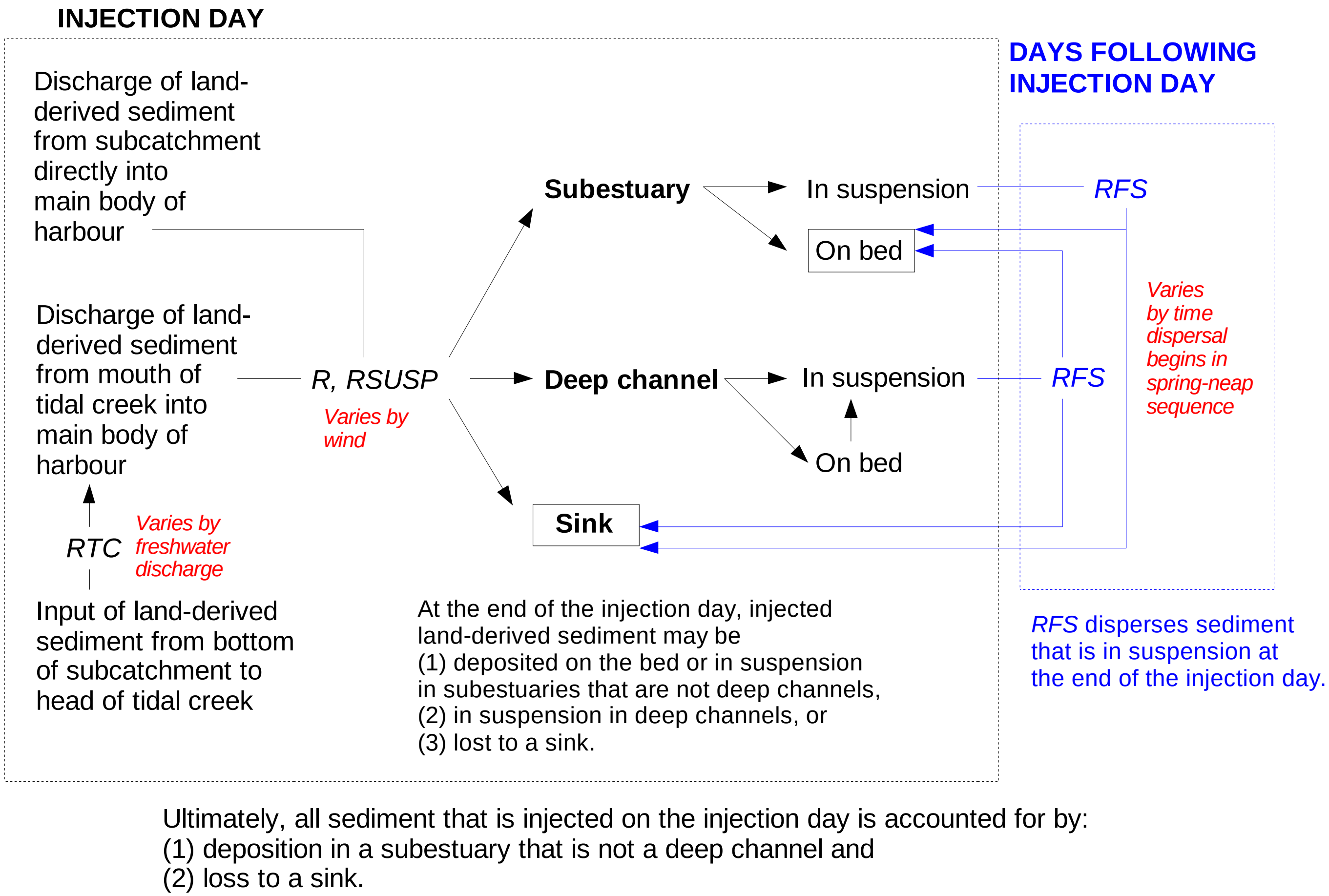
**Table 4.3:**

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 | |

**Figure 4.2:**

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



$R_{catch,kest,iparticle}$ is the fraction of the land-derived sediment load of constituent particle size *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 particle size *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 particle size *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 particle size *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:

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

For every subcatchment, *R* and *RSUSP* are determined using the DHI model suite for each of a number of constituent particle sizes 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 (two 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 particle size, which permits different particle sizes 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 particle size *iparticle* deposited in subestuary *kestdestination* is given by:

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

Finally, the same terms *R*, *RSUSP* and *RFS* also govern the dispersal of heavy metals associated with land-derived sediments in the harbour.

Using the same terms *R* ,*RSUSP* and *RFS* to describe the dispersal of both land-derived sediments and heavy metals has the effect of "locking" the heavy metals to the sediments. Thus, as different sediment particle sizes disperse independently around the harbour in the USC-3 model, so the heavy metals associated with the different particle sizes also disperse.

## 4.4 Building the bed-sediment column

In this section, the development of the bed sediment column, which also holds the heavy metals attached to the sediment particles, is described.

### 4.4.1 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 $D_{50}$ particle size 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 particle size *iparticle* in the bed sediment, $D_{iparticle}$ is the diameter of particle size *iparticle*, and there are *nparticle* constituent particle sizes 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 particle size *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 particle sizes) in the active layer:

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

and $SEDIMENTMASSAL_{iparticle}$ is the mass of particle size *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 particle size *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 particle size *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, $\tau_{critical}$. 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 $SEDIMENTMASS = \rho_{settled} \times A \times ED50$, where $\rho_{settled}$ 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 $SEDIMENTMASS_{ilayer} = \rho_{settled} \times A \times THICK_{ilayer}$, 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 particle sizes according to the percentage of each constituent particle size in the bed sediment. If erosion removes a number of sediment layers from the bed and each layer has a different particle size composition, then partitioning of the eroded sediment amongst the constituent particle sizes 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 particle size *iparticle*. Note that:

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

A corresponding mass of heavy metal is removed from the bed sediment. There is a certain mass of heavy metal associated with each constituent particle size in each layer of the sediment column. Since erosion of the bed sediment to the depth of *ED50* releases sediment from *nlayerseroded* sediment layers in the sediment column, then the corresponding mass of heavy metal released from the heavy-metal column is given by:

$$HEAVYMETALMASS_{iparticle} = \sum_{ilayer=1}^{nlayerseroded} HEAVYMETALMASS_{ilayer,iparticle}$$

where $HEAVYMETALMASS_{ilayer,iparticle}$ is the mass of heavy metal associated with constituent particle size *iparticle* in layer *ilayer* of the sediment column.

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 particle sizes is identical to the proportioning of the deposited mass amongst the particle sizes.

Heavy metals are deposited correspondingly. The total mass of heavy metal to be deposited is deposited on the bed in a single layer with the sediments. In so doing, distribution of the heavy metals across the constituent particle sizes is maintained.

The resuspension of bed sediments and attached contaminants by waves and currents has now been accounted for, and the concentration of heavy metal in the surface layer can be calculated, which is a primary model output. This calculation takes account of mixing of the bed sediment. The estimate of heavy-metal concentration is made to apply at the end of the resuspension day (i.e., the day the sediment was resuspended), even though *RFS* acts beyond that day to fully disperse and deposit resuspended sediment. The way heavy-metal concentration is calculated is explained in the section on model implementation.

### 4.4.2 Days it is raining

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

The mass of land-derived sediment of each constituent particle size *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 $\mathit{LANDSEDIMENT\underline{EMB}MASS}_{jcatch,\ iparticle}$. The corresponding heavy-metal load is $\mathit{LANDHEAVYMETAL\underline{EMB}MASS}_{jcatch,\ iparticle}$. These loads may already have been attenuated if they passed through a tidal creek on their way from the bottom of the catchment 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 $\mathit{LANDSEDIMENT\underline{EMB}MASS}_{jcatch,\ iparticle}$. 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 particle sizes is identical to the proportioning of the deposited mass amongst the particle sizes.

Heavy metals are deposited correspondingly. The total mass of heavy metal to be deposited is deposited on the bed in a single layer with the land-derived sediments. In so doing, distribution of the heavy metals across the constituent particle sizes is maintained.

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 and the concentration of heavy metals in the surface layer can be calculated. This is the primary model output. The calculation takes account of mixing of the bed sediment. The estimate of heavy-metal concentration is made to apply at the end of the day it was raining, even though *RFS* acts beyond that day to fully disperse and deposit both the injected land-derived sediments and the resuspended estuarine bed sediments. The way heavy-metal concentration is calculated is explained in the section on model implementation.

# 5 Model Implementation

The implementation of the USC-3 model for Southeastern Manukau Harbour / Pahurehure Inlet consists of specifying the sediment particle sizes to be addressed in the model, defining subestuaries and subcatchments, specifying the weather time series used to drive the model, defining the way land-derived sediments and associated heavy metals are to be fed into the harbour at the subcatchment outlets, evaluating the various terms that control sediment and associated heavy-metal transport and deposition inside the harbour, defining the way heavy-metal concentration in the estuarine bed-sediment surface layer is to be evaluated, and specifying the mixing depth.

Other information required to drive the model, including harbour bed-sediment initial conditions (e.g., particle size, metal concentration in the surface layer, subcatchment sediment and metal loads), varies depending on the particular scenario being addressed. This information is not treated as part of the model implementation; instead, it is reported where the scenario model runs are reported.

## 5.1 Sediment particle sizes

Four sediment particle sizes are treated by the model: 4, 12, 40 and 125 $\mu$m. These particle sizes represent: sediment washload / slowly-settling, low-density sediment flocs; fine silt; coarse silt; and fine sand, respectively. These particle sizes are deemed to compose the land-derived sediment, the estuarine bed sediment, and the suspended-sediment load that derives from the estuarine bed sediment, with the following conditions and exceptions.

- Fall speeds of 0.0001 m $s^{-1}$ and 0.001 m $s^{-1}$ were assigned to the 12 and 40 $\mu$m fractions, respectively. The fall speeds for the 12 and 40 $\mu$m fractions are Stokes fall speeds assuming sediment density of 2.65 g $m^{-3}$ (quartz). Hence, the 12 and 40 $\mu$m fractions are implied to be, as a result, in an unaggregated state.
- The fall speed for the 4 $\mu$m fraction was set at 0.00001 m $s^{-1}$ to represent sediment washload and slowly-settling, low-density sediment flocs. 4 $\mu$m is a nominal size for this fraction.
- The estuarine bed sediment may include a 125 $\mu$m fraction, which is required in some parts of the harbour to reproduce the observed bed-sediment median particle size. This fraction may be supplied to the harbour by erosion from the land, but it may not be subsequently resuspended (in the model) by waves or tidal currents, which is likely to be a reasonable condition inside Pahurehure Inlet.

## 5.2 DHI estuary model suite

The DHI estuary model suite 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 Southeastern Manukau Harbour / Pahurehure Inlet are described in Pritchard et al. (2008b). Field data collected for the purposes of DHI model calibration are described in Pritchard et al. (2008a).

The calibrated MIKE3 MT model was used to simulate the resuspension and transport of the 4 µm (washload / slowly-settling, low-density sediment flocs), 12 µm and 40 µm sediment particle sizes, and the various terms in the USC-3 model that describe sediment transport, resuspension and deposition were determined from the results of those simulations (The 125 µm fraction is not allowed to move.)

## 5.3 Subdivision of harbour and catchment

### 5.3.1 Subestuaries

The subdivision of Southeastern Manukau Harbour / Pahurehure Inlet into subestuaries for the purposes of application of the USC-3 model is shown in Figure 5.1. Further details of the subdivision are shown in Table 5.1.

#### 5.3.1.1 Tidal creeks

Five subestuaries are designated as tidal creeks: Puhinui Creek (14–PUK), Pukaki Creek (15–PKK), Drury Creek Inner (16–DCI), Glassons Creek Inner (17–GCK) and Clarks Creek (18–CCK). Sediments deposited in tidal creeks may not be subsequently removed by resuspension, and land-derived sediments that pass through tidal creeks are attenuated.

#### 5.3.1.2 Sinks

One of the subestuaries is designated as a sink: Manukau Harbour (19–MHB). Sediments deposited in 19–MHB may not be subsequently removed by resuspension. Furthermore, sediments deposited in 19–MHB are “removed from the model”, meaning that no predictions are made of sediment or contaminant accumulation in subestuary 19–MHB.

The designation of 19–MHB as a sink is based on the assumption that the bulk of any sediment transported into the wider harbour is dispersed widely and does not re-enter the southeastern sector of the harbour or Pahurehure Inlet. By virtue of its designation as a sink, 19–MHB is also prevented from eroding and supplying sediment to the southeastern sector of the harbour or Pahurehure Inlet.

#### 5.3.1.3 Deep channels

Four subestuaries are designated as deep channels (Pahurehure Channel Inner, Pahurehure Channel Outer, Manukau Channel North, Manukau Channel South). Since sediment is not allowed to deposit in or erode from deep channels, predictions of sediment and contaminant accumulation are not made in these subestuaries.

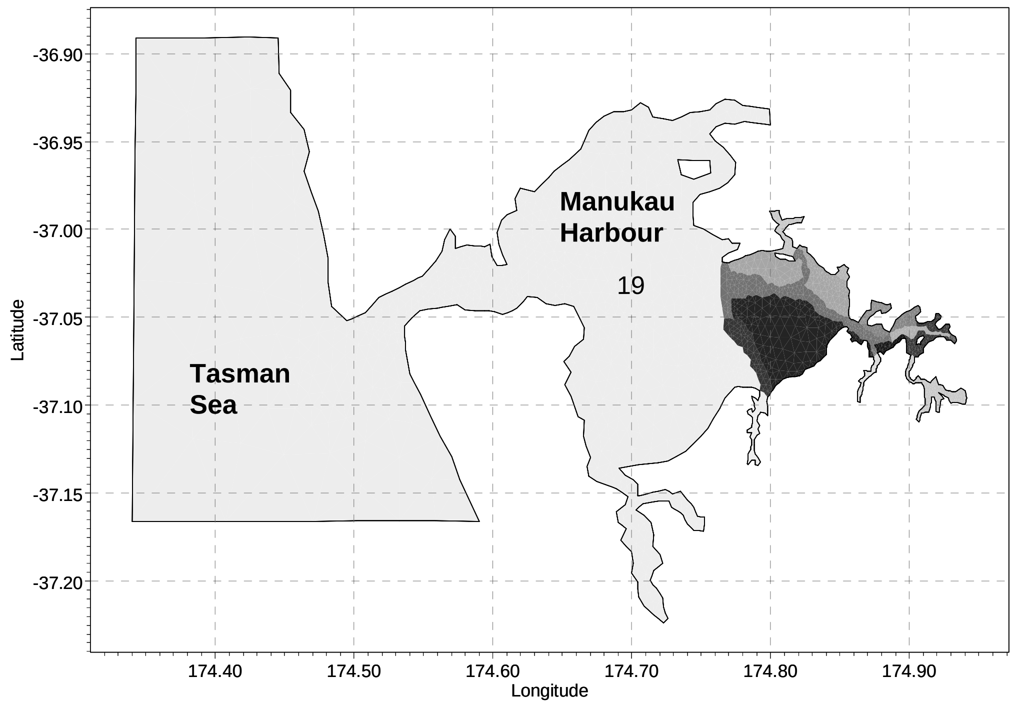
**Table 5.1:**

Characteristics of 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 – HIB | Hikihiki Bank | 23,840,949 | | | |
| 2 – KKA | Karaka | 385,175 | | | |
| 3 – GMW | Glassons Mouth West | 167,768 | | | |
| 4 – GME | Glassons Mouth East | 635,090 | | | |
| 5 – CHN | Cape Horn | 254,352 | | | |
| 6 – DCO | Drury Creek Outer | 1,038,072 | | | |
| 7 – PHI | Pahurehure Inner | 1,778,269 | | | |
| 8 – PBA | Pahurehure Basin | 172,434 | | | |
| 9 – PKA | Papakura | 1,442,876 | | | |
| 10 – KPT | Kauri Point | 807,656 | | | |
| 11 – WMC | Waimahia Creek | 1,193,113 | | | |
| 12 – WEY | Weymouth | 6,014,049 | | | |
| 13 – WIL | Wiroa Island | 6,511,696 | | | |
| 14 – PUK | Puhinui Creek | 562,042 | | ✓ | |
| 15 – PKK | Pukaki Creek | 2,246,659 | | ✓ | |
| 16 – DCI | Drury Creek Inner | 3,759,221 | | ✓ | |
| 17 – GCK | Glassons Creek Inner | 982,487 | | ✓ | |
| 18 – CCK | Clarks Creek | 2,379,880 | | ✓ | |
| 19 – MHB | Manukau Harbour | n/a | ✓ | | |
| 20 – PCI | Pahurehure Channel Inner | n/a | | | ✓ |
| 21 – PCO | Pahurehure Channel Inner | n/a | | | ✓ |
| 22 – MNC | Manukau Channel North | n/a | | | ✓ |
| 23 – MSC | Manukau Channel South | n/a | | | ✓ |

**Figure 5.1:**

Division of Southeastern Manukau Harbour / Pahurehure Inlet into subestuaries for the purposes of application of the USC-3 model.



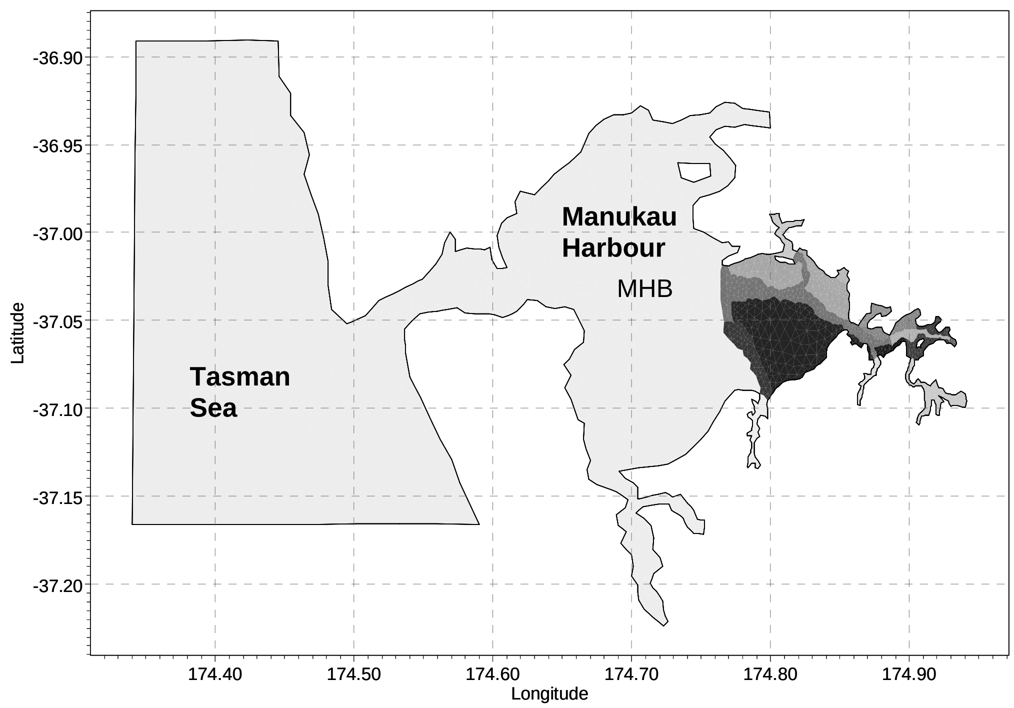



**Figure 5.1: (continued)**

Division of Southeastern Manukau Harbour / Pahurehure Inlet into subestuaries for the purposes of application of the USC-3 model.

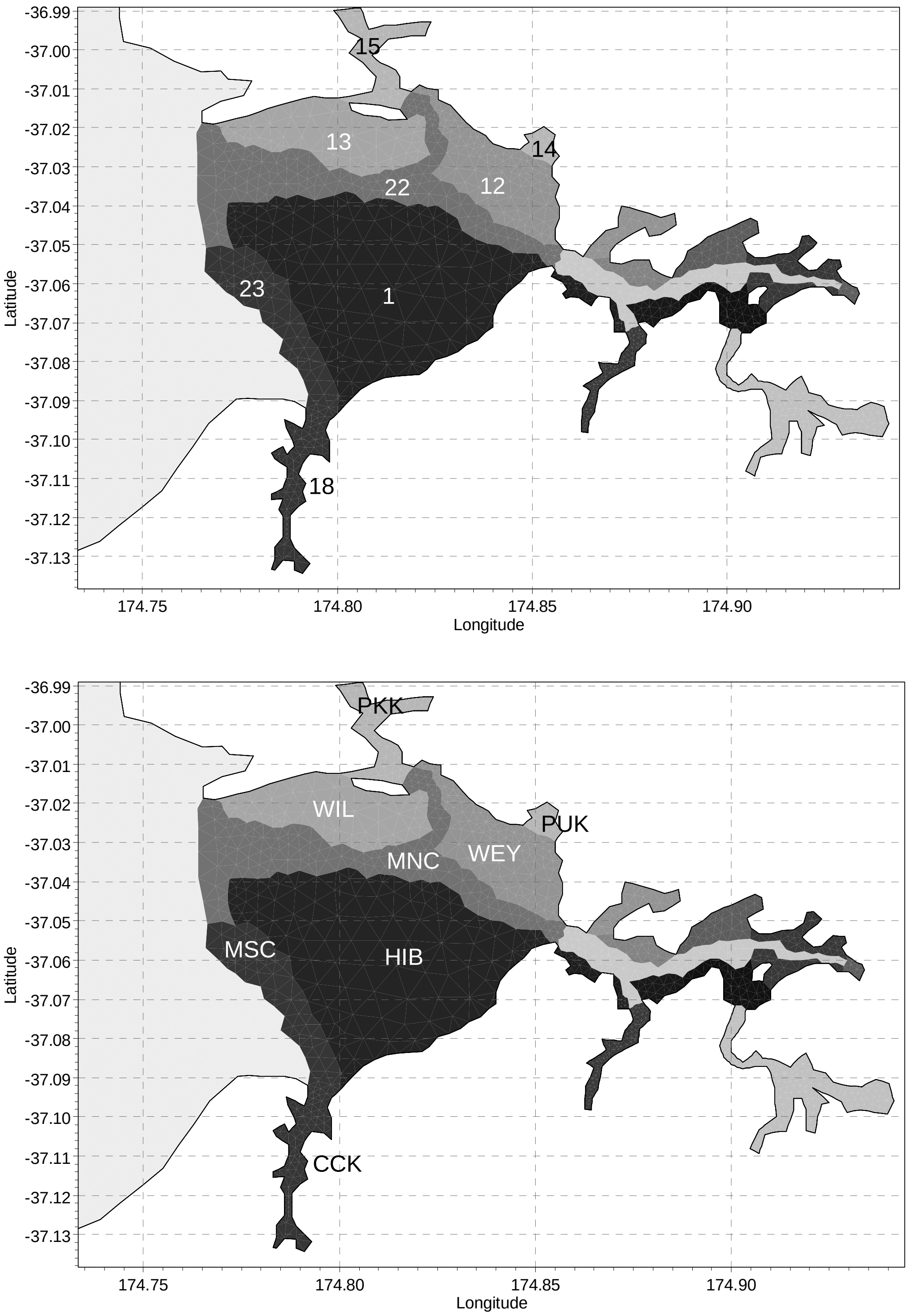
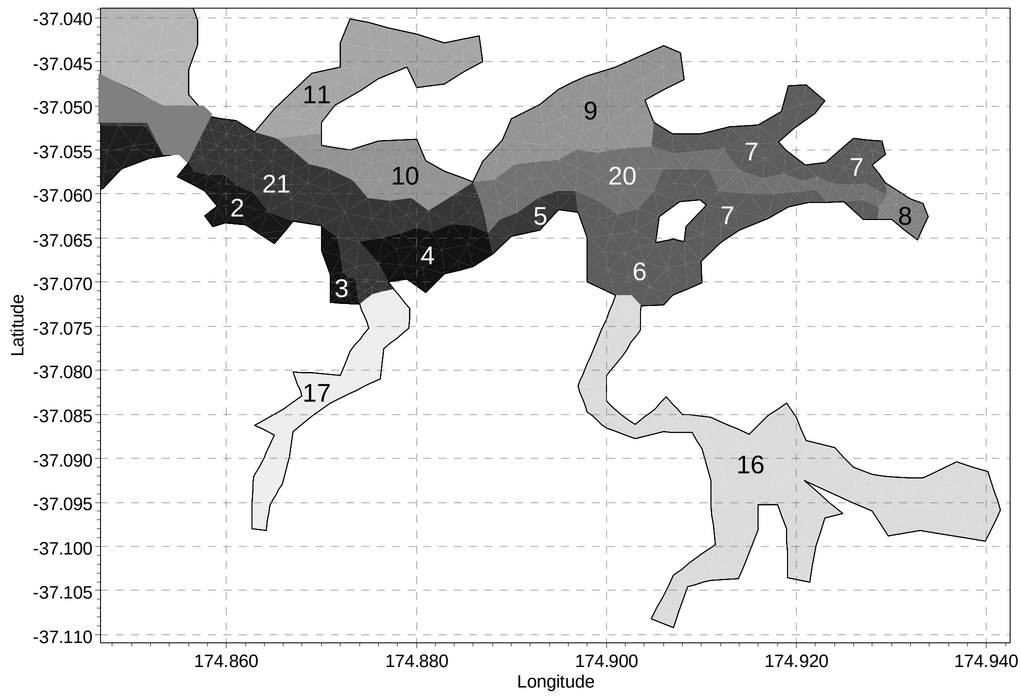
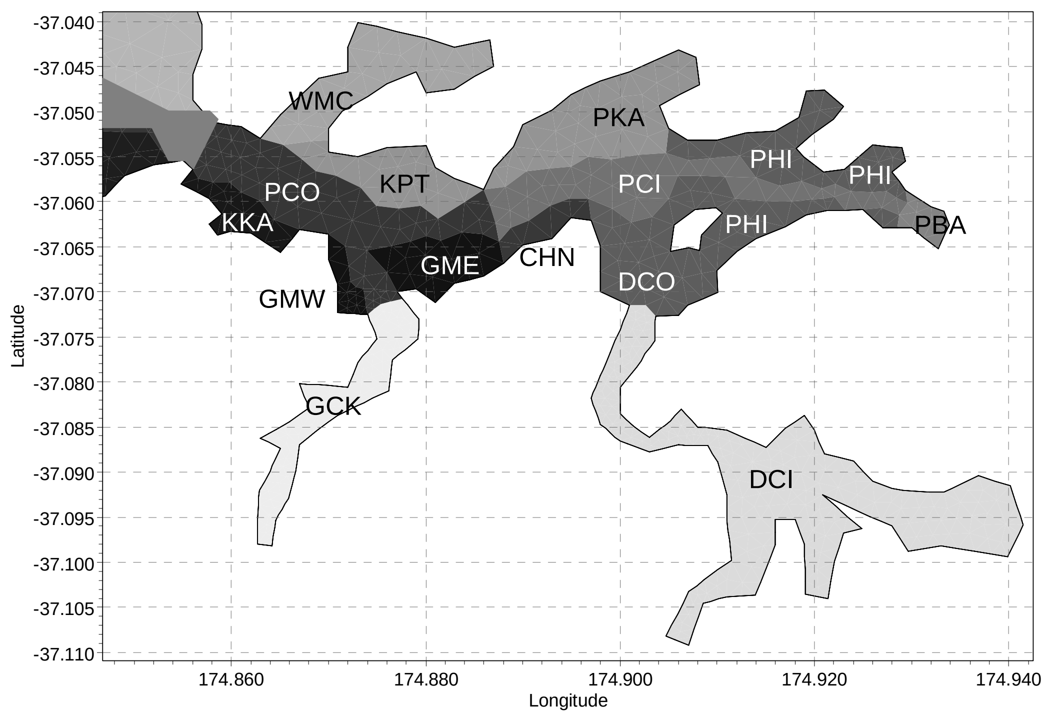


**Figure 5.1: (continued)**
Division of Southeastern Manukau Harbour / Pahurehure Inlet into subestuaries for the purposes of application of the USC-3 model.



### 5.3.2 Subcatchments

The subdivision of the catchment surrounding Southeastern Manukau Harbour / Pahurehure Inlet into subcatchments for the purposes of application of the USC-3 model is shown in Table 5.2 and Figure 5.2.

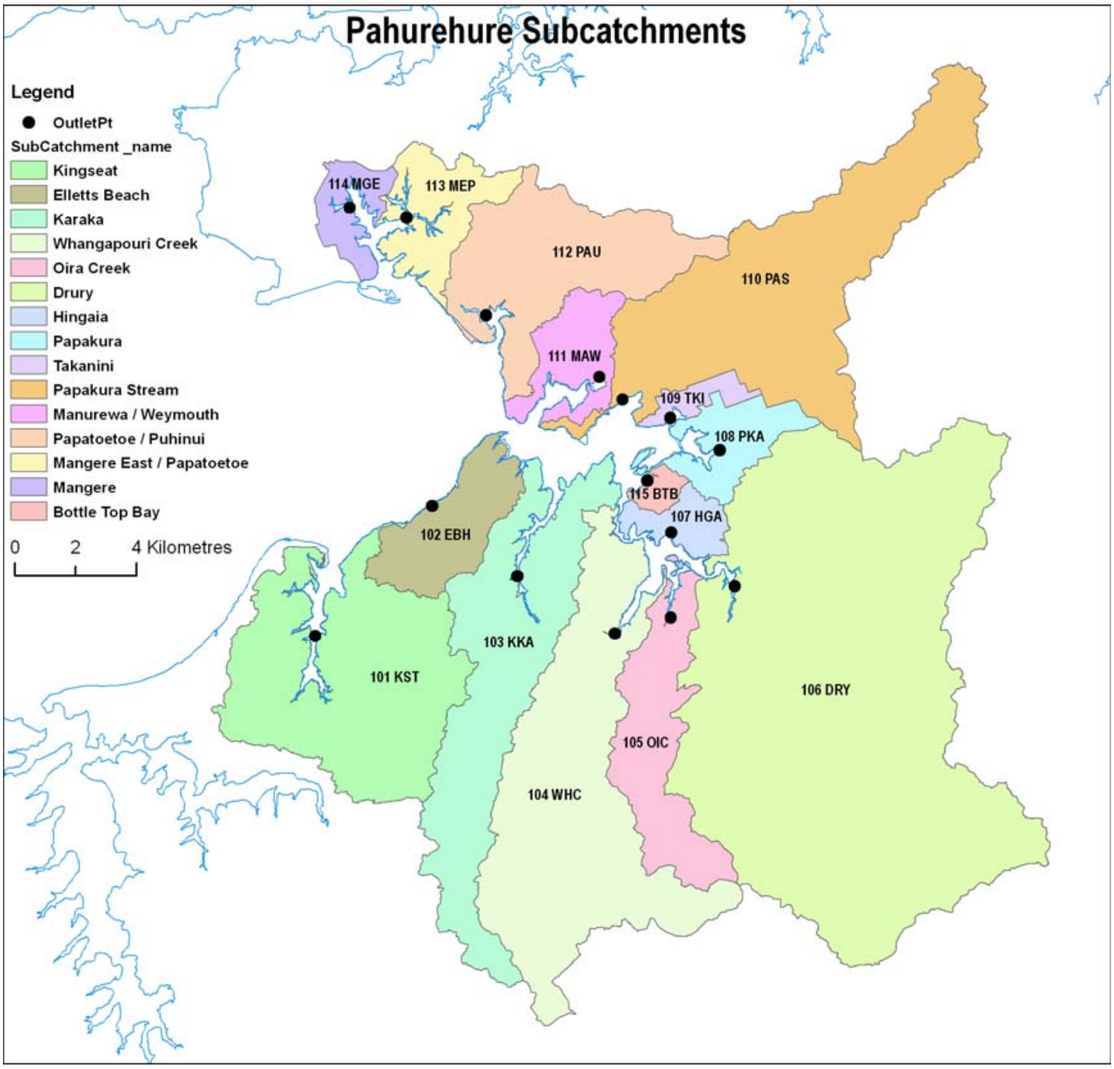
**Table 5.2:**

Division of the catchment of Southeastern Manukau Harbour / Pahurehure Inlet into subcatchments for the purposes of application of the USC-3 model.

| Code | Subcatchment |
|---|---|
| 101 - KST | Kingseat |
| 102 - EBH | Elletts Beach |
| 103 - KKA | Karaka |
| 104 - WHC | Whangapouri Creek |
| 105 - OIC | Oira Creek |
| 106 - DRY | Drury |
| 107 - HGA | Hingaia |
| 108 - PKA | Papakura |
| 109 - TKI | Takanini |
| 110 - PAS | Papakura Stream |
| 111 - MAW | Manurewa / Weymouth |
| 112 - PAU | Papatoetoe / Puhinui |
| 113 - MEP | Mangere East / Papatoetoe |
| 114 - MGE | Mangere |
| 115 - BTB | Bottle Top Bay |

**Figure 5.2:**

Division of the catchment of Southeastern Manukau Harbour / Pahurehure Inlet into subcatchments for the purposes of application of the USC-3 model.



## 5.4 Evaluation of land-derived sediment and contaminant loads at BOC

### 5.4.1 Sediment

#### 5.4.1.1 GLEAMS (rural) loads

The GLEAMS model provides daily land-derived sediment loads at the bottom of each subcatchment split by constituent particle size. For this implementation, GLEAMS predicts sediments from all of the rural areas in each subcatchment. Hence, “GLEAMS sediments” is synonymous with “sediments from sources in rural areas”.

Even though the daily GLEAMS 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. This is described and explained in this section.

Catchment landuse in both the 100-year future period (for the purposes of this explanation, 2001–2100, which is the period of interest as far as management decisions and policy formulation are concerned) and the 60-year historical period (1940–2001, which is the period for calibrating and validating the USC-3 model) is typically fixed in 10-year blocks for input into the GLEAMS model. For example, in the future period, landuse may be fixed in each of five 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; and
- block 5 representing the period 2041–2050.

The final block, block 6, represents the 50-year period 2051–2100.

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 is run separately for each block, driven by a 50-year daily rainfall time series to create a corresponding 50-year daily rural sediment runoff time series from each subcatchment. The 50-year rainfall series used to drive the GLEAMS simulations is typically from the past 50 years, on the assumption that future weather will not be that much different to past weather. (That assumption, of course, may not be true, and future-period rainfall used to drive the GLEAMS model may be altered to reflect the anticipated changes in climate in future years.)

