# Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study: Predictions of Sediment, Zinc and Copper Accumulation Under Future Development Scenario 1

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# Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study: Predictions of Sediment, Zinc and Copper Accumulation Under Future Development Scenario 1

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Prepared for
Auckland Regional Council

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# PREFACE

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

The scope of the study entailed:

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

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

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

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

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

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

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

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

The three general stormwater management intervention scenarios evaluated were:

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

**International Peer Review Panel**

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

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

**Key Findings of the Study**

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

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

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

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

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

**Research and Investigation Questions**

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

- Sediment and chemical contaminant dynamics within tidal creeks.

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

- The fate of other contaminants derived from urban sources.

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

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

**Technical reports**

The study has produced a series of technical reports:

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

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

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

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

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

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

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

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

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

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

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

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

# Contents

# 1 Executive Summary

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

This report describes predictions that have been made by the USC-3 ("Urban Stormwater Contaminant") model. 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 to be made for a number of development scenarios, where scenarios differ by zinc source control applied to anthropogenic metal generation in industrial 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 areas and stormwater treatment is at current levels of service.

Details of the USC-3 model have been given in Green (2007)[1]. The way the model has been implemented for the Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study, and then calibrated against data from the historical period 1940–2001, has been explained in detail by Green (2008)[2].

The model suite predicts that, for the future period 2001–2100 under Scenario 1, Drury subcatchment is the principal source of sediment to the harbour, and Papakura Stream subcatchment is the next largest source. Sediment runoff from subcatchments that lie to the south of Pahurehure Inlet is predicted to derive typically mainly from rural sources. With one exception, sediment runoff from subcatchments that lie to the north of Pahurehure Inlet is predicted to derive mainly from urban sources. The exception is Papakura Stream subcatchment. For most subcatchments there is no obvious trend – decrease or increase – in amount of sediment runoff over the future period.

Papatoetoe / Puhinui subcatchment is predicted to be the largest source of zinc, and nearly all of that is derived from anthropogenic sources. Anthropogenic copper and zinc is copper and zinc that does not originate as a naturally-occuring trace metal in the soils of the urban part of the study area. Copper and zinc loads estimated for the urban parts of the study area include both anthropogenic and naturally-occurring copper and zinc. Copper and zinc loads estimated for the rural parts of the study include only naturally-occurring copper and zinc levels. The next largest sources of zinc are predicted to be Papakura Stream subcatchment, which drains parts of Manurewa, Drury subcatchment, which contains part of the town of Papakura and the town of Drury, and Papakura subcatchment, which contains most of the town of Papakura. For

[1]Green, M.O., 2007. Central Waitemata Harbour Study. USC-3 Model Description, Implementation and Calibration. NIWA Client Report HAM2007-167. Prepared for Auckland Regional Council.
[2] Green, M.O., 2008. Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study: Implementation and Calibration of the USC-3 Model. NIWA Client Report HAM2008-140. Prepared for Auckland Regional Council.

subcatchments with any anthropogenic zinc (all except four subcatchments on the southern side of the Inlet), the contribution to the total zinc load from anthropogenic sources is predicted to range between 79–99%. The fraction of the total sediment runoff in these same subcatchments that is attributable to urban sources is predicted to range between 0.21–1.0. Therefore, zinc is predicted to always derive mainly from anthropogenic sources, even though sediment may derive mainly from rural sources. Anthropogenic zinc loads are predicted to decrease rapidly in the first 10–15 years in the future period in most subcatchments, then level off, or slightly increase, after that time.

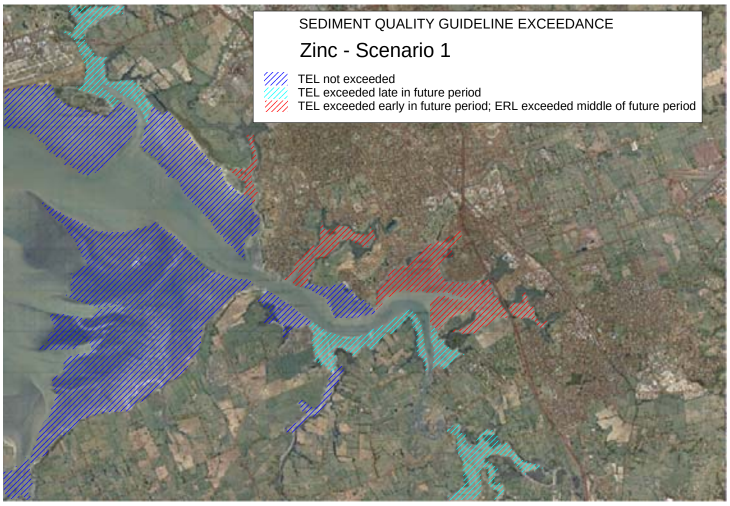
Papatoetoe / Puhinui subcatchment is also predicted to be the largest source of copper, and nearly all of that is predicted to derive from anthropogenic sources. For subcatchments with any anthropogenic copper, the contribution to the total copper load from anthropogenic sources is predicted to range between 74–99%. Unlike zinc, anthropogenic copper loads are predicted to increase in most subcatchments over the future period.

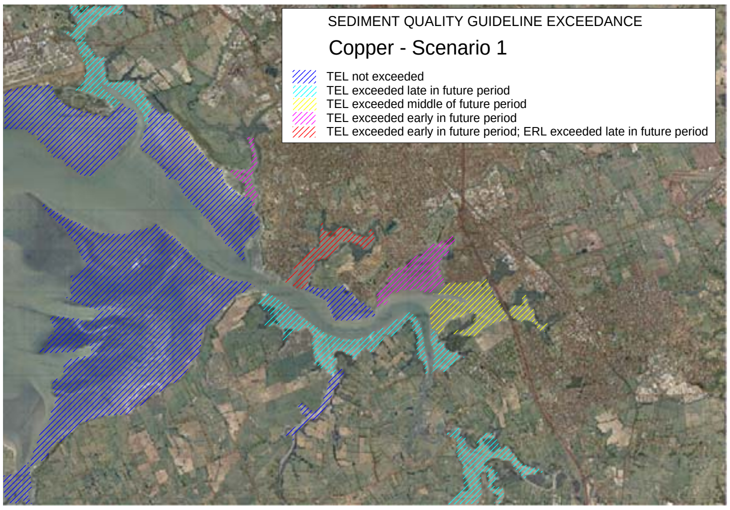
Since sediment runoff is predicted to remain more-or-less constant throughout the future period, changes in metal loads will dictate changes in the concentration at which metals will be delivered to the harbour, which in turn drives the changes in metal concentration in the harbour bed sediments. Zinc concentrations are predicted to fall early in the future period, and then level off, which mirrors exactly the predicted anthropogenic zinc runoff in the future period. This is a noteworthy result, since it means that zinc concentration in the estuary bed sediments will spend much of the future period equilibrating with (i.e., approaching asymptotically) the steady concentration of zinc in the land runoff. The same is not true for copper, however. In this case, anthropogenic copper runoff is predicted to increase throughout the future period, which drives a corresponding increase in the concentration at which copper is delivered to the harbour.

The predicted fate of sediments is virtually identical to 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 fate of zinc and copper from each subcatchment largely mirrors the fate of sediment, but with a few significant differences related to the fact that metals preferentially attach to the finer sediment particle sizes, which are transported into the sheltered reaches of tidal creeks and lost to Manukau Harbour over the long term.

Plots of predicted change in metal (zinc and copper) concentration in the surface mixed layer of the estuarine bed sediments for the future period under Scenario 1 are presented, together with a tabulation of the times at which sediment-quality guideline threshold values (Threshold Effects Level – TEL, Effects Range Low – ERL and Probable Effects Level – PEL) are predicted to be first exceeded. The predictions of metal concentration are more sensitive to uncertainty in the metal runoff from the catchment than they are to uncertainty in sediment runoff.

The two figures below summarise the predictions.




- There is no threat on the horizon for subestuaries designated "TEL not exceeded".

These subestuaries are the intertidal flats of Southeastern Manukau Harbour (Hikihiki Bank, Weymouth and Wiroa Island); Glassons Creek tidal creek and Clarks Creek tidal creek, which drain predominantly rural subcatchments; and Kauri Point, in an exposed location in the middle of Pahurehure Inlet.

- The threat is low for subestuaries designated "TEL exceeded late in future period".

These subestuaries are those clustered around the mouth of Glassons Creek on the southern side of the Inlet (Karaka, Glassons Mouth West, Glassons Mouth East, Cape Horn and Drury Creek Outer); Drury Creek Inner tidal creek, which drains the semi-rural Drury subcatchment; and Pukaki Creek tidal creek.

- The threat is heightened in the remaining subestuaries, in which the zinc TEL is predicted to be exceeded early in the future period, and the zinc ERL is predicted to be exceeded in the middle of the future period.  Exceedance of copper sediment-quality guideline thresholds is predicted to be somewhat delayed relative to zinc.  Management may need to act now or soon to safeguard ecological values in these areas.

These subestuaries are Puhinui Creek tidal creek, subestuaries in the inner, sheltered reaches of Pahurehure Inlet (Pahurehure Inner and Pahurehure Basin), and the sheltered embayments along the northern shoreline of Pahurehure Inlet (Papakura and Waimahia Creek), all of which drain major urban centres.

Over half of the catchment of the Southeastern Manukau Harbour is occupied by Franklin District, with the remainder divided approximately equally between Papakura District and Manukau City.  A breakdown by Territorial Authority of the sediment and metal loads predicted for the future period 2001–2100 under Scenario 1 is provided.

# 2 Introduction

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

Specifically, the model will be used to:

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

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

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

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

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

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

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

(

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

## 2.1 Model suite

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

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

- The Contaminant Load Model (CLM)- a contaminant/sediment-generation model, which predicts sediment and contaminant concentrations (including zinc, copper) in stormwater at a point source, in urban streams, or at end-of-pipe where stormwater discharges into the receiving environment. Note the main distinction between the use of GLEAMS and CLM for estimating sediment generation in this study is that the former is largely used for rural areas and the latter for urban areas. Further details are given in Moores and Timperley (2008).
- The USC-3 (Urban Stormwater Contaminant) contaminant/sediment accumulation model, which predicts sedimentation and accumulation of contaminants (including zinc, copper) in the bed sediments of the estuary. Underlying the USC-3 model is yet another suite of models: the **DHI** Water and Environment **MIKE3 FM HD** hydrodynamic model, the **DHI MIKE3 FM MT** (mud) sediment transport model, and the **SWAN** wave model (Holthuijsen et al. 1993), which simulate harbour hydrodynamics and sediment transport. Combined, these three models can be used to simulate tidal propagation, tide- and wind-driven currents, freshwater mixing, waves, and sediment transport and deposition within a harbour." .

## 2.2 This report

This report describes predictions that have been made by the USC-3 model for the Southeastern Manukau / Pahurehure Inlet Contaminant Study. The model, which functions as a decision-support scheme, predicts sedimentation and accumulation of contaminants (including zinc and copper) in the bed sediments of estuaries on the "planning timescale", which is decades and greater. In this report, anthropogenic copper and zinc is copper and zinc that does not originate as a naturally-occuring trace metal in the soils of the <u>urban</u> part of the study area. Copper and zinc loads estimated for the urban parts of the study area include both anthropogenic and naturally-occurring copper and zinc. Copper and zinc loads estimated for the rural parts of the study include only naturally-occurring copper and zinc levels.

Table 2.1 shows the scenarios for which predictions are to be made, where scenarios differ by zinc source control applied to anthropogenic metal generation in industrial 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.

Predictions for Scenario 1 are reported herein.

**Table 2.1:**

The scenarios for which predictions of sediment and contaminant accumulation are to be made, where scenarios differ by zinc source control applied to anthropogenic metal generation in industrial 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 | Source control applied to anthropogenic metal generation in urban areas | Stormwater treatment applied to urban areas |
|---|---|---|---|
| **1** | **Future population growth and urban development** | **No additional** | **No additional** |
| **2** | **Future population growth and** | **Zinc source** | **No additional** |

- The "no additional" stormwater treatment modelled in Scenario 1 consists of specific stormwater treatment ponds (data provided by ARC, Papakura DC and Manukau CC) in addition to ponds on all commercial and industrial construction sites, and catchpits on all roads and in topographical depressions. All urban drainage except for that from roofs is assumed to pass through catchpits before entering the stormwater network.

# 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. The model provides:

- Predictions of sedimentation in different parts of the estuary, which may be compared and used in an assessment of sediment effects.
- Predictions of the change in bed composition over time, which reflects degradation of habitat (e.g., change of sandy substrate to silt), and which may bring associated ecological degradation (e.g., mangrove spread, loss of shellfish beds).
- Predictions of the accumulation of heavy metals in the surface mixed layer of the estuary bed sediments, which may be compared to sediment-quality guidelines to infer associated ecological effects.
- An explicit analysis of the links between sediment sources in the catchment and sediment sinks in the estuary. This type of analysis effectively links "subestuary effects" to "subcatchment causes", thus showing where best management practices on the land can be most effectively focused. Without an understanding of the link between source and sink, assessment of sediment sources on the land lacks any effects context.

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

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

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

The USC-3 model requires as inputs:

- estimates of future heavy-metal loads from the land;
- estimates of future sediment loads and particle sizes from the land;
- estimates of the natural metal concentrations in catchment soils.

Parameters required by the model include:

- bed-sediment mixing depth in the harbour;
- 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;
- 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 zinc source control of industrial areas.

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

The model has been calibrated for Southeastern Manukau Harbour / Pahurehure Inlet 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 subcatchments on a similar scale to the subestuary. Each subcatchment discharges through one outlet to the harbour.

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

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

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

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

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

- For the injection into the harbour of sediment that is eroded from the land when it rains the model timestep is two complete tidal cycles (referred to herein as “one day”).
- For the resuspension of estuarine bed sediments by waves and tidal currents the model timestep is also one day.
- Each day an injection and/or resuspension event may occur, or no event may occur. The rainfall, wind and tide range on the day govern whether or not an event occurs. The rainfall, wind and tide range on each day 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 subcatchments 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 (e.g., clay, silt, fine sand, sand). The proportions of the constituent particle sizes in each layer of the sediment column may vary, depending on how they develop in the simulation. This results in finer or coarser layers as the case may be.

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

For example, the erosion rate is determined by a weighted-mean particle size of the bed sediment that reflects the combined presence of the constituent particle sizes. This has 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 <u>all</u> 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 metals in the surface mixed layer is evaluated in the model by taking account of mixing of the bed sediment, which has the effect of reducing extreme concentration gradients in the bed sediment that would otherwise occur in the absence of mixing.

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

### 3.2.1 Comparison with the USC-2 model

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

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

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

Some useful information is now recapped.

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

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

The subdivision of the Southeastern Manukau Harbour / Pahurehure Inlet into subestuaries for the purposes of application of the USC-3 model is shown in Figure 3.1. Further details of the subdivision are shown in Table 3.1:

- Five subestuaries are designated as tidal creeks: Puhinui Creek (14–PUK), Pukaki Creek (15–PKK), Drury Creek Inner (16–DCI), Glassons Creek Inner (17–GCK) and Clarks Creek (18–CCK).  Sediments deposited in tidal creeks may not be subsequently removed by resuspension, and land-derived sediments that pass through tidal creeks are attenuated.
- One of the subestuaries is designated as a sink: Manukau Harbour (19–MHB). Sediments deposited in 19–MHB may not be subsequently removed by resuspension.  Furthermore, sediments deposited in 19–MHB are “removed from the model”, meaning that no predictions are made of sediment or contaminant accumulation in subestuary 19–MHB.
- The designation of 19–MHB as a sink is based on the assumption that the bulk of any sediment transported into the wider harbour is dispersed widely and does not

re-enter the southeastern sector of the harbour or Pahurehure Inlet. By virtue of its designation as a sink, 19–MHB is also prevented from eroding and supplying sediment to the southeastern sector of the harbour or Pahurehure Inlet.

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

The subdivision of the catchment surrounding Southeastern Manukau Harbour / Pahurehure Inlet into subcatchments for the purposes of application of the USC-3 model is shown in Table 3.2 and Figure 3.2.

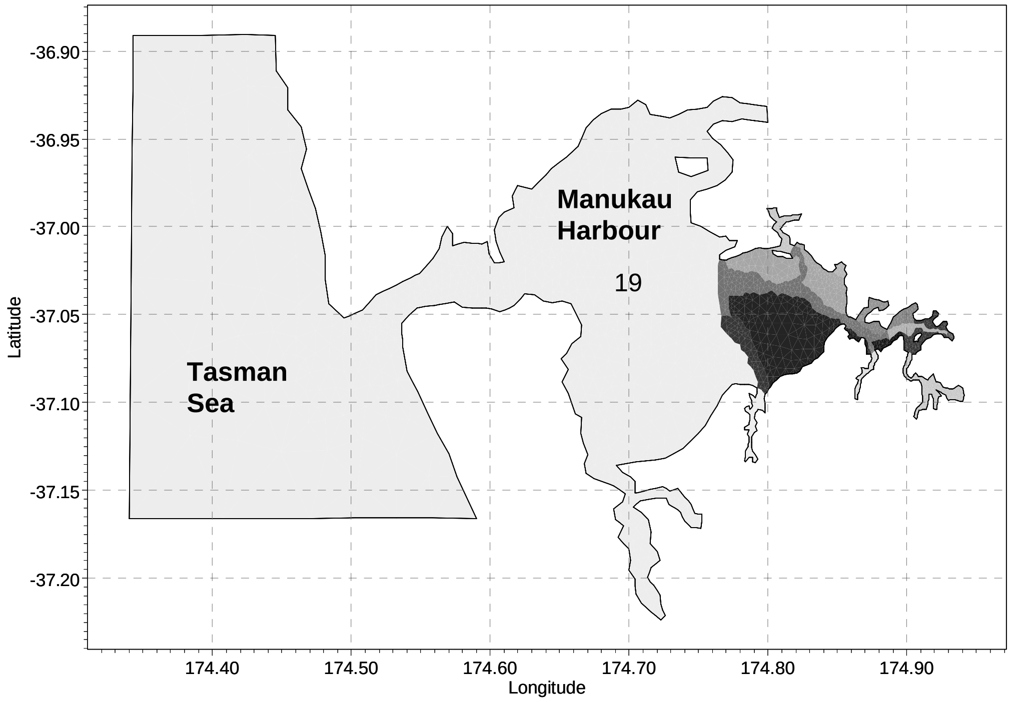
**Table 3.1:**

Characteristics of subestuaries for the purposes of application of the USC-3 model. The area shown in the table is the total subestuary area.

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

**Figure 3.1:**

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



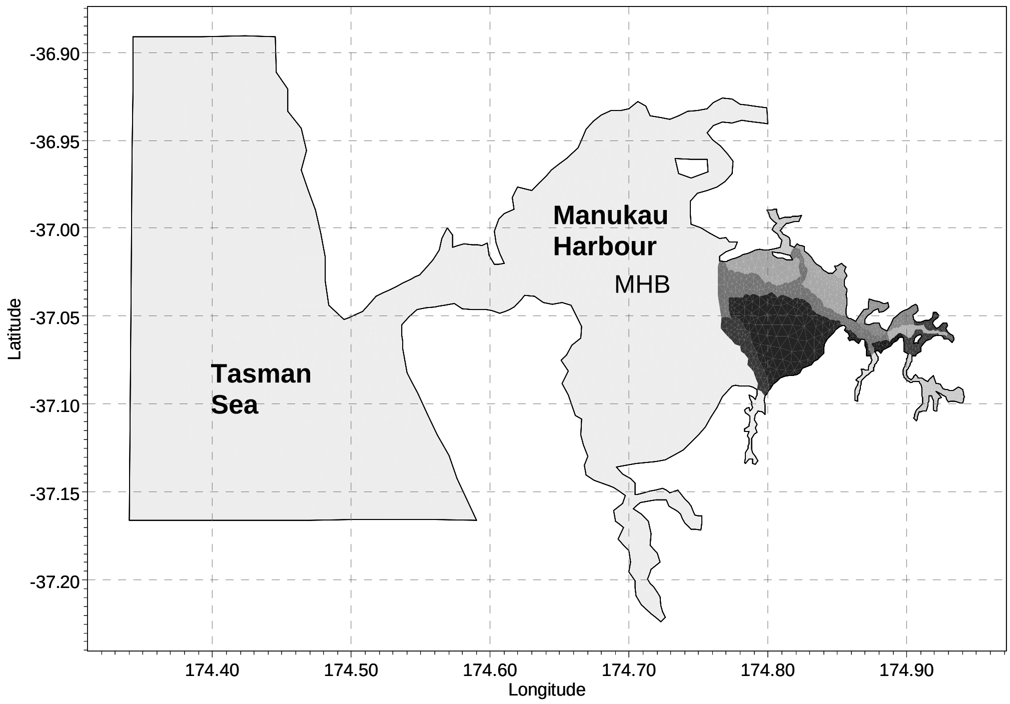
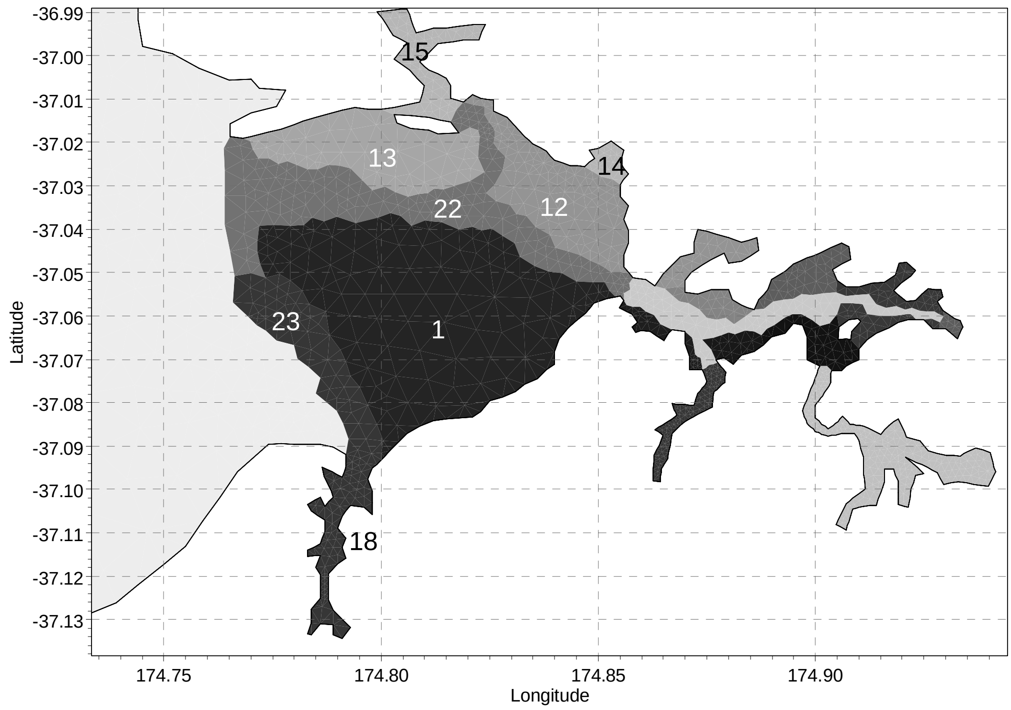



