Auckland Regional Council
TE RAUHĪTANGA TAIAO

Central Waitemata Harbour Contaminant Study

Predictions of Sediment, Zinc and Copper Accumulation under Future Development Scenario 1

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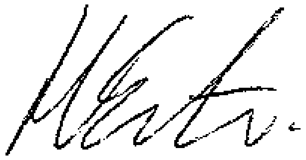	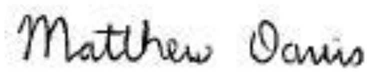
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Central Waitemata Harbour Contaminant Study. Predictions of Sediment, Zinc and Copper Accumulation under Future Development Scenario 1

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Prepared for
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Preface

The Waitemata 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. An earlier study examined long-term accumulation of sediment and stormwater chemical contaminants in the Upper Waitemata Harbour. However, previously little was known about the existing and long-term accumulation of sediment and stormwater chemical contaminants in the central harbour. The Central Waitemata Harbour 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 sedimentation 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 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:

- Henderson Creek (which drains the largest subcatchment and with the largest urban area, as well as substantial areas of rural land) contributes the largest loads of sediment, copper and zinc to the Central Waitemata Harbour. The second largest loads come from the Upper Waitemata Harbour.

- Substantial proportions of the subcatchment sediment, copper and zinc loads are accumulating in the Henderson, Whau, Meola and Motions tidal creeks and in the Shoal Bay, Hobson Bay and Waterview embayments.

- Central Waitemata Harbour bed sediment concentrations of copper and zinc are not expected to reach toxic levels based on current assumptions of future trends in urban 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. (For example, whereas the study addresses the Whau River as a whole, differences exist within parts of the Whau River that may merit a different magnitude or type of intervention than may be inferred from considering the Whau River and its long-term contaminant trends as a whole.) 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 Hauraki Gulf.

Technical reports

The study has produced a series of technical reports:

Technical Report TR2008/032
Central Waitemata Harbour Contaminant Study. Landuse Scenarios.

Technical Report TR2008/033
Central Waitemata Harbour Contaminant Study. Background Metal Concentrations in Soils: Methods and Results.

Technical Report TR2008/034
Central Waitemata Harbour Contaminant Study. Harbour Sediments.

Technical Report TR2008/035
Central Waitemata Harbour Contaminant Study. Trace Metal Concentrations in Harbour Sediments.

Technical Report TR2008/036
Central Waitemata Harbour Contaminant Study. Hydrodynamics and Sediment Transport Fieldwork.

Technical Report TR2008/037
Central Waitemata Harbour Contaminant Study. Harbour Hydrodynamics, Wave and Sediment Transport Model Implementation and Calibration.

Technical Report TR2008/038
Central Waitemata Harbour Contaminant Study. Development of the Contaminant Load Model.

Technical Report TR2008/039
Central Waitemata Harbour Contaminant Study. Predictions of Stormwater Contaminant Loads.

Technical Report TR2008/040
Central Waitemata Harbour Contaminant Study. GLEAMS Model Structure, Setup and Data Requirements.

Technical Report TR2008/041
Central Waitemata Harbour Contaminant Study. GLEAMS Model Results for Rural and Earthworks Sediment Loads.

Technical Report TR2008/042
Central Waitemata Harbour Contaminant Study. USC-3 Model Description, Implementation and Calibration.

Technical Report TR2008/043
Central Waitemata Harbour Contaminant Study. Predictions of Sediment, Zinc and Copper Accumulation under Future Development Scenario 1.

Technical Report TR2008/044
Central Waitemata Harbour Contaminant Study. Predictions of Sediment, Zinc and Copper Accumulation under Future Development Scenarios 2, 3 and 4.

Technical Report TR2009/109
Central Waitemata Harbour Contaminant Study. Rainfall Analysis.

Contents

1 Executive Summary

The main aim of the Central Waitemata Harbour (CWH) Contaminant Study is to model contaminant (zinc, copper) and sediment accumulation within the CWH for the purposes of, amongst other things, identifying significant contaminant sources, and testing efficacy of stormwater treatment and zinc source control of industrial roofs.

This report describes predictions that have been made by the USC-3 ("Urban Stormwater Contaminant") model, which has been developed specifically 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.

Predictions are made for a number of development scenarios, where scenarios differ by zinc source control applied industrial roofs in urban areas, and stormwater treatment applied in urban areas. Each scenario covers 100 years into the future from the present day, which is defined as 2001.

The predictions reported herein are for Scenario 1, for which there is no zinc source control of industrial roofs and no additional stormwater treatment.

Details of the USC-3 model have been given in Green (2008). The way the model has been implemented for the CWH, and then calibrated against data from the historical period 1940–2001, has also been explained in detail by Green (2008).

The model suite predicts that, for the future period 2001–2100 under Scenario 1, Henderson Creek sub-catchment is the principal sediment source to the harbour, and the Upper Waitemata Harbour sub-catchment and the Whau River sub-catchment are the next largest sources. For all sub-catchments except Henderson Creek, sediment run-off from rural sources is a very small fraction of the total sediment run-off. This reflects the urbanisation of the catchment.

A key prediction is that total (rural plus urban sources) sediment run-off from the catchment will decrease over the next 15–20 years, as urbanisation proceeds and rural sources of sediment, primarily in the Henderson Creek sub-catchment, correspondingly decline. This turns out to be a key driver of the behaviour of the harbour in the future.

The Henderson Creek and Whau River sub-catchments are also the principal sources of zinc and copper to the harbour. Oakley Creek and Shoal Bay North sub-catchments are the next largest contributors. For all sub-catchments except Henderson Creek, natural zinc contributes less than 10 % to the total zinc load. The rest comes from anthropogenic (urban) sources. The proportion of the total copper load that is due to natural sources is typically slightly greater than that for zinc.

Concentrations at which total (anthropogenic plus natural) zinc is delivered to the harbour generally decrease for the first 15–20 years into the future period, and then they approximately level off. This is driven primarily by a decrease in anthropogenic zinc loads, which in turn is due mainly to a reduction in galvanised steel roofs in the catchment. The decrease in total sediment loads that is also predicted to occur over the next 15–20 years slows the decrease in metal concentrations. In contrast, concentrations at which total (anthropogenic plus natural) copper is delivered to the harbour generally increase steadily from 2001, reflecting an increase in anthropogenic copper loads over the future period. The increase in copper loads combines with the decrease in sediment loads to accelerate the change in concentration. In both cases (zinc and copper), the concentrations at which total metals are predicted to be delivered to the harbour under Scenario 1 are much higher than the present-day concentrations in the estuarine bed sediments.

A detailed analysis is presented of the fate in the harbour of sediment, zinc and copper from each sub-catchment. The fate of zinc and copper mirrors almost exactly the fate of sediment.

- Very little of the sediment from the four sub-catchments that drain to the southern shore of the harbour throat (Hobsons Bay, Stanley Street, Cook Street, Westmere/St Marys Bay) crosses the harbour to deposit in Shoal Bay. In contrast, a significant fraction of the sediment discharged from all the other sub-catchments is deposited in Shoal Bay. This is related to the natural constriction in the harbour that is crossed by the Harbour Bridge, which acts to mix and steer ebb flows and associated suspended sediments into Shoal Bay.
- In addition to depositing in Shoal Bay, sediment from the Coxs Bay, Motions Creek and Meola Creek sub-catchments is also dispersed widely to the west into the main body of the harbour. Te Tokaroa reef appears to prevent sediments from Motions Creek sub-catchment mixing locally with sediments from Meola Creek sub-catchment. Further afield to the west, however, sediments from the two catchments are effectively mixed.
- Sediment from Oakley Creek sub-catchment is deposited in the Waterview Embayment subestuary, which is the enclosed embayment through which that sub-catchment discharges, and is dispersed widely in the southwestern and western sectors of the main body of the harbour. Sediment from the Whau River sub-catchment accumulates in the tidal creek at the base of that sub-catchment, and is dispersed widely in the southwestern and western sectors of the main body. Sediment from the Henderson Creek sub-catchment accumulates in the tidal creek at the base of that sub-catchment and in Limeburners Bay, which is in a sheltered position at the mouth of Henderson Creek. In addition to that, sediment is dispersed widely in the southwestern, western and northwestern sectors of the main body of the harbour. Sediment from the Hobsonville sub-catchment is also dispersed widely in the southwestern, western and northwestern sectors of the main body.
- About two-thirds of the sediment from Little Shoal Bay sub-catchment is lost to the Hauraki Gulf. A quarter turns the corner to the east and gets trapped in

Shoal Bay. That pattern is reversed for Shoal Bay North and Shoal Bay East sub-catchments, both of which drain directly into Shoal Bay: a little more than 50 % of the sediment from each sub-catchment is deposited in Shoal Bay, and about 40 % is lost to the Hauraki Gulf.

A detailed analysis is presented of the sources of sediment, zinc and copper that deposit in each subestuary. It is not always the case that metal in any particular subestuary will derive from sources in the same proportion as sediments. In general, sediments and metals that deposit in tidal creeks (Henderson Creek, Whau River) and sheltered embayments (Limeburners Bay, Waterview Embayment, Hobsons Bay) are sourced from the respective immediately adjacent sub-catchment. Shoal Bay is the exception, as it receives sediments and metals from every sub-catchment except the four that drain on the southern shore of the harbour throat, for the reason mentioned previously. Elsewhere, throughout the main body of the harbour, sediments and metals from most sub-catchments are rather thoroughly mixed together.

The predicted sedimentation rates in the harbour under Scenario 1 are smaller than Green's (2008) hindcast sedimentation rates for the historical period 1940–2001, which is due to the reduction in catchment sediment run-off that is predicted to occur in the future, primarily over the next 15–20 years. In the intertidal parts of the main body of the harbour, sedimentation is predicted to reduce at the time sediment run-off reduces. The subtidal part of the main body of the harbour will also experience a reduction in sedimentation, after which a new transportational regime (approximately zero sedimentation) will be established. The subestuaries that lie to the west of Te Tokaroa reef in the transition between the throat and the main body of the harbour (Waterview Flats, Point Chevalier and Meola subestuaries) will erode for a time, after which a new transportational regime is established. In contrast, in Motions subestuary, which lies to the east of Te Tokaroa reef, sedimentation will decline significantly, but will remain positive thereafter. For the tidal creeks, sedimentation will not obviously be affected, and sediment will continue to accumulate. Sedimentation in Shoal Bay will also not obviously be affected.

A detailed analysis is presented of the predicted changes in metal concentration in the surface mixed layer of the harbour bed sediments under Scenario 1. The total metal concentration is presented and discussed, which is defined as the metal carried on all sediment particle sizes divided by the total (sum of all particle sizes) sediment.

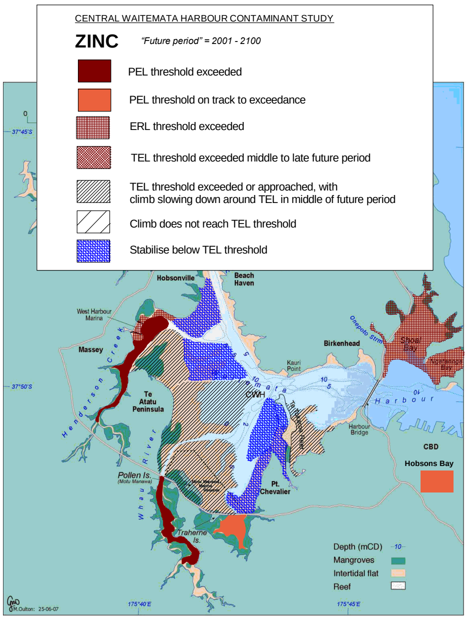
The changes in sedimentation that are predicted by the model are seen to have profound effects on heavy-metal concentrations in the harbour in the future, as follows.

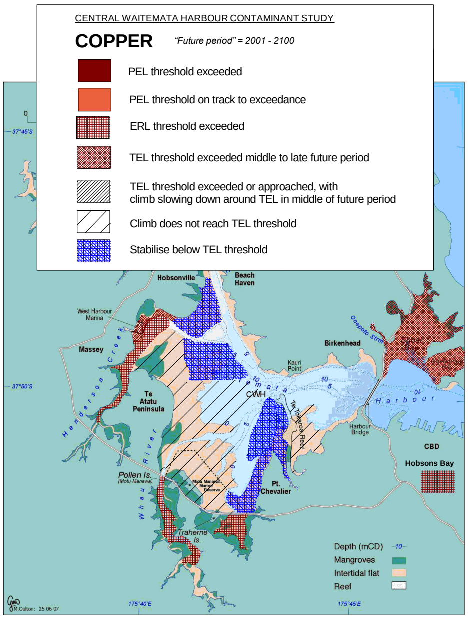
Zinc and copper concentrations are predicted to rise continuously in subestuaries that will experience virtually constant sedimentation throughout the future period. This includes the Henderson Creek and Whau River tidal creeks; the Waterview Embayment and Hobsons Bay sheltered embayments; Limeburners Bay, which acts like an extension of Henderson Creek; and Shoal Bay.

The situation is more complicated in subestuaries that will remain depositional, but with a decrease in sedimentation rate partway through the future period. In Motions subestuary, which lies to the east of Te Tokaroa reef, zinc and copper concentrations do not stabilise when sediment run-off from the catchment reduces, although the rate at which they continue to climb drops significantly. The same is the case for the intertidal subestuaries in the main body of the harbour: the rise in zinc and copper concentrations early in the future period slows down when the sedimentation rates drop, but the rise is not fully arrested.

For subestuaries that will become transportational partway through the future period the situation is different again. Zinc and copper concentrations in the subestuaries that are situated to the west of Te Tokaroa reef in the transition zone between the harbour throat and the main body of the harbour (Meola, Point Chevalier, Waterview Flats) reach an equilibrium partway through the future period. This is a response to the change in sedimentation regime – from depositional to transportational – that also occurs at this time, and which in turn is a response to the reduction in sediment run-off from the catchment, as previously described. Although an equilibrium concentration is attained, in the sense that the concentration becomes steady, it is more the case that these subestuaries become "moribund" (or "stagnant") when deposition switches off. The same thing occurs in the Central Subtidal subestuary, ie, metal concentrations stabilise when the subestuary becomes moribund under a change in sedimentation regime from depositional to transportational.

Figures 40 and 41 (see Section 4)

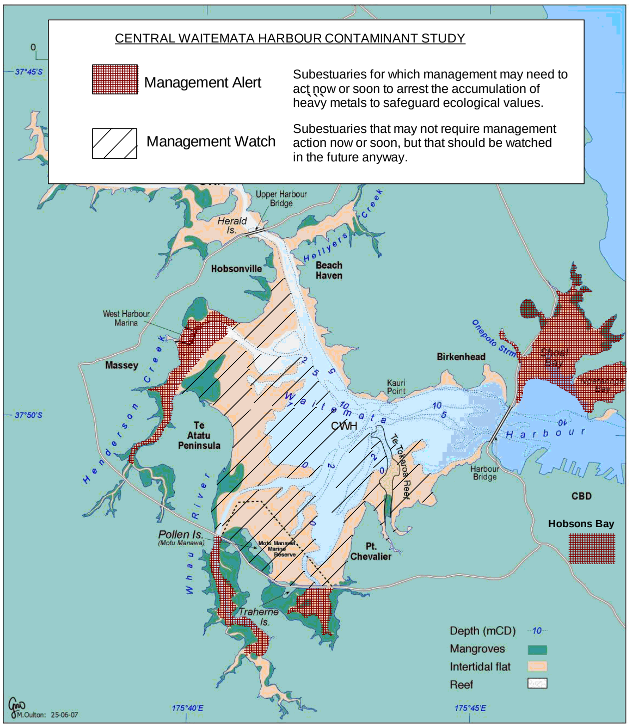




Finally, the times in the future at which sediment quality guideline threshold levels are predicted to be exceeded are tabulated. This culminates in a high-level, simplified summary of the results for Scenario 1. In this view, subestuaries are classified as either "Management Alert" or "Management Watch". The classification is based on zinc only, since zinc is predicted to accumulate in greater concentrations than copper.

- Subestuaries assigned to Management Alert are the tidal creeks around the fringes of the harbour (Henderson Creek and the associated Limeburners Bay, Whau River, Waterview Embayment), Shoal Bay and Hobsons Bay. Management may need to act now or soon to arrest the accumulation of heavy metals to safeguard ecological values in these subestuaries. The rationale is that ERL (Effects Range Low) thresholds either already have been or soon will be exceeded, and in some cases PEL (Probable Effects Level) thresholds will be exceeded.
- "Management Watch" includes all the other subestuaries in the harbour. These may not require management action now or soon, but they should be watched in the future anyway. The rationale is that the TEL (Threshold Effects Level) threshold is either not predicted to be exceeded or, if it is, it will be exceeded decades into the future, in many cases when the rate at which metals are building up is reducing anyway.

Figures 42 (see Section 5)



2 Introduction

Modelling and empirical data indicate that stormwater contaminants are rapidly accumulating in the highly urbanised side branches of the Central Waitemata Harbour (CWH). However, there is no clear understanding of the fate of contaminants exported from these side branches into the main body of the harbour, or that of contaminants discharged directly into the harbour.

The main aim of the study is to model contaminant (zinc, copper) and sediment accumulation within the CWH for the purposes of, amongst other things, identifying significant contaminant sources, and testing efficacy of stormwater treatment and zinc source control of industrial roofs.

2.1 Study aims

The study aims to:

- predict contaminant loads based on past, present and future land use and population growth for each sub-catchment discharging into the CWH, allowing for stormwater treatment and zinc source control of industrial roofs;
- predict dispersal and accumulation (or loss) of sediment and stormwater contaminants in the CWH;
- calibrate and validate the dispersal/accumulation model;
- apply the various models to predict catchment contaminant loads and accumulation of copper, zinc and sediment in the CWH under specific scenarios that depict various combinations of projected land use/population growth, stormwater treatment efficiency, and zinc source control of industrial roofs;
- determine from the model predictions the relative contributions of sediment and contaminant from individual sub-catchments and local authorities;
- provide an assessment of the environmental consequences of model outputs;
- provide technical reports on each component of the work; and
- provide a desktop application.

2.2 Model suite

The study centres on the application of three models that are linked to each other in a single suite:

- 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[1].
- The CLM 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.
- 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 model: an estuarine sediment-transport model, which simulates the dispersal of contaminants/sediments by physical processes such as tidal currents and waves.

2.3 This report

This report describes predictions that have been made by the USC-3 ("Urban Stormwater Contaminant") model, which has been developed specifically for the Central Waitemata Harbour 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 predictions reported herein are the culmination of the study. Table 1 shows the scenarios for which predictions are to be made, where scenarios differ by zinc source control applied to industrial roofs, and stormwater treatment applied in urban areas.

The four scenarios are:

1. Scenario 1 is the existing scenario and includes all existing stormwater treatment such as catchpits for all roads, all urban paved and all pervious surfaces; ponds for commercial and industrial construction sites; and specific installed devices.
2. Scenario 2 is the source-control scenario and includes the existing stormwater treatment from Scenario 1 plus painting of presently-unpainted galvanised steel roofs on industrial buildings.
3. Scenario 3 applies moderate additional stormwater treatement and includes the existing stormwater treatment from Scenario 1 plus raingardens (in addition to catchpits) for all roads carrying >20,000 vpd; hay bales and silt fences (in addition to catchpits) for residential infill

[1] We use the term "contaminant" herein to mean chemical contaminants such as zinc and copper, and we refer to "sediments" separately.

construction sites; raingardens or multimedia filters (in addition to catchpits) for industrial paved surfaces; and pond/wetland systems for treating 20% of the stormwater in each Stormwater Management Unit.

4. Scenario 4 is a combination of Scenario 2 and Scenario 3.

Each scenario covers 100 years into the future from the present day, which is defined as 2001.

Predictions for Scenario 1 are reported herein.

Table 1
The scenarios for which predictions of sediment and contaminant accumulation are to be made, where scenarios differ by zinc source control applied to industrial roofs in urban areas, and stormwater treatment applied in urban areas. Each scenario covers 100 years into the future from the present day, which is defined as 2001.

Scenario	Population/urban development	Zinc source control applied to industrial roofs	Stormwater treatment applied to urban areas
1	Future population growth and urban development	No additional	No additional
2	Future population growth and urban development	Zinc source control of industrial roofs	No additional
3	Future population growth and urban development	No additional	Moderate additional treatment
4	Future population growth and urban development	Zinc source control of industrial roofs	Moderate additional treatment

3 The USC-3 Model

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 associated with catchment development scenarios that will cause changes in sediment and contaminant loads from the catchment. T he 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 (eg, change of sandy substrate to silt), and which may bring associated ecological degradation (eg, 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 "sub-catchment 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. The USC-2 model was initially applied in the Upper Waitemata Harbour for the Auckland Regional Council (ARC).

The USC-3 model has been 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 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.

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 intervention options.

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 has been calibrated against annual-average sedimentation rates in the harbour and metal concentrations in harbour bed sediments (Green, 2008).

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 sub-catchments on a similar scale. Each sub-catchment 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 (eg, in sheltered parts of the harbour, or on days when there is no wind), and the erosion of sediment that occurs under other conditions (eg, 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 run-off.

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 are determined by the long-term weather sequence that drives the model.
- The rainfall, wind and tide range on the day govern the way land-derived sediment is injected into the harbour. At the end of the day on which injection occurs, land-derived sediment may be settled onto the bed in any part of the harbour, may be in suspension in any part of the harbour, or may be lost to

sinks. 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 sub-catchments and various subestuaries each time it rains (according to the rules), and between the various subestuaries to account for the action of waves of tidal currents (again, according to the rules).

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 the 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. 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 (eg, 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 a profound 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 **all** of the constituent particle sizes, including the finer fractions, which otherwise might be very mobile.

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 a profound 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 bed-sediment weighted-mean particle size, which controls the erosion rate as mentioned above, is calculated over the thickness of the bed-sediment active layer.

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; for example, shell-lagged channels. 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 metal 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.

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, such as the Upper Waitemata Harbour. This will not be acceptable in the case of more open water bodies, such as the Central Waitemata Harbour, where wind waves frequently resuspend bed sediments on shallow intertidal flats.

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 the CWH study, this is prevented by not allowing erosion to occur below a certain basement level that is set at the start of the simulation. A subestuary may be purely transportational over the duration of the simulation, meaning that the net change in sediment level can be zero.

3.3 Model details

Model details have been given in Green (2008), to which the reader is referred for a full account. Details are given of:

- The characteristics of special subestuaries (tidal creeks, sinks and deep channels).

- The resuspension of estuarine bed sediments by waves and currents.
- The injection into the harbour of sediments and contaminants when it rains.
- Building the bed-sediment column.

3.4 Model implementation

The way the model has been implemented for the Central Waitemata Harbour has been explained in detail by Green (2008), to which the reader is referred for a full account.

The implementation consists of specifying the sediment particle sizes to be addressed in the model, defining subestuaries and sub-catchments, 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 sub-catchment 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 mixed layer is to be evaluated, and specifying the mixing depth. Other information required to drive the model, including harbour bed-sediment initial conditions (eg, particle size, metal concentration in the surface mixed layer) and sub-catchment 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.

Some useful information is now recapped.

Four constituent sediment particle sizes (D_{con}) are treated by the model: 12, 40, 125 and 180 μm. These particle sizes are chosen to compose the estuarine bed sediment and the suspended-sediment load that derives from the bed sediment, based on analysis of substrate and suspended-sediment samples. These particle sizes represent fine silt, coarse silt, fine sand and medium sand, respectively. The 180 μm fraction is not allowed to move in the USC-3 model, which makes it a passive diluent.

The same constituent particle sizes are also deemed to compose the land-derived sediment.

The subdivision of the Central Waitemata Harbour into subestuaries for the purposes of application of the USC-3 model is shown in Figure 1. Further details of the subdivision are shown in Table 2.

Three subestuaries are designated as tidal creeks: Henderson Creek (HEN), Whau River (WHA) and Hobsons Bay (HBA). Green (2008) provides further justification and discussion of this designation. Sediments deposited in tidal creeks may not be subsequently removed by resuspension, and land-derived sediments that pass through tidal creeks are attenuated. Only nominal predictions of sedimentation and contaminant accumulation are made for the three tidal creeks in the model. This accords with the terms of the study.

Three of the subestuaries are designated as sinks: Hauraki Gulf (HGF), Waterview Embayment (WAT) and the Upper Waitemata Harbour (UWH). Green (2008) provides further justification and discussion of this designation. Sediments deposited in sinks also may not be subsequently removed by resuspension.

Furthermore, sediments deposited in HGF and UWH are "removed from the model", meaning that no predictions are made of sediment or contaminant accumulation in those subestuaries. Modelling sediment and contaminant accumulation in the Hauraki Gulf is beyond the scope of this study. The earlier (2004) Upper Waitemata Harbour Contaminant Study reported predictions of sediment, zinc and copper accumulation in the Upper Waitemata Harbour under a number of catchment development scenarios (Green et al., 2004b and 2004c).

Five subestuaries are designated as deep channels. 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. Green (2008) provides further justification and discussion of this designation.

Figure 1

Division of the Central Waitemata Harbour into subestuaries for the purposes of application of the USC-3 model. See Table 2 for naming and numbering scheme.

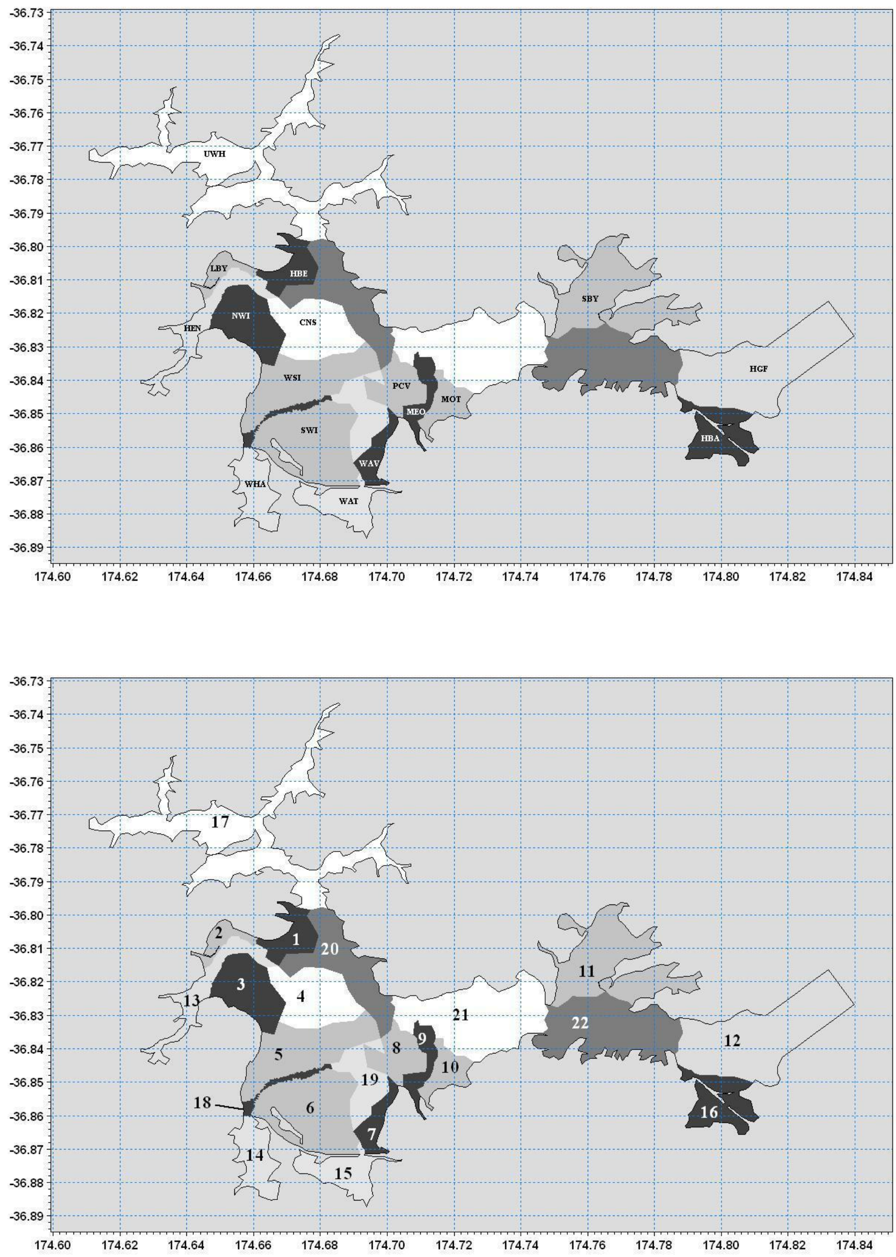


Table 2

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	Predictions
1 -HBE	Hobsonville	1599322				Full
2 - LBY	Limeburners Bay	834747				Full
3 - NWI	Northwestern Intertidal	3052405				Full
4 - CNS	Central Subtidal	3677757				Full
5 - WSI	Western Intertidal	4693359				Full
6 - SEI	Southwestern Intertidal	5474496				Full
7 - WAV	Waterview Flats	1082372				Full
8 - PCV	Point Chevalier	1958962				Full
9 - MEO	Meola	1079382				Full
10 - MOT	Motions	1404598				Full
11 - SBY	Shoal Bay	6465419				Full
12 - HGF	Hauraki Gulf	n/a	✓			None
13 - HEN	Henderson Creek	2277921		✓		Nominal
14 - WHA	Whau River	2116217		✓		Nominal
15 - WAT	Waterview Embayment	2129185	✓			Full
16 - HBA	Hobsons Bay	2470576		✓		Nominal
17 - UWH	Upper Waitemata Harbour	n/a	✓			None
18 - WC	Whau Channel	n/a			✓	n/a
19 - WS	Whau Subtidal	n/a			✓	n/a
20 - UC	Upper Channel	n/a			✓	n/a
21 - MC	Middle Channel	n/a			✓	n/a
22 - OC	Outer Channel	n/a			✓	n/a

The subdivision of the catchment surrounding the Central Waitemata Harbour into sub-catchments for the purposes of application of the USC-3 model is shown in Figure 2 and Table 3. The Upper Waitemata Harbour, shown in outline at the head of the Central Waitemata Harbour in Figure 2, is treated in the model as a sub-catchment of the Central Waitemata Harbour.

Figure 2
Division of the catchment of the Central Waitemata Harbour into sub-catchments for the purposes of application of the USC-3 model. The Upper Waitemata Harbour, shown in outline at the head of the Central Waitemata Harbour, is treated in the model as a sub-catchment of the Central Waitemata Harbour.

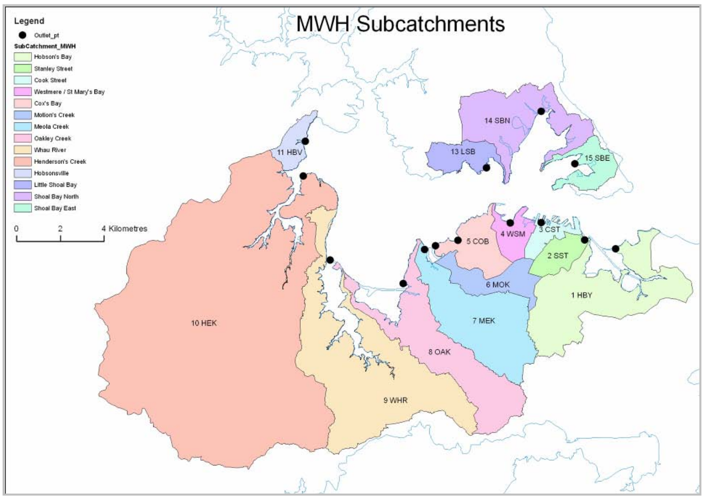


Table 3
Division of the catchment of the Central Waitemata Harbour into sub-catchments for the purposes of application of the USC-3 model.

Code	Sub-catchment
1 - HBY	Hobsons Bay
2 - SST	Stanley Street
3 - CST	Cook Street
4 - WSM	Westmere/St Marys Bay
5 - COB	Coxs Bay
6 - MOK	Motions Creek
7 - MEK	Meola Creek
8 - OAK	Oakley Creek
9 - WHR	Whau River
10 - HEK	Henderson Creek
11 - HBV	Hobsonville
12 - UWH	Upper Waitemata Harbour
13 - LSB	Little Shoal Bay
14 - SBN	Shoal Bay North
15 - SBE	Shoal Bay East

The GLEAMS model provides daily land-derived sediment loads at the bottom of each sub-catchment split by constituent particle size. For this implementation, GLEAMS predicts sediments from all of the rural areas in each sub-catchment. 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 done with a “random block sampling” scheme, which is intended to capture 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.

The CLM model predicts annual urban sediment loads, split by constituent particle size, that derive from all of the urban areas in each sub-catchment. 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 sub-catchment is broken down into daily loads over that same year in proportion to the daily GLEAMS sediment loads.

The CLM also provides annual anthropogenic metal (zinc and copper) loads at the bottom of each sub-catchment, 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 metal load emanating from each sub-catchment is broken down into daily loads over that same year in proportion to the daily GLEAMS sediment loads. 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.

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.

For outfalls that discharge into freshwater creeks that in turn discharge directly into the main body of the harbour, there is no attenuation of either sediment or metal loads. For outfalls that discharge directly into the main body of the harbour, there is also no attenuation of either sediment or metal loads. For outfalls that discharge into the main body through a tidal creek, the sediment and metal loads may both be attenuated. In all cases, the CLM will determine how the metal load is partitioned amongst the various constituent particle sizes that make up the land-derived sediment load.

A large set of terms (*R*, *R5*, *RSUSP*, *R5SUSP* and *RFS*) control the movement of sediments and attached metals inside the harbour. This applies to estuarine sediments (with attached metals) that may be resuspended by waves and tidal currents on any given day, and to sediments and metals eroded from the land and delivered to the harbour by freshwater run-off.

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 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 the Central Waitemata Harbour, mixing acts uniformly over a depth of 5 cm, which is based, primarily, on radioisotopic and x-ray analysis of sediment cores reported by Swales et al. (2008b).

After mixing, the concentration of heavy metal in the mixed layer is given by the ratio of the total amount of heavy metal (attached to all particle sizes) in the mixed layer to the total amount of sediment (ie, all particle sizes) in the mixed layer. Hence, heavy-metal concentration is expressed as mass of heavy metal per mass of sediment. Furthermore, heavy-metal concentrations are total-sediment concentrations.

The model is run by time series of daily sediment and metal run-off from the catchment, and daily rainfall and wind. To ensure that extreme sediment-generation events 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 reported here.

3.5 Model behaviour

The main drivers of the model behaviour are demonstrated in Green (2008) by way of a simple analogy. The harbour can be viewed as a bucket that contains sediment and metal, and sediment and metal from another bucket – the catchment – gets tipped into the harbour bucket as the simulation proceeds. At the start of the simulation, metal is present in the harbour bucket at some average concentration. If metal is present in the catchment bucket at the same concentration, then the concentration in the harbour bucket will not change as the simulation proceeds. On the other hand, if metal is present in the sub-catchment at a greater (or lesser) concentration, then the concentration in the harbour bucket will increase (or decrease) as the simulation proceeds. If there is enough time and if the metal concentration in the catchment bucket does not change, then the concentration in the harbour bucket will attain the same concentration as in the catchment bucket, which is termed "equilibrium" (The term "equilibrium" applies strictly to closed systems, such as the buckets being described here, but for open systems, such as the Central Waitemata Harbour, the correct term is "steady state".). All other things being equal, the rate at which equilibrium is approached varies directly with how far from equilibrium the harbour is, that is, the difference between the metal concentration in the harbour and the metal concentration in sediment from the catchment.