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

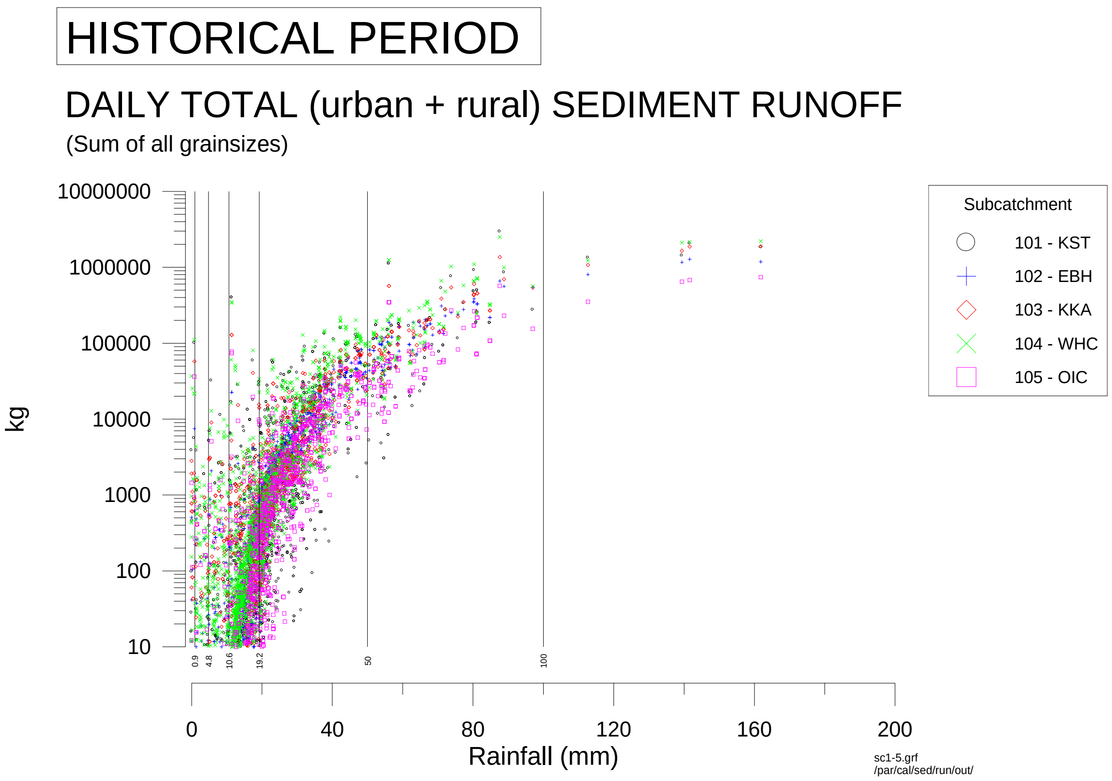
To create the daily rural sediment loads needed by the USC-3 model for the period 2001–2010, 5 x 2-year sub-blocks are randomly selected from the 50-year GLEAMS sediment runoff time series from block 1. The selected sub-blocks are placed back-to-back to provide the daily inputs for the 10-year period 2001–2010. This procedure is repeated, randomly selecting 5 x 2-year sub-blocks from each block of GLEAMS data, until the 100-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, and they get transferred to the USC-3 model by using sequences of GLEAMS output to drive the USC-3 model (Figure 5.3). 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 (this is the reason GLEAMS 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 100-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".

**Figure 5.3:**

Daily rural sediment runoff versus daily rainfall, assembled from a 100-year time series of daily rural sediment runoff used to drive the USC-3 model. The 100-year time series was in turn constructed from a number of 50-year GLEAMS simulations as described in the text. This procedure results in noticeable variability in rural sediment yield (sediment runoff per unit rainfall), which then appears in the USC-3 model. Extreme events are captured by a number of 100-year time series (such extremes do appear in this example).




### 5.4.1.2 CLM (urban) loads

The CLM model predicts annual urban sediment loads, split by constituent particle size, that derive from all of the urban areas in each subcatchment. Hence "CLM sediments" is synonymous with "sediments from sources in urban areas". The urban (CLM) sediment loads need to be added to the rural (GLEAMS) sediment loads, but because the annual timestep of the CLM does not match the daily timestep in the USC-3 model associated with injection of land-derived material into the harbour, the CLM loads need to be further manipulated before they can be added to the GLEAMS loads and used in the USC-3 model.

Each annual load of urban sediment is fully distributed over the days in that year such that no part of the annual load is "carried over" into a succeeding year. Specifically, the annual urban-sediment load emanating from each subcatchment is broken down into daily loads over that same year in proportion to the daily GLEAMS sediment loads. For instance, if 1% of the GLEAMS sediment load for a particular year appears on a particular day, then 1% of the CLM annual sediment load is forced to appear on that same day.

### 5.4.2 Contaminant

#### 5.4.2.1 Anthropogenic

The CLM provides annual anthropogenic metal loads at the bottom of each subcatchment, split by sediment constituent particle size that carries the load. Because the annual timestep of the CLM does not match the daily timestep in the USC-3 model associated with injection of land-derived material into the harbour, these loads need to be further manipulated before they can be used in the USC-3 model.

Each annual anthropogenic load of metal is fully distributed over the days in that year such that no part of the annual load is "carried over" into a succeeding year. Specifically, the annual anthropogenic heavy-metal load emanating from subcatchment *jcatch* is broken down into daily loads over that same year in proportion to the daily GLEAMS sediment load:

$$LANDHEAVYMETALBOCMASS_{jcatch,day} =$$

$$LANDHEAVYMETALBOCMASS_{jcatch} \times$$

$$[\sum_{iparticle=1}^{nparticle} LANDSEDIMENTBOCMASS_{jcatch,iparticle,day} /$$

$$\sum_{day=1}^{nday} \sum_{iparticle=1}^{nparticle} LANDSEDIMENTBOCMASS_{jcatch,iparticle,day}]$$

where:

- $LANDHEAVYMETAL\underline{BOC}MASS_{jcatch}$ is the annual anthropogenic heavy-metal load emanating from subcatchment *jcatch*;
- $LANDHEAVYMETAL\underline{BOC}MASS_{jcatch,day}$ is the daily anthropogenic heavy-metal load emanating from subcatchment *jcatch* over that same year;
- $LANDSEDIMENT\underline{BOC}MASS_{jcatch,iparticle,day}$ is the daily GLEAMS rural sediment load from subcatchment *jcatch* and there are *nday* days in the year.

Using this scheme, the annual-average concentration (mass of metal per mass of sediment) at which anthropogenic heavy metals are carried to the harbour will vary from year to year, since the annual anthropogenic heavy metal load may vary independently of the annual sediment load.

#### 5.4.2.2 Natural

Natural heavy-metal loads, which get added to anthropogenic loads to form total loads, are calculated by multiplying the total (rural plus urban) sediment load by the concentration at which natural heavy metals are carried on soils.

## 5.5 Transfer of land-derived sediment and contaminant loads to EMB

Conversion (1) accounts for any reduction (attenuation) of the land-derived sediment load as it transits between the bottom of catchment (BOC) and the edge of the main body of the harbour (EMB).

Conversion (2) accounts for any reduction of the land-derived metal load as it transits between BOC and EMB. At the same time, the metal load is partitioned amongst the various constituent particle sizes that make up the land-derived sediment load.

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

Conversion 1. There is no load attenuation.

Conversion 2. There is no load attenuation, and the CLM will determine how the metal load is partitioned amongst the various constituent particle sizes that make up the land-derived sediment load.

### 5.5.2 Outfalls that discharge directly into the main body of the harbour

Conversion 1. There is no load attenuation.

Conversion 2. There is no load attenuation, and the CLM will determine how the metal load is partitioned amongst the various constituent particle sizes that make up the land-derived sediment load.

### 5.5.3 Outfalls that discharge into the main body through a tidal creek

Conversion 1. Load attenuation is achieved by applying *RTC*. This is described in the next section, where sediment transport in the harbour is described.

Conversion 2. Load attenuation is achieved by applying *RTC*. This is described in the next section, where sediment transport in the harbour is described. The CLM will determine how the metal load is partitioned amongst the various constituent particle sizes that make up the land-derived sediment load.

## 5.6 Sediment transport in the harbour

Table 5.3 summarises the way the various terms that control sediment transport in the harbour are implemented in the USC-3 model of the Southeastern Manukau Harbour / Pahurehure Inlet. (The particular rainfall bands, winds and tide sequences shown in the Table are explained in a later section).

**Table 5.3:**

The way the various terms that control sediment transport in the harbour are implemented in the USC-3 model of the Southeastern Manukau Harbour / Pahurehure Inlet. (The particular rainfall bands, winds and tide sequences shown in the Table are explained in a later section.)

| Environmental conditions | *RTC* | *R, RSUSP* | *ED50, R5, R5SUSP* | *RFS* |
|---|---|---|---|---|
| Tide range | *Average* | *Average* | *Average* | Range (2):<br>*Neap–mean–spring …*<br>*Spring–mean–neap …* |
| Winds | *Calm* | range (5):<br>*Calm*<br>*8.7 m/s NE*<br>*8.3 m/s SE*<br>*8.7 m/s SW*<br>*8.4 m/s NW* | | *Calm* |
| Freshwater inputs (rainfall) | Range (6):<br>*0.9–4.8 mm*<br>*4.8–10.6 mm*<br>*10.6–19.2 mm*<br>*19.2–50.0 mm*<br>*50.0–100.0 mm*<br>*>50 mm* | *Median discharge* | *Median discharge* | *Baseflow* |

### 5.6.1 Resuspension of estuarine bed sediments by waves and currents

#### 5.6.1.1 ED50

*ED50* was determined for each of four $D_{50}$ particle sizes (4, 12, 40 and 125 μm) and five winds (Table 5.3). Wind was chosen to vary because it is the primary control on waves, which in turn control resuspension of bed sediment. Wind is also the primary control on resuspension and dispersal of estuarine bed sediment on the day of resuspension. The tide range and the freshwater inputs were fixed.

The simulation duration in every case was one day (one complete tidal cycle).

*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 5.4. The bed sediment with the smallest median particle size apparently erodes less than the bed sediments with larger median particle size. However, 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 5.4 shows that wind direction at the example site in question does not have much of an effect on *ED50* by the end of the resuspension day, which is the case at most sites. There is a distinct variation in *ED50* from site to site (Figure 5.5). Inside Pahurehure Inlet, *ED50* varies in magnitude from smallest to largest in the order:

- Pahurehure Basin;
- the intertidal areas at the head of the inlet (Pahurehure Inner);
- Glassons Mouth West, which is in a sheltered position facing east, at the mouth of Glassons Creek;
- the sheltered embayments along the northern shore (Papakura and Waimahia Creek);
- the intertidal flats along the southern shore near the mouth of the inlet (Karaka);
- the intertidal flats in the central reaches of Pahurehure Inlet (Drury Creek Outer, Cape Horn and Glassons Mouth East along the southern shores, and Kauri Point along the northern shores).

*ED50* was determined for each of four $D_{50}$ particle sizes: 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.

**Figure 5.4:**

*ED50*, subestuary 10 (Kauri Point) by the end of the resuspension day.

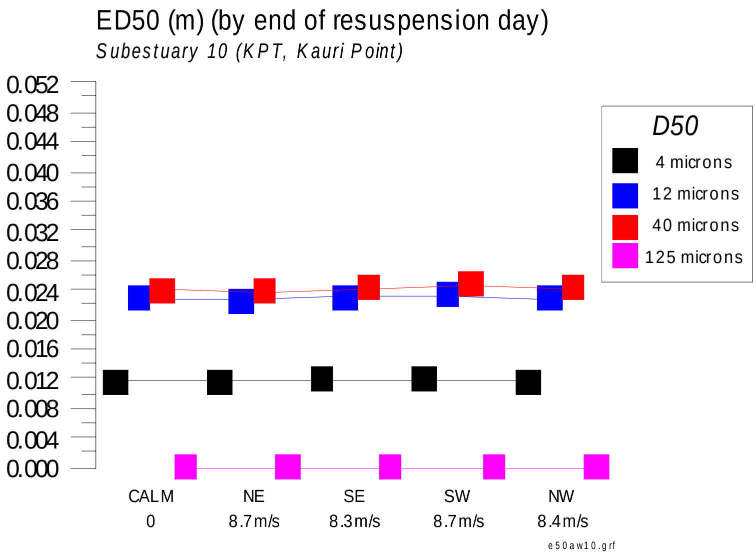
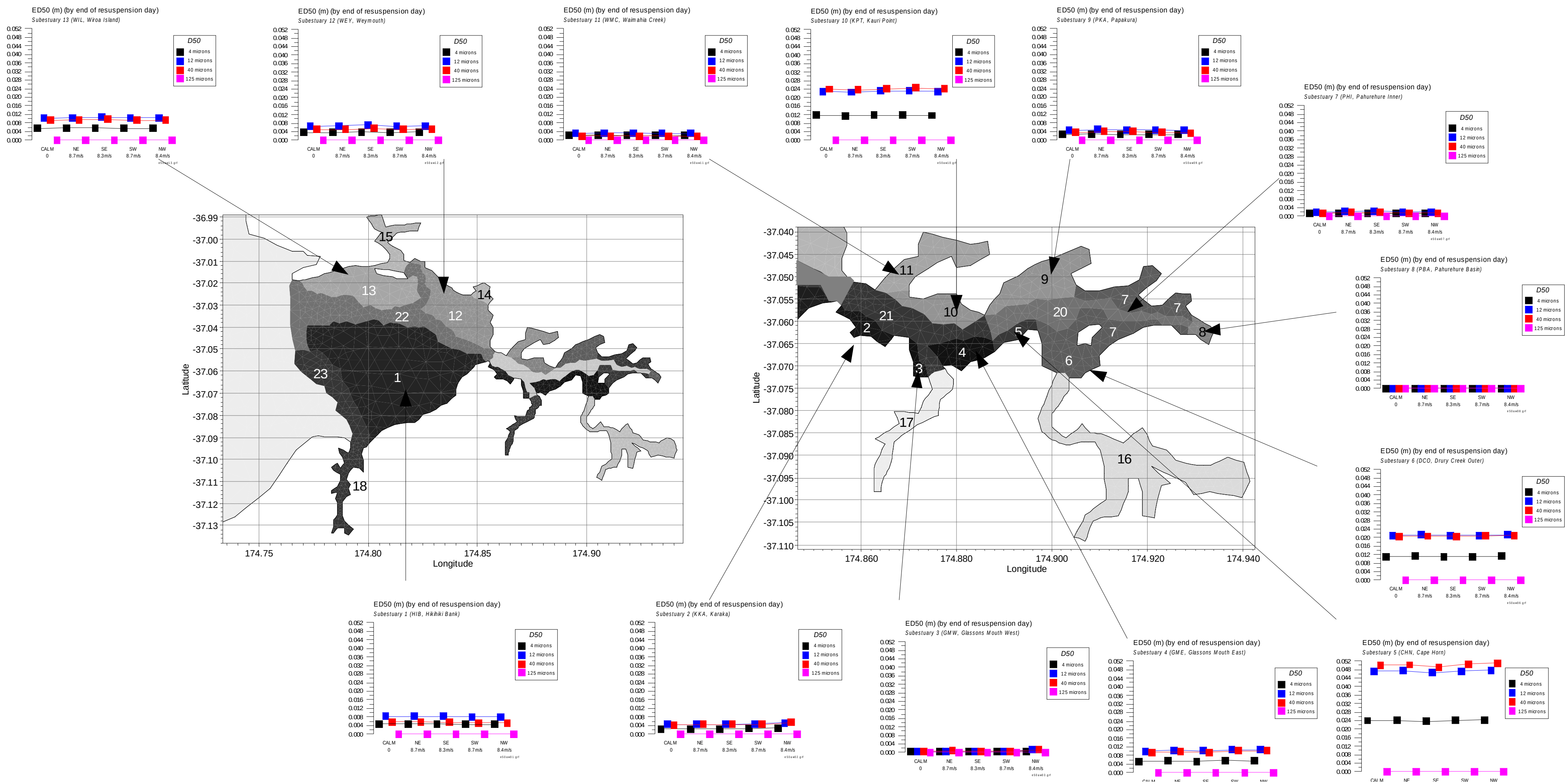


**Figure 5.5:**

*ED50* by the end of the resuspension day.

# ED50 (m) (by end of resuspension day)



#### 5.6.1.2 R5 and R5SUSP

*R5* and *R5SUSP* were determined for each of the four $D_{con}$ constituent particle sizes (4, 12, 40 and 125 μm, where 4 μm represents washload / low-density, slowly-settling sediment flocs) and the environmental conditions shown in Table 5.3.

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.

For the purposes of this explanation, assume the origin subestuary is subestuary #1 and there are three subestuaries in total in the model domain. At the end of the model run, a sediment budget is constructed (Table 5.4 shows an example), consisting of:

- Term 1: the mass of sediment eroded from the bed of the origin subestuary by the end of the model run (a negative number, e.g., -100 kg).
- Term 2: the mass of sediment deposited in all the other subestuaries except the origin subestuary at the end of the model run (positive numbers, e.g., 20 kg for subestuary #2 and 40 kg subestuary #3).
- Term 3: the mass of sediment remaining in suspension in all subestuaries including the origin subestuary at the end of the model run (positive numbers, e.g., 20, 10 and 10 kg for subestuaries #1, #2 and #3, respectively).

**Table 5.4:**

Example calculation of *ED50*, *R5* and *R5SUSP*.

| Subestuary | kg sediment on bed | kg sediment in suspension | *ED50* | *R5* | *R5SUSP* |
|---|---|---|---|---|---|
| 1 (origin) | -100 (1) | 20 (3) | 100/(area × density) | 0 | 20/100 |
| 2 | 20 (2) | 10 (3) | | 20/100 | 10/100 |
| 3 | 40 (2) | 10 (3) | | 40/100 | 10/100 |

The sediment budget, defined as the sum of all terms, necessarily sums to zero, meaning that all of the sediment eroded from the origin subestuary is accounted for.

- Term (1) is converted to ED50 by ED50 = (-1.0 × term (1)) / (origin subestuary area × density of settled sediment), where the density of settled sediment is assumed to be 1200 kg $m^{-3}$.
- R5 is calculated as term (2) / (-1.0 × term (1)) for each subestuary.

- R5SUSP is calculated as term (3) / (-1.0 × term (1)) for each subestuary.

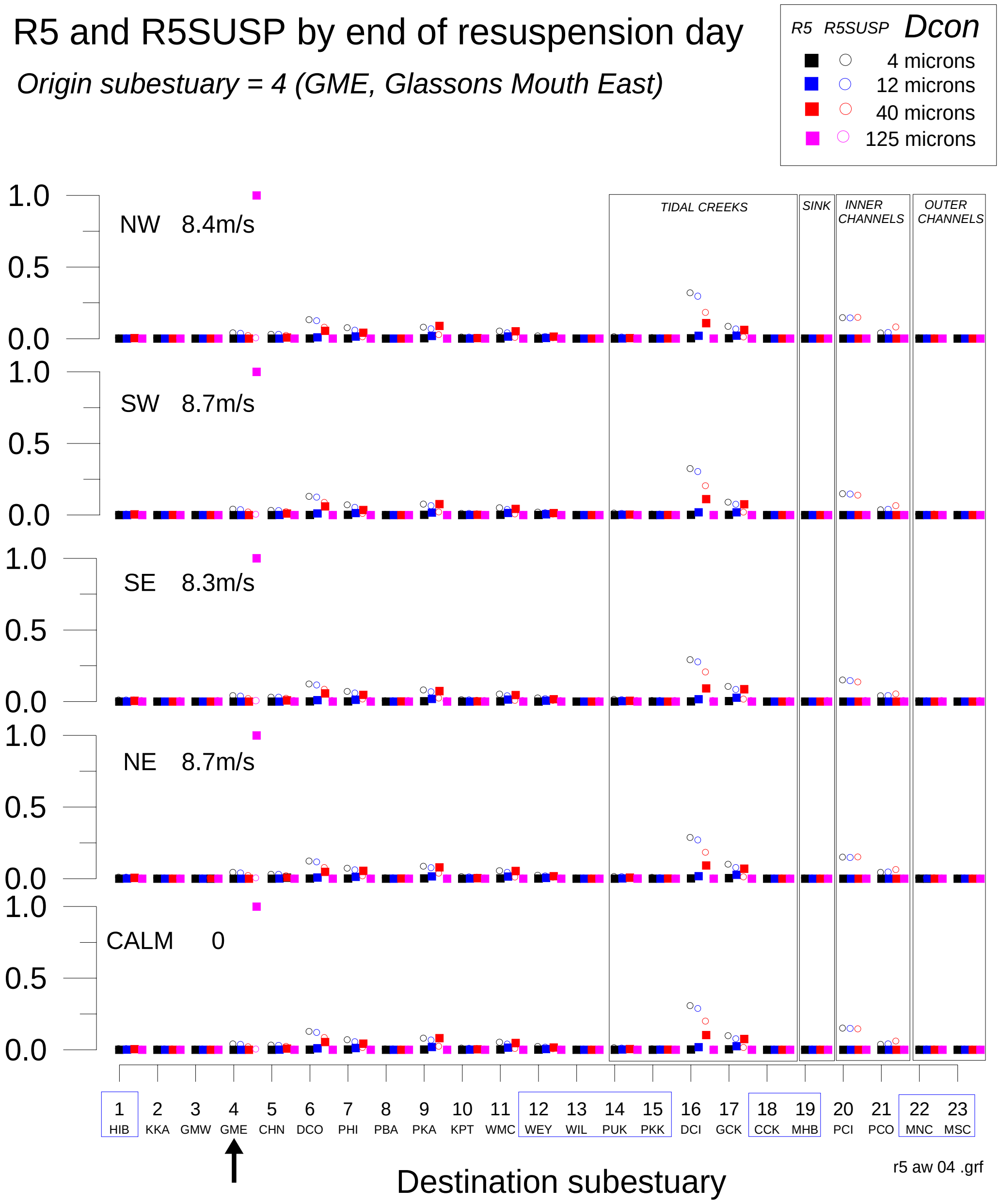
An example of *R5* and *R5SUSP* is shown in Figure 5.6. Sediment resuspended from subestuary 4 (Glassons Mouth East) is seen to spread primarily to the east, further inside the inlet, to Cape Horn (5–CHN), Drury Creek Outer (6–DCO), Pahurehure Inner (7–PHI), Papakura (9–PKA), and Waimahia Creek (11–WMC). No sediment reaches Pahurehure Basin (8–PBA) by the end of the resuspension day, however sediment is pushed into the Drury Creek Inner (16–DCI) and Glassons Creek (17–GCK) tidal creeks. Sediment is left in suspension in the channels inside the inlet (20–PCI and 21–PCO), but no sediment reaches the Manukau Harbour by the end of the resuspension day. More of the 4-μm fraction (washload / slowly-settling, low-density sediment flocs) is left in suspension at the end of the resuspension day compared to the fractions with higher fall speed, and the 4-μm fraction also is seen to be dispersed more widely. The different wind directions do not seem to have much effect on the dispersal patterns, presumably because the origin subestuary is centrally located in the inlet, 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*. Sediment may be resuspended only in subestuaries 1 to 13 (*ED50* may be nonzero). Sediment may not be resuspended in all other subestuaries (*ED50* is zero).
- 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*. $R5SUSP_{kestorigin,kestdestination}$ may be nonzero when *kestorigin* = *kestdestination*.

**Figure 5.6:**

*R5* and *R5SUSP* (dimensionless) showing the dispersal of estuarine bed sediment resuspended from subestuary 4 (Glassons Mouth East – shown the arrow) by the end of the resuspension day.



### 5.6.2 Injection into the harbour of sediments and contaminants when it rains

#### 5.6.2.1 RTC

*RTC* was determined for the eight cases where a subcatchment discharges into a subestuary that is defined as a tidal creek. These are given in Table 5.5.

**Table 5.5:**
The eight cases where a subcatchment discharges into a subestuary that is defined as a tidal creek.

| Subcatchment that discharges into a tidal creek | Subestuary that is the tidal creek discharged into |
|---|---|
| 112 Papatoetoe / Puhinui (PAU) | 14 Puhinui Creek (PUK) |
| 113 Mangere East / Papatoetoe (MEP) | 15 Pukaki Creek (PKK) |
| 114 Mangere (MGE) | 15 Pukaki Creek (PKK) |
| 104 Whangapouri Creek (WHC) | 16 Drury Creek Inner (DCI) |
| 105 Oira Creek (OIC) | 16 Drury Creek Inner (DCI) |
| 106 Drury (DRY) | 16 Drury Creek Inner (DCI) |
| 103 Karaka (KKA) | 17 Glassons Creek Inner (GCK) |
| 101 Kingseat (KST) | 18 Clarks Creek (CCK) |

*RTC* was determined for each of four $D_{con}$ constituent particle sizes (4, 12, 40 and 125 μm) and one set of environmental conditions.

Freshwater input was chosen to vary (Table 5.3) because it is the primary control on tidal-creek dynamics, which in turn affects export of land-derived sediment into the main body of the harbour. Table 5.6 shows the freshwater inputs associated with each of six rainfall bands addressed in the *RTC* simulations. The freshwater runoff from each subcatchment in each rainfall band was established using the TP108 approach (ARC, 1999).

**Table 5.6:**
Freshwater inputs ($m^3\ s^{-1}$) associated with each of six rainfall bands addressed in the *RTC* simulations.

| Subcatchment | Rainfall (mm) | | | | | |
|---|---|---|---|---|---|---|
| | 0.9–4.8 | 4.8–10.6 | 10.6–19.2 | 19.2–50.0 | 50–100 | >100 |
| 101 - KST | 0.18 | 0.18 | 0.33 | 0.97 | 6.25 | 21.10 |
| 102 - EBH | 0.03 | 0.03 | 0.08 | 0.30 | 2.18 | 7.44 |
| 103 - KKA | 0.30 | 0.30 | 0.42 | 0.94 | 5.46 | 18.34 |
| 104 - WHC | 0.50 | 0.55 | 0.84 | 1.84 | 9.50 | 30.05 |
| 105 - OIC | 0.17 | 0.17 | 0.24 | 0.55 | 3.15 | 10.40 |
| 106 - DRY | 1.00 | 1.08 | 1.88 | 4.75 | 26.32 | 82.28 |
| 107 - HGA | 0.125 | 0.13 | 0.15 | 0.22 | 0.77 | 2.28 |
| 108 - PKA | 0.14 | 0.18 | 0.31 | 0.67 | 2.96 | 8.39 |
| 109 - TKI | 0.125 | 0.14 | 0.18 | 0.29 | 1.00 | 2.70 |
| 110 - PAS | 0.25 | 0.36 | 0.79 | 2.03 | 10.12 | 29.40 |
| 111 - MAW | 0.125 | 0.19 | 0.35 | 0.67 | 2.22 | 5.52 |
| 112 - PAU | 0.24 | 0.46 | 0.99 | 2.08 | 7.59 | 19.41 |
| 113 - MEP | 0.26 | 0.30 | 0.41 | 0.60 | 2.25 | 5.89 |
| 114 - MGE | 0.23 | 0.25 | 0.31 | 0.47 | 1.48 | 3.88 |
| 115 - BTB | 0.11 | 0.11 | 0.13 | 0.17 | 0.44 | 1.14 |

A unit load of land-derived sediment was injected into the head of each tidal creek in suspension (Figure 5.7). The sediment was injected continuously over the first 24 hours of each simulation. The injected sediment was tracked until “equilibrium” was attained. This was defined as the time when all (at least 99%) of the injected sediment could be accounted for by settlement to the bed (anywhere in the harbour where deposition is permitted) or loss to a sink. *RTC* is defined as the ratio of sediment exported from the tidal creek by the end of the simulation to the amount of sediment injected into the tidal creek.

**Figure 5.7:**

Sediment injection point for the *RTC* simulations. Also shown is the injection point for the *R* simulations.

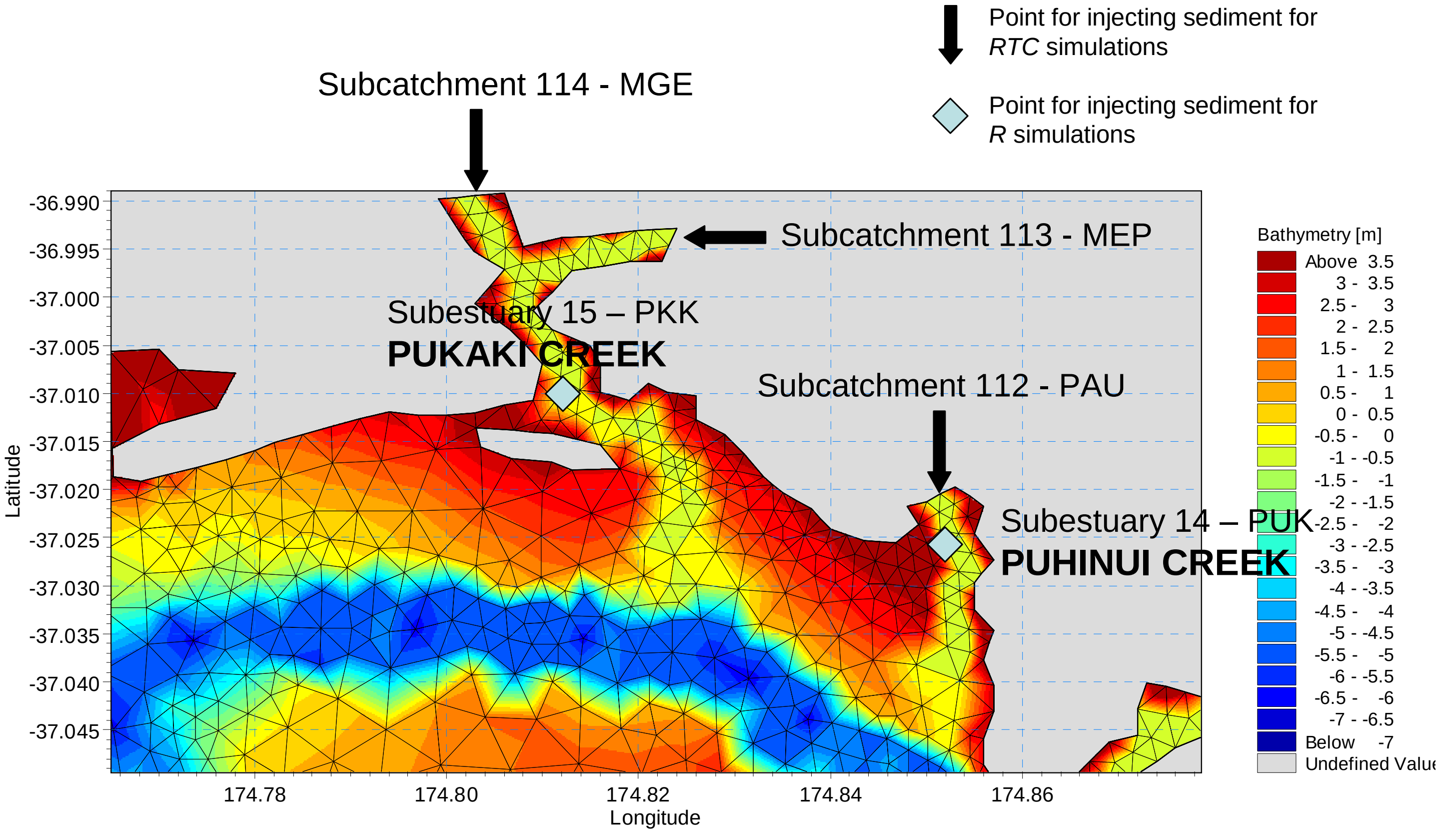


**Figure 5.7: (continued)**

Sediment injection point for the *RTC* simulations. Also shown is the injection point for the *R* simulations.