**Figure 3.1 (continued)**

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



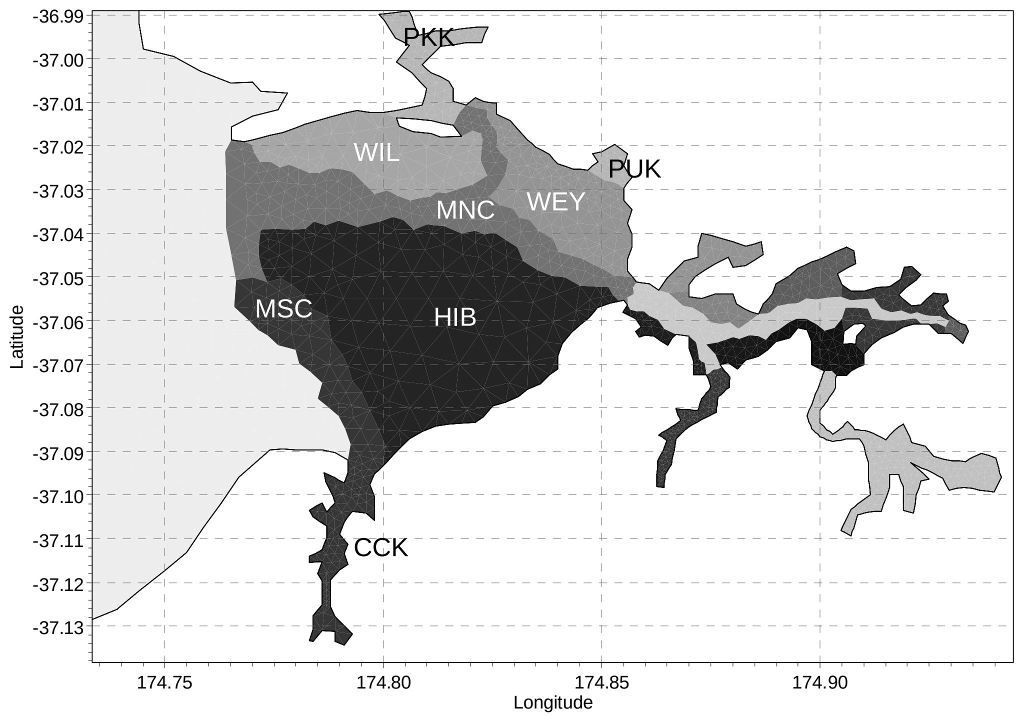
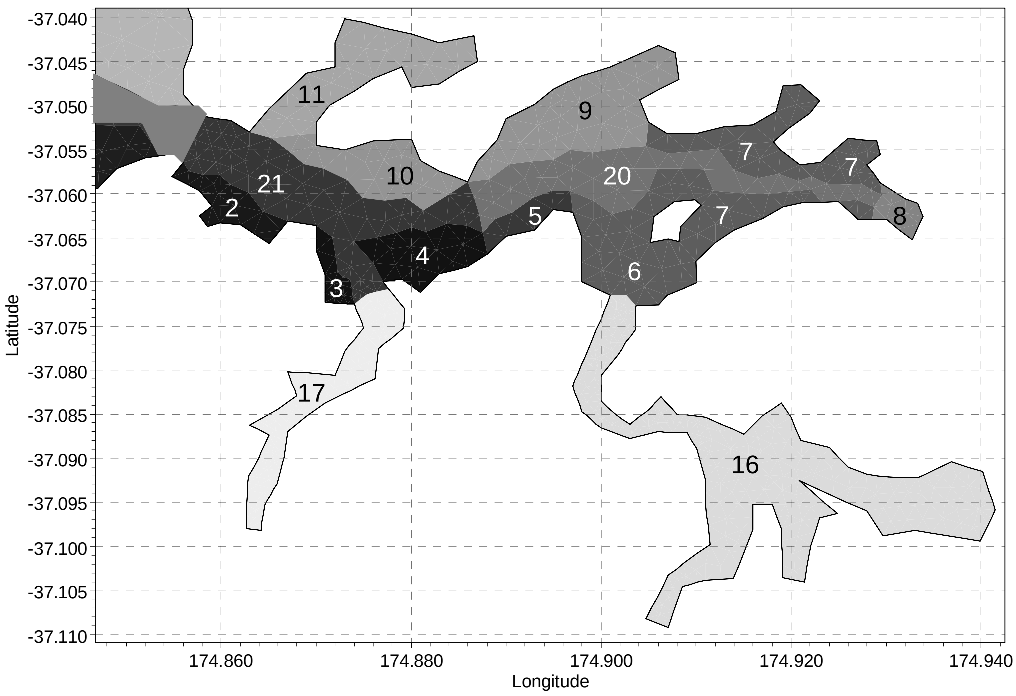



**Figure 3.1 (continued)**

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



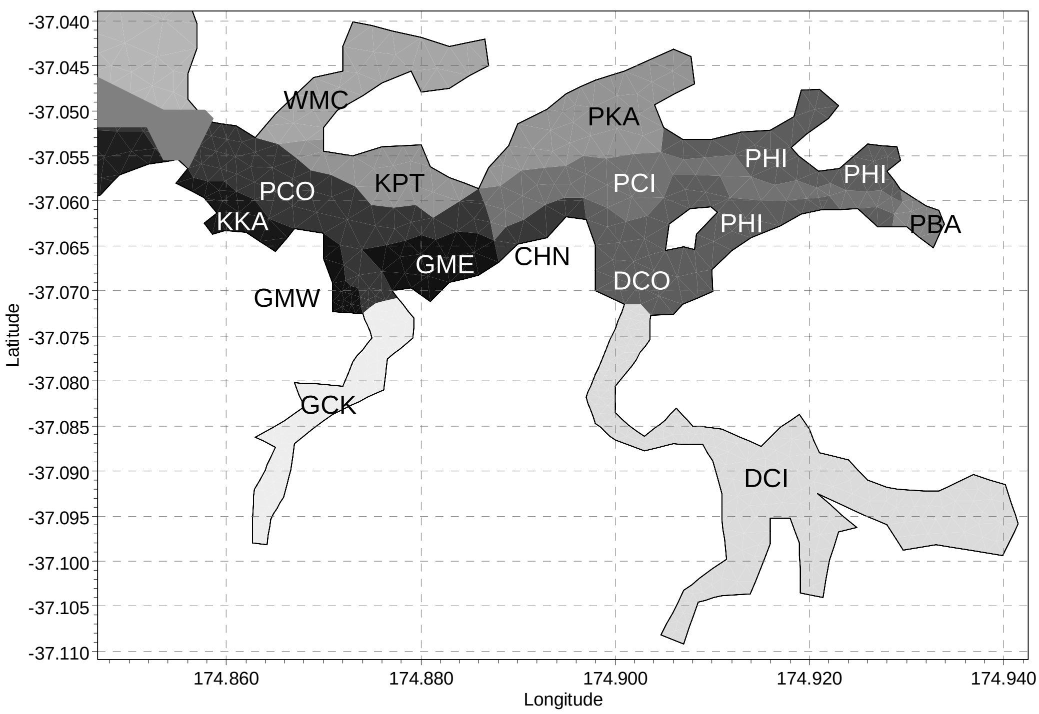



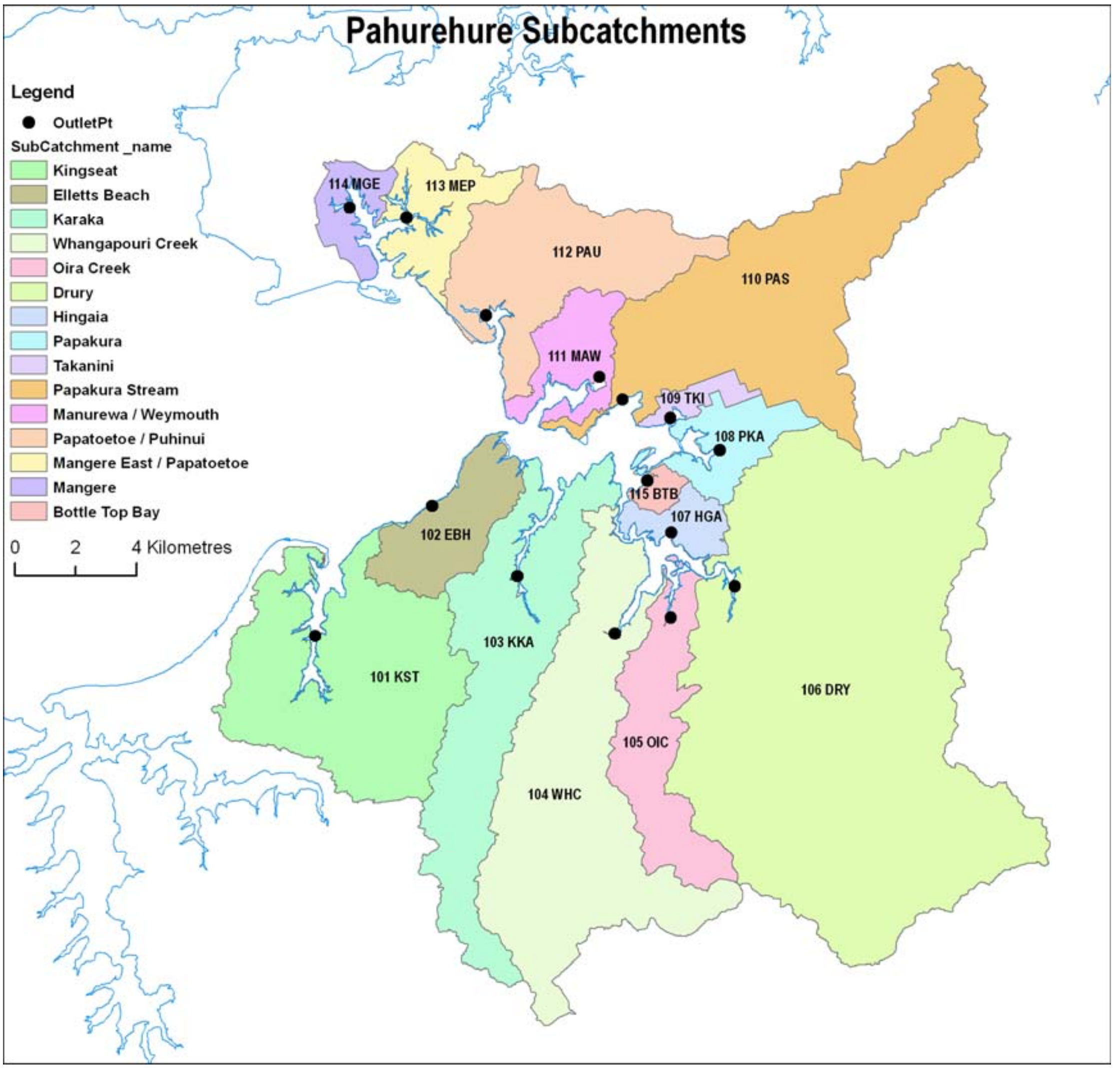
**Table 3.2:**

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

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

**Figure 3.2**

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



The GLEAMS model provides daily land-derived sediment loads at the bottom of each subcatchment split by constituent particle size. For this implementation, GLEAMS predicts sediments from all of the rural areas in each subcatchment. Hence, “GLEAMS sediments” is synonymous with “sediments from sources in rural areas”. Even though the daily GLEAMS timestep matches the one-day timestep in the USC-3 model associated with injection of land-derived material into the harbour, there is still some manipulation required to assemble these loads for input into the USC-3 model. This is 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 subcatchment. Hence “CLM sediments” is synonymous with “sediments from sources in urban areas”. The urban (CLM) sediment loads need to be added to the rural (GLEAMS) sediment loads, but because the annual timestep of the CLM does not match the daily timestep in the USC-3 model associated with injection of land-derived material into the harbour, the CLM loads need to be further manipulated before they can be added to the GLEAMS loads and used in the USC-3 model. Each annual load of urban sediment is fully distributed over the days in that year such that no part of the annual load is “carried over” into a succeeding year. The distribution was made proportionally, corresponding to the daily GLEAMS sediment loads for that same year.

The CLM also provides annual anthropogenic metal (zinc and copper) loads at the bottom of each subcatchment, split by sediment constituent particle size that carries the load. Because the annual timestep of the CLM does not match the daily timestep in the USC-3 model associated with injection of land-derived material into the harbour, these loads need to be further manipulated before they can be used in the USC-3 model. Each annual anthropogenic load of metal is fully distributed over the days in that year such that no part of the annual load is “carried over” into a succeeding year. 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.

A large set of terms (*R*, *R5*, *RSUSP*, *R5SUSP* and *RFS*) controls 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 runoff.

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 from deeper in the sediment column towards the surface.

Mixing therefore has the net effect of reducing gradients in heavy-metal concentrations in the bed sediment. For example, a recently deposited layer carrying heavy metals at a concentration greater than in the underlying bed sediment will get mixed downwards, obliterating the concentration gradient between the recently deposited layer and the underlying bed sediment, and slightly raising the concentration in the surface mixed layer (which now includes the recently deposited layer) as a whole. If the recently deposited layer carries metal at a concentration less than the underlying bed sediment, then concentration in the surface mixed layer will be reduced. For the application of the USC-3 model here, mixing is assumed to act uniformly over a depth of 4 cm, which is based, primarily, on radioisotopic and X-ray analysis of sediment cores reported by Reed et al. (2008).

After mixing, the concentration of heavy metal in the surface mixed layer is given by the ratio of the total amount of heavy metal (attached to all particle sizes) in the surface mixed layer to the total amount of sediment (i.e., all particle sizes) in the surface mixed layer. 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 driven by time series of daily sediment and metal runoff 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 calibration

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

The 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 of the historical period came to match observations from that same period. The terms that may be adjusted were (1) the fraction of the sediment runoff from the land that is treated as washload / slowly-settling, low-density flocs, (2) the areas over which sediments may deposit, (3) the various terms that control sediment and attached metal dispersal and deposition, and (4) the metal retention factor. Adjustments in these terms were made until realistic sediment dispersal patterns, sedimentation rates and metal accumulation rates were simultaneously obtained.

The metal retention factor *MRF*, which is the fraction of the metal load emanating from each subcatchment that is attached to the corresponding sediment particulate load, is the key calibration parameter. This term is used to reduce the concentration at which metals are delivered to the harbour in the model, and is chosen to yield a time-rate-of-change of metal concentrations over the historical period that ends in target concentrations being achieved. The physical interpretation is that (1 – *MRF* ) represents the proportion of the metal load emanating from the catchment that gets lost to a dissolved phase and which does not accumulate (by definition) in the estuary bed sediments, and/or (1 – *MRF* ) represents the proportion of the metal load emanating from the catchment that gets attached to very fine particles that never settle and so do not accumulate in the bed of the harbour. The calibrated value of *MRF* was very similar to that arrived at in the calibration of the USC-3 model of the Central Waitemata Harbour (Green, 2007), and that value furthermore has some experimental basis (Ellwood et al., 2008). Therefore, the calibration was not implausible.

# 4 Model Predictions – Scenario 1

Scenario 1 addresses future population growth and urban development in the catchment of Southeastern Manukau Harbour / Pahurehure Inlet. 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 anthropogenic metal generation in industrial areas.
- There is no stormwater treatment in urban areas above existing levels of service.

Full details of how urban areas are depicted in Scenario 1 in the Contaminant Load Model are provided in Moores and Timperley (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 Landuse

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

## 4.2 Sediment inputs

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

- The GLEAMS predictions of rural sediment runoff for the future period are presented in detail by Parshotam (2008). For these predictions, GLEAMS used the future-period landuse data described in Parshotam et al. (2008a). The implementation of GLEAMS is documented by Parshotam et al. (2008b) and Parshotam et al. (2008c). Note that the rural sediment runoff is the same under all scenarios (1, 2, 3 and 4), because the scenarios differ by zinc source control of industrial areas and stormwater treatment (Table 2.1).
- The CLM predictions of urban sediment runoff for the future period are presented in detail by Moores and Timperley (2008). These predictions vary by scenario. For Scenario 1, no special stormwater treatment is applied in urban areas. For these predictions, the CLM used the future-period landuse data described in Moores and Timperley (2008). The implementation of the CLM is documented by Moores and Timperley (2008).

### 4.2.1 Sediment inputs from rural sources

Fifty time series, each covering the future period 2001–2100, of daily rural sediment runoff from each subcatchment 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 landuse scenario, that corresponding to the year 2001. This is justified, since rural landuse is assumed not to change from 2001. The GLEAMS run was driven by a 50-year rainfall time series covering the period 1 January 1956 to 31 December 2005.

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 runoff may be unique.

The split of the rural sediment load amongst the constituent particle sizes 12, 40 and 125 µm is shown in Table 4.1, predicted by GLEAMS for the year 2001 and applied throughout the future period (All tables and figures for this chapter are presented in one place at the end of the chapter). Note that one-half of the 12 µm sediment load is assigned to the 4 µm particle size (washload / low-density, slowly-settling flocs), which was determined during the calibration process (Green, 2008).

### 4.2.2 Sediment inputs from urban sources

Fifty time series, each covering the future period 2001–2100, of daily urban sediment runoff from each subcatchment 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 runoff from each subcatchment for the future period. The fifty required time series of daily urban sediment runoff (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 runoff for each year in proportion to the corresponding daily GLEAMS sediment loads for that same year.

The split of the urban sediment load from each subcatchment amongst the constituent particle sizes 12, 40 and 125 µm was calculated by the CLM. Results are shown in Table 4.2, averaged over all years in the future period, which hides some temporal variability. Note that one-half of the 12 µm sediment load is assigned to the 4 µm particle size (washload / low-density, slowly-settling flocs), which was determined during the calibration process (Green, 2008).

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

The daily rural and daily urban sediment runoffs were added to give daily total sediment runoffs. This results in 50 daily time series (one time series for each USC 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 runoff may vary from time series to time series, since this is constructed from random sampling of the GLEAMS outputs. The sum-over-each-year of the urban component of the total sediment runoff will be the same for every time series, since these derive from the prediction by the CLM of annual urban sediment loads. However, the distribution of the daily urban sediment runoff throughout the year may vary from time series to time series, as this depends on the daily rural (GLEAMS) sediment runoff.

Table 4.3 and Figure 4.1 show some statistics of the total (urban plus rural) sediment runoff.

- Drury subcatchment (106 – DRY) is the principal source of sediment to the harbour. This is also the largest subcatchment, so it is not necessarily the case that sediment yield (sediment generation per unit area) is also largest for this subcatchment. Papakura Stream subcatchment (110 – PAS) is the next largest source, which is also the next largest subcatchment. The two smallest sediment sources are Bottle Top Bay subcatchment (115 – BTB) and Takanini subcatchment (109 – TKI), which are also the smallest subcatchments. The catchment rankings in terms of sediment runoff are not greatly different to the rankings for the historical period 1940–2001 reported by Green (2008). In particular, the largest and smallest sediment sources are unchanged.
- 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 4.2 shows the annual sediment runoff for the future period, and Figure 4.3 shows how annual sediment runoff during the historical period 1940–2001 dovetails with annual sediment runoff during the future period 2001–2100. Table 4.4 shows for each subcatchment the average (over the future period) fraction of the annual sediment runoff that comes from urban sources. The rest comes from rural sources. Figure 4.4 shows how the rural–urban split for each subcatchment varies over time during the future period, and Figure 4.5 shows the dovetail with the historical period.

- Sediment runoff from subcatchments that lie to the south of Pahurehure Inlet is predicted to derive typically mainly from rural sources. Subcatchments 101 (Kingseat), 102 (Elletts Beach), 103 (Karaka) and 105 (Oira Creek) have no urban areas, hence all the sediment in these subcatchments is predicted to derive from rural sources. That was also the case for the historical period. The town of Pukekohe is located in subcatchment 104 (Whangapouri Creek), which accounts for the 33% of the sediment runoff in that case being attributable to urban sources; this is up from 26% in the historical period. Similarly, for subcatchment 106 (Drury; this subcatchment contains part of the town of Papakura and the town of Drury), more sediment runoff is attributable in the future period to urban sources: 21% compared to 15% in the historical period. Subcatchments 107 (Hingaia) and 115 (Bottle Top Bay) are both predicted to see a significant increase in sediment from urban sources. For Hingaia, the increase is from 16% to 56%, and for Bottle Top Bay the increase is from 14% to 100%, which occurs in a step at the start of the future period.

- Subcatchment 108 (Papakura), which drains at the top of the Inlet and which contains most of the town of Papakura, began the historical period with urban sources contributing 20–30% of the sediment runoff, and this contribution increased slightly to result in an average over the historical period of 32%. There is no significant change predicted for the future period, which also averages 32% of sediment runoff from urban sources.
- Sediment runoff from subcatchments that lie to the north of Pahurehure Inlet is predicted to derive mainly from urban sources, with one exception. Takanini (109) and Manurewa / Weymouth (111) subcatchments closed the historical period with sediment runoff practically exclusively from urban sources, and this is predicted to remain the case for the future period. The exception is subcatchment 110 (Papakura Stream), for which 33% of the sediment runoff is predicted to derive from urban sources on average over the future period, compared to 26% over the historical period.
- For subcatchment 112 (Papatoetoe / Puhinui), which discharges to the northern shore of Manukau Harbour, 92% of the sediment runoff is predicted to derive from urban sources over the future period. This is about the level reached by the end of the historical period, but the average over the historical period was much smaller (53%). The other subcatchments that discharge to the northern shore of Manukau Harbour are less urbanised: subcatchment 113 (Mangere East / Papatoetoe) is predicted to average 27% and subcatchment 114 (Mangere) is predicted to average 25% of sediment runoff due to urban sources in the future period. In both cases, these figures were approximately reached at the end of the historical period.
- For most subcatchments there is no obvious trend in magnitude of sediment runoff predicted for the future period.

Figure 4.6 shows daily total (rural plus urban) sediment runoff plotted against rainfall. The large variability in the response of the catchment to rainfall is apparent, which is due to GLEAMS capturing the effects on sediment generation of antecedent rainfall and rainfall intensity on the day of generation.

## 4.3 Metal inputs

### 4.3.1 Natural metal inputs

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

### 4.3.2 Anthropogenic metal inputs

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

Figure 4.7 shows the anthropogenic zinc loads, and Table 4.5 shows how the zinc load is carried on the 12, 40 and 125 µm sediment constituent particle sizes. Note that one-half of the 12 µm zinc load is assigned to the 4 µm particle size sediment (washload / low-density, slowly-settling flocs), which was determined during the calibration process (Green, 2008). Figure 4.8 shows how the historical-period hindcast zinc loads dovetail with the future-period predicted loads.