The role of the mixing depth is also explained and explored. The greater the mixing depth relative to the thickness of any deposited sediment layer, the more pre-existing sediment will be incorporated into the new surface mixed layer, and the smaller will be the change in metal concentration in the new surface mixed layer after mixing has occurred. This equates to a slower change in metal concentration in the surface mixed layer over time under repeated deposition events. The converse of all that is: the smaller the mixing depth relative to the thickness of the deposited layer, the quicker the change in metal concentration in the surface mixed layer over time under repeated deposition events. Given a particular set of sediment and heavy-metal inputs from the catchment, the model predictions of heavy-metal concentration in the surface mixed layer of the estuary bed sediments are most sensitive to variations in the mixing depth. In effect, the mixing depth determines the "inertia" of the system.

3.6 Model calibration

The calibration of the model is described by Green (2008), to which the reader is referred for a detailed account.

Model calibration 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 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 first part of the calibration process consisted of adjusting (1) the areas over which sediments may deposit and (2) the rate at which sediments and metals are lost to both pre-defined and "dynamic" sinks, until realistic sedimentation rates and patterns of sediment dispersal were obtained. The calibrated model produced a convincing picture of, firstly, the fate of sediments from the sub-catchments surrounding the Central Waitemata Harbour and, secondly, the sources of sediments depositing in the subestuaries. Hindcast sedimentation rates were compared to radioisotopic sedimentation rates, which were determined by radioisotopic dating of sediment cores. The hindcast sedimentation rates were generally smaller than the radioisotopic sedimentation rates, however the patterns of sedimentation were similar in important respects.

The second part of the calibration process consisted of adjusting a "metal retention factor" until a good match was obtained between hindcast and observed zinc and copper concentrations in the bed sediments of three test subestuaries at the end of the historical period. The metal retention factor, which is the fraction of the metal load emanating from each sub-catchment that is attached to the corresponding sediment particulate load, was used to uniformly reduce the concentration at which metals are delivered to the harbour in the model. A value for the factor was chosen to yield a time-rate-of-change of metal concentrations over the historical period that ended in target concentrations being achieved. The term (1 – metal retention factor) may be interpreted as representing the loss of metal to a dissolved phase, attachment of metal to very fine sediment, and/or attachment of metal to aggregates ("flocs") of sediment, none of which is explicitly accounted for in the USC-3 model. Subsequent work by Ellwood et al. (2008) has provided experimental confirmation of the value of the metal retention factor determined in the calibration.

4 Model Predictions – Scenario 1

Scenario 1 addresses future population growth and urban development in the catchment of the Central Waitemata Harbour. This scenario covers 100 years into the future from the present day, which is defined as 2001.

As far as urban areas go:

- No zinc source control measures are applied to industrial roofs in urban areas.
- There is no additional stormwater treatment over existing levels of service in urban areas.

Full details of how urban areas are depicted in Scenario 1 are provided in Timperley and Reed (2008).

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 will be presented.

4.1 Land use

The methods applied to develop a description of the land use for the future period, and the land use so derived, are documented in Parshotam and Wadhwa (2008a).

4.2 Sediment inputs

The total sediment run-off from the catchment into the harbour is the sum of the sediment run-off from rural areas, which is predicted by GLEAMS, and the sediment run-off from urban areas, which is predicted by the CLM.

- The GLEAMS predictions of rural sediment run-off for the future period are presented in detail by Parshotam (2008). For these predictions, GLEAMS used the future-period land use data described in Parshotam and Wadhwa (2008a). The implementation of GLEAMS for the Central Waitemata Harbour Study is documented by Parshotam and Wadhwa (2008b). Note that the rural sediment run-off is the same under all scenarios (1, 2, 3 and 4), because the scenarios differ by zinc source control of industrial roofs and stormwater treatment (Table 1).
- The CLM predictions of urban sediment run-off for the future period are presented in detail by Timperley and Reed (2008). These predictions vary by scenario. For Scenario 1, no additional stormwater treatment over existing levels of service is applied in urban areas. For these predictions, the CLM used the future-period land use data described in Parshotam and Wadhwa

(2008a). The implementation of the CLM for the Central Waitemata Harbour Study is documented by Timperley and Reed (2008).

4.2.1 Sediment inputs from rural sources

Fifty time series, each covering the future period 2001–2100, of daily rural sediment run-off from each sub-catchment are required (one time series for each USC model run in the Monte Carlo package). Each of these 50 time series was constructed by block sampling of predictions from GLEAMS.

GLEAMS was run for just one land use – that corresponding to the year 2001. This is justified, since rural land use is assumed not to change from 2001. The GLEAMS run was driven by a 50-year rainfall time series covering the period 1 January 1954 to 31 December 2003.

The block sampling scheme has been described in Green (2008). Because it is a random scheme, each of the 50 time series of daily rural sediment run-off may be unique.

The split of the rural sediment load amongst the constituent particle sizes (12, 40, 125 and 180 μm) is shown in Table 4 (all tables for this chapter are presented in one place at the end of the chapter), which was based on suspended-sediment sampling at various sites in the Auckland region. Further details are given in Parshotam and Wadhwa (2008b). This particle size split was applied to the rural sediment load from every sub-catchment.

4.2.2 Sediment inputs from urban sources

Fifty time series, each covering the future period 2001–2100, of daily urban sediment run-off from each sub-catchment are also required (as before, one time series for each USC model run in the Monte Carlo package).

The CLM was used to produce predictions of annual (not daily) urban sediment run-off from each sub-catchment for the future period. The 50 required time series of daily urban sediment run-off (one time series for each USC model run in the Monte Carlo package, with each time series covering the period 2001–2100) were constructed by distributing the urban sediment run-off for each year in proportion to the corresponding daily GLEAMS sediment loads for that same year. This scheme has been described in Green (2008).

The split of the urban sediment load from each sub-catchment amongst the constituent particle sizes (12, 40, 125 and 180 μm) was calculated by the CLM (Table 5).

4.2.3 Sediment inputs from the Upper Waitemata Harbour

Since it can be viewed as a source of metals and sediments to the Central Waitemata Harbour, the Upper Waitemata Harbour is treated in the USC-3 model as a sub-catchment of the CWH.

The sediment inputs from the Upper Waitemata Harbour (sub-catchment 12) were not derived from either GLEAMS or the CLM. Instead, these were derived from USC-2 model predictions performed as part of the 2004 Upper Waitemata Harbour Contaminant Study. Specifically, sediment inputs from the UWH to the CWH were set equal to the loss of sediments from the UWH to the CWH as predicted by the USC-2 model under the "Development #1" scenario. Further details are given in Green et al. (2004a, 2004b, 2004c). The USC-2 model as it was implemented for the UWH did not distinguish between sediments of rural and urban origin. It is not possible to "back calculate" this split.

The sediment load split shown in Table 4 was applied to sediment inputs from the UWH.

4.2.4 Total (rural plus urban) sediment inputs

The daily rural and daily urban sediment run-offs were added to give daily total sediment run-offs. This results in 50 daily time series (one time series for each USC model run in the Monte Carlo package, with each time series covering the period 2001–2100).

Note that the rural component of the total sediment run-off 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 run-off will be the same for every time series, since these derive from the prediction by the CLM of annual urban sediment loads. However, the **distribution** of the daily urban sediment run-off throughout the year may vary from time series to time series, as this depends on the daily rural (GLEAMS) sediment run-off.

Table 6 and Figure 3 (all figures for this chapter are presented in one place at the end of the chapter) show some statistics of the total (urban plus rural) sediment run-off.

- The Henderson Creek sub-catchment (10 – HEK) is the principal sediment source to the harbour. The Upper Waitemata Harbour sub-catchment (11 – UWH) and the Whau River sub-catchment (9 – WHR) are the next largest sources. This was also the case during the historical period, which was simulated as part of the calibration of the USC-3 model (Green, 2008).
- 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 4 shows the annual sediment run-off.

- For all sub-catchments except sub-catchment 10 – HEK (Henderson Creek), the sediment run-off from rural sources is a very small fraction of the total sediment run-off. This trend developed during the historical period (1940 to 2001; reported in Green, 2008), which showed the proportion of the total sediment run-off from rural sources decreasing over time in the historical period, and the proportion of the sediment run-off from urban sources correspondingly increasing. This, of course, reflects the increasing urbanisation of the catchment over time.
- For sub-catchment 10 – HEK (Henderson Creek), which is the principal source of sediment to the harbour, rural sources still constitute a significant fraction of the total sediment run-off.
- Sediment loads from the Upper Waitemata Harbour (12 – UWH) are relatively more significant in the future period than they were in the historical period. This may be due to the lag in urbanisation of the catchment surrounding the Upper Waitemata Harbour compared to urbanisation of the catchment of the Central Waitemata Harbour.

[Note that the spikiness in the sediment loads from the Upper Waitemata Harbour arises from the way the USC-2 model was implemented in the 2004 Upper Waitemata Harbour Contaminant Study. In that implementation, rainfall events were programmed to occur on a regular basis, but with the USC-3 model events occur randomly, which makes them look much more natural. Over the long-term (100 years), the sedimentation patterns that arise under regularly recurring rainfall events are not that different to the patterns that arise under randomly distributed rainfall events. It will be seen that metal run-off from the Upper Waitemata Harbour and the concentration at which metals are discharged from the Upper Waitemata Harbour into the Central Waitemata Harbour are similarly spiky.]

Figure 5 shows daily total (rural plus urban) sediment run-off 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.

4.3 Metal inputs

4.3.1 Natural metal inputs

Table 7 shows the concentration at which zinc is carried on soils in the sub-catchments of the Central Waitemata Harbour, which is taken from Reed (2008).

Table 8 shows the concentration at which copper is carried on soils in the sub-catchments of the Central Waitemata Harbour, also from Reed (2008).

To calculate daily inputs of natural metals to the harbour:

- The 12 µm fraction of the daily total (urban plus rural) sediment load was multiplied by the <25 µm zinc or copper (as the case may be) concentration and the resulting metal load was carried in the USC model by the 12 µm sediment constituent particle size.
- The 40 µm fraction of the daily total (urban plus rural) sediment load was multiplied by the 25–63 µm zinc or copper (as the case may be) concentration and the resulting metal load was carried in the USC model by the 40 µm sediment constituent particle size.
- The 125 µm fraction of the daily total (urban plus rural) sediment load was multiplied by the 63–250 µm zinc or copper (as the case may be) concentration and the resulting metal load was carried in the USC model by the 125 µm sediment constituent particle size.
- The 180 µm fraction of the daily total (urban plus rural) sediment load was multiplied by the 63–250 µm zinc or copper (as the case may be) concentration and the resulting metal load was carried in the USC model by the 180 µm sediment constituent particle size.

Natural metal inputs from the Upper Waitemata Harbour (sub-catchment 12) were treated differently, as described below.

4.3.2 Anthropogenic metal inputs

The CLM was used to produce a prediction of annual anthropogenic zinc and copper loads at the bottom of each sub-catchment, split by sediment constituent particle size that carries that load, for each year during the future period 2001–2100.

- For Scenario 1, there is no zinc source control applied to industrial roofs in urban areas, and there is no additional (over existing levels of service) stormwater treatment applied in urban areas.

Figure 6 shows the anthropogenic zinc loads, and Table 9 shows how the zinc load is carried on the sediment constituent particle sizes.

Figure 7 shows the anthropogenic copper loads, and Table 10 shows how the copper load is carried on the sediment constituent particle sizes.

Anthropogenic metal inputs from the Upper Waitemata Harbour (sub-catchment 12) were treated differently, as described below.

4.3.3 Metal inputs from the Upper Waitemata Harbour

As was the case for sediments, metal inputs from the Upper Waitemata Harbour (sub-catchment 12) were derived from USC-2 model predictions performed as part of the 2004 Upper Waitemata Harbour Contaminant Study. Specifically, total (anthropogenic plus natural) metal inputs from the UWH to the CWH were set equal to the loss of total metals from the UWH to the CWH as predicted by the USC-2 model under the "Development #1" scenario. Further details are given in Green et al. (2004a, 2004b, 2004c). The USC-2 model as it was implemented for the UWH did not distinguish between anthropogenic and natural metals. It is not possible to "back calculate" this split.

An average split, calculated from Table 9 (for zinc) and Table 10 (for copper), was used to specify how the total zinc and copper loads emanating from the Upper Waitemata Harbour were carried by the sediment constituent particle sizes.

4.3.4 Total (anthropogenic plus natural) metal inputs

As explained in Green (2008), 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 sub-catchment is broken down into daily loads over that same year in proportion to the daily GLEAMS sediment loads.

The daily anthropogenic metal loads so formed were added to the daily natural metal loads to form the daily total metal loads. The total (anthropogenic plus natural) metal loads are shown in Table 11 (zinc) and Table 12 (copper). Those same two tables show how those total metal loads are constituted between anthropogenic and natural sources.

For zinc:

- Sub-catchment 10 – HEK (Henderson Creek) and sub-catchment 9 – WHR (Whau River) are the principal sources of zinc to the harbour. Sub-catchment 8 – OAK (Oakley Creek) and sub-catchment 14 – SBN (Shoal Bay North) contribute the next largest loads.
- For all sub-catchments except 10 – HEK (Henderson Creek), natural zinc contributes less than 10 % to the total zinc load. In most cases, the contribution is less than 5 %.

For copper:

- Sub-catchment 10 – HEK (Henderson Creek) and sub-catchment 9 – WHR (Whau River) are the principal sources of copper to the harbour. Sub-catchment 8 – OAK (Oakley Creek) and sub-catchment 14 – SBN (Shoal Bay North) contribute the next largest loads.
- The proportion of the total copper load that is due to natural sources is typically slightly greater than the proportion of the total zinc load that is due to

natural sources. For sub-catchment 10 – HEK (Henderson Creek), which is the largest source of copper and sediment to the harbour, anthropogenic copper makes up 76 % of the total load. For all other sub-catchments the proportion is greater than 90 %.

4.4 Concentration at which metals are delivered to the harbour

The concentrations at which total (anthropogenic plus natural) metals are delivered to the harbour over the future period under Scenario 1 are shown in Figures 8 and 9.

Concentrations of total (anthropogenic plus natural) zinc generally decrease for the first 15–20 years into the future period, and then they approximately level off. This is driven primarily by a decrease in anthropogenic zinc loads (Figure 6)[2], although there is also a decrease in total sediment loads around that same time (Figure 4), which slows the decrease in metal concentrations that would have occurred if the sediment loads had not also reduced. The decrease in total sediment loads will also be seen (below) to have a significant effect on sedimentation rates.

In contrast, concentrations of total (anthropogenic plus natural) copper generally increase steadily from 2001, reflecting an increase in anthropogenic copper loads over the future period (Figure 7)[3]. The increase in copper loads combines with the decrease in sediment loads, to accelerate the change in concentration.

In both cases (zinc and copper), the concentrations at which total metals are predicted to be delivered to the harbour over the future period under Scenario 1 are typically much higher than the present-day concentrations in the estuarine bed sediments. Mixing will retard the rise in metal concentrations in the estuarine bed sediments, thus conferring 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, which has the effect of reducing metal concentrations in the surface mixed layer compared to the concentrations at which they left the catchment.

4.5 Estuarine bed sediments at the start of the future period

The split of the bed sediment in each subestuary amongst the constituent particle sizes needs to be specified at the start of the future period. The particle size distribution of the present-day estuarine bed sediments, which has been described by Swales et al. (2008b) as part of the Central Waitemata Harbour Study, was used to specify this split.

[2] The reduction in zinc loads over the first 15–20 years in the future period is due primarily to the assumed disappearance of galvanised steel roofs. Subsequent to that time there is a very slow increase in loads that is due to a continued increase in road traffic (Timperley and Reed, 2008).

[3] The increase in copper loads throughout the future period is due to increasing vehicle traffic and assumed increasing use of copper sheet roofing (Timperley and Reed, 2008a).

Swales et al. provided maps of percent clay and fine silt (<25 μm), percent medium silt (25–63 μm) and percent very fine sand (63–125 μm). The <25 micron particle size class was equated with the 12 μm constituent particle size in the USC-3 model; 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. The percentages for the three particle size classes reported by Swales et al. do not add up to 100 %, which suggests the presence of a coarser mode. The presence of a fraction coarser than 125 μm is confirmed by looking at Swales et al.'s maps of median and mean particle size, which typically exceed 125 μm. The 180 μm fraction in the USC-3 model was assigned so that the resulting D50 in the USC-3 model matched Swales et al.'s observed median particle size. The results of this analysis are shown in Table 13.

The metal concentrations in the surface mixed layer of each subestuary must also be specified at the start of the future period. These were taken from Ahrens et al. (2007) who sampled harbour bed sediments as part of the Central Waitemata Harbour Study. Ahrens et al. reported the concentration of metal associated with each of three sediment particle size classes: <25 μm, 25–63 μm, and 63–250 μm. The <25 μm particle size class was equated with the 12 μm constituent particle size in the USC-3 model; the 25–63 μm particle size class was equated with the 40 μm constituent particle size; and the 63–250 μm particle size class was equated with both the 125 and 180 μm constituent particle sizes. Table 14 shows the zinc concentrations in each subestuary applied in the USC-3 model at the start of the future period, and Table 15 likewise shows the copper concentrations. Also shown in Tables 14 and 15 is total metal concentration, which is defined as the metal carried on all sediment particle sizes divided by the total (sum of all particle sizes) sediment. To calculate this, the estuarine bed-sediment particle size split shown in Table 13 was used.

4.6 Results

4.6.1 Patterns of sediment and contaminant dispersal

4.6.1.1 Fate

Table 16 (sediment), Table 17 (zinc) and Table 18 (copper) show the fate of sediment and contaminant from each sub-catchment.

The fate of sediments from each sub-catchment is substantially the same as that described by Green (2008) for the historical period, 1940–2001, which was simulated as part of the calibration of the USC-3 model. This is not surprising, as the fate of sediments depends to a large extent on circulation patterns in the harbour, which are not expected to change between the historical and future periods. The discussion on sediment fate provided here is a little more detailed than that provided by Green (2008) for the historical period.

The fate of zinc and copper mirrors almost exactly the fate of sediment. This is not surprising, since zinc and copper are carried (in the model) by sediments. Throughout the following discussion, sediments only are referred to, just to keep the text simple. However, the comments refer equally to zinc and copper.

Refer to Table 16 during the following discussion of sediment fate.

Sub-catchments that discharge to the southern shore of the harbour throat and to the east of the Harbour Bridge (see Figure 10 for summary):

- Sediment from the Hobsons Bay sub-catchment (1 – HBY) deposits almost exclusively in Hobsons Bay subestuary (16 – HBA), which is at the base of that same sub-catchment. The sediment that does escape from Hobsons Bay subestuary is entirely lost to the Hauraki Gulf. This seems reasonable, given the proximity of the mouth of Hobsons Bay subestuary to the entrance of the Hauraki Gulf.
- About one-third of the sediment load from the Stanley Street sub-catchment (2 – SST) turns the corner and deposits in the adjacent Hobsons Bay subestuary (16 – HBA), with the remainder being lost to the Hauraki Gulf. Sediment from the two sub-catchments that drain to the south shore of the harbour throat a little further to the west (3 – CST and 4 – WSM) evidently does not turn that same corner to the same extent, and as a result is almost entirely lost to the Hauraki Gulf.
- It is noteworthy that little of the sediment from the four sub-catchments that drain to the southern shore of the harbour throat crosses the harbour to deposit in Shoal Bay subestuary (11 – SBY).
- It will be seen that a significant portion of the sediment loads discharged from all sub-catchments to the west of the Harbour Bridge is deposited in Shoal Bay subestuary. This contrasts sharply with the four sub-catchments that drain into the harbour to the east of the Harbour Bridge. Figure 11 shows a schematic.

There is a distinct change of pattern moving further to the west into the transition zone between the harbour throat and the main body of the harbour, where the Coxs Bay (5 – COB), Motions Creek (6 – MOK) and Meola Creek (7 – MEK) sub-catchments enter into the harbour (see Figure 12 for summary):

- A significant fraction of the sediment from each of these sub-catchments is now seen to cross the harbour and deposit in Shoal Bay subestuary (11 – SBY), and similar significant fractions are lost to the Hauraki Gulf. Each of these sub-catchments drains to the west of the natural constriction in the harbour that is crossed by the Harbour Bridge, which might act to mix and steer ebb flows and associated suspended sediments across the harbour to where they may enter and deposit in Shoal Bay subestuary.
- Sediment from each of these sub-catchments is also dispersed widely to the west into the main body of the harbour, at least as far as the Western Intertidal (5 – WSI) subestuary.

- Sediment from Coxs Bay (5 – COB) and Motions Creek (6 – MOK) sub-catchments deposits locally in Motions subestuary (10 – MOT), which lies to the east of Te Tokaroa reef.
- Sediment from Meola Creek sub-catchment (7 – MEK) deposits locally in Meola subestuary (9 – MEO) and the adjacent Point Chevalier subestuary (8 – PCV), which both lie to the west of Te Tokaroa reef.
- Therefore, Te Tokaroa reef appears to prevent sediments from Motions Creek sub-catchment mixing locally with sediments from the Meola Creek sub-catchment. Further afield to the west, however, sediments from the two sub-catchments are effectively mixed. Figure 13 shows a schematic.

The Oakley Creek (8 – OAK), Whau River (9 – WHR), Henderson Creek (10 – HEK), Hobsonville (11 – HBV) and Upper Waitemata Harbour (12 – UWH) sub-catchments drain into the main body of the harbour.

- It is noteworthy, again, that a significant fraction of the sediment from all of these sub-catchments is seen to cross the harbour and deposit in Shoal Bay subestuary (11 – SBY), and similar significant fractions are lost to the Hauraki Gulf (This was also the case for the sub-catchments that drained to the harbour in the transition zone between the harbour throat and the main body.). This suggests that Shoal Bay intercepts a large fraction of the sediment that originates from all sub-catchments to the west of Shoal Bay, which (presumably) would otherwise be lost to the Hauraki Gulf. Because of this, Shoal Bay experiences a relatively large sedimentation rate. Green (2008) noted that this was in fact consistent with Swales et al.'s measurements that indicated that, of all subestuaries in the Central Waitemata Harbour excluding tidal creeks, Shoal Bay had the highest sedimentation rate over the past 50 years.
- Figure 14 shows a schematic of the fate of sediment from the Oakley Creek (8 – OAK) and Whau River (9 – WHR) sub-catchments. A significant fraction of sediment from Oakley Creek sub-catchment does not escape the Waterview Embayment subestuary (15 – WAT), which is the enclosed embayment through which that sub-catchment discharges. Apart from that, sediment from Oakley Creek is dispersed widely in the southwestern and western sectors of the main body amongst the Point Chevalier (8 – PCV), Waterview Flats (7 – WAV), Southwestern Intertidal (6 – WSI), and Western Intertidal (5 – WSI) subestuaries. A significant fraction of sediment from the Whau River sub-catchment accumulates in the Whau River subestuary (14 – WHA), which is the tidal creek at the base of that sub-catchment. Apart from that, sediment from the Whau River disperses widely in the southwestern and western sectors of the main body amongst the Southwestern Intertidal (6 – WSI), and Western Intertidal (5 – WSI) subestuaries.
- Figure 25 shows a schematic of the fate of sediment from the Henderson Creek (10 – HEK) and Hobsonville (11 – HBV) sub-catchments. A significant fraction of sediment from the Henderson Creek sub-catchment accumulates in the Henderson Creek subestuary (13 – HEN), which is the tidal creek at the

base of that sub-catchment. Apart from that, sediment from Henderson Creek disperses widely in the southwestern, western and northwestern sectors of the main body amongst the Southwestern Intertidal (6 – WSI), Western Intertidal (5 – WSI), Central Subtidal (4 – CNS) and Northwestern Intertidal (3 – NWI) subestuaries. Sediment from Henderson Creek is also deposited in Limeburners Bay subestuary (2 – LBY), which is in a sheltered position at the mouth of Henderson Creek. Sediment from the Hobsonville sub-catchment (11 – HBV) is also distributed widely in the southwestern, western and northwestern sectors of the main body, in a very similar way to the dispersal of sediments from Henderson Creek sub-catchment. The outlets of these two sub-catchments are nearby to each other.

- Sediment emanating from the Upper Waitemata Harbour (12 – UWH) spreads widely throughout the entire main body of the Central Waitemata Harbour, with the interception of a significant fraction of its load by Shoal Bay subestuary (11 – SBY) along the path to the Hauraki Gulf.

Figure 16 shows a schematic of the fate of sediment from the Little Shoal Bay (13 – LSB), Shoal Bay North (14 – SBN) and Shoal Bay East (15 – SBE) sub-catchments. Little Shoal Bay sub-catchment drains to the north shore of the harbour throat, immediately to the west of the natural constriction in the harbour that is crossed by the Harbour Bridge, and to the west of Shoal Bay subestuary (11 – SBY). The Shoal Bay North and Shoal Bay East sub-catchments both discharge directly into Shoal Bay subestuary.

- About two-thirds of the sediment from Little Shoal Bay sub-catchment is lost to the Hauraki Gulf. A quarter turns the corner to the east and gets trapped in Shoal Bay. That pattern is reversed for Shoal Bay North and Shoal Bay East sub-catchments, both of which drain directly into Shoal Bay: a little more than 50 % of the sediment from each sub-catchment is deposited in Shoal Bay, and about 40 % is lost to the Hauraki Gulf.

4.6.1.2 Origin

Table 19 (sediment), Table 20 (zinc) and Table 21 (copper) show the origin of sediment and contaminant deposited in each subestuary. Figures 17 to 28 show schematic summaries of the origins of sediment and metals, subestuary by subestuary. Figure 29 shows all of those figures on the one page for sediments, and Figure 30 shows the same for metals.

Because the fate of zinc and copper almost exactly follows 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. To illustrate, imagine sediment in a particular subestuary derives from sources 1, 2 and 3 in the proportions 50 %, 30 % and 20 %. Metals will not necessarily derive from those sources in the same proportions: for instance, metals might derive from sources 1, 2 and 3 in the proportions 0 %, 60 % and 40 %. This can be a significant effect, but the reasons for it are subtle. In essence, it occurs when the total catchment metal load is not distributed amongst the sub-catchments in the same proportions as the total catchment sediment load. That will nearly always be the case, and it is certainly the case for the Central Waitemata Harbour. In the illustration above, sub-catchment 1 contributes some sediment to the harbour, but it contributes no metal at all.

Referring now to Tables 19, 20 and 21:

- Sediment in the Hobsonville subestuary (1 – HBE), situated on the northwest shore of the main body of the harbour, originates primarily from the adjacent sources: Hobsonville sub-catchment (30 %), the Upper Waitemata Harbour (37 %), and Henderson Creek sub-catchment (33 %). This suggests that this is a relatively sheltered part of the main body, with minimal transfer of sediment into this part of the harbour from other parts. 65 % of the zinc and 63 % of the copper derives from the adjacent Hobsonville sub-catchment, which is significantly higher than the amount of sediment that derives from Hobsonville sub-catchment (30 %). Figure 17 shows a schematic summary.

- Limeburners Bay subestuary (2 – LBY) is in a sheltered position at the mouth of Henderson Creek and, as a result primarily receives sediment from Henderson Creek sub-catchment (93 %). Most of the zinc (86 %) and copper (88 %) also comes from Henderson Creek sub-catchment. Figure 18 shows a schematic summary.

- Sediment deposited in the Northwestern Intertidal subestuary (3 – NWI) and in the Central Subtidal subestuary (4 – CNS) is also sourced almost exclusively (93 % in both cases) from the Henderson Creek sub-catchment. These are exposed areas, and unlikely to be sheltered in the same sense as Hobsonville and Limeburners Bay subestuaries. It is more the case that the Henderson Creek sub-catchment is the exclusive source of sediments to the Central Subtidal and Northwestern Intertidal subestuaries because that sub-catchment supplies the largest loads of sediment to the harbour. In other words, 3 – NWI and 4 – CNS are immediately adjacent to the largest (by far) sediment supply, and so are dominated by that supply. In that regard it is noteworthy that 4 – CNS, which is further from the Henderson Creek outlet and further out in the main body of the harbour, does show sediment arriving from a slightly wider range of sources. Figures 19 and 20 show schematic summaries.

  Most of the zinc and copper in these two subestuaries is also sourced almost exclusively from the Henderson Creek sub-catchment (89 % of zinc and 92 % of copper for 3 – NWI; 90 % of zinc and 90 % of copper for 4 – CNS). As with sediments, zinc and copper derive from a wider range of sources in 4 – CNS.

- The Western Intertidal (5 – WSI) and Southwestern Intertidal (6 – SWI) subestuaries are further from the outlet of Henderson Creek and so are less dominated by sediments from Henderson Creek sub-catchment. They are also reasonably exposed. As a result, both of these subestuaries receive sediment and metals from a correspondingly wide range of sources: from the north (Upper Waitemata Harbour and Hobsonville sub-catchments), the northwest (Henderson Creek sub-catchment), the southwest (Whau River sub-catchment), the southeast (Oakley Creek sub-catchment) and the east (Meola Creek sub-catchment). Figures 21 and 22 show schematic summaries.

The bulk of sediment in the Western Intertidal subestuary (5 – WSI) comes from Henderson Creek sub-catchment (61 %), with a lesser proportion from the Upper Waitemata Harbour sub-catchment (17 %) and Whau River sub-catchment (15 %). These proportions are quite different for metals, with more metal coming from the Whau River sub-catchment: 37 % of zinc and 43 % of copper come from Henderson Creek sub-catchment (compare with 61 % of sediment), and 35 % of zinc and 30 % of copper come from Whau River sub-catchment (compare with 15 % of sediment).

A similar situation holds for the Southwestern Intertidal (6 – SWI) subestuary. In this case, sediments are roughly equally distributed between Henderson Creek (34 %) and Whau River (30 %) sub-catchments, but metals come principally from Whau River: 43 % of zinc and 44 % of copper come from Whau River sub-catchment, while only 18 % of zinc and 21 % of copper come from Henderson Creek sub-catchment.

- The Waterview Flats subestuary (7 – WAV) is dominated by sediments from the adjacent Oakley Creek sub-catchment (39 %) and the more distant Henderson Creek sub-catchment (34 %). Although this is in a reasonably sheltered part of the main body of the harbour it does in fact receive sediments from sub-catchments to the west (Whau River and Henderson Creek sub-catchments) and the east (Meola Creek sub-catchment). Metals also come principally from Oakley Creek sub-catchment, although the proportions (68 % for zinc and 61 % for copper) are much higher compared to sediment (39 %). Like sediments, metals also come from sub-catchments to the west and east. Figure 23 shows a schematic summary.
- That same pattern is seen in the three adjacent subestuaries to the east (8 – PCV, 9 – MEO and 10 – MOT). Figures 24, 25 and 26 show schematic summaries. In all of these subestuaries, sediment principally derives from the respective adjacent source, but there are also contributions from sources to the west and east. The easternmost source is Coxs Bay sub-catchment; further to the east sub-catchments drain directly into the harbour throat, which loses sediment readily to the Hauraki Gulf. In all of these subestuaries, metals, like sediments, derive from a wide range of sources to the west and east. It is noteworthy that Henderson Creek sub-catchment is a significant source of sediments to Point Chevalier subestuary (44 %) and Meola subestuary (45 %), both of which lie to the west of Te Tokaroa reef, but Henderson Creek is only a minor source of sediments to Motions subestuary (16 %), which lies to the east of Te Tokaroa reef. This indicates that the reef is an effective barrier.

The principal sources of zinc in the Point Chevalier subestuary (8 – PCV) are Henderson Creek sub-catchment (23 %), Meola Creek sub-catchment (18 %) and Oakley Creek sub-catchment (29 %). The principal sources of copper in the Point Chevalier subestuary (8 – PCV) are Henderson Creek sub-catchment

(28 %), Meola Creek sub-catchment (17 %) and Oakley Creek sub-catchment (25 %).

In Meola subestuary (9 – MEO), event though sediment comes principally from Henderson Creek sub-catchment (45 %), zinc (42 %) and copper (35 %) come principally from the adjacent Meola Creek sub-catchment.

In Motions subestuary (10 – MOT), sediment comes principally from Motions Creek sub-catchment (29 %), with a slightly smaller contribution of sediment from the Coxs Bay sub-catchment (26 %). Most of the zinc (52 %) and copper (48 %) comes from the Motions Creek sub-catchment, with most of the remainder coming from the Coxs Bay sub-catchment (26 % zinc, 28 % copper).

- Shoal Bay subestuary (11 – SBY) receives sediment and metals from all sub-catchments except those four that drain on the south shore of the harbour throat, as previously described. Figure 29 shows a schematic summary. Henderson Creek sub-catchment is the principal source of sediment (45 %), presumably because it is a far larger source than the local sources Shoal Bay North and Shoal Bay East. Metals come from the local Shoal Bay North sub-catchment (18 % zinc, 16 % copper) and the distant Henderson Creek sub-catchment (23 % zinc, 27 % copper).
- Sediment and metals that deposit in the Henderson Creek subestuary (13 – HEN) and the Whau River subestuary (14 – WHA), both of which are tidal creeks, originate virtually exclusively from the sub-catchment that drains into the respective tidal creek headwaters. This is also the case for the Waterview Embayment subestuary (15 – WAT), which acts like a sink at the base of the Oakley Creek sub-catchment. Figure 28 shows a schematic summary.
- In contrast, sediment and metals that deposit in Hobsons Bay subestuary (16 – HBA) are captured from virtually every sub-catchment around the harbour, which is by virtue of its position at the harbour mouth. The majority, however, comes from the local Hobsons Bay sub-catchment (53 % of the sediment, 59 % of the zinc, and 59 % of the copper).

4.6.2 Sedimentation

The predicted sedimentation rate in each subestuary is shown in Table 22.

By radioisotopic dating of sediment cores, Swales et al. (2008b) determined an average sedimentation rate over the past 50 years or so of 3.2 mm year^{-1} for intertidal sites in the Central Waitemata Harbour (range 0.7 – 6.8 mm year^{-1}), and 3.3 mm year^{-1} for subtidal sites (range 2.2 – 5.3 mm year^{-1}). Sedimentation rates were more variable at intertidal sites compared to subtidal sites.

The sedimentation rates predicted here for the future period (Table 22) show the same patterns that were observed by Swales et al. (2008a) and hindcast by Green (2008) for the 1940–2001 historical period.