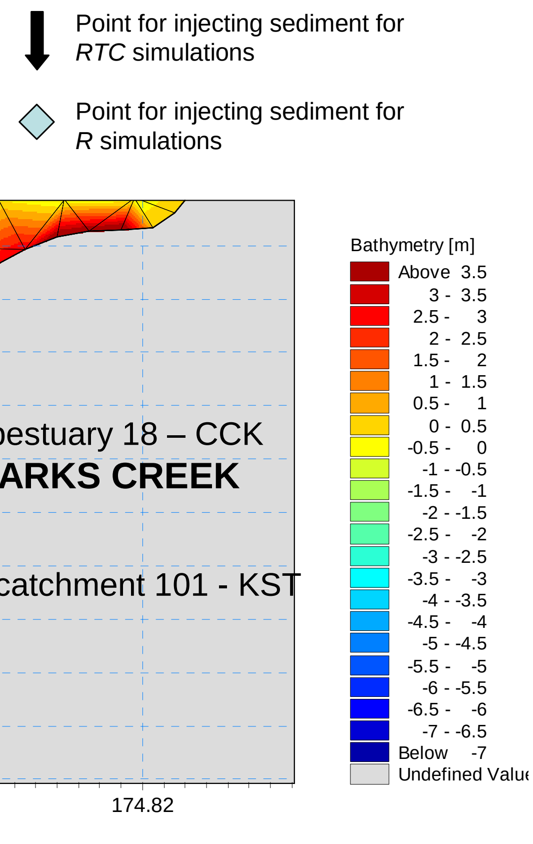
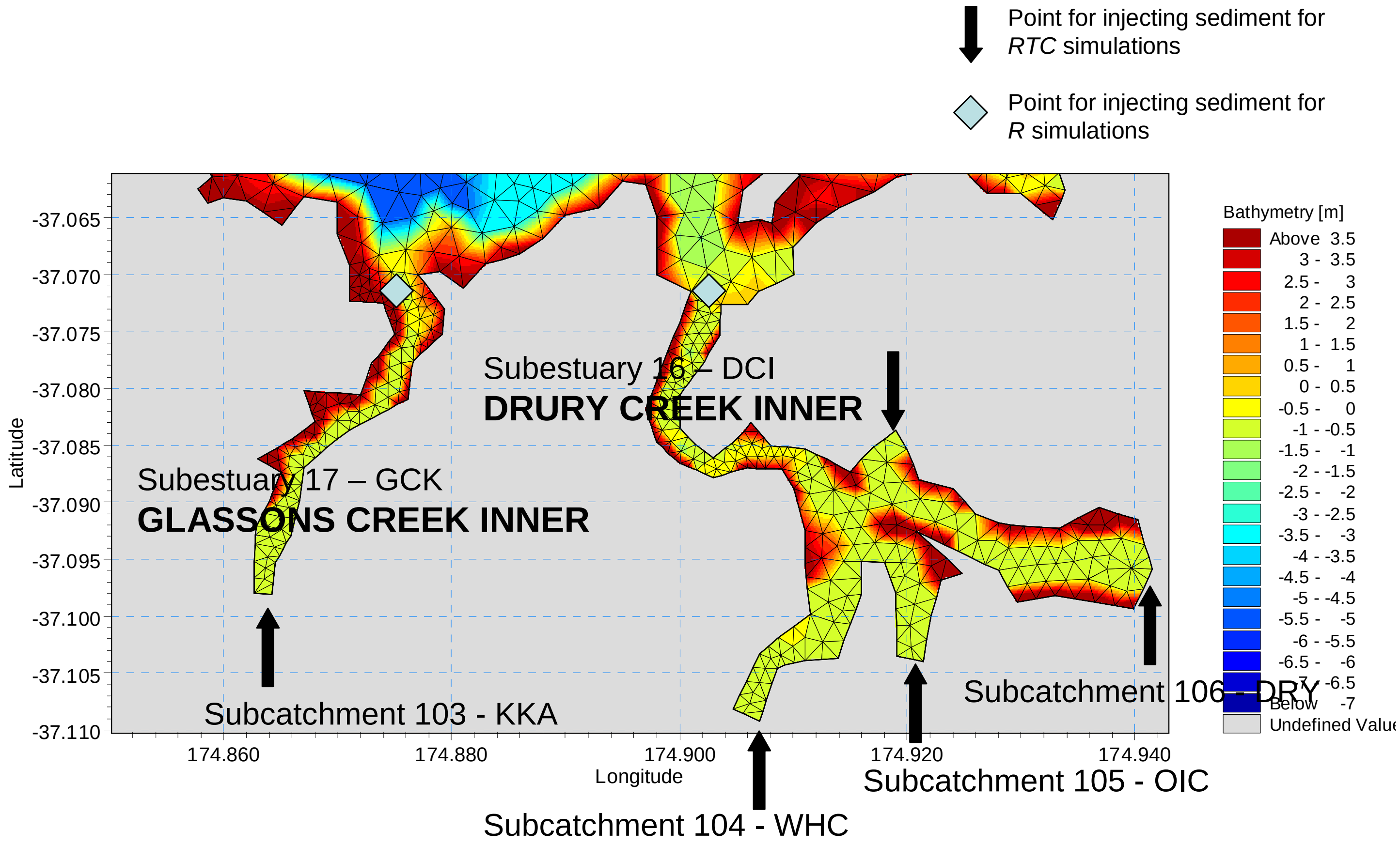


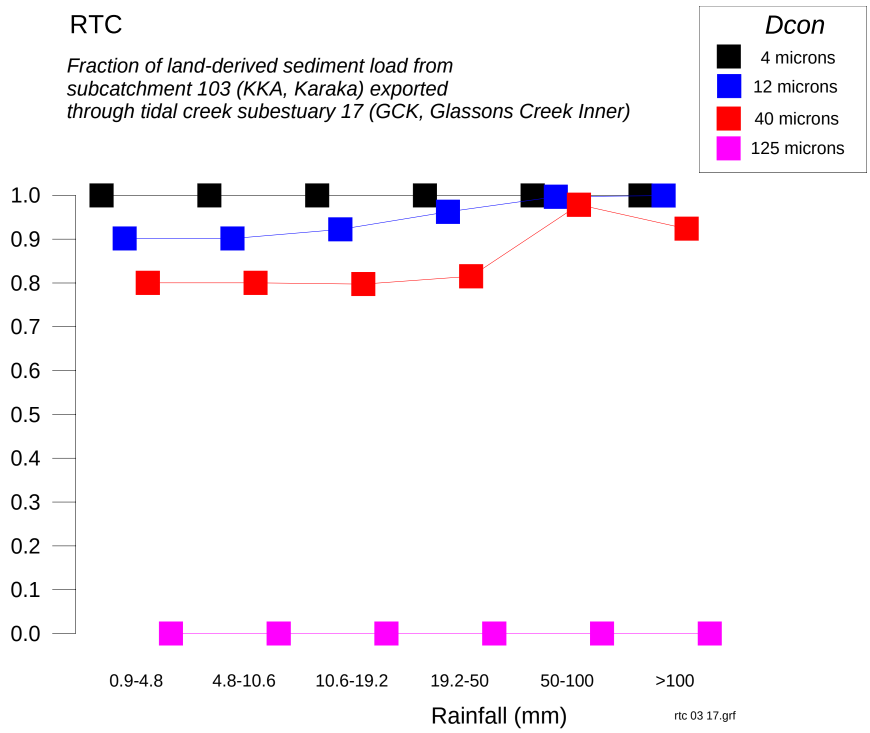
**Figure 5.7: (continued)**

Sediment injection point for the *RTC* simulations. Also shown is the injection point for the *R* simulations.



An example of *RTC* is shown in Figure 5.8. There is virtually no retention of 4 µm sediment (washload / low-density, slowly-settling sediment flocs) in Glassons Creek Inner tidal creek during rainfall. Compared to 4 µm sediment, more 12 µm and 40 µm sediment is retained in the tidal creek. As rainfall and the corresponding freshwater discharge increase, a greater portion of both the 12 µm and 40 µm sediments is flushed from the tidal creek.

**Figure 5.8:**
*RTC* for attenuating the land-derived sediment load from subcatchment 103 (Karaka) as it passes through subestuary 17, Glassons Creek Inner, which is a tidal creek.




#### 5.6.2.2 R and RSUSP

*R* and *RSUSP* were determined for each of the four $D_{con}$ constituent particle sizes (4, 12, 40 and 125 µm, where 4 µm represents washload / low-density, slowly-settling sediment flocs) and the environmental conditions shown in Table 5.3.

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. For the subcatchments that discharge into subestuaries that are designated as tidal creeks (Table 5.5), the injection point was at the mouth of the corresponding tidal creek (see Figure 5.7). For all other subcatchments, 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.

For the purposes of this explanation, assume the origin subcatchment is subcatchment #1 and there are three subestuaries in total in the model domain. At the end of the model run, a sediment budget is constructed (Table 5.7), consisting of the amount of sediment deposited in each subestuary by the end of the injection day, and the amount of sediment remaining in suspension in each subestuary by the end of the injection day. *R* and *RSUSP* are calculated from the sediment budget as shown in Table 5.7.

**Table 5.7:**

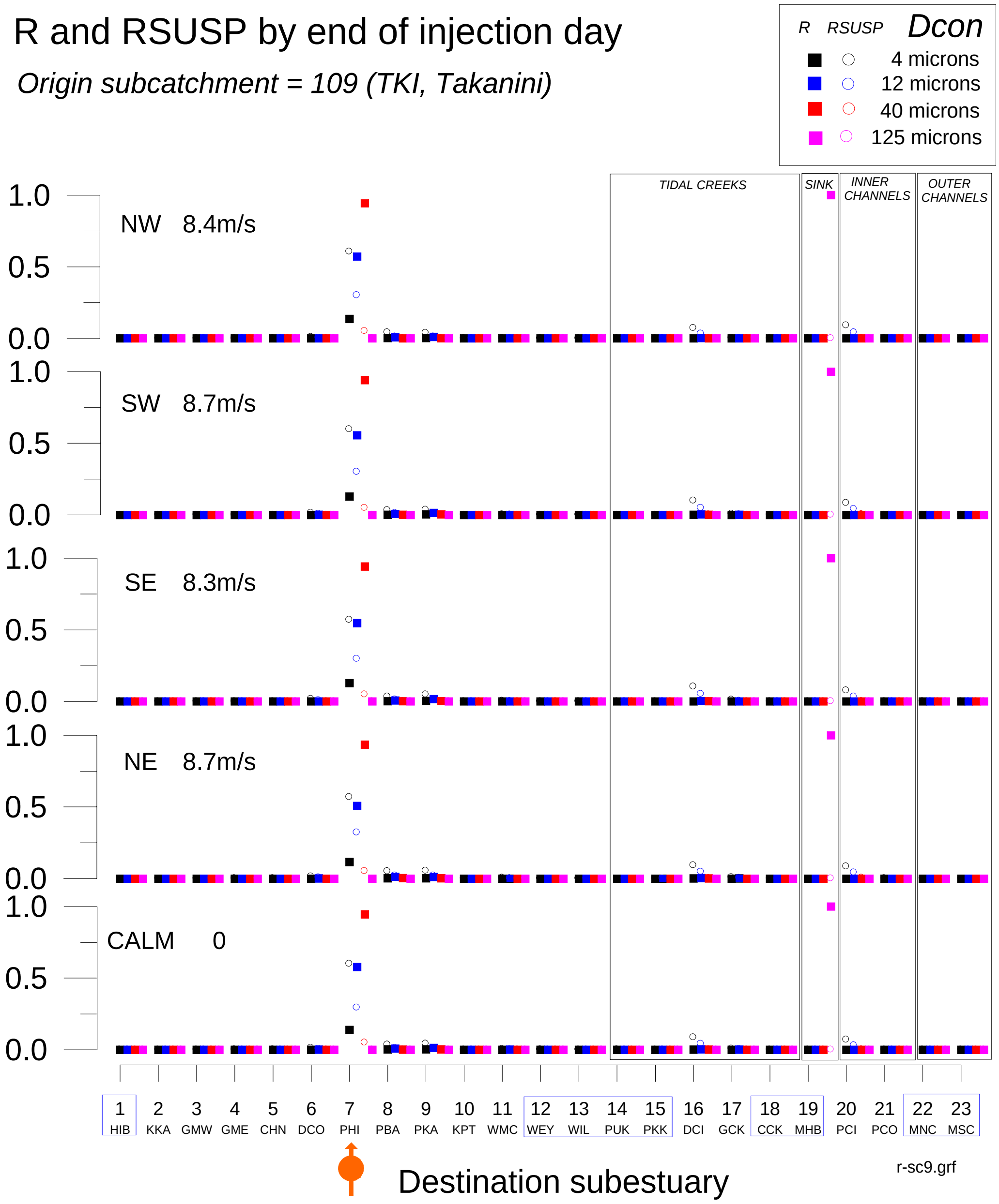
Example calculation of *R* and *RSUSP*.

| **Subcatchment** | **kg sediment injected** | **Subestuary** | **kg sediment deposited** | ***R*** | **kg sediment in suspension** | ***RSUSP*** |
|---|---|---|---|---|---|---|
| 1 | 1000 | 1 | 100 | 100/1000 | 0 | 0/1000 |
| | | 2 | 200 | 200/1000 | 500 | 500/1000 |
| | | 3 | 300 | 300/1000 | 0 | 0/1000 |

An example of *R* and *RSUSP* is shown in Figure 5.9, for land-derived sediment from Takanini subcatchment discharged initially into the Pahurehure Inner (7–PHI) subestuary. Some sediment does reach Papakura (9–PKA) to the west of the initial injection point, and Pahurehure Basin (8–PBA) to the east of the initial injection point, but most of the injected sediment remains largely confined to the Pahurehure Inner (7–PHI) subestuary by the end of the injection day. A small fraction of the injected sediment does reach the Drury Creek Inner (16–DCI) tidal creek, and some remains in suspension in the Pahurehure Inner Channel (20–PCI). More of the 4 μm fraction (washload / low-density, slowly-settling sediment flocs) is left in suspension at the end of the injection day compared to the fractions with higher fall speed, and the 4 μm fraction also is seen to be dispersed more widely.

**Figure 5.9:**

*R* and *RSUSP* (dimensionless) showing the dispersal of land-derived sediment injected from subcatchment 109 (Takanini – shown the arrow) by the end of the injection day.




Note:

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

### 5.6.3 Dispersal of sediment on days following resuspension / injection day

#### 5.6.3.1 RFS

*RFS* was determined for each of the four $D_{con}$ constituent particle sizes (4, 12, 40 and 125 μm, where 4 μm represents washload / low-density, slowly-settling sediment flocs) and the environmental conditions shown in Table 5.3. 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, as shown in Table 5.3.

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. Table 5.8 shows an example.

**Table 5.8:**

Example calculation of *RFS*.

| Subestuary | kg sediment in suspension at start of DHI model run | kg sediment in suspension at end of DHI model run | *RFS* |
|---|---|---|---|
| 1 (origin) | 1000 | 200 | 200/1000 |
| 2 | 0 | 500 | 500/1000 |
| 3 | 0 | 300 | 300/1000 |

Figure 5.10 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 the Glassons Mouth East subestuary (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.). No sediment that was resuspended from Glassons Mouth East reached the Manukau Harbour by the end of the resuspension day. All particle sizes (except the 125 μm fraction, which cannot move) disperse further on the days following resuspension. Note, in particular, the loss of sediment to the Manukau Harbour, which includes deposition on intertidal flats (1–HIB, 12–WEY, 13–WIL), transport up tidal creeks (14–PUK, 15–PKK) and loss to the wider harbour (19–MHB). The 4 μm particle size experiences the greatest loss, which is expected.

**Figure 5.10:**

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 Glassons Mouth East subestuary.

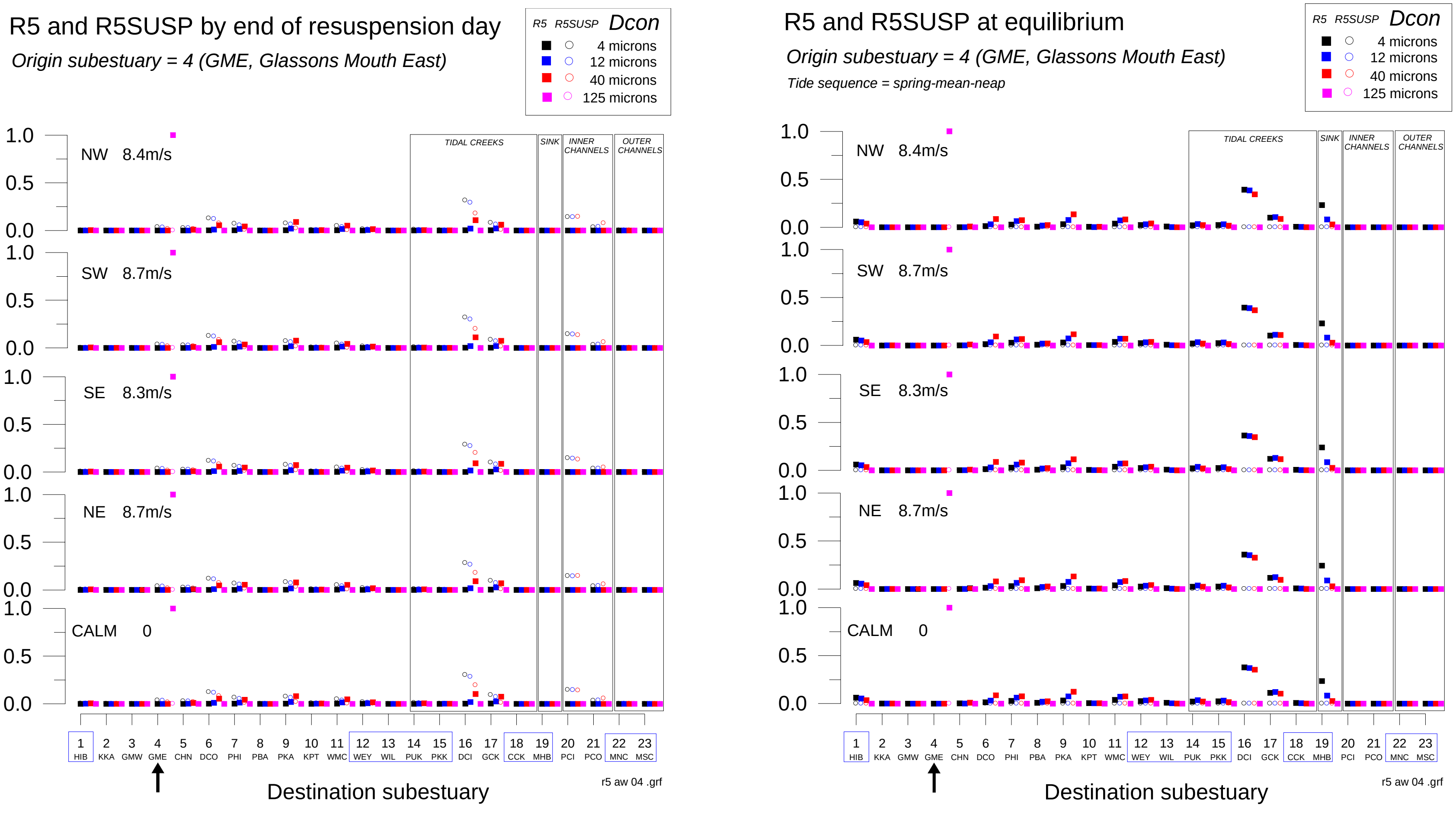
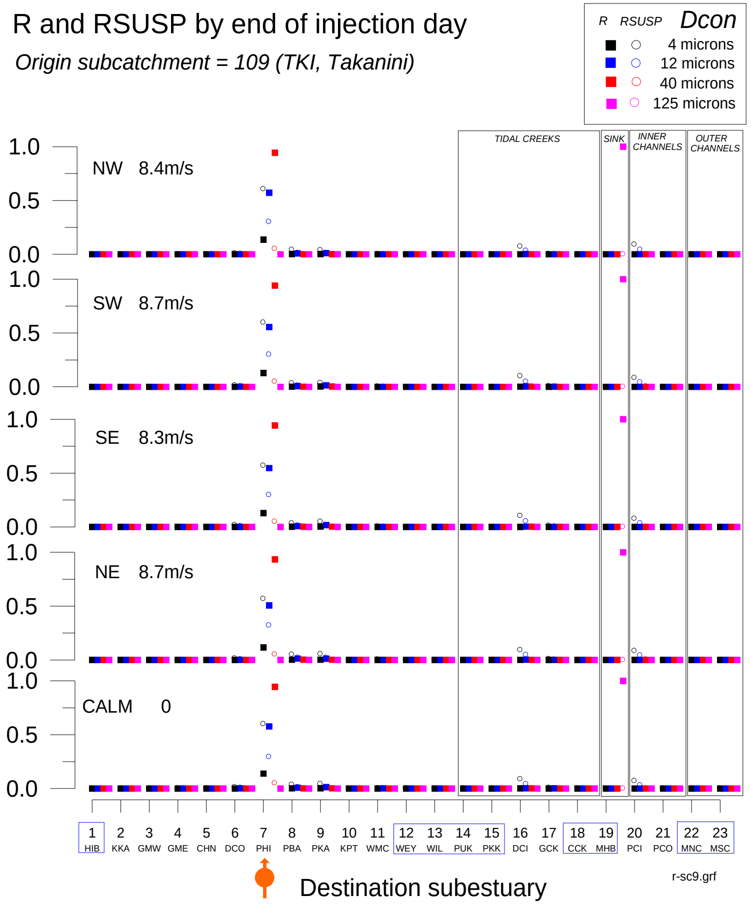
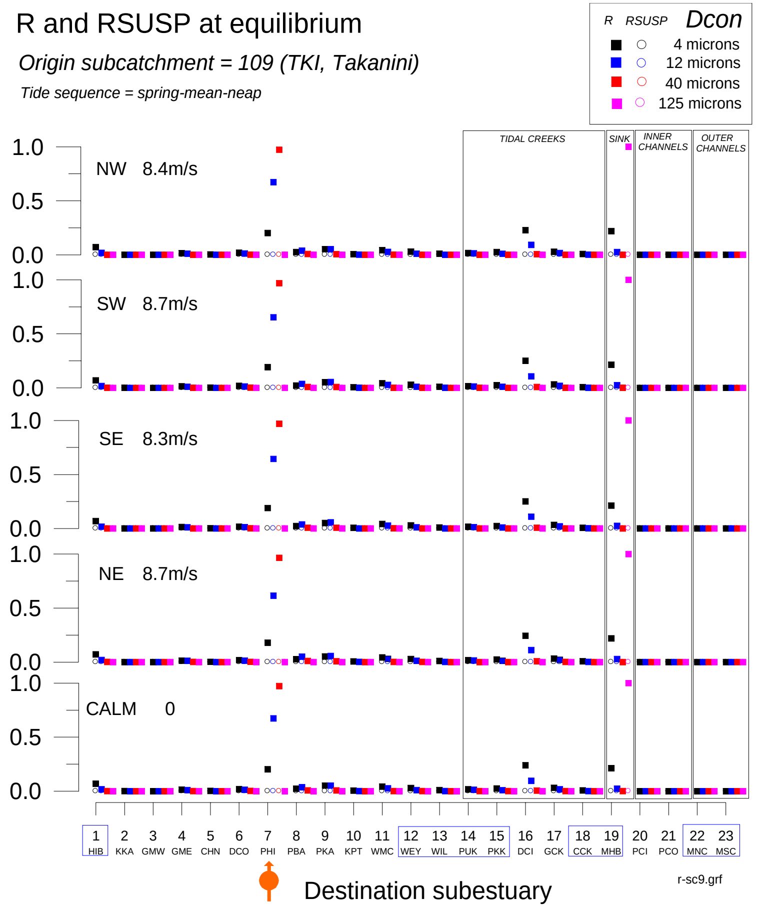


Figure 5.11 shows a comparison between *R* at the end of the injection day and *R* at equilibrium (i.e., after applying *RFS*) for land-derived sediment injected from the Takanini (subcatchment 109) outfall (Note that after application of *RFS* no sediment is left suspended anywhere in the model domain. Hence, there is no sediment in the deep channels, since sediment in deep channels can only be in suspension.). The 4 µm particle size (washload / low-density, slowly-settling sediment flocs) is seen to disperse more widely than the larger particle sizes on the days following injection. Note, in particular, the spread of sediment throughout the middle reaches of Pahurehure Inlet, deposition in Drury Creek, and loss of sediment to Manukau Harbour.

**Figure 5.11:**

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 Takanini (subcatchment 109) outfall.



## 5.7 Calculation of heavy-metal concentration in surface mixed layer

Mixing on the one hand moves sediments (and attached heavy metals) near the surface of the sediment column deeper into the sediment column, and on the other hand moves sediments deeper in the sediment column towards the surface. Mixing therefore has the net effect of reducing gradients in heavy-metal concentrations in the bed sediment. For example, a recently deposited layer carrying heavy metals at a concentration greater than in the underlying bed sediment will get mixed downwards, obliterating the concentration gradient between the recently deposited layer and the underlying bed sediment, and slightly raising the concentration in the surface mixed layer (which now includes the recently deposited layer) as a whole. If the recently deposited layer carries metal at a concentration less than the underlying bed sediment, then concentration in the mixed layer will be reduced.

For the application of the USC-3 model in Southeastern Manukau Harbour / Pahurehure Inlet, mixing is assumed to act uniformly over the surface mixed layer, which extends to a depth of *MIXDEPTH* (mixing depth) from the surface.

After mixing, the concentration of heavy metals in the surface mixed layer is given by the ratio of the total amount of heavy metal (attached to all particle sizes) in the surface mixed layer to the total amount of sediment (i.e., all particle sizes) in the surface mixed layer:

$$HEAVYMETALCONC\underline{SML} =$$

$$\sum_{iparticle=1}^{nparticle} HEAVYMETALMASS\underline{SML}_{iparticle} \Big/ \sum_{iparticle=1}^{nparticle} SEDIMENTMASS\underline{SML}_{iparticle}$$

Hence, heavy-metal concentration is expressed as mass of heavy metal per mass of sediment. Furthermore, heavy-metal concentrations are “total-sediment” concentrations.

- ❑ Note that *HEAVYMETALCONC<u>SML</u>* is the primary output of the USC-3 model.

Sediment and heavy metals are taken from the (layered) bed sediment column each time the heavy-metal concentration is to be evaluated, as follows:

$$HEAVYMETALCONC\underline{SML} =$$

$$\sum_{ilayer=1}^{nlayersmixed} \sum_{iparticle=1}^{nparticle} HEAVYMETALMASS\underline{SML}_{iparticle,ilayer} \Big/ SEDIMENTMASS\underline{SML}_{iparticle,ilayer}$$

where there are *nlayersmixed* layers in the bed sediment column corresponding to the mixing depth *MIXDEPTH*.

As noted previously, if it is not raining, the heavy-metal concentration is made to apply at the end of the resuspension day (i.e., the day the sediment was resuspended), even though *RFS* acts beyond that day to fully disperse and deposit resuspended sediment.

Similarly, if is it raining, the heavy-metal concentration is made to apply at the end of the day it was raining, even though *RFS* acts beyond that day to fully disperse and deposit both the injected land-derived sediments and the resuspended estuarine bed sediments.

## 5.8 Completion of the time series for driving the USC-3 model

The scheme for evaluating the land-derived sediment and contaminant loads at BOC (described previously) resulted in a 100-year time series of daily rainfall and corresponding 100-year time series of sediment runoff emanating from the bottom of each subcatchment. The daily timestep of these series matches the daily timestep of the USC-3 model. These series are used to drive the USC-3 model.

Further daily time series are required to drive the model. These are the rainfall band, the wind, and the tide range. These are used to choose the various parameters in the model that get applied on a daily basis (for example, see Table 5.3).

### 5.8.1 Rainfall band

The rainfall band on each day is evaluated from the daily rainfall time series. Rainfall bands are shown in Table 5.3. Furthermore:

- If the daily rainfall is less than 0.9 mm it is said to be "not raining".
- If the daily rainfall is greater than 0.9 mm it is said to be "raining".

A threshold of 0.9 mm rainfall was chosen as the rainfall required across the catchment to have any significant effect on freshwater inflows and sediment delivery to the harbour.

Rainfall bands above the 0.9-mm threshold (Table 5.3) were chosen to span extreme events.

### 5.8.2 Wind

The wind on each day is randomly chosen from the possibilities shown in Table 5.3.

The random choice is constructed so that calm winds occur 80% of the time. Here, "calm" means wind speed less than 4 m $s^{-1}$, which is not sufficient to raise any significant wave activity in the harbour. The "non-calm" wind speeds (Table 5.3) were chosen to represent more extreme wind events, which in turn is intended to depict larger and "more effective" sediment resuspension and transport episodes.

If it is not calm, then:

- winds from the northeast are chosen 3% of the time;
- winds from the southeast are chosen 2% of the time;
- winds from the southwest are chosen 13% of the time;

- winds from the northwest are chosen 2% of the time.

This scheme yields wind speeds and directions at frequencies that correspond to frequencies that emerge from analysis of 3-hourly wind data from Auckland Airport for the period 1980–2005.

### 5.8.3 Tide range

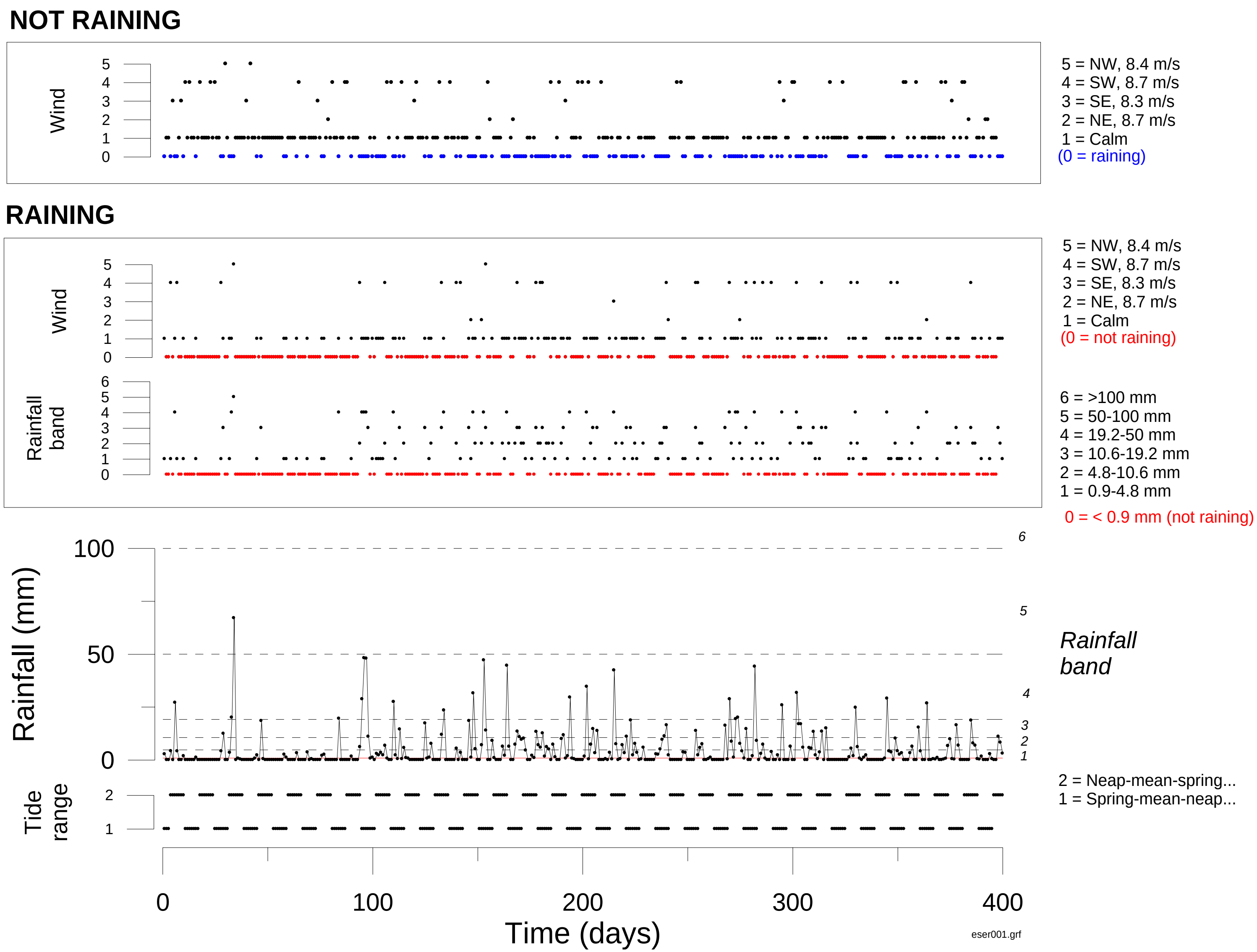
The tide range is “deterministic”, meaning that it can be predicted exactly in advance. For each of the $N$ model simulations in a Monte Carlo “package”, the tide range at the starting point in the simulation at hand is chosen randomly.

### 5.8.4 Complete set of time series

An example of a complete set of time series (all with a daily timestep) for driving the USC-3 model is shown in Figure 5.12.

**Figure 5.12:**

First 400 days of a complete set of time series, all with a daily timestep, for driving the USC-3 model.



## 5.9 Mixing depth

Reed et al. (2008) reported depth of the surface mixed layer (SML) at one site in Southeastern Manukau Harbour (Weymouth Intertidal flats) and at five sites inside Pahurehure Inlet (near the mouth of Waimahia Creek; near the mouth of the Papakura subestuary; two sites in the Pahurehure Inner subestuary; and at the mouth of Drury Creek). In all cases, depth of the SML, inferred from profiles of $^{7}Be$ in bed sediments, was found to be 3–4 cm. The mixing depth in the USC-3 model is physically equivalent to the depth of the SML. Hence, the mixing depth in the model was set to 4 cm uniformly throughout the model domain. The mixing depth in the USC-3 model applies to the sediment column as a whole (i.e., to all constituent particle sizes).

# 6 Model Calibration

The USC-3 model was run for the historical period 1940 to 2001, with sediment and metal 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.

The parameters that may be adjusted to achieve model calibration are:

- the fraction of the sediment runoff from the land that is treated as washload / slowly-settling, low-density flocs;
- the areas over which sediments may deposit;
- the various terms that control sediment and attached metal dispersal and deposition; and
- the metal retention factor, which is the fraction of the metal load emanating from each subcatchment that is attached to the corresponding sediment particulate load.

Adjustments in these terms are made until realistic sediment dispersal patterns, sedimentation rates and metal accumulation rates are simultaneously obtained. The model with those adjusted terms then constitutes the calibrated model.

For model calibration, the USC-3 model was run in a Monte Carlo package, which consisted of 50 individual USC-3 model runs. The average of the 50 individual model outputs was used in the calibration process.

## 6.1 Landuse – historical period

The method applied to develop a description of the landuse for the historical period, and the landuse so derived, are documented in Parshotam et al. (2008a).

## 6.2 Sediment inputs – historical period

The total sediment runoff from the catchment into the harbour is the sum of the sediment runoff from rural areas, which is hindcast by GLEAMS, and the sediment runoff from urban areas, which is hindcast by the CLM.

The implementation of GLEAMS for the Study is documented by Parshotam et al. (2008b) and Parshotam et al. (2008c). The GLEAMS historical-period hindcasts are presented in detail by Parshotam (2008).

The implementation of the CLM for the Study is documented by Moores and Timperley (2008). The CLM historical-period hindcasts are also presented there in some detail.

<u>Note</u>: for the historical period only, the GLEAMS hindcasts were of sediment runoff from rural areas plus sediment runoff from greenfields bare earth (earthworks) in urban

areas. Correspondingly, the CLM hindcasts were of sediment runoff from urban areas not including sediment runoff from greenfields bare earth (earthworks).

### 6.2.1 Sediment inputs from rural sources

Fifty time series, each covering the period 1940–2001, of daily rural sediment runoff from each subcatchment are required (one time series for each USC-3 model run in the Monte Carlo package). Each of these 50 time series was constructed by block sampling of hindcasts from GLEAMS.

GLEAMS was run for four historical landuses, these corresponding to the years 1945, 1959, 1987 and 2001. Each of these runs was driven by a 50-year rainfall time series covering the period 1 January 1956 to 31 December 2005.

For the purposes of the block sampling, these landuses, and the corresponding GLEAMS hindcasts of rural sediment runoff, were deemed to apply for the following periods of time:

- 1945 landuse applies to the period 1940–1953;
- 1959 landuse applies to the period 1954–1978;
- 1987 landuse applies to the period 1979–1996;
- 2001 landuse applies to the period 1997–2001.

The block sampling scheme has been described earlier in this report. Because it is a random scheme, each of the 50 time series of daily rural sediment runoff may be unique.

The split of the rural sediment load amongst the constituent particle sizes 12, 40 and 125 µm is shown in Table 6.1, hindcast by GLEAMS and averaged over all years in the historical period, which hides some temporal variability. (All tables and figures for this chapter are presented in one place at the end of the chapter.) The reader is referred to Parshotam (2008) for further details. Note that sediment is assigned to the 4 µm particle size (washload / low-density, slowly-settling flocs) as part of the calibration process (to be described).

### 6.2.2 Sediment inputs from urban sources

Fifty time series, each covering the period 1940–2001, of daily urban sediment runoff from each subcatchment are also required (as before, one time series for each USC-3 model run in the Monte Carlo package).

The CLM was used to produce a hindcast of annual (not daily) urban sediment runoff from each subcatchment for the period 1940–2001. The fifty required time series of daily urban sediment runoff (one time series for each USC-3 model run in the Monte Carlo package, with each time series covering the period 1940–2001) were constructed by distributing the urban sediment runoff for each year in proportion to the corresponding daily GLEAMS sediment loads for that same year, as described earlier in this report.

The split of the urban sediment load from each subcatchment amongst the constituent particle sizes 12, 40 and 125 µm was calculated by the CLM. Results are shown in Table 6.2, averaged over all years in the historical period, which hides some temporal variability. Again, sediment is assigned to the 4 µm particle size (washload / low-density, slowly-settling flocs) as part of the calibration process (to be described).