Figure 4.9 shows the anthropogenic copper loads, and Table 4.6 shows how the copper load is carried on the 12, 40 and 125 µm sediment constituent particle sizes. Note that one-half of the 12 µm copper load is assigned to the 4 µm particle size sediment (washload / low-density, slowly-settling flocs), which was determined during the calibration process (Green, 2008). Figure 4.10 shows how the historical-period hindcast copper loads dovetail with the future-period predicted loads.

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

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

The daily anthropogenic metal loads so formed were added to the daily natural metal loads to form the daily total metal loads. Table 4.7 and Table 4.8 show the total (anthropogenic plus natural) metal loads, and how those total loads are constituted between anthropogenic and natural sources.

For zinc:

- Subcatchment 112 (Papatoetoe / Puhinui) is predicted to be the largest source of zinc, and nearly all of that (97%) is derived from anthropogenic sources. Subcatchment 112 was also the largest source of zinc in the historical period. The next largest sources of zinc are predicted to be subcatchment 110 (Papakura Stream, which drains parts of Manurewa), 106 (Drury, which contains part of the town of Papakura and the town of Drury), and 108 (Papakura, which contains most of the town of Papakura), in that order.
- For subcatchments with any anthropogenic zinc (all except 101, 102, 103 and 105), the contribution to the total zinc load from anthropogenic sources is predicted to range between 79–99%. The fraction of the total sediment runoff in these same subcatchments that is attributable to urban sources is predicted to range between 0.21–1.0. Therefore, zinc is predicted to always derive mainly from anthropogenic sources, even though sediment may derive mainly from rural sources.

- Anthropogenic zinc loads are predicted to decrease rapidly in the first 10–15 years in the future period in most subcatchments, then level off, or slightly increase, after that time. It is noteworthy that the model hindcasts showed zinc runoff increasing throughout the historical period. Hence, zinc runoff is maximum around the present day.

For copper:

- Subcatchment 112 (Papatoetoe / Puhinui) is also predicted to be the largest source of copper, and nearly all of that (96%) is predicted to derive from anthropogenic sources.
- For subcatchments with any anthropogenic copper (all except 101, 102, 103 and 105), the contribution to the total copper load from anthropogenic sources is predicted to range between 74–99%. This is similar to zinc (79–99%).
- Unlike zinc, anthropogenic copper loads are predicted to increase in most subcatchments over the future period.

## 4.4 Concentration at which metals are delivered to the harbour

The concentration at which total (anthropogenic plus natural) zinc is predicted to be delivered to the harbour over the future period is shown in Figure 4.11. A comparison with the historical period is shown in Figure 4.12. The corresponding figures for copper are 4.13 and 4.14.

Since sediment runoff is predicted to remain more-or-less constant throughout the future period, changes in metal loads will dictate changes in the concentration at which metals will be delivered to the harbour.

For those subcatchments with any anthropogenic zinc (all except 101, 102, 103 and 105), concentrations are predicted to fall early in the future period, and then level off. This mirrors exactly the predicted zinc runoff in the future period. This is a noteworthy result, since it means that zinc concentration in the estuary bed sediments will spend much of the future period equilibrating with (i.e., approaching asymptotically) the steady concentration of zinc in the land runoff.

The same is not true for copper, however. In this case, anthropogenic copper runoff is predicted to increase throughout the future period, which drives a corresponding increase in the concentration at which copper is delivered to the harbour.

## 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. Reed et al. (2008) described the particle size distribution of the present-day estuarine bed sediments in four size classes (0–8 µm, 8–25 µm, 25–63 µm and >63 µm) from analysis of surface-sediment samples (Table 4.9). The 0–8 µm particle size class was equated with the 4-µm constituent particle size in the USC-3 model; the 8–25 µm particle size class was equated with the 12-µm constituent particle size; the 25–63 µm particle size class was equated with the 40-µm constituent particle size; and the 63–125 µm particle size class was equated with the 125-µm constituent particle size.

The metal concentrations in the surface mixed layer of each subestuary must also be specified at the start of the future period. Reed et al. (2008) also reported the concentration of metal associated with the same four sediment particle size classes (0–8 µm, 8–25 µm, 25–63 µm and >63 µm) (Table 4.10 for zinc, and Table 4.11 for copper). These data were used to initiate the model.

## 4.6 Results

### 4.6.1 Patterns of sediment and contaminant dispersal

#### 4.6.1.1 Fate

The predicted fate of sediment from each subcatchment is shown in Table 4.12 and Figure 4.15. The predicted fate of sediments is virtually identical to 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 that follows is copied, with minor changes, from Green (2008) for the historical period:

- Most of the sediment discharged from subcatchment 101 (Kingseat) is retained in the tidal creek (18–CCK) at the base of the subcatchment.
- Most of the sediment discharged from subcatchment 102 (Elletts Beach) deposits on the adjacent intertidal flats (1–HIB) and the rest is lost to the wider Manukau Harbour. None is deposited in Pahurehure Inlet.
- About 20% of the sediment from subcatchment 103 (Karaka) deposits in Glassons Creek tidal creek (17–GCK) at the base of the subcatchment, and about 30% deposits around the mouth of the tidal creek (2–KKA, 3–GMW, 4–GME, 5–CHN). The sediment that escapes the vicinity of the tidal creek is dispersed widely, including being lost to Manukau Harbour, deposited on the intertidal flats in the southeastern reaches of Manukau Harbour (1–HIB), transported into Drury Creek tidal creek (16–DCI), deposited in the inner reaches of the Inlet (6–DCO, 7–PHI, 8–PBA and 9–PKA), and deposited on the opposite side of the outer reaches of the Inlet (11–WMC).
- About 25% of the sediment from subcatchments 104, 105 and 106 (Whangapouri Creek, Oira Creek and Drury Creek) deposits in the tidal creek (16–DCI) that all of these subcatchments drain into. Drury Creek tidal creek traps a greater proportion (about 25%) of sediment from its adjacent subcatchment(s) than Glassons Creek tidal creek (19%). (It will be seen that Drury Creek tidal creek also traps a

significant fraction of the sediment from the subcatchments that discharge into the inner reaches of Pahurehure Inlet. For instance, 7%, 15%, 17% and 11% of the sediment from subcatchments 108 (Papakura), 109 (Takanini), 110 (Papakura Stream) and 115 (Bottle Top Bay), respectively, is trapped in Drury Creek tidal creek.). The sediment that escapes from the tidal creek is dispersed widely, including being lost to Manukau Harbour. However, compared to sediment that escapes from Glassons Creek tidal creek, sediment that escapes from Drury Creek tidal creek tends to deposit more in the inner reaches of Pahurehure Inlet (6–DCO and 7–PHI).

- Subcatchment 107 (Hingaia) also discharges into Drury Creek tidal creek, but closer to the mouth. Compared to subcatchments 104, 105 and 106, which discharge to the upper reaches of Drury Creek tidal creek, somewhat less sediment from subcatchment 107 is trapped in Drury Creek tidal creek and somewhat more deposits in the inner reaches of Pahurehure Inlet. A little surprisingly, less is lost to Manukau Harbour. Subcatchment 115 (Bottle Top Bay), which discharges at the mouth of Drury Creek tidal creek, extends this pattern, with less sediment deposited inside Drury Creek tidal creek, and more sediment deposited in the inner reaches of Pahurehure Inlet.
- Sediment from subcatchment 108 (Papakura) deposits primarily in the enclosed Pahurehure Basin (8–PBA) at the base of the subcatchment. Continuing the pattern that is being established here, the sediment that escapes the basin is dispersed widely, including being lost to Manukau Harbour, but with deposition mainly in the inner reaches of the Inlet (7–PHI). As noted above, a significant fraction (7%) of the sediment is deposited back up in Drury Creek tidal creek (16–DCI).
- Subcatchment 109 (Takanini) discharges into the inner reaches of Pahurehure Inlet, which captures the largest fraction of the sediment load. Sediment is also carried back into Pahurehure Basin (8–PBA), lost to Manukau Harbour and, as noted above, deposited in Drury Creek tidal creek (16–DCI).
- Subcatchment 110 (Papakura Stream) discharges into the head of Papakura subestuary (9–PKA), which is embayed and which consequently captures the largest fraction of the sediment runoff. Sediment is also deposited in the inner reaches of the Inlet and, as noted previously, in Drury Creek tidal creek (16–DCI). Compared to sediment from subcatchment 109, which discharges further inside the Inlet, more sediment from subcatchment 110 is lost to Manukau Harbour (11% compared to 6%).
- Subcatchment 111 (Manurewa / Weymouth) discharges into the head of Waimahia Creek subestuary (11–WMC). Like the Papakura subestuary, this is embayed and captures the largest fraction of the sediment runoff. Compared to sediment from subcatchment 110, which discharges further inside the Inlet, more sediment from subcatchment 111 deposits in the outer reaches of the Inlet, and slightly more sediment is lost to Manukau Harbour (12% compared to 11%).
- Sediment from subcatchment 112 (Papatoetoe / Puhinui) deposits in Puhinui Creek tidal creek (14–PUK) at the base of the subcatchment, and also disperses widely in

Manukau Harbour, including being deposited on the Weymouth intertidal flats (12–WEY) outside the mouth of the tidal creek.

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

The fate of zinc (Table 4.13) and copper (Table 4.14) from each subcatchment largely mirrors the fate of sediment, but with a few significant differences. Firstly, for the subcatchments that discharge into Pahurehure Inlet, more metal is deposited in the two tidal creeks that drain into the Inlet (Glassons Creek and Drury Creek). Secondly, more metal from, in particular, the subcatchments that drain to the northern shore of Pahurehure Inlet, is lost to Manukau Harbour. Both of these differences are attributable to the fact that metals preferentially attach to the finer sediment particle sizes, which are transported into the sheltered reaches of tidal creeks and lost to Manukau Harbour over the long term.

#### 4.6.1.2 Origin

The predicted source of sediment that deposits in each subestuary is shown in Table 4.15 and summarised in Figures 4.16, 4.17 and 4.18. To be a primary source of sediment for any particular subestuary, there must be a sediment-transport pathway between the subestuary and the subcatchment in question, and the subcatchment must generate sediment. Even if the pathway is tenuous, a subcatchment may still be a principal source if it generates an overwhelming amount of sediment compared to all of the other subcatchments. For this reason, it will be seen that subcatchments 106 (Drury), 110 (Papakura Stream) and 112 (Papatoetoe / Puhinui) are principal sources of sediment to most subestuaries, since these subcatchments generate the most sediment out of all the subcatchments (Table 4.3).

The predicted source of sediments is similar to that described by Green (2008) for the historical period, 1940–2001, which was simulated as part of the calibration of the USC-3 model. The differences relate to differences in the relative dominance of sediment sources. The discussion on sediment source that follows is adapted from Green (2008) for the historical period.

For subestuaries in or around the fringes of Southeastern Manukau Harbour (Figure 4.16):

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

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

For subestuaries in the interior of Pahurehure Inlet (Figure 4.17):

- Karaka subestuary (2–KKA) receives sediment from: Karaka subcatchment (103), which drains into the adjacent Glassons Creek; Drury subcatchment (106), which is the largest sediment generator; and Whangapouri Creek subcatchment (104), which is also a large sediment generator. Still on the southern shore and in the vicinity of the mouth of Glassons Creek, almost the same pattern applies to Glassons Mouth West (3–GMW), Glassons Mouth East (4–GME) and Cape Horn (5–CHN) subestuaries. For the latter two subestuaries, subcatchment 110, which is a principal sediment generator, also makes a notable contribution.
- Subestuaries in the inner reaches of Pahurehure Inlet, which are more sheltered, tend to receive sediment from locally adjacent subcatchments and the principal sediment generators. This includes Drury Creek Outer (6–DCO), Pahurehure Inner (7–PHI) and Papakura (9–PKA).
- Kauri Point (10–KPT) receives sediment mainly from the principal sediment generators, which Green (2008) noted was interesting. As was the case for the intertidal flats of Manukau Harbour, this implies that sediment deposited at Kauri Point is a thorough mixture of sediment from all subcatchments. This seems plausible, given its central, exposed location.
- Waimahia Creek (11-WMC), which is a sheltered embayment, receives sediment mainly from its adjacent subcatchment (111) and the principal sediment generator 106.

For tidal creeks that drain into the interior of Pahurehure Inlet and for Pahurehure Basin (Figure 4.18):

- The pattern of sediment supply to Glassons Creek Inner tidal creek (17–GCK) is very similar to the pattern of supply to the subestuaries at the mouth of the tidal creek (3–GMW, 4–GME and 5–CHN). Green (2008) noted that this is a little unexpected, since the subestuaries around the mouth are more exposed than the tidal creek, and the tidal creek should, as a result, be more dominated by sediment runoff from the subcatchment that it drains. This might indicate a weakness in the model.

- Sediment deposited in Drury Creek Inner tidal creek (16–DCI) comes mainly from the subcatchment that it drains, as expected. Nonetheless, it is notable that a significant fraction comes from the principal sediment generator 110, and it has been previously noted that sediment from many subcatchments does in fact deposit in Drury Creek Inner tidal creek. This highlights the role of tidal creeks as sediment traps, and suggests that the unexpected result concerning Glassons Creek Inner tidal creek may not actually be suspect.
- Finally, sediment deposited in the enclosed Pahurehure Basin (8–PBA) at the head of the Inlet comes mainly from the adjacent subcatchment.

Green (2008) noted that because the fate of zinc and copper is tied closely to the fate of sediment, it is tempting to expect that metal in any particular subestuary will derive from sources in the same proportion that sediment derives from sources. However, that is not necessarily the case. Green (2007) gave the following explanation. Imagine sediment in a particular subestuary derives from sources 1, 2 and 3 in the proportions 50%, 30% and 20%, but metals might derive from sources 1, 2 and 3 in the proportions 0%, 60% and 40%. This occurs when the total catchment metal load is not distributed amongst the subcatchments in the same proportions as the total catchment sediment load. In this case, subcatchment 1 contributes some sediment to the harbour, but it contributes no metal at all.

The source of zinc that deposits in each subestuary is shown in Table 4.16 and summarised in Figures 4.19, 4.20 and 4.21.

The source of copper that deposits in each subestuary is shown in Table 4.17 and summarised in Figures 4.22, 4.23 and 4.24.

For subestuaries in or around the fringes of Southeastern Manukau Harbour (Figure 4.19 for zinc, and Figure 4.22 for copper):

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

For subestuaries in the interior of Pahurehure Inlet (Figure 4.20 for zinc, and Figure 4.23 for copper):

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

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

For tidal creeks that drain into the interior of Pahurehure Inlet and for Pahurehure Basin (Figure 4.21 for zinc, and Figure 4.24 for copper ):

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

### 4.6.2 Sedimentation

The annual-average sedimentation rate in each subestuary predicted for the future period is shown in Table 4.18 and Figure 4.25. For comparison, the annual-average sedimentation rate hindcast for the historical period by Green (2008) is also shown.

Green (2008) noted that the hindcast sedimentation rates by the calibrated model were generally smaller than measured sedimentation rates reported by Reed et al. (2008) from radioisotopic analysis of sediment cores, and that at least part of the reason for this may be that sediment inputs from the wider Manukau Harbour into Pahurehure Inlet, driven by tidal currents and waves, are not accounted for in the model. The predicted sedimentation rates for the future are not greatly different to the hindcast rates, which reflects the fact that sediment runoff for the future period is not predicted to be that much different to hindcast sediment runoff for the historical period (Table 4.19). The greatest differences in sedimentation rate are seen in Puhinui Creek tidal creek (14–PUK) (ratio of predicted to hindcast sedimentation rate of 1.26) and Pahurehure Basin (8–PBA) (ratio of 0.89). The former is explained largely by the increase in the future period of sediment runoff from Papatoetoe / Puhinui subcatchment (112), which is the main source of sediment to Puhinui Creek. The latter is explained largely by the decrease in the future period of sediment runoff from Papakura subcatchment (108), which is the main source of sediment to Pahurehure Basin.

Green (2008) noted that the obvious spatial pattern evident in the core data was the distinction between sedimentation outside Pahurehure Inlet (zero) and inside Pahurehure Inlet (non-zero), which was reproduced for the historical period by the model. The predictions for the future period show the same distinction (Figure 4.26). The core data yielded sedimentation rates inside Pahurehure Inlet of order 10 mm year$^{-1}$, and the model reported hindcast rates for the historical period of that same order, with two exceptions: subestuary 2 (Karaka; $10^{-1}$ mm year$^{-1}$) and subestuary 10 (Kauri Point, also $10^{-1}$ mm year$^{-1}$). The former subestuary is close to the mouth of Pahurehure Inlet, and the latter is in an exposed position in the middle reaches of the inlet. Green (2008) concluded that there was no obvious spatial pattern inside Pahurehure Inlet in either the core data or the model hindcast data. The predictions for the future period also show no obvious spatial pattern inside the Inlet.

However, Figure 4.26, which shows the predicted change in bed-sediment level in each subestuary throughout the future period (as opposed to an annual-average sedimentation rate), does reveal something of a pattern. Specifically (referring to Figure 4.26), more sediment tends to accumulate in the inner reaches of Pahurehure Inlet (subestuaries 6, 7, 8 and 9) than in the outer reaches of Pahurehure Inlet (subestuaries 2, 3, 4, 5, 10 and 11). Furthermore, the tidal creeks that drain to Pahurehure Inlet (16 and 17) accumulate sediment at very much the same rate (as each other). Green (2008), referring to an equivalent plot, concluded the same for the historical period.

### 4.6.3 Metal concentration in estuarine bed sediments

Figures 4.27 to 4.32 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 open areas of the harbour, concentrations will tend to be uniform across subestuaries, but in the side 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).

Table 4.20 (zinc) and Table 4.21 (copper) show 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).

Note that the PEL is not predicted to be exceeded anywhere.

For context and to develop a better understanding of the predictions, the information in Tables 4.20 and 4.21 on sediment-quality guideline threshold exceedance should be considered together with the trends shown in Figures 4.27 to 4.32. Summary figures will be presented in the Conclusions.

- The intertidal flats in Southeastern Manukau Harbour (Hikihiki Bank, Weymouth, Wiroa Island) are predicted to experience only a very slow increase in zinc and copper concentrations in the future period (Figure 4.27), and no sediment-quality guideline threshold is predicted to be exceeded. The defining characteristic of these subestuaries, which are all exposed to large wind fetches across Manukau Harbour, is a very low sedimentation rate. Under a small sedimentation rate, surface-layer 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 the surface mixed layer. It is likely that in the most exposed parts of these intertidal flats, physical mixing is in fact greater than indicated by the 0.04-m mixing depth assumed throughout the USC model domain. A greater mixing depth would be even more effective at retarding any climb in metal concentrations in the surface mixed layer.

- Zinc concentration in the tidal creek that drains to the southern shoreline of Manukau Harbour (Clarks Creek) is predicted to decline from the present-day concentration (Figure 4.28). The reason is that the initial (2001) concentration in Clarks Creek was set to 98 mg $kg^{-1}$ (Table 4.10) (based on analysis of present-day estuarine surface-sediment samples by Reed et al., 2008), yet zinc in the model is delivered to the tidal creek at approximately the natural soil concentration of 35 mg $kg^{-1}$ throughout the future period (This occurs because Clarks Creek tidal creek is largely dominated by runoff from the immediately adjacent Kingseat subcatchment, which has no urban areas). As a result, zinc concentration in the tidal creek is driven <u>downwards</u>. This is a questionable result, for the following reasons. The present-day surface-sediment zinc concentration of 98 mg $kg^{-1}$ reported by Reed et al. (2008) suggests that there is a significant source of metal, other than the immediate subcatchment, to Clarks Creek tidal creek, and/or the concentration at which zinc is carried on soils in the Kingseat subcatchment is much larger than 35 mg $kg^{-1}$. Both of these seem unlikely[3], which suggests that the 98 mg $kg^{-1}$

[3] Although orchards and market gardens in the catchment could provide an additional significant source of metals that would raise soil metal concentrations above the assumed natural level.

measurement is inaccurate. Supporting that suggestion is the fact that the 98 mg $kg^{-1}$ measurement is amongst the highest of any subestuary (Table 4.10).

A second USC future-period simulation was conducted using a different initial (2001) concentration of 39 mg $kg^{-1}$ in Clarks Creek[4]. The result is shown by the blue line in Figure 4.28, which shows a very slow increase in zinc concentration over the future period. No sediment-quality guideline threshold is exceeded. This is the preferred prediction for zinc.

Copper is not predicted to exceed any sediment-quality guideline threshold in Clarks Creek.

- The two tidal creeks that drain to the southern shoreline inside Pahurehure Inlet (Drury Creek Inner and Glassons Creek Inner) are predicted to experience a slow rise in metal concentrations (Figure 4.28).

  For Drury Creek Inner tidal creek, zinc and copper concentrations are predicted to exceed the TEL threshold late in the future period. As noted previously, Drury Creek Inner tidal creek receives zinc and copper mainly from the Drury Creek subcatchment that it drains. This subcatchment is the largest generator of sediment and a significant generator of metals. More to the point, however, is that this subcatchment contains part of the town of Papakura and the town of Drury and a significant fraction of the metals derive from anthropogenic sources. This means that metals are delivered in freshwater at the base of the subcatchment at a concentration that is greater than the concentration that natural metals are attached to soils, which drives a corresponding climb in metal concentrations in the tidal creek.

  For Glassons Creek Inner tidal creek, zinc and copper concentrations are not predicted to exceed the TEL threshold. However, zinc concentration does rise close to the TEL by the end of the future period. Glassons Creek Inner tidal creek receives a significant fraction of its sediment and metal loads from the adjacent Karaka subcatchment. Since this subcatchment has no urban areas, metal loads are delivered at the outlet at the concentration at which they are present naturally in soils. Compared to Drury Creek Inner tidal creek, for instance, this reduces the rate at which metal concentrations in the tidal creek rise.

  It is noteworthy that the initial (2001) zinc concentration in Glassons Creek Inner, based on analysis of present-day estuarine surface-sediment samples by Reed et al. (2008), was 98 mg $kg^{-1}$ (Table 4.10). This is the same as the value reported for Clarks Creek, which, as just noted, is suspect. For the same reasons, the Glassons Creek Inner value is also suspect. Hence, another USC simulation for the future period was conducted, this time using a different initial (2001) concentration of 58 mg $kg^{-1}$ in Glassons Creek Inner[5]. The second simulation, which is shown by the

[4] This concentration was arrived at by running the USC model for the historical period 1940–2001, which yielded a hindcast value for 2001 of 39 mg/kg. The historical-period simulation used model inputs described by Green (2008), with an initial (1940) concentration in Clarks Creek set at 35 mg/kg, which is the concentration at which natural zinc is assumed to be carried on soils in the catchment. The idea in setting that initial concentration is that, over a long period of time, and with no anthropogenic metal inputs, metal concentrations in the estuary would have equilibrated with metal concentrations in sediment runoff from the land.