- The highest predicted sedimentation rate outside of tidal creeks is found in Limeburners Bay (2 – LBY). Limeburners Bay may be viewed as an extension of the Henderson Creek tidal creek, which drains directly into Limeburners Bay, and which Limeburners Bay primarily receives sediments from.
- The next highest predicted sedimentation rate outside of tidal creeks is found in Shoal Bay (11 – SBY). As noted previously, Shoal Bay receives sediment from all sub-catchments except those four that drain on the south shore of the harbour throat, and a high sedimentation rate was anticipated as a result.
- The predicted sedimentation rates are lower in the Point Chevalier, Waterview Flats, Meola and Motions subestuaries compared to predicted sedimentation rates on the intertidal flats in the western main body of the harbour (Southwestern Intertidal, Western Intertidal, Northwestern Intertidal subestuaries). This is broadly in line with Swales et al. (2008a), who designated the Point Chevalier/Motions area as a "temporary sink", with relatively lower sedimentation rates.
- Swales et al.'s (2008b) radioisotopic sedimentation rates on the intertidal flats in the western main body of the harbour are quite variable compared to the predicted sedimentation rates for the same areas (Southwestern Intertidal, Western Intertidal and Northwestern Intertidal subestuaries). Swales et al. designated the "Whau Flats" as a temporary sink, and the "Central Basin" as a sink. The predicted sedimentation rates do not show that distinction. Instead, they show a lower sedimentation rate in the subtidal Central Subtidal subestuary (4 – CNS) compared to the adjacent intertidal flats to the west. Swales et al. shows that same pattern – lower radioisotopic sedimentation rate towards the subtidal zone compared to up on the adjacent intertidal flat – a little further to the south.
- Finally, the predicted sedimentation rates in the three tidal creeks (Henderson Creek, Whau River and Hobsons Bay) exceeded the predicted sedimentation rates at all places outside of the tidal creeks. This concurs with previous observations of sedimentation in tidal creeks in the Auckland region (eg, Vant et al. 1993; Oldman and Swales, 1999; Swales et al. 1997; Swales et al. 2008a).

The predicted sedimentation rate for Hobsonville subestuary is very low, both outright and compared to all of the other subestuaries throughout the harbour, and especially those nearby to that particular part of the harbour. This casts doubt on the model performance in this subestuary.

Green's (2008) hindcast sedimentation rates for the historical period 1940–2001 were smaller than Swales et al.'s (2008a) radioisotopic sedimentation rates (albeit, as noted above, the patterns of sedimentation were similar). The predicted sedimentation rates for the future period under Scenario 1 are, in turn, smaller (by about one half or more) than Green's (2008) hindcast sedimentation rates for the historical period (Table 22). The smaller sedimentation rates for the future period compared to the historical period are explainable by the reduction in catchment sediment run-off in the future period compared to the historical period. Table 23 shows this reduction, which is typically more than one half for each sub-catchment.

The sedimentation rates shown in Table 22 are averages over the entire simulation period, and as such they hide an important detail: sedimentation rates drop, and in some cases reverse (the subestuary erodes) 15–25 years into the future period (Figure 31). This is driven by a corresponding decrease in sediment run-off from the catchment, which is discernible in Figure 4, but more clearly illustrated in Figure 32. The response of the sedimentation to the drop in sediment run-off from the catchment varies from subestuary to subestuary, as follows:

- In the intertidal parts of the main body of the harbour (Northwestern Intertidal, Western Intertidal, Southwestern Intertidal subestuaries), sedimentation reduces at the time sediment run-off reduces, but remains positive thereafter until the end of the simulation. The reduction in sedimentation is greatest for the Western Intertidal subestuary – in fact, it nearly enters a new transportational (approximately zero sedimentation) regime. This subestuary lies between the respective outlets of the Henderson Creek and Whau River sub-catchments. Compared to that, the reduction in sedimentation is less for the Northwestern Intertidal subestuary, which is close to the outlet of the Henderson Creek sub-catchment, and the Southwestern Intertidal subestuary, which is close to the outlet of the Whau River sub-catchment.
- The subtidal part of the main body of the harbour (Central Subtidal subestuary) also experiences a reduction in sedimentation, after which a new transportational regime (approximately zero sedimentation) is established.
- For the subestuaries that lie to the west of Te Tokaroa reef in the transition between the throat and the main body of the harbour (Waterview Flats, Point Chevalier and Meola subestuaries), sedimentation goes negative (the subestuary erodes) until a new transportational regime is established. In contrast, for Motions subestuary, which lies to the east of Te Tokaroa reef in the transition between the throat and the main body of the harbour, sedimentation declines significantly, but remains positive until the end of the simulation.
- For the tidal creeks, sedimentation is not obviously affected, and sediment continues to accumulate.
- Sedimentation in Shoal Bay subestuary (11 – SBY) is also not obviously affected.

The sedimentation patterns just described are summarised in a schematic in Figure 33.

The sedimentation rate in any given subestuary results from the balance over time between sediment inputs and sediment losses. Inputs are made up of sediment from the land and sediment eroded from other subestuaries and transported to the subestuary in question. The predicted changes in sedimentation in the intertidal parts of the main body of the harbour are readily understandable in terms of the reduction in sediment run-off from the catchment. In those parts of the harbour that are predicted to ultimately become transportational (the subtidal part of the main body, and the subestuaries that lie to the west of Te Tokaroa reef in the transition between the throat and the main body of the harbour), the reduction in sediment run-off from the catchment effectively reduces sediment inputs to the point where they are matched by removal of sediments (to other parts of the harbour) by waves and currents. This results in the establishment of a transportational regime. It is not immediately apparent why sedimentation in the tidal creeks is predicted to be not obviously affected by the reduction in sediment run-off from the catchment. A possible explanation is related to a differential reduction in sediment run-off, as follows. Given that much of the sediment run-off generated during larger rainfall events is exported from the tidal creeks, and virtually all of the sediment run-off generated during smaller rainfall events is deposited inside the tidal creeks[4], then if sediment run-off during larger events is reduced more than sediment run-off during smaller events, this would not necessarily translate into a marked change in sedimentation rate.

These changes in sedimentation will have profound effects on heavy-metal concentrations in the harbour in the future, for the following reasons.

A reduction in sediment run-off from the land accompanied by an increase in heavy-metal run-off will obviously cause the concentration at which metals are delivered to the harbour to increase. As noted previously, this increase will drive a corresponding increase in metal concentration in the bed sediments of the harbour. However, and this is the point, this can only occur in those areas of the harbour where sediments (and attached metals) actually deposit. For subestuaries that become erosional (negative sedimentation) or transportational (zero sedimentation), metal concentrations will be unaffected by the changes in concentration at which metals are being delivered from the land. In essence, the reduction in sediment run-off causes the **behaviour** of these subestuaries to fundamentally change, that is, to switch from depositional to erosional / transportational. It is worth noting that in more sheltered harbours (such as the Upper Waitemata Harbour), where erosion of estuary bed sediments is never significant, this change in behaviour is not possible, and the metal concentration in the bed sediment is driven entirely by the disequilibrium between the concentration at which metals are delivered from the land and concentration at which metals are present in the bed sediments.

4.6.3 Metal concentration in estuarine bed sediments

Figures 34 to 37 show the predicted change in metal concentration in the surface mixed layer of the estuarine bed sediments for the future period under Scenario 1. These show the total metal concentration, which is defined as the metal carried on all sediment particle sizes divided by the total (sum of all particle sizes) sediment.

Predicted metal concentrations are subestuary averages. In the main body of the harbour, concentrations will tend to be uniform across subestuaries, but in the side

[4] The simulations performed using the DHI model suite during the implementation of the USC-3 model for the purposes of evaluating the *RTC* term showed this (Green, 2008).

branches there may be strong spatial gradients in concentration. In particular, concentrations in the upper reaches of the tidal creeks are likely to be much higher than indicated by the predictions (and conversely they may be lower in the lower reaches).

The change in metal concentrations through the future period will be seen to be principally controlled by the sedimentation regime.

The following comments relate to subestuaries that experience virtually constant sedimentation throughout the future period (Figure 34):

- Zinc and copper concentrations in the bed sediments of the tidal creeks/sinks (Henderson Creek, Whau River, Waterview Embayment and Hobsons Bay subestuaries) rise continuously through the future period under a sedimentation rate that remains positive and virtually constant through the period. It is noteworthy that this continuous rise occurs for zinc, even though the concentration at which zinc is delivered to the harbour tends to stabilise around one-third of the way through the future period (Figure 8). This shows that zinc concentrations in the bed sediments of these subestuaries do not reach an equilibrium with the input zinc concentrations by the end of the future period. The concentration at which copper is delivered to the harbour does not stabilise in the future period (ie, it increases throughout the future; see Figure 9), hence copper concentrations cannot attain equilibrium.
- Limeburners Bay subestuary, with a large sedimentation rate, acts like an extension of Henderson Creek subestuary. As a consequence, zinc and copper concentrations rise continuously throughout the future period.
- Zinc and copper concentrations in Shoal Bay under a sedimentation rate that also remains positive and virtually constant throughout the future period behave in the same way as zinc and copper concentrations in the tidal creeks/sinks, and for the same reasons. So, zinc and copper concentrations both rise throughout the future period, and this occurs even though the concentration at which zinc is being delivered from the sub-catchment stabilises. As in the case of tidal creeks/sinks, this indicates that zinc concentrations do not reach equilibrium.

The following comments relate to subestuaries that remain depositional, but experience a decrease in sedimentation rate partway through the future period (Figure 35):

- In Motions subestuary, which lies to the east of Te Tokaroa reef in the transition zone between the harbour throat and the main body of the harbour, zinc and copper concentrations do not stabilise when sediment run-off from the catchment reduces, although the rate at which they continue to climb drops significantly. This is due to the reduction in sedimentation rate (previously described): in essence, under the reduced sedimentation, mixing brings together proportionately more pre-existing sediment (with lower metal concentrations) with newly-deposited sediment (with higher metal concentrations) into the surface mixed layer, which retards the rise in metal concentration in that layer.

- The same is the case for the Northwestern Intertidal, Western Intertidal and Southwestern Intertidal subestuaries in the main body of the harbour: a rise in zinc and copper concentrations early in the future period becomes retarded when the sedimentation rates drop, but because these subestuaries do not become transportational, that rise is not fully arrested.

The following comments relate to subestuaries that become transportational partway through the future period (Figure 36):

- Zinc and copper concentrations in the subestuaries that are situated to the west of Te Tokaroa reef in the transition zone between the harbour throat and the main body of the harbour (Meola, Point Chevalier, Waterview Flats subestuaries) reach an equilibrium partway through the future period. This is a response to the change in sedimentation regime – from depositional to transportational – that also occurs at this time, and which in turn is a response to the reduction in sediment run-off from the catchment, as previously described. Although an equilibrium concentration is attained, in the sense that the concentration becomes steady, it is more the case that these subestuaries become "moribund" (or "stagnant") when deposition switches off.

  It is noteworthy that, early in the future period, before going moribund, metal (both zinc and copper) concentrations in the Waterview Flats and Point Chevalier subestuaries rise at approximately the same rate as the metal concentrations in the Southwestern Intertidal subestuary (see Figure 36), which is adjacent to the west. In contrast, metal concentrations in the Meola subestuary rise at about the same rate as in Motions subestuary, which is adjacent to the east, before going moribund (also shown in Figure 36).

- The same thing occurs in the Central Subtidal subestuary, ie, metal concentrations stabilise when the subestuary becomes moribund under a change in sedimentation regime from depositional to transportational, which in turn is a response to the reduction in sediment run-off from the catchment. Prior to becoming moribund, metal concentrations tend to rise at about the same rate as in the Western Intertidal subestuary, which is adjacent.

For Hobsonville subestuary, which had a doubtful (very small) predicted sedimentation rate, zinc and copper concentrations are predicted to rise only very slowly in the future period (Figure 37).

Finally, Figures 38 (zinc) and 39 (copper) show how the model predictions for the future period dovetail with the model hindcasts for the historical period (1940–2001) in the three test subestuaries that were the focus of the model calibration conducted by Green (2008). These figures show the measured concentration at the start of the historical period, which was the starting concentration for the calibration simulations, and the measured concentration at the end of the historical period, which was the target concentration for the calibration (further details are given in Green, 2008). The measured concentration at the end of the historical period has also been used as the starting concentration for the future period.

For zinc, the two periods are seen to dovetail nicely, meaning that the hindcast concentration at the end of the historical period is the same as the starting concentration for the future period, and the trend established in the historical period merges smoothly into the trend in the future period. The matching of end and starting concentrations is good in the case of zinc, which occurs because the hindcasts are based on a calibrated metal retention factor which was chosen to ensure the best reproduction of the target (at the end of historical period) zinc concentration. Nevertheless, this does not guarantee that the trends will merge, so the fact that they do is a satisfying result.

The dovetail is less satisfactory for copper in terms of matching the hindcast concentration at the end of the historical period with the starting concentration for the future period. This is due to the fact that the zinc metal retention factor was applied in the copper hindcasts, which did not result in quite as good achievement of the target copper concentrations at the end of the historical period. Regardless of that, it is noteworthy, and again satisfying, that the trends do blend nicely across the two periods.

4.6.4 Exceedance of sediment quality guideline threshold values

Table 24 shows a tabulation of the times at which sediment quality guideline threshold values are predicted to be first exceeded in the future period under Scenario 1. Three thresholds are considered for each metal:

- Threshold Effects Level (TEL) (125 mg kg^{-1} for zinc; 19 mg kg^{-1} for copper).
- Effects Range Low (ERL) (150 mg kg^{-1} for zinc; 34 mg kg^{-1} for copper).
- Probable Effects Level (PEL) (271 mg kg^{-1} for zinc; 108 mg kg^{-1} for copper).

A more informed appreciation of this matter is to be gained by studying the predicted trends in metal concentrations shown in Figures 34 to 37 – understanding the trends provides the necessary context for interpreting the threshold exceedance times. The following comments relate to the trends shown in those figures. Figure 40 (zinc) and Figure 41 (copper) show schematic summaries.

- For the subestuaries that experience virtually constant sedimentation throughout the future period (the tidal creeks/sinks of Henderson Creek, Whau River, Waterview Embayment and Hobsons Bay subestuaries; Shoal Bay subestuary; and Limeburners Bay subestuary, which acts as an extension of the Henderson Creek tidal creek), and that see metal concentrations rise continuously as a result, the ERL threshold is exceeded for zinc and copper in all cases, with two exceptions. The first exception is copper in Shoal Bay subestuary. However, the ERL threshold in that case is on track to being exceeded shortly beyond the close of the future period (ie, shortly after 2100). The second exception is zinc and copper in Limeburners Bay subestuary; however, the ERL threshold for zinc, at least, is on track to being exceeded shortly after 2100.

  ERL threshold exceedance tends to occur earlier in the case of the tidal creeks/sinks, which begin the future period with higher metal concentrations.

In the case of the Henderson Creek and Whau River subestuaries, the future period began with the zinc and copper ERL thresholds already exceeded.

The PEL threshold for zinc is predicted to be exceeded before 2100 for two of the four tidal creeks/sinks (Henderson Creek, Whau River). These are the only cases where the PEL threshold is predicted to be exceeded. Note, though, that zinc is on track to exceed the PEL threshold in Waterview Embayment and Hobsons Bay shortly after 2100.

- For those subestuaries that remain depositional, but experience a decrease in sedimentation rate partway through the future period, the climb in metal concentrations reduces when the sedimentation rate decreases. For the subestuaries in this category that are in the main body of the harbour, which are all intertidal, (Northwestern Intertidal, Western Intertidal, Southwestern Intertidal), the TEL threshold tends to be breached or closely approached for zinc, but this typically occurs in the middle to late part of the future period, with the climb in concentration slowing down around the TEL threshold. For copper, the climb in concentration slows down before the TEL threshold is reached.

  Motions Creek subestuary, which is in this category, but situated in the transition zone between the throat and the main body of the harbour, to the east of Te Tokaroa reef, behaves similarly. That is, the climb in zinc concentration slows down around the TEL threshold, and the climb in copper concentration slows down before the TEL threshold is reached.

- The Waterview Flats, Point Chevalier and Meola subestuaries see concentrations stabilise, partway through the future period, as a result of becoming transportational when sediment run-off from the catchment reduces. These three subestuaries are in the transition zone between the throat and the main body of the harbour, to the west of Te Tokaroa reef. For all of these subestuaries, zinc and copper concentrations both tend to stabilise well below the TEL threshold.

  Zinc and copper concentrations in the other subestuary that becomes transportational – the Central Subtidal subestuary in the main body of the harbour – stabilise early in the future period well below the TEL threshold.

Table 4

Split of rural sediment load amongst the constituent particle sizes (12, 40, 125 and 180 μm) that was applied to every sub-catchment for the future period.

Constituent particle size (μm)	Fraction of rural sediment load
12	0.5
40	0.3
125	0.2
180	0.0

Table 5

Average (over the simulation) fraction of urban sediment load assigned to each constituent grain size (12, 40, 125 and 180 μm) during the future period under Scenario 1, calculated by the CLM.

Sub-catchment	Constituent particle size (μm)			
	12	40	125	180
1 – HBY	0.37	0.33	0.29	0.00
2 – SST	0.37	0.33	0.29	0.00
3 – CST	0.38	0.33	0.29	0.00
4 – WSM	0.37	0.33	0.29	0.00
5 – COB	0.37	0.33	0.29	0.00
6 – MOK	0.37	0.34	0.29	0.00
7 – MEK	0.37	0.33	0.29	0.00
8 – OAK	0.38	0.33	0.29	0.00
9 – WHR	0.37	0.33	0.29	0.00
10 – HEK	0.37	0.33	0.29	0.00
11 – HBV	0.37	0.33	0.29	0.00
12 – UWH	–	–	–	–
13 – LSB	0.37	0.33	0.29	0.00
14 – SBN	0.37	0.33	0.29	0.00
15 – SBE	0.37	0.33	0.29	0.00

Table 6

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

Sub-catchment	Average per year (kg)	Sum over simulation (kg)
1 – HBY	418,002	41,800,244
2 – SST	148,377	14,837,731
3 – CST	30,882	3,088,220
4 – WSM	139,193	13,919,330
5 – COB	163,923	16,392,245
6 – MOK	212,111	21,211,056
7 – MEK	272,216	27,221,628
8 – OAK	491,537	49,153,744
9 – WHR	1,005,664	100,566,352
10 – HEK	5,130,998	513,099,808
11 – HBV	99,170	9,916,956
12 – UWH	1,048,197	104,819,688
13 – LSB	103,146	10,314,576
14 – SBN	380,115	38,011,480
15 – SBE	94,385	9,438,470

Table 7

Concentration (mg kg^{-1}) at which zinc is carried on soils in the sub-catchments of the Central Waitemata Harbour, from Reed (2008).

Sub-catchment	<25 μm	25–63 μm	63–250 μm
1 – HBY	72.4	62.9	57.7
2 – SST	86.3	104	80.5
3 – CST	86.3	104	80.5
4 – WSM	86.3	104	80.5
5 – COB	87.2	81.3	37.2
6 – MOK	121	115	78.9
7 – MEK	47.3	39.7	28.9
8 – OAK	72.6	79	39.5
9 – WHR	68	57.8	43
10 – HEK	68	57.8	43
11 – HBV	68	57.8	43
12 – UWH	–	–	–
13 – LSB	47.3	39.7	28.9
14 – SBN	47.3	39.7	28.9
15 – SBE	86.3	104.0	80.5

Table 8

Concentration (mg kg^{-1}) at which copper is carried on soils in the sub-catchments of the Central Waitemata Harbour, from Reed (2008).

Sub-catchment	<25 μm	25–63 μm	63–250 μm
1 – HBY	20	18	14.8
2 – SST	27.6	30.7	25.2
3 – CST	27.6	30.7	25.2
4 – WSM	27.6	30.7	25.2
5 – COB	26	24.9	12.9
6 – MOK	37.7	36.3	26.7
7 – MEK	10.9	9.8	7.4
8 – OAK	44.1	40.4	28.3
9 – WHR	32.5	31.1	26.6
10 – HEK	32.5	31.1	26.6
11 – HBV	32.5	31.1	26.6
12 – UWH	–	–	–
13 – LSB	10.9	9.8	7.4
14 – SBN	10.9	9.8	7.4
15 – SBE	27.6	30.7	25.2

Table 9

Average (over the simulation) fraction of anthropogenic zinc load carried by each sediment constituent particle size (12, 40, 125 and 180 μm), predicted by the CLM.

Sub-catchment	Sediment constituent grain size (μm)			
	12	40	125	180
1 – HBY	0.44	0.32	0.25	0.0
2 – SST	0.43	0.32	0.25	0.0
3 – CST	0.44	0.32	0.24	0.0
4 – WSM	0.43	0.32	0.25	0.0
5 – COB	0.44	0.32	0.24	0.0
6 – MOK	0.42	0.32	0.26	0.0
7 – MEK	0.44	0.32	0.24	0.0
8 – OAK	0.44	0.32	0.24	0.0
9 – WHR	0.45	0.32	0.24	0.0
10 – HEK	0.44	0.32	0.24	0.0
11 – HBV	0.42	0.32	0.25	0.0
12 – UWH	–	–	–	–
13 – LSB	0.44	0.32	0.24	0.0
14 – SBN	0.43	0.32	0.25	0.0
15 – SBE	0.44	0.32	0.24	0.0

Table 10

Average (over the simulation) fraction of anthropogenic copper load carried by each sediment constituent particle size (12, 40, 125 and 180 μm), predicted by the CLM.

Sub-catchment	Sediment constituent grain size (μm)			
	12	40	125	180
1 – HBY	0.42	0.32	0.26	0.0
2 – SST	0.40	0.33	0.27	0.0
3 – CST	0.41	0.32	0.26	0.0
4 – WSM	0.40	0.33	0.27	0.0
5 – COB	0.42	0.32	0.26	0.0
6 – MOK	0.40	0.33	0.27	0.0
7 – MEK	0.42	0.32	0.26	0.0
8 – OAK	0.41	0.33	0.26	0.0
9 – WHR	0.42	0.32	0.26	0.0
10 – HEK	0.42	0.32	0.26	0.0
11 – HBV	0.41	0.33	0.26	0.0
12 – UWH	–	–	–	–
13 – LSB	0.42	0.32	0.26	0.0
14 – SBN	0.41	0.33	0.26	0.0
15 – SBE	0.42	0.32	0.26	0.0

Table 11

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 model run in the Monte Carlo package of 50 USC model runs.

Sub-catchment	Sum over simulation of anthropogenic zinc (kg)	Sum over simulation of total (anthropogenic plus natural) zinc (kg)	Fraction of total due to anthropogenic	Fraction of total due to natural
1 – HBY	74,104	76,888	0.96	0.04
2 – SST	41,033	42,375	0.97	0.03
3 – CST	10,435	10,714	0.97	0.03
4 – WSM	46,220	47,479	0.97	0.03
5 – COB	26,856	28,092	0.96	0.04
6 – MOK	67,428	69,778	0.97	0.03
7 – MEK	46,150	47,276	0.98	0.02
8 – OAK	108,751	112,089	0.97	0.03
9 – WHR	174,029	180,057	0.97	0.03
10 – HEK	268,130	298,885	0.90	0.10
11 – HBV	17,626	18,220	0.97	0.03
12 – UWH	–	70,970	–	–
13 – LSB	17,390	17,817	0.98	0.02
14 – SBN	86,396	87,967	0.98	0.02
15 – SBE	19,188	20,042	0.96	0.04

Table 12

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 model run in the Monte Carlo package of 50 USC model runs.

Sub-catchment	Sum over simulation of anthropogenic copper (kg)	Sum over simulation of total (anthropogenic plus natural) copper (kg)	Fraction of total due to anthropogenic	Fraction of total due to natural
1 – HBY	13,823	14,591	0.95	0.05
2 – SST	7409	7825	0.95	0.05
3 – CST	6003	6089	0.99	0.01
4 – WSM	7190	7580	0.95	0.05
5 – COB	5422	5800	0.93	0.07
6 – MOK	10,373	11,117	0.93	0.07
7 – MEK	9264	9533	0.97	0.03
8 – OAK	18,654	20,612	0.91	0.09
9 – WHR	32,398	35,506	0.91	0.09
10 – HEK	49,708	65,563	0.76	0.24
11 – HBV	3373	3680	0.92	0.08
12 – UWH	–	7659	–	–
13 – LSB	3385	3487	0.97	0.03
14 – SBN	14,942	15,317	0.98	0.02
15 – SBE	3895	4159	0.94	0.06

Table 13

Present-day split of estuarine bed sediments amongst constituent particle sizes, derived from Swales et al.'s (2008a) data, and applied at the start of the future period.

Subestuary	Fraction of bed sediment composed of 12 µm grain size	Fraction of bed sediment composed of 40 µm grain size	Fraction of bed sediment composed of 125 µm grain size	Fraction of bed sediment composed of 180 µm grain size	Bed sediment D50 (microns)
1 -HBE	0.05	0.04	0.45	0.46	141
2 - LBY	0.03	0.05	0.30	0.62	151
3 - NWI	0.02	0.03	0.55	0.40	142
4 - CNS	0.02	0.10	0.35	0.53	144
5 - WSI	0.02	0.03	0.40	0.55	150
6 - SEI	0.06	0.15	0.60	0.19	116
7 - WAV	0.03	0.10	0.25	0.62	147
8 - PCV	0.01	0.02	0.30	0.67	159
9 - MEO	0.01	0.02	0.35	0.62	156
10 - MOT	0.01	0.02	0.35	0.62	156
11 - SBY	0.07	0.20	0.60	0.13	107
12 - HGF	–	–	–	–	–
13 - HEN	0.40	0.40	0.15	0.05	49
14 - WHA	0.40	0.40	0.15	0.05	49
15 - WAT	0.40	0.40	0.15	0.05	49
16 - HBA	0.40	0.40	0.15	0.05	49
17 - UWH	–	–	–	–	–

Table 14

Zinc concentrations in each subestuary applied in the USC-3 model at the start of the future period. The total metal concentration is calculated from the constituent concentrations (this table) and the split of the bed sediment amongst the constituent particle sizes (Table 13).

Subestuary	Metal concentration on 12 µm constituent grain size (mg/kg)	Metal concentration on 40 µm constituent grain size (mg/kg)	Metal concentration on 125 µm constituent grain size (mg/kg)	Metal concentration on 180 µm constituent grain size (mg/kg)	Total metal concentration (mg/kg)
1 -HBE	120	75	104	104	103
2 - LBY	141	85	75	75	77
3 - NWI	120	56	64	64	65
4 - CNS	135	82	104	104	102
5 - WSI	129	64	102	102	101
6 - SEI	134	67	81	81	82
7 - WAV	136	76	65	65	68
8 - PCV	134	70	66	66	67
9 - MEO	146	94	89	89	89
10 - MOT	146	94	89	89	89
11 - SBY	126	70	103	103	98
12 - HGF	–	–	–	–	–
13 - HEN	150	150	150	150	150
14 - WHA	180	180	180	180	180
15 - WAT	120	120	120	120	120
16 - HBA	70	70	70	70	70
17 - UWH	–	–	–	–	–

Table 15

Copper concentrations in each subestuary applied in the USC-3 model at the start of the future period. The total metal concentration is calculated from the constituent concentrations (this table) and the split of the bed sediment amongst the constituent particle sizes (Table 13).

Subestuary	Metal concentration on 12 µm constituent particle size (mg kg^{-1})	Metal concentration on 40 µm constituent particle size (mg kg^{-1})	Metal concentration on 125 µm constituent particle size (mg kg^{-1})	Metal concentration on 180 µm constituent particle size (mg kg^{-1})	Total metal concentration (mg kg^{-1})
1 -HBE	23.7	14.6	7.6	7.6	9
2 - LBY	28.3	17.8	8.3	8.3	9
3 - NWI	25.1	9.8	4.8	4.8	5
4 - CNS	24.0	15.9	5.5	5.5	7
5 - WSI	22.9	12.4	5.4	5.4	6
6 - SEI	23.9	12.0	7.3	7.3	9
7 - WAV	25.1	13.9	6.1	6.1	7
8 - PCV	25.1	8.7	7.0	7.0	7
9 - MEO	30.4	12.4	8.2	8.2	8
10 - MOT	30.4	12.4	8.2	8.2	8
11 - SBY	21.2	9.7	7.5	7.5	9
12 - HGF	–	–	–	–	–
13 - HEN	30	30	30	30	30
14 - WHA	30	30	30	30	30
15 - WAT	20	20	20	20	20
16 - HBA	10	10	10	10	10
17 - UWH	–	–	–	–	–

Table 16

Fate of sediment from each sub-catchment (read the table across the page): percentage and mass (kg) of total sediment load from each sub-catchment deposited in each subestuary; average over 50 model runs in the Monte Carlo package.

FATE OF SEDIMENT (%)

Sub-catchment	Subestuary																
	1 HBE	2 LBY	3 NWI	4 CNS	5 WSI	6 SWI	7 WAV	8 PCV	9 MEO	10 MOT	11 SBY	12 HGF	13 HEN	14 WHA	15 WAT	16 HBA	17 UWH
Hobsons Bay																	
1 – HBY	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	87	0
South Shore of throat																	
2 – SST	0	0	0	0	0	0	0	0	0	0	1	64	0	0	0	35	0
3 – CST	0	0	0	0	0	0	0	0	0	0	1	95	0	0	0	4	0
4 – WSM	0	0	0	0	0	0	0	0	0	0	1	95	0	0	0	4	0
Transition between throat and main body																	
5 – COB	0	0	0	0	1	3	0	1	0	16	38	37	0	0	0	3	0
6 – MOK	0	0	0	0	1	4	0	2	0	14	42	34	0	0	0	3	0
7 – MEK	0	0	0	0	2	6	1	5	5	1	43	35	0	0	0	3	0
Main body																	
8 – OAK	0	0	0	0	2	15	5	3	1	1	24	21	0	0	23	4	0
9 – WHR	0	0	0	0	5	23	0	1	0	0	17	17	0	33	0	2	0
10 – HEK	0	8	16	3	4	5	0	1	0	0	20	17	22	0	0	2	0
11 – HBV	4	13	2	0	5	8	1	2	1	0	34	28	0	0	0	2	0
12 – UWH	0	2	5	1	6	15	1	2	1	1	35	24	1	0	0	5	0
Shoal Bay																	
13 – LSB	0	0	0	0	0	0	0	0	0	0	24	67	0	0	0	6	1
14 – SBN	0	0	0	0	0	0	0	0	0	0	56	39	0	0	0	5	0
15 – SBE	0	0	0	0	0	0	0	0	0	0	55	39	0	0	0	5	0

Table 16 (cont.)

Fate of sediment from each sub-catchment (read the table across the page): percentage and mass (kg) of total sediment load from each sub-catchment deposited in each subestuary; average over 50 model runs in the Monte Carlo package.

FATE OF SEDIMENT (kg)

	Subestuary																
Subcatchment	1 HBE	2 LBY	3 NWI	4 CNS	5 WSI	6 SWI	7 WAV	8 PCV	9 MEO	10 MOT	11 SBY	12 HGF	13 HEN	14 WHA	15 WAT	16 HBA	17 UWH
Hobsons Bay																	
1 – HBY	0	1	14	7	176	226	35	389	260	491	24,252	5,293,150	0	0	0	36,480,872	0
South Shore of throat																	
2 – SST	1	4	102	83	1,098	2,420	182	1,455	812	1,464	133,325	9,524,098	0	0	0	5,172,613	0
3 – CST	1	2	44	34	513	963	93	651	617	1,583	28,504	2,921,211	0	0	0	133,975	0
4 – WSM	2	5	112	62	1,006	2,002	217	1,592	1,406	4,579	113,564	13,257,501	0	0	0	536,955	0
Transition between throat and main body																	
5 – COB	294	1,013	30,339	9,105	186,316	548,598	48,152	109,143	63,001	2,620,254	6,255,416	6,033,665	0	0	24	483,441	0
6 – MOK	461	1,528	43,037	13,840	240,456	831,647	64,572	327,293	75,369	2,894,372	8,931,910	7,215,130	0	0	0	566,354	0
7 – MEK	855	2,315	62,212	21,417	560,462	1,609,072	151,102	1,314,663	1,283,204	347,019	11,660,498	9,427,670	0	0	1	774,369	0
Main body																	
8 – OAK	1,378	3,966	120,746	47,441	1,092,136	7,428,444	2,322,732	1,419,938	286,082	613,217	12,004,508	10,544,647	292	2,331	11,419,598	1,837,852	38
9 – WHR	4,449	10,117	412,726	76,472	5,496,169	22,682,936	382,163	743,400	297,314	342,560	17,203,044	17,281,518	16,004	33,104,188	61,315	2,439,182	305
10 – HEK	421,369	41,137,144	81,927,608	13,169,888	22,935,472	25,134,210	2,025,876	5,110,905	2,409,721	1,589,621	101,427,472	88,713,608	114,524,232	9,093	33,518	12,336,528	132,169
11 – HBV	392,332	1,282,052	189,808	23,925	538,970	777,125	54,682	156,928	72,925	33,474	3,391,291	2,787,972	25,346	0	0	188,216	23
12 – UWH	474,805	1,735,992	5,331,308	742,337	6,346,362	15,374,622	962,533	2,308,066	872,718	1,436,085	36,897,004	25,611,754	1,332,151	671	6,916	5,369,317	0
Shoal Bay																	
13 – LSB	42	70	4,187	1,894	39,407	48,106	3,154	15,239	8,533	18,368	2,498,058	6,949,649	1,831	1,224	14,096	658,331	52,078
14 – SBN	19	53	1,950	899	19,003	40,312	3,712	18,615	10,651	16,823	21,374,176	14,793,161	0	0	0	1,731,313	0
15 – SBE	4	11	387	182	4,036	8,441	828	4,301	2,122	2,656	5,235,982	3,681,257	0	0	0	497,965	0

Table 17

Fate of zinc from each sub-catchment (read the table across the page): percentage and mass (kg) of total zinc load from each sub-catchment deposited in each subestuary; average over 50 model runs in the Monte Carlo package.

FATE OF ZINC (%)

Sub-catchment	Subestuary																
	1 HBE	2 LBY	3 NWI	4 CNS	5 WSI	6 SWI	7 WAV	8 PCV	9 MEO	10 MOT	11 SBY	12 HGF	13 HEN	14 WHA	15 WAT	16 HBA	17 UWH
Hobsons Bay																	
1 – HBY	0	0	0	0	0	0	0	0	0	0	0	11	0	0	0	89	0
South Shore of throat																	
2 – SST	0	0	0	0	0	0	0	0	0	0	1	62	0	0	0	37	0
3 – CST	0	0	0	0	0	0	0	0	0	0	1	95	0	0	0	4	0
4 – WSM	0	0	0	0	0	0	0	0	0	0	1	95	0	0	0	4	0
Transition between throat and main body																	
5 – COB	0	0	0	0	1	4	0	1	0	17	37	36	0	0	0	3	0
6 – MOK	0	0	0	0	1	4	0	2	0	14	41	34	0	0	0	3	0
7 – MEK	0	0	0	0	2	6	1	5	5	1	42	34	0	0	0	3	0
Main body																	
8 – OAK	0	0	0	0	3	15	5	4	1	1	24	21	0	0	22	4	0
9 – WHR	0	0	0	0	6	22	0	1	0	0	16	17	0	34	0	2	0
10 – HEK	0	7	13	2	4	5	0	1	0	0	21	18	25	0	0	2	0
11 – HBV	3	13	2	0	6	8	1	2	1	0	34	28	0	0	0	2	0
12 – UWH	0	2	5	0	3	14	1	1	0	1	38	28	1	0	0	5	0
Shoal Bay																	
13 – LSB	0	0	0	0	0	1	0	0	0	0	24	67	0	0	0	6	1
14 – SBN	0	0	0	0	0	0	0	0	0	0	56	39	0	0	0	5	0
15 – SBE	0	0	0	0	0	0	0	0	0	0	56	39	0	0	0	5	0

Table 17 (cont.)