### 6.2.3 Total (rural plus urban) sediment inputs

The daily rural and daily urban sediment runoffs were added to give daily total sediment runoffs. This results in 50 daily time series (one time series for each USC-3 model run in the Monte Carlo package, with each time series covering the period 1940–2001).

Note that the rural component of the total sediment runoff may vary from time series to time series, since this is constructed from random sampling of the GLEAMS outputs. The sum-over-each-year of the urban component of the total sediment runoff will be the same for every time series, since these derive from the hindcast by the CLM of annual urban sediment loads. However, the distribution of the daily urban sediment runoff throughout the year may vary from time series to time series, as this depends on the daily rural (GLEAMS) sediment runoff.

Table 6.3 and Figure 6.1 show some statistics of the total (urban plus rural) sediment runoff.

- The Drury subcatchment (106 – DRY) is the principal source of sediment to the harbour. This is also the largest subcatchment, so it is not necessarily the case that sediment yield (sediment generation per unit area) is also largest for this subcatchment. Parshotam (2008) gives details on sediment yields. The Papakura Stream subcatchment (110 – PAS) is the next largest source, which is also the next largest catchment. The two smallest sediment sources are the Bottle Top Bay subcatchment (115 – BTB) and the Takanini subcatchment (109 – TKI), which are also the smallest subcatchments.
- The larger rainfall events deliver more sediment to the harbour than the smaller rainfall events. However, summed over the duration of the simulation, medium-size events deliver more sediment than both smaller and larger events. Small-size events occur more frequently than medium-size events, but they deliver less sediment per event. Large-size events deliver more sediment per event than medium-size events, but they occur less frequently.

Figure 6.2 shows the annual sediment runoff, and Table 6.4 shows for each subcatchment the average (over the historical period) fraction of the annual sediment runoff that comes from urban sources. The rest comes from rural sources. Figure 6.3 shows how the rural–urban split for each subcatchment varies over time during the historical period.

- Sediment runoff from subcatchments that lie to the south of Pahurehure Inlet typically derived mainly from rural sources. For those subcatchments that did have urban sources of sediment, those urban sources increased in relative significance over time in the historical period. Subcatchments 101 (Kingseat), 102 (Elletts Beach), 103 (Karaka) and 105 (Oira Creek) had no urban areas, hence all the sediment in these subcatchments derived from rural sources. The town of Pukekohe is located in subcatchment 104 (Whangapouri Creek), which accounts for the 26% of the sediment runoff in that case that was attributable to urban sources. That fraction did not change appreciably over the historical period. Early in the historical period nearly all of the sediment runoff from subcatchment 106 (Drury; this subcatchment contains part of the town of Papakura and the town of Drury) was attributable to rural sources, but the urban contribution began to increase from about 1960. Averaged over the historical period, the urban contribution for subcatchment 106 was 15%. Subcatchments 107 (Hingaia) and 115 (Bottle Top Bay) behaved similarly to subcatchment 106: early in the historical period sediment runoff was primarily from rural sources; urban sources began to contribute around 1960; and the historical-period-average contribution from urban sources was about 15%.

- Subcatchment 108 (Papakura), which drains at the top of the Inlet and which contains most of the town of Papakura, began the historical period with urban sources contributing 20–30% of the sediment runoff, and this contribution increased slightly to result in an average over the historical period of 32%.
- With one exception, sediment runoff from subcatchments that lie to the north of Pahurehure Inlet typically derived mainly from urban sources, and the relative significance of those urban sources increased over time in the historical period. The most urbanised of these subcatchments was Manurewa / Weymouth (111), for which 80% of the sediment runoff derived from urban sources, averaged over the historical period. Subcatchment 109 (Takanini) was the second-most urbanised subcatchment (65% of sediment from urban sources averaged over the historical period). For both of these subcatchments (111 and 109), nearly all of the sediment runoff was from urban sources by the end of the historical period. The exception was subcatchment 110 (Papakura Stream), which averaged 26% of sediment from urban sources.
- Sediment runoff from subcatchment 112 (Papatoetoe / Puhinui), which discharges to the northern shore of Manukau Harbour, was similarly urbanised, with 53% of the sediment runoff attributable to urban sources, averaged over the historical period. That fraction increased significantly over the historical period, beginning the period around 10% and ending around 90%. The other subcatchments that discharge to the northern shore of Manukau Harbour are less urbanised: subcatchment 113 (Mangere East / Papatoetoe) averaged 30% and subcatchment 114 (Mangere) averaged just 10% of sediment runoff due to urban sources.
- For most subcatchments there was no obvious trend in magnitude of sediment runoff over the historical period. The exception was subcatchment 112 (Papatoetoe / Puhinui), which underwent significant urbanisation in the historical period.

Figure 6.4 shows daily total (rural plus urban) sediment runoff plotted against rainfall. The large variability in the response of the catchment to rainfall is apparent, which is due to GLEAMS capturing the effects on sediment generation of antecedent rainfall and rainfall intensity on the day of generation.

## 6.3 Metal inputs – historical period

### 6.3.1 Natural metal inputs

Zinc was assigned to sediment runoff from the land at a concentration of 35 mg $kg^{-1}$ for all particle size fractions. Copper was likewise assigned at 7 mg $kg^{-1}$.

### 6.3.2 Anthropogenic metal inputs

The CLM was used to produce a hindcast of annual anthropogenic zinc and copper loads at the bottom of each subcatchment, split by sediment constituent particle size that carries that load, for each year during the historical period.

The implementation of the CLM for this study is documented by Moores and Timperley (2008). The CLM historical-period hindcasts are also presented there in some detail.

Figure 6.5 shows the anthropogenic zinc loads, and Table 6.5 shows how the zinc load is carried on the 12, 40 and 125 µm sediment constituent particle sizes.

Figure 6.6 shows the anthropogenic copper loads, and Table 6.6 shows how the copper load is carried on the 12, 40 and 125 µm sediment constituent particle sizes.

Note that metals are assigned to the 4 µm sediment particle size (washload / low-density, slowly-settling flocs) as part of the calibration process (to be described).

### 6.3.3 Total (anthropogenic plus natural) metal inputs

Each annual anthropogenic load of metal is fully distributed over the days in that year such that no part of the annual load is "carried over" into a succeeding year. Specifically, the annual anthropogenic heavy-metal load emanating from each subcatchment is broken down into daily loads over that same year in proportion to the daily GLEAMS sediment loads, as described earlier in this report.

The daily anthropogenic metal loads so formed were added to the daily natural metal loads to form the daily total metal loads. Table 6.7 (zinc) and Table 6.8 (copper) show the total (anthropogenic plus natural) metal loads, and how those total loads are constituted between anthropogenic and natural sources.

For zinc:

- Subcatchment 112 (Papatoetoe / Puhinui) was the largest source of zinc, and nearly all of that (97%) derived from anthropogenic sources. The next largest source was subcatchment 108 (Papakura), which contains most of the town of Papakura, and 97% of the zinc was from anthropogenic sources. The third largest source was subcatchment 106 (Drury), which contains part of the town of Papakura and the town of Drury, and 80% of the zinc was from anthropogenic sources.

- For subcatchments with any anthropogenic zinc (all except 101, 102, 103 and 105), the contribution to the total zinc load from anthropogenic sources ranged between 79–97%. The fraction of the total sediment runoff in these same subcatchments that was attributable to urban sources ranged between 0.10–0.80. Therefore, zinc always derived mainly from anthropogenic sources, even though sediment may have derived mainly from rural sources.
- Anthropogenic zinc loads tended to increase in all subcatchments over the historical period.

For copper:

- Subcatchment 112 (Papatoetoe / Puhinui) was also the largest source of copper, and nearly all of that (91%) derived from anthropogenic sources.
- For subcatchments with any anthropogenic copper (all except 101, 102, 103 and 105), the contribution to the total copper load from anthropogenic sources ranged between 38–93%. Anthropogenic copper tended to make a smaller contribution to the total copper load than anthropogenic zinc did to the total zinc load (79–97%).
- Anthropogenic copper loads tended to increase in all subcatchments over the historical period.

## 6.4 Concentration at which metals are delivered to the harbour – historical period

The concentrations at which total (anthropogenic plus natural) metals are delivered to the harbour over the historical period are shown in Figures 6.7 and 6.8.

Concentrations generally increased through the historical period, as anthropogenic metal loads increased, while sediment runoff remained more-or-less constant. The exceptions were those subcatchments with no urbanised land (subcatchments 101, 102, 103 and 105). Here, concentrations remained fixed at the natural (catchment soil) level (35 mg $kg^{-1}$ for zinc; 7 mg $kg^{-1}$ for copper).

Where there is an anthropogenic metal load, the concentrations at which total metals have been delivered to the harbour over the historical period are typically much higher than the present-day concentrations in the estuarine bed sediments (to be described). The discrepancy is due to bed-sediment mixing in the harbour, which confers an “inertia” to the system. This occurs through mixing of highly contaminated sediments that arrive during rainstorms from the catchment down into the “ballast” of less contaminated estuarine sediments. This has the effect of reducing metal concentrations in the surface mixed layer compared to the concentrations at which metals left the catchment. I t is noteworthy that the increase over the historical period in concentration at which metals are delivered to the harbour will have driven a corresponding increase in the rate of increase of metal concentrations in the surface mixed layer of the estuarine bed sediments.

## 6.5 Initial conditions

For each subestuary, the split of the sediment in the surface mixed layer amongst the constituent particle sizes needs to be specified for the start of the historical period. Without any better information available, the particle size distribution in the surface mixed layer of the present-day estuarine bed sediments, described by Reed et al. (2008), was applied. Reed et al. (2008) provided information on bed-sediment composition across four size classes from surface-sediment samples: 0–8 µm, 8–25 µm, 25–63 µm and >63 µm (Table 6.9). The 0–8 µm particle size class was equated with the 4 µm constituent particle size in the USC-3 model; the 8–25 µm particle size class was equated with the 12 µm constituent particle size; the 25–63 µm particle size class was equated with the 40 µm constituent particle size; and the 63–125 µm particle size class was equated with the 125 µm constituent particle size.

Metal concentrations in the surface mixed layer of the estuary bed sediments must also be specified for the start of the historical period. Reed et al. (2008) measured zinc and copper concentrations at the base of sediment cores collected at six sites. One of these sites was outside Pahurehure Inlet (subestuary 12) and the other five sites were inside Pahurehure Inlet (subestuaries 4, 6, 7, 9 and 11). These sites are collectively referred to as the “test subestuaries” from here on. Given the sedimentation rate, which was estimated from the same cores, base-of-core concentrations in the test subestuaries correspond approximately to the surface mixed layer concentrations at the start of the historical period. The base-of-core concentrations, which were reported for the total sediment only, were therefore assigned uniformly to each particle size class in the test subestuaries to initiate the model at the start of the historical period (Table 6.10). For the rest of the subestuaries, where core data are not available, a surface mixed layer concentration of 35 mg $kg^{-1}$ for zinc and 7 mg $kg^{-1}$ for copper was assumed for each particle size class for the start of the historical period. These concentrations correspond to the natural concentration at which each metal is estimated to be present in catchment soils. The idea is that, over a long period of time, and with no anthropogenic metal inputs, metal concentrations in the estuary would have equilibrated with metal concentrations in sediment runoff from the land.

## 6.6 Terms to be adjusted in the calibration procedure

The calibration process consisted of adjusting (1) the fraction of the sediment runoff from the land that is assigned to the 4 µm constituent particle size (washload / slowly-settling, low-density flocs), (2) the areas over which sediments may deposit, (3) the various *ED50*, *R*, *R5*, *RSUSP*, *R5SUSP* and *RFS* terms, and (4) the metal retention factor.

(1) The first adjustment is intended to account for flocculation of land-derived sediment as it is discharged into the harbour. Because these flocs are assumed to

be low-density aggregates with a very small settling speed, they disperse widely. Therefore, the greater the fraction of the land-derived sediment load that is assigned to the 4 µm constituent particle size, the more widely sediment (with attached metals) is dispersed.

(2) The second adjustment reduces the deposition area in each subestuary relative to the total area, which increases sedimentation per unit mass of sediment deposited. The calibration process was started by assuming that deposition occurs over the entire area of each subestuary (Table 5.1).

(3) The *ED50*, *R*, *R5*, *RSUSP*, *R5SUSP* and *RFS* terms, which all together describe the movement and fate of sediments and heavy metals in the harbour under the influence of freshwater plumes, tidal currents and waves, were determined by a number of independent (that is, separate) runs of the DHI model suite. These same terms, when implemented in the USC-3 model, describe, in effect, the strength and direction of "connections" between subestuaries. The connections may form a complex network, with multiple cross-connections or interactions possible. Because of these interactions, any small errors associated with the connection strengths and directions may also interact, and grow as a result.

For instance, a particular run of the DHI model may indicate a small net loss of sediment from one subestuary (#1) and the transfer of that sediment to a neighbouring subestuary (#2), resulting in a small net gain in subestuary #2 by the end of the model run. A problem may occur in the USC-3 model when that small loss/gain pair is repeatedly applied over many timesteps, in which case any small error in the estimate of the connection may become magnified. This problem may be exacerbated when subestuaries are connected to each other in "chains", for instance, in the case of subestuary #1 losing sediment to subestuary #2 which in turn loses sediment to subestuary #3. In that case, any small errors will be passed along the chain, getting magnified as they go. This kind of problem is unavoidable in any scheme that seeks to extrapolate error-prone calculations beyond the scale at which the calculations are first performed. In the case of the USC-3 model, we are attempting to scale-up patterns of sediment dispersal that apply at a roughly daily timescale to a final timescale that is order $10^4$ times larger than daily.

In very general terms, estuaries will be dispersive, meaning that sediments will be passed more-or-less randomly in all directions between subestuaries. This should minimise the growth of errors as described. However, that notion cannot be entirely true, since there obviously will be preferred sediment-transport routes, particularly into the pre-defined sinks, which (by definition) do not give up sediments back to the larger system. In addition to the pre-defined sinks, there may also be "dynamic" sinks, which arise from the behaviour of the system. In fact, any subestuary in the model domain may act as a sink, even if not defined as such when the USC-3 model is set up. This is an important feature of the model, and will arise from the particular connections (strengths and directions) between subestuaries.

There may be a need to adjust the various *ED50*, *R*, *R5*, *RSUSP*, *R5SUSP* and *RFS* terms in the calibration process in order to correct for small errors that affect the rate of sediment transfer into both pre-defined and dynamic sinks in the domain. In principle, any such adjustment may be specific to the particular sequence of weather being used to drive the USC-3 model, since the weather sequence, in general terms, controls the rate at which sediments move around the harbour, and therefore the rate at which they are lost to sinks.  In practice here, however, this is not expected to be an issue.

(4) The metal retention factor *MRF* is used to set the fraction of the daily metal load emanating from each subcatchment that gets attached to the daily sediment particulate load, which then gets injected into and dispersed throughout the harbour. Specifically, the fraction of the metal load that gets attached to the sediment particulate matter at the bottom of the catchment is equal to *MRF*.  The fraction of the load that does not get attached to sediment particulate matter, and which therefore in effect does not even enter into the model domain, is equal to (1 – *MRF)*.  The physical interpretation is that (1 – *MRF)* is the fraction of the metal load that is dissolved (discussed further below).

## 6.7 Calibration targets

Adjustments in the previous terms are made until realistic sediment dispersal patterns, sedimentation rates and metal accumulation rates are simultaneously obtained.

(1) Reed et al. (2008) reported sedimentation rates over approximately the last 50 years in the six test subestuaries from radioisotopic analysis of sediment cores (Table 6.11).  The aim of the calibration process is to produce hindcast sedimentation rates that match these measured sedimentation rates.

(2) The target metal concentrations are measurements of total-sediment concentration (both zinc and copper) in the surface mixed layer of the present-day estuarine bed sediments.  There are two sources of information that could be used for this: firstly, the top-of-core metal concentrations reported by Reed et al. (2008) from the six test subestuaries; secondly, metal concentrations reported by Reed et al. (2008) from analysis of surface-sediment samples, which are available for all subestuaries (Table 6.11).  Whichever is chosen, the aim of the calibration process is to produce hindcast metal concentrations for the year 2001 (the last year in the historical period) that match the target metal concentrations.

## 6.8 Results

The calibration was finally achieved by:

(1) Assigning 50% of the 12 µm constituent of the sediment runoff from the land to the 4 µm constituent particle size (i.e., washload / slowly-settling, low-density flocs).

(2) Setting the area over which sediments may deposit in each subestuary to be one-half of each respective total subestuary area reported in Table 5.1.

(3) Adjusting the *ED50* erosion depths to just one tenth of the values evaluated by the DHI model.

(4) Setting the metal retention factor to 0.3.

The first adjustment was required primarily to increase the area over which sediments are dispersed, in line with an expert judgment (described below).

The intent of the second and third adjustments was to increase sedimentation rates throughout the harbour, which is in line with observations (described below). The second adjustment reduced the deposition area in each subestuary relative to the total area, which increased sedimentation per unit mass of sediment deposited. Exactly the same adjustment was required to achieve calibration of the USC-3 model of the Central Waitemata Harbour. The third adjustment, which was virtually equivalent to removing erosion from the model (in fact, the model performance was virtually unchanged when erosion was actually switched off in the model), was required to ensure that the model retained sediment within Pahurehure Inlet. The reasons for this are not clear, but three possibilities follow. Firstly, the DHI model simply overestimated erosion. Secondly, the return of sediment from Manukau Harbour back into Pahurehure Inlet on the days following the resuspension day was not properly handled by the DHI model. Thirdly, Manukau Harbour behaved as an overly aggressive dynamic sink, and significantly reducing erosion inside Pahurehure Inlet fixed this problem by reducing the flux of sediment from the bed into the water column, which then could be lost to this sink.

The intent of the fourth adjustment was to reduce the concentration at which metals are delivered to the harbour in the model so that target concentrations could be achieved (described below). This in turn reduces the disequilibrium between the input metal concentrations and the concentrations at which metals are present in the pre-existing estuarine bed sediments, which retards the rate at which metal concentrations change in the estuarine bed sediments.

### 6.8.1 Sediment and metal dispersal patterns

The fate of sediment from each subcatchment hindcast by the calibrated model is shown in Table 6.12 and Figure 6.9.

- Most of the sediment discharged from subcatchment 101 (Kingseat) is retained in the tidal creek (18–CCK) at the base of the subcatchment.
- Most of the sediment discharged from subcatchment 102 (Elletts Beach) deposits on the adjacent intertidal flats (1–HIB) and the rest is lost to the wider Manukau Harbour. None is deposited in Pahurehure Inlet.
- About 20% of the sediment from subcatchment 103 (Karaka) deposits in Glassons Creek tidal creek (17–GCK) at the base of the subcatchment, and about 30% deposits around the mouth of the tidal creek (2–KKA, 3–GMW, 4–GME, 5–CHN). The sediment that escapes the vicinity of the tidal creek is dispersed widely, including being lost to Manukau Harbour, deposited on the intertidal flats in the southeastern reaches of Manukau Harbour (1–HIB), transported into Drury Creek tidal creek (16–DCI), deposited in the inner reaches of the Inlet (6–DCO, 7–PHI, 8–PBA and 9–PKA), and deposited on the opposite side of the outer reaches of the Inlet (11–WMC).

- About 25% of the sediment from subcatchments 104, 105 and 106 (Whangapouri Creek, Oira Creek and Drury Creek) deposits in the tidal creek (16–DCI) that all of these subcatchments drain into. Drury Creek tidal creek traps a greater proportion (25%) of sediment from its adjacent subcatchment(s) than Glassons Creek tidal creek (20%). [It will be seen that Drury Creek tidal creek also traps a significant fraction of the sediment from the subcatchments that discharge into the inner reaches of Pahurehure Inlet. For instance, 7%, 15%, 17% and 11% of the sediment from subcatchments 108 (Papakura), 109 (Takanini), 110 (Papakura Stream) and 115 (Bottle Top Bay), respectively, is trapped in Drury Creek tidal creek.] The sediment that escapes from the tidal creek is dispersed widely, including being lost to Manukau Harbour. However, compared to sediment that escapes from Glassons Creek tidal creek, sediment that escapes from Drury Creek tidal creek tends to deposit more in the inner reaches of Pahurehure Inlet (6–DCO and 7–PHI).
- Subcatchment 107 (Hingaia) also discharges into Drury Creek tidal creek, but closer to the mouth. Compared to subcatchments 104, 105 and 106, which discharge to the upper reaches of Drury Creek tidal creek, somewhat less sediment from subcatchment 107 is trapped in Drury Creek tidal creek and somewhat more deposits in the inner reaches of Pahurehure Inlet. A little surprisingly, less is lost to Manukau Harbour. Subcatchment 115 (Bottle Top Bay), which discharges at the mouth of Drury Creek tidal creek, extends this pattern, with less sediment deposited inside Drury Creek tidal creek, and more sediment deposited in the inner reaches of Pahurehure Inlet.
- Sediment from subcatchment 108 (Papakura) deposits primarily in the enclosed Pahurehure Basin (8–PBA) at the base of the subcatchment. Continuing the pattern that is being established here, the sediment that escapes the basin is dispersed widely, including being lost to Manukau Harbour, but with deposition mainly in the inner reaches of the Inlet (7–PHI). As noted above, a significant fraction (7%) of the sediment is deposited back up in Drury Creek tidal creek (16–DCI).
- Subcatchment 109 (Takanini) discharges into the inner reaches of Pahurehure Inlet, which captures the largest fraction of the sediment load. Sediment is also carried back into Pahurehure Basin (8–PBA), lost to Manukau Harbour and, as noted above, deposited in Drury Creek tidal creek (16–DCI).
- Subcatchment 110 (Papakura Stream) discharges into the head of Papakura subestuary (9–PKA), which is embayed and which consequently captures the largest fraction of the sediment runoff. Sediment is also deposited in the inner reaches of the Inlet and, as noted previously, in Drury Creek tidal creek (16–DCI). Compared to sediment from subcatchment 109, which discharges further inside the Inlet, more sediment from subcatchment 110 is lost to Manukau Harbour (11% compared to 6%).
- Subcatchment 111 (Manurewa / Weymouth) discharges into the head of Waimahia Creek subestuary (11–WMC). Like the Papakura subestuary, this is embayed and captures the largest fraction of the sediment runoff. Compared to sediment from subcatchment 110, which discharges further inside the Inlet, more sediment from subcatchment 111 deposits in the outer reaches of the Inlet, and slightly more sediment is lost to Manukau Harbour (12% compared to 11%).

- Sediment from subcatchment 112 (Papatoetoe / Puhinui) deposits in Puhinui Creek tidal creek (14–PUK) at the base of the subcatchment, and also disperses widely in Manukau Harbour, including being deposited on the Weymouth intertidal flats (12–WEY) outside the mouth of the tidal creek.
- Subcatchments 113 (Mangere East / Papatoetoe) and 114 (Mangere) both drain into Pukaki Creek tidal creek (15–PKK), which in turn captures the bulk of the sediment runoff. Pukaki Creek traps more sediment from its adjacent subcatchment than does Puhinui Creek (~75% compared to 30%). The sediment that escapes from Pukaki Creek is dispersed widely in Manukau Harbour. Little is deposited on the Wiroa Island intertidal flats (13–WIL) outside the mouth of the tidal creek, which are exposed to the dominant westerly winds that blow across large fetches in Manukau Harbour.

The fate of zinc (Table 6.13) and copper (Table 6.14) from each subcatchment largely mirrors the fate of sediment, but with a few significant differences. Firstly, for the subcatchments that discharge into Pahurehure Inlet, more metal is deposited in the two tidal creeks that drain into the Inlet (Glassons Creek and Drury Creek). Secondly, more metal from, in particular, the subcatchments that drain to the northern shore of Pahurehure Inlet, is lost to Manukau Harbour. Both of these differences are attributable to the fact that metals preferentially attach to the finer sediment particle sizes, which are transported into the sheltered reaches of tidal creeks and lost to Manukau Harbour over the long term.

The source of sediment that deposits in each subestuary hindcast by the calibrated model is shown in Table 6.15 and summarised in Figures 6.10, 6.11 and 6.12. To be a primary source of sediment for any particular subestuary, there must be a sediment-transport pathway between the subestuary and the subcatchment in question, and the subcatchment must generate sediment. Even if the pathway is tenuous, a subcatchment may still be a principal source if it generates an overwhelming amount of sediment compared to all of the other subcatchments. For this reason, it will be seen that subcatchments 106 (Drury), 110 (Papakura Stream) and 112 (Papatoetoe / Puhinui) are principal sources of sediment to most subestuaries, since these subcatchments generate the most sediment out of all the subcatchments.

For subestuaries in or around the fringes of Southeastern Manukau Harbour (Figure 6.10):

- The intertidal flats of Hikihiki Bank (1–HIB) receive sediment primarily from Elletts Beach subcatchment, which is adjacent. It also receives a significant amount of sediment from a wide range of other sources, including the principal sediment generators 106, 110 and 112. The intertidal flats of Wiroa Island (13–WIL) and Weymouth (12–WEY) also receive sediment from the principal sediment generators 106, 110 and 112. It is noteworthy that sediment supply to the intertidal flats of the Southeastern Manukau is quite similar to the proportion at which it comes off the greater catchment; this implies that sediment runoff from the individual subcatchments is well-mixed together in the Southeastern Manukau, which is reasonable to expect.

- That is not so much the case for the tidal creeks that fringe the Southeastern Manukau, which show local influences. For Clarks Creek (18–CCK), most of the sediment is sourced from the Kingseat (101) subcatchment, which the tidal creek drains. The same is true for Pukaki Creek (15–PKK), which receives most of its sediment from the adjacent subcatchments 113 (Mangere East / Papatoetoe) and 114 (Mangere). Puhinui Creek tidal creek (14–PUK) receives most of its sediment from the adjacent subcatchment 112 (Papatoetoe / Puhinui), plus significant contributions from the other principal sediment generators 106 and 110.

For subestuaries in the interior of Pahurehure Inlet (Figure 6.11):

- Karaka subestuary (2–KKA) receives sediment from: Karaka subcatchment (103), which drains into the adjacent Glassons Creek; Drury subcatchment (106), which is the largest sediment generator; Whangapouri Creek subcatchment (104), which is also a large sediment generator; and Manurewa / Weymouth (111), which is immediately opposite. Still on the southern shore and in the vicinity of the mouth of Glassons Creek, almost the same pattern applies to Glassons Mouth West (3–GMW), Glassons Mouth East (4–GME) and Cape Horn (5–CHN) subestuaries. For the latter two subestuaries, subcatchment 110, which is a principal sediment generator, also makes a notable contribution.
- Subestuaries in the inner reaches of Pahurehure Inlet, which are more sheltered, tend to receive sediment from locally adjacent subcatchments and the principal sediment generators. This includes Drury Creek Outer (6–DCO), Pahurehure Inner (7–PHI) and Papakura (9–PKA).
- Kauri Point (10–KPT) receives sediment mainly from the principal sediment generators which is interesting. As was the case for the intertidal flats of Manukau Harbour, this implies that sediment deposited at Kauri Point is a thorough mixture of sediment from all subcatchments. This seems plausible, given its central, exposed location.
- Waimahia Creek (11-WMC), which is a sheltered embayment, receives sediment mainly from its adjacent subcatchment (111) and the principal sediment generators 106 and 110.

For tidal creeks that drain into the interior of Pahurehure Inlet and for Pahurehure Basin (Figure 6.12):

- The pattern of sediment supply to Glassons Creek Inner tidal creek (17–GCK) is very similar to the pattern of supply to the subestuaries at the mouth of the tidal creek (3–GMW, 4–GME and 5–CHN). This is a little unexpected, since the subestuaries around the mouth are more exposed than the tidal creek, and the tidal creek should, as a result, be more dominated by sediment runoff from the subcatchment that it drains. This might indicate a weakness in the model.
- Sediment deposited in Drury Creek Inner tidal creek (16–DCI) comes mainly from the subcatchment that it drains, as expected. Nonetheless, it is notable that a significant fraction comes from the principal sediment generator 110, and it has been previously noted that sediment from many subcatchments does in fact deposit in Drury Creek Inner tidal creek. This highlights the role of tidal creeks as sediment

traps, and suggests that the unexpected result concerning Glassons Creek Inner tidal creek may not actually be suspect.

- Finally, sediment deposited in the enclosed Pahurehure Basin (8–PBA) at the head of the Inlet comes mainly from the adjacent subcatchment.

Because the fate of zinc and copper is tied closely to the fate of sediment, it is tempting to expect that metal in any particular subestuary will derive from sources in the same proportion that sediment derives from sources. However, that is not necessarily the case. Green (2007) gave the following explanation. Imagine sediment in a particular subestuary derives from sources 1, 2 and 3 in the proportions 50%, 30% and 20%, but metals might derive from sources 1, 2 and 3 in the proportions 0%, 60% and 40%. This occurs when the total catchment metal load is not distributed amongst the subcatchments in the same proportions as the total catchment sediment load. In this case, subcatchment 1 contributes some sediment to the harbour, but it contributes no metal at all.

The source of zinc that deposits in each subestuary is shown in Table 6.16 and summarised in Figures 6.13, 6.14 and 6.15.

The source of copper that deposits in each subestuary is shown in Table 6.17 and summarised in Figures 6.16, 6.17 and 6.18.

For subestuaries in or around the fringes of Southeastern Manukau Harbour (Figure 6.13 for zinc, and Figure 6.16 for copper):

- The intertidal flats of Southeastern Manukau Harbour (1–HIB, 12–WEY and 13–WIL) receive zinc primarily from the subcatchment that is the principal zinc generator, 112. This is also true for copper, and is consistent with the previous conclusion that runoff from all subcatchments is well-mixed together in the Southeastern Manukau
- In contrast, the tidal creeks that fringe the Southeastern Manukau show local influences, which was also true for sediment. Hence, most of the zinc and copper that deposits in Clarks Creek tidal creek (18–CCK) derives from the local Kingseat subcatchment; most of the zinc and copper in Pukaki Creek (15–PKK) derives from the adjacent subcatchments 113 (Mangere East / Papatoetoe) and 114 (Mangere); and nearly all of the zinc and copper in Puhinui Creek tidal creek (14–PUK) derives from the adjacent subcatchment 112 (Papatoetoe / Puhinui), which is also the largest generator of zinc and copper.

For subestuaries in the interior of Pahurehure Inlet (Figure 6.14 for zinc, and Figure 6.17 for copper):

- For the subestuaries around the mouth of Glassons Creek (2–KKA, 3–GMW, 4–GME and 5–CHN) the patterns of zinc supply and copper supply are similar to the pattern of sediment supply, but with a couple of notable differences. The first is a larger contribution from the Manurewa / Weymouth subcatchment (111), which is higher-ranked as a metal generator than a sediment generator. The second is the small contribution of metal from the adjacent subcatchment 103 compared to the significant contribution of sediment from the same subcatchment. The reason is that the Karaka subcatchment (103) is all rural and is therefore a relatively very small metal generator.

- The patterns of zinc supply and copper supply are also similar to the pattern of sediment supply for subestuaries in the inner reaches of Pahurehure Inlet, with one exception: subcatchment 108 (Papakura), which is a high-ranked metal generator, makes a significant metal contribution, whereas that was not the case for sediment.
- Kauri Point (10–KPT) receives metal mainly from the principal metal generators, which was also the case for sediment, and which was taken as being indicative of thorough mixing in this area, which in turn is consistent with the exposure at this location.
- Waimahia Creek (11-WMC), which is a sheltered embayment, receives metal mainly from its adjacent subcatchment (111), which is also the case for sediment.

For tidal creeks that drain into the interior of Pahurehure Inlet and for Pahurehure Basin (Figure 6.15 for zinc, and Figure 6.18 for copper ):

- As was the case for sediment, the pattern of metal supply to Glassons Creek Inner tidal creek (17–GCK) is very similar to the pattern of metal supply to the subestuaries at the mouth of the tidal creek (3–GMW, 4–GME and 5–CHN). This was noted as being a little unexpected, although it is also consistent with the way tidal creeks act as sediment traps.
- Zinc and copper deposited in Drury Creek Inner tidal creek (16–DCI) comes mainly from the subcatchment (106) that it drains, which was also the case for sediment. This is expected since subcatchment 106 is a large generator of both sediment and metal.
- Finally, zinc and copper deposited in the enclosed Pahurehure Basin (8–PBA) at the head of the Inlet comes almost exclusively from the adjacent subcatchment 108, which was also the case for sediment.

### 6.8.2 Sedimentation rates

The hindcast sedimentation rates by the calibrated model are generally smaller than measured sedimentation rates reported by Reed et al. (2008) from radioisotopic analysis of sediment cores (Table 6.18 and Figure 6.19). At least part of the reason for this may be that sediment inputs from the wider Manukau Harbour into Pahurehure Inlet, driven by tidal currents and waves, are not accounted for in the model.

The obvious spatial pattern evident in the core data is the distinction between sedimentation outside Pahurehure Inlet (zero) and inside Pahurehure Inlet (non-zero), which is reproduced by the model. The core data yielded sedimentation rates inside Pahurehure Inlet of order 10 mm year$^{-1}$, and the model reported hindcast rates of that same order, with two exceptions: subestuary 2 (Karaka; 10$^{-1}$ mm year$^{-1}$) and subestuary 10 (Kauri Point, also 10$^{-1}$ mm year$^{-1}$). The former subestuary is close to the mouth of Pahurehure Inlet, and the latter is in an exposed position in the middle reaches of the inlet. Figure 6.19 reveals no obvious spatial pattern inside Pahurehure

Inlet in either the core data or the model hindcast data. However, Figure 6.20, which shows the hindcast change in bed-sediment level in each subestuary throughout the historical period (as opposed to an annual-average sedimentation rate), does reveal something of a pattern. Specifically (referring to Figure 6.20), more sediment tends to accumulate in the inner reaches of Pahurehure Inlet (subestuaries 6, 7, 8 and 9) than in the outer reaches of Pahurehure Inlet (subestuaries 2, 3, 4, 5, 10 and 11). Furthermore, the tidal creeks that drain to Pahurehure Inlet (16 and 17) accumulate sediment at very much the same rate (as each other).

### 6.8.3 Metal accumulation

The performance of the calibrated model for hindcasting zinc accumulation in the six test subestuaries is shown in Figure 6.21. The black line shows the zinc accumulation hindcast by the model with the initial condition (start of the historical period) shown by the black symbol (Table 6.10). The target concentration (end of historical period) shown by the black symbol is the top-of-core concentration (Table 6.11).