[5] As before, this was arrived at by running the USC model for the historical period 1940–2001, using model inputs described by Green (2008), which yielded a hindcast value for 2001 of 58 mg/kg for Glassons Creek Inner. As before,

blue line in Figure 4.28, yielded an increase in zinc concentration over the future period that does not rise close to the TEL. This is the preferred prediction.

- Metal concentrations in the two tidal creeks that drain to the northern shoreline of Manukau Harbour are predicted to exceed sediment-quality guideline thresholds (Figure 4.29).

  For Puhinui Creek, the TEL is predicted to be exceeded early in the future period for both zinc and copper, and the zinc ERL is predicted to be exceeded midway in the future period. The copper ERL is on track to being exceeded shortly beyond the close of the future period. Puhinui Creek drains the Papatoetoe / Puhinui subcatchment, which is highly urbanised, and which is the largest generator of both zinc and copper.

  For Pukaki Creek, the zinc and copper TEL is predicted to be exceeded late in the future period, but the ERL is not exceeded in either case. Pukaki Creek deposits runoff mainly from the Mangere East / Papatoetoe and Mangere subcatchments, which it drains. These are less urbanised than the adjacent Papatoetoe / Puhinui subcatchment.

- For subestuaries along the southern shoreline of the outer reaches of Pahurehure Inlet (Karaka, Glassons Mouth West, Glassons Mouth East and Cape Horn), the copper TEL is predicted to be exceeded very late in the future period (Figure 4.30). The same is true for zinc, with the exception of Karaka, for which zinc concentration just reaches the TEL at the end of the future period. These subestuaries do receive runoff from the more urbanised subcatchments on the opposite (i.e., northern) side of the Inlet, but are more influenced by the rural subcatchments that they lie adjacent to on the southern side of the Inlet, including the semi-rural Drury subcatchment. They can be seen as occupying something of a transition zone between the more highly impacted northern shore and inner reaches of Pahurehure Inlet, and the less impacted Manukau Harbour.

- Zinc concentrations in the subestuaries in the inner reaches of Pahurehure Inlet are predicted to exceed the TEL and either exceed or approach the ERL by the end of the future period (Figure 4.31). Copper concentrations are predicted to exceed the TEL.

  For Pahurehure Basin and Pahurehure Inner, which are both at the head of the Inlet, the zinc TEL is exceeded early in the future period and the ERL is exceeded in the middle of the future period. Those exceedances are somewhat delayed in Drury Creek Outer, where the TEL is exceeded later in the future period and the ERL is almost reached by the end of the future period. Copper concentration in Pahurehure Basin and Pahurehure Inner is predicted to exceed the TEL in the middle of the future period, and the TEL exceedance in Drury Creek Outer occurs a little later than that. The copper ERL in all cases is not exceeded. The inner reaches of the Inlet are sheltered, and subestuaries as a result deposit runoff principally from respective adjacent subcatchments. These subcatchments in turn tend to be highly urbanised, which results in metal arriving in high concentrations at

the initial (1940) concentration in Glassons Creek Inner for the historical-period simulation was set at 35 mg/kg, which is the concentration at which natural zinc is assumed to be carried on soils in the catchment.

the respective outlets, which drives a corresponding relatively rapid rise in metal concentrations in the estuary.

- Embayments along the northern shoreline of the outer reaches of Pahurehure Inlet (Papakura and Waimahia Creek) are predicted to exceed sediment-quality guideline thresholds (Figure 4.32). For both Papakura and Waimahia Creek, the zinc TEL is predicted to be exceeded early in the future period, and the zinc ERL is exceeded in the middle of the future period. For both Papakura and Waimahia Creek, the copper TEL is also exceeded early in the future period, but the copper ERL exceedance is delayed relative to the zinc ERL exceedance. For Waimahia Creek, the copper ERL is exceeded late in the future period, and for Papakura the copper ERL is on track to being exceeded shortly beyond the close of the future period. Both of these embayments are sheltered, and deposit metals primarily from their respective adjacent subcatchments, which are highly urbanised.
- Metal concentrations at Kauri Point (Figure 4.32) are not predicted to exceed any threshold. This is in an exposed position and has a low sedimentation rate. Hence, mixing of the surface layer will effectively retard any rise in metal concentrations.

Figures 4.33 to 4.50 show the sensitivity of the Scenario 1 zinc and copper predictions to uncertainty in the total (rural plus urban) sediment runoff and the anthropogenic metal runoff from the catchment.

- Figures 4.33 to 4.38 show the Scenario 1 predictions bracketed by predictions made by: doubling the sediment runoff while keeping the metal runoff unchanged; doubling the metal runoff while keeping the sediment runoff unchanged; and doubling both the sediment and metal runoff.
- Figures 4.39 to 4.44 show the Scenario 1 predictions bracketed by predictions made by: halving the sediment runoff while keeping the metal runoff unchanged; halving the metal runoff while keeping the sediment runoff unchanged; and halving both the sediment and metal runoff.
- Figures 4.45 to 4.50 show the Scenario 1 predictions bracketed by predictions made by: halving the sediment runoff and, at the same time, doubling the metal runoff; and doubling the sediment runoff and, at the same time, halving the metal runoff.

The predictions of metal concentration in the estuary bed sediments are more sensitive to variations in metal runoff than they are to variations in sediment runoff. The reason is that changes in sediment runoff have simultaneously opposing effects on the metal concentration. For instance, reducing the sediment runoff causes the concentration at which metals are delivered to the base of the catchment to increase, which increases the metal concentration in the estuary sediments. But, at the same time, and counteracting that effect, the sedimentation in the harbour is reduced, which causes the metal concentration in the estuary to decrease. This occurs because the surface-layer mixing under the reduced sedimentation rate will be more effective at mixing contaminated sediment from the catchment with less-contaminated pre-existing estuarine sediment. In contrast, a reduction in metal runoff will cause the concentration at which metals are delivered to the base of the catchment to decrease, which decreases the metal concentration in the estuary surface mixed layer, and there is no counteracting effect.

**Table 4.1:**

Split of rural sediment load amongst the 12, 40 and 125 µm constituent particle sizes, predicted by GLEAMS for the year 2001 and applied throughout the future period. The fraction of the sediment load that is assigned to the 4 µm particle size (washload / low-density, slowly-settling flocs) was determined in the calibration process.

| Subcatchment | **Constituent** particle **size (**µm**)** | | |
|---|---|---|---|
| | **12** | **40** | **125** |
| 101 - KST | 0.688 | 0.306 | 0.006 |
| 102 - EBH | 0.446 | 0.552 | 0.002 |
| 103 - KKA | 0.610 | 0.381 | 0.008 |
| 104 - WHC | 0.857 | 0.139 | 0.004 |
| 105 - OIC | 0.914 | 0.085 | 0.001 |
| 106 - DRY | 0.988 | 0.012 | 0.000 |
| 107 - HGA | 0.427 | 0.549 | 0.023 |
| 108 - PKA | 0.908 | 0.092 | 0.000 |
| 109 - TKI | 1.000 | 0.000 | 0.000 |
| 110 - PAS | 1.000 | 0.000 | 0.000 |
| 111 - MAW | – | – | – |
| 112 - PAU | 0.976 | 0.023 | 0.002 |
| 113 - MEP | 0.399 | 0.561 | 0.040 |
| 114 - MGE | 0.491 | 0.468 | 0.041 |
| 115 - BTB | 0.640 | 0.360 | 0.000 |

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**Table 4.2:**

Split of urban sediment load amongst the 12, 40 and 125 µm constituent particle sizes, predicted by the CLM and averaged over all years in the future period. The fraction of the sediment load that is assigned to the 4 µm particle size (washload / low-density, slowly-settling flocs) was determined in the calibration process.

| Subcatchment | **Constituent grainsize (**µm**)** | | |
|---|---|---|---|
| | **12** | **40** | **125** |
| 101 - KST | – | – | – |
| 102 - EBH | – | – | – |
| 103 - KKA | – | – | – |
| 104 - WHC | 0.53 | 0.33 | 0.14 |
| 105 - OIC | – | – | – |
| 106 - DRY | 0.45 | 0.33 | 0.22 |
| 107 - HGA | 0.44 | 0.35 | 0.21 |
| 108 - PKA | 0.55 | 0.31 | 0.13 |
| 109 - TKI | 0.47 | 0.35 | 0.18 |
| 110 - PAS | 0.40 | 0.34 | 0.26 |
| 111 - MAW | 0.47 | 0.34 | 0.20 |
| 112 - PAU | 0.47 | 0.32 | 0.21 |
| 113 - MEP | 0.46 | 0.34 | 0.20 |
| 114 - MGE | 0.59 | 0.27 | 0.14 |
| 115 - BTB | 0.50 | 0.32 | 0.18 |

**Table 4.3:**

Statistics of the total (rural plus urban) sediment runoff. The historical period is shown for comparison. 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.

| Subcatchment | Average per year (kg) | Sum over simulation (kg) | Rank | Rank, historical period |
|---|---|---|---|---|
| 101 - KST | 637,692 | 63,769,180 | 6 | 7 |
| 102 - EBH | 449,302 | 44,930,228 | 9 | 9 |
| 103 - KKA | 569,445 | 56,944,496 | 7 | 8 |
| 104 - WHC | 839,846 | 83,984,552 | 4 | 4 |
| 105 - OIC | 244,061 | 24,406,112 | 11 | 12 |
| 106 - DRY | 3,229,387 | 322,938,656 | 1 | 1 |
| 107 - HGA | 100,079 | 10,007,908 | 13 | 13 |
| 108 - PKA | 497,377 | 49,737,656 | 8 | 6 |
| 109 - TKI | 35,720 | 3,572,033 | 14 | 14 |
| 110 - PAS | 1,483,335 | 148,333,488 | 2 | 2 |
| 111 - MAW | 232,180 | 23,217,994 | 12 | 10 |
| 112 - PAU | 1,226,855 | 122,685,472 | 3 | 3 |
| 113 - MEP | 678,231 | 67,823,080 | 5 | 5 |
| 114 - MGE | 279,038 | 27,903,770 | 10 | 11 |
| 115 - BTB | 16,164 | 1,616,428 | 15 | 15 |

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**Table 4.4:**

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

| Subcatchment | Average (over the simulation) fraction of sediment runoff from urban sources | | |
|---|---|---|---|
| | Future period | Historical period | Ratio, future / historical |
| 101 - KST | 0.00 | 0.00 | 1.00 |
| 102 - EBH | 0.00 | 0.00 | 1.00 |
| 103 - KKA | 0.00 | 0.00 | 1.00 |
| 104 - WHC | 0.33 | 0.26 | 1.29 |
| 105 - OIC | 0.00 | 0.00 | 1.00 |
| 106 - DRY | 0.21 | 0.15 | 1.39 |
| 107 - HGA | 0.56 | 0.16 | 3.50 |
| 108 - PKA | 0.32 | 0.32 | 1.00 |
| 109 - TKI | 0.99 | 0.65 | 1.53 |
| 110 - PAS | 0.33 | 0.26 | 1.24 |
| 111 - MAW | 1.00 | 0.80 | 1.25 |
| 112 - PAU | 0.92 | 0.53 | 1.74 |
| 113 - MEP | 0.27 | 0.30 | 0.90 |
| 114 - MGE | 0.25 | 0.10 | 2.52 |
| 115 - BTB | 1.00 | 0.14 | 7.13 |

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**Table 4.5:**

Split of anthropogenic zinc load amongst the 12, 40 and 125 µm constituent particle sizes, predicted by the CLM and averaged over all years in the future period. The fraction of the zinc load that is assigned to the 4 µm particle size sediment (washload / low-density, slowly-settling flocs) was determined in the calibration process.

| Subcatchment | Constituent grainsize (µm) | | |
|---|---|---|---|
| | 12 | 40 | 125 |
| 101 - KST | – | – | – |
| 102 - EBH | – | – | – |
| 103 - KKA | – | – | – |
| 104 - WHC | 0.51 | 0.32 | 0.17 |
| 105 - OIC | – | – | – |
| 106 - DRY | 0.51 | 0.31 | 0.18 |
| 107 - HGA | 0.50 | 0.32 | 0.18 |
| 108 - PKA | 0.53 | 0.30 | 0.16 |
| 109 - TKI | 0.50 | 0.32 | 0.18 |
| 110 - PAS | 0.50 | 0.31 | 0.18 |
| 111 - MAW | 0.50 | 0.32 | 0.18 |
| 112 - PAU | 0.52 | 0.31 | 0.17 |
| 113 - MEP | 0.51 | 0.31 | 0.18 |
| 114 - MGE | 0.54 | 0.29 | 0.17 |
| 115 - BTB | 0.50 | 0.31 | 0.18 |

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**Table 4.6:**

Split of anthropogenic copper load amongst the 12, 40 and 125 µm constituent particle sizes, predicted by the CLM and averaged over all years in the future period. The fraction of the copper load that is assigned to the 4 µm particle size sediment (washload / low-density, slowly-settling flocs) was determined in the calibration process.

| Subcatchment | Constituent grainsize (µm) | | |
|---|---|---|---|
| | 12 | 40 | 125 |
| 101 - KST | – | – | – |
| 102 - EBH | – | – | – |
| 103 - KKA | – | – | – |
| 104 - WHC | 0.45 | 0.33 | 0.21 |
| 105 - OIC | – | – | – |
| 106 - DRY | 0.45 | 0.33 | 0.23 |
| 107 - HGA | 0.43 | 0.34 | 0.23 |
| 108 - PKA | 0.48 | 0.33 | 0.19 |
| 109 - TKI | 0.43 | 0.34 | 0.23 |
| 110 - PAS | 0.44 | 0.34 | 0.23 |
| 111 - MAW | 0.44 | 0.33 | 0.22 |
| 112 - PAU | 0.48 | 0.32 | 0.21 |
| 113 - MEP | 0.43 | 0.34 | 0.23 |
| 114 - MGE | 0.49 | 0.30 | 0.21 |
| 115 - BTB | 0.43 | 0.34 | 0.23 |

\implement\metal loads\scen 1\SE Manukau Future metal loads for USC scenario 1.xls

**Table 4.7:**

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

| Subcatchment | 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 |
|---|---|---|---|---|
| 101 - KST | 0 | 2,206 | 0.00 | 1.00 |
| 102 - EBH | 0 | 1,555 | 0.00 | 1.00 |
| 103 - KKA | 0 | 1,970 | 0.00 | 1.00 |
| 104 - WHC | 23,969 | 26,875 | 0.89 | 0.11 |
| 105 - OIC | 0 | 844 | 0.00 | 1.00 |
| 106 - DRY | 42,951 | 54,124 | 0.79 | 0.21 |
| 107 - HGA | 5,801 | 6,148 | 0.94 | 0.06 |
| 108 - PKA | 34,312 | 36,033 | 0.95 | 0.05 |
| 109 - TKI | 10,515 | 10,639 | 0.99 | 0.01 |
| 110 - PAS | 46,832 | 51,964 | 0.90 | 0.10 |
| 111 - MAW | 32,597 | 33,400 | 0.98 | 0.02 |
| 112 - PAU | 124,212 | 128,457 | 0.97 | 0.03 |
| 113 - MEP | 18,241 | 20,587 | 0.89 | 0.11 |
| 114 - MGE | 5,194 | 6,159 | 0.84 | 0.16 |
| 115 - BTB | 2,901 | 2,957 | 0.98 | 0.02 |

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**Table 4.8:**

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

| Subcatchment | 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 |
|---|---|---|---|---|
| 101 - KST | 0 | 441 | 0.00 | 1.00 |
| 102 - EBH | 0 | 311 | 0.00 | 1.00 |
| 103 - KKA | 0 | 394 | 0.00 | 1.00 |
| 104 - WHC | 5,709 | 6,291 | 0.91 | 0.09 |
| 105 - OIC | 0 | 169 | 0.00 | 1.00 |
| 106 - DRY | 6,417 | 8,652 | 0.74 | 0.26 |
| 107 - HGA | 1,224 | 1,293 | 0.95 | 0.05 |
| 108 - PKA | 7,171 | 7,515 | 0.95 | 0.05 |
| 109 - TKI | 2,083 | 2,108 | 0.99 | 0.01 |
| 110 - PAS | 8,377 | 9,403 | 0.89 | 0.11 |
| 111 - MAW | 6,967 | 7,127 | 0.98 | 0.02 |
| 112 - PAU | 20,062 | 20,910 | 0.96 | 0.04 |
| 113 - MEP | 2,832 | 3,302 | 0.86 | 0.14 |
| 114 - MGE | 758 | 951 | 0.80 | 0.20 |
| 115 - BTB | 460 | 471 | 0.98 | 0.02 |

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**Table 4.9:**

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

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

Par\implement\estuary bed sediment\present day/grainsize and metal working 1.xls

**Table 4.10:**

Present-day zinc concentration in the surface mixed layer of the estuarine bed sediments reported by Reed et al. (2008) from analysis of surface-sediment samples. The total metal concentration is calculated given the particle size composition reported in Table 4.9.

| Subestuary | Metal concentration, 0–8 µm sediment grainsize (mg/kg) | Metal concentration, 8–25 µm sediment grainsize (mg/kg) | Metal concentration, 25–63 µm sediment grainsize (mg/kg) | Metal concentration, 63–125 µm sediment grainsize (mg/kg) | Total metal concentration (mg/kg) |
|---|---|---|---|---|---|
| 1 – HIB | 84 | 84 | 55 | 40 | 50 |
| 2 – KKA | 95 | 95 | 61 | 50 | 71 |
| 3 – GMW | 89 | 89 | 65 | 55 | 77 |
| 4 – GME | 89 | 89 | 65 | 55 | 77 |
| 5 – CHN | 100 | 100 | 74 | 66 | 76 |
| 6 – DCO | 103 | 103 | 73 | 69 | 74 |
| 7 – PHI | 113 | 113 | 88 | 66 | 91 |
| 8 – PBA | 122 | 122 | 94 | 83 | 108 |
| 9 – PKA | 104 | 104 | 70 | 66 | 97 |
| 10 – KPT | 100 | 100 | 74 | 66 | 76 |
| 11 – WMC | 104 | 104 | 70 | 66 | 97 |
| 12 – WEY | 84 | 84 | 55 | 40 | 50 |
| 13 – WIL | 84 | 84 | 55 | 40 | 50 |
| 14 – PUK | 93 | 93 | 57 | 34 | 80 |
| 15 – PKK | 93 | 93 | 57 | 34 | 80 |
| 16 – DCI | 103 | 103 | 71 | 79 | 83 |
| 17 – GCK | 105 | 105 | 80 | 80 | 98 |
| 18 – CCK | 105 | 105 | 80 | 80 | 98 |
| 19 – MHB | 84 | 84 | 55 | 40 | 50 |

Par\implement\estuary bed sediment\present day/grainsize and metal working 1.xls

**Table 4.11:**

Present-day copper concentration in the surface mixed layer of the estuarine bed sediments reported by Reed et al. (2008) from analysis of surface-sediment samples. The total metal concentration is calculated given the particle size composition reported in Table 4.9.

| Subestuary | Metal concentration, 0–8 μm sediment grainsize (mg/kg) | Metal concentration, 8–25 μm sediment grainsize (mg/kg) | Metal concentration, 25–63 μm sediment grainsize (mg/kg) | Metal concentration, 63–125 μm sediment grainsize (mg/kg) | Total metal concentration (mg/kg) |
|---|---|---|---|---|---|
| 1 – HIB | 11 | 11 | 7 | 4 | 6 |
| 2 – KKA | 12 | 12 | 8 | 5 | 9 |
| 3 – GMW | 12 | 12 | 8 | 6 | 10 |
| 4 – GME | 12 | 12 | 8 | 6 | 10 |
| 5 – CHN | 13 | 13 | 9 | 8 | 9 |
| 6 – DCO | 12 | 12 | 9 | 9 | 9 |
| 7 – PHI | 13 | 13 | 10 | 7 | 10 |
| 8 – PBA | 13 | 13 | 10 | 10 | 12 |
| 9 – PKA | 13 | 13 | 9 | 8 | 12 |
| 10 – KPT | 13 | 13 | 9 | 8 | 9 |
| 11 – WMC | 13 | 13 | 9 | 8 | 12 |
| 12 – WEY | 11 | 11 | 7 | 4 | 6 |
| 13 – WIL | 11 | 11 | 7 | 4 | 6 |
| 14 – PUK | 13 | 13 | 7 | 4 | 11 |
| 15 – PKK | 13 | 13 | 7 | 4 | 11 |
| 16 – DCI | 13 | 13 | 9 | 11 | 11 |
| 17 – GCK | 13 | 13 | 10 | 10 | 12 |
| 18 – CCK | 13 | 13 | 10 | 10 | 12 |
| 19 – MHB | 11 | 11 | 7 | 4 | 6 |