Fate of zinc from each sub-catchment (read the table across the page): percentage and mass (kg) of total zinc load from each sub-catchment deposited in each subestuary; average over 50 model runs in the Monte Carlo package.

FATE OF ZINC (kg)

	Subestuary																
Subcatchment	1 HBE	2 LBY	3 NWI	4 CNS	5 WSI	6 SWI	7 WAV	8 PCV	9 MEO	10 MOT	11 SBY	12 HGF	13 HEN	14 WHA	15 WAT	16 HBA	17 UWH
Hobsons Bay																	
1 – HBY	0	0	0	0	0	0	0	1	0	1	42	8,759	0	0	0	68,084	0
South Shore of throat																	
2 – SST	0	0	0	0	4	8	1	4	2	4	367	26,171	0	0	0	15,813	0
3 – CST	0	0	0	0	3	3	0	4	4	8	97	10,129	0	0	0	466	0
4 – WSM	0	0	0	0	4	7	1	6	5	15	396	45,206	0	0	0	1,837	0
Transition between throat and main body																	
5 – COB	1	2	55	16	377	1,021	88	206	106	4,705	10,527	10,182	0	0	0	801	0
6 – MOK	1	5	154	48	940	3,089	228	1,130	236	9,532	28,942	23,651	0	0	0	1,806	0
7 – MEK	1	4	113	39	1,105	2,985	257	2,427	2,458	571	19,807	16,186	0	0	0	1,310	0
Main body																	
8 – OAK	3	9	292	119	3,064	17,102	5,947	3,934	731	1,435	26,956	23,969	1	5	24,498	4,005	0
9 – WHR	7	16	734	147	11,060	39,942	667	1,449	509	590	29,260	29,731	27	61,718	100	4,076	1
10 – HEK	195	20,904	38,667	6,149	12,002	16,315	1,106	3,026	1,339	835	62,444	55,075	73,611	5	18	7,080	76
11 – HBV	617	2,353	344	45	1,054	1,546	97	288	123	58	6,188	5,118	42	0	0	343	0
12 – UWH	129	1,113	3,253	285	2,272	10,057	386	832	284	565	27,225	19,985	862	0	4	3,703	0
Shoal Bay																	
13 – LSB	0	0	8	4	82	89	6	32	17	33	4,306	11,958	4	3	29	1,140	106
14 – SBN	0	0	5	2	49	105	9	48	24	36	49,163	34,547	0	0	0	3,977	0
15 – SBE	0	0	1	0	11	19	2	12	6	6	11,179	7,756	0	0	0	1,048	0

Table 18

Fate of copper from each sub-catchment (read the table across the page): percentage and mass (kg) of total copper load from each sub-catchment deposited in each subestuary; average over 50 model runs in the Monte Carlo package.

FATE OF COPPER (%)

Sub-catchment	Subestuary																
	1 HBE	2 LBY	3 NWI	4 CNS	5 WSI	6 SWI	7 WAV	8 PCV	9 MEO	10 MOT	11 SBY	12 HGF	13 HEN	14 WHA	15 WAT	16 HBA	17 UWH
Hobsons Bay																	
1 – HBY	0	0	0	0	0	0	0	0	0	0	0	11	0	0	0	89	0
South Shore of throat																	
2 – SST	0	0	0	0	0	0	0	0	0	0	1	61	0	0	0	38	0
3 – CST	0	0	0	0	0	0	0	0	0	0	1	95	0	0	0	4	0
4 – WSM	0	0	0	0	0	0	0	0	0	0	1	95	0	0	0	4	0
Transition between throat and main body																	
5 – COB	0	0	0	0	1	4	0	1	0	14	40	37	0	0	0	3	0
6 – MOK	0	0	0	0	1	5	0	1	0	12	43	34	0	0	0	3	0
7 – MEK	0	0	0	0	2	7	0	4	3	1	44	35	0	0	0	3	0
Main body																	
8 – OAK	0	0	0	0	2	16	4	2	0	1	26	23	0	0	21	4	0
9 – WHR	0	0	0	0	4	22	0	1	0	0	18	17	0	35	0	2	0
10 – HEK	0	7	13	1	3	6	0	1	0	0	22	19	25	0	0	2	0
11 – HBV	3	13	2	0	5	9	1	1	1	0	35	29	0	0	0	2	0
12 – UWH	0	2	5	0	4	15	1	2	0	1	37	27	1	0	0	5	0
Shoal Bay																	
13 – LSB	0	0	0	0	0	1	0	0	0	0	24	68	0	0	0	6	1
14 – SBN	0	0	0	0	0	0	0	0	0	0	55	40	0	0	0	5	0
15 – SBE	0	0	0	0	0	0	0	0	0	0	54	40	0	0	0	5	0

Table 18 (cont.)

Fate of copper from each sub-catchment (read the table across the page): percentage and mass (kg) of total copper load from each sub-catchment deposited in each subestuary; average over 50 model runs in the Monte Carlo package.

FATE OF COPPER (kg)

	Subestuary																
Subcatchment	1 HBE	2 LBY	3 NWI	4 CNS	5 WSI	6 SWI	7 WAV	8 PCV	9 MEO	10 MOT	11 SBY	12 HGF	13 HEN	14 WHA	15 WAT	16 HBA	17 UWH
Hobsons Bay																	
1 – HBY	0	0	0	0	0	0	0	0	0	0	8	1,634	0	0	0	12,949	0
South Shore of throat																	
2 – SST	0	0	0	0	1	2	0	1	0	1	66	4,755	0	0	0	3,000	0
3 – CST	0	0	0	0	1	2	0	1	1	2	59	5,758	0	0	0	265	0
4 – WSM	0	0	0	0	0	1	0	1	1	2	65	7,216	0	0	0	294	0
Transition between throat and main body																	
5 – COB	0	0	12	4	69	229	17	39	19	783	2,308	2,150	0	0	0	168	0
6 – MOK	0	1	25	8	141	518	35	154	35	1,342	4,747	3,818	0	0	0	291	0
7 – MEK	0	1	24	8	191	653	47	346	299	90	4,233	3,372	0	0	0	269	0
Main body																	
8 – OAK	1	2	57	21	463	3,217	822	506	94	199	5,456	4,681	0	1	4,351	737	0
9 – WHR	1	3	139	27	1,500	7,651	117	226	81	94	6,303	6,164	5	12,364	19	805	0
10 – HEK	38	4,455	8,202	969	2,181	3,723	233	571	254	163	14,221	12,379	16,599	1	4	1,544	16
11 – HBV	100	466	64	8	172	330	19	49	20	10	1,300	1,061	8	0	0	71	0
12 – UWH	18	121	361	35	329	1,121	51	116	38	71	2,822	2,100	90	0	0	385	0
Shoal Bay																	
13 – LSB	0	0	2	1	12	19	1	4	2	5	829	2,358	1	1	6	224	23
14 – SBN	0	0	1	0	7	19	1	7	3	5	8,464	6,108	0	0	0	699	0
15 – SBE	0	0	0	0	2	4	0	2	1	1	2,266	1,663	0	0	0	220	0

Table 19

Source of sediment in each subestuary (refer table on the next page): percentage and mass (kg) of total sediment load deposited in each subestuary originating from each sub-catchment; average over 50 model runs in the Monte Carlo package.

SOURCE OF SEDIMENT (%)

Subestuary	Sub-catchment														
	1 HBY	2 SST	3 CST	4 WSM	5 COB	6 MOK	7 MEK	8 OAK	9 WHR	10 HEK	11 HBV	12 UWH	13 LSB	14 SBN	15 SBE
Northwest shore of main body															
1 – HBE	0	0	0	0	0	0	0	0	0	33	30	37	0	0	0
2 – LBY	0	0	0	0	0	0	0	0	0	93	3	4	0	0	0
Main body															
3 – NWI	0	0	0	0	0	0	0	0	0	93	0	6	0	0	0
4 – CNS	0	0	0	0	0	0	0	0	1	93	0	5	0	0	0
5 – WSI	0	0	0	0	0	1	1	3	15	61	1	17	0	0	0
6 – SWI	0	0	0	0	1	1	2	10	30	34	1	21	0	0	0
Transition between throat and main body															
7 – WAV	0	0	0	0	1	1	3	39	6	34	1	16	0	0	0
8 – PCV	0	0	0	0	1	3	11	12	6	44	1	20	0	0	0
9 – MEO	0	0	0	0	1	1	24	5	6	45	1	16	0	0	0
10 – MOT	0	0	0	0	26	29	3	6	3	16	0	14	0	0	0
Shoal Bay															
11 – SBY	0	0	0	0	3	4	5	5	8	45	1	16	1	9	2
Hauraki Gulf															
12 – HGF	2	4	1	6	3	3	4	5	8	40	1	11	3	7	2
Tidal creeks/sinks															
13 – HEN	0	0	0	0	0	0	0	0	0	99	0	1	0	0	0
14 – WHA	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0
15 – WAT	0	0	0	0	0	0	0	99	1	0	0	0	0	0	0
16 – HBA	53	7	0	1	1	1	1	3	4	18	0	8	1	3	1
Upper Waitemata Harbour															
17 – UWH	0	0	0	0	0	0	0	0	0	72	0	0	28	0	0

Table 19 (cont.)

Source of sediment in each subestuary (refer table on the next page): percentage and mass (kg) of total sediment load deposited in each subestuary originating from each sub-catchment; average over 50 model runs in the Monte Carlo package.

SOURCE OF SEDIMENT (kg)

	Subcatchment														
Subestuary	1 HBY	2 SST	3 CST	4 WSM	5 COB	6 MOK	7 MEK	8 OAK	9 WHR	10 HEK	11 HBV	12 UWH	13 LSB	14 SBN	15 SBE
Northwest shore of main body															
1 – HBE	0	1	1	2	294	461	855	1,378	4,449	421,369	392,332	474,805	42	19	4
2 – LBY	1	4	2	5	1,013	1,528	2,315	3,966	10,117	41,137,144	1,282,052	1,735,992	70	53	11
Main body															
3 – NWI	14	102	44	112	30,339	43,037	62,212	120,746	412,726	81,927,608	189,808	5,331,308	4,187	1,950	387
4 – CNS	7	83	34	62	9,105	13,840	21,417	47,441	76,472	13,169,888	23,925	742,337	1,894	899	182
5 – WSI	176	1,098	513	1,006	186,316	240,456	560,462	1,092,136	5,496,169	22,935,472	538,970	6,346,362	39,407	19,003	4,036
6 – SWI	226	2,420	963	2,002	548,598	831,647	1,609,072	7,428,444	22,682,936	25,134,210	777,125	15,374,622	48,106	40,312	8,441
Transition between throat and main body															
7 – WAV	35	182	93	217	48,152	64,572	151,102	2,322,732	382,163	2,025,876	54,682	962,533	3,154	3,712	828
8 – PCV	389	1,455	651	1,592	109,143	327,293	1,314,663	1,419,938	743,400	5,110,905	156,928	2,308,066	15,239	18,615	4,301
9 – MEO	260	812	617	1,406	63,001	75,369	1,283,204	286,082	297,314	2,409,721	72,925	872,718	8,533	10,651	2,122
10 – MOT	491	1,464	1,583	4,579	2,620,254	2,894,372	347,019	613,217	342,560	1,589,621	33,474	1,436,085	18,368	16,823	2,656
Shoal Bay															
11 – SBY	24,252	133,325	28,504	113,564	6,255,416	8,931,910	11,660,498	12,004,508	17,203,044	101,427,472	3,391,291	36,897,004	2,498,058	21,374,176	5,235,982
Hauraki Gulf															
12 – HGF	5,293,150	9,524,098	2,921,211	13,257,501	6,033,665	7,215,130	9,427,670	10,544,647	17,281,518	88,713,608	2,787,972	25,611,754	6,949,649	14,793,161	3,681,257
Tidal creeks / sinks															
13 – HEN	0	0	0	0	0	0	0	292	16,004	114,524,232	25,346	1,332,151	1,831	0	0
14 – WHA	0	0	0	0	0	0	0	2,331	33,104,188	9,093	0	671	1,224	0	0
15 – WAT	0	0	0	0	24	0	1	11,419,598	61,315	33,518	0	6,916	14,096	0	0
16 – HBA	36,480,872	5,172,613	133,975	536,955	483,441	566,354	774,369	1,837,852	2,439,182	12,336,528	188,216	5,369,317	658,331	1,731,313	497,965
Upper Waitemata Harbour															
17 – UWH	0	0	0	0	0	0	0	38	305	132,169	23	0	52,078	0	0

Table 20

Source of zinc in each subestuary (refer table on the next page): percentage and mass (kg) of total zinc load deposited in each subestuary originating from each sub-catchment; average over 50 model runs in the Monte Carlo package.

SOURCE OF ZINC (%)

Subestuary	Sub-catchment														
	1 HBY	2 SST	3 CST	4 WSM	5 COB	6 MOK	7 MEK	8 OAK	9 WHR	10 HEK	11 HBV	12 UWH	13 LSB	14 SBN	15 SBE
Northwest shore of main body															
1 – HBE	0	0	0	0	0	0	0	0	1	20	65	13	0	0	0
2 – LBY	0	0	0	0	0	0	0	0	0	86	10	5	0	0	0
Main body															
3 – NWI	0	0	0	0	0	0	0	1	2	89	1	7	0	0	0
4 – CNS	0	0	0	0	0	1	1	2	2	90	1	4	0	0	0
5 – WSI	0	0	0	0	1	3	3	10	35	37	3	7	0	0	0
6 – SWI	0	0	0	0	1	3	3	19	43	18	2	11	0	0	0
Transition between throat and main body															
7 – WAV	0	0	0	0	1	3	3	68	8	13	1	4	0	0	0
8 – PCV	0	0	0	0	2	8	18	29	11	23	2	6	0	0	0
9 – MEO	0	0	0	0	2	4	42	13	9	23	2	5	0	0	0
10 – MOT	0	0	0	0	26	52	3	8	3	5	0	3	0	0	0
Shoal Bay															
11 – SBY	0	0	0	0	4	10	7	10	11	23	2	10	2	18	4
Hauraki Gulf															
12 – HGF	3	8	3	14	3	7	5	7	9	17	2	6	4	11	2
Tidal creeks/sinks															
13 – HEN	0	0	0	0	0	0	0	0	0	99	0	1	0	0	0
14 – WHA	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0
15 – WAT	0	0	0	0	0	0	0	99	0	0	0	0	0	0	0
16 – HBA	59	14	0	2	1	2	1	3	4	6	0	3	1	3	1
Upper Waitemata Harbour															
17 – UWH	0	0	0	0	0	0	0	0	0	42	0	0	58	0	0

Table 20 (cont.)

Source of zinc in each subestuary (read the table across the page): percentage and mass (kg) of total zinc load deposited in each subestuary originating from each sub-catchment; average over 50 model runs in the Monte Carlo package.

SOURCE OF ZINC (kg)

	Subcatchment														
Subestuary	1 HBY	2 SST	3 CST	4 WSM	5 COB	6 MOK	7 MEK	8 OAK	9 WHR	10 HEK	11 HBV	12 UWH	13 LSB	14 SBN	15 SBE
Northwest shore of main body															
1 – HBE	0	0	0	0	1	1	1	3	7	195	617	129	0	0	0
2 – LBY	0	0	0	0	2	5	4	9	16	20,904	2,353	1,113	0	0	0
Main body															
3 – NWI	0	0	0	0	55	154	113	292	734	38,667	344	3,253	8	5	1
4 – CNS	0	0	0	0	16	48	39	119	147	6,149	45	285	4	2	0
5 – WSI	0	4	3	4	377	940	1,105	3,064	11,060	12,002	1,054	2,272	82	49	11
6 – SWI	0	8	3	7	1,021	3,089	2,985	17,102	39,942	16,315	1,546	10,057	89	105	19
Transition between throat and main body															
7 – WAV	0	1	0	1	88	228	257	5,947	667	1,106	97	386	6	9	2
8 – PCV	1	4	4	6	206	1,130	2,427	3,934	1,449	3,026	288	832	32	48	12
9 – MEO	0	2	4	5	106	236	2,458	731	509	1,339	123	284	17	24	6
10 – MOT	1	4	8	15	4,705	9,532	571	1,435	590	835	58	565	33	36	6
Shoal Bay															
11 – SBY	42	367	97	396	10,527	28,942	19,807	26,956	29,260	62,444	6,188	27,225	4,306	49,163	11,179
Hauraki Gulf															
12 – HGF	8,759	26,171	10,129	45,206	10,182	23,651	16,186	23,969	29,731	55,075	5,118	19,985	11,958	34,547	7,756
Tidal creeks / sinks															
13 – HEN	0	0	0	0	0	0	0	1	27	73,611	42	862	4	0	0
14 – WHA	0	0	0	0	0	0	0	5	61,718	5	0	0	3	0	0
15 – WAT	0	0	0	0	0	0	0	24,498	100	18	0	4	29	0	0
16 – HBA	68,084	15,813	466	1,837	801	1,806	1,310	4,005	4,076	7,080	343	3,703	1,140	3,977	1,048
Upper Waitemata Harbour															
17 – UWH	0	0	0	0	0	0	0	0	1	76	0	0	106	0	0

Table 21

Source of copper in each subestuary (refer table on the next page): percentage and mass (kg) of total copper load deposited in each subestuary originating from each sub-catchment; average over 50 model runs in the Monte Carlo package.

SOURCE OF COPPER (%)

Subestuary	Sub-catchment														
	1 HBY	2 SST	3 CST	4 WSM	5 COB	6 MOK	7 MEK	8 OAK	9 WHR	10 HEK	11 HBV	12 UWH	13 LSB	14 SBN	15 SBE
Northwest shore of main body															
1 – HBE	0	0	0	0	0	0	0	0	1	24	63	11	0	0	0
2 – LBY	0	0	0	0	0	0	0	0	0	88	9	2	0	0	0
Main body															
3 – NWI	0	0	0	0	0	0	0	1	2	92	1	4	0	0	0
4 – CNS	0	0	0	0	0	1	1	2	3	90	1	3	0	0	0
5 – WSI	0	0	0	0	1	3	4	9	30	43	3	6	0	0	0
6 – SWI	0	0	0	0	1	3	4	18	44	21	2	6	0	0	0
Transition between throat and main body															
7 – WAV	0	0	0	0	1	3	3	61	9	17	1	4	0	0	0
8 – PCV	0	0	0	0	2	8	17	25	11	28	2	6	0	0	0
9 – MEO	0	0	0	0	2	4	35	11	10	30	2	4	0	0	0
10 – MOT	0	0	0	0	28	48	3	7	3	6	0	3	0	0	0
Shoal Bay															
11 – SBY	0	0	0	0	4	9	8	10	12	27	2	5	2	16	4
Hauraki Gulf															
12 – HGF	3	7	9	11	3	6	5	7	9	19	2	3	4	9	3
Tidal creeks/sinks															
13 – HEN	0	0	0	0	0	0	0	0	0	99	0	1	0	0	0
14 – WHA	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0
15 – WAT	0	0	0	0	0	0	0	99	0	0	0	0	0	0	0
16 – HBA	59	14	1	1	1	1	1	3	4	7	0	2	1	3	1
Upper Waitemata Harbour															
17 – UWH	0	0	0	0	0	0	0	0	0	41	0	0	59	0	0

Table 21 (cont.)

Source of copper in each subestuary (refer table on the next page): percentage and mass (kg) of total copper load deposited in each subestuary originating from each sub-catchment; average over 50 model runs in the Monte Carlo package.

SOURCE OF COPPER (kg)

Subestuary	Subcatchment 1 HBY	2 SST	3 CST	4 WSM	5 COB	6 MOK	7 MEK	8 OAK	9 WHR	10 HEK	11 HBV	12 UWH	13 LSB	14 SBN	15 SBE
Northwest shore of main body															
1 – HBE	0	0	0	0	0	0	0	1	1	38	100	18	0	0	0
2 – LBY	0	0	0	0	0	1	1	2	3	4,455	466	121	0	0	0
Main body															
3 – NWI	0	0	0	0	12	25	24	57	139	8,202	64	361	2	1	0
4 – CNS	0	0	0	0	4	8	8	21	27	969	8	35	1	0	0
5 – WSI	0	1	1	0	69	141	191	463	1,500	2,181	172	329	12	7	2
6 – SWI	0	2	2	1	229	518	653	3,217	7,651	3,723	330	1,121	19	19	4
Transition between throat and main body															
7 – WAV	0	0	0	0	17	35	47	822	117	233	19	51	1	1	0
8 – PCV	0	1	1	1	39	154	346	506	226	571	49	116	4	7	2
9 – MEO	0	0	1	1	19	35	299	94	81	254	20	38	2	3	1
10 – MOT	0	1	2	2	783	1,342	90	199	94	163	10	71	5	5	1
Shoal Bay															
11 – SBY	8	66	59	65	2,308	4,747	4,233	5,456	6,303	14,221	1,300	2,822	829	8,464	2,266
Hauraki Gulf															
12 – HGF	1,634	4,755	5,758	7,216	2,150	3,818	3,372	4,681	6,164	12,379	1,061	2,100	2,358	6,108	1,663
Tidal creeks / sinks															
13 – HEN	0	0	0	0	0	0	0	0	5	16,599	8	90	1	0	0
14 – WHA	0	0	0	0	0	0	0	1	12,364	1	0	0	1	0	0
15 – WAT	0	0	0	0	0	0	0	4,351	19	4	0	0	6	0	0
16 – HBA	12,949	3,000	265	294	168	291	269	737	805	1,544	71	385	224	699	220
Upper Waitemata Harbour															

Table 22

Sedimentation rate in each subestuary over the future period under Scenario 1. "Average" is the average over 50 model runs in the Monte Carlo package. Also shown, for reference, is the sedimentation over the historical period hindcast by Green (2008).

Subestuary	Sedimentation rate		
	Average, mm yr^{-1}	Historical, mm yr^{-1}	Average/ Historical
1 – HBE	0.03	0.1	0.4
2 – LBY	1.8	3.3	0.5
3 – NWI	1.0	2.1	0.5
4 – CNS	0.1	0.2	0.5
5 – WSI	0.3	1.3	0.2
6 – SWI	0.5	1.1	0.4
7 – WAV	0.2	0.3	0.6
8 – PCV	0.2	0.3	0.6
9 – MEO	0.2	0.3	0.6
10 – MOT	0.2	1.3	0.2
11 – SBY	1.2	2.2	0.5
12 – HGF	–	–	–
13 – HEN	3.4	5.7	0.6
14 – WHA	1.0	3.7	0.3
15 – WAT	0.4	0.9	0.4
16– HBY	1.9	4.9	0.4
17 – UWH	–	–	–

Table 23

Ratio of the annual average total (rural plus urban) sediment run-off during the historical period 1940–2001 (hindcast by Green, 2008), and the total sediment run-off during the future period under Scenario 1. These statistics are for the sum of all particle sizes, and are for just one USC model run in the Monte Carlo package of 50 USC model runs.

Sub-catchment	Ratio
1 – HBY	0.28
2 – SST	0.48
3 – CST	0.17
4 – WSM	0.57
5 – COB	0.33
6 – MOK	0.59
7 – MEK	0.35
8 – OAK	0.38
9 – WHR	0.29
10 – HEK	0.60
11 – HBV	0.29
12 – UWH	0.63
13 – LSB	0.21
14 – SBN	0.33
15 – SBE	0.29

Table 24

Times (years from 2001) at which sediment quality guideline threshold values are predicted to be first exceeded in the future period under Scenario 1. "X" denotes the future period began with the threshold exceeded. "–" denotes the threshold is not exceeded by the end of the future period. "TEL" denotes Threshold Effects Level. "ERL" denotes Effects Range Low. "PEL" denotes Probable Effects Level.

Subestuary	Zinc			Copper		
	TEL	ERL	PEL	TEL	ERL	PEL
1 – HBE	–	–	–	–	–	–
2 – LBY	66	–	–	62	–	–
3 – NWI	–	–	–	–	–	–
4 – CNS	–	–	–	–	–	–
5 – WSI	37	–	–	–	–	–
6 – SWI	74	–	–	86	–	–
7 – WAV	–	–	–	–	–	–
8 – PCV	–	–	–	–	–	–
9 – MEO	–	–	–	–	–	–
10 – MOT	–	–	–	–	–	–
11 – SBY	39	61	–	58	–	–
12 – UWH	N/A	N/A	N/A	N/A	N/A	N/A
13 – HEN	X	X	58	X	10	–
14 – WHA	X	X	60	X	15	–
15 – WAT	X	15	–	X	55	–
16 – HBA	34	48	–	33	76	–

Figure 3

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

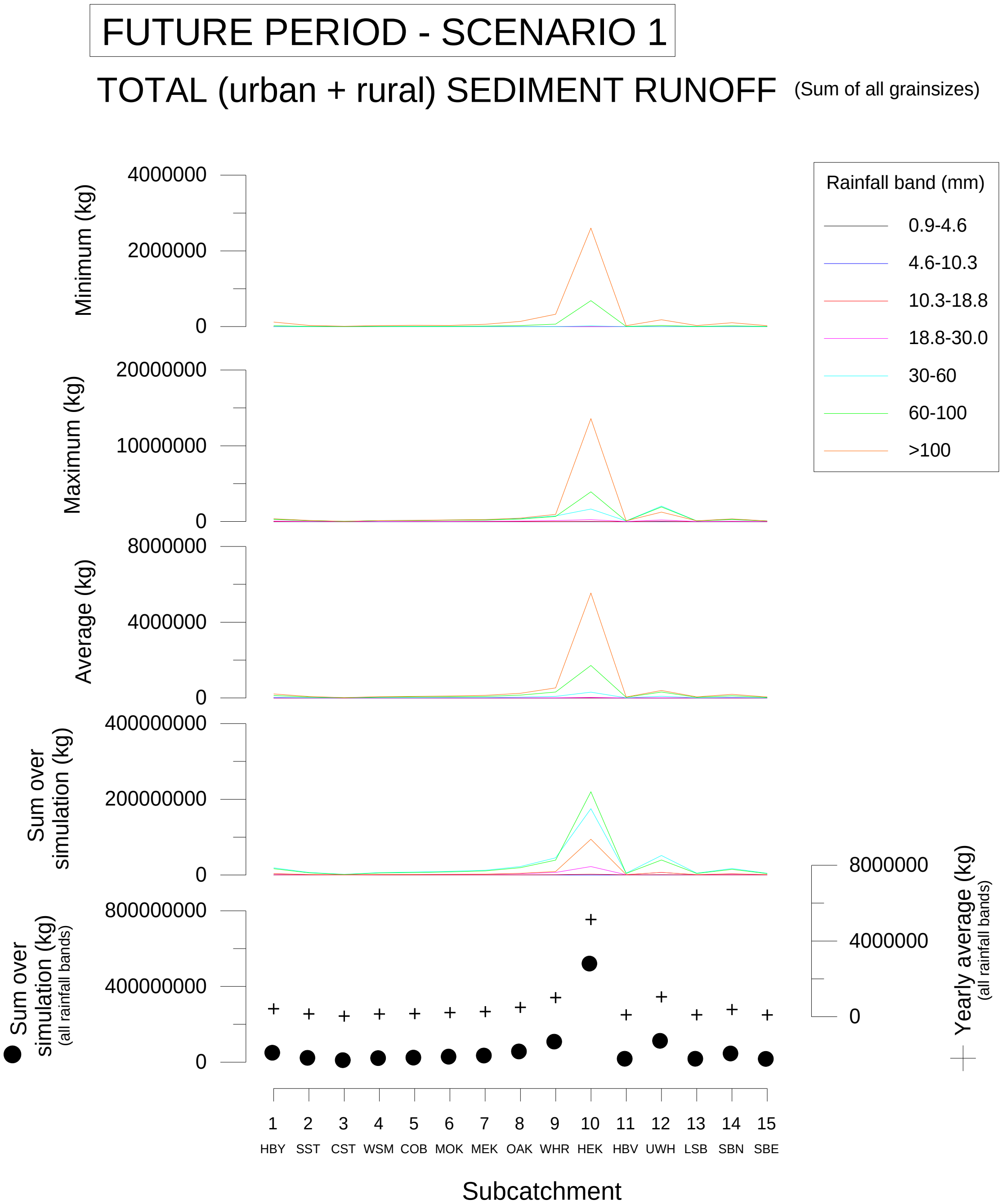


Figure 4

Annual sediment run-off. This is the sum of all grain sizes, as it appears for just one USC model run in the Monte Carlo package of 50 USC 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 2001 and year 100 is 2100.

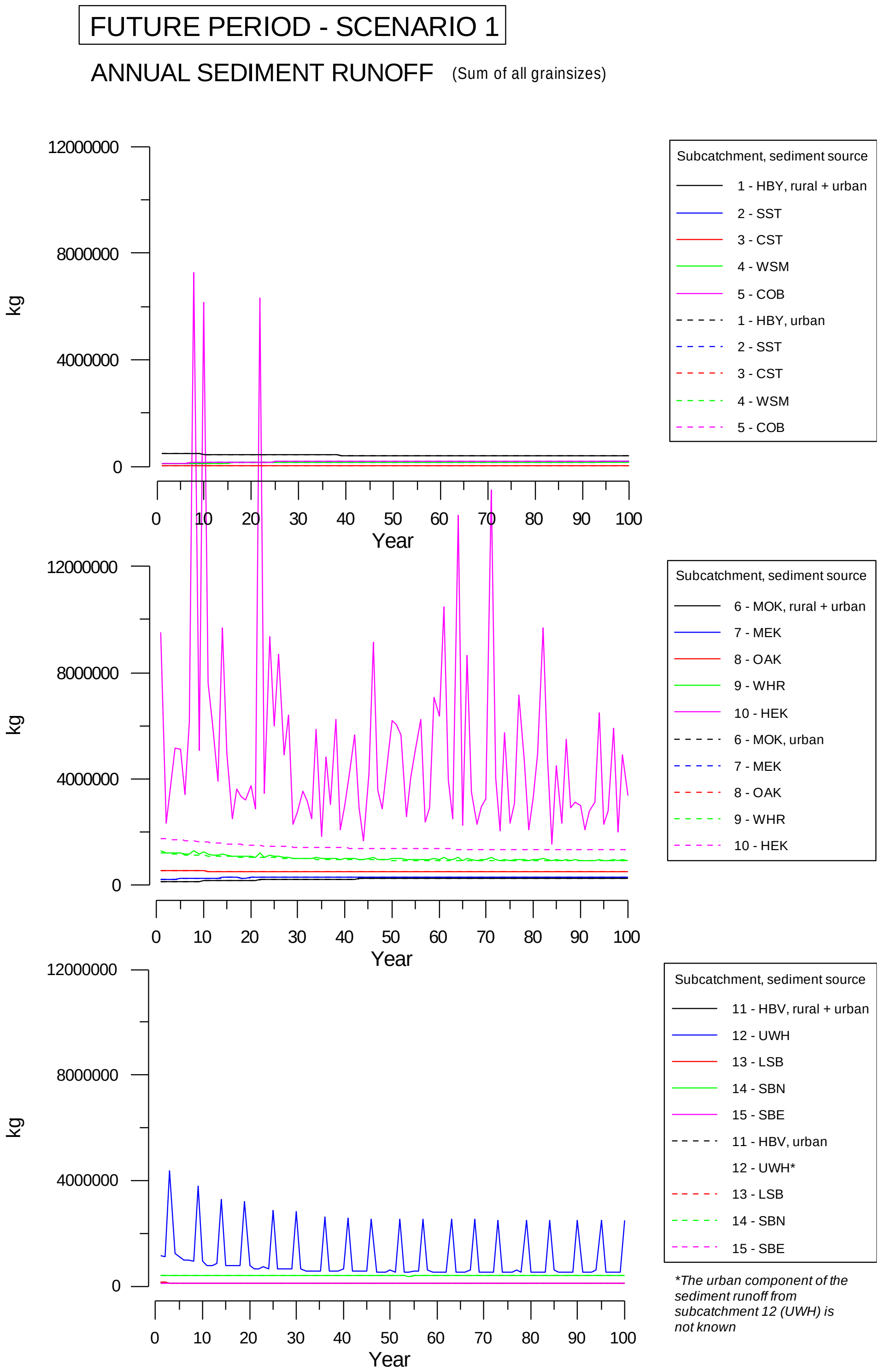


Figure 5

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

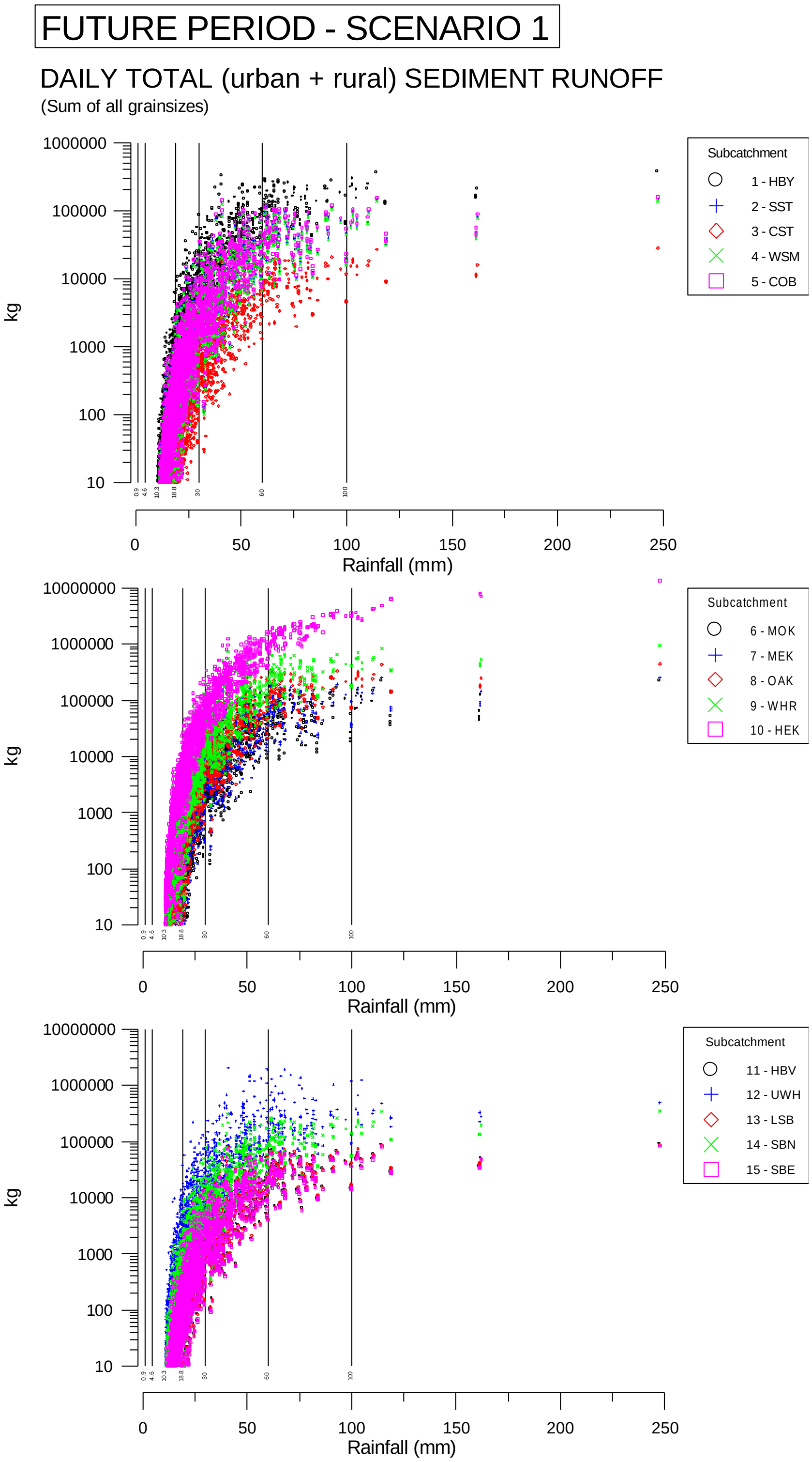


Figure 6

Anthropogenic zinc loads (total carried by all sediment constituent grain sizes). Year 1 is 2001 and year 100 is 2100.