- The model over-hindcasts the top-of-core target concentrations in subestuaries 6–DCO (Drury Creek Outer) and 11–WMC (Waimahia Creek). In those cases, the model actually converges much better on the present-day metal concentrations determined from analysis of surface-sediment samples (the blue symbols). The latter in fact seem to be more reasonable than the former, as the core data imply that metal concentrations have barely increased over the historical period in 6–DCO and 11–WMC, which is not the case in the other test subestuaries that are inside Pahurehure Inlet.
- The model does a good job of hindcasting the top-of-core target concentrations in the rest of the test subestuaries.

The performance of the calibrated model for hindcasting copper accumulation in the 6 test subestuaries is shown in Figure 6.22. It needs to be noted that the model was in fact not calibrated against copper. Instead, the model as calibrated for zinc was applied without further adjustment to hindcasting copper, and it is those results that are shown in Figure 6.22. Given that, the model performance is quite satisfactory: for some subestuaries the top-of-core concentrations are achieved, and for others the surface-sediment-sample concentrations are achieved. It should be noted that, overall, the change in copper concentration over the historical period was not very great.

## 6.9 Discussion

The metal retention factor *MRF* is the key calibration parameter. Green (2007) pointed out that the metal retention factor may be accounting for any number of uncertainties in the USC-3 model and the underlying models (GLEAMS, CLM, and the DHI model suite), which provide inputs and parameters to the USC-3 model. This includes uncertainties in inputs, uncertainties in initial conditions, deficiencies in depiction of known processes, and lack of representation of other processes.

In the calibration of the USC-3 model for the Central Waitemata Harbour, one value of the metal retention factor applied to every subcatchment was found to yield good hindcasts of zinc accumulation for each of the test subestuaries.  Furthermore, the metal retention factor derived from the zinc calibration was found to also perform reasonably well for hindcasting copper.  This is also the case here, for the Southeastern Manukau Harbour / Pahurehure Inlet. Green (2007) noted that this shows that metal loads are being delivered to the harbour in the model at uniformly too-high concentrations, which points at a physical interpretation of the metal retention factor: (1 – *MRF* ) represents the proportion of the metal load emanating from the catchment that gets lost to a dissolved phase and which does not accumulate (by definition) in the estuary bed sediments, and/or (1 – *MRF* ) represents the proportion of the metal load emanating from the catchment that gets attached to very fine particles that never settle and so do not accumulate in the bed of the harbour.

Experimental work by Ellwood et al. (2008) confirmed a large loss of zinc to the dissolved phase as it transited the Whau River tidal creek (Central Waitemata Harbour) in the freshwater runoff.  Specifically, ~70% of the zinc load associated with the particulate phase discharged in freshwater was recycled into the dissolved phase (average over a large range of metal input loads and concentrations).  This measured loss was similar to (1 – *MRF*)  determined by calibration of the USC-3 model for the Central Waitemata Harbour (0.6). It is also similar to (1 – *MRF*) determined by calibration for the Southeastern Manukau Harbour / Pahurehure Inlet (0.7).  Hence, the calibration – in both cases – is not implausible.

Green (2007) noted that neither the loss of metal to a dissolved phase nor attachment of metals to very fine particles that do not settle was explicitly accounted for in the application of the USC-3 model to the Central Waitemata Harbour, and the metal retention factor could be seen as implicitly accounting for these processes.  The application of the USC-3 model to Southeastern Manukau Harbour / Pahurehure Inlet has attempted to take account of the latter process (i.e., dispersal of very fine particles that do not, or at least very slowly, settle).  This suggests that the metal retention factor, at least in the case of the Southeastern Manukau Harbour / Pahurehure Inlet, is accounting more for the loss of metal to a dissolved phase.

**Table 6.1:**

Split of rural sediment load amongst the 12, 40 and 125 µm constituent particle sizes, hindcast by GLEAMS and averaged all years in the historical period. Sediment was assigned to the 4 µm particle size (washload / low-density, slowly-settling flocs) as part of the calibration process.

| Subcatchment | Constituent particle size (µm) | | |
|---|---|---|---|
| | 12 | 40 | 125 |
| 101 - KST | 0.688 | 0.306 | 0.006 |
| 102 - EBH | 0.446 | 0.552 | 0.002 |
| 103 - KKA | 0.612 | 0.380 | 0.008 |
| 104 - WHC | 0.865 | 0.130 | 0.004 |
| 105 - OIC | 0.916 | 0.084 | 0.001 |
| 106 - DRY | 0.987 | 0.012 | 0.000 |
| 107 - HGA | 0.439 | 0.545 | 0.016 |
| 108 - PKA | 0.815 | 0.181 | 0.004 |
| 109 - TKI | 0.879 | 0.117 | 0.004 |
| 110 - PAS | 0.994 | 0.006 | 0.000 |
| 111 - MAW | 0.415 | 0.545 | 0.040 |
| 112 - PAU | 0.874 | 0.125 | 0.001 |
| 113 - MEP | 0.409 | 0.552 | 0.039 |
| 114 - MGE | 0.487 | 0.469 | 0.044 |
| 115 - BTB | 0.366 | 0.632 | 0.002 |

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**Table 6.2:**

Split of urban sediment load amongst the 12, 40 and 125 µm constituent particle sizes, hindcast by the CLM and averaged over all years in the historical period. Sediment was assigned to the 4 µm particle size (washload / low-density, slowly-settling flocs) as part of the calibration process.

| Subcatchment | Constituent particle size (µm) | | |
|---|---|---|---|
| | 12 | 40 | 125 |
| 101 - KST | – | – | – |
| 102 - EBH | – | – | – |
| 103 - KKA | – | – | – |
| 104 - WHC | 0.39 | 0.33 | 0.28 |
| 105 - OIC | – | – | – |
| 106 - DRY | 0.37 | 0.34 | 0.29 |
| 107 - HGA | 0.37 | 0.34 | 0.29 |
| 108 - PKA | 0.40 | 0.33 | 0.27 |
| 109 - TKI | 0.37 | 0.33 | 0.29 |
| 110 - PAS | 0.36 | 0.34 | 0.30 |
| 111 - MAW | 0.38 | 0.33 | 0.29 |
| 112 - PAU | 0.42 | 0.33 | 0.26 |
| 113 - MEP | 0.51 | 0.49 | 0.00 |
| 114 - MGE | 0.42 | 0.31 | 0.27 |
| 115 - BTB | 0.37 | 0.33 | 0.29 |

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**Table 6.3:**

Statistics of the total (rural plus urban) sediment runoff. These statistics are for the sum of all particle sizes, and are for just one USC-3 model run in the Monte Carlo package of 50 USC-3 model runs.

| Subcatchment | Average per year (kg) | Sum over simulation (kg) | Rank |
|---|---|---|---|
| 101 - KST | 589,058 | 36,521,584 | 7 |
| 102 - EBH | 433,653 | 26,886,468 | 9 |
| 103 - KKA | 530,478 | 32,889,622 | 8 |
| 104 - WHC | 784,250 | 48,623,504 | 4 |
| 105 - OIC | 235,013 | 14,570,780 | 12 |
| 106 - DRY | 2,849,247 | 176,653,328 | 1 |
| 107 - HGA | 107,913 | 6,690,623 | 13 |
| 108 - PKA | 602,782 | 37,372,464 | 6 |
| 109 - TKI | 45,670 | 2,831,564 | 14 |
| 110 - PAS | 1,380,532 | 85,592,976 | 2 |
| 111 - MAW | 292,952 | 18,163,050 | 10 |
| 112 - PAU | 923,546 | 57,259,856 | 3 |
| 113 - MEP | 738,963 | 45,815,692 | 5 |
| 114 - MGE | 291,972 | 18,102,236 | 11 |
| 115 - BTB | 27,823 | 1,725,041 | 15 |

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**Table 6.4:**

Average (over the historical period) fraction of the annual sediment runoff in each subcatchment that comes from urban sources. The rest comes from rural sources.

| Subcatchment | Average (over the simulation) fraction of sediment runoff from urban sources |
|---|---|
| 101 - KST | 0.00 |
| 102 - EBH | 0.00 |
| 103 - KKA | 0.00 |
| 104 - WHC | 0.26 |
| 105 - OIC | 0.00 |
| 106 - DRY | 0.15 |
| 107 - HGA | 0.16 |
| 108 - PKA | 0.32 |
| 109 - TKI | 0.65 |
| 110 - PAS | 0.26 |
| 111 - MAW | 0.80 |
| 112 - PAU | 0.53 |
| 113 - MEP | 0.30 |
| 114 - MGE | 0.10 |
| 115 - BTB | 0.14 |

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**Table 6.5:**

Split of anthropogenic zinc load amongst the 12, 40 and 125 µm constituent particle sizes, hindcast by the CLM and averaged over all years in the historical period. Zinc was assigned to the 4 µm particle size (washload / low-density, slowly-settling flocs) as part of the calibration process.

| Subcatchment | Constituent particle size (µm) | | |
|---|---|---|---|
| | 12 | 40 | 125 |
| 101 - KST | – | – | – |
| 102 - EBH | – | – | – |
| 103 - KKA | – | – | – |
| 104 - WHC | 0.54 | 0.28 | 0.17 |
| 105 - OIC | – | – | – |
| 106 - DRY | 0.54 | 0.28 | 0.17 |
| 107 - HGA | 0.53 | 0.29 | 0.18 |
| 108 - PKA | 0.55 | 0.28 | 0.17 |
| 109 - TKI | 0.54 | 0.28 | 0.18 |
| 110 - PAS | 0.53 | 0.29 | 0.18 |
| 111 - MAW | 0.53 | 0.29 | 0.18 |
| 112 - PAU | 0.55 | 0.28 | 0.17 |
| 113 - MEP | 0.60 | 0.38 | 0.02 |
| 114 - MGE | 0.53 | 0.27 | 0.20 |
| 115 - BTB | 0.55 | 0.28 | 0.16 |

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**Table 6.6:**

Split of anthropogenic copper load amongst the 12, 40 and 125 µm constituent particle sizes, hindcast by the CLM and averaged over all years in the historical period. Copper was assigned to the 4 µm particle size (washload / low-density, slowly-settling flocs) as part of the calibration process

| Subcatchment | Constituent particle size (µm) | | |
|---|---|---|---|
| | 12 | 40 | 125 |
| 101 - KST | – | – | – |
| 102 - EBH | – | – | – |
| 103 - KKA | – | – | – |
| 104 - WHC | – | – | – |
| 105 - OIC | – | – | – |
| 106 - DRY | 0.40 | 0.33 | 0.27 |
| 107 - HGA | 0.39 | 0.33 | 0.28 |
| 108 - PKA | 0.40 | 0.34 | 0.26 |
| 109 - TKI | 0.39 | 0.33 | 0.27 |
| 110 - PAS | 0.39 | 0.33 | 0.28 |
| 111 - MAW | 0.40 | 0.33 | 0.27 |
| 112 - PAU | 0.43 | 0.32 | 0.25 |
| 113 - MEP | 0.53 | 0.47 | 0.00 |
| 114 - MGE | 0.43 | 0.30 | 0.27 |
| 115 - BTB | 0.40 | 0.34 | 0.26 |

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**Table 6.7:**

Total (anthropogenic plus natural) zinc loads and how those total loads are constituted between anthropogenic and natural sources. These figures are for the total zinc carried by all sediment constituent particle sizes, and are for just one USC-3 model run in the Monte Carlo package of 50 USC-3 model runs.

| Subcatchment | Sum over simulation of anthropogenic zinc (kg) | Sum over simulation of total (anthropogenic plus natural) zinc (kg) | Percentage of total due to anthropogenic | Percentage of total due to natural |
|---|---|---|---|---|
| 101 - KST | 0 | 1,264 | 0.00 | 1.00 |
| 102 - EBH | 0 | 930 | 0.00 | 1.00 |
| 103 - KKA | 0 | 1,138 | 0.00 | 1.00 |
| 104 - WHC | 14,749 | 16,432 | 0.90 | 0.10 |
| 105 - OIC | 0 | 504 | 0.00 | 1.00 |
| 106 - DRY | 25,153 | 31,265 | 0.80 | 0.20 |
| 107 - HGA | 1,765 | 1,996 | 0.88 | 0.12 |
| 108 - PKA | 36,790 | 38,083 | 0.97 | 0.03 |
| 109 - TKI | 7,260 | 7,358 | 0.99 | 0.01 |
| 110 - PAS | 20,585 | 25,128 | 0.87 | 0.13 |
| 111 - MAW | 15,581 | 16,209 | 0.96 | 0.04 |
| 112 - PAU | 54,876 | 56,858 | 0.97 | 0.03 |
| 113 - MEP | 21,441 | 23,027 | 0.93 | 0.07 |
| 114 - MGE | 2,397 | 3,024 | 0.79 | 0.21 |
| 115 - BTB | 869 | 929 | 0.94 | 0.06 |

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**Table 6.8:**

Total (anthropogenic plus natural) copper loads and how those total loads are constituted between anthropogenic and natural sources. These figures are for the total copper carried by all sediment constituent particle sizes, and are for just one USC-3 model run in the Monte Carlo package of 50 USC-3 model runs.

| Subcatchment | Sum over simulation of anthropogenic copper (kg) | Sum over simulation of total (anthropogenic plus natural) copper (kg) | Percentage of total due to anthropogenic | Percentage of total due to natural |
|---|---|---|---|---|
| 101 - KST | 0 | 253 | 0.00 | 1.00 |
| 102 - EBH | 0 | 186 | 0.00 | 1.00 |
| 103 - KKA | 0 | 228 | 0.00 | 1.00 |
| 104 - WHC | 1,061 | 1,398 | 0.76 | 0.24 |
| 105 - OIC | 0 | 101 | 0.00 | 1.00 |
| 106 - DRY | 1,084 | 2,306 | 0.47 | 0.53 |
| 107 - HGA | 114 | 161 | 0.71 | 0.29 |
| 108 - PKA | 1,869 | 2,128 | 0.88 | 0.12 |
| 109 - TKI | 245 | 264 | 0.93 | 0.07 |
| 110 - PAS | 1,781 | 2,689 | 0.75 | 0.25 |
| 111 - MAW | 1,326 | 1,451 | 0.91 | 0.09 |
| 112 - PAU | 2,984 | 3,381 | 0.88 | 0.12 |
| 113 - MEP | 664 | 981 | 0.68 | 0.32 |
| 114 - MGE | 76 | 201 | 0.38 | 0.62 |
| 115 - BTB | 8 | 20 | 0.40 | 0.60 |

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**Table 6.9:**

Present-day composition of the surface mixed layer of the estuarine bed sediments reported by Reed et al. (2008) from analysis of surface-sediment samples.

| Subestuary | Fraction of bed sediment, 0–8 µm | Fraction of bed sediment, 8–25 µm | Fraction of bed sediment, 25–63 µm | Fraction of bed sediment, 63–125 µm | Bed sediment D50 (microns) |
|---|---|---|---|---|---|
| 1 – HIB | 0.01 | 0.18 | 0.09 | 0.72 | 96 |
| 2 – KKA | 0.05 | 0.37 | 0.20 | 0.38 | 61 |
| 3 – GMW | 0.11 | 0.50 | 0.19 | 0.21 | 40 |
| 4 – GME | 0.11 | 0.50 | 0.19 | 0.21 | 40 |
| 5 – CHN | 0.07 | 0.22 | 0.04 | 0.67 | 88 |
| 6 – DCO | 0.04 | 0.12 | 0.04 | 0.80 | 103 |
| 7 – PHI | 0.10 | 0.41 | 0.09 | 0.40 | 59 |
| 8 – PBA | 0.15 | 0.46 | 0.08 | 0.31 | 48 |
| 9 – PKA | 0.14 | 0.65 | 0.18 | 0.03 | 19 |
| 10 – KPT | 0.07 | 0.22 | 0.04 | 0.67 | 88 |
| 11 – WMC | 0.14 | 0.65 | 0.18 | 0.03 | 19 |
| 12 – WEY | 0.01 | 0.18 | 0.09 | 0.72 | 96 |
| 13 – WIL | 0.01 | 0.18 | 0.09 | 0.72 | 96 |
| 14 – PUK | 0.17 | 0.55 | 0.15 | 0.13 | 30 |
| 15 – PKK | 0.17 | 0.55 | 0.15 | 0.13 | 30 |
| 16 – DCI | 0.05 | 0.14 | 0.04 | 0.77 | 100 |
| 17 – GCK | 0.17 | 0.55 | 0.15 | 0.13 | 30 |
| 18 – CCK | 0.17 | 0.55 | 0.15 | 0.13 | 30 |
| 19 – MHB | 0.01 | 0.18 | 0.09 | 0.72 | 96 |

Par\implement\estuary bed sediment\present day\particle size and metal working 1.xls

**Table 6.10:**

Zinc and copper concentrations applied in the model to each constituent particle size in the surface mixed layer of the estuary bed sediments at the start of the historical period. The concentrations in subestuaries 4, 6, 7, 9, 11 and 12 are base-of-core values reported by Reed et al. (2008). The rest are concentrations at which natural metals are present in catchment soils, as explained in the text.

| Subestuary | Zinc concentration (mg/kg) | Copper concentration (mg/kg) |
|---|---|---|
| 1 – HIB | 35 | 7 |
| 2 – KKA | 35 | 7 |
| 3 – GMW | 35 | 7 |
| 4 – GME | 36 | 5 |
| 5 – CHN | 35 | 7 |
| 6 – DCO | 14 | 2 |
| 7 – PHI | 29 | 3 |
| 8 – PBA | 35 | 7 |
| 9 – PKA | 43 | 9 |
| 10 – KPT | 35 | 7 |
| 11 – WMC | 45 | 8 |
| 12 – WEY | 30 | 6 |
| 13 – WIL | 35 | 7 |
| 14 – PUK | 35 | 7 |
| 15 – PKK | 35 | 7 |
| 16 – DCI | 35 | 7 |
| 17 – GCK | 35 | 7 |
| 18 – CCK | 35 | 7 |
| 19 – MHB | 35 | 7 |

Par\implement\estuary bed sediment\present day\particle size and metal working 1.xls

**Table 6.11:**

Sedimentation rate and top-of-core metal concentrations from analysis of cores in 6 test subestuaries reported by Reed et al. (2008), and metal concentrations reported by Reed et al. (2008) from analysis of surface-sediment samples. Either metal concentration (top-of-core or from analysis of surface-sediment samples) could be used as target concentrations in the calibration.

| Subestuary | Sedimentation rate, mm/year | Top-of-core | | From analysis of surface-sediment samples | |
|---|---|---|---|---|---|
| | | Zinc concentration (mg/kg) | Copper concentration (mg/kg) | Zinc concentration (mg/kg) | Copper concentration (mg/kg) |
| 1 – HIB | – | – | – | 50 | 6 |
| 2 – KKA | – | – | – | 71 | 9 |
| 3 – GMW | – | – | – | 77 | 10 |
| 4 – GME | 3.2 | 75 | 8 | 77 | 10 |
| 5 – CHN | – | – | – | 76 | 9 |
| 6 – DCO | 3.1 | 37 | 3 | 74 | 9 |
| 7 – PHI | 4.0 | 95 | 11 | 91 | 10 |
| 8 – PBA | – | – | – | 108 | 12 |
| 9 – PKA | 2.2 | 90 | 9 | 97 | 12 |
| 10 – KPT | – | – | – | 76 | 9 |
| 11 – WMC | 4.5 | 66 | 6 | 97 | 12 |
| 12 – WEY | 0.0 | 31 | 4 | 50 | 6 |
| 13 – WIL | – | – | – | 50 | 6 |
| 14 – PUK | – | – | – | 80 | 11 |
| 15 – PKK | – | – | – | 80 | 11 |
| 16 – DCI | – | – | – | 83 | 11 |
| 17 – GCK | – | – | – | 98 | 12 |
| 18 – CCK | – | – | – | 98 | 12 |
| 19 – MHB | – | – | – | 50 | 6 |

Par\implement\estuary bed sediment\present day\particle size and metal working 1.xls

**Table 6.12:**

Fate of sediment from each subcatchment. Reading across the page: percentage of total sediment load from each subcatchment deposited in each subestuary. Hindcast by the calibrated USC-3 model; average over 50 model runs in a Monte Carlo package.

## FATE – Sediment

| Subcatchment | Subestuary | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1-HIB | 2-KKA | 3-GMW | 4-GME | 5-CHN | 6-DCO | 7-PHI | 8-PBA | 9-PKA | 10-KPT | 11-WMC | 12-WEY | 13-WIL | 14-PUK | 15-PKK | 16-DCI | 17-GCK | 18-CCK | 19-MHB |
| *Discharge to southeastern shoreline of Manukau Harbour* | | | | | | | | | | | | | | | | | | | |
| **101 - KST** | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 97 | 2 |
| **102 - EBH** | 69 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 25 |
| *Discharge to southern shoreline of Pahurehure Inlet* | | | | | | | | | | | | | | | | | | | |
| **103 - KKA** | 4 | 3 | 15 | 9 | 3 | 6 | 9 | 1 | 4 | 0 | 4 | 2 | 0 | 2 | 2 | 8 | 19 | 0 | 9 |
| **104 - WHC** | 3 | 1 | 3 | 3 | 1 | 15 | 16 | 2 | 9 | 0 | 3 | 1 | 0 | 1 | 1 | 26 | 5 | 0 | 8 |
| **105 - OIC** | 3 | 1 | 3 | 3 | 1 | 15 | 16 | 2 | 9 | 0 | 3 | 2 | 0 | 1 | 1 | 25 | 5 | 0 | 8 |
| **106 - DRY** | 3 | 1 | 3 | 3 | 1 | 15 | 16 | 2 | 9 | 0 | 3 | 2 | 0 | 1 | 1 | 25 | 5 | 0 | 9 |
| **107 - HGA** | 2 | 1 | 3 | 3 | 1 | 22 | 19 | 6 | 11 | 0 | 3 | 1 | 0 | 1 | 1 | 21 | 4 | 0 | 2 |
| *Discharge to Pahurehure Basin* | | | | | | | | | | | | | | | | | | | |
| **108 - PKA** | 3 | 0 | 0 | 1 | 0 | 2 | 12 | 62 | 4 | 0 | 2 | 1 | 0 | 1 | 1 | 7 | 1 | 0 | 4 |
| *Discharge to northern shoreline of Pahurehure Inlet* | | | | | | | | | | | | | | | | | | | |
| **109 - TKI** | 4 | 0 | 0 | 1 | 0 | 8 | 40 | 7 | 8 | 0 | 3 | 2 | 0 | 1 | 1 | 15 | 2 | 0 | 6 |
| **110 - PAS** | 5 | 0 | 1 | 2 | 1 | 6 | 13 | 2 | 28 | 0 | 4 | 2 | 1 | 2 | 2 | 17 | 3 | 1 | 11 |
| **111 - MAW** | 3 | 2 | 2 | 8 | 1 | 0 | 1 | 0 | 1 | 0 | 63 | 1 | 0 | 1 | 1 | 2 | 1 | 0 | 12 |
| *Discharge to northeastern shoreline of Manukau Harbour* | | | | | | | | | | | | | | | | | | | |
| **112 - PAU** | 9 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 2 | 0 | 2 | 13 | 1 | 30 | 5 | 3 | 1 | 1 | 28 |
| **113 - MEP** | 4 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 3 | 0 | 1 | 76 | 1 | 1 | 0 | 11 |
| **114 - MGE** | 4 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 3 | 0 | 1 | 74 | 1 | 1 | 0 | 12 |
| *Discharge to southern shoreline of Pahurehure Inlet* | | | | | | | | | | | | | | | | | | | |
| **115 - BTB** | 2 | 0 | 1 | 3 | 1 | 41 | 20 | 4 | 9 | 0 | 2 | 1 | 0 | 1 | 1 | 11 | 2 | 0 | 3 |

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**Table 6.13:**

Fate of zinc from each subcatchment. Reading across the page: percentage of total zinc load from each subcatchment deposited in each subestuary. Hindcast by the calibrated USC-3 model; average over 50 model runs in a Monte Carlo package.

## FATE – Zinc

| Subcatchment | Subestuary | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1-HIB | 2-KKA | 3-GMW | 4-GME | 5-CHN | 6-DCO | 7-PHI | 8-PBA | 9-PKA | 10-KPT | 11-WMC | 12-WEY | 13-WIL | 14-PUK | 15-PKK | 16-DCI | 17-GCK | 18-CCK | 19-MHB |
| *Discharge to southeastern shoreline of Manukau Harbour* | | | | | | | | | | | | | | | | | | | |
| **101 - KST** | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 98 | 1 |
| **102 - EBH** | 47 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 47 |
| *Discharge to southern shoreline of Pahurehure Inlet* | | | | | | | | | | | | | | | | | | | |
| **103 - KKA** | 3 | 2 | 12 | 7 | 3 | 5 | 7 | 1 | 4 | 0 | 3 | 2 | 0 | 1 | 2 | 7 | 33 | 0 | 8 |
| **104 - WHC** | 2 | 1 | 2 | 3 | 1 | 13 | 14 | 2 | 8 | 0 | 2 | 1 | 0 | 1 | 1 | 40 | 4 | 0 | 5 |
| **105 - OIC** | 2 | 1 | 2 | 3 | 1 | 13 | 14 | 2 | 8 | 0 | 2 | 1 | 0 | 1 | 1 | 40 | 3 | 0 | 5 |
| **106 - DRY** | 2 | 1 | 2 | 3 | 1 | 13 | 14 | 2 | 8 | 0 | 2 | 1 | 0 | 1 | 1 | 40 | 3 | 0 | 5 |
| **107 - HGA** | 2 | 1 | 3 | 2 | 1 | 17 | 15 | 5 | 9 | 0 | 2 | 1 | 0 | 1 | 1 | 27 | 4 | 0 | 9 |
| *Discharge to Pahurehure Basin* | | | | | | | | | | | | | | | | | | | |
| **108 - PKA** | 2 | 0 | 0 | 0 | 0 | 4 | 13 | 58 | 4 | 0 | 1 | 1 | 0 | 0 | 1 | 4 | 1 | 0 | 11 |
| *Discharge to northern shoreline of Pahurehure Inlet* | | | | | | | | | | | | | | | | | | | |
| **109 - TKI** | 2 | 0 | 0 | 1 | 0 | 9 | 41 | 6 | 11 | 0 | 2 | 1 | 0 | 1 | 1 | 9 | 1 | 0 | 12 |
| **110 - PAS** | 3 | 0 | 1 | 2 | 1 | 7 | 15 | 2 | 34 | 0 | 2 | 1 | 0 | 1 | 1 | 9 | 2 | 0 | 18 |
| **111 - MAW** | 3 | 2 | 2 | 6 | 1 | 1 | 1 | 0 | 1 | 0 | 48 | 1 | 0 | 1 | 1 | 3 | 1 | 0 | 28 |
| *Discharge to northeastern shoreline of Manukau Harbour* | | | | | | | | | | | | | | | | | | | |
| **112 - PAU** | 8 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 2 | 17 | 1 | 40 | 4 | 3 | 1 | 1 | 20 |
| **113 - MEP** | 4 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 3 | 0 | 1 | 72 | 1 | 1 | 0 | 14 |
| **114 - MGE** | 3 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 2 | 0 | 1 | 76 | 1 | 0 | 0 | 12 |
| *Discharge to southern shoreline of Pahurehure Inlet* | | | | | | | | | | | | | | | | | | | |
| **115 - BTB** | 2 | 0 | 1 | 2 | 1 | 25 | 19 | 4 | 8 | 0 | 2 | 1 | 0 | 1 | 1 | 15 | 2 | 0 | 16 |

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**Table 6.14:**

Fate of copper from each subcatchment. Reading across the page: percentage of total copper load from each subcatchment deposited in each subestuary. Hindcast by the calibrated USC-3 model; average over 50 model runs in a Monte Carlo package.

## FATE – Copper

| Subcatchment | Subestuary | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1-HIB | 2-KKA | 3-GMW | 4-GME | 5-CHN | 6-DCO | 7-PHI | 8-PBA | 9-PKA | 10-KPT | 11-WMC | 12-WEY | 13-WIL | 14-PUK | 15-PKK | 16-DCI | 17-GCK | 18-CCK | 19-MHB |
| *Discharge to southeastern shoreline of Manukau Harbour* | | | | | | | | | | | | | | | | | | | |
| **101 - KST** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 98 | 1 |
| **102 - EBH** | 47 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 48 |
| *Discharge to southern shoreline of Pahurehure Inlet* | | | | | | | | | | | | | | | | | | | |
| **103 - KKA** | 3 | 2 | 11 | 7 | 2 | 4 | 6 | 1 | 4 | 0 | 3 | 2 | 0 | 1 | 1 | 6 | 40 | 0 | 6 |
| **104 - WHC** | 2 | 1 | 2 | 3 | 1 | 12 | 13 | 2 | 7 | 0 | 2 | 1 | 0 | 1 | 1 | 47 | 3 | 0 | 4 |
| **105 - OIC** | 2 | 1 | 2 | 3 | 1 | 12 | 13 | 2 | 7 | 0 | 2 | 1 | 0 | 1 | 1 | 46 | 3 | 0 | 4 |
| **106 - DRY** | 2 | 1 | 2 | 3 | 1 | 12 | 13 | 2 | 7 | 0 | 2 | 1 | 0 | 1 | 1 | 48 | 3 | 0 | 4 |
| **107 - HGA** | 2 | 2 | 4 | 2 | 1 | 16 | 14 | 4 | 8 | 0 | 2 | 1 | 0 | 1 | 1 | 29 | 3 | 0 | 12 |
| *Discharge to Pahurehure Basin* | | | | | | | | | | | | | | | | | | | |
| **108 - PKA** | 1 | 0 | 0 | 0 | 0 | 5 | 13 | 55 | 3 | 0 | 1 | 1 | 0 | 0 | 0 | 3 | 1 | 0 | 15 |
| *Discharge to northern shoreline of Pahurehure Inlet* | | | | | | | | | | | | | | | | | | | |
| **109 - TKI** | 2 | 0 | 0 | 0 | 0 | 10 | 40 | 6 | 13 | 0 | 1 | 1 | 0 | 1 | 1 | 7 | 1 | 0 | 17 |
| **110 - PAS** | 2 | 0 | 1 | 2 | 1 | 7 | 16 | 2 | 33 | 0 | 2 | 1 | 0 | 1 | 1 | 7 | 1 | 0 | 23 |
| **111 - MAW** | 3 | 1 | 1 | 6 | 1 | 0 | 1 | 0 | 1 | 0 | 45 | 1 | 0 | 1 | 1 | 2 | 1 | 0 | 34 |
| *Discharge to northeastern shoreline of Manukau Harbour* | | | | | | | | | | | | | | | | | | | |
| **112 - PAU** | 7 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 2 | 17 | 0 | 45 | 4 | 2 | 1 | 1 | 16 |
| **113 - MEP** | 4 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 2 | 0 | 1 | 75 | 1 | 1 | 0 | 12 |
| **114 - MGE** | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 2 | 0 | 1 | 79 | 1 | 0 | 0 | 10 |
| *Discharge to southern shoreline of Pahurehure Inlet* | | | | | | | | | | | | | | | | | | | |
| **115 - BTB** | 2 | 0 | 1 | 2 | 1 | 26 | 19 | 4 | 9 | 0 | 2 | 1 | 0 | 1 | 1 | 11 | 2 | 0 | 21 |

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**Table 6.15:**

Source of sediment that deposits in each subestuary. Reading across the page: percentage of total sediment load deposited in each subestuary from each subcatchment. Hindcast by the calibrated USC-3 model; average over 50 model runs in a Monte Carlo package.

SOURCE – Sediment

| Subestuary | Subcatchment | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 101 KST | 102 EBH | 103 KKA | 104 WHC | 105 OIC | 106 DRY | 107 HGA | 108 PKA | 109 TKI | 110 PAS | 111 MAW | 112 PAU | 113 MEP | 114 MGE | 115 BTB |
| *Manukau Harbour* | | | | | | | | | | | | | | | |
| **1-HIB** | 1 | 45 | 3 | 3 | 1 | 14 | 0 | 2 | 0 | 11 | 1 | 12 | 4 | 2 | 0 |
| *Southern / outer Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **2-KKA** | 0 | 0 | 25 | 11 | 3 | 42 | 2 | 0 | 0 | 2 | 11 | 2 | 1 | 0 | 0 |
| **3-GMW** | 0 | 0 | 38 | 10 | 3 | 38 | 1 | 0 | 0 | 6 | 3 | 0 | 0 | 0 | 0 |
| **4-GME** | 0 | 0 | 18 | 10 | 3 | 38 | 1 | 2 | 0 | 12 | 9 | 4 | 2 | 1 | 0 |
| **5-CHN** | 0 | 0 | 23 | 11 | 3 | 40 | 1 | 1 | 0 | 14 | 6 | 1 | 0 | 0 | 0 |
| *Inner Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **6-DCO** | 0 | 0 | 4 | 16 | 5 | 56 | 3 | 2 | 0 | 11 | 0 | 1 | 0 | 0 | 2 |
| **7-PHI** | 0 | 0 | 5 | 13 | 4 | 46 | 2 | 7 | 2 | 18 | 0 | 1 | 0 | 0 | 1 |
| *Pahurehure Basin* | | | | | | | | | | | | | | | |
| **8-PBA** | 0 | 0 | 1 | 3 | 1 | 12 | 1 | 74 | 1 | 5 | 0 | 1 | 0 | 0 | 0 |
| *Northern / outer Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **9-PKA** | 0 | 0 | 3 | 9 | 3 | 31 | 1 | 3 | 0 | 47 | 0 | 2 | 1 | 0 | 0 |
| **10-KPT** | 0 | 2 | 6 | 6 | 2 | 26 | 1 | 6 | 1 | 20 | 2 | 14 | 10 | 4 | 0 |
| **11-WMC** | 0 | 0 | 5 | 5 | 2 | 20 | 1 | 3 | 0 | 12 | 43 | 5 | 2 | 1 | 0 |
| *Manukau Harbour* | | | | | | | | | | | | | | | |
| **12-WEY** | 0 | 2 | 4 | 4 | 1 | 16 | 0 | 3 | 0 | 12 | 1 | 44 | 8 | 3 | 0 |
| **13-WIL** | 0 | 4 | 4 | 6 | 2 | 26 | 0 | 6 | 1 | 22 | 2 | 18 | 5 | 2 | 0 |
| *Tidal creeks draining to Manukau Harbour* | | | | | | | | | | | | | | | |
| **14-PUK** | 0 | 0 | 2 | 3 | 1 | 11 | 0 | 1 | 0 | 7 | 1 | 72 | 1 | 1 | 0 |
| **15-PKK** | 0 | 0 | 1 | 1 | 0 | 4 | 0 | 1 | 0 | 3 | 0 | 5 | 60 | 23 | 0 |
| *Tidal creeks draining to Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **16-DCI** | 0 | 0 | 3 | 15 | 4 | 52 | 2 | 3 | 0 | 17 | 0 | 2 | 1 | 0 | 0 |
| **17-GCK** | 0 | 0 | 28 | 10 | 3 | 39 | 1 | 2 | 0 | 11 | 0 | 3 | 1 | 0 | 0 |
| **18-CCK** | 94 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 |
| **19-MHB** | 1 | 10 | 4 | 6 | 2 | 23 | 0 | 2 | 0 | 14 | 3 | 24 | 7 | 3 | 0 |

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**Table 6.16:**

Source of zinc that deposits in each subestuary. Reading across the page: percentage of total zinc load deposited in each subestuary from each subcatchment. Hindcast by the calibrated USC-3 model; average over 50 model runs in a Monte Carlo package.