Par\implement\estuary bed sediment\present day/grainsize and metal working 1.xls

**Table 4.12:**

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

## FATE – Sediment

| Subcatchment | Subestuary | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1-HIB | 2-KKA | 3-GMW | 4-GME | 5-CHN | 6-DCO | 7-PHI | 8-PBA | 9-PKA | 10-KPT | 11-WMC | 12-WEY | 13-WIL | 14-PUK | 15-PKK | 16-DCI | 17-GCK | 18-CCK | 19-MHB |
| *Discharge to southeastern shoreline of Manukau Harbour* | | | | | | | | | | | | | | | | | | | |
| **101 - KST** | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 98 | 1 |
| **102 - EBH** | 69 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 25 |
| *Discharge to southern shoreline of Pahurehure Inlet* | | | | | | | | | | | | | | | | | | | |
| **103 - KKA** | 4 | 3 | 15 | 9 | 3 | 6 | 9 | 1 | 5 | 0 | 4 | 2 | 0 | 2 | 2 | 8 | 19 | 0 | 9 |
| **104 - WHC** | 3 | 1 | 3 | 3 | 1 | 15 | 16 | 2 | 9 | 0 | 3 | 1 | 0 | 1 | 1 | 26 | 5 | 0 | 8 |
| **105 - OIC** | 3 | 1 | 3 | 3 | 1 | 15 | 16 | 2 | 9 | 0 | 3 | 2 | 0 | 1 | 1 | 25 | 5 | 0 | 8 |
| **106 - DRY** | 3 | 1 | 3 | 3 | 1 | 15 | 16 | 2 | 9 | 0 | 3 | 2 | 0 | 1 | 1 | 25 | 5 | 0 | 9 |
| **107 - HGA** | 2 | 1 | 3 | 3 | 1 | 22 | 19 | 6 | 11 | 0 | 3 | 1 | 0 | 1 | 1 | 21 | 4 | 0 | 2 |
| *Discharge to Pahurehure Basin* | | | | | | | | | | | | | | | | | | | |
| **108 - PKA** | 3 | 0 | 0 | 1 | 0 | 2 | 12 | 62 | 4 | 0 | 2 | 1 | 0 | 1 | 1 | 7 | 1 | 0 | 4 |
| *Discharge to northern shoreline of Pahurehure Inlet* | | | | | | | | | | | | | | | | | | | |
| **109 - TKI** | 4 | 0 | 0 | 1 | 0 | 8 | 40 | 7 | 8 | 0 | 3 | 2 | 0 | 1 | 1 | 15 | 2 | 0 | 6 |
| **110 - PAS** | 5 | 0 | 1 | 2 | 1 | 6 | 13 | 2 | 28 | 0 | 4 | 2 | 1 | 2 | 2 | 17 | 3 | 1 | 11 |
| **111 - MAW** | 3 | 2 | 2 | 8 | 1 | 0 | 1 | 0 | 1 | 0 | 63 | 1 | 0 | 1 | 1 | 2 | 1 | 0 | 12 |
| *Discharge to northeastern shoreline of Manukau Harbour* | | | | | | | | | | | | | | | | | | | |
| **112 - PAU** | 9 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 2 | 0 | 2 | 13 | 1 | 30 | 5 | 3 | 1 | 1 | 28 |
| **113 - MEP** | 4 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 3 | 0 | 1 | 76 | 1 | 1 | 0 | 11 |
| **114 - MGE** | 4 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 3 | 0 | 1 | 74 | 1 | 1 | 0 | 12 |
| *Discharge to southern shoreline of Pahurehure Inlet* | | | | | | | | | | | | | | | | | | | |
| **115 - BTB** | 2 | 0 | 1 | 3 | 1 | 41 | 20 | 4 | 9 | 0 | 2 | 1 | 0 | 1 | 1 | 11 | 2 | 0 | 3 |

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**Table 4.13:**

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

## FATE – Zinc

| Subcatchment | Subestuary | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1-HIB | 2-KKA | 3-GMW | 4-GME | 5-CHN | 6-DCO | 7-PHI | 8-PBA | 9-PKA | 10-KPT | 11-WMC | 12-WEY | 13-WIL | 14-PUK | 15-PKK | 16-DCI | 17-GCK | 18-CCK | 19-MHB |
| *Discharge to southeastern shoreline of Manukau Harbour* | | | | | | | | | | | | | | | | | | | |
| **101 - KST** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 98 | 1 |
| **102 - EBH** | 47 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 47 |
| *Discharge to southern shoreline of Pahurehure Inlet* | | | | | | | | | | | | | | | | | | | |
| **103 - KKA** | 3 | 2 | 12 | 7 | 3 | 5 | 7 | 1 | 4 | 0 | 3 | 2 | 0 | 1 | 2 | 7 | 33 | 0 | 8 |
| **104 - WHC** | 2 | 1 | 2 | 3 | 1 | 14 | 14 | 2 | 8 | 0 | 2 | 1 | 0 | 1 | 1 | 40 | 3 | 0 | 5 |
| **105 - OIC** | 2 | 1 | 2 | 3 | 1 | 13 | 14 | 2 | 8 | 0 | 2 | 1 | 0 | 1 | 1 | 40 | 3 | 0 | 5 |
| **106 - DRY** | 2 | 1 | 2 | 3 | 1 | 13 | 14 | 2 | 8 | 0 | 2 | 1 | 0 | 1 | 1 | 41 | 3 | 0 | 5 |
| **107 - HGA** | 2 | 1 | 3 | 2 | 1 | 17 | 15 | 5 | 9 | 0 | 2 | 1 | 0 | 1 | 1 | 27 | 3 | 0 | 9 |
| *Discharge to Pahurehure Basin* | | | | | | | | | | | | | | | | | | | |
| **108 - PKA** | 2 | 0 | 0 | 0 | 0 | 4 | 12 | 59 | 3 | 0 | 1 | 1 | 0 | 0 | 1 | 4 | 1 | 0 | 11 |
| *Discharge to northern shoreline of Pahurehure Inlet* | | | | | | | | | | | | | | | | | | | |
| **109 - TKI** | 2 | 0 | 0 | 1 | 0 | 9 | 43 | 6 | 11 | 0 | 2 | 1 | 0 | 1 | 1 | 9 | 1 | 0 | 12 |
| **110 - PAS** | 3 | 0 | 1 | 2 | 1 | 7 | 15 | 2 | 35 | 0 | 2 | 1 | 0 | 1 | 1 | 9 | 2 | 0 | 18 |
| **111 - MAW** | 3 | 2 | 2 | 6 | 1 | 1 | 1 | 0 | 1 | 0 | 49 | 1 | 0 | 1 | 1 | 2 | 1 | 0 | 27 |
| *Discharge to northeastern shoreline of Manukau Harbour* | | | | | | | | | | | | | | | | | | | |
| **112 - PAU** | 8 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 2 | 17 | 1 | 40 | 4 | 3 | 1 | 1 | 19 |
| **113 - MEP** | 3 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 2 | 0 | 1 | 76 | 1 | 0 | 0 | 12 |
| **114 - MGE** | 4 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 2 | 0 | 1 | 75 | 1 | 1 | 0 | 12 |
| *Discharge to southern shoreline of Pahurehure Inlet* | | | | | | | | | | | | | | | | | | | |
| **115 - BTB** | 2 | 0 | 1 | 2 | 1 | 26 | 19 | 4 | 9 | 0 | 2 | 1 | 0 | 1 | 1 | 14 | 2 | 0 | 16 |

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**Table 4.14:**

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

## FATE – Copper

| Subcatchment | Subestuary | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1-HIB | 2-KKA | 3-GMW | 4-GME | 5-CHN | 6-DCO | 7-PHI | 8-PBA | 9-PKA | 10-KPT | 11-WMC | 12-WEY | 13-WIL | 14-PUK | 15-PKK | 16-DCI | 17-GCK | 18-CCK | 19-MHB |
| *Discharge to southeastern shoreline of Manukau Harbour* | | | | | | | | | | | | | | | | | | | |
| **101 - KST** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 98 | 1 |
| **102 - EBH** | 47 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 48 |
| *Discharge to southern shoreline of Pahurehure Inlet* | | | | | | | | | | | | | | | | | | | |
| **103 - KKA** | 3 | 2 | 11 | 7 | 2 | 4 | 6 | 1 | 4 | 0 | 3 | 2 | 0 | 1 | 1 | 6 | 40 | 0 | 6 |
| **104 - WHC** | 2 | 1 | 2 | 3 | 1 | 13 | 14 | 2 | 8 | 0 | 2 | 1 | 0 | 1 | 1 | 43 | 3 | 0 | 4 |
| **105 - OIC** | 2 | 1 | 2 | 3 | 1 | 13 | 13 | 2 | 7 | 0 | 2 | 1 | 0 | 1 | 1 | 46 | 3 | 0 | 4 |
| **106 - DRY** | 2 | 1 | 2 | 3 | 1 | 13 | 13 | 2 | 8 | 0 | 2 | 1 | 0 | 1 | 1 | 44 | 3 | 0 | 4 |
| **107 - HGA** | 2 | 2 | 4 | 2 | 1 | 17 | 14 | 4 | 8 | 0 | 2 | 1 | 0 | 1 | 1 | 28 | 3 | 0 | 10 |
| *Discharge to Pahurehure Basin* | | | | | | | | | | | | | | | | | | | |
| **108 - PKA** | 2 | 0 | 0 | 0 | 0 | 4 | 12 | 58 | 3 | 0 | 1 | 1 | 0 | 0 | 1 | 4 | 1 | 0 | 12 |
| *Discharge to northern shoreline of Pahurehure Inlet* | | | | | | | | | | | | | | | | | | | |
| **109 - TKI** | 2 | 0 | 0 | 1 | 0 | 10 | 42 | 6 | 12 | 0 | 2 | 1 | 0 | 1 | 1 | 7 | 1 | 0 | 15 |
| **110 - PAS** | 2 | 0 | 1 | 2 | 1 | 7 | 15 | 2 | 35 | 0 | 2 | 1 | 0 | 1 | 1 | 8 | 1 | 0 | 20 |
| **111 - MAW** | 3 | 1 | 2 | 6 | 1 | 0 | 1 | 0 | 1 | 0 | 47 | 1 | 0 | 1 | 1 | 2 | 1 | 0 | 31 |
| *Discharge to northeastern shoreline of Manukau Harbour* | | | | | | | | | | | | | | | | | | | |
| **112 - PAU** | 7 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 2 | 17 | 1 | 42 | 4 | 2 | 1 | 1 | 18 |
| **113 - MEP** | 3 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 2 | 0 | 1 | 79 | 1 | 0 | 0 | 10 |
| **114 - MGE** | 3 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 2 | 0 | 1 | 77 | 1 | 0 | 0 | 11 |
| *Discharge to southern shoreline of Pahurehure Inlet* | | | | | | | | | | | | | | | | | | | |
| **115 - BTB** | 2 | 0 | 1 | 2 | 1 | 26 | 19 | 4 | 9 | 0 | 2 | 1 | 0 | 1 | 1 | 12 | 2 | 0 | 19 |

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**Table 4.15:**

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

SOURCE – Sediment

| Subestuary | Subcatchment | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 101 KST | 102 EBH | 103 KKA | 104 WHC | 105 OIC | 106 DRY | 107 HGA | 108 PKA | 109 TKI | 110 PAS | 111 MAW | 112 PAU | 113 MEP | 114 MGE | 115 BTB |
| *Manukau Harbour* | | | | | | | | | | | | | | | |
| **1-HIB** | 1 | 43 | 3 | 3 | 1 | 14 | 0 | 2 | 0 | 11 | 1 | 15 | 3 | 2 | 0 |
| *Southern / outer Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **2-KKA** | 0 | 0 | 26 | 12 | 3 | 45 | 1 | 0 | 0 | 2 | 8 | 2 | 1 | 0 | 0 |
| **3-GMW** | 0 | 0 | 38 | 10 | 3 | 40 | 1 | 0 | 0 | 6 | 2 | 0 | 0 | 0 | 0 |
| **4-GME** | 0 | 0 | 18 | 10 | 3 | 40 | 1 | 1 | 0 | 12 | 7 | 5 | 2 | 1 | 0 |
| **5-CHN** | 0 | 0 | 23 | 11 | 3 | 42 | 1 | 1 | 0 | 14 | 4 | 1 | 0 | 0 | 0 |
| *Inner Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **6-DCO** | 0 | 0 | 4 | 16 | 5 | 58 | 3 | 1 | 0 | 11 | 0 | 1 | 0 | 0 | 1 |
| **7-PHI** | 0 | 0 | 5 | 13 | 4 | 49 | 2 | 6 | 1 | 18 | 0 | 1 | 0 | 0 | 0 |
| *Pahurehure Basin* | | | | | | | | | | | | | | | |
| **8-PBA** | 0 | 0 | 1 | 4 | 1 | 16 | 1 | 68 | 1 | 6 | 0 | 1 | 0 | 0 | 0 |
| *Northern / outer Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **9-PKA** | 0 | 0 | 3 | 9 | 2 | 32 | 1 | 2 | 0 | 46 | 0 | 2 | 1 | 0 | 0 |
| **10-KPT** | 0 | 2 | 6 | 6 | 2 | 27 | 1 | 5 | 0 | 20 | 1 | 17 | 9 | 4 | 0 |
| **11-WMC** | 0 | 0 | 6 | 6 | 2 | 24 | 1 | 2 | 0 | 13 | 36 | 7 | 2 | 1 | 0 |
| *Manukau Harbour* | | | | | | | | | | | | | | | |
| **12-WEY** | 0 | 2 | 4 | 4 | 1 | 16 | 0 | 2 | 0 | 11 | 1 | 49 | 6 | 3 | 0 |
| **13-WIL** | 0 | 4 | 4 | 6 | 2 | 27 | 0 | 4 | 0 | 22 | 2 | 22 | 4 | 2 | 0 |
| *Tidal creeks draining to Manukau Harbour* | | | | | | | | | | | | | | | |
| **14-PUK** | 0 | 0 | 2 | 2 | 1 | 10 | 0 | 1 | 0 | 6 | 0 | 76 | 1 | 0 | 0 |
| **15-PKK** | 0 | 0 | 1 | 1 | 0 | 5 | 0 | 1 | 0 | 4 | 0 | 7 | 57 | 23 | 0 |
| *Tidal creeks draining to Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **16-DCI** | 0 | 0 | 3 | 14 | 4 | 54 | 1 | 2 | 0 | 17 | 0 | 3 | 0 | 0 | 0 |
| **17-GCK** | 0 | 0 | 27 | 10 | 3 | 40 | 1 | 1 | 0 | 11 | 0 | 4 | 1 | 0 | 0 |
| **18-CCK** | 93 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 2 | 0 | 0 | 0 |
| **19-MHB** | 1 | 9 | 4 | 5 | 2 | 24 | 0 | 2 | 0 | 13 | 2 | 29 | 6 | 3 | 0 |

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**Table 4.16:**

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

# SOURCE – Zinc

| Subestuary | Subcatchment | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **101 KST** | **102 EBH** | **103 KKA** | **104 WHC** | **105 OIC** | **106 DRY** | **107 HGA** | **108 PKA** | **109 TKI** | **110 PAS** | **111 MAW** | **112 PAU** | **113 MEP** | **114 MGE** | **115 BTB** |
| *Manukau Harbour* | | | | | | | | | | | | | | | |
| **1-HIB** | 0 | 4 | 0 | 3 | 0 | 6 | 1 | 4 | 1 | 9 | 6 | 59 | 4 | 1 | 0 |
| *Southern / outer Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **2-KKA** | 0 | 0 | 3 | 13 | 0 | 26 | 7 | 0 | 0 | 1 | 39 | 8 | 1 | 0 | 0 |
| **3-GMW** | 0 | 0 | 7 | 18 | 1 | 35 | 6 | 0 | 0 | 17 | 16 | 0 | 0 | 0 | 1 |
| **4-GME** | 0 | 0 | 2 | 10 | 0 | 20 | 2 | 2 | 1 | 13 | 28 | 18 | 1 | 0 | 1 |
| **5-CHN** | 0 | 0 | 3 | 13 | 0 | 26 | 2 | 1 | 0 | 25 | 21 | 5 | 0 | 0 | 1 |
| *Inner Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **6-DCO** | 0 | 0 | 0 | 18 | 1 | 36 | 5 | 7 | 5 | 18 | 1 | 4 | 0 | 0 | 4 |
| **7-PHI** | 0 | 0 | 0 | 12 | 0 | 24 | 3 | 14 | 14 | 25 | 1 | 4 | 0 | 0 | 2 |
| *Pahurehure Basin* | | | | | | | | | | | | | | | |
| **8-PBA** | 0 | 0 | 0 | 2 | 0 | 4 | 1 | 84 | 3 | 3 | 0 | 2 | 0 | 0 | 0 |
| *Northern / outer Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **9-PKA** | 0 | 0 | 0 | 7 | 0 | 14 | 2 | 4 | 4 | 60 | 1 | 6 | 0 | 0 | 1 |
| **10-KPT** | 0 | 0 | 1 | 4 | 0 | 8 | 1 | 7 | 2 | 11 | 7 | 50 | 6 | 2 | 1 |
| **11-WMC** | 0 | 0 | 0 | 3 | 0 | 5 | 1 | 2 | 1 | 4 | 71 | 11 | 1 | 0 | 0 |
| *Manukau Harbour* | | | | | | | | | | | | | | | |
| **12-WEY** | 0 | 0 | 0 | 1 | 0 | 2 | 0 | 1 | 0 | 3 | 2 | 88 | 2 | 1 | 0 |
| **13-WIL** | 0 | 1 | 0 | 4 | 0 | 7 | 1 | 7 | 2 | 12 | 9 | 51 | 4 | 1 | 1 |
| *Tidal creeks draining to Manukau Harbour* | | | | | | | | | | | | | | | |
| **14-PUK** | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 96 | 0 | 0 | 0 |
| **15-PKK** | 0 | 0 | 0 | 1 | 0 | 2 | 0 | 1 | 0 | 2 | 2 | 20 | 56 | 16 | 0 |
| *Tidal creeks draining to Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **16-DCI** | 0 | 0 | 0 | 23 | 1 | 47 | 3 | 3 | 2 | 10 | 2 | 7 | 0 | 0 | 1 |
| **17-GCK** | 0 | 0 | 10 | 14 | 0 | 28 | 3 | 4 | 2 | 12 | 3 | 21 | 1 | 0 | 1 |
| **18-CCK** | 59 | 1 | 0 | 1 | 0 | 2 | 0 | 2 | 1 | 4 | 3 | 25 | 2 | 1 | 0 |
| **19-MHB** | 0 | 1 | 0 | 2 | 0 | 5 | 1 | 7 | 2 | 16 | 16 | 43 | 4 | 1 | 1 |

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**Table 4.17:**

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

SOURCE – Copper

| Subestuary | Subcatchment | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 101 KST | 102 EBH | 103 KKA | 104 WHC | 105 OIC | 106 DRY | 107 HGA | 108 PKA | 109 TKI | 110 PAS | 111 MAW | 112 PAU | 113 MEP | 114 MGE | 115 BTB |
| *Manukau Harbour* | | | | | | | | | | | | | | | |
| **1-HIB** | 0 | 5 | 0 | 4 | 0 | 5 | 1 | 4 | 1 | 9 | 7 | 57 | 4 | 1 | 0 |
| *Southern / outer Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **2-KKA** | 0 | 0 | 3 | 15 | 0 | 21 | 8 | 0 | 0 | 1 | 43 | 7 | 1 | 0 | 0 |
| **3-GMW** | 0 | 0 | 7 | 21 | 1 | 29 | 8 | 0 | 0 | 16 | 18 | 0 | 0 | 0 | 1 |
| **4-GME** | 0 | 0 | 2 | 13 | 0 | 17 | 2 | 2 | 1 | 12 | 32 | 16 | 1 | 0 | 1 |
| **5-CHN** | 0 | 0 | 3 | 16 | 0 | 22 | 3 | 1 | 0 | 25 | 24 | 4 | 0 | 0 | 1 |
| *Inner Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **6-DCO** | 0 | 0 | 0 | 22 | 1 | 30 | 6 | 8 | 5 | 19 | 1 | 4 | 0 | 0 | 3 |
| **7-PHI** | 0 | 0 | 0 | 15 | 0 | 20 | 3 | 16 | 15 | 25 | 1 | 3 | 0 | 0 | 2 |
| *Pahurehure Basin* | | | | | | | | | | | | | | | |
| **8-PBA** | 0 | 0 | 0 | 2 | 0 | 3 | 1 | 86 | 3 | 3 | 0 | 1 | 0 | 0 | 0 |
| *Northern / outer Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **9-PKA** | 0 | 0 | 0 | 9 | 0 | 12 | 2 | 5 | 5 | 60 | 1 | 5 | 0 | 0 | 1 |
| **10-KPT** | 0 | 0 | 1 | 5 | 0 | 7 | 1 | 8 | 2 | 11 | 8 | 48 | 6 | 2 | 0 |
| **11-WMC** | 0 | 0 | 0 | 3 | 0 | 4 | 1 | 2 | 1 | 4 | 76 | 9 | 1 | 0 | 0 |
| *Manukau Harbour* | | | | | | | | | | | | | | | |
| **12-WEY** | 0 | 0 | 0 | 2 | 0 | 2 | 0 | 1 | 0 | 3 | 2 | 87 | 2 | 1 | 0 |
| **13-WIL** | 0 | 0 | 0 | 5 | 0 | 7 | 1 | 8 | 2 | 12 | 10 | 49 | 4 | 1 | 0 |
| *Tidal creeks draining to Manukau Harbour* | | | | | | | | | | | | | | | |
| **14-PUK** | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 96 | 0 | 0 | 0 |
| **15-PKK** | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 2 | 2 | 19 | 57 | 16 | 0 |
| *Tidal creeks draining to Pahurehure Inlet* | | | | | | | | | | | | | | | |
| **16-DCI** | 0 | 0 | 0 | 30 | 1 | 43 | 4 | 3 | 2 | 8 | 2 | 6 | 0 | 0 | 1 |
| **17-GCK** | 0 | 0 | 14 | 17 | 0 | 23 | 4 | 4 | 2 | 11 | 4 | 19 | 1 | 0 | 1 |
| **18-CCK** | 64 | 0 | 0 | 1 | 0 | 2 | 0 | 2 | 1 | 3 | 3 | 21 | 1 | 0 | 0 |
| **19-MHB** | 0 | 1 | 0 | 3 | 0 | 3 | 1 | 9 | 3 | 18 | 21 | 35 | 3 | 1 | 1 |

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**Table 4.18:**

Sedimentation rate. "Predicted" is the predicted average over the future period and over 50 model runs. "Hindcast" is the hindcast average over the historical period and over 50 model runs reported by Green (2008).

| Subestuary | Hindcast, mm/year | Predicted, mm/year | Predicted / hindcast |
|---|---|---|---|
| 1 – HIB | 0.02 | 0.03 | 1.07 |
| 2 – KKA | 0.58 | 0.62 | 1.06 |
| 3 – GMW | 5.14 | 5.57 | 1.08 |
| 4 – GME | 1.70 | 1.82 | 1.07 |
| 5 – CHN | 1.18 | 1.27 | 1.08 |
| 6 – DCO | 3.03 | 3.30 | 1.09 |
| 7 – PHI | 2.28 | 2.45 | 1.07 |
| 8 – PBA | 4.86 | 4.34 | 0.89 |
| 9 – PKA | 2.37 | 2.56 | 1.08 |
| 10 – KPT | 0.14 | 0.15 | 1.08 |
| 11 – WMC | 1.49 | 1.44 | 0.96 |
| 12 – WEY | 0.04 | 0.04 | 1.15 |
| 13 – WIL | 0.01 | 0.01 | 1.10 |
| 14 – PUK | 2.86 | 3.61 | 1.26 |
| 15 – PKK | 1.73 | 1.67 | 0.96 |
| 16 – DCI | 1.52 | 1.66 | 1.09 |
| 17 – GCK | 1.55 | 1.69 | 1.09 |
| 18 – CCK | 1.07 | 1.17 | 1.08 |
| 19 – MHB | - | - | - |

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**Table 4.19:**

Ratio of the annual average total (rural plus urban) sediment runoff during the future period under Scenario 1 and during the historical period 1940–2001 hindcast by Green (2008).