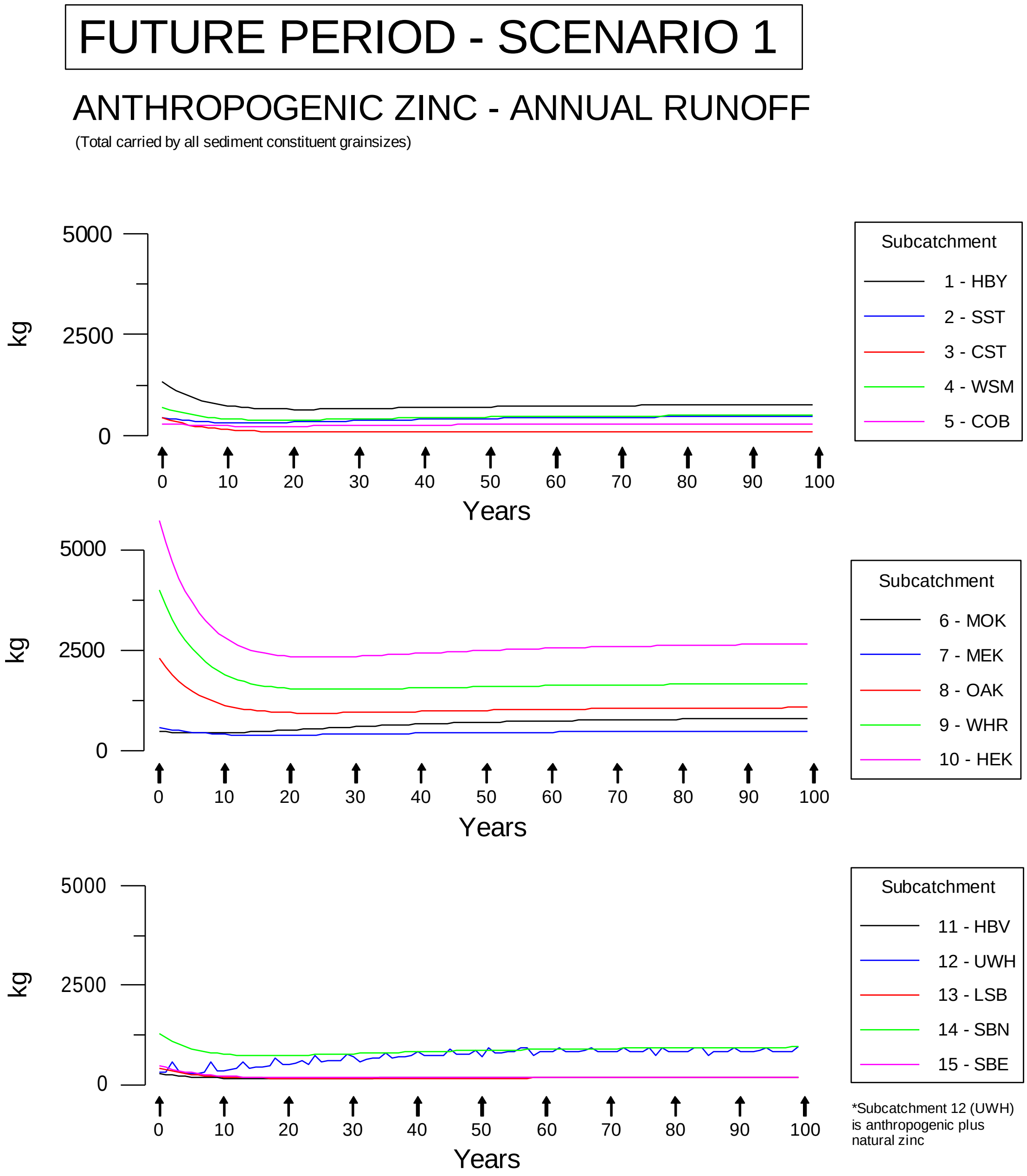


Figure 7

Anthropogenic copper loads (total carried by all sediment constituent grain sizes).

Year 1 is 2001 and year 100 is 2100.

FUTURE PERIOD - SCENARIO 1

ANTHROPOGENIC COPPER - ANNUAL RUNOFF

(Total carried by all sediment constituent grainsizes)

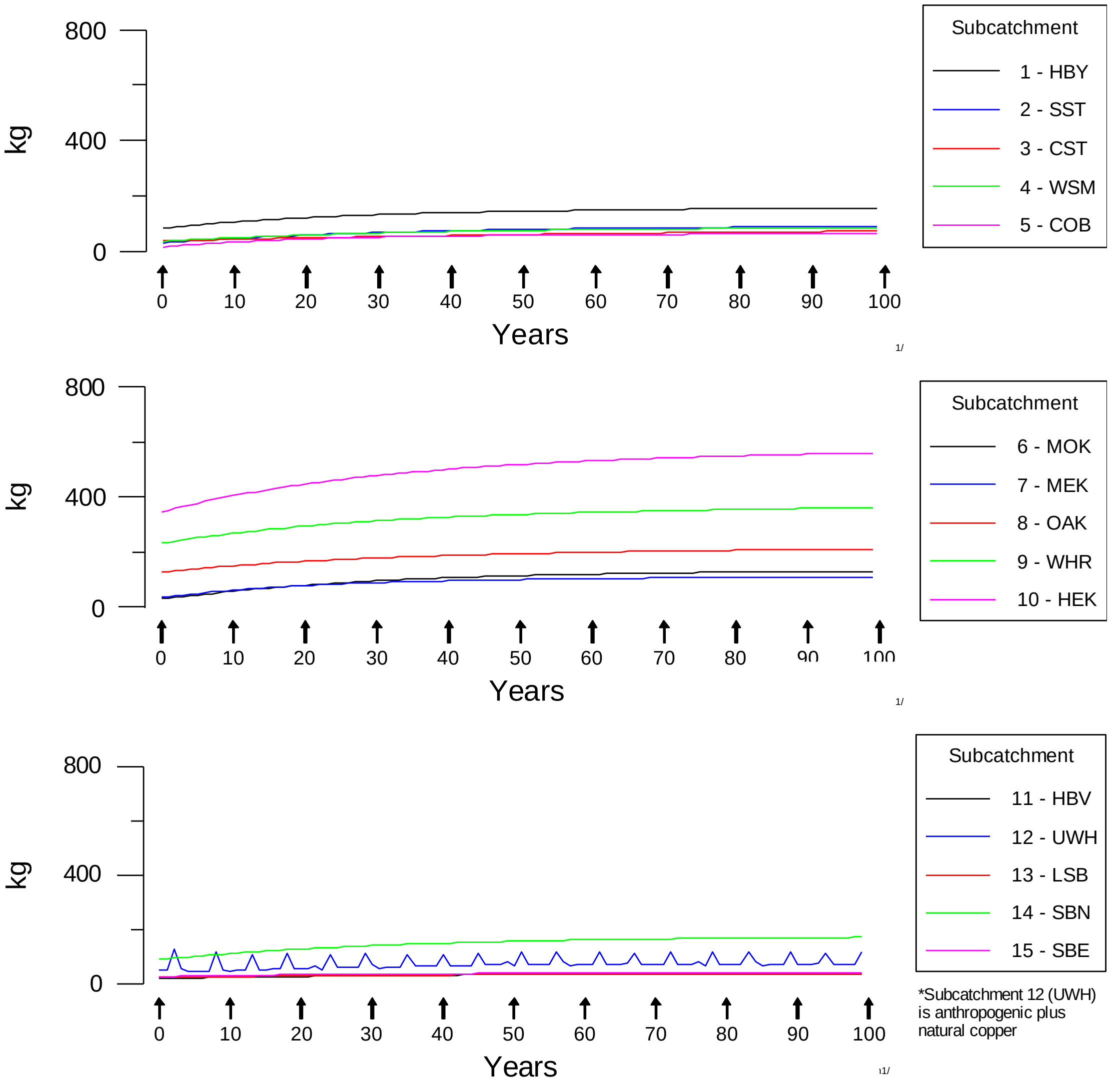


Figure 8

Concentrations at which total (anthropogenic plus natural) zinc is delivered to the harbour over the future period, Scenario 1. 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 model run in the Monte Carlo package of 50 USC model runs.

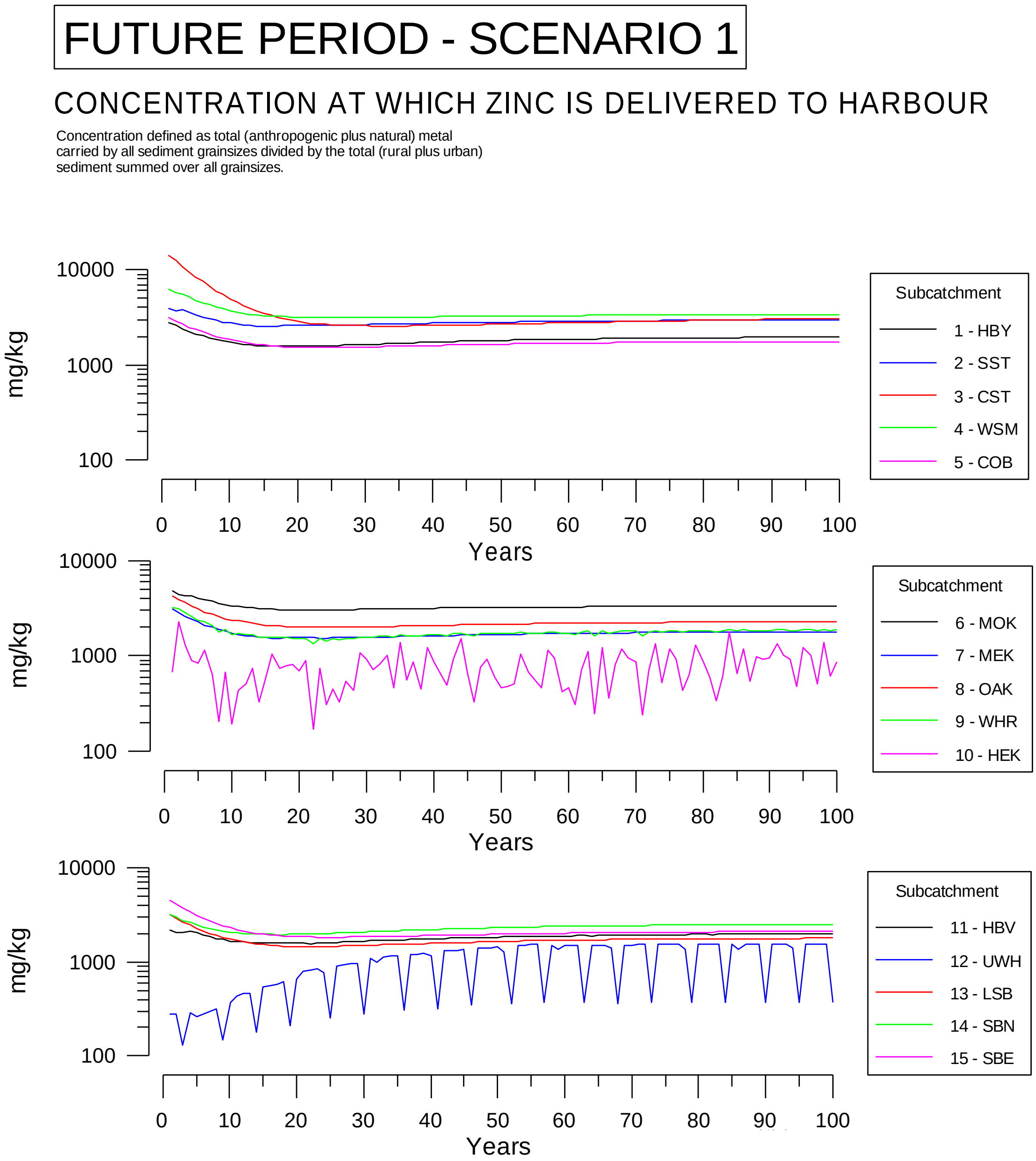


Figure 9

Concentrations at which total (anthropogenic plus natural) copper is delivered to the harbour over the future period, Scenario 1. Concentration is defined here as the total (anthropogenic plus natural) metal carried by all sediment grain sizes divided by the total (rural plus urban) sediment summed over all grain sizes. These figures are for just one USC model run in the Monte Carlo package of 50 USC model runs.

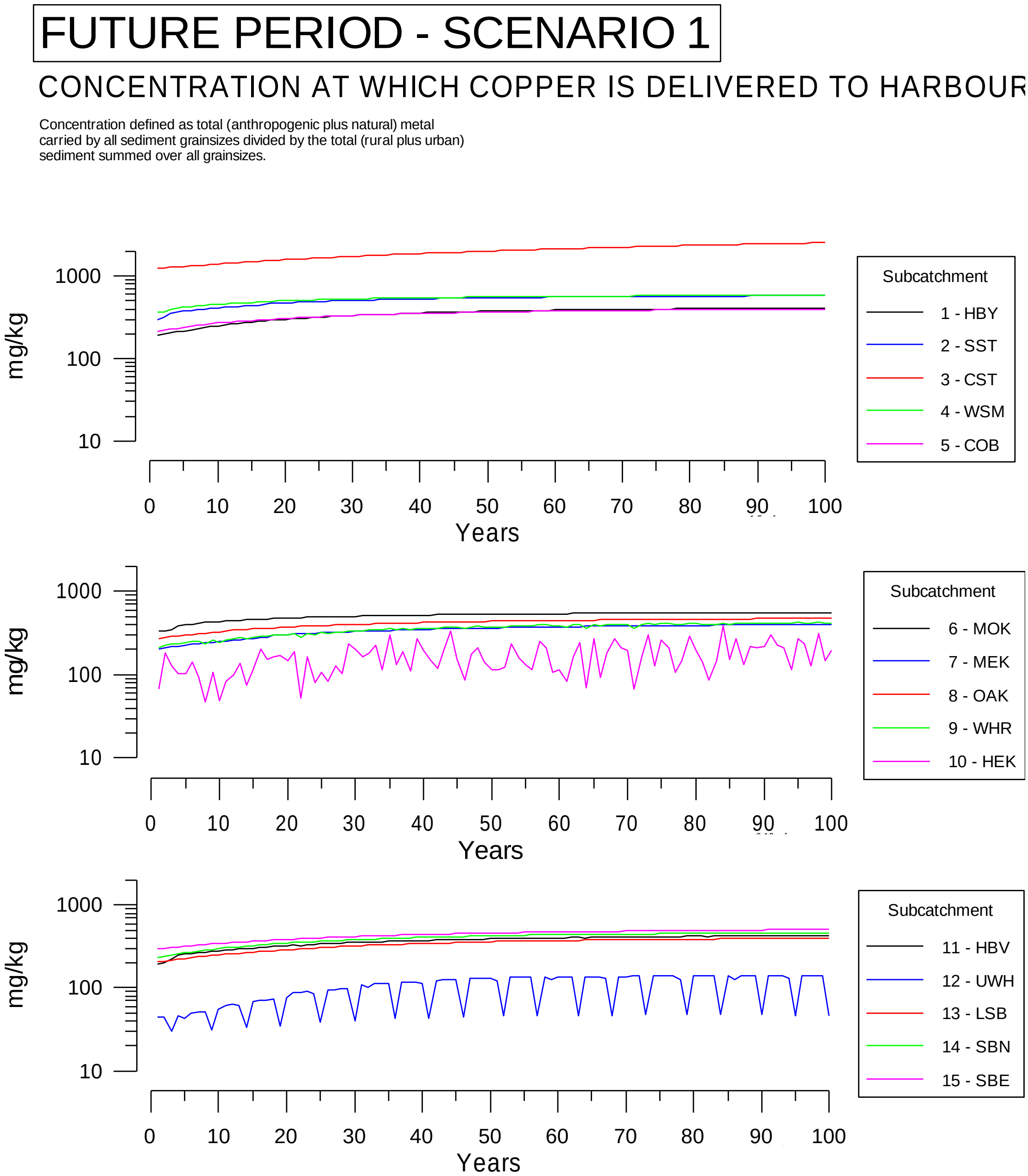


Figure 10
Schematic summarising fate of sediment and metals originating from sub-catchments that discharge to the southern shore of the harbour throat and to the east of the Harbour Bridge.

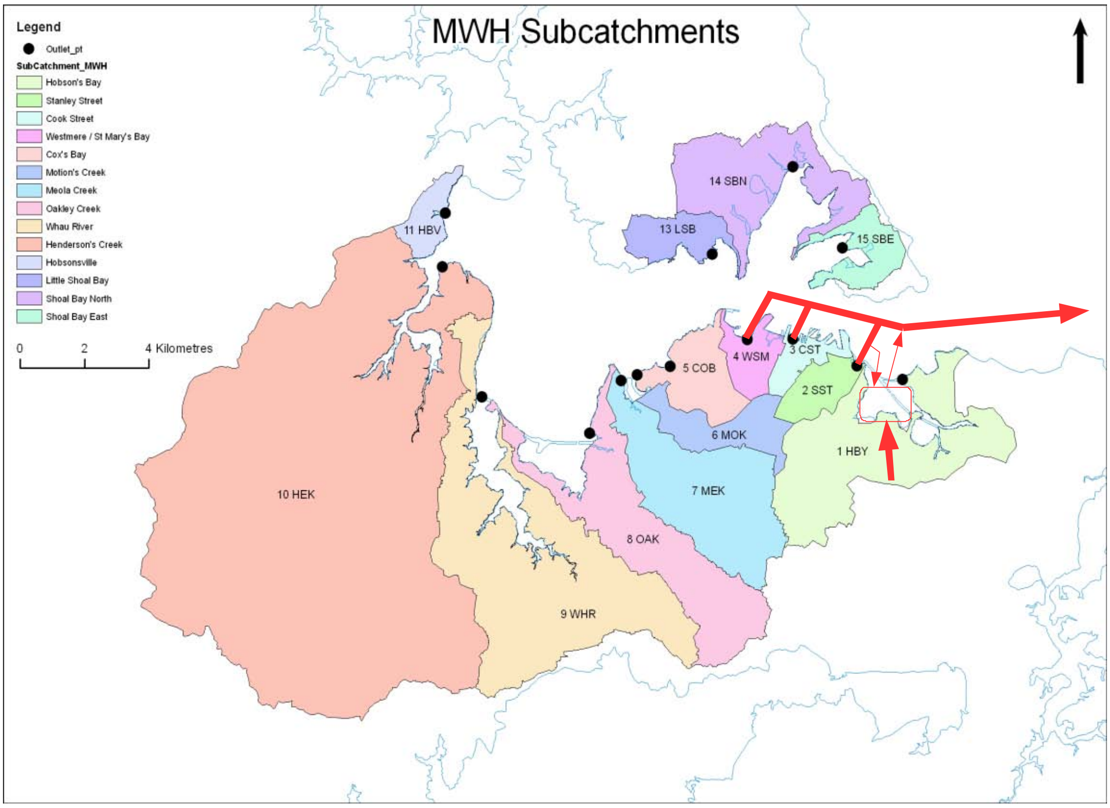


Figure 11

Schematic of the different fates, as far as Shoal Bay subestuary is concerned, of sediments and metals from sub-catchments that discharge to the east of the Harbour Bridge compared to sub-catchments that discharge to the west of the Harbour Bridge.

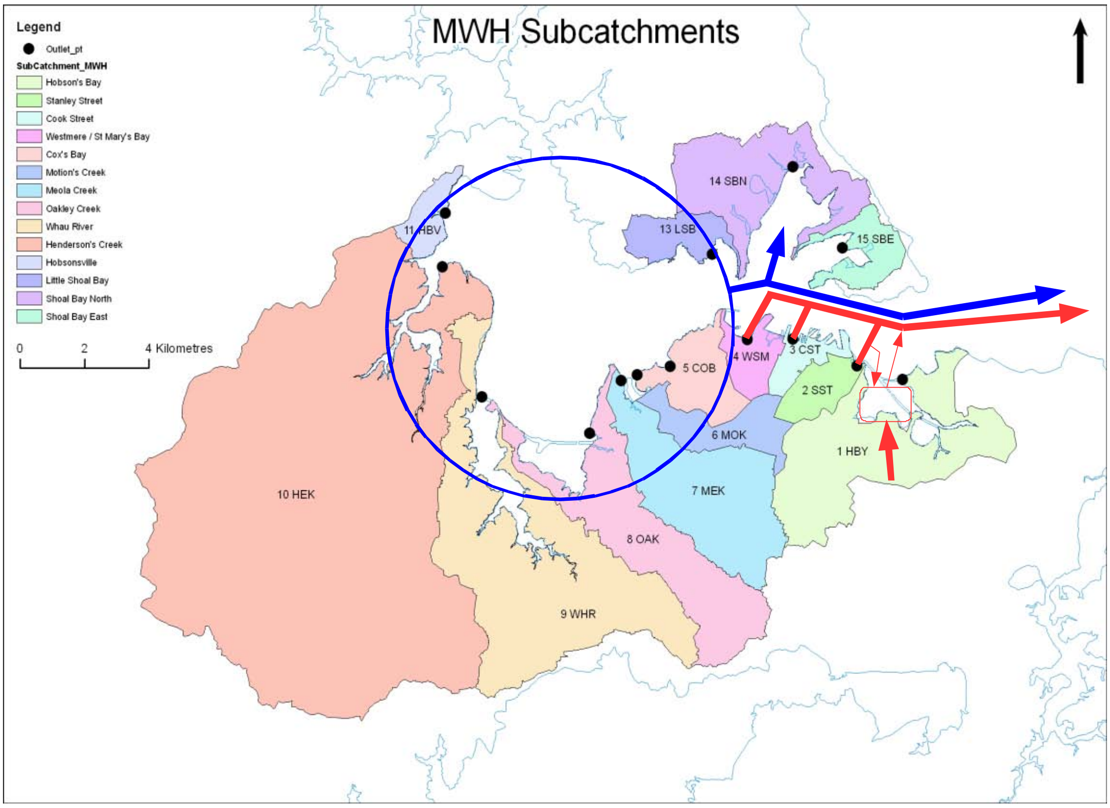


Figure 12
Schematic summarising fate of sediment and metals originating from sub-catchments that discharge to the southern shore of the transition zone between the harbour throat and the main body of the harbour.

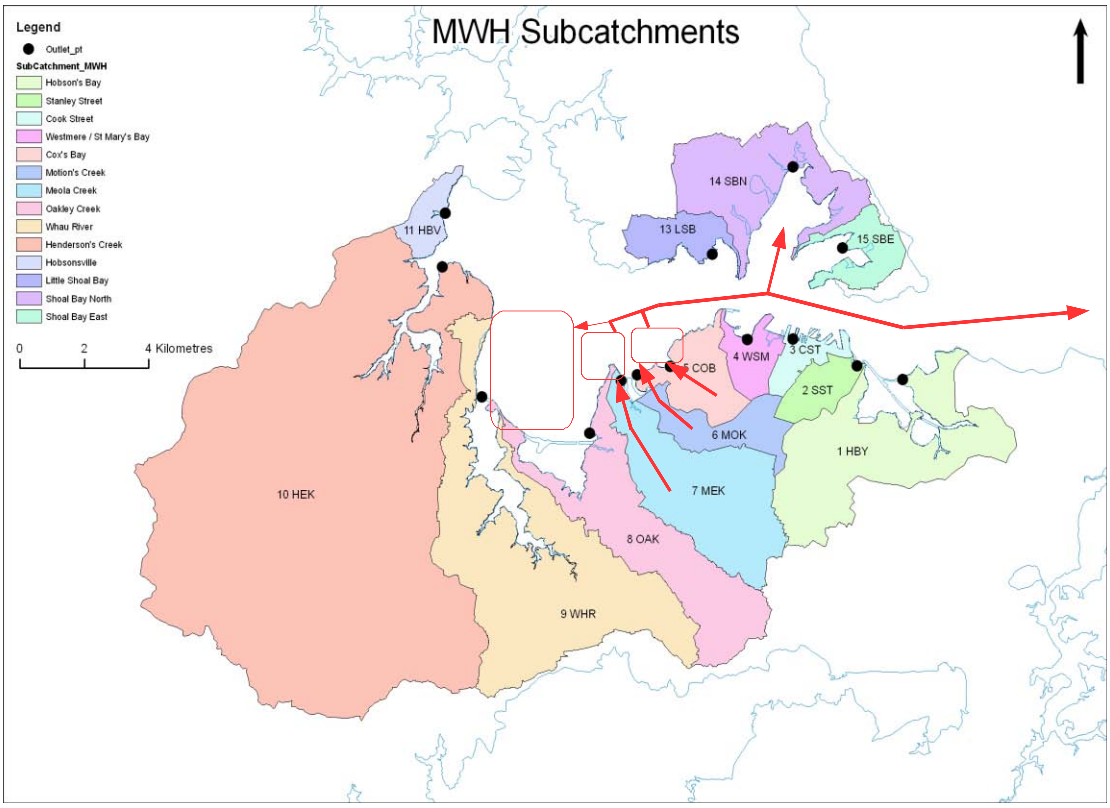


Figure 13

Schematic showing how Te Tokaroa reef prevents sediments and metals from Motions Creek and Meola Creek sub-catchments mixing locally. Further afield to the west they become effectively mixed.

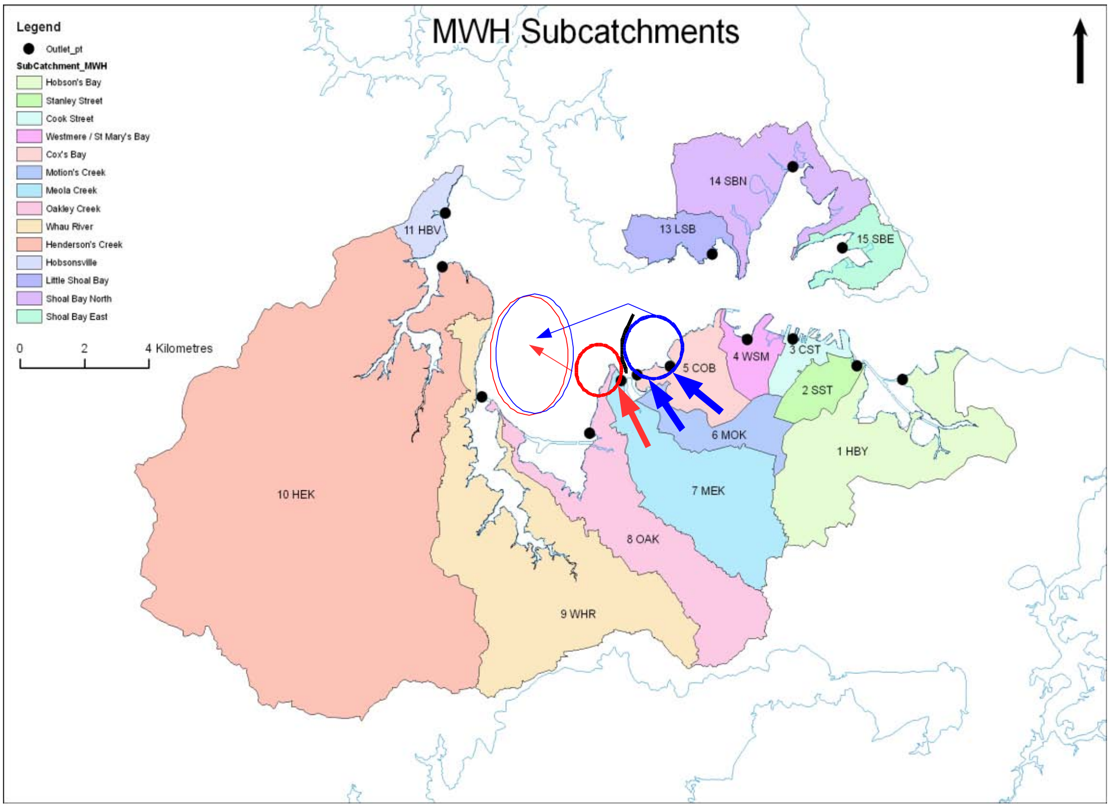


Figure 14
Schematic summarising fate of sediment and metals originating from the Oakley Creek and Whau River sub-catchments.

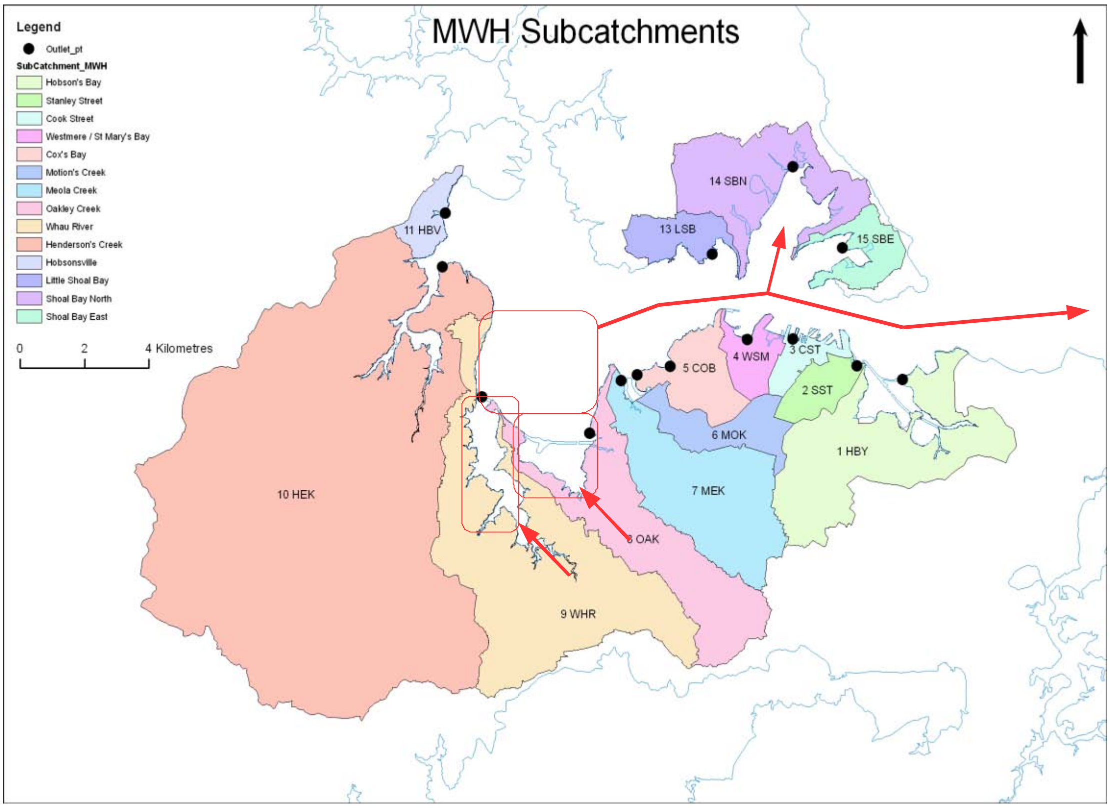


Figure 15

Schematic summarising fate of sediment and metals originating from the Henderson Creek and Hobsonville sub-catchments.

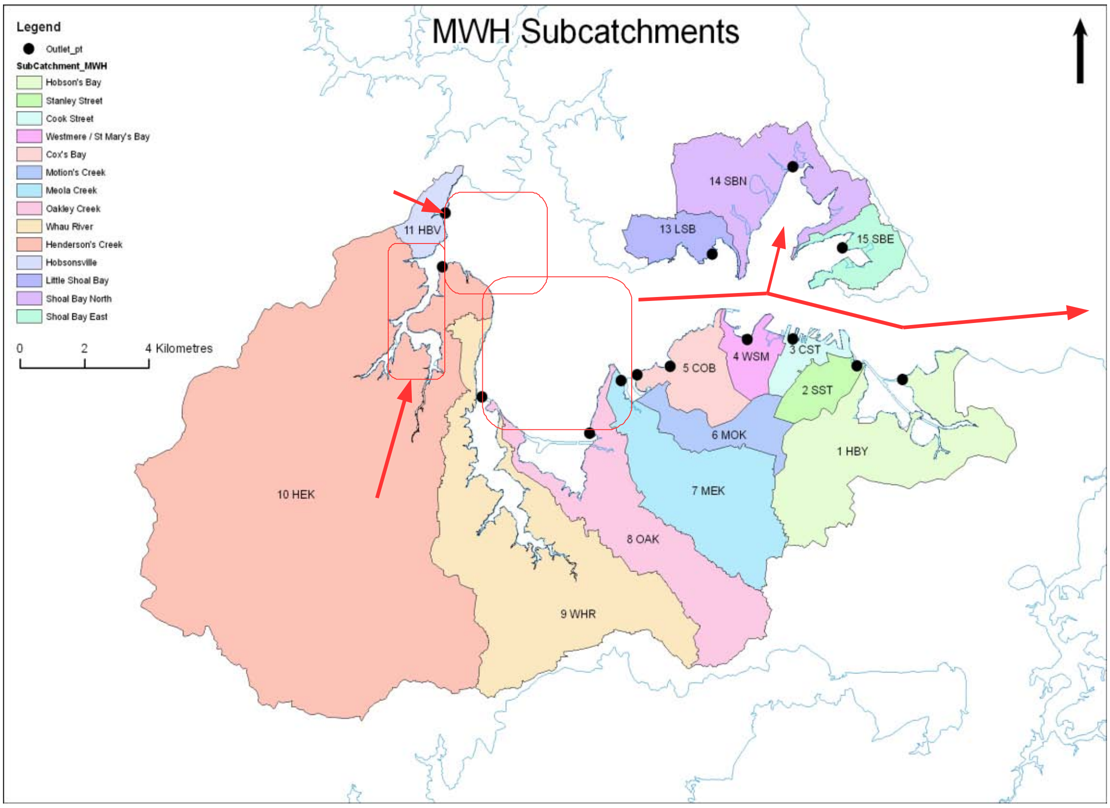


Figure 16

Schematic summarising fate of sediment and metals originating from the Little Shoal Bay, Shoal Bay North and Shoal Bay East sub-catchments.