## SOURCE – Zinc

| Subestuary | Subcatchment | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **101 KST** | **102 EBH** | **103 KKA** | **104 WHC** | **105 OIC** | **106 DRY** | **107 HGA** | **108 PKA** | **109 TKI** | **110 PAS** | **111 MAW** | **112 PAU** | **113 MEP** | **114 MGE** | **115 BTB** |
| *Manukau Harbour* | | | | | | | | | | | | | | | |
| **1-HIB** | 0 | 5 | 0 | 4 | 0 | 7 | 0 | 8 | 2 | 8 | 6 | 48 | 10 | 1 | 0 |
| *Southern / outer Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **2-KKA** | 0 | 0 | 4 | 15 | 0 | 29 | 4 | 1 | 0 | 1 | 36 | 7 | 2 | 0 | 0 |
| **3-GMW** | 0 | 0 | 8 | 21 | 1 | 39 | 4 | 0 | 0 | 14 | 14 | 0 | 0 | 0 | 0 |
| **4-GME** | 0 | 0 | 2 | 12 | 0 | 22 | 1 | 4 | 1 | 11 | 26 | 15 | 4 | 0 | 0 |
| **5-CHN** | 0 | 0 | 3 | 15 | 0 | 29 | 1 | 3 | 1 | 22 | 20 | 4 | 1 | 0 | 1 |
| *Inner Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **6-DCO** | 0 | 0 | 0 | 19 | 1 | 37 | 3 | 12 | 6 | 15 | 1 | 3 | 1 | 0 | 2 |
| **7-PHI** | 0 | 0 | 0 | 12 | 0 | 22 | 2 | 25 | 16 | 18 | 1 | 3 | 1 | 0 | 1 |
| *Pahurehure Basin* | | | | | | | | | | | | | | | |
| **8-PBA** | 0 | 0 | 0 | 1 | 0 | 2 | 0 | 91 | 2 | 2 | 0 | 1 | 0 | 0 | 0 |
| *Northern / outer Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **9-PKA** | 0 | 0 | 0 | 8 | 0 | 16 | 1 | 9 | 5 | 52 | 1 | 5 | 1 | 0 | 1 |
| **10-KPT** | 0 | 0 | 1 | 5 | 0 | 9 | 1 | 13 | 3 | 9 | 6 | 38 | 14 | 2 | 0 |
| **11-WMC** | 0 | 0 | 0 | 3 | 0 | 6 | 0 | 4 | 1 | 4 | 67 | 10 | 3 | 0 | 0 |
| *Manukau Harbour* | | | | | | | | | | | | | | | |
| **12-WEY** | 0 | 0 | 0 | 2 | 0 | 3 | 0 | 3 | 1 | 3 | 2 | 81 | 5 | 1 | 0 |
| **13-WIL** | 0 | 1 | 0 | 4 | 0 | 8 | 1 | 13 | 3 | 10 | 8 | 41 | 10 | 1 | 0 |
| *Tidal creeks draining to Manukau Harbour* | | | | | | | | | | | | | | | |
| **14-PUK** | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 94 | 1 | 0 | 0 |
| **15-PKK** | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 11 | 73 | 10 | 0 |
| *Tidal creeks draining to Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **16-DCI** | 0 | 0 | 0 | 24 | 1 | 47 | 2 | 6 | 3 | 8 | 2 | 5 | 1 | 0 | 1 |
| **17-GCK** | 0 | 0 | 10 | 15 | 0 | 29 | 2 | 8 | 3 | 10 | 3 | 16 | 3 | 0 | 1 |
| **18-CCK** | 60 | 1 | 0 | 1 | 0 | 3 | 0 | 3 | 1 | 3 | 3 | 20 | 4 | 0 | 0 |
| **19-MHB** | 0 | 1 | 0 | 3 | 0 | 5 | 1 | 13 | 3 | 13 | 14 | 35 | 10 | 1 | 0 |

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**Table 6.17:**

Source of copper that deposits in each subestuary. Reading across the page: percentage of total copper load deposited in each subestuary from each subcatchment. Hindcast by the calibrated USC-3 model; average over 50 model runs in a Monte Carlo package.

# SOURCE – Copper

| Subestuary | Subcatchment | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 101 KST | 102 EBH | 103 KKA | 104 WHC | 105 OIC | 106 DRY | 107 HGA | 108 PKA | 109 TKI | 110 PAS | 111 MAW | 112 PAU | 113 MEP | 114 MGE | 115 BTB |
| *Manukau Harbour* | | | | | | | | | | | | | | | |
| **1-HIB** | 0 | 16 | 1 | 4 | 0 | 6 | 0 | 5 | 1 | 10 | 7 | 42 | 6 | 1 | 0 |
| *Southern / outer Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **2-KKA** | 0 | 0 | 8 | 15 | 1 | 24 | 5 | 1 | 0 | 1 | 39 | 5 | 1 | 0 | 0 |
| **3-GMW** | 0 | 0 | 17 | 18 | 1 | 30 | 4 | 0 | 0 | 16 | 14 | 0 | 0 | 0 | 0 |
| **4-GME** | 0 | 0 | 5 | 12 | 1 | 20 | 1 | 2 | 0 | 13 | 29 | 12 | 2 | 0 | 0 |
| **5-CHN** | 0 | 0 | 8 | 15 | 1 | 24 | 1 | 1 | 0 | 26 | 20 | 3 | 0 | 0 | 0 |
| *Inner Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **6-DCO** | 0 | 0 | 1 | 21 | 2 | 33 | 3 | 12 | 3 | 21 | 1 | 3 | 0 | 0 | 1 |
| **7-PHI** | 0 | 0 | 1 | 14 | 1 | 22 | 2 | 21 | 8 | 28 | 1 | 2 | 0 | 0 | 0 |
| *Pahurehure Basin* | | | | | | | | | | | | | | | |
| **8-PBA** | 0 | 0 | 0 | 2 | 0 | 3 | 0 | 89 | 1 | 3 | 0 | 1 | 0 | 0 | 0 |
| *Northern / outer Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **9-PKA** | 0 | 0 | 1 | 8 | 1 | 13 | 1 | 6 | 3 | 63 | 1 | 4 | 1 | 0 | 0 |
| **10-KPT** | 0 | 1 | 2 | 6 | 0 | 9 | 1 | 10 | 1 | 13 | 8 | 39 | 10 | 2 | 0 |
| **11-WMC** | 0 | 0 | 1 | 3 | 0 | 5 | 0 | 2 | 0 | 4 | 75 | 7 | 1 | 0 | 0 |
| *Manukau Harbour* | | | | | | | | | | | | | | | |
| **12-WEY** | 0 | 0 | 1 | 2 | 0 | 3 | 0 | 2 | 0 | 3 | 2 | 83 | 3 | 1 | 0 |
| **13-WIL** | 0 | 2 | 1 | 5 | 0 | 8 | 1 | 10 | 1 | 14 | 10 | 39 | 7 | 1 | 0 |
| *Tidal creeks draining to Manukau Harbour* | | | | | | | | | | | | | | | |
| **14-PUK** | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 95 | 0 | 0 | 0 |
| **15-PKK** | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 2 | 1 | 12 | 66 | 14 | 0 |
| *Tidal creeks draining to Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **16-DCI** | 0 | 0 | 1 | 29 | 2 | 49 | 2 | 3 | 1 | 7 | 1 | 3 | 0 | 0 | 0 |
| **17-GCK** | 0 | 0 | 31 | 14 | 1 | 22 | 2 | 4 | 1 | 10 | 3 | 11 | 2 | 0 | 0 |
| **18-CCK** | 85 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 2 | 1 | 7 | 1 | 0 | 0 |
| **19-MHB** | 0 | 4 | 1 | 2 | 0 | 4 | 1 | 14 | 2 | 23 | 21 | 23 | 5 | 1 | 0 |

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**Table 6.18:**

Sedimentation rate: "Hindcast" is the average over the historical period and over 50 model runs by the calibrated model, and "Measured" is that reported by Reed et al. (2008) from radioisotopic analysis of sediment cores.

| Subestuary | Hindcast, mm/year | Measured, mm/year |
|---|---|---|
| 1 – HIB | 0.02 | - |
| 2 – KKA | 0.58 | - |
| 3 – GMW | 5.14 | - |
| 4 – GME | 1.70 | 3.2 |
| 5 – CHN | 1.18 | - |
| 6 – DCO | 3.03 | 3.1 |
| 7 – PHI | 2.28 | 4.0 |
| 8 – PBA | 4.86 | - |
| 9 – PKA | 2.37 | 2.2 |
| 10 – KPT | 0.14 | - |
| 11 – WMC | 1.49 | 4.5 |
| 12 – WEY | 0.04 | 0.0 |
| 13 – WIL | 0.01 | - |
| 14 – PUK | 2.86 | - |
| 15 – PKK | 1.73 | - |
| 16 – DCI | 1.52 | - |
| 17 – GCK | 1.55 | - |
| 18 – CCK | 1.07 | - |
| 19 – MHB | - | - |

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**Figure 6.1:**
Statistics of the total (rural plus urban) sediment runoff. These statistics are for the sum of all particle sizes, and are for just one USC-3 model run in the Monte Carlo package of 50 USC-3 model runs.

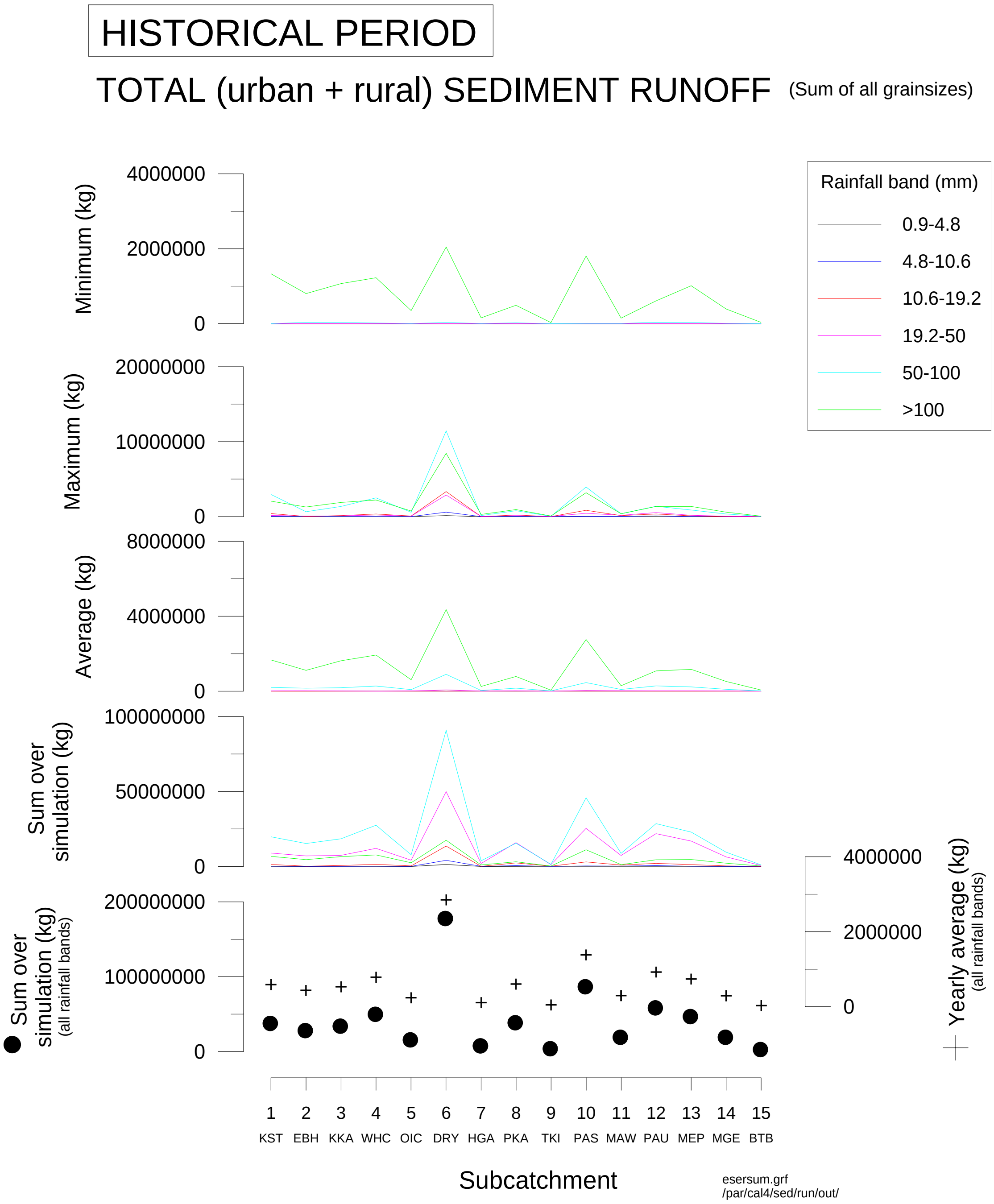


**Figure 6.2:**

Annual sediment runoff. This is the sum of all particle sizes, as it appears for just one USC-3 model run in the Monte Carlo package of 50 USC-3 model runs. This figure shows the urban component of the total load, and the total load. The rural component of the total load is the difference between those two. Year 1 is 1940 and year 62 is 2001.

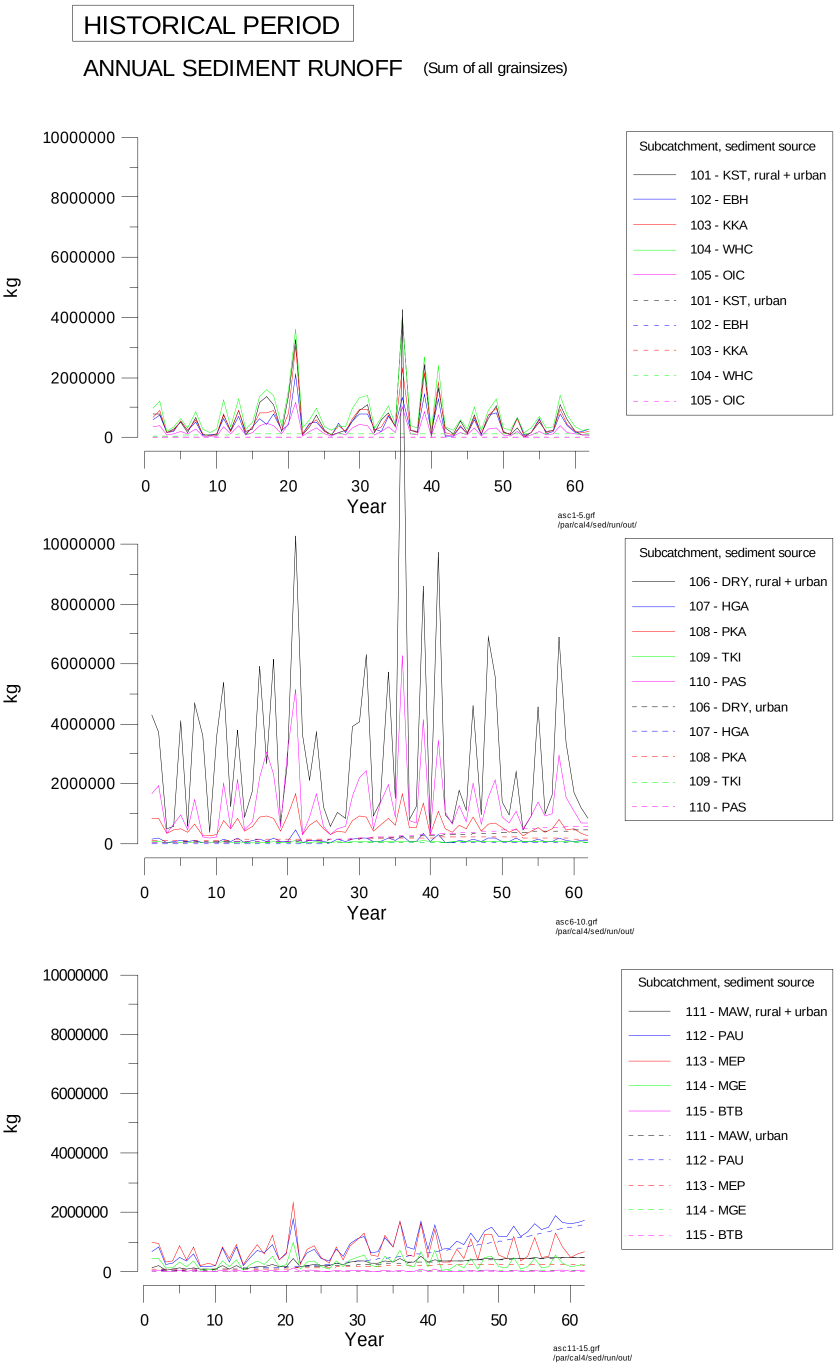


**Figure 6.3:**

Fraction of the annual sediment runoff in each subcatchment that comes from urban sources. The rest comes from rural sources. Year 1 is 1940 and year 62 is 2001.

HISTORICAL PERIOD

FRACTION OF ANNUAL SEDIMENT RUNOFF FROM URBAN SOURCES

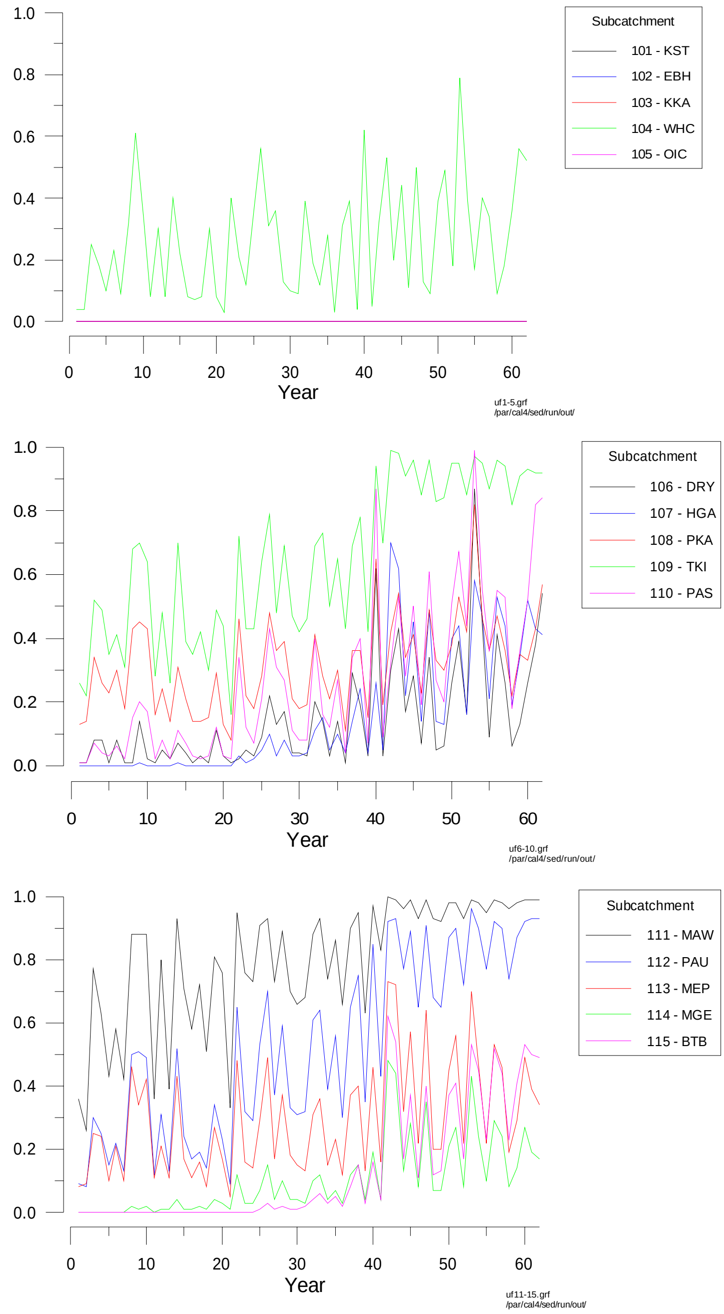


**Figure 6.4:**

Daily total (rural plus urban) sediment runoff plotted against daily rainfall.  This is the sum of all particle sizes, as it appears for just one USC-3 model run in the Monte Carlo package of 50 USC-3 model runs.

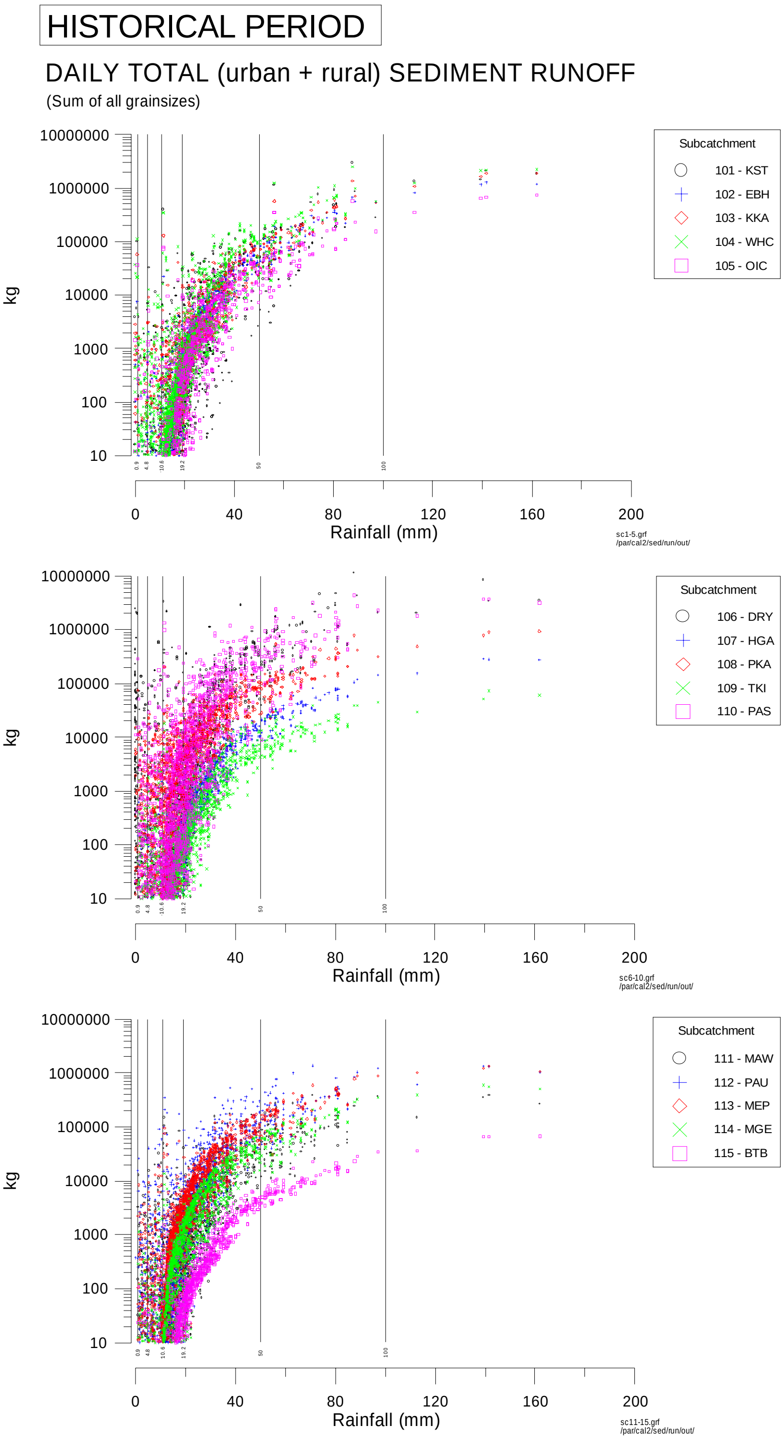


**Figure 6.5:**

Anthropogenic zinc loads (total carried by all sediment constituent particle sizes). Year 1 is 1940 and year 62 is 2001.

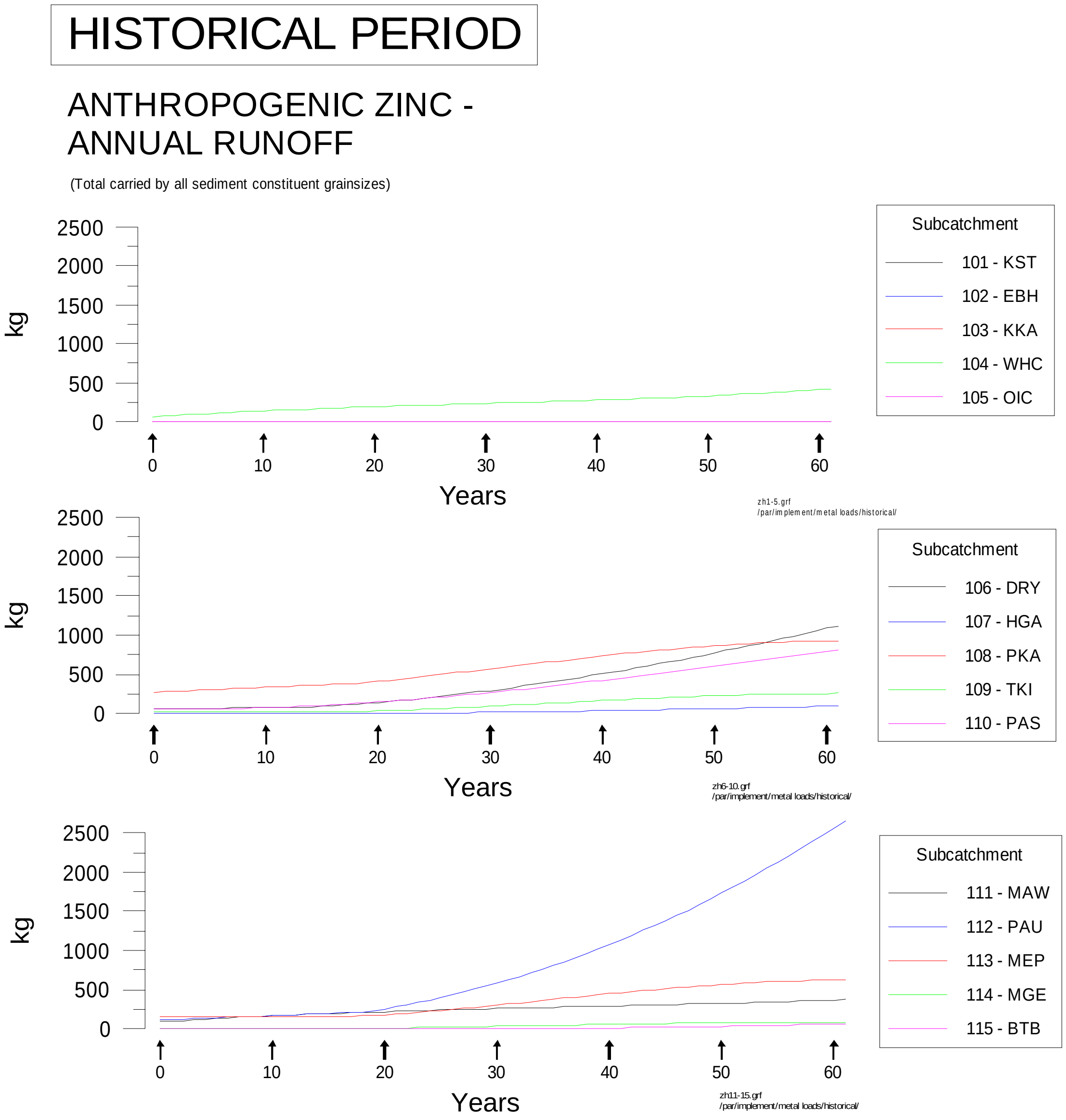


**Figure 6.6:**

Anthropogenic copper loads (total carried by all sediment constituent particlen sizes).  Year 1 is 1940 and year 62 is 2001.

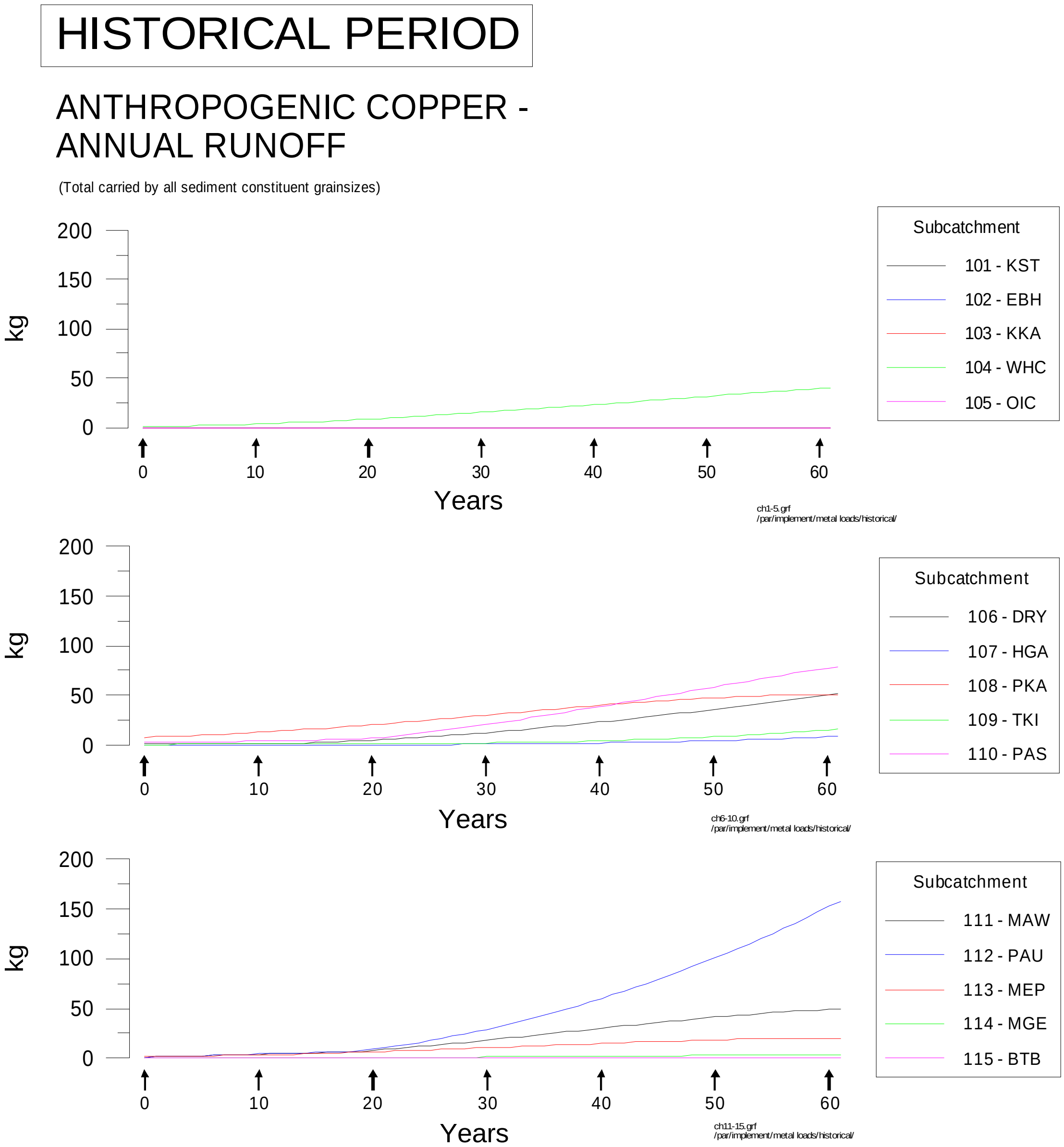


**Figure 6.7:**
Concentrations at which total (anthropogenic plus natural) zinc is delivered to the harbour over the historical period. Concentration is defined here as the total (anthropogenic plus natural) metal carried by all sediment particle sizes divided by the total (rural plus urban) sediment summed over all particle sizes. These figures are for just one USC-3 model run in the Monte Carlo package of 50 USC-3 model runs.

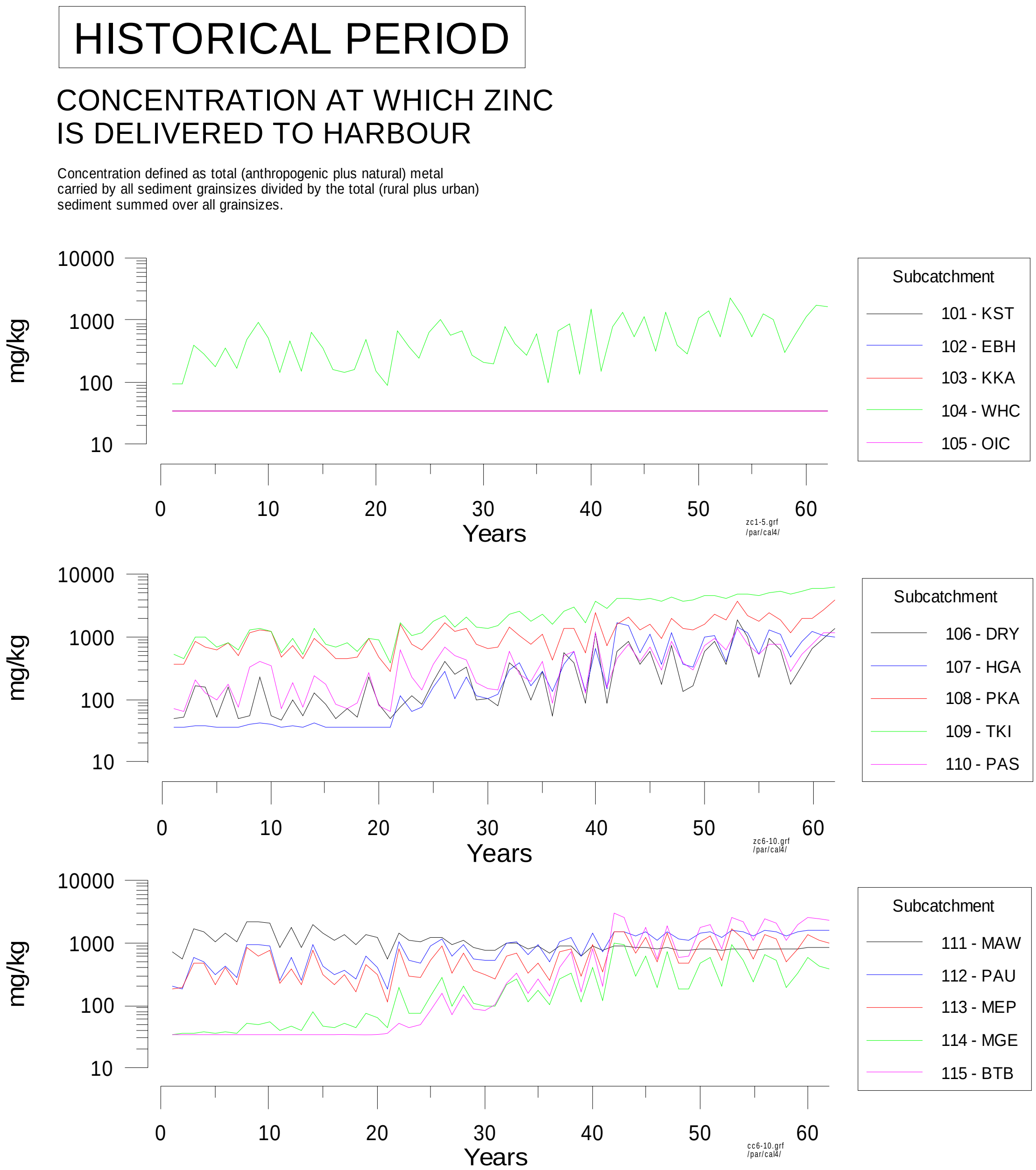


**Figure 6.8:**

Concentrations at which total (anthropogenic plus natural) copper is delivered to the harbour over the historical period. Concentration is defined here as the total (anthropogenic plus natural) metal carried by all sediment particle sizes divided by the total (rural plus urban) sediment summed over all particle sizes. These figures are for just one USC-3 model run in the Monte Carlo package of 50 USC-3 model runs.