| Subcatchment | Ratio |
|---|---|
| 101 - KST | 1.08 |
| 102 - EBH | 1.04 |
| 103 - KKA | 1.07 |
| 104 - WHC | 1.07 |
| 105 - OIC | 1.04 |
| 106 - DRY | 1.13 |
| 107 - HGA | 0.93 |
| 108 - PKA | 0.83 |
| 109 - TKI | 0.78 |
| 110 - PAS | 1.07 |
| 111 - MAW | 0.79 |
| 112 - PAU | 1.33 |
| 113 - MEP | 0.92 |
| 114 - MGE | 0.96 |
| 115 - BTB | 0.58 |

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**Table 4.20:**

Times (years from 2001) at which zinc 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.

| | Zinc | | |
|---|---|---|---|
| **Subestuary** | **TEL** | **ERL** | **PEL** |
| 1-HIB | - | - | - |
| 2-KKA | - | - | - |
| 3-GMW | 90 | - | - |
| 4-GME | 80 | - | - |
| 5-CHN | 94 | - | - |
| 6-DCO | 72 | - | - |
| 7-PHI | 37 | 68 | - |
| 8-PBA | 18 | 62 | - |
| 9-PKA | 25 | 51 | - |
| 10-KPT | - | - | - |
| 11-WMC | 27 | 51 | - |
| 12-WEY | - | - | - |
| 13-WIL | - | - | - |
| 14-PUK | 35 | 57 | - |
| 15-PKK | 79 | - | - |
| 16-DCI | 90 | - | - |
| 17-GCK | - | - | - |
| 18-CCK | - | - | - |

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**Table 4.21:**

Times (years from 2001) at which copper 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.

| | Copper | | |
|---|---|---|---|
| **Subestuary** | **TEL** | **ERL** | **PEL** |
| 1-HIB | - | - | - |
| 2-KKA | 93 | - | - |
| 3-GMW | 72 | - | - |
| 4-GME | 76 | - | - |
| 5-CHN | 85 | - | - |
| 6-DCO | 67 | - | - |
| 7-PHI | 51 | - | - |
| 8-PBA | 53 | - | - |
| 9-PKA | 37 | - | - |
| 10-KPT | - | - | - |
| 11-WMC | 34 | 93 | - |
| 12-WEY | - | - | - |
| 13-WIL | - | - | - |
| 14-PUK | 42 | - | - |
| 15-PKK | 83 | - | - |
| 16-DCI | 66 | - | - |
| 17-GCK | - | - | - |
| 18-CCK | - | - | - |

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**Figure 4.1:**

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

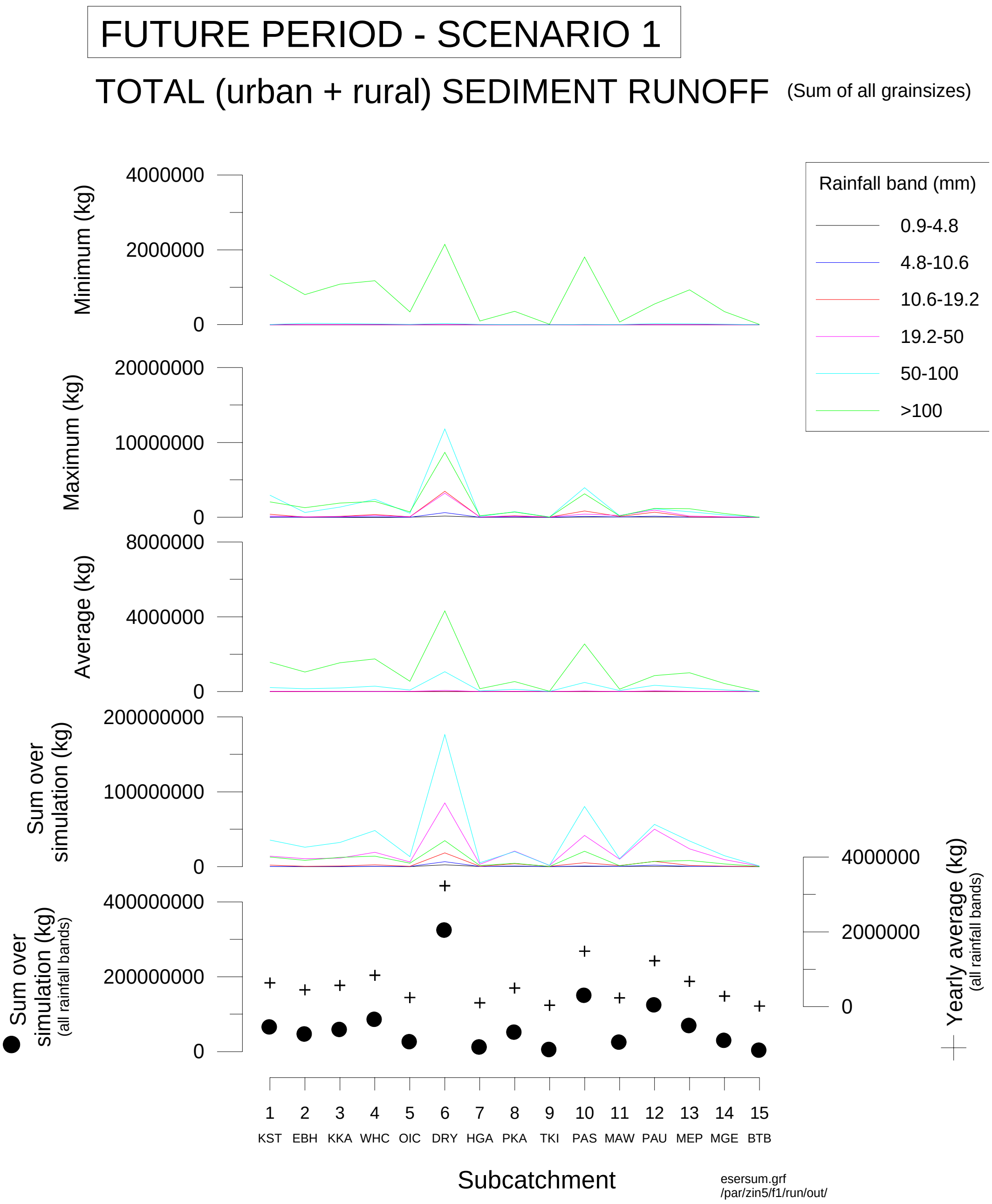


**Figure 4.2:**

Annual sediment runoff. This is the sum of all particle 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 4.3:**

Comparison of the annual sediment runoff for the historical period (1940–2001) and the future period (2001–2100). 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.

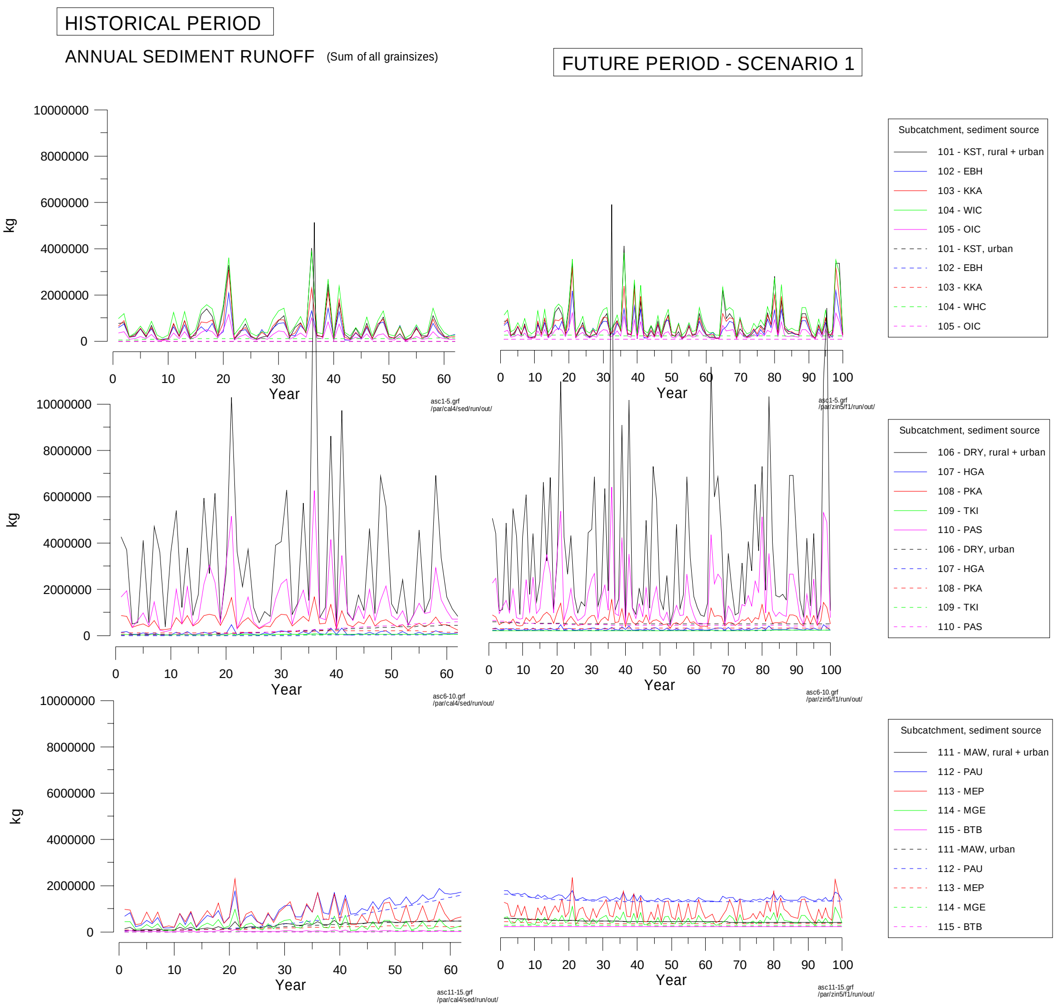


**Figure 4.4:**

Fraction of the annual sediment runoff in each subcatchment that comes from urban sources. The rest comes from rural sources. Year 1 is 2001 and year 100 is 2100.

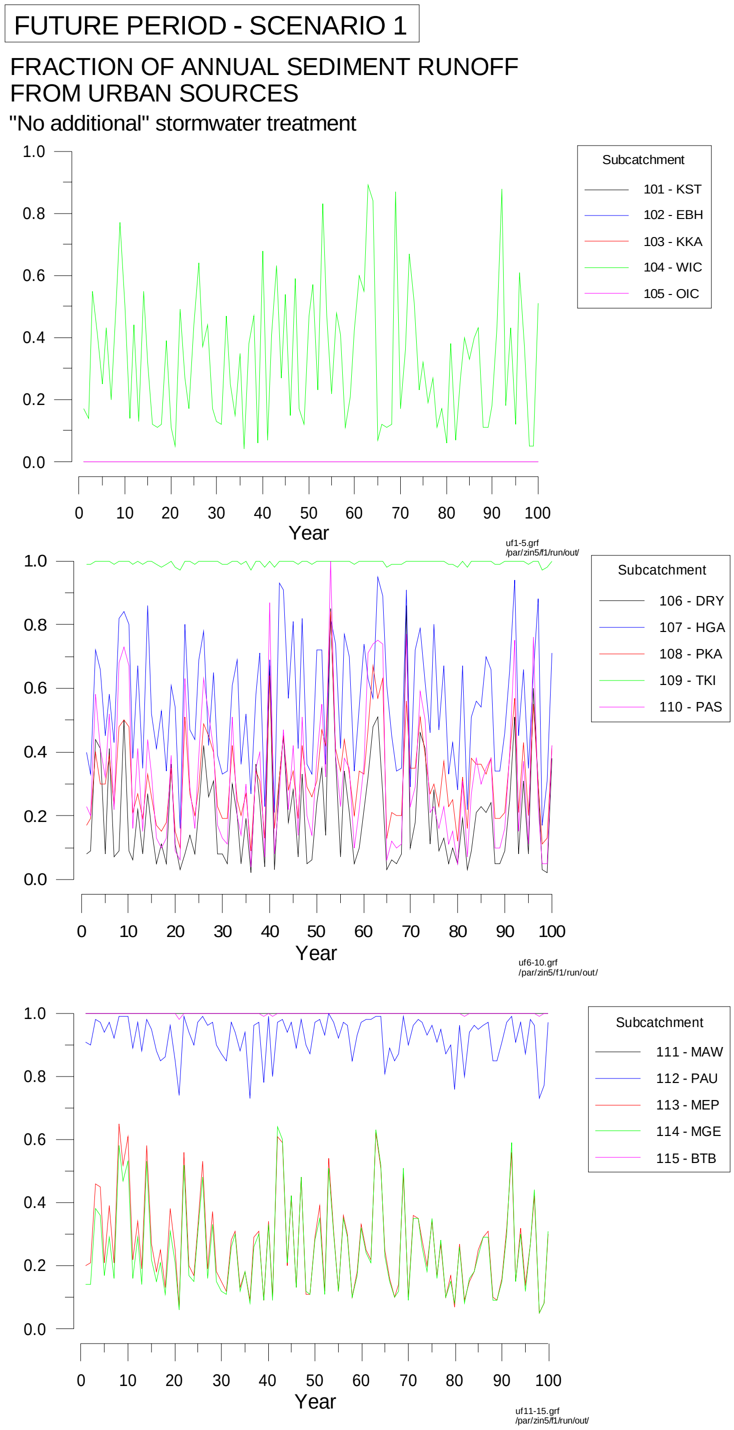


**Figure 4.5:**

Comparison of the fraction of the annual sediment runoff in each subcatchment that comes from urban sources for the historical period (1940–2001) and the future period (2001–2100).

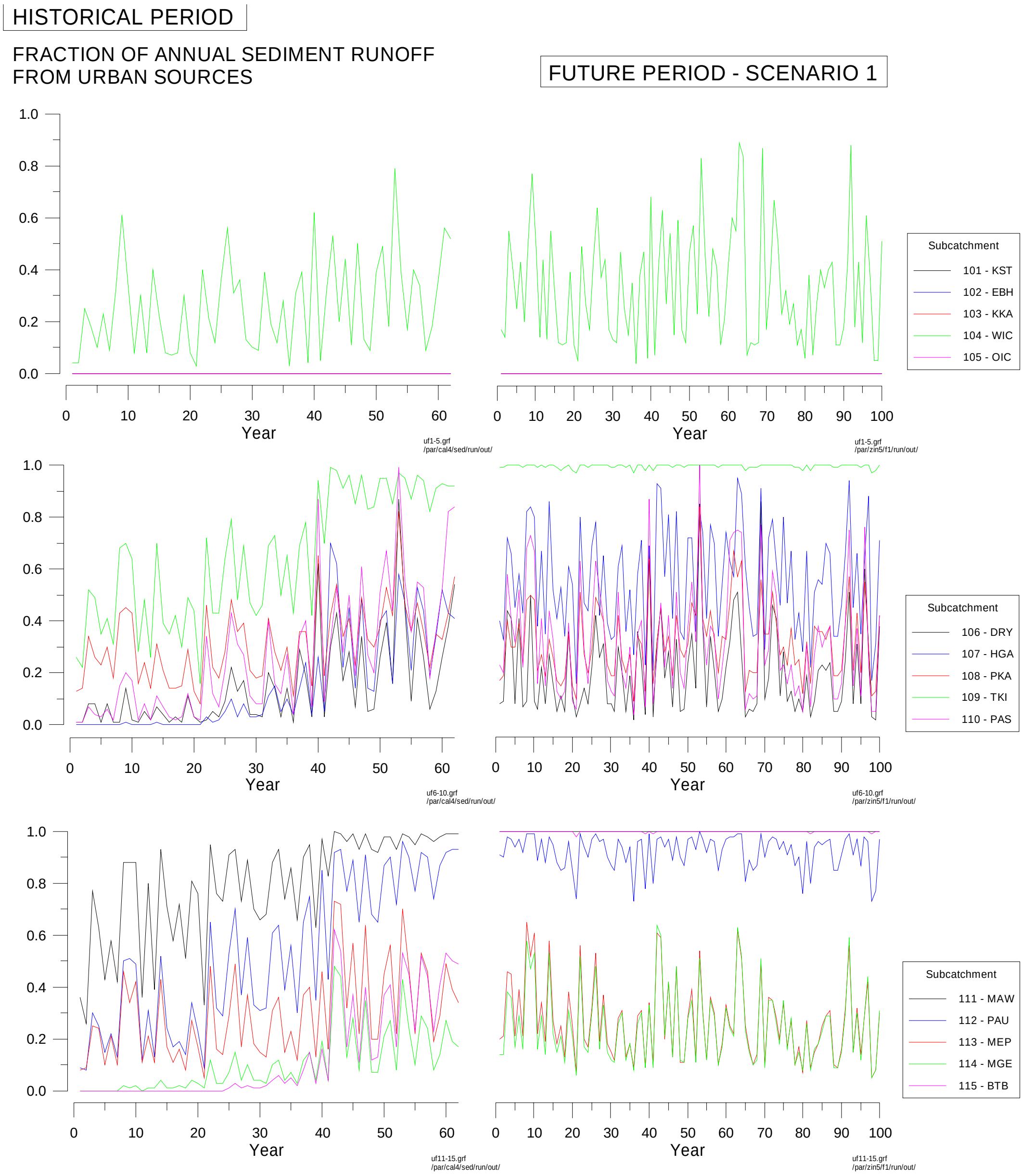


**Figure 4.6:**

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

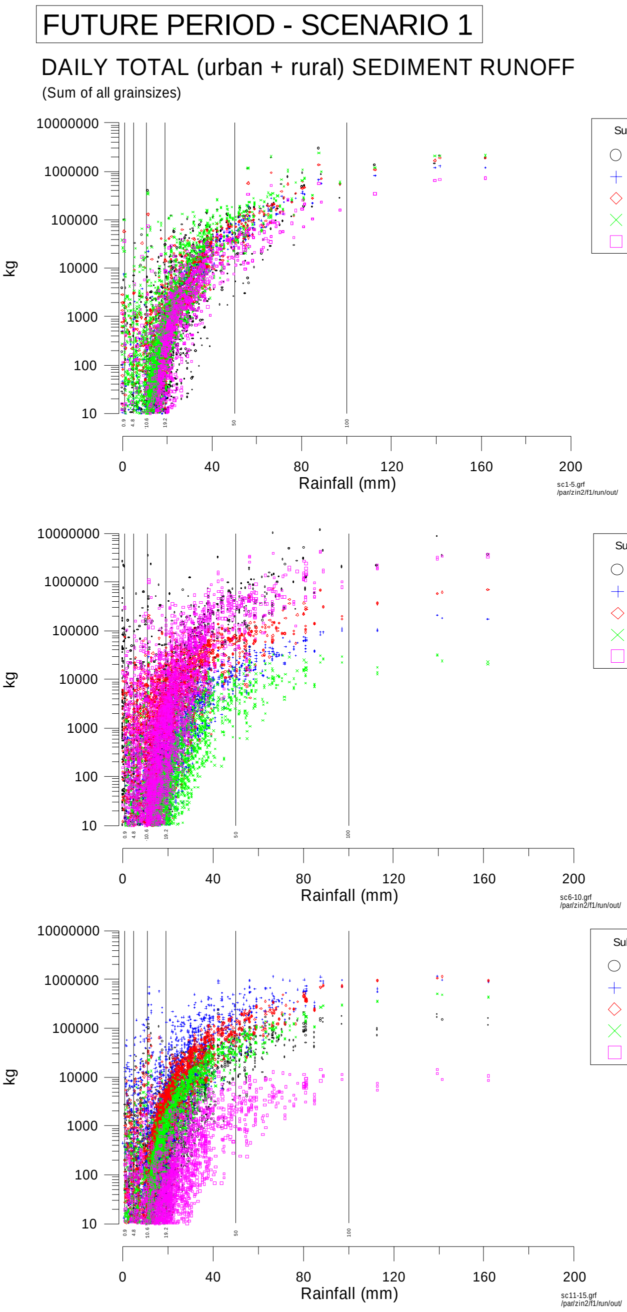


**Figure 4.7:**

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

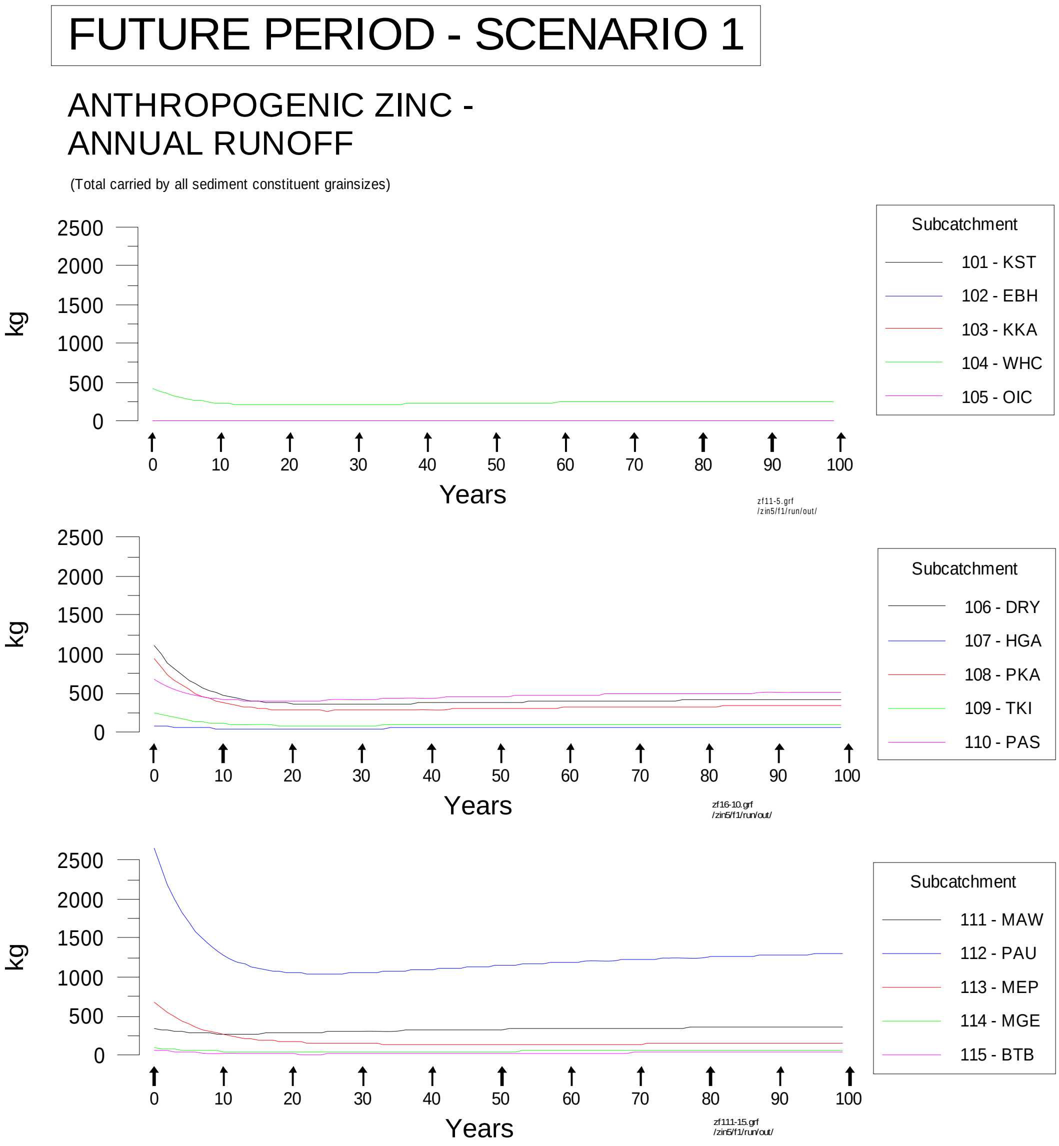


**Figure 4.8:**

Comparison of anthropogenic zinc runoff during the historical period (1940–2001) and the future period (2001–2100).