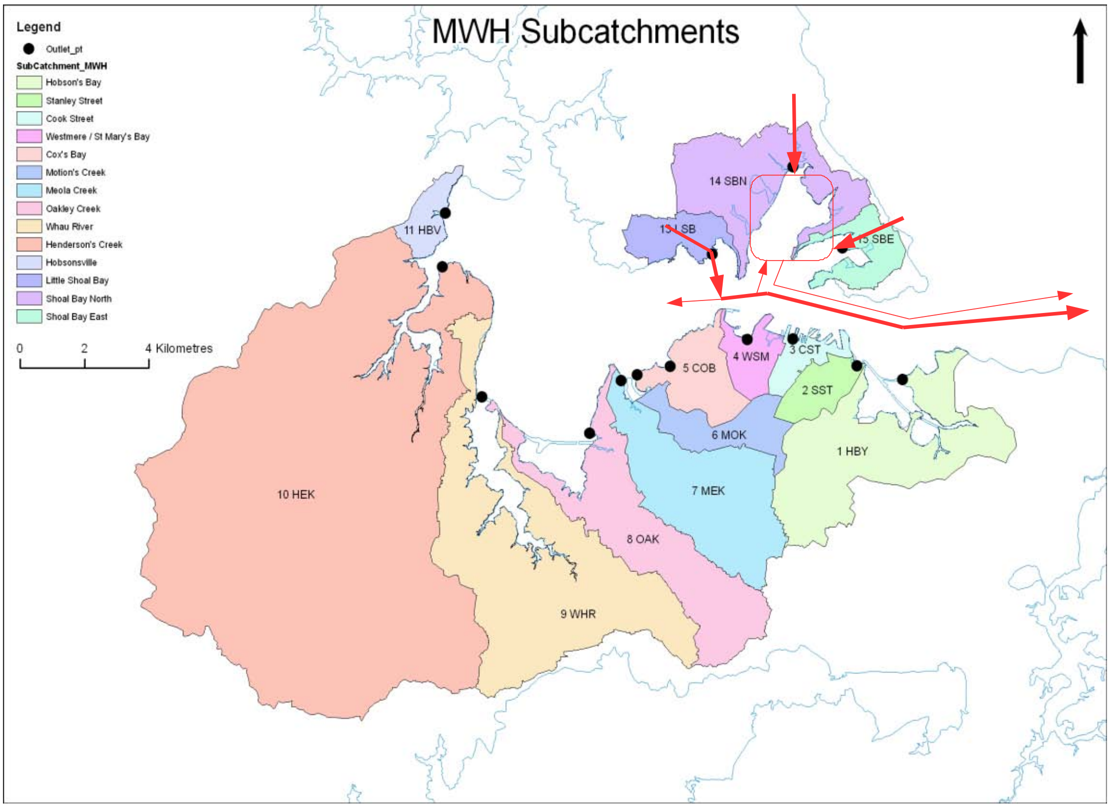


Figure 17

Schematic summarising origin of sediment and metals that deposit in Hobsonville subestuary.

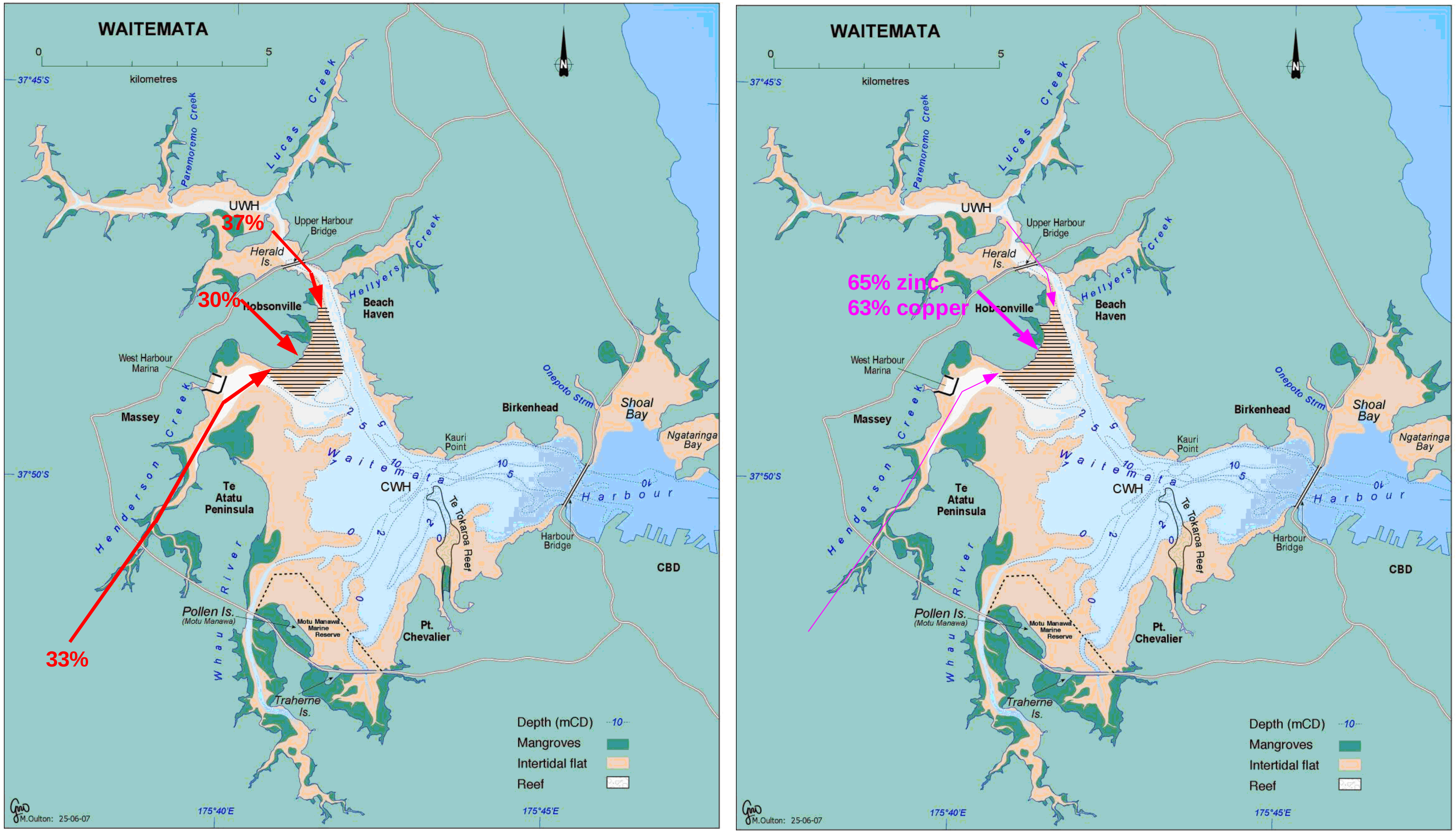


Figure 18

Schematic summarising origin of sediment and metals that deposit in Limeburners Bay subestuary.

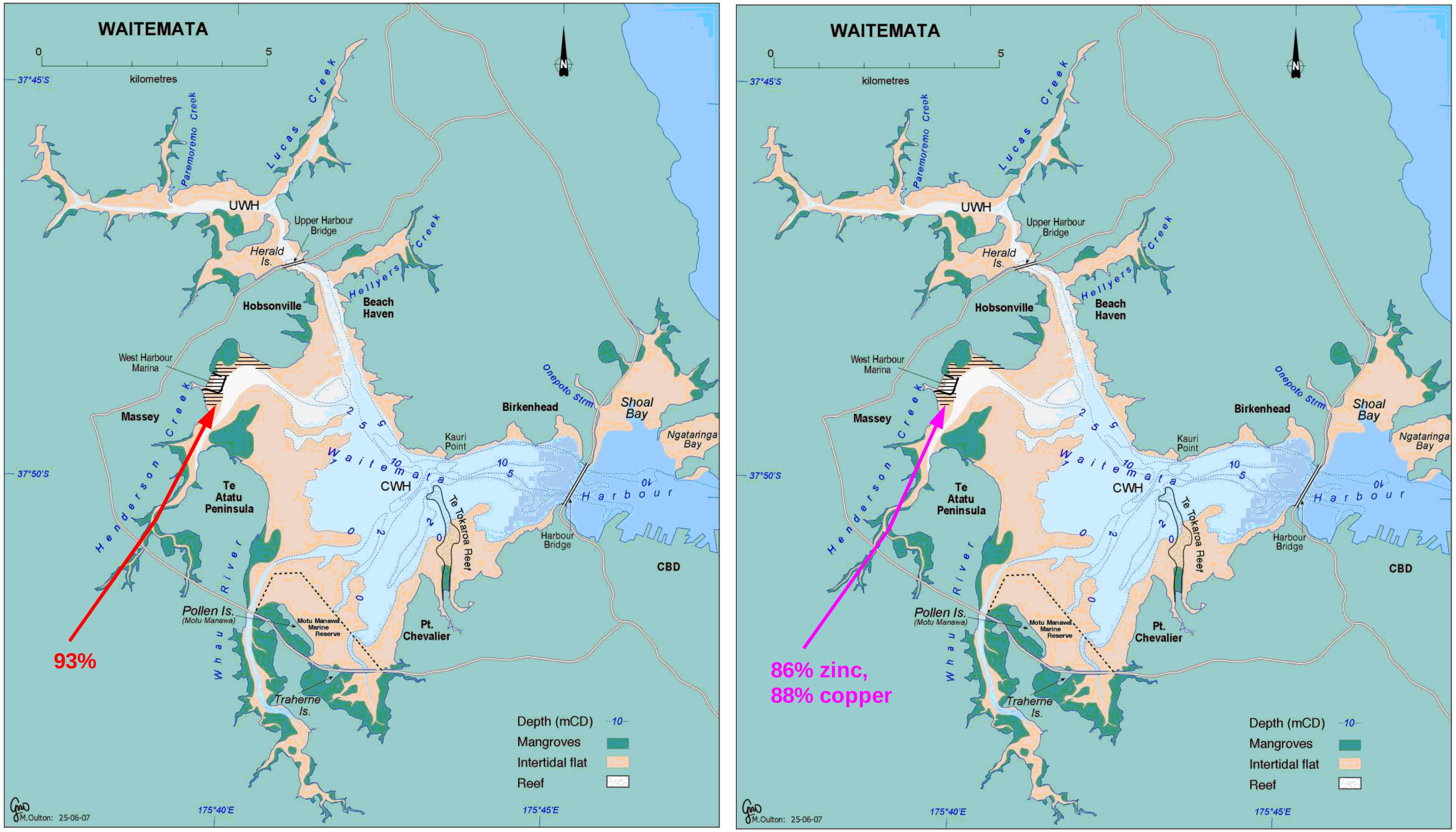


Figure 19

Schematic summarising origin of sediment and metals that deposit in Northwestern Intertidal subestuary.

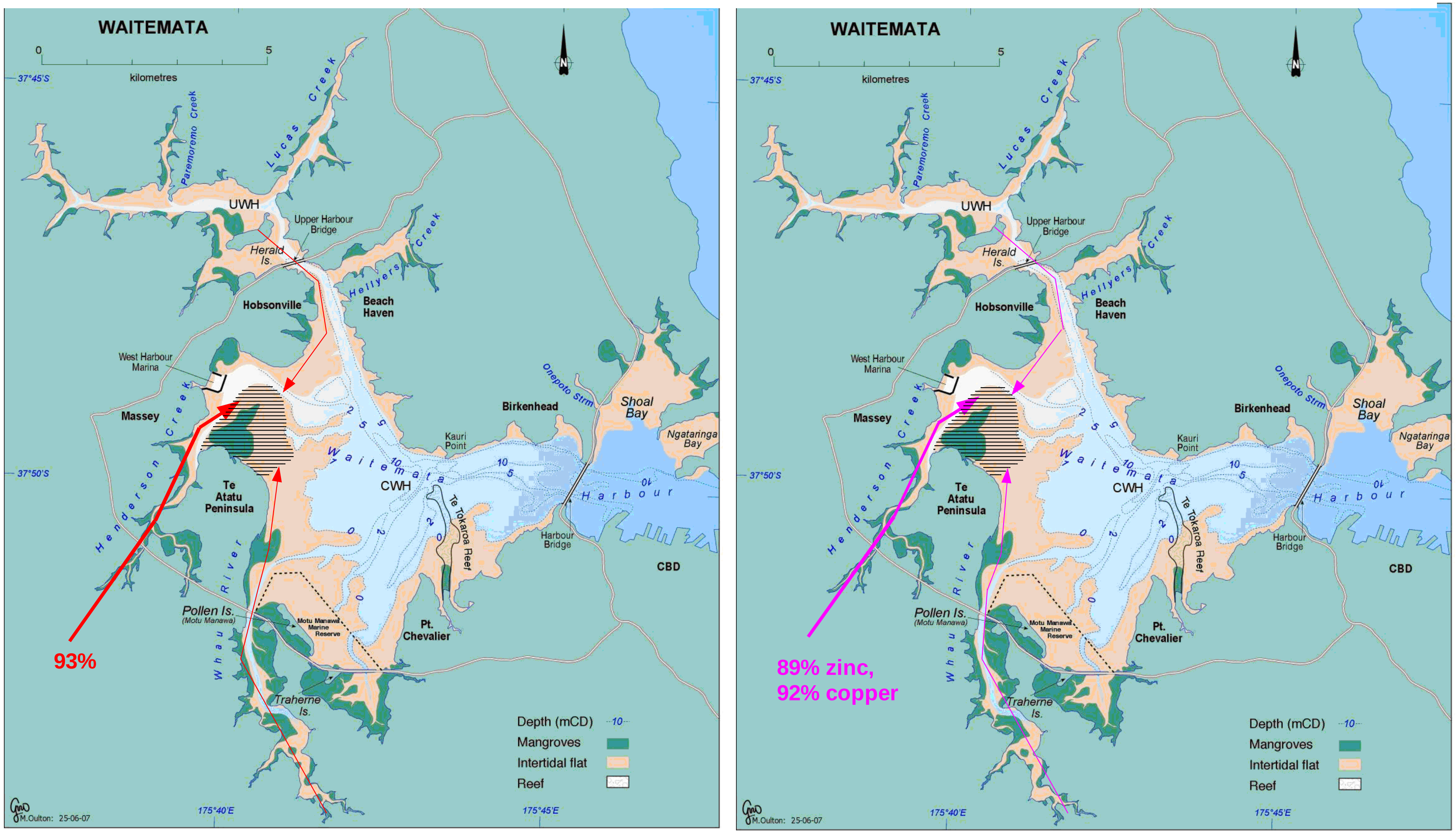


Figure 20

Schematic summarising origin of sediment and metals that deposit in Central Subtidal subestuary.

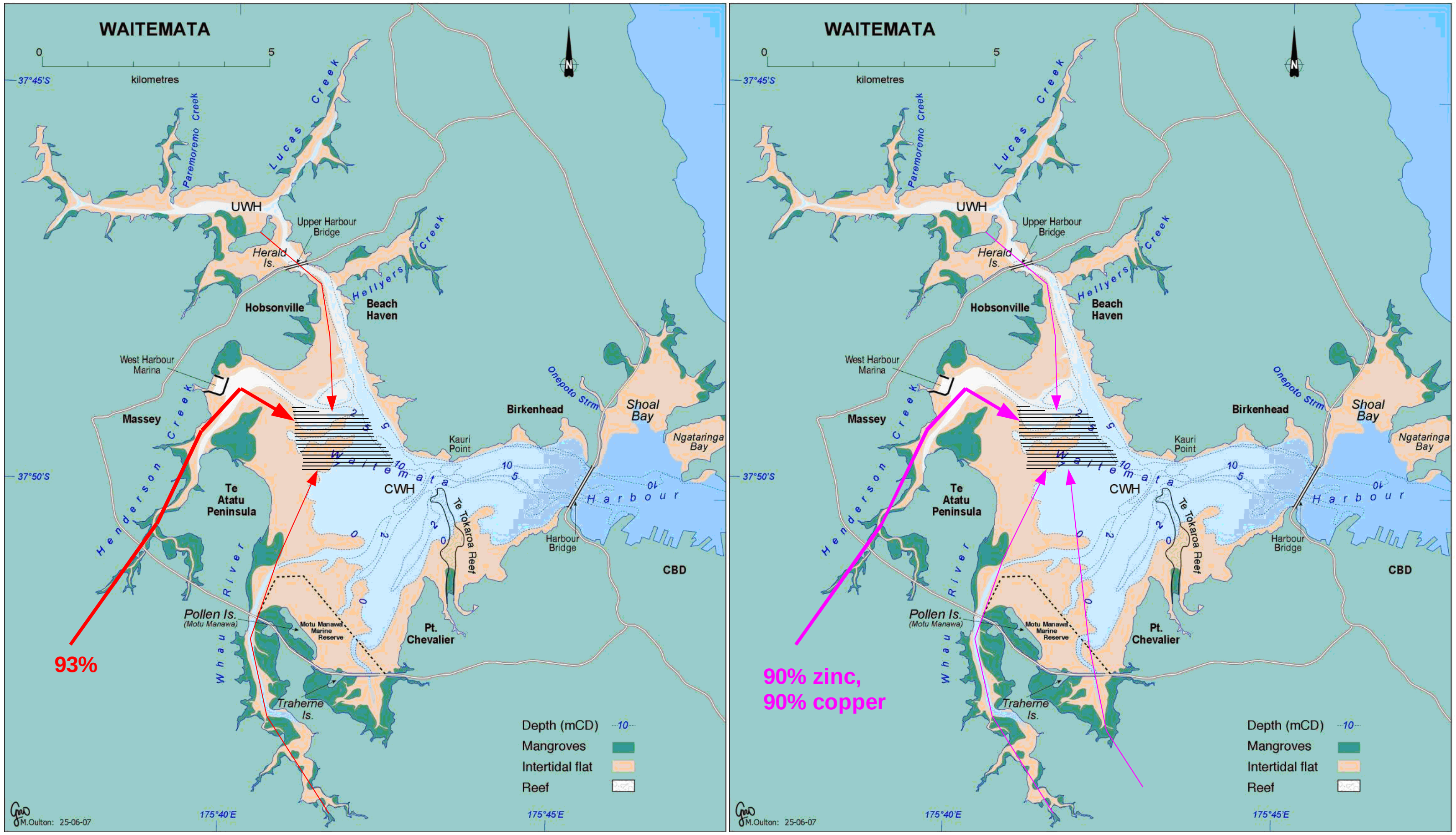
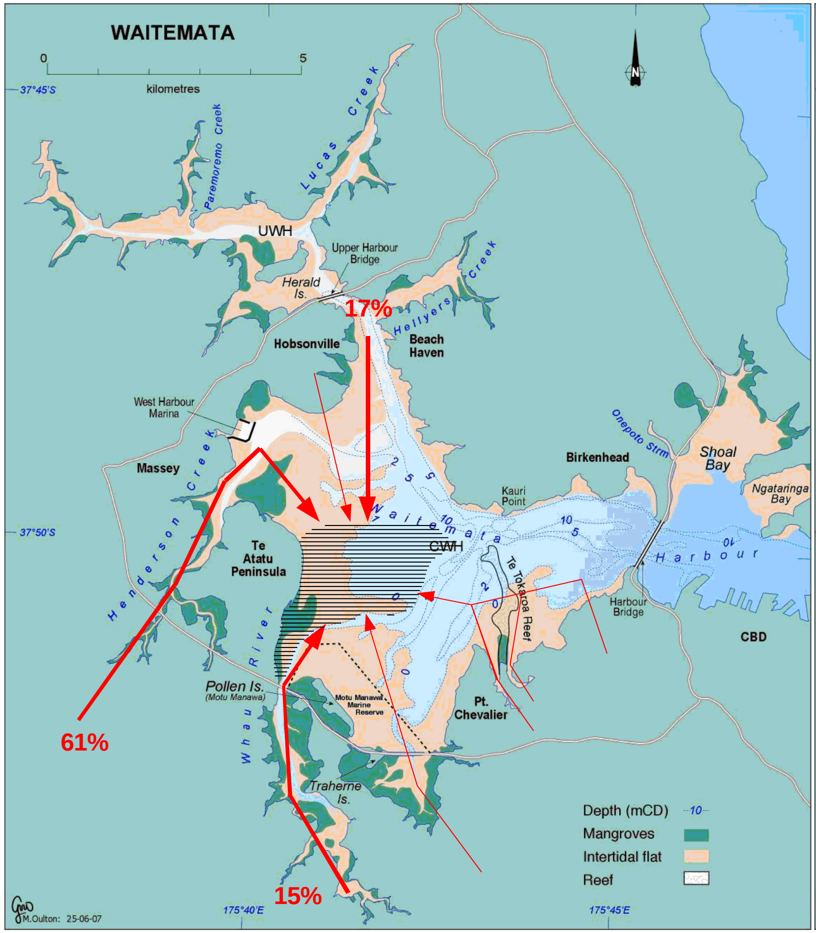


Figure 21

Schematic summarising origin of sediment and metals that deposit in Western Intertidal subestuary.



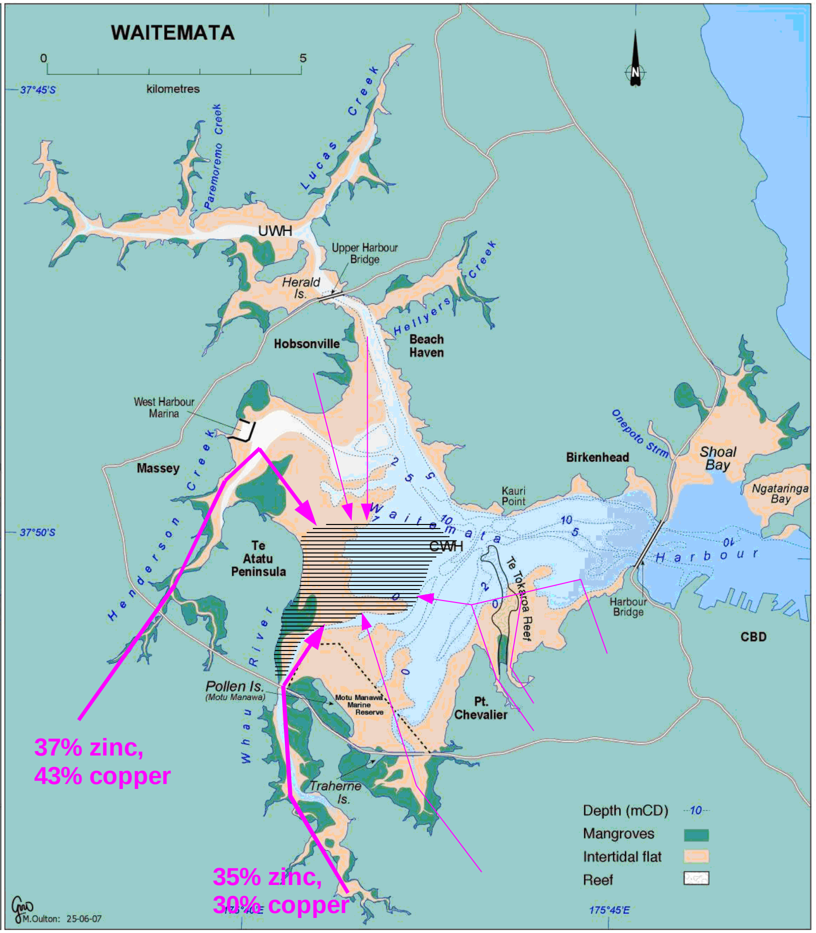


Figure 22

Schematic summarising origin of sediment and metals that deposit in Southwestern Intertidal subestuary.

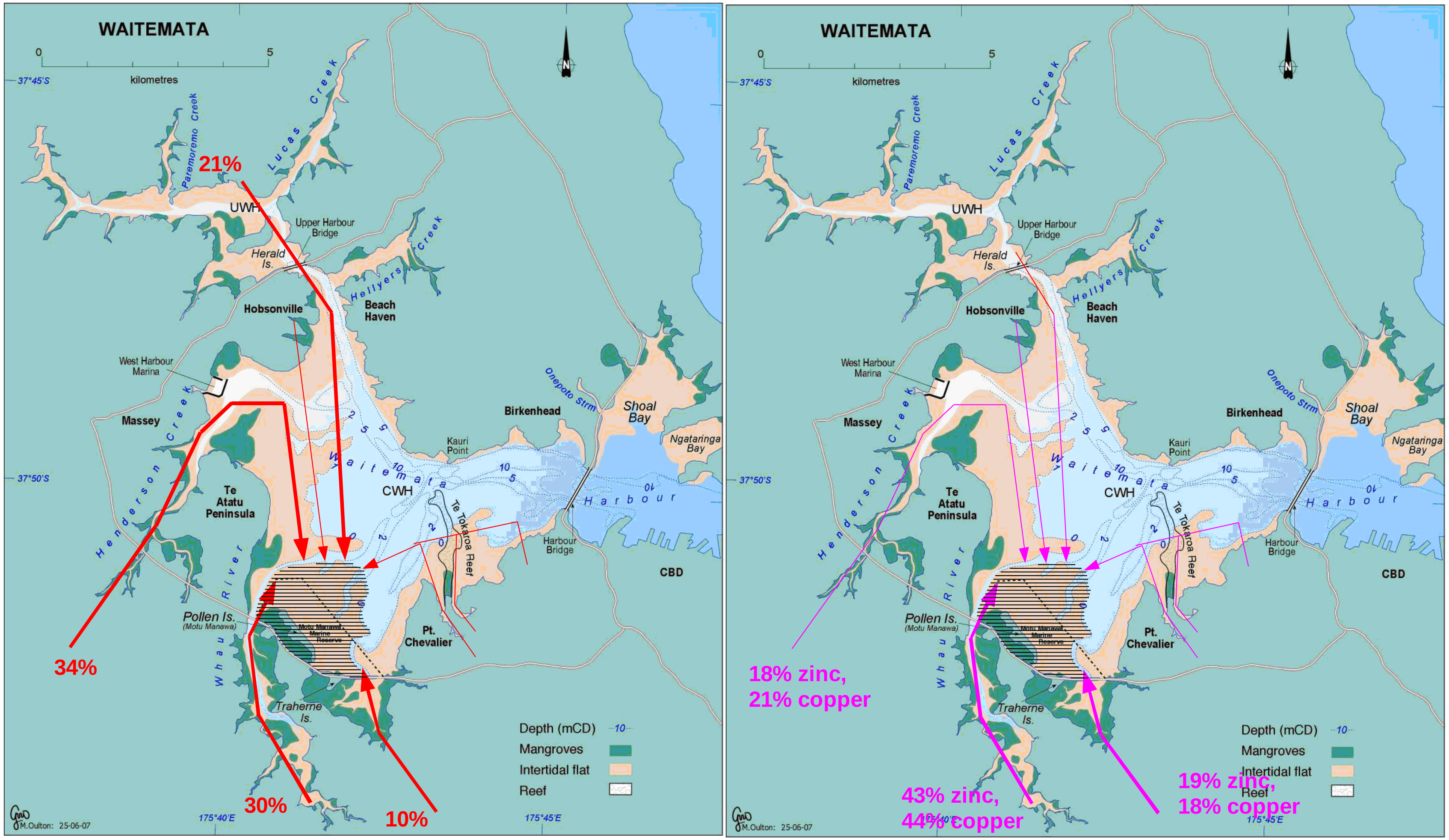


Figure 23

Schematic summarising origin of sediment and metals that deposit in Waterview Flats subestuary.

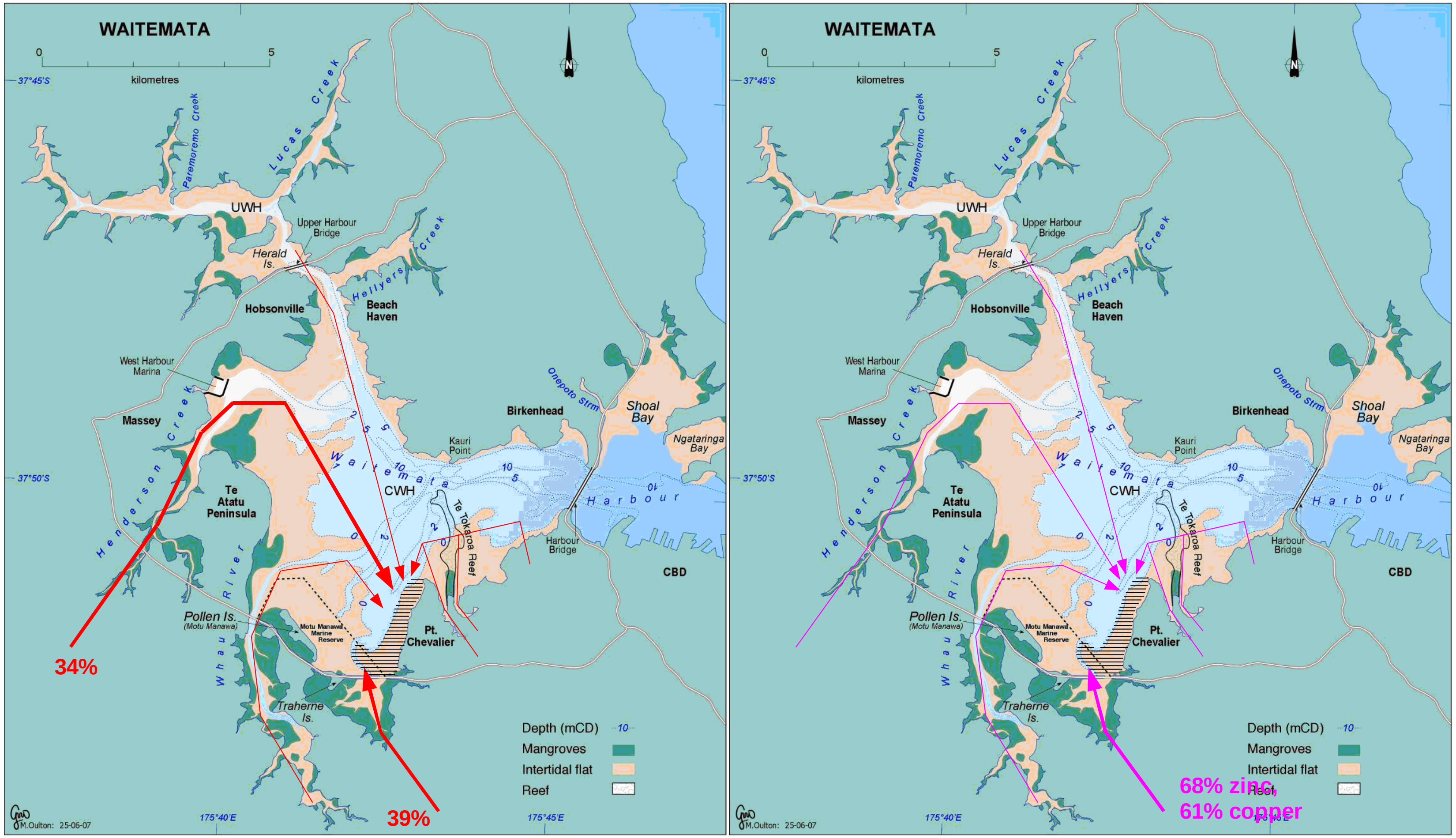


Figure 24

Schematic summarising origin of sediment and metals that deposit in Point Chevalier subestuary.

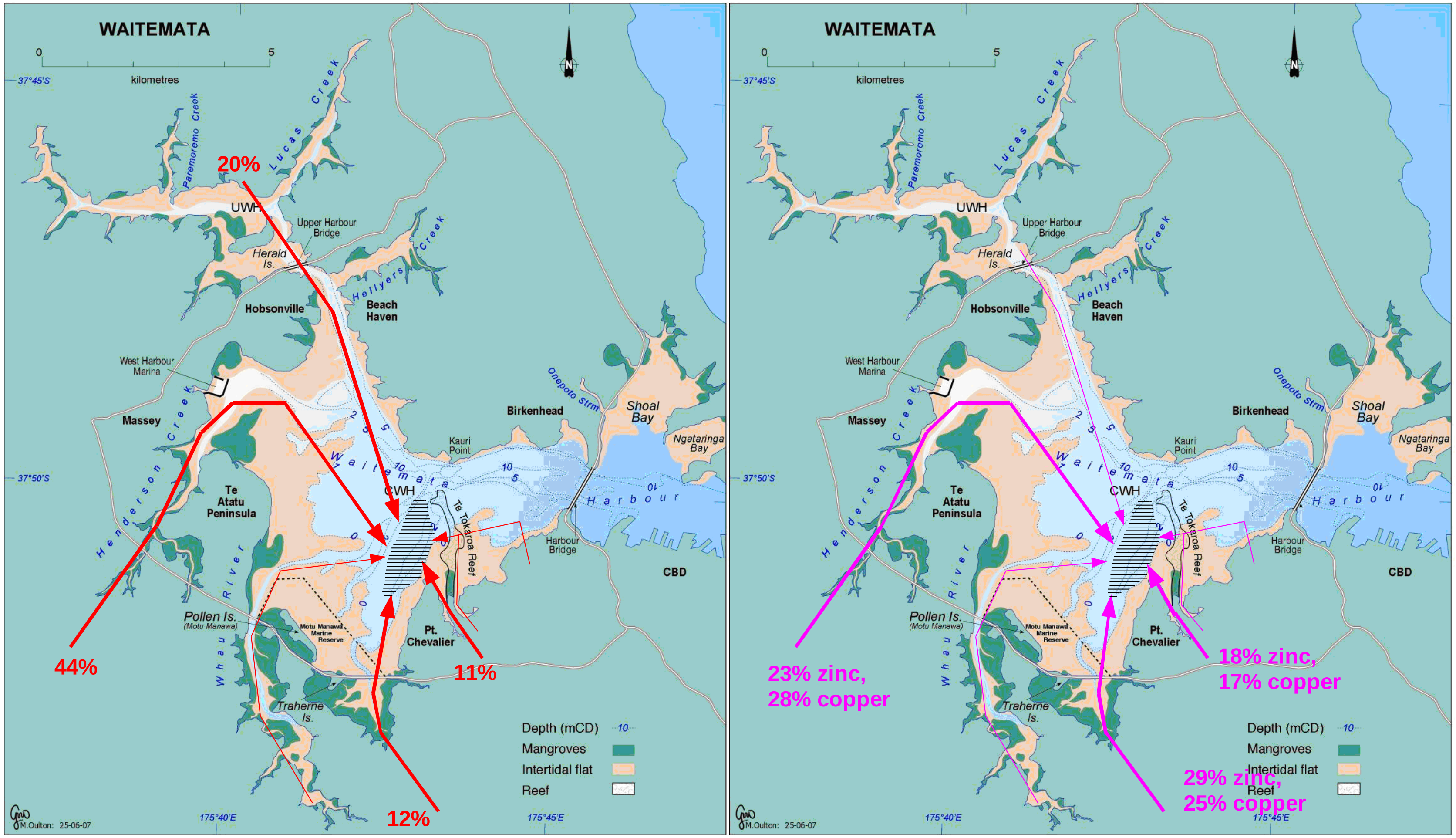


Figure 25

Schematic summarising origin of sediment and metals that deposit in Meola subestuary.