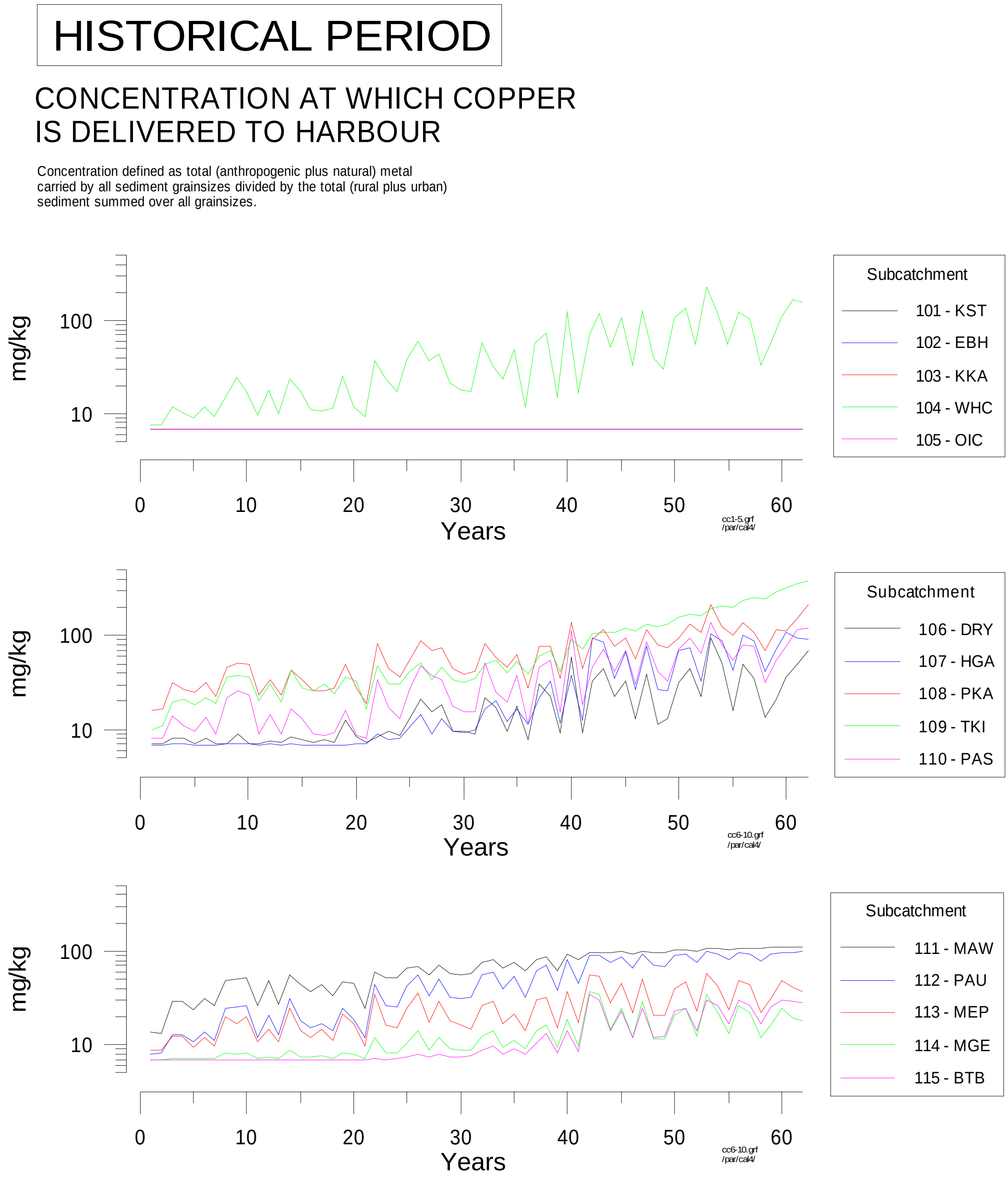
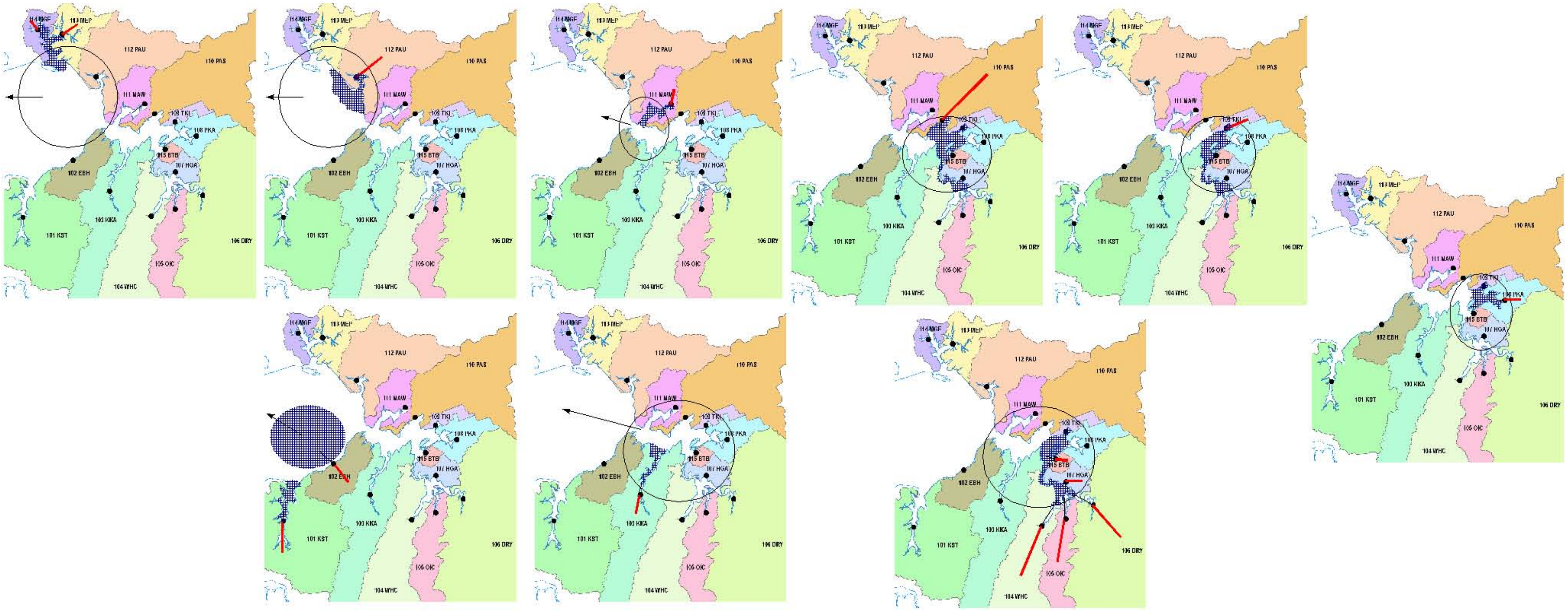


**Figure 6.9:**

Fate of sediment from each subcatchment. The hatched regions indicate principal areas of deposition of sediment from each subcatchment, and the open circle denotes the wider area over which sediments are dispersed. The thin black arrow represents loss to Manukau Harbour.

FATE – Sediment

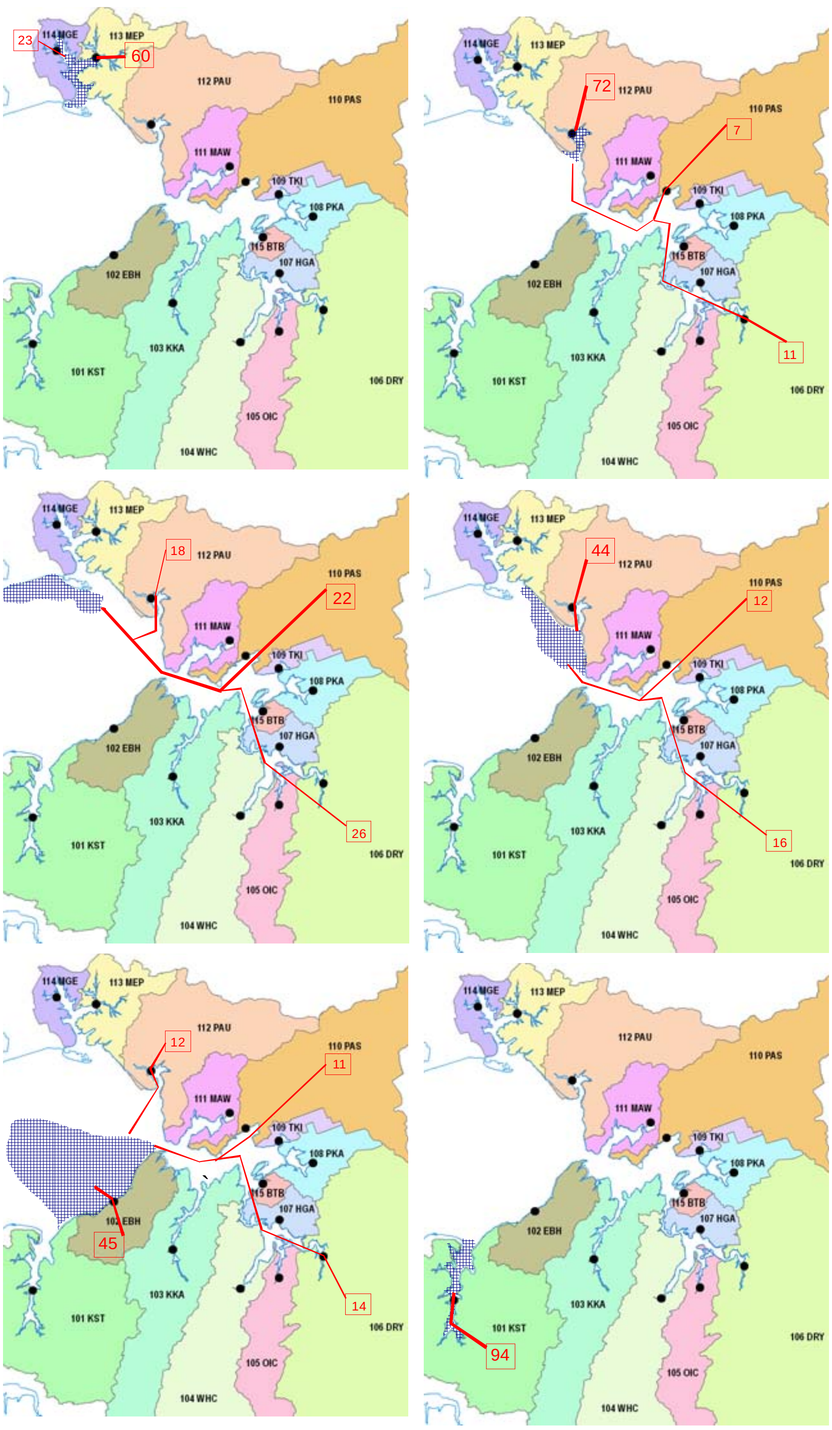


\cal2\sed\run\out\sediment fate map cb1 all.odg

**Figure 6.10:**

Source of sediment that deposits in each subestuary. The hatching indicates the subestuary. The number at the end of each red line connecting a subcatchment with a subestuary is the percentage of the total sediment deposited in the subestuary that is sourced from that subcatchment.

SOURCE – Sediment (Manukau Harbour)

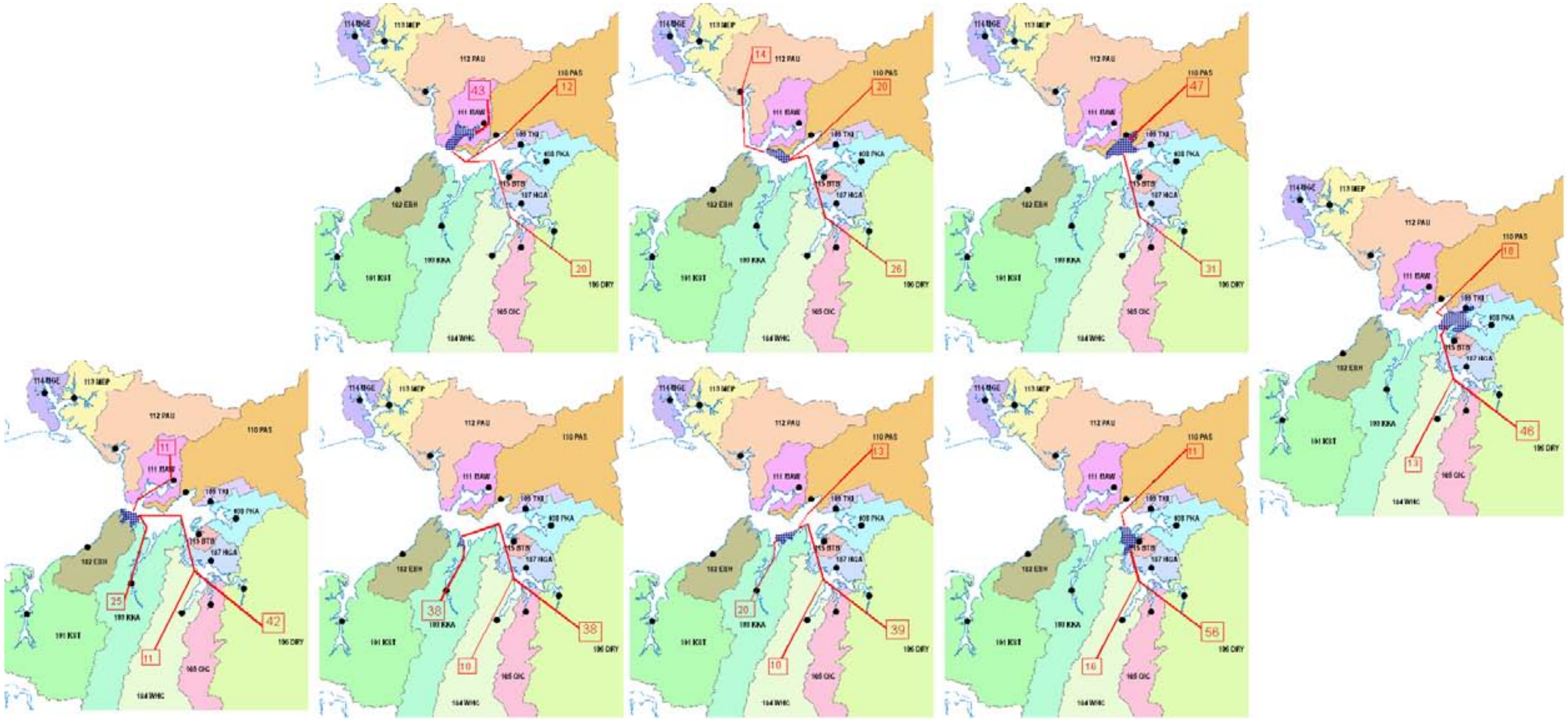



\cal4\sed\run\out\sediment source map cc1 manuaku.odg

**Figure 6.11:**

Source of sediment that deposits in each subestuary. The hatching indicates the subestuary. The number at the end of each red line connecting a subcatchment with a subestuary is the percentage of the total sediment deposited in the subestuary that is sourced from that subcatchment.

## SOURCE – Sediment (Pahurehure Inlet)

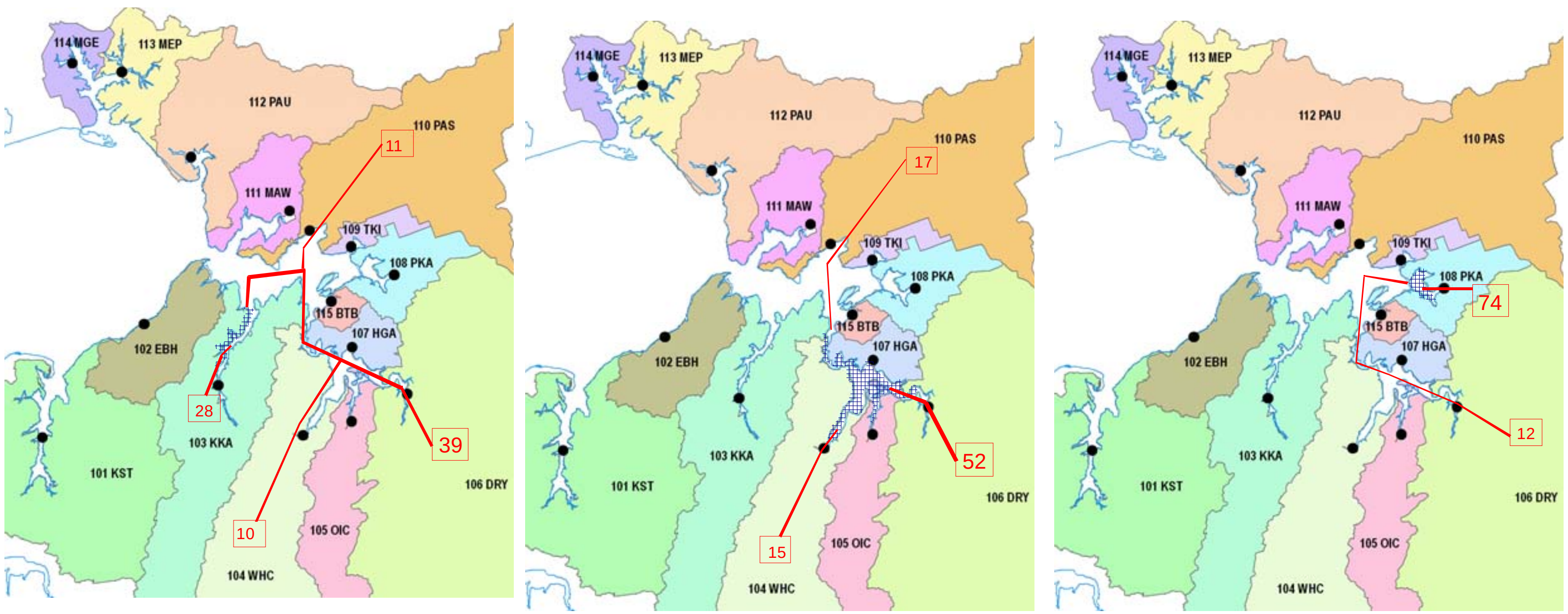


\cal4\sed\run\out\sediment source map cc1 inlet.odg

**Figure 6.12:**

Source of sediment that deposits in each subestuary. The hatching indicates the subestuary. The number at the end of each red line connecting a subcatchment with a subestuary is the percentage of the total sediment deposited in the subestuary that is sourced from that subcatchment.

SOURCE – Sediment (tidal creeks & basin, Pahurehure Inlet)

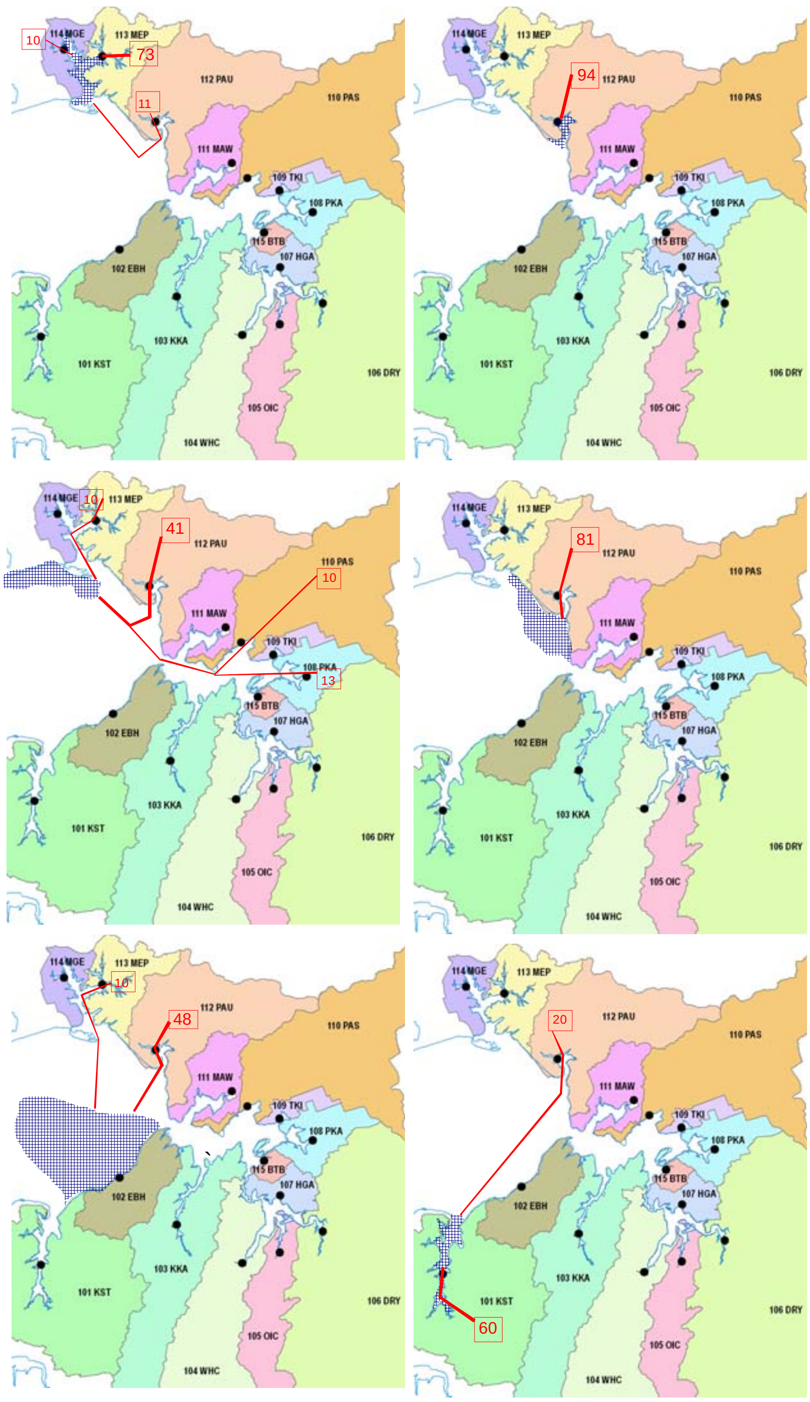



\cal4\sed\run\out\sediment source map cc1 tidal creeks-basin.odg

**Figure 6.13:**

Source of zinc that deposits in each subestuary. The hatching indicates the subestuary. The number at the end of each red line connecting a subcatchment with a subestuary is the percentage of the total zinc deposited in the subestuary that is sourced from that subcatchment.

SOURCE – Zinc (Manukau Harbour)

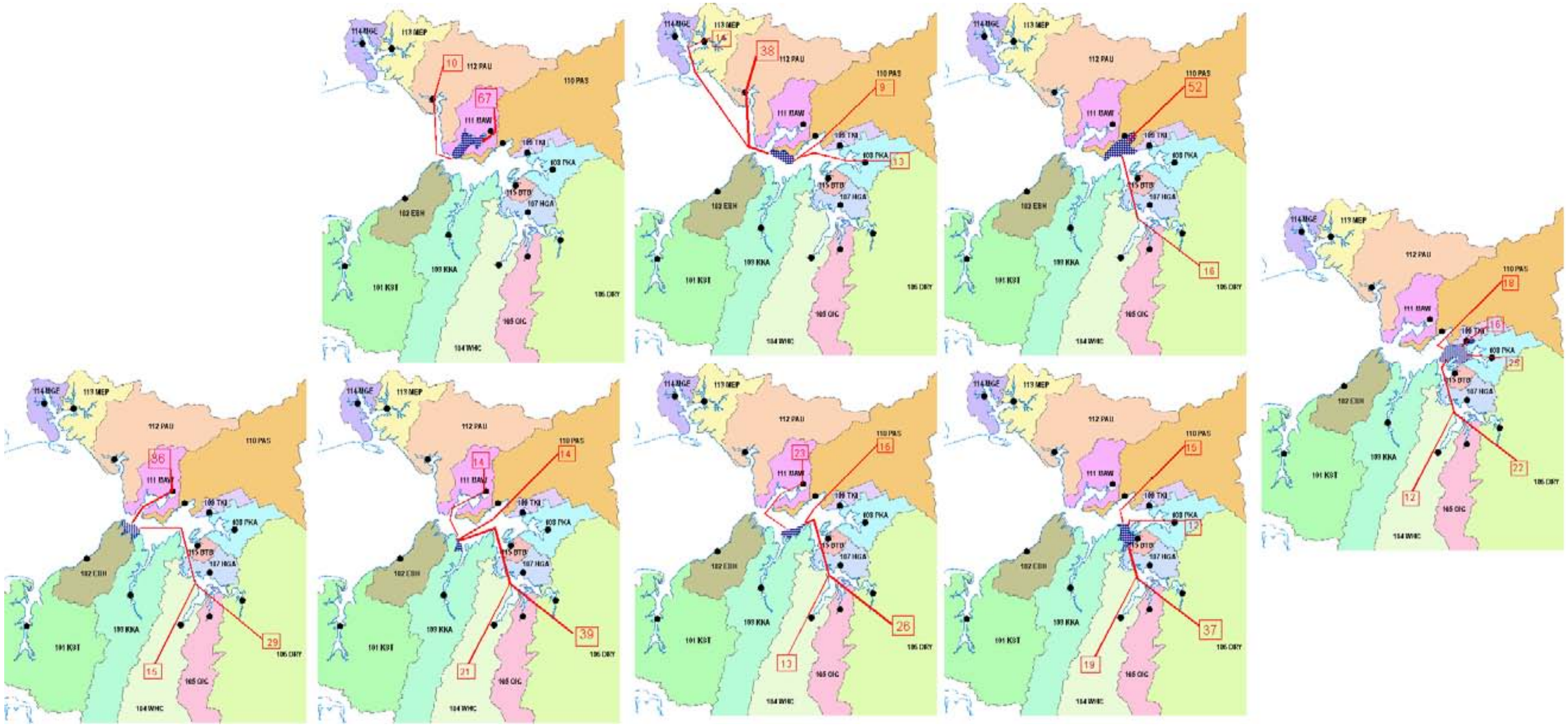



\cal4\zin\run\out\zinc source map cc5 manuaku.odg

**Figure 6.14:**

Source of zinc that deposits in each subestuary. The hatching indicates the subestuary. The number at the end of each red line connecting a subcatchment with a subestuary is the percentage of the total zinc deposited in the subestuary that is sourced from that subcatchment.

SOURCE – Zinc (Pahurehure Inlet)

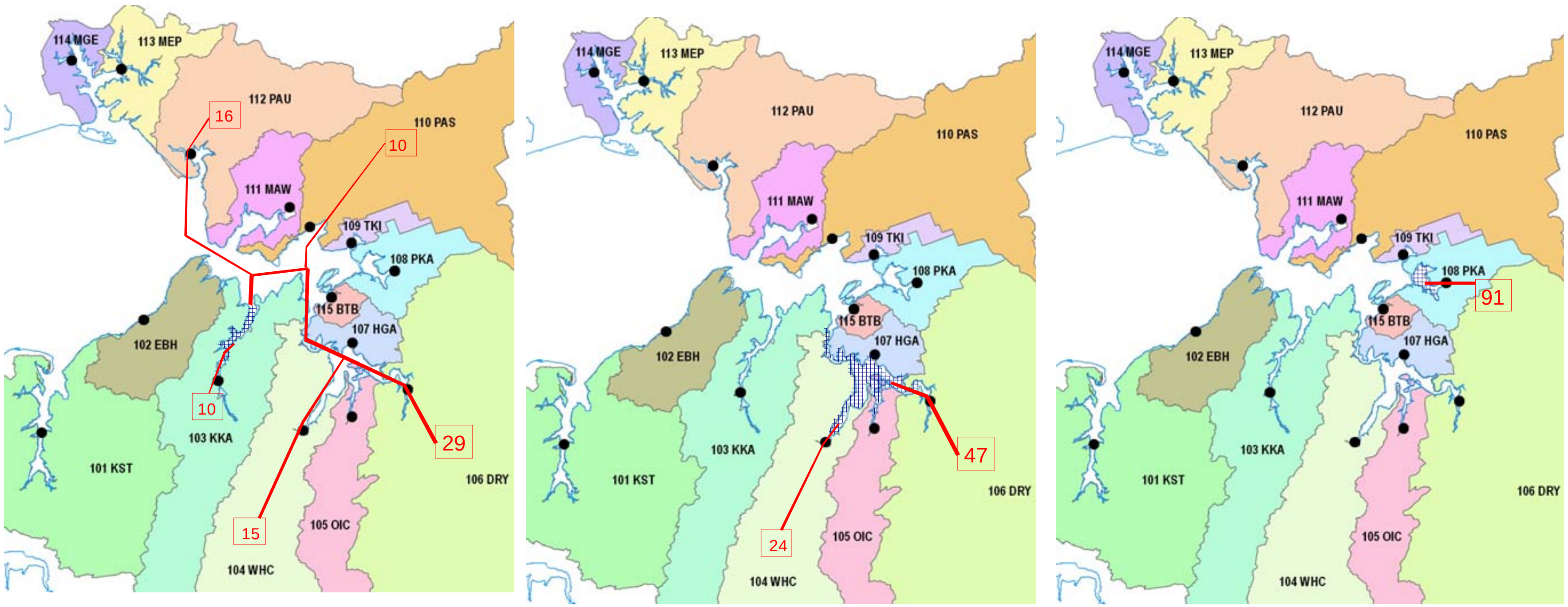


\cal4\zin\run\out\zinc source map cc5 inlet.odg

**Figure 6.15:**

Source of zinc that deposits in each subestuary. The hatching indicates the subestuary. The number at the end of each red line connecting a subcatchment with a subestuary is the percentage of the total zinc deposited in the subestuary that is sourced from that subcatchment.

SOURCE – Zinc (tidal creeks & basin, Pahurehure Inlet)




\cal4\zin\run\out\zinc source map cc5 tidal creeks-basin.odg

**Figure 6.16:**

Source of copper that deposits in each subestuary. The hatching indicates the subestuary. The number at the end of each red line connecting a subcatchment with a subestuary is the percentage of the total copper deposited in the subestuary that is sourced from that subcatchment.