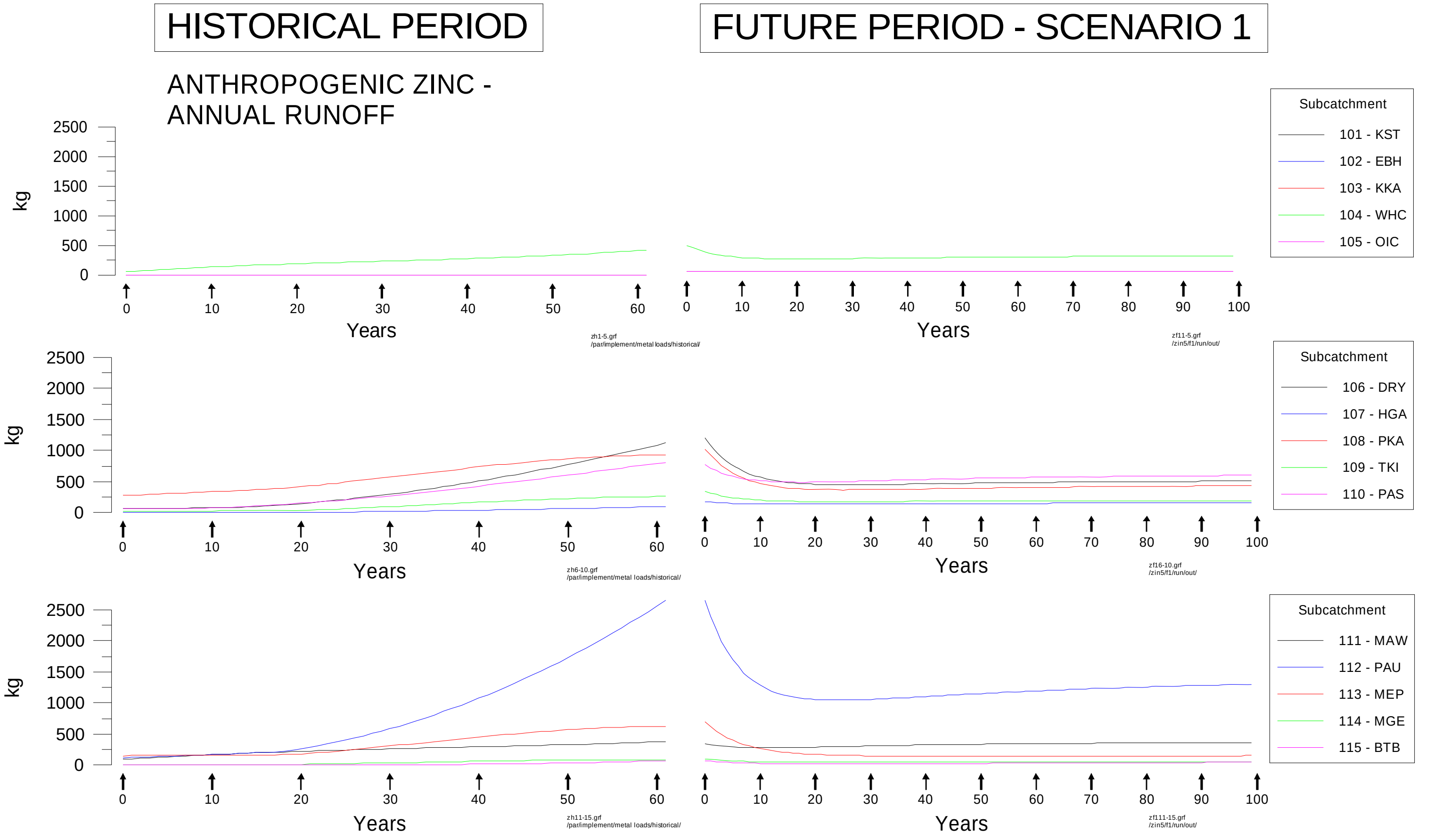


**Figure 4.9:**

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

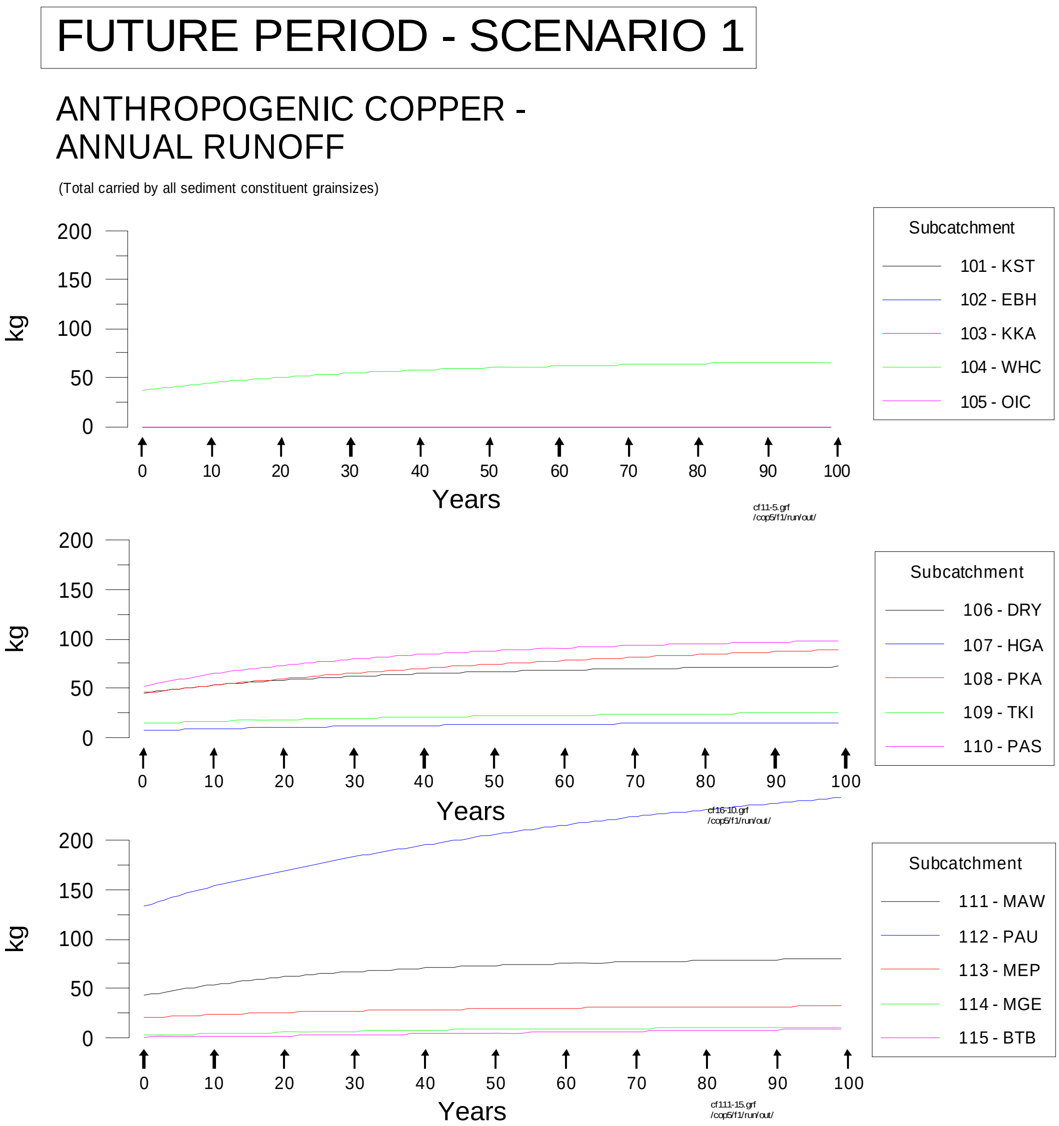


**Figure 4.10:**

Comparison of anthropogenic copper runoff during the historical period (1940–2001) and the future period (2001–2100).

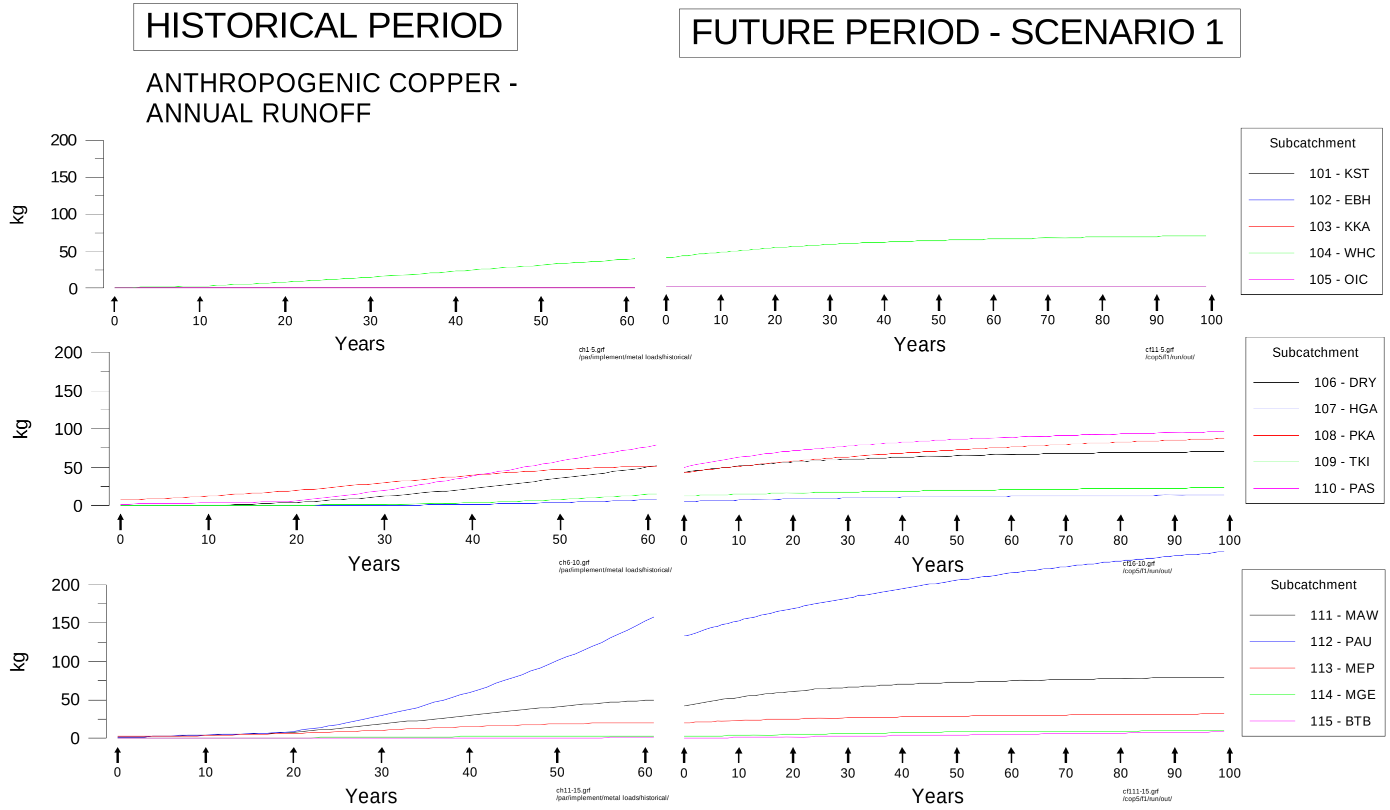


**Figure 4.11:**

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

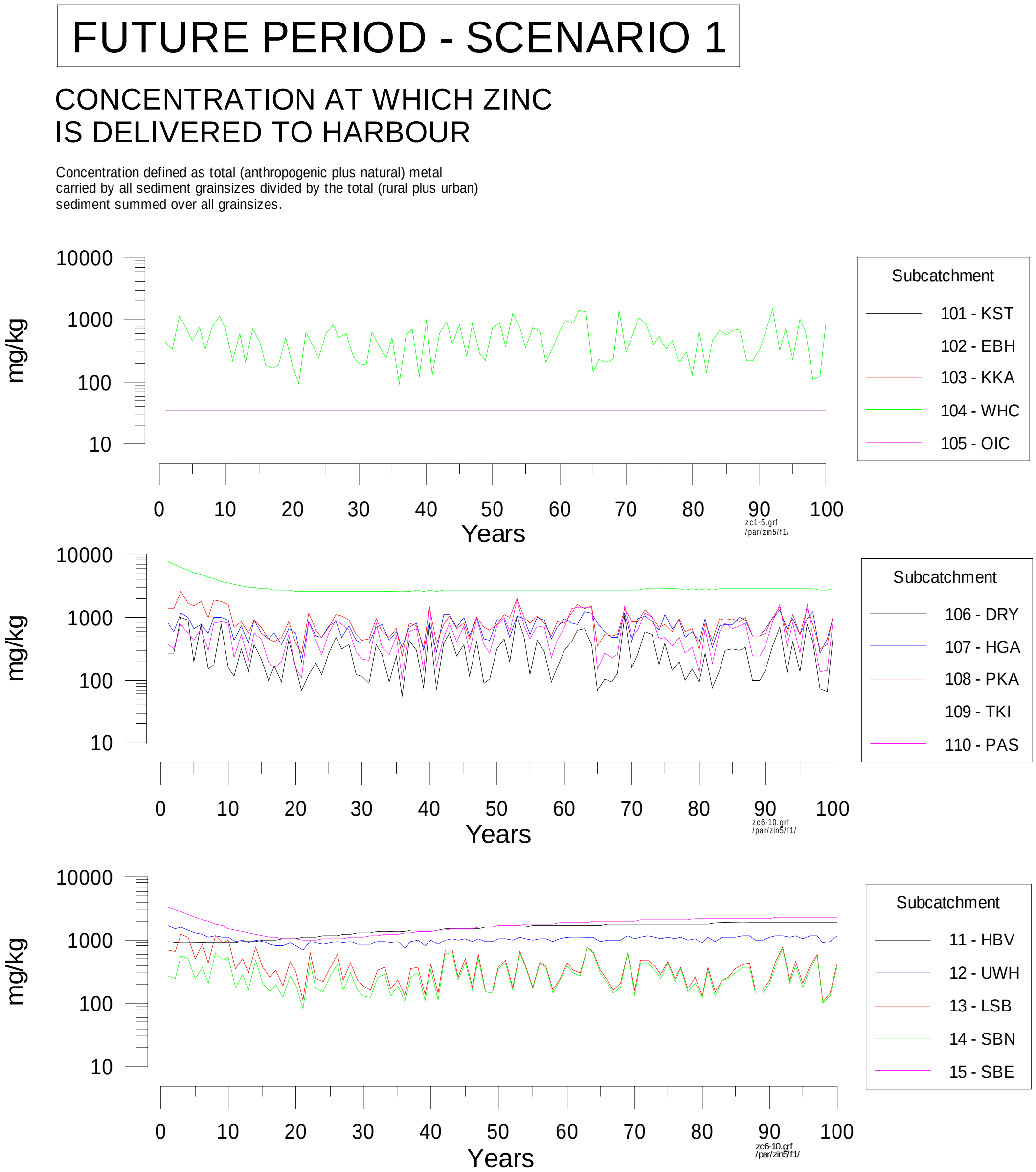


**Figure 4.12:**

Comparison of concentration at which zinc is delivered to the harbour during the historical period (1940–2001) and the future period (2001–2100).

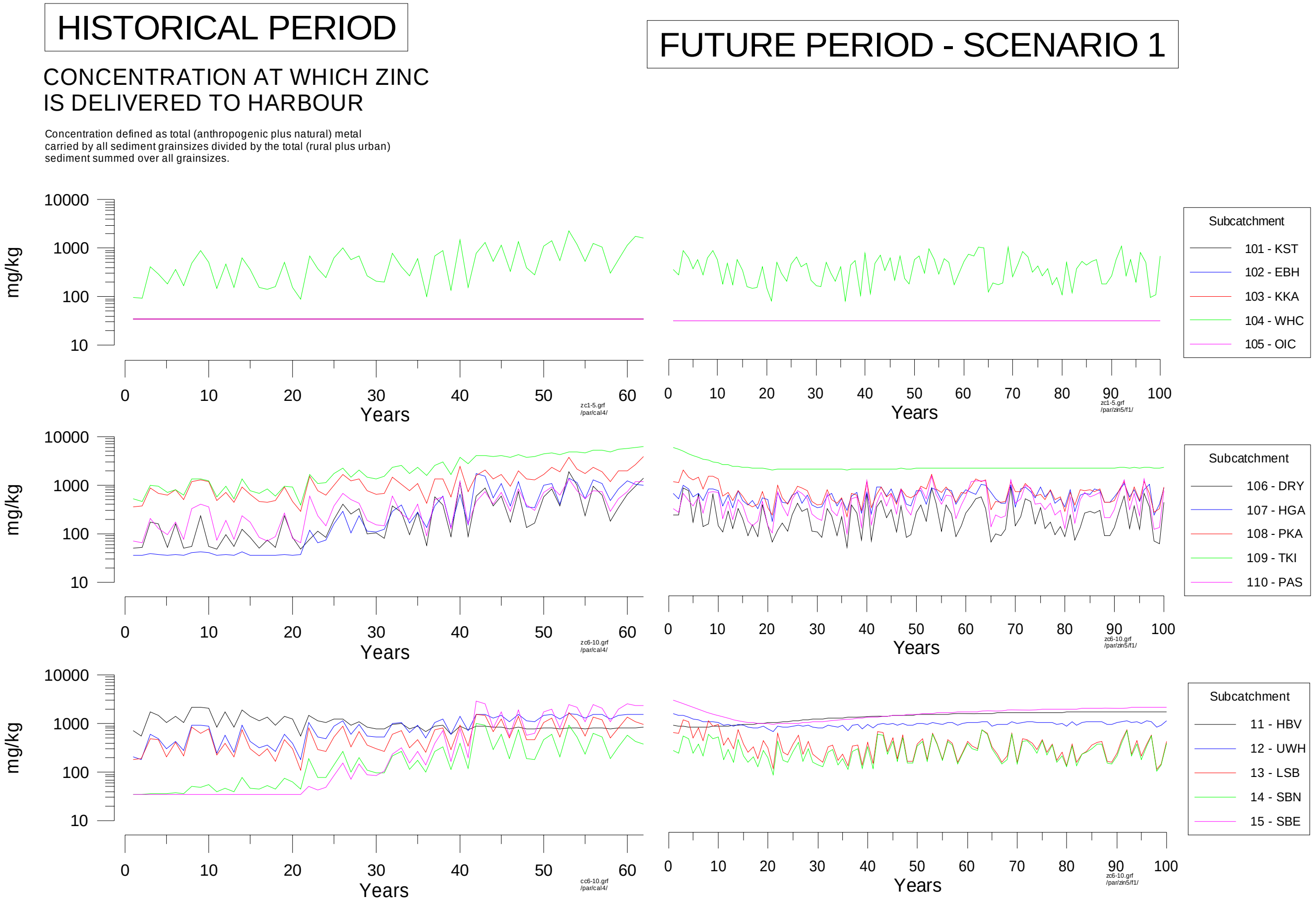


**Figure 4.13:**

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

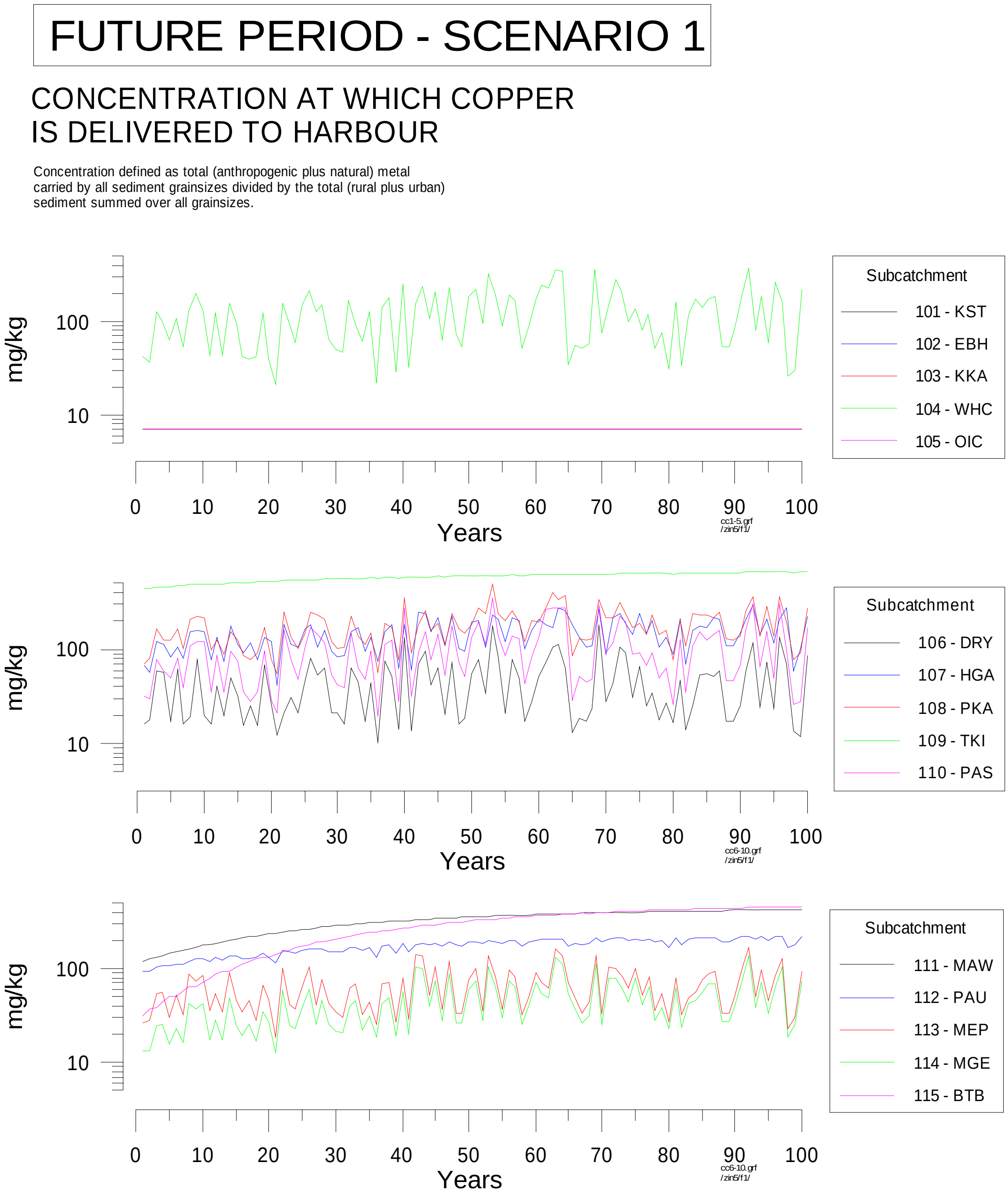


**Figure 4.14:**

Comparison of concentration at which copper is delivered to the harbour during the historical period (1940–2001) and the future period (2001–2100).