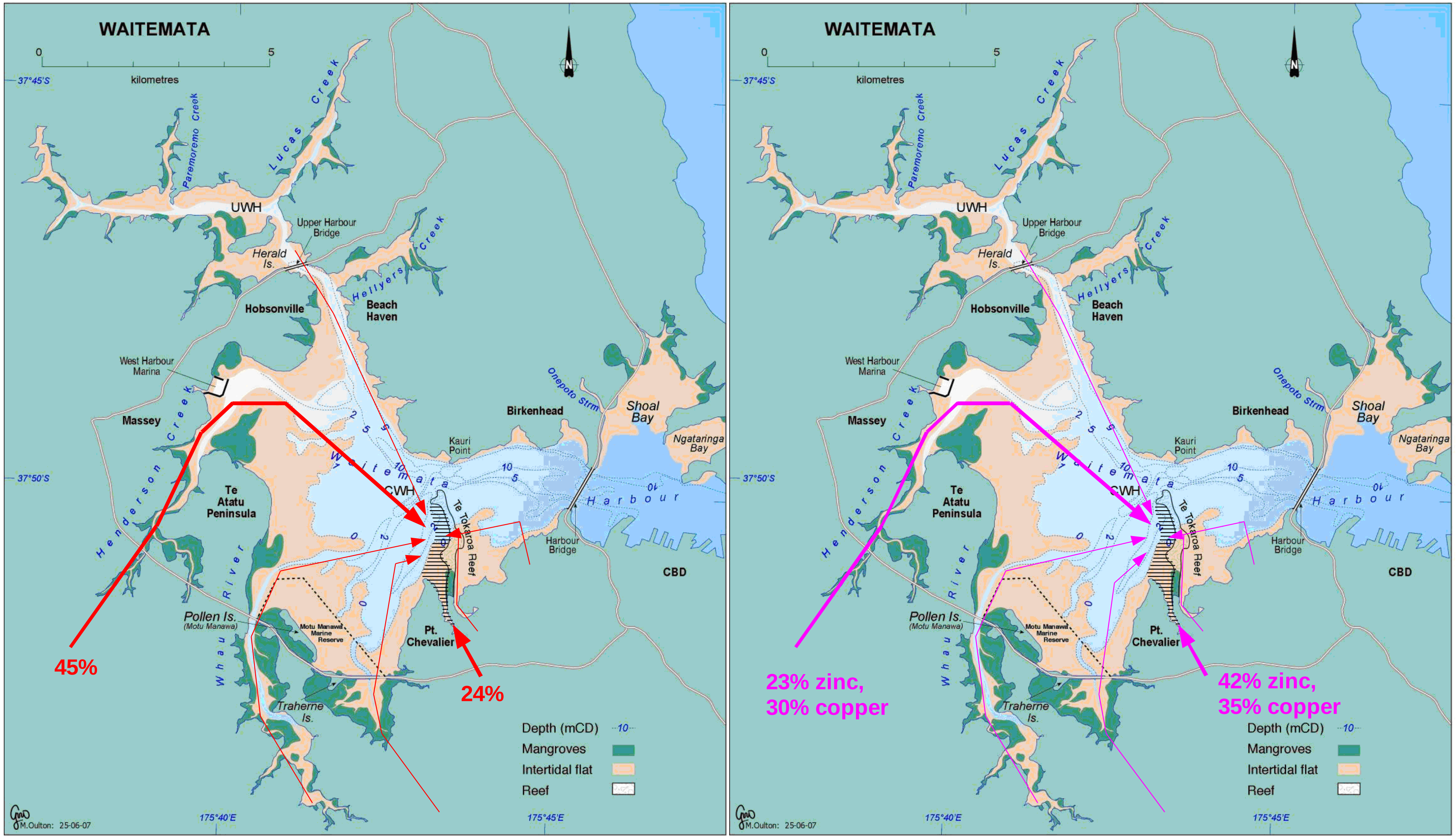


Figure 26

Schematic summarising origin of sediment and metals that deposit in Motions subestuary.

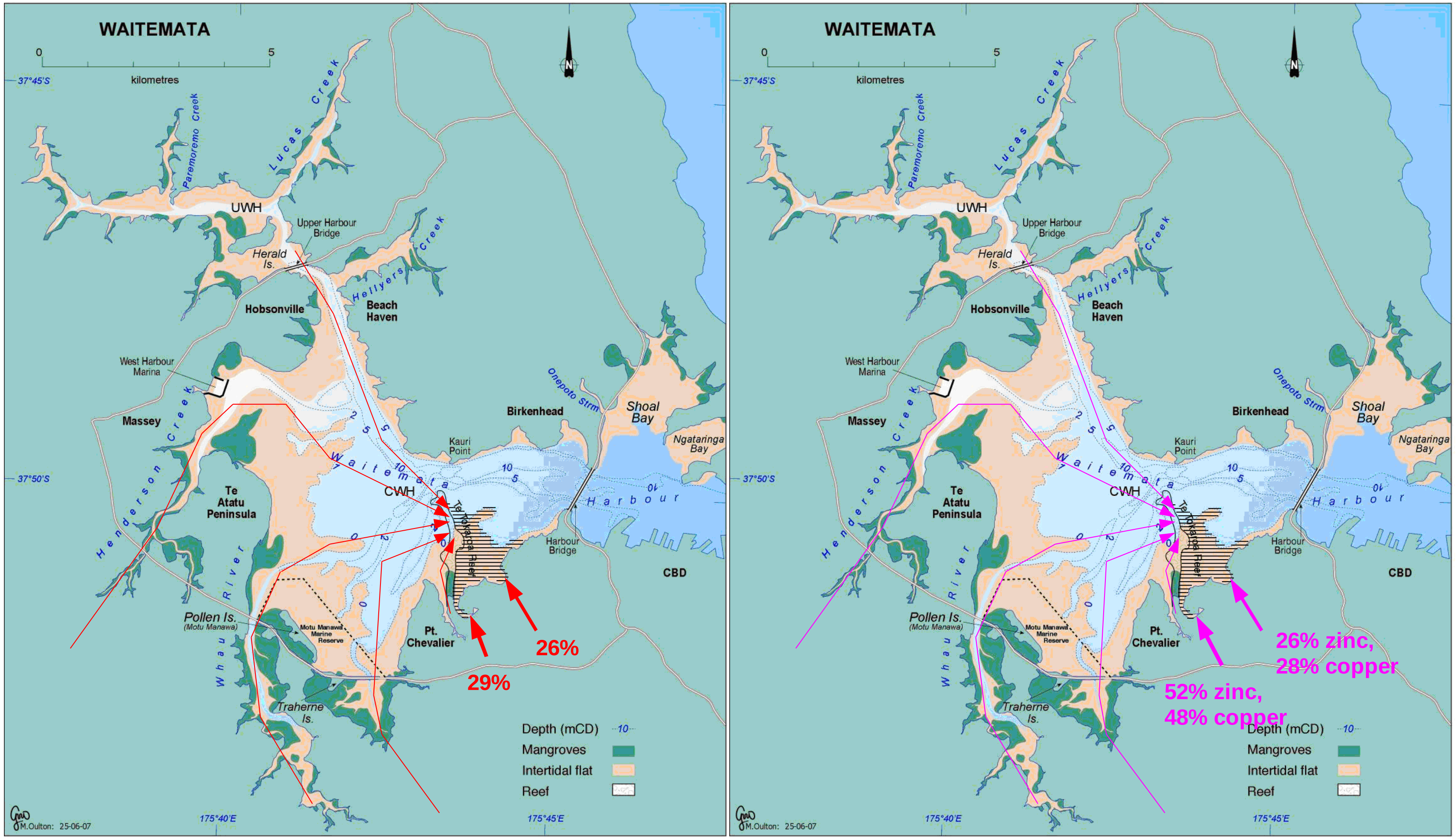


Figure 27

Schematic summarising origin of sediment and metals that deposit in Shoal Bay subestuary.

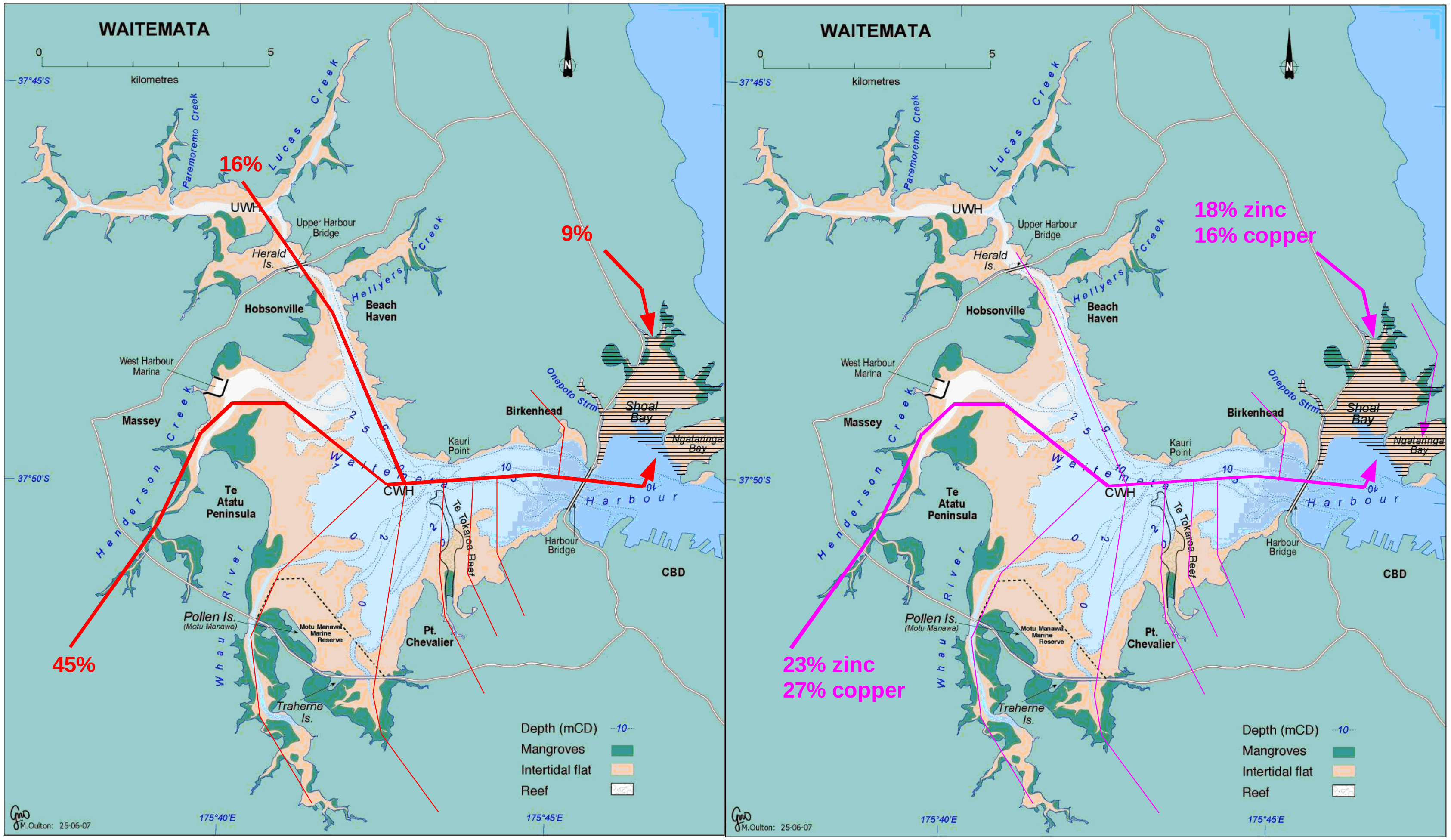
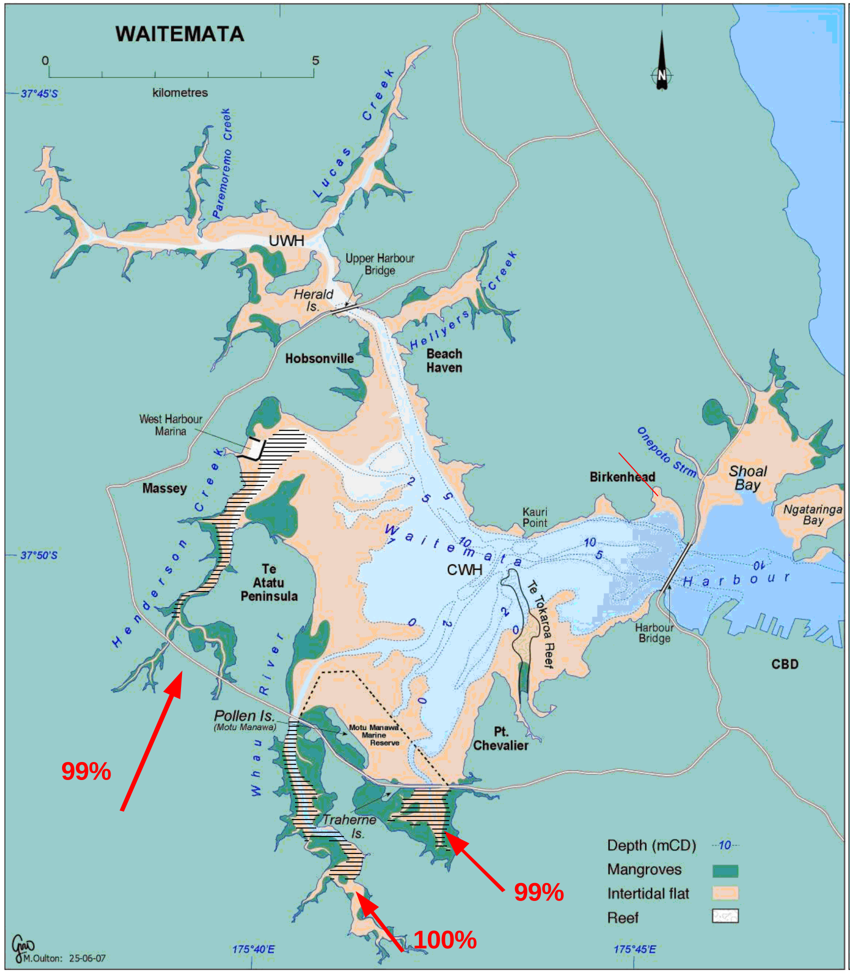


Figure 28

Schematic summarising origin of sediment and metals that deposit in Henderson Creek, Whau River and Waterview Embayment subestuaries.



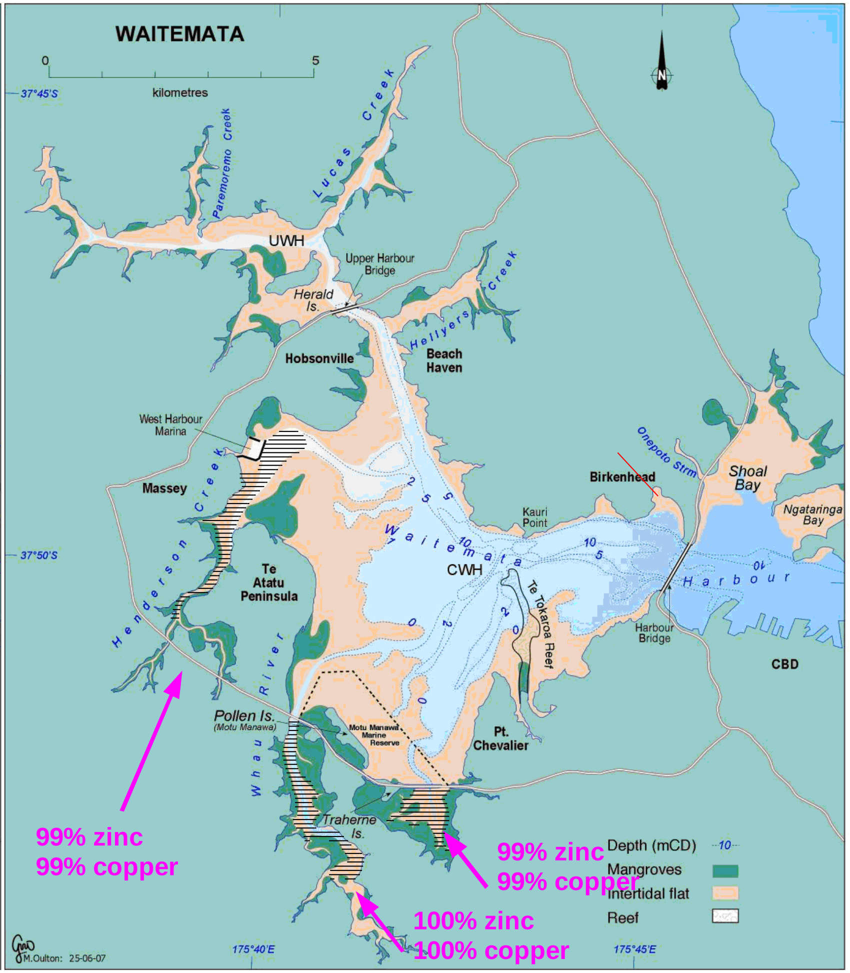


Figure 29
Schematic summarising origin of sediment – all subestuaries.

Figure 30
Schematic summarizing origin of metals – all subestuaries.

Figure 31

Sedimentation (change in height of bed sediment) in each subestuary over the future period under Scenario 1. This is the average over 50 model runs in the Monte Carlo package.

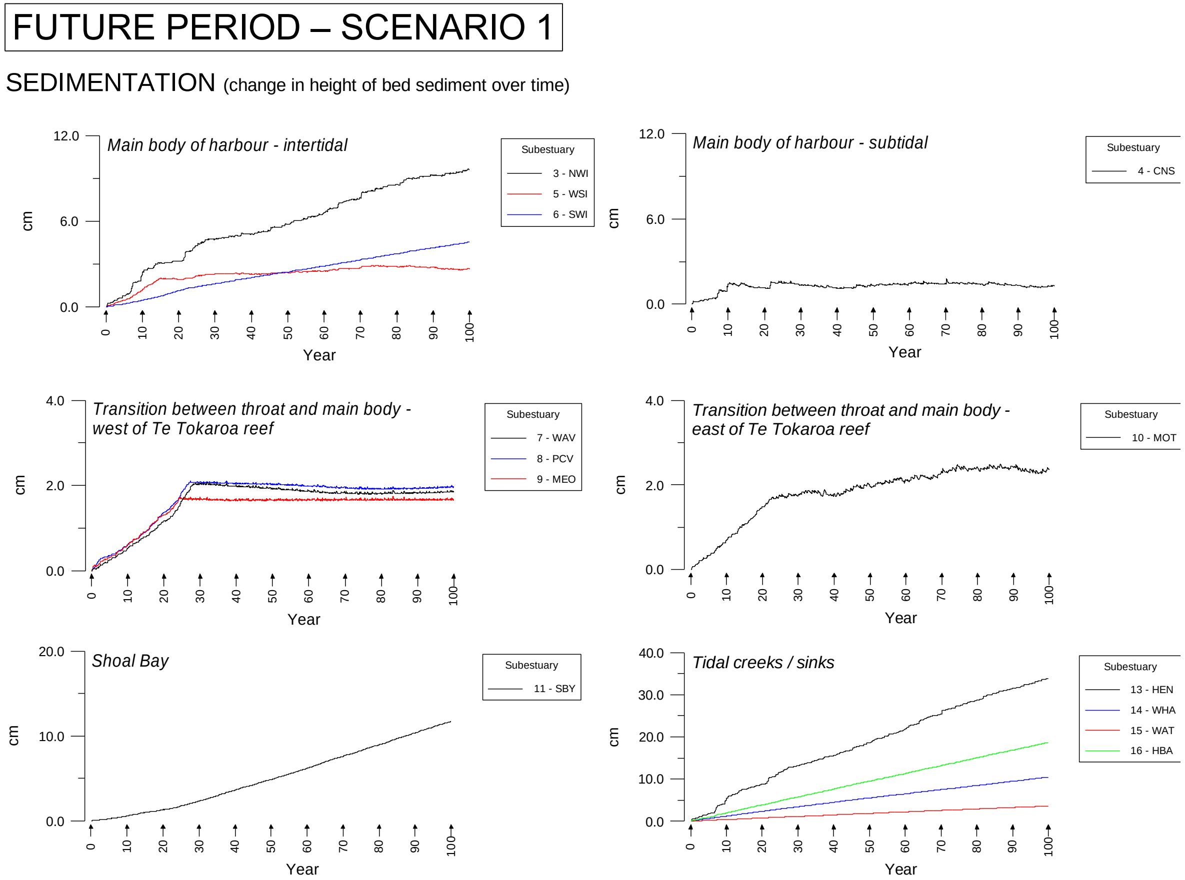


Figure 32

Annual sediment run-off from all sub-catchments combined over the future period, as it appears for just one USC model run in the Monte Carlo package of 50 USC model runs. This is the total sediment (rural plus urban), and the sum of all particle sizes. Year 1 is 2001 and year 100 is 2100.

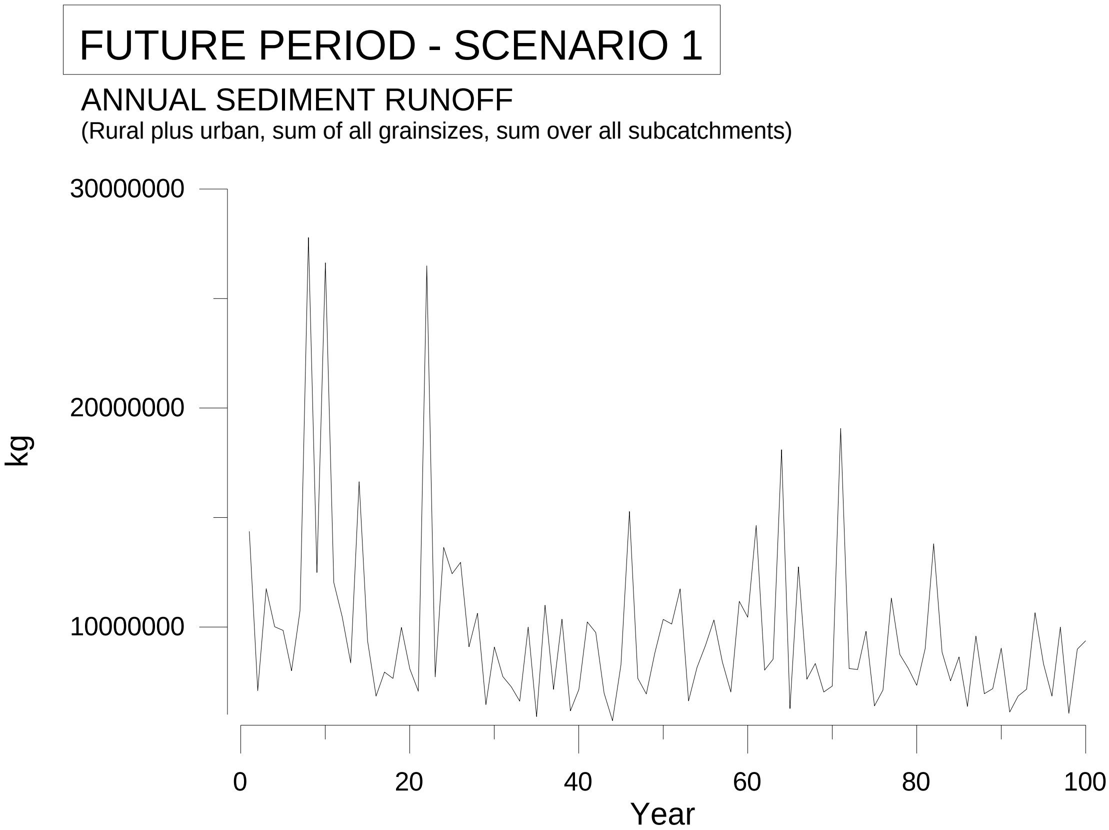


Figure 33

Schematic showing changes in sedimentation in the future period under Scenario 1 caused by a widespread reduction in sediment run-off from the catchment.

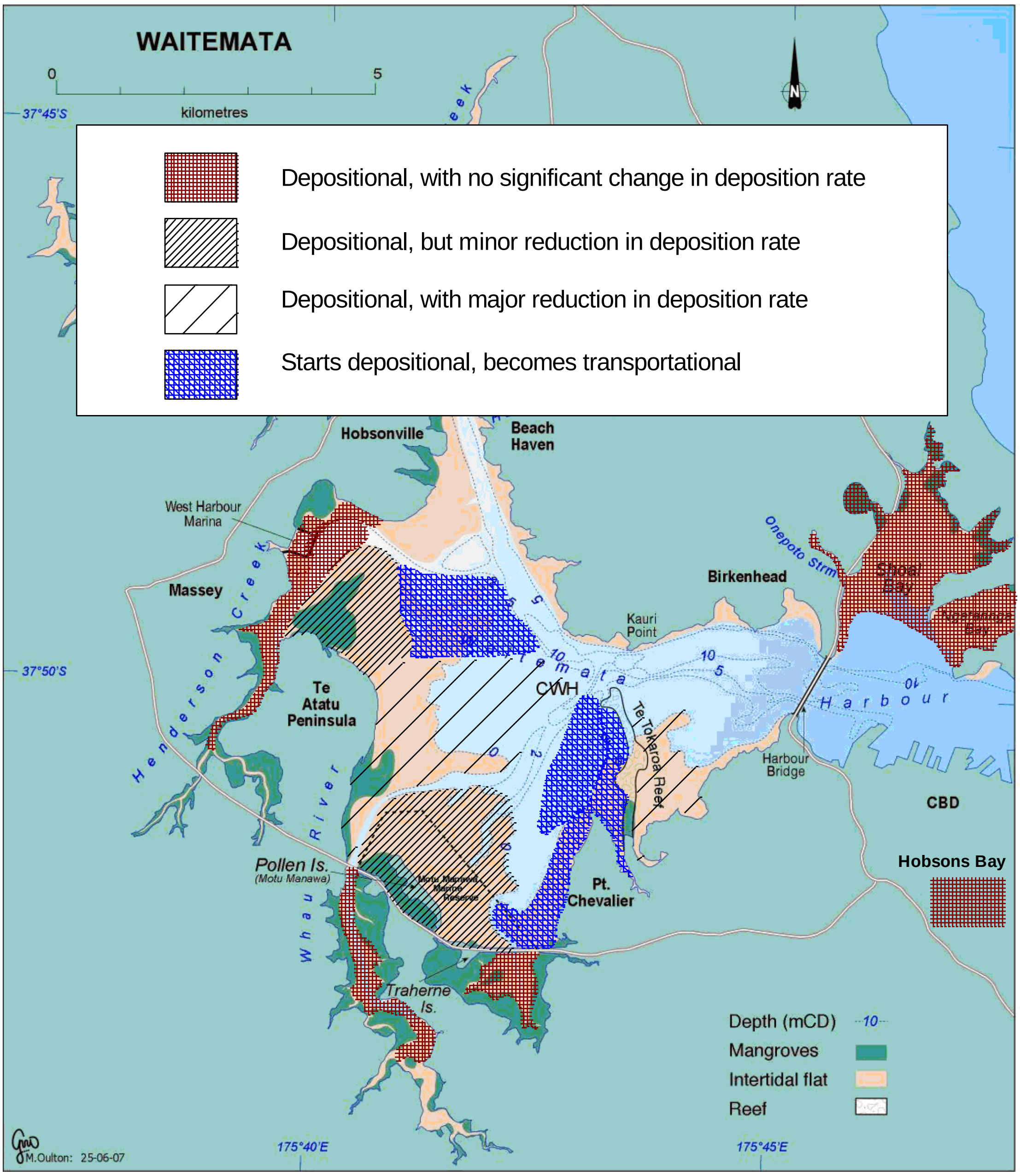


Figure 34

Predicted change in metal concentration for the future period under Scenario 1 for subestuaries that experience a virtually constant sedimentation rate throughout the period. Year 1 is 2001 and year 100 is 2101. Metal concentration is total metal per total sediment in the surface mixed layer.

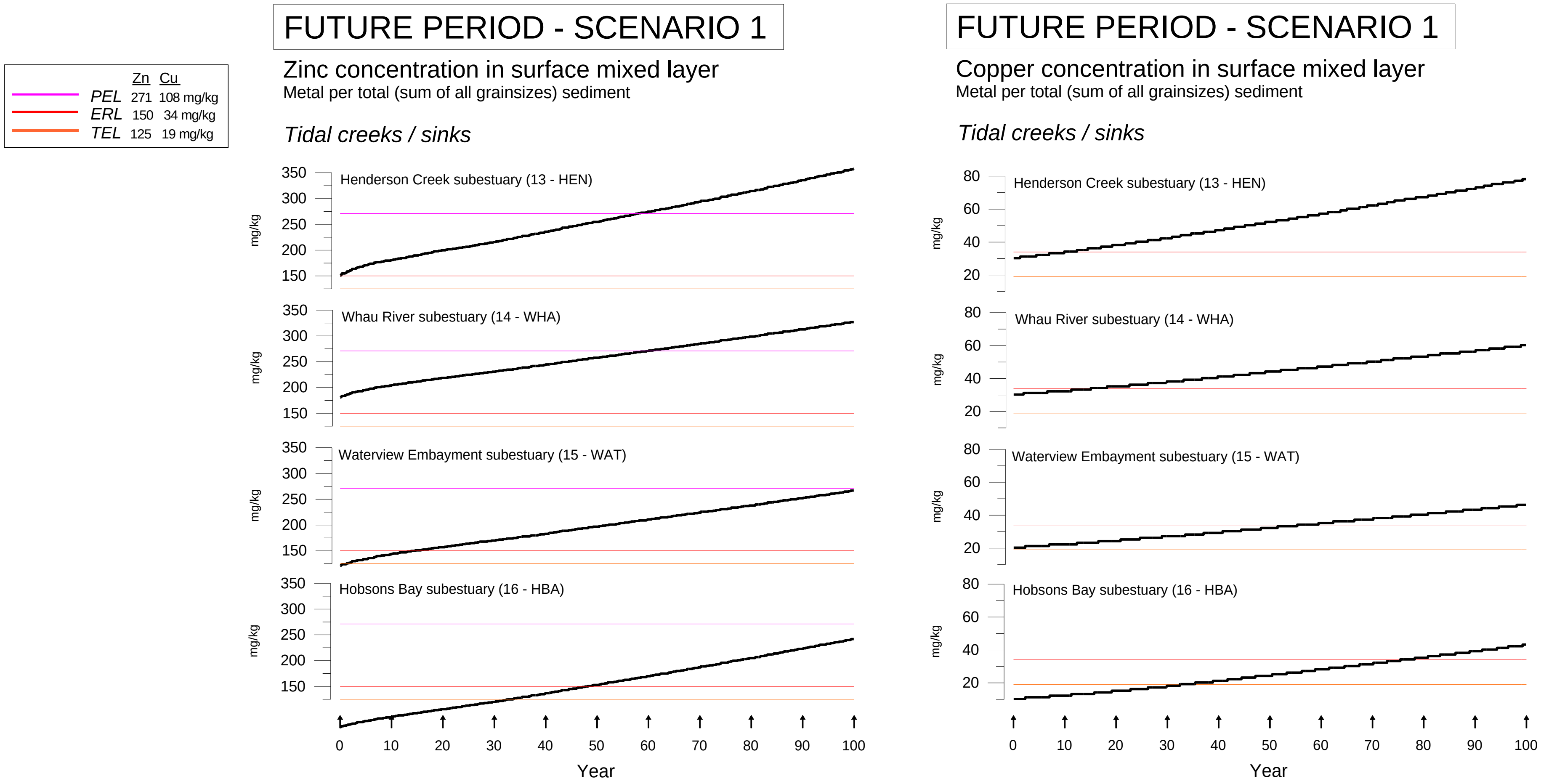


Figure 34 (cont.)
Predicted change in metal concentration for the future period under Scenario 1 for subestuaries that experience a virtually constant sedimentation rate throughout the period. Year 1 is 2001 and year 100 is 2101. Metal concentration is total metal per total sediment in the surface mixed layer.

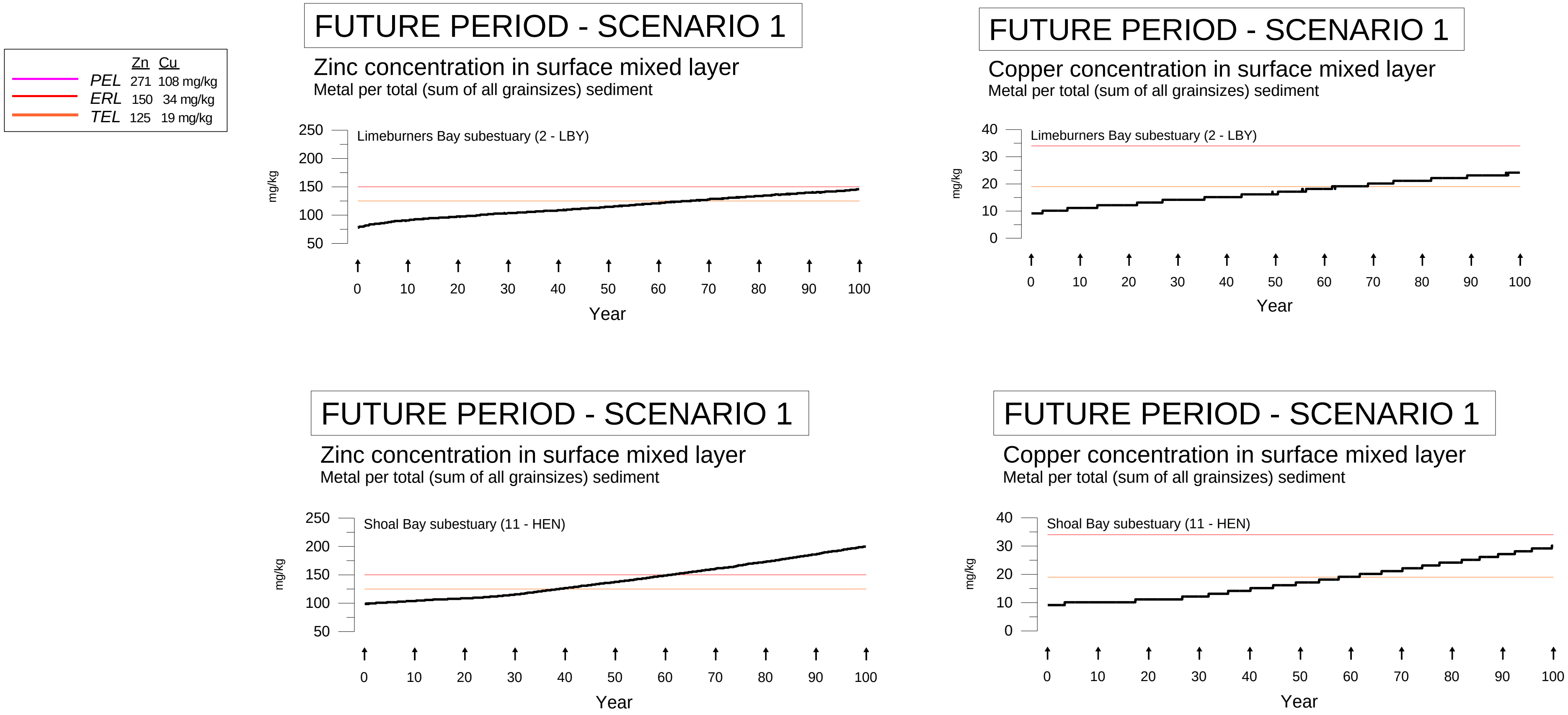


Figure 35

Predicted change in metal concentration for the future period under Scenario 1 for subestuaries that remain depositional but experience a decrease in sedimentation rate partway through the period. Year 1 is 2001 and year 100 is 2101. Metal concentration is total metal per total sediment in the surface mixed layer.