SOURCE – Copper (Manukau Harbour)

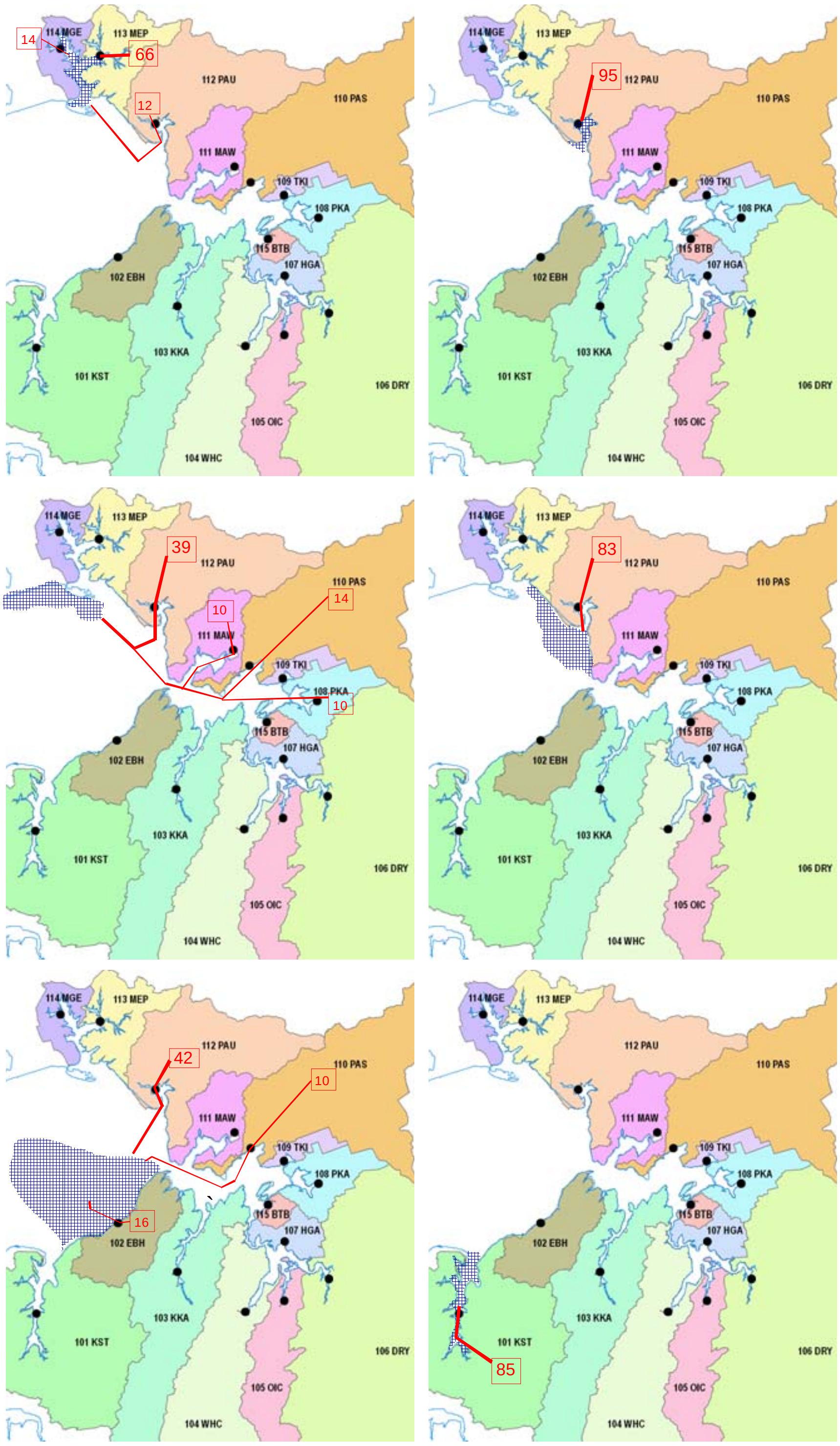



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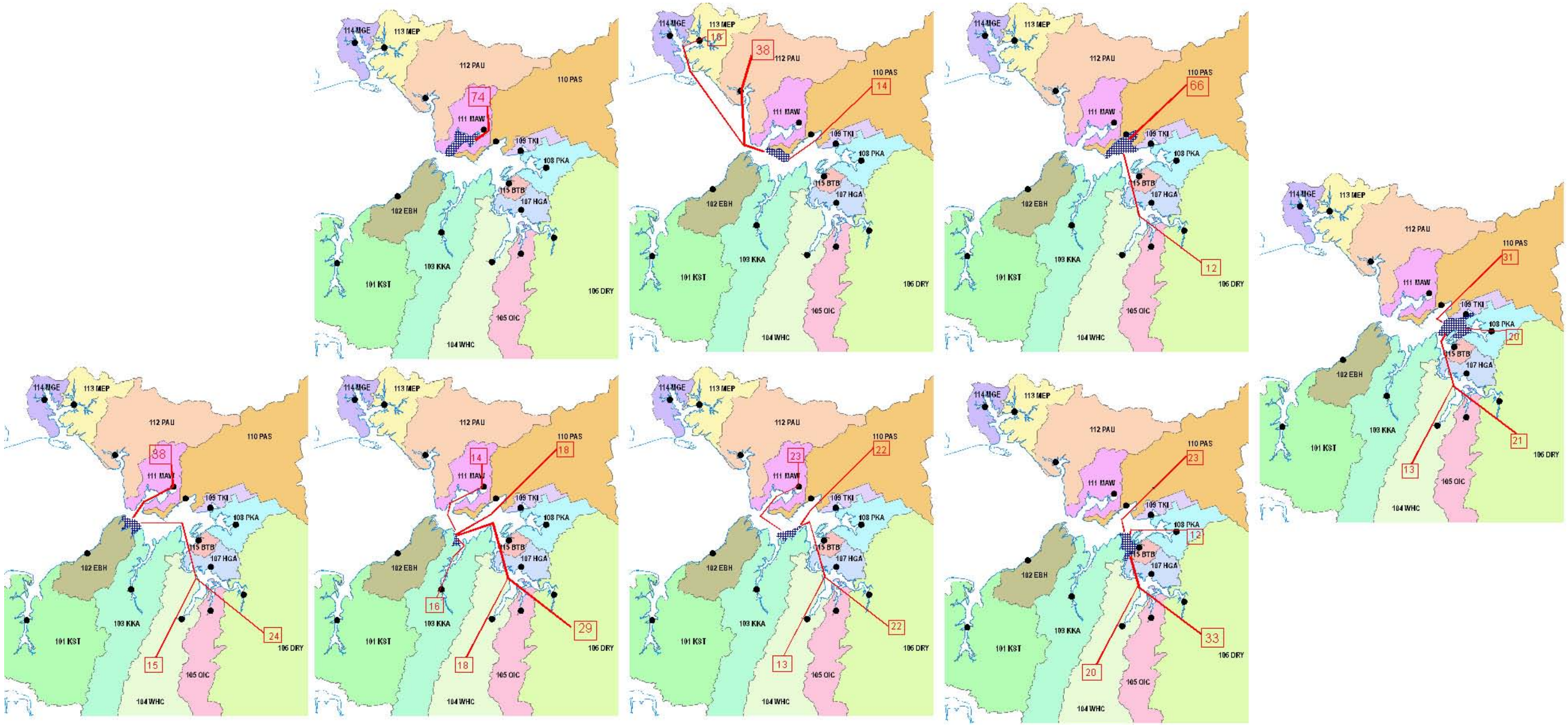
**Figure 6.17:**

Source of copper that deposits in each subestuary. The hatching indicates the subestuary. The number at the end of each red line connecting a subcatchment with a subestuary is the percentage of the total copper deposited in the subestuary that is sourced from that subcatchment.

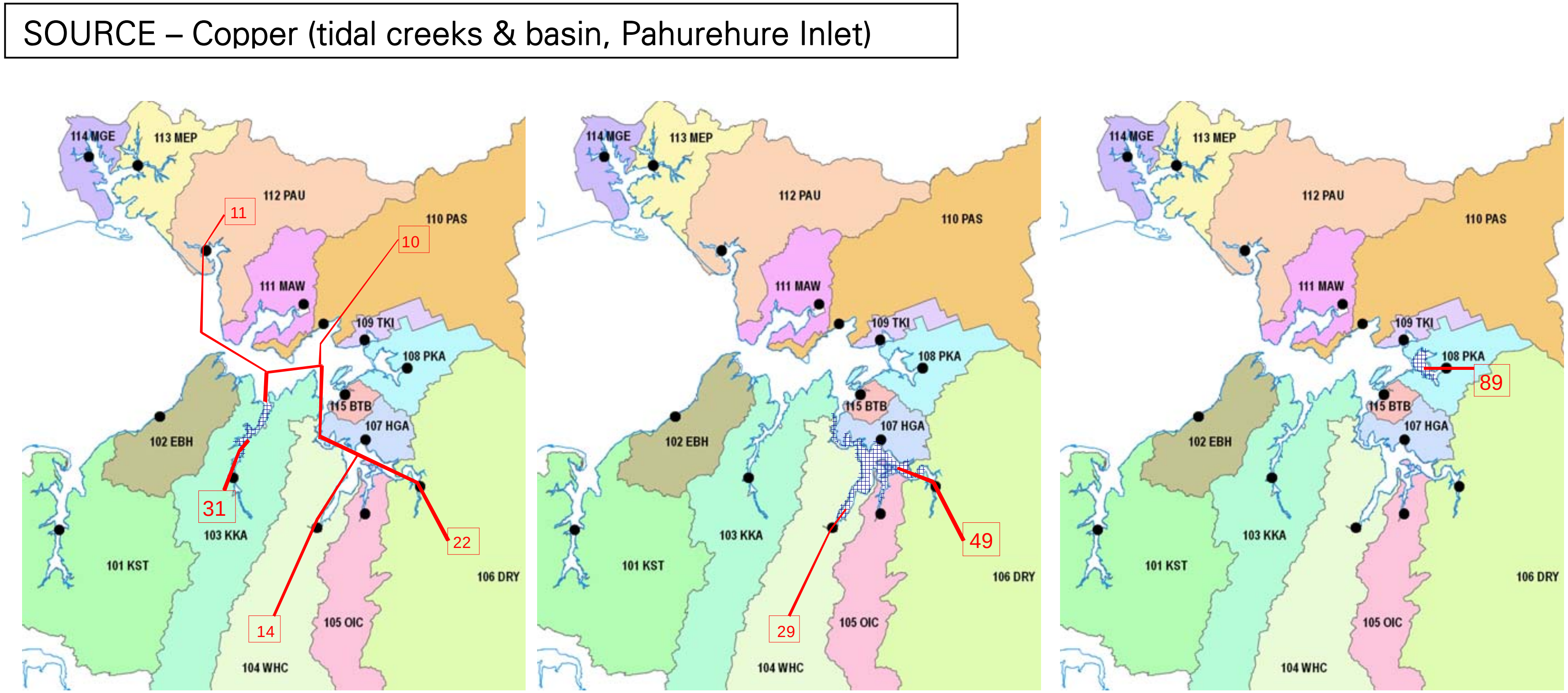
## SOURCE – Copper (Pahurehure Inlet)




\cal4\cop\run\out\copper source map cc8 inlet.odg

**Figure 6.18:**

Source of copper that deposits in each subestuary. The hatching indicates the subestuary. The number at the end of each red line connecting a subcatchment with a subestuary is the percentage of the total copper deposited in the subestuary that is sourced from that subcatchment.




\cal4\cop\run\out\copper source map cc8 tidal creeks-basin.odg

**Figure 6.19:**

Sedimentation rate in each subestuary. “Hindcast” is the average over the historical period and over 50 model runs hindcast by the calibrated model. “Measured” is that reported by Reed et al. (2008) from radioisotopic analysis of sediment cores.

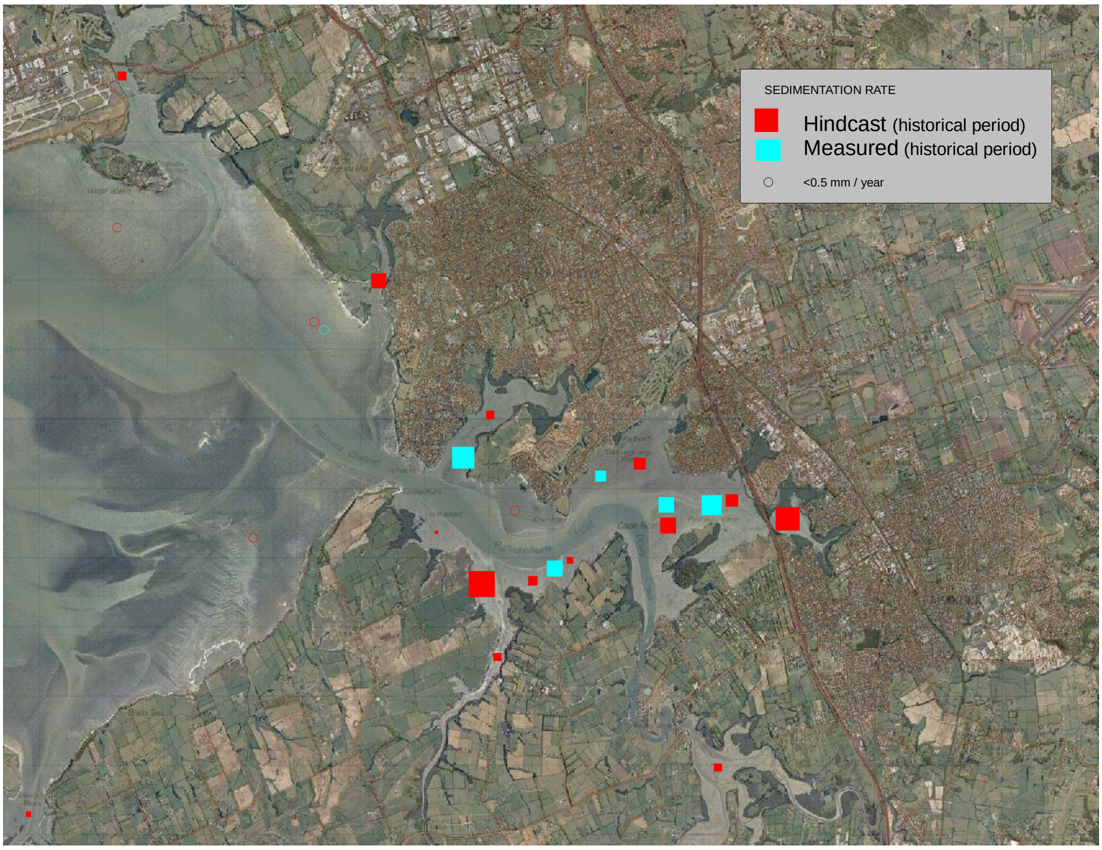


**Figure 6.20:**

Hindcast change in bed-sediment level over the historical period (average of 50 model runs in the Monte Carlo package).

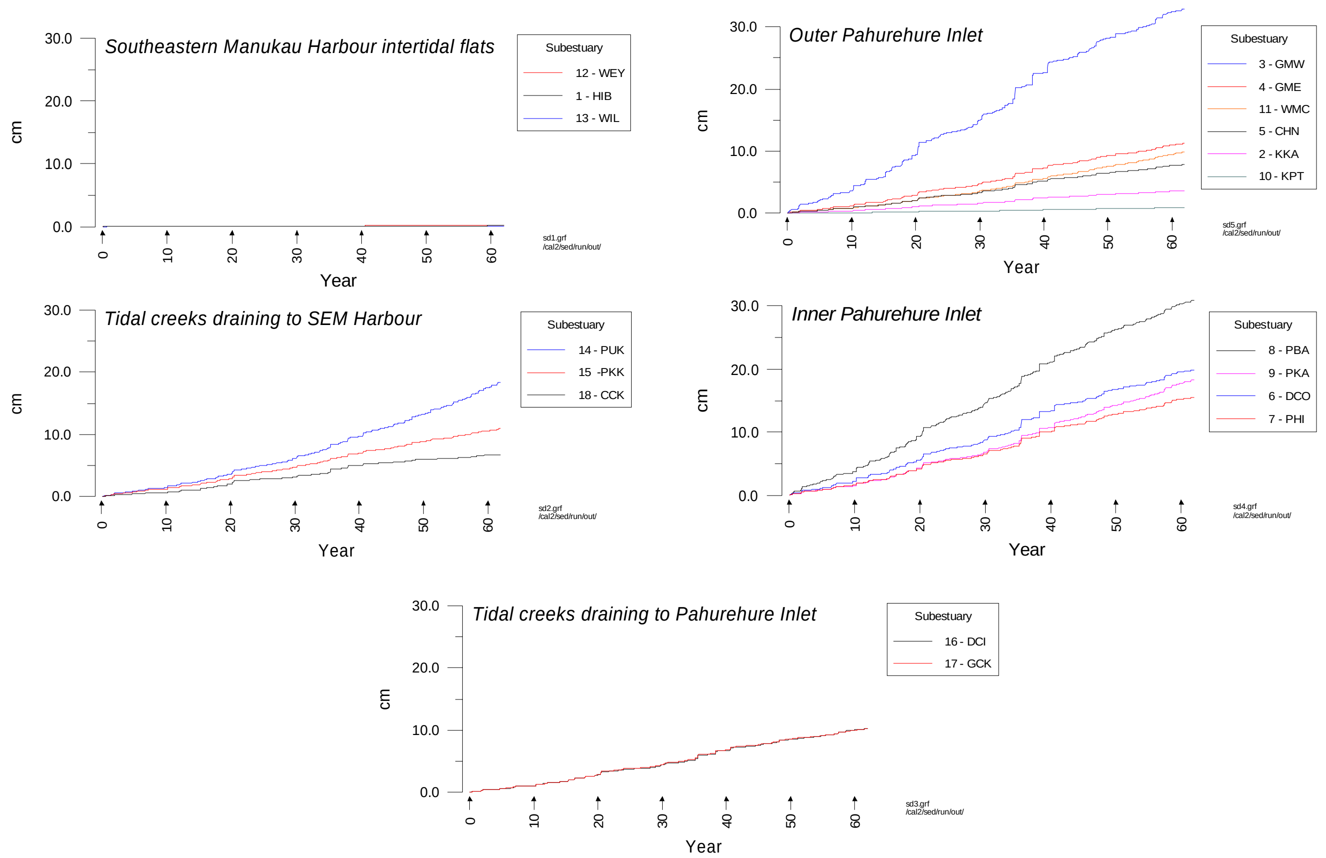


**Figure 6.21:**

Performance of the calibrated model for hindcasting zinc in the test subestuaries. See the text for explanation of symbols.

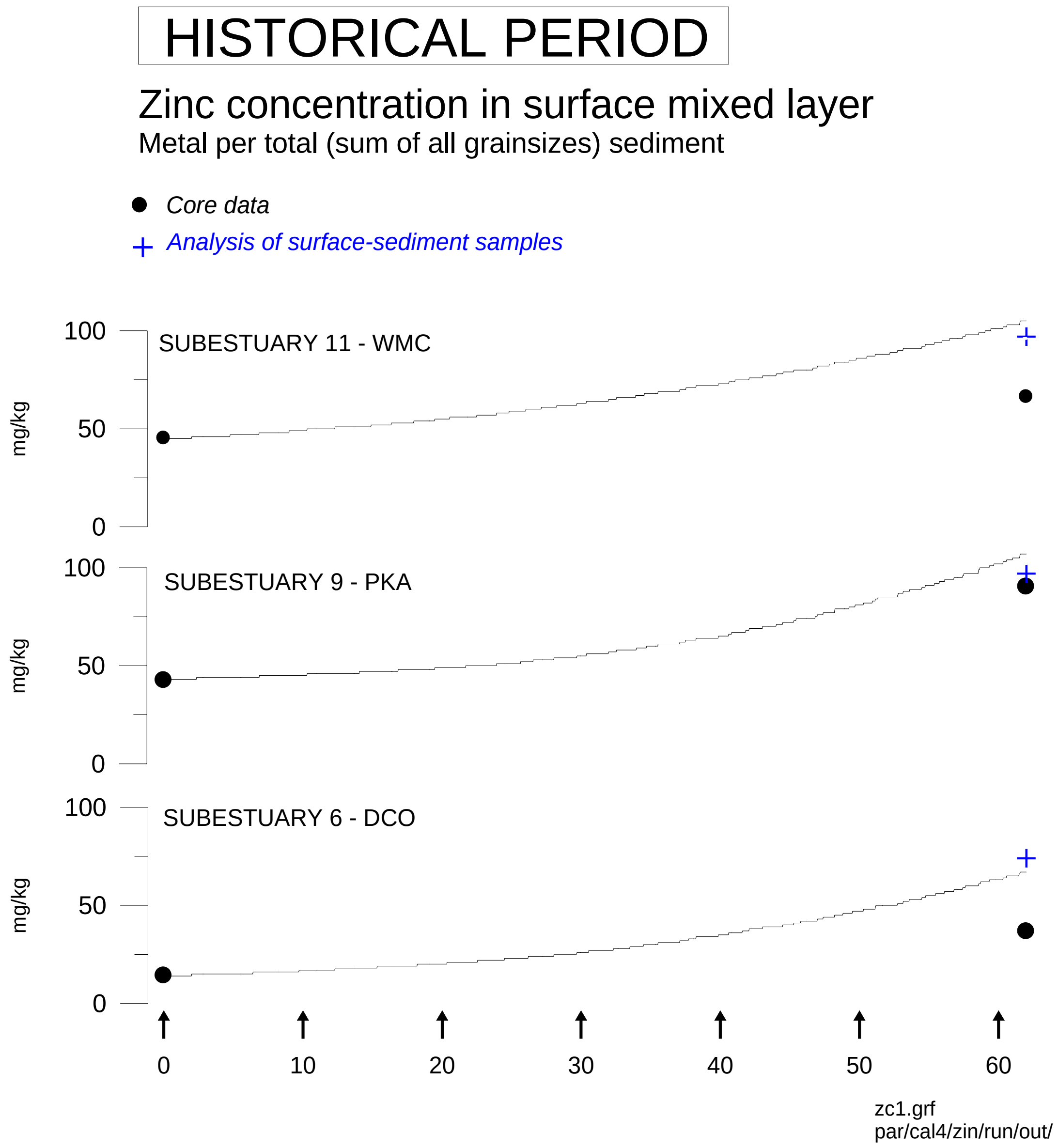


**Figure 6.21: (continued)**

Performance of the calibrated model for hindcasting zinc in the test subestuaries. See the text for explanation of symbols.

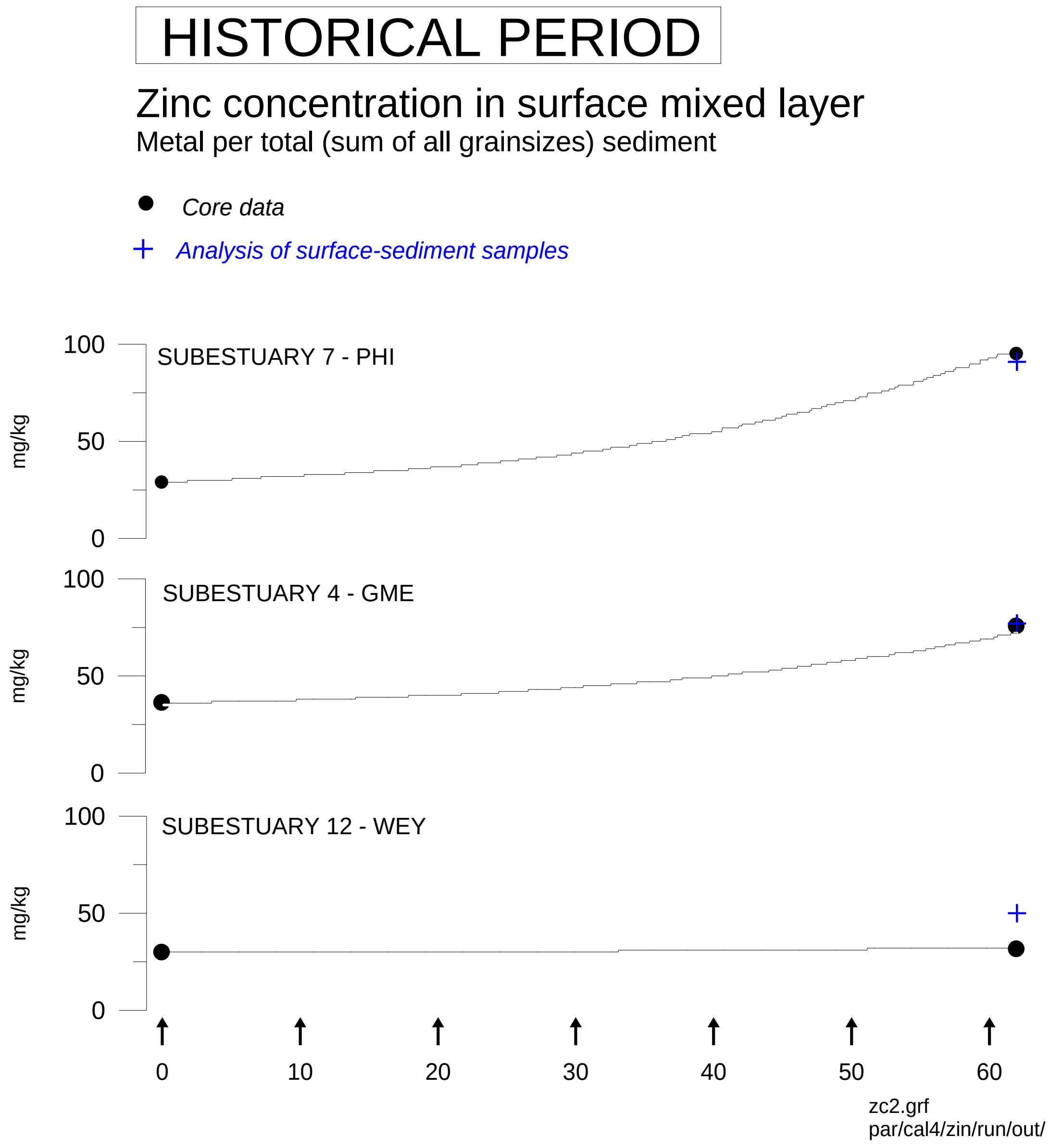


**Figure 6.22:**
Performance of the calibrated model for hindcasting copper in the test subestuaries. See the text for explanation of symbols.

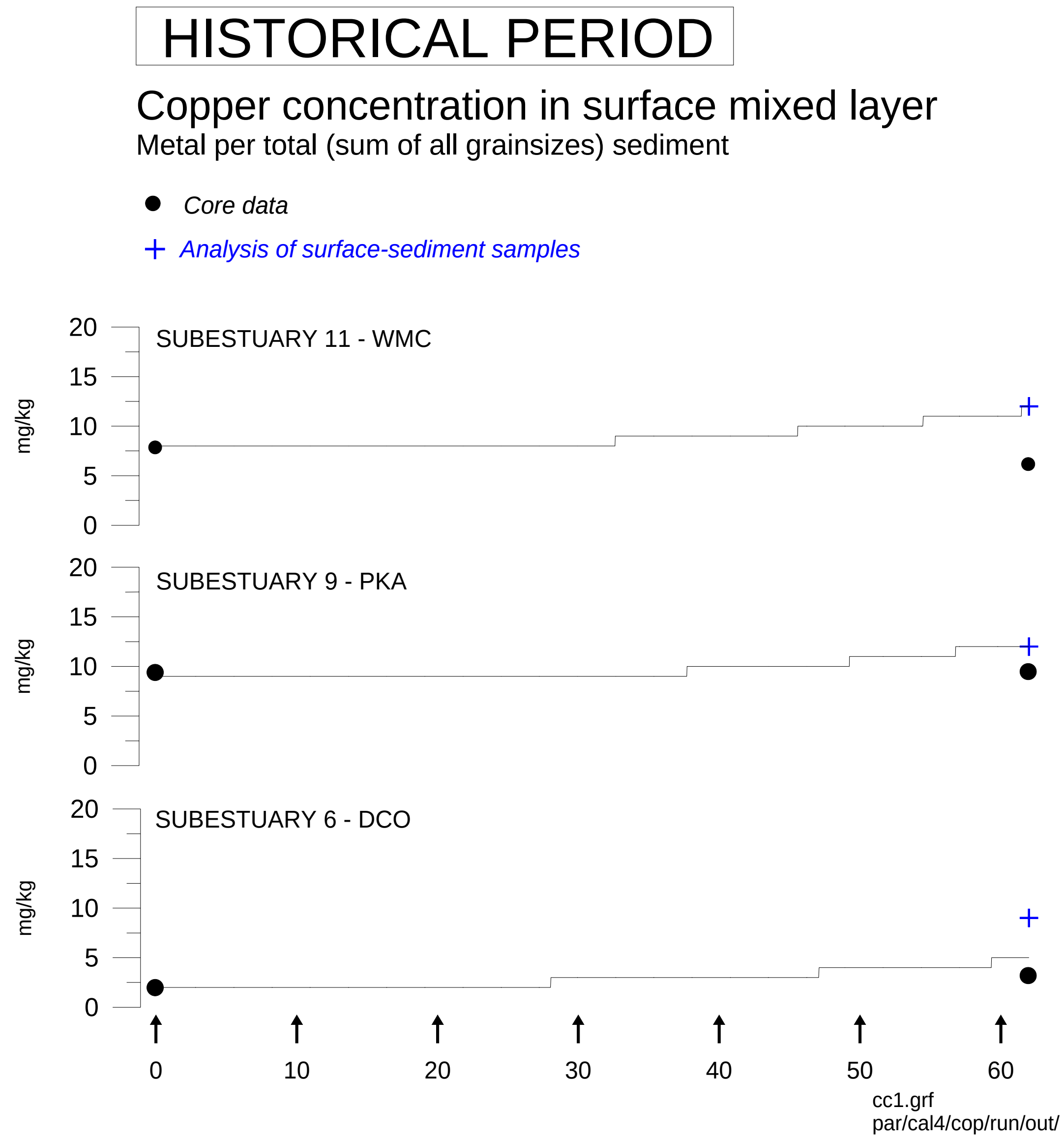
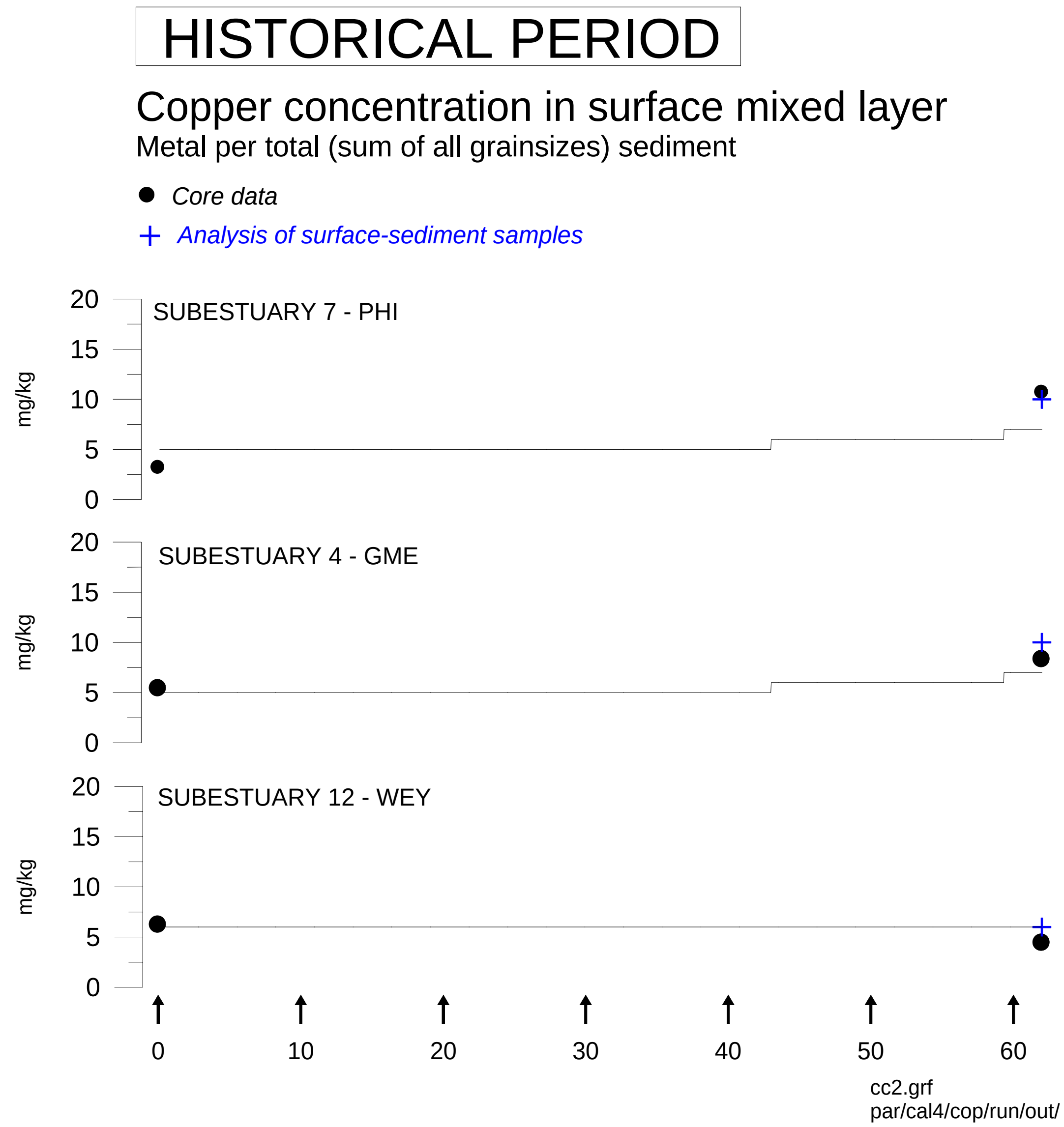


**Figure 6.22: (continued)**
Performance of the calibrated model for hindcasting copper in the test subestuaries. See the text for explanation of symbols.



# 7 Conclusions

The USC-3 model has been implemented for Southeastern Manukau Harbour / Pahurehure Inlet, and calibrated through a simulation of the historical period 1940 to 2001. The calibration involved adjusting (1) the fraction of the sediment runoff from the land that is treated as washload / slowly-settling, low-density flocs, (2) the areas over which sediments may deposit, (3) the various terms that control sediment and attached metal dispersal and deposition, and (4) the metal retention factor.

The analysis of the fate of sediments from the surrounding subcatchments hindcast by the calibrated model paints a fairly convincing picture, as does the analysis of the sources of sediments depositing in the subestuaries.

The hindcast sedimentation rates by the calibrated model are generally smaller than measured sedimentation rates. At least part of the reason for this may be that sediment inputs from the wider Manukau Harbour into Pahurehure Inlet, driven by tidal currents and waves, is not accounted for in the model. Spatial patterns in measured sedimentation, such as they are, are reasonably well hindcast by the calibrated model.

The metal retention factor *MRF*, which is the fraction of the metal load emanating from each subcatchment that is attached to the corresponding sediment particulate load, is the key calibration parameter. This term is used to reduce the concentration at which metals are delivered to the harbour in the model, and is chosen to yield a time-rate-of-change of metal concentrations over the historical period that ends in the target concentrations being achieved. The calibrated value of *MRF* was very similar to that arrived at in the calibration of the USC-3 model of the Central Waitemata Harbour, and that value furthermore has some experimental basis. Therefore the calibration is not implausible.

The USC-3 model is now ready to make predictions for future catchment development scenarios.

# 8 References


Auckland Regional Council (1999). Guidelines for stormwater runoff modelling in the Auckland Region. Auckland Regional Council, Technical Publication No. 108.

Ellwood, M.J.; Wilson, P.; Vopel, K. & Green, M.O. (2008). Trace metal cycling in the Whau Estuary, Auckland, New Zealand. Environmental Chemistry, 5: 289–298.

Green, M.O. (2007). Central Waitemata Harbour Contaminant Study. USC-3 Model Description, Implementation and Calibration. Auckland Regional Council Technical Report TR2008/042

Moores, J. and Timperley, M. 2008. Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study: Predictions of Stormwater Contaminant Loads. Auckland Regional Council Technical Report TR2008/053

Parshotam, A. 2008. Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study: Sediment Load Model Results. Auckland Regional Council Technical Report TR2008/052

Parshotam, A.,Wadhwa S., Semadeni Davies, A. and Moores, J. 2008a. Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study: Land Use Analysis. Auckland Regional Council Technical Report TR2008/049

Parshotam, A., Wadhwa, S., Semadeni Davies, A. and Woods, R. 2008b. Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study: Sediment Load Model Structure, Setup and Input Data. Auckland Regional Council Technical Report TR2008/050

Parshotam, A., Moores, J., Pattinson, P. and Harper, S. 2008c. Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study: Sediment Load Model Evaluation. Auckland Regional Council Technical Report TR2008/051

Pritchard, M.; Hancock, N. & Lewis, M. (2008a). Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study: Harbour Hydrodynamics and Sediment Transport Fieldwork. Auckland Regional Council Technical Report TR2008/055

Pritchard, M.; Gorman, R. & Lewis, M. (2008b). Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study: Hydrodynamic, Wave and Sediment-Transport Model Implementation and Calibration. Auckland Regional Council Technical Report TR2008/056

Reed, J., Swales, A., Ovenden, R., Buckthought, D., Rush, N., Wadhwa, S., Okey, M. and Harper, S. 2008. Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study: Harbour Sediments. Auckland Regional Council Technical Report TR2008/054