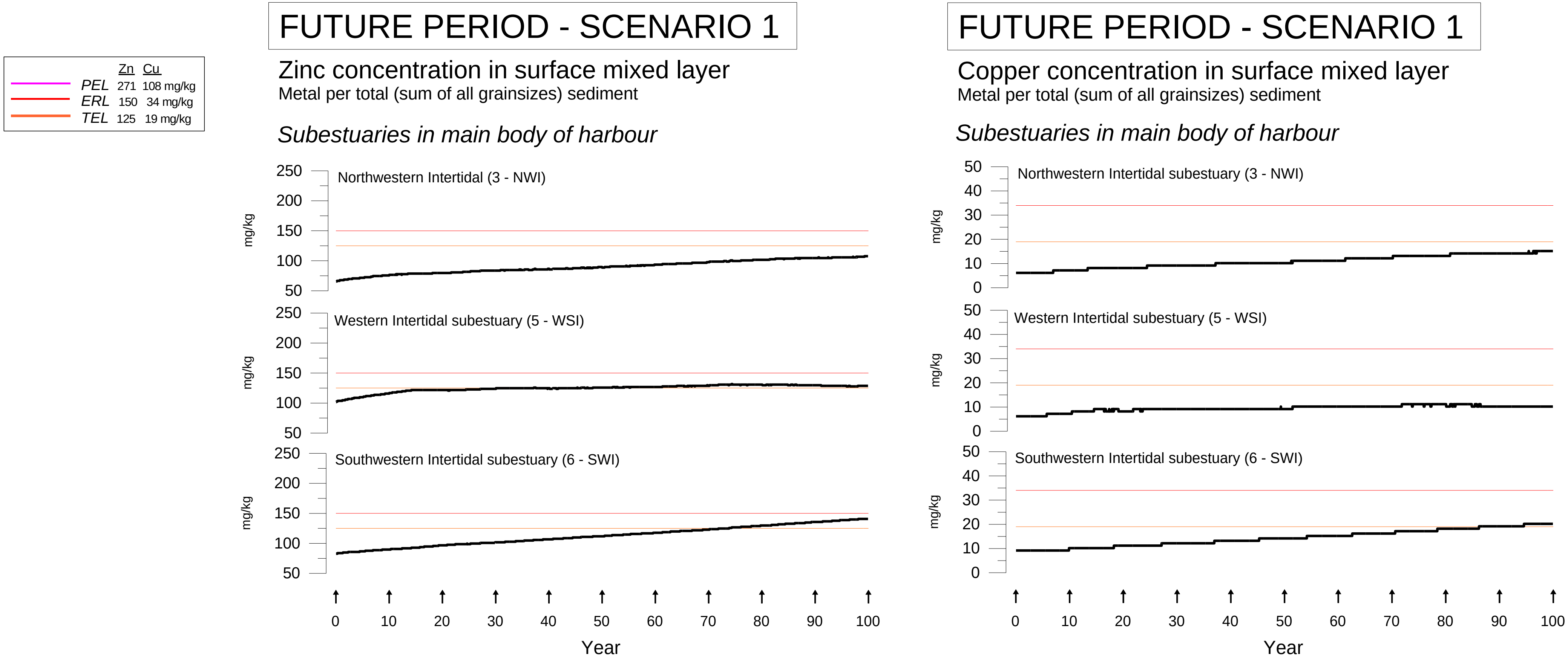


Figure 35 (cont.)
Predicted change in metal concentration for the future period under Scenario 1 for subestuaries that remain depositional but experience a decrease in sedimentation rate partway through the period. Year 1 is 2001 and year 100 is 2101. Metal concentration is total metal per total sediment in the surface mixed layer.

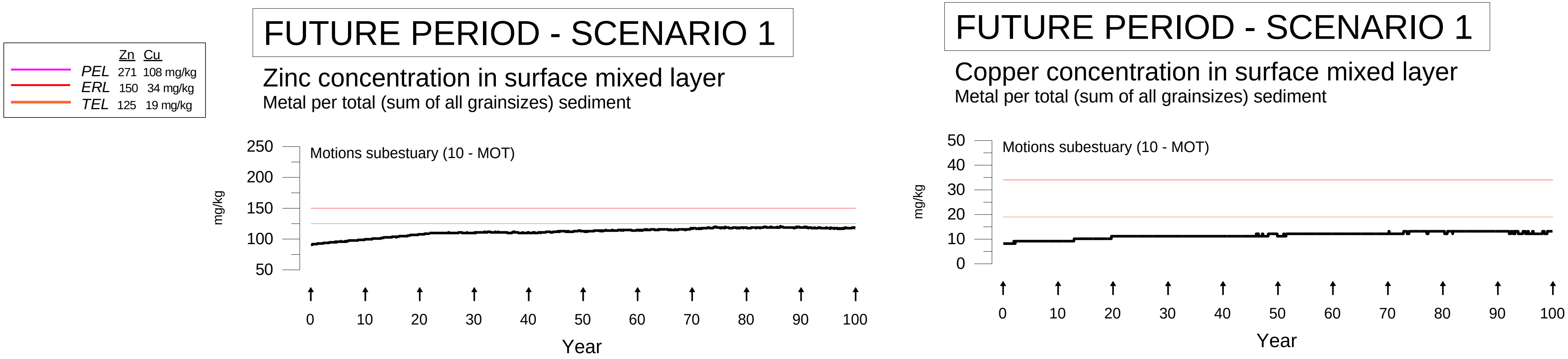


Figure 36
Predicted change in metal concentration for the future period under Scenario 1 for subestuaries that become transportational partway through the period. Year 1 is 2001 and year 100 is 2101. Metal concentration is total metal per total sediment in the surface mixed layer.

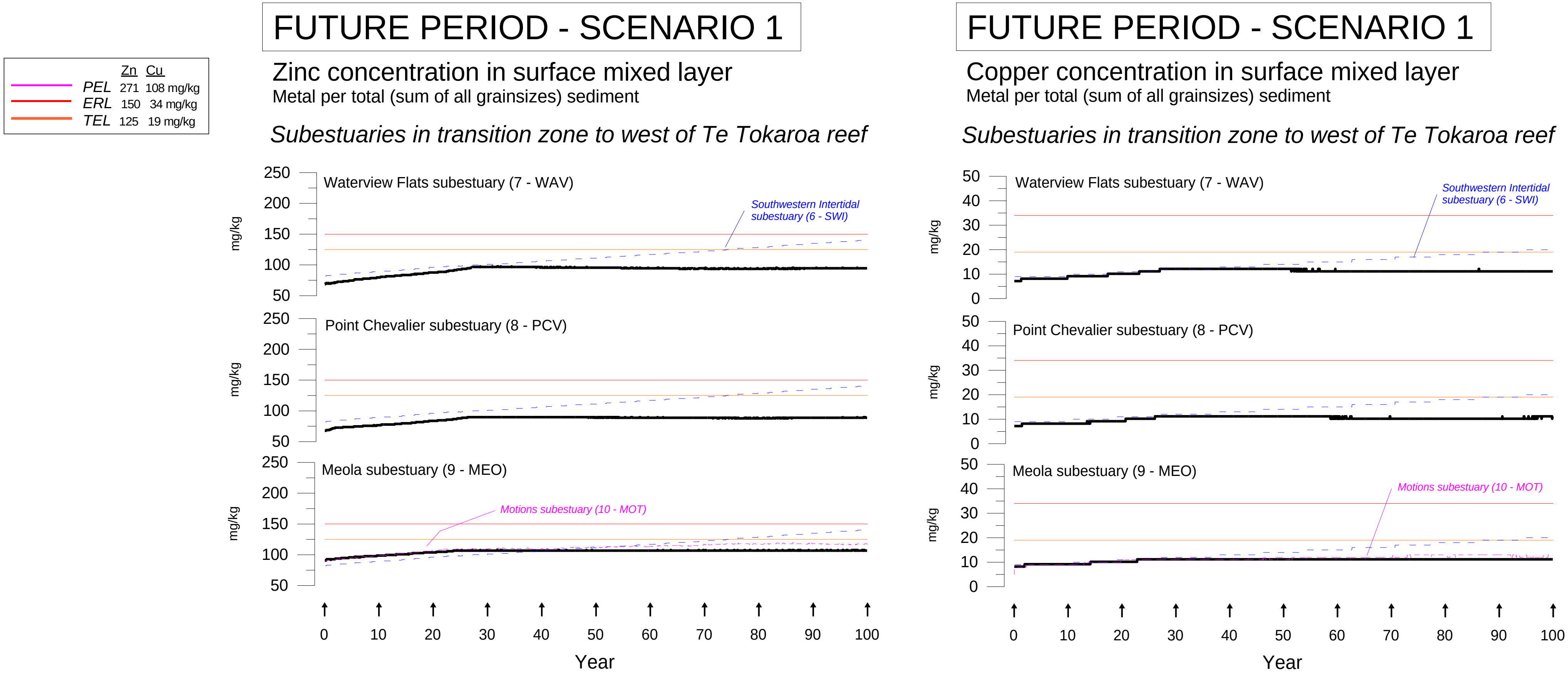
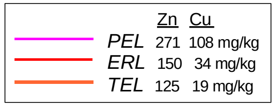
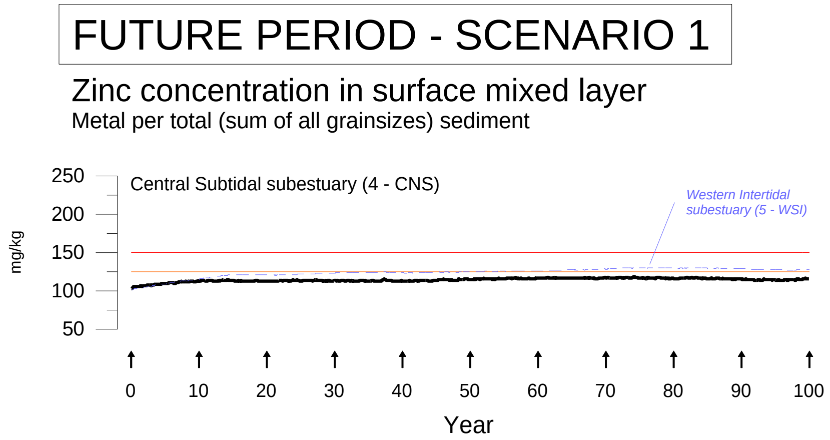


Figure 36 (cont.)
Predicted change in metal concentration for the future period under Scenario 1 for subestuaries that become transportational partway through the period. Year 1 is 2001 and year 100 is 2101. Metal concentration is total metal per total sediment in the surface mixed layer.





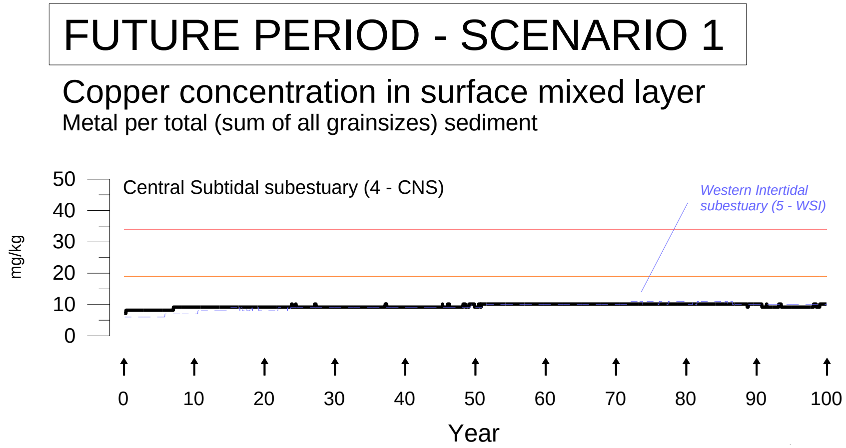
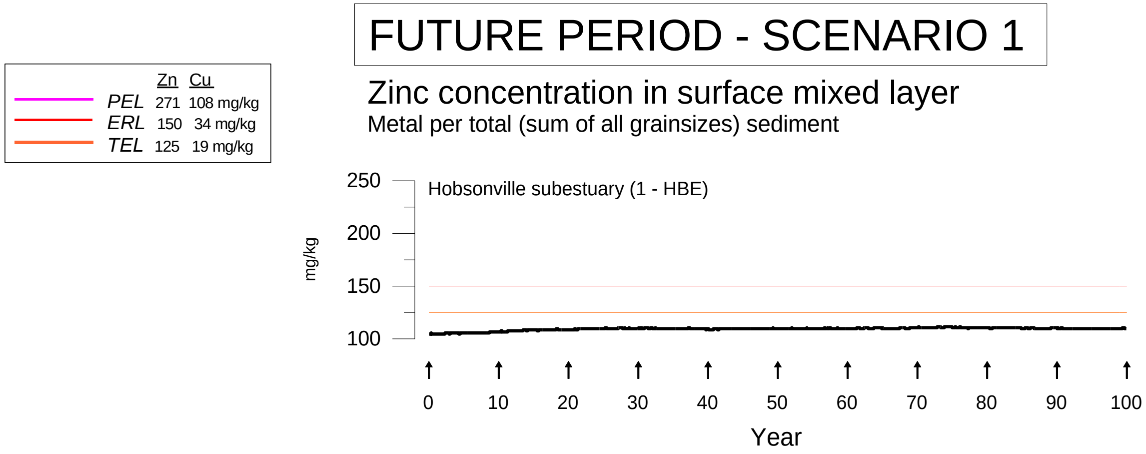


Figure 37
Predicted change in metal concentration for the future period under Scenario 1 for Hobsonville subestuary. Year 1 is 2001 and year 100 is 2101. Metal concentration is total metal per total sediment in the surface mixed layer.



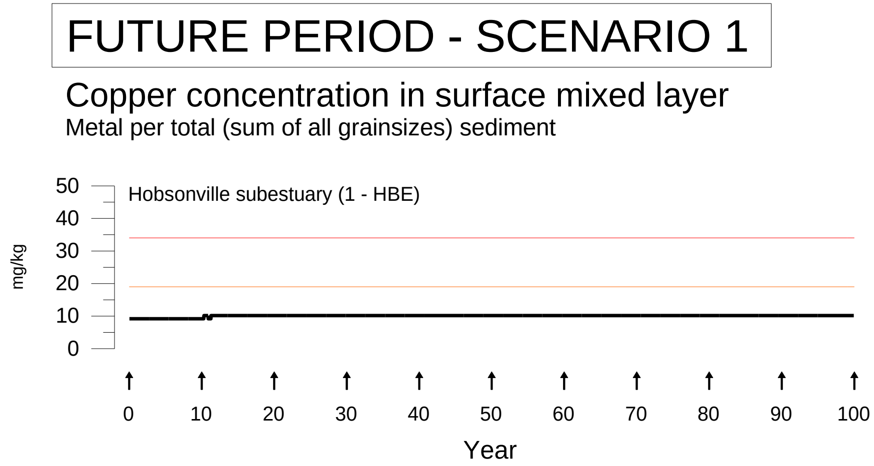
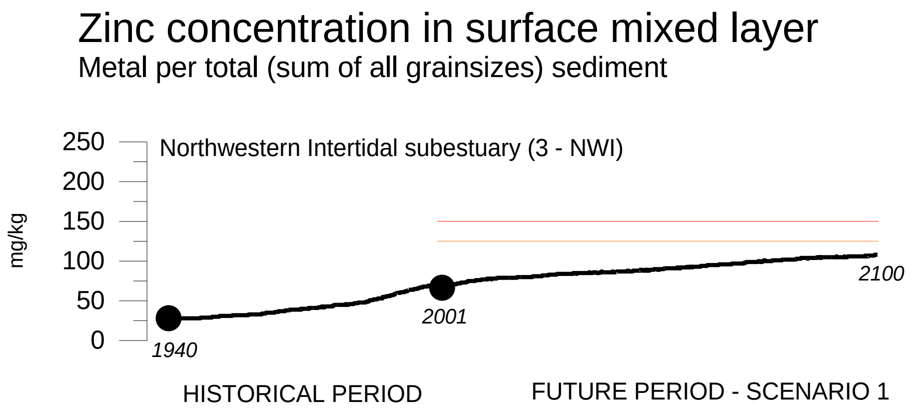
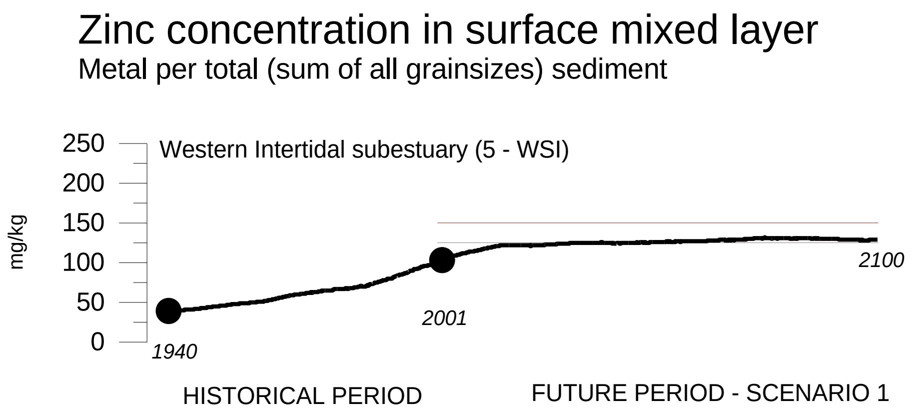


Figure 38

Model predictions for zinc for the historical period compared to model predictions for the future period. The filled circle at the start of the historical period was the starting concentration used in the model calibration, and the filled circle at the end of the historical period was the target concentration. That same filled circle was the starting concentration for the future period.





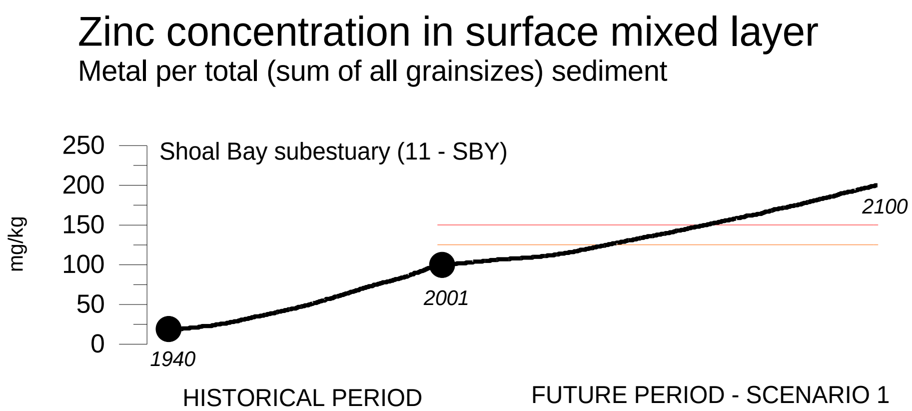
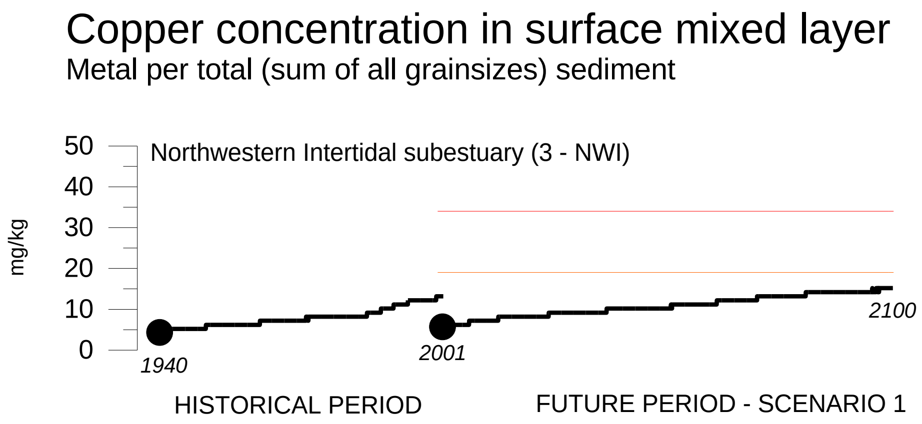
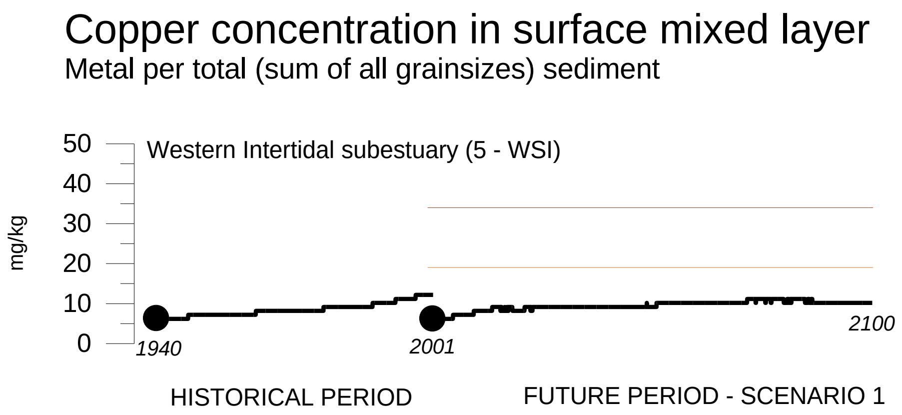


Figure 39
Model predictions for copper for the historical period compared to model predictions for the future period. The filled circle at the start of the historical period was the starting concentration used in the model calibration, and the filled circle at the end of the historical period was the target concentration. That same filled circle was the starting concentration for the future period.





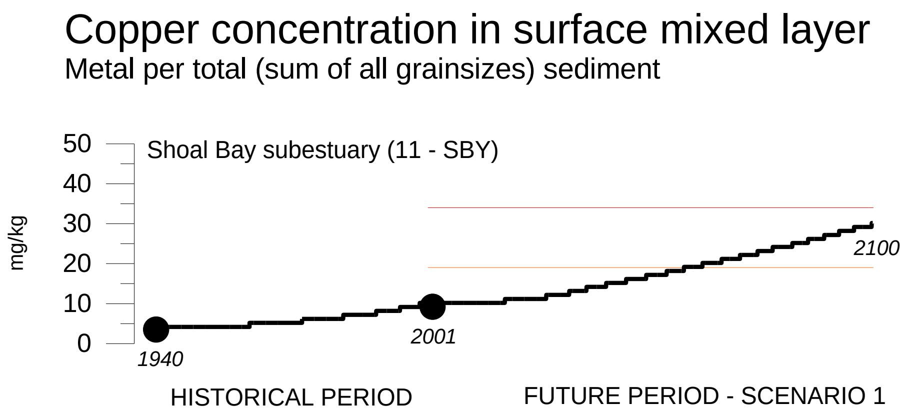


Figure 40

Schematic summary of zinc sediment quality guideline exceedance throughout the harbour.

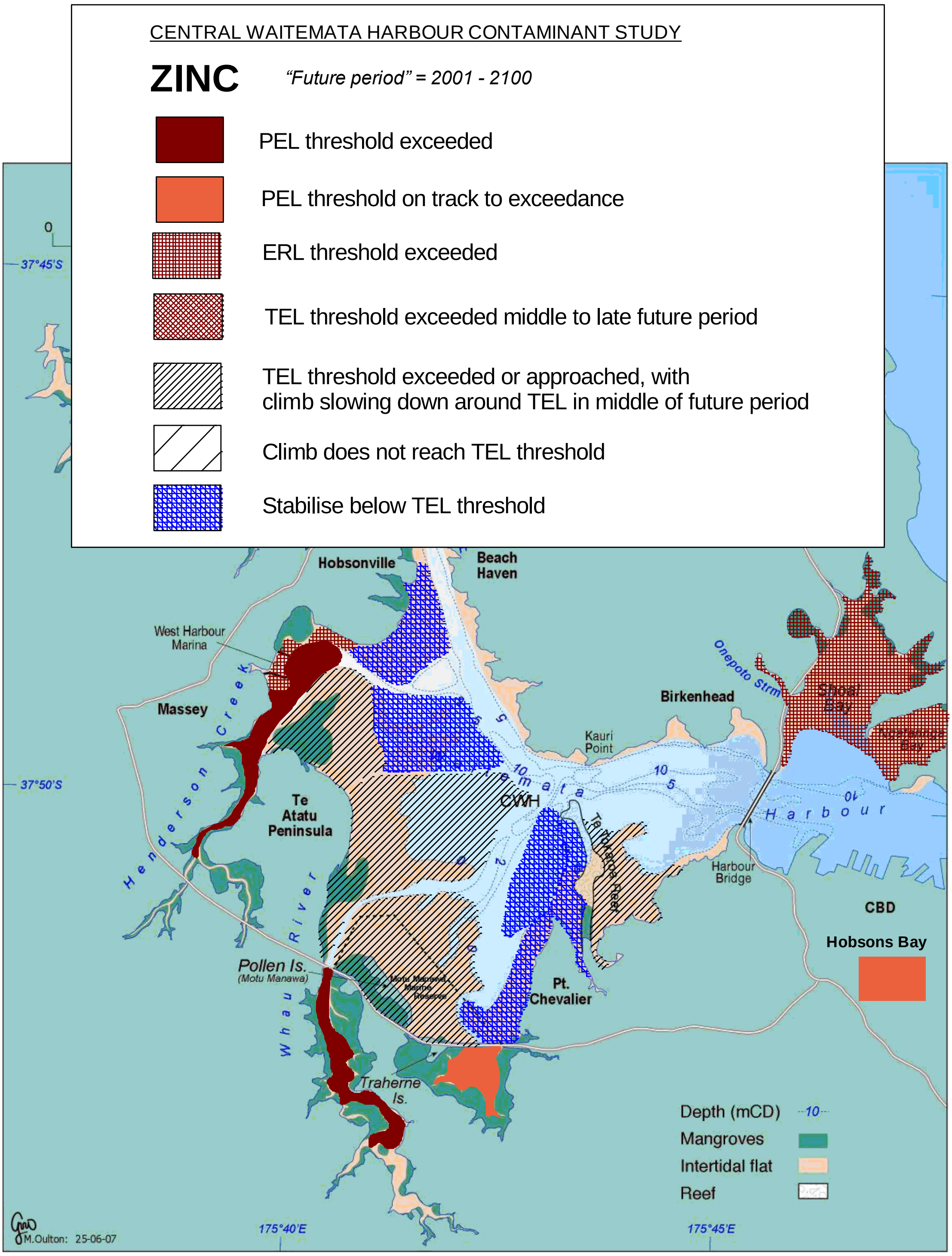
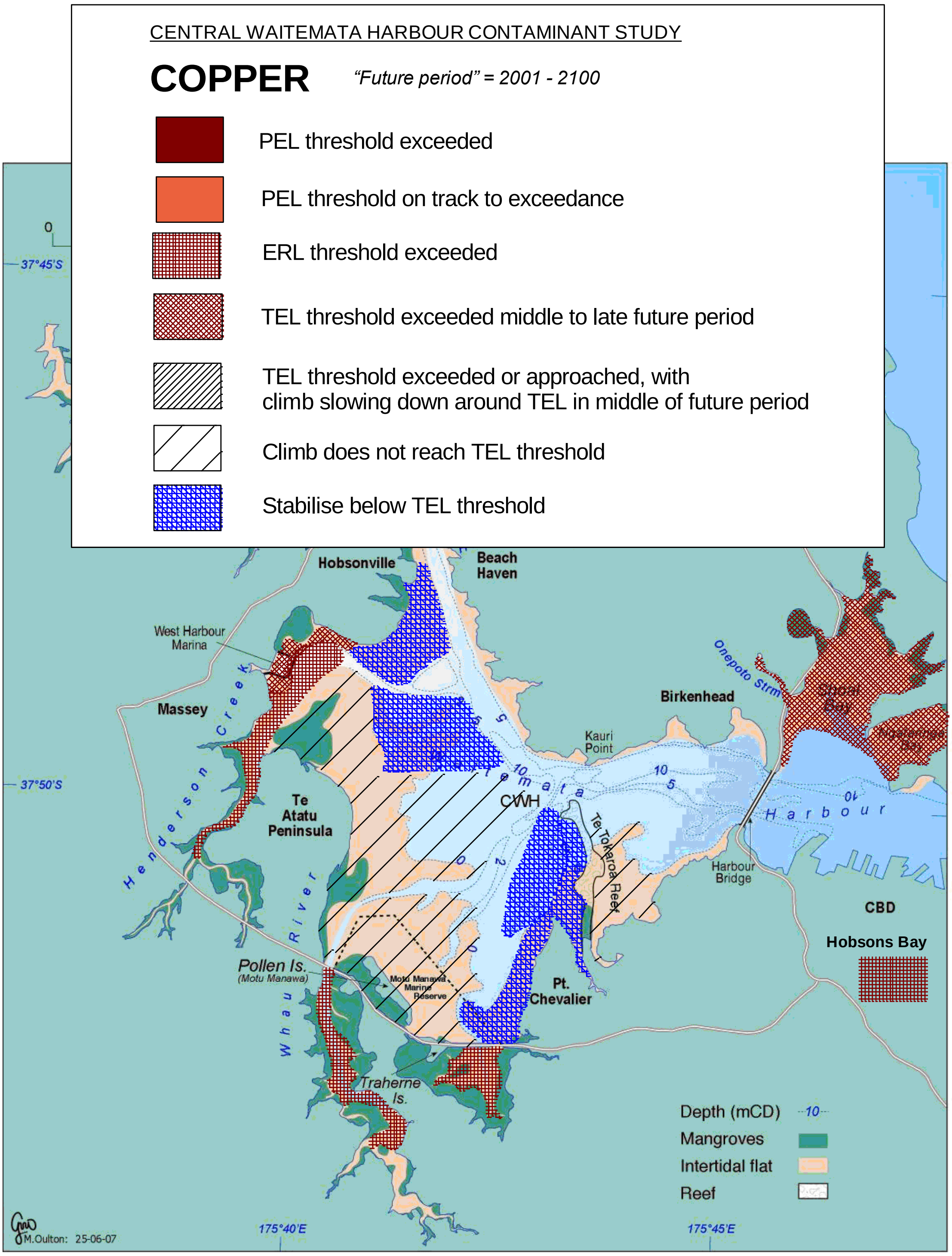


Figure 41

Schematic summary of copper sediment quality guideline exceedance throughout the harbour.



5 Conclusions

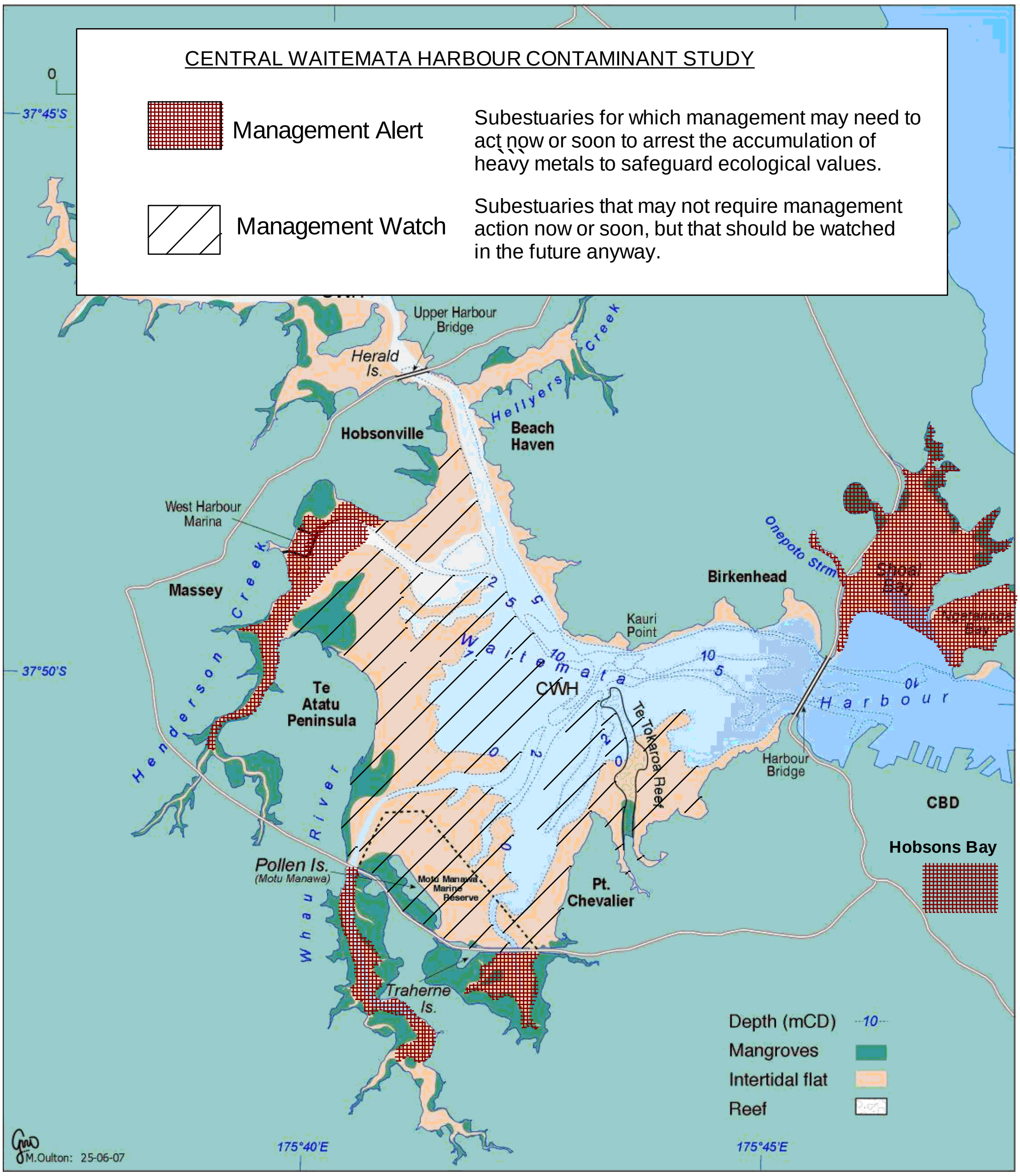
Figure 42 provides a high-level, simplified summary of the results for Scenario 1. In this view, subestuaries are classified as either "Management Alert" or "Management Watch". The classification is based on zinc only, since zinc is predicted to accumulate in greater concentrations than copper.

- "Management Alert" includes the categories "PEL threshold exceeded", "PEL threshold on track to exceedance" and "ERL threshold exceeded" shown in Figure 40. This denotes subestuaries for which management may need to act now or soon to arrest the accumulation of heavy metals to safeguard ecological values. The rationale is that ERL thresholds either already have been or soon will be exceeded, and in some cases PEL thresholds will be exceeded. Subestuaries assigned to Management Alert are the tidal creeks around the fringes of the harbour (Henderson Creek and the associated Limeburners Bay, Whau River, Waterview Embayment), Shoal Bay and Hobsons Bay.
- "Management Watch" includes all the other categories shown in Figure 40. This denotes subestuaries that may not require management action now or soon, but that should be watched in the future anyway. The rationale is that the TEL threshold is either not predicted to be exceeded or, if it is, it is decades into the future, in many cases when the rate at which metals are building up is reducing anyway.

Modelling was carried out using the best information and tools available at the time. Considerable effort also went into gathering additional information for the model(s). The results therefore represent the best available information, and provide a good basis for stormwater management. However, the limitations of making 100-year predictions of sediment and contaminant run-off, dispersal and accumulation in a complex, energetic receiving environment must be acknowledged. Ongoing monitoring is required to test and support the modelling.

Figure 42

A high-level, simplified summary of the results for Scenario 1. Refer to the text for explanation.



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