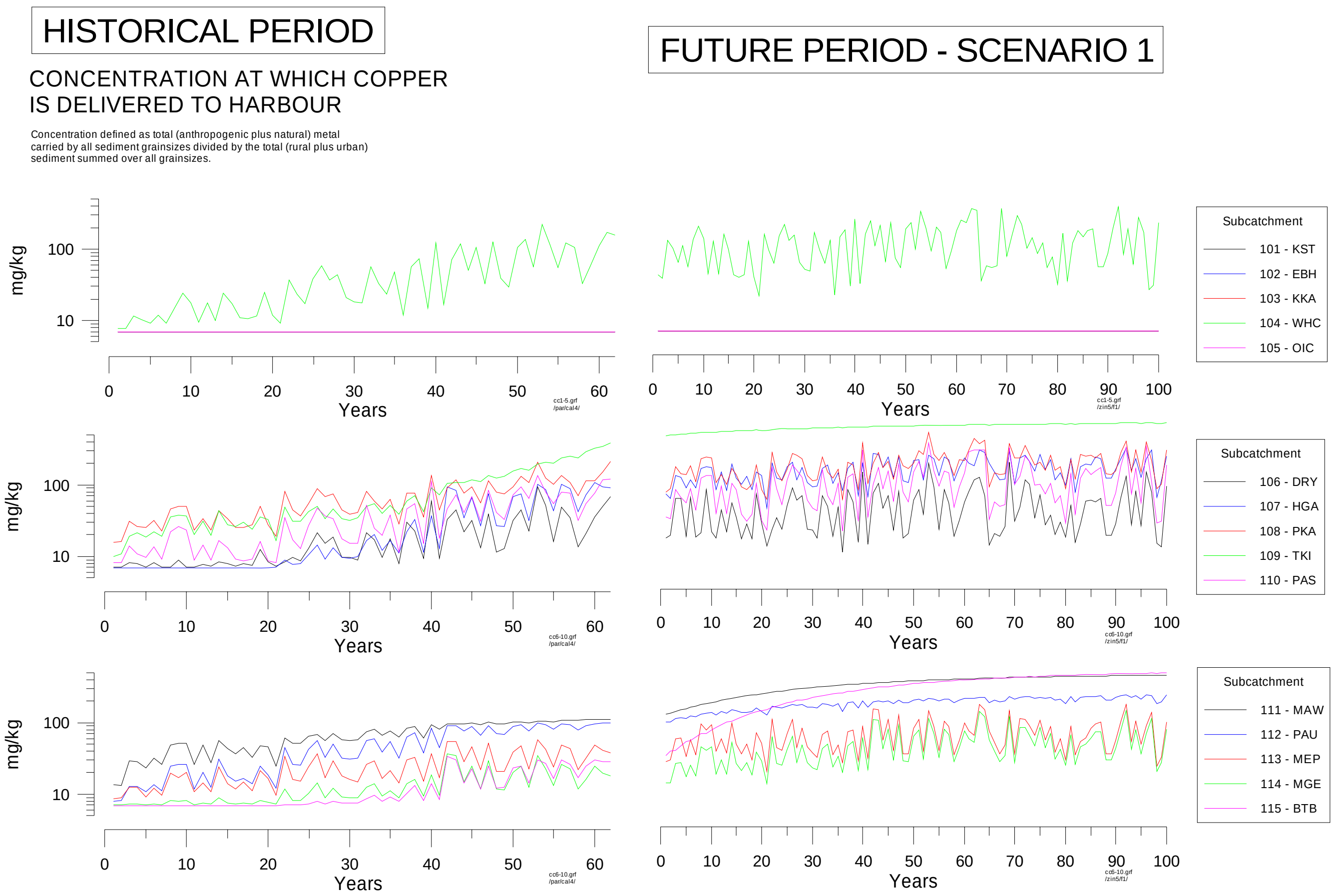
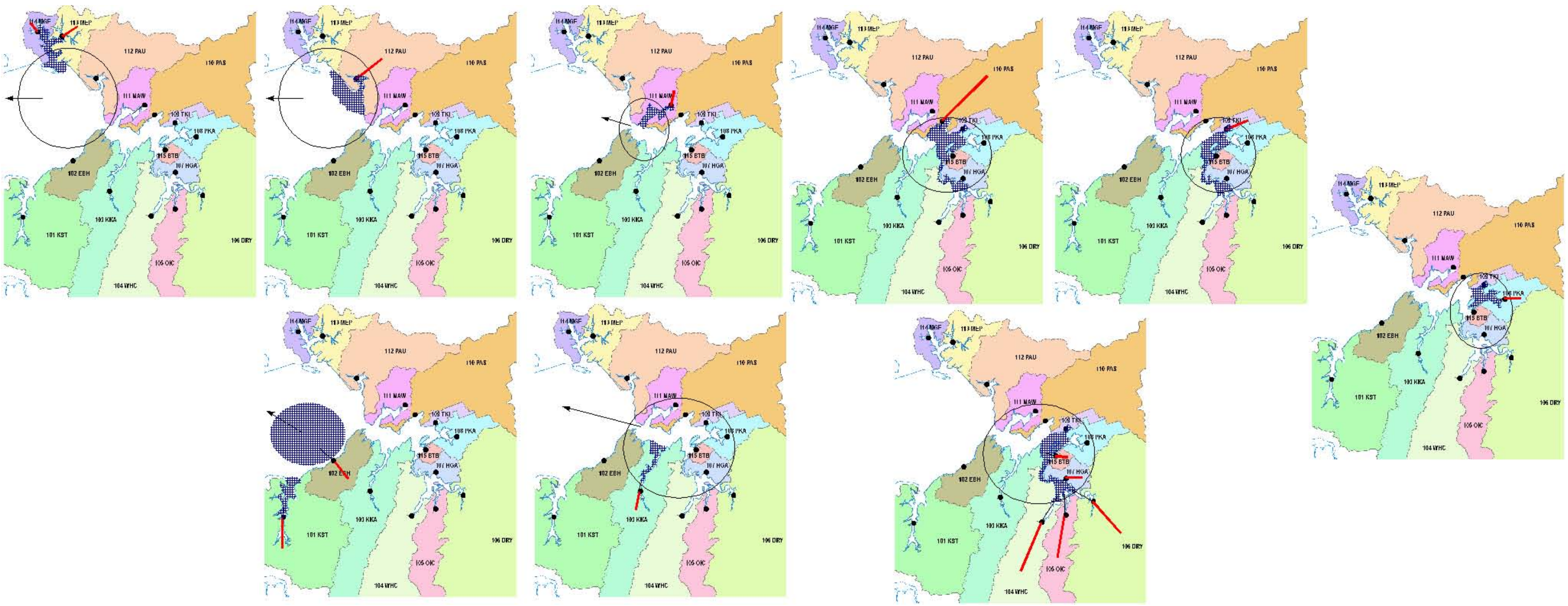


**Figure 4.15:**

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

FATE – Sediment



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

**Figure 4.16:**

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

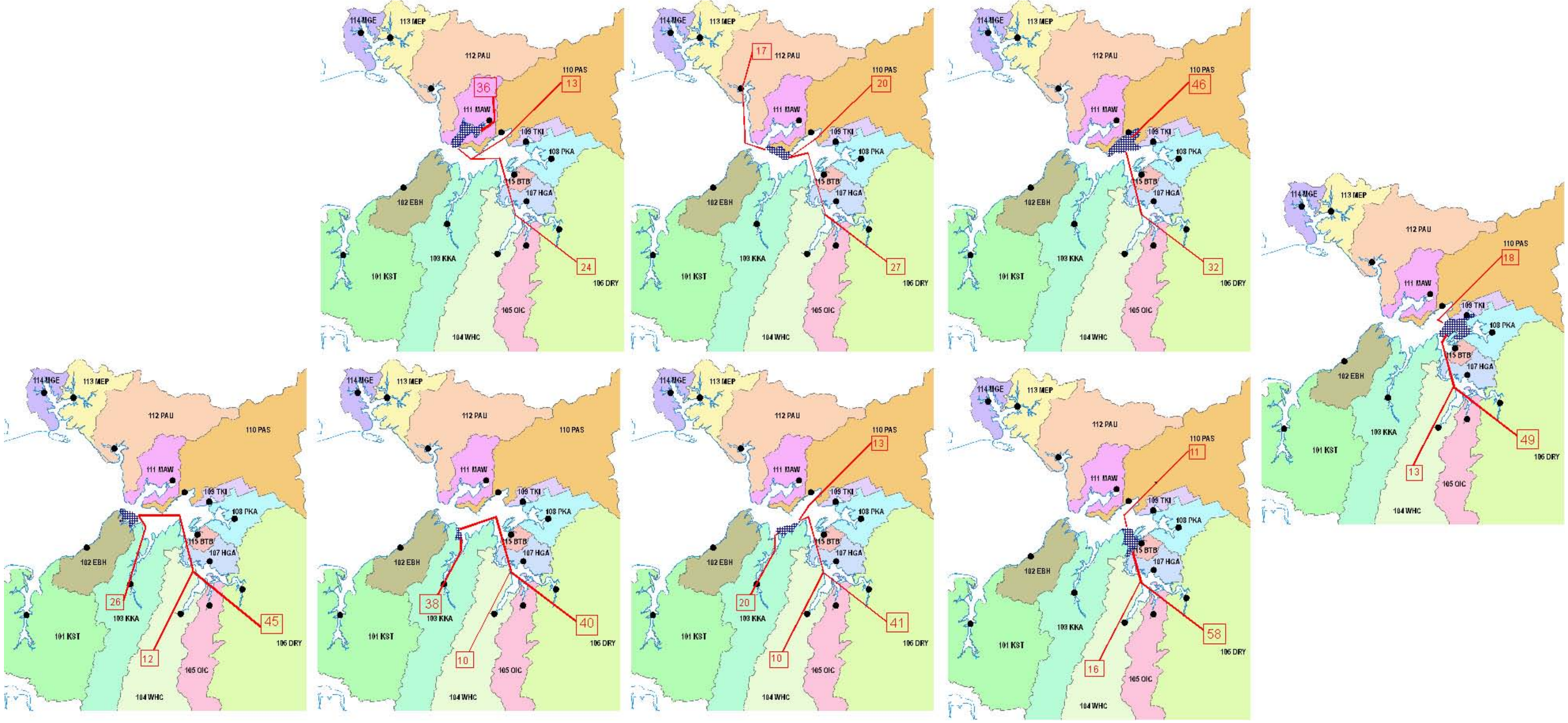
SOURCE – Sediment (Manukau Harbour)

\zin5\f1\run\out\sediment source map z1b manuaku.odg

**Figure 4.17:**

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

SOURCE – Sediment (Pahurehure Inlet)

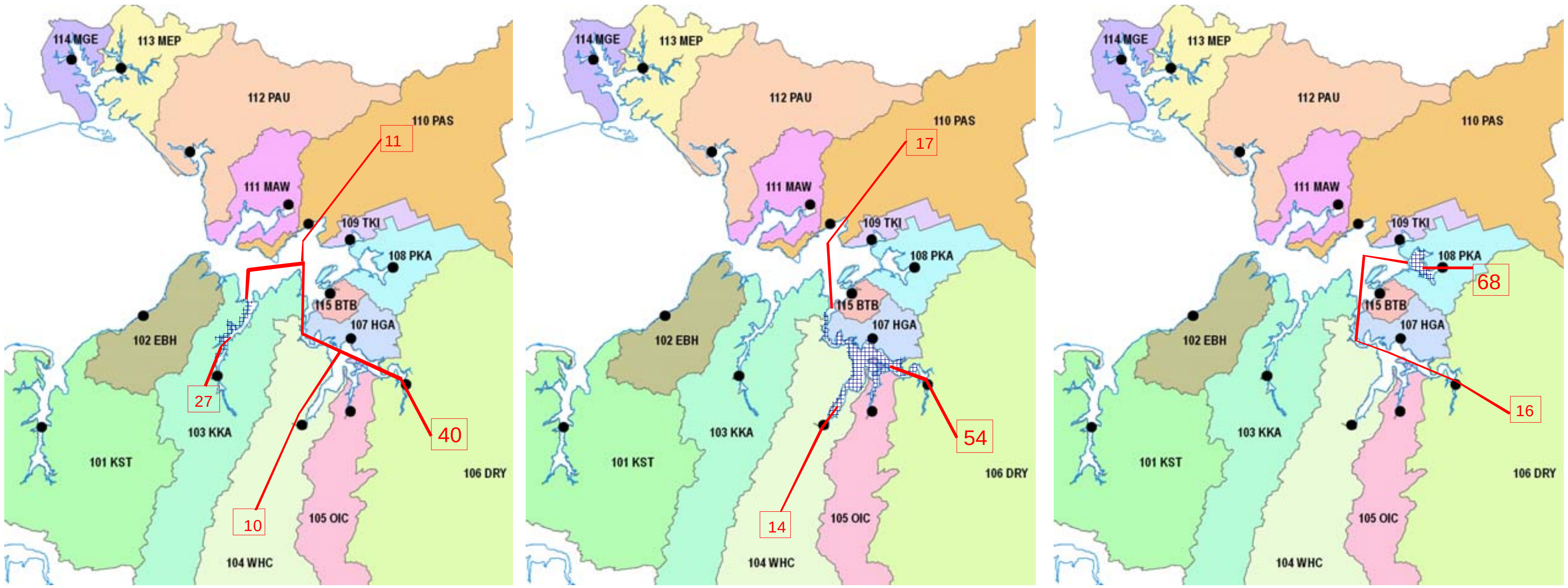



\zin5\f1\run\out\sediment source map z1b inlet.odg

**Figure 4.18:**

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

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




\zin5\f1\run\out\sediment source map z1b tidal creeks-basin.odg

**Figure 4.19:**

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

SOURCE – Zinc (Manukau Ha rbour)

\zin5\f1\run\out\zinc source map z1b manuaku.odg

**Figure 4.20:**

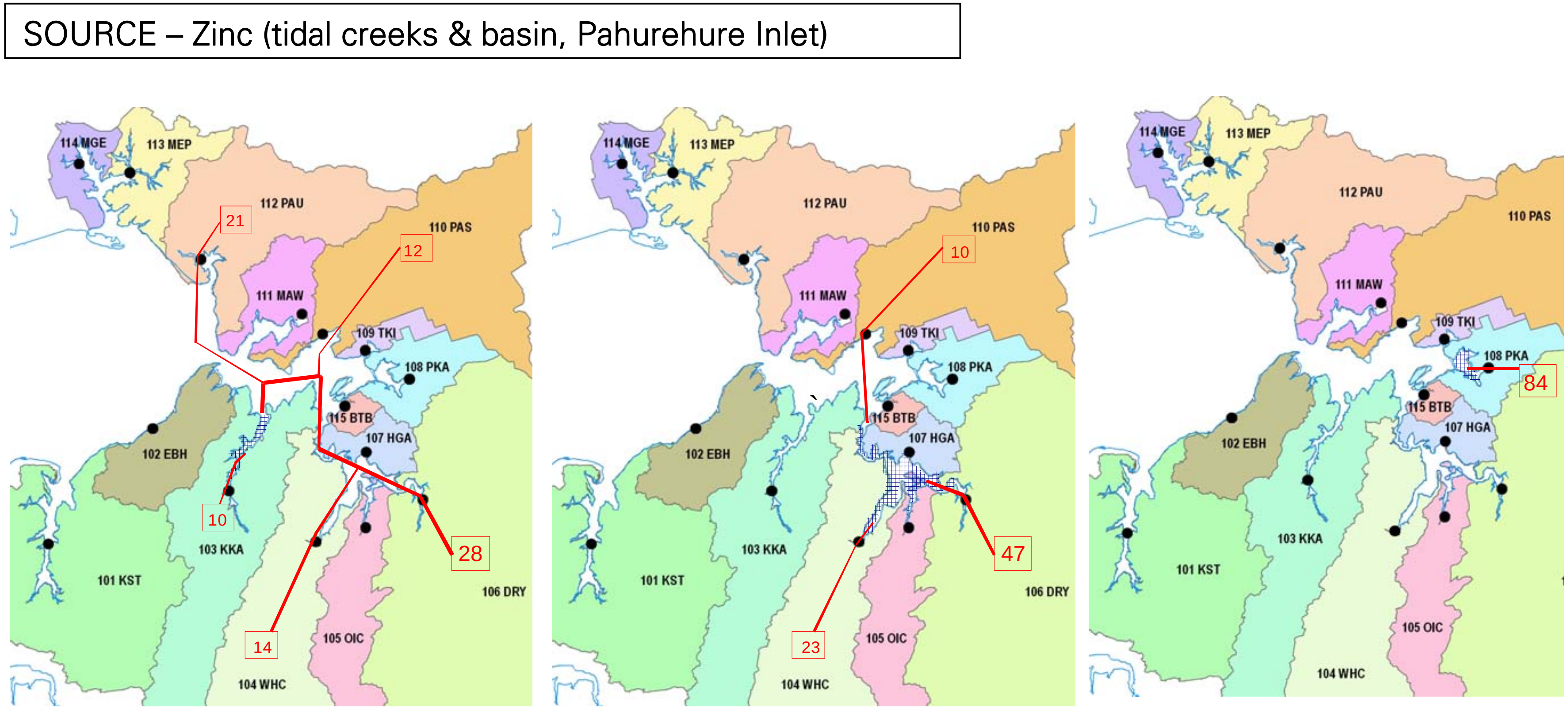
Source of zinc that deposits in each subestuary. The hatching indicates the subestuary. The number at the end of each red line connecting a subcatchment with a subestuary is the percentage of the total zinc deposited in the subestuary that is sourced from that subcatchment.

SOURCE – Zinc (Pahurehure Inlet)

\zin5\f1\run\out\zinc source map z1b inlet.odg

**Figure 4.21:**

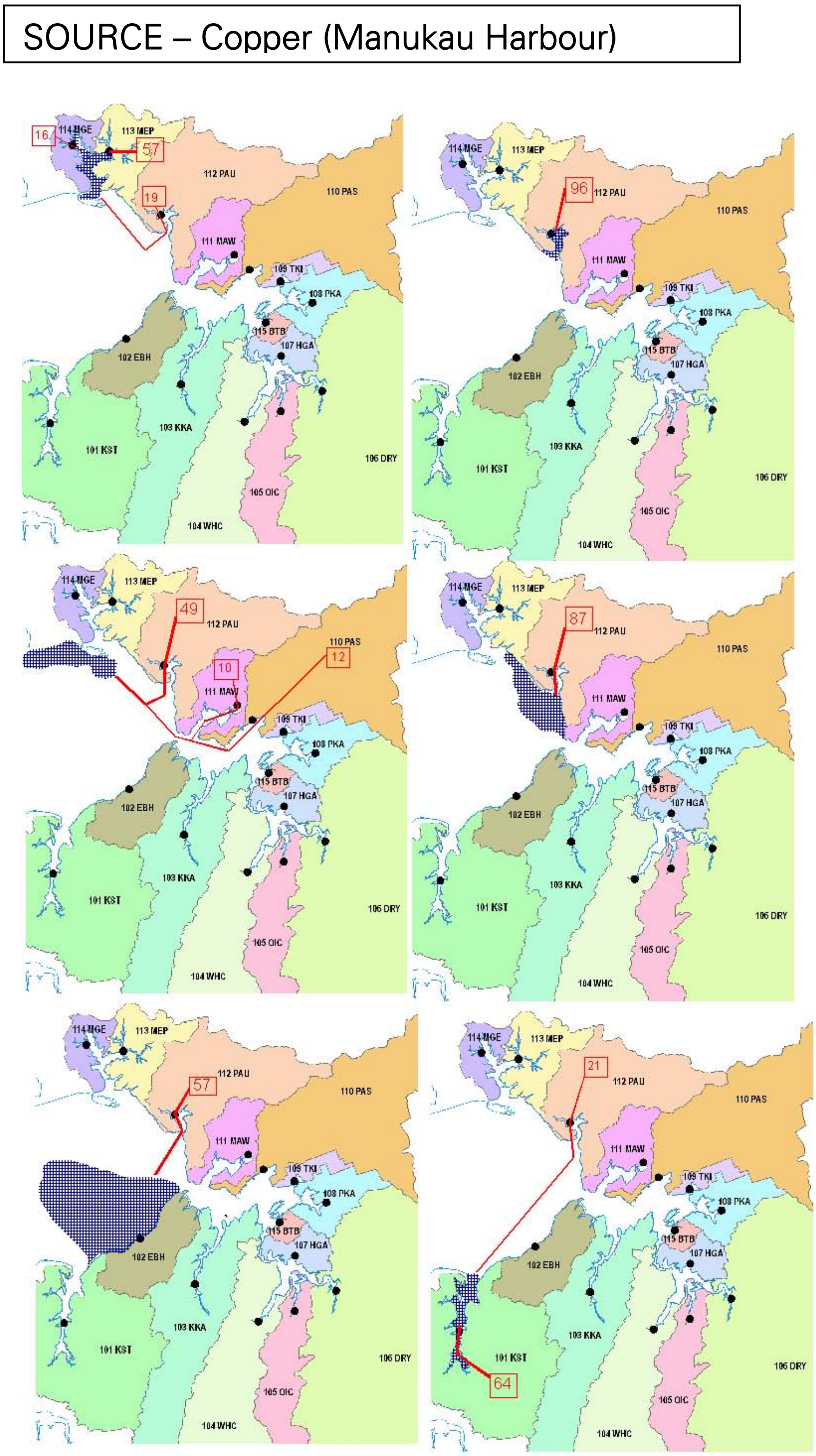
Source of zinc that deposits in each subestuary. The hatching indicates the subestuary. The number at the end of each red line connecting a subcatchment with a subestuary is the percentage of the total zinc deposited in the subestuary that is sourced from that subcatchment.




\zin5\f1\run\out\zinc source map z1b tidal creeks-basin.odg

**Figure 4.22:**

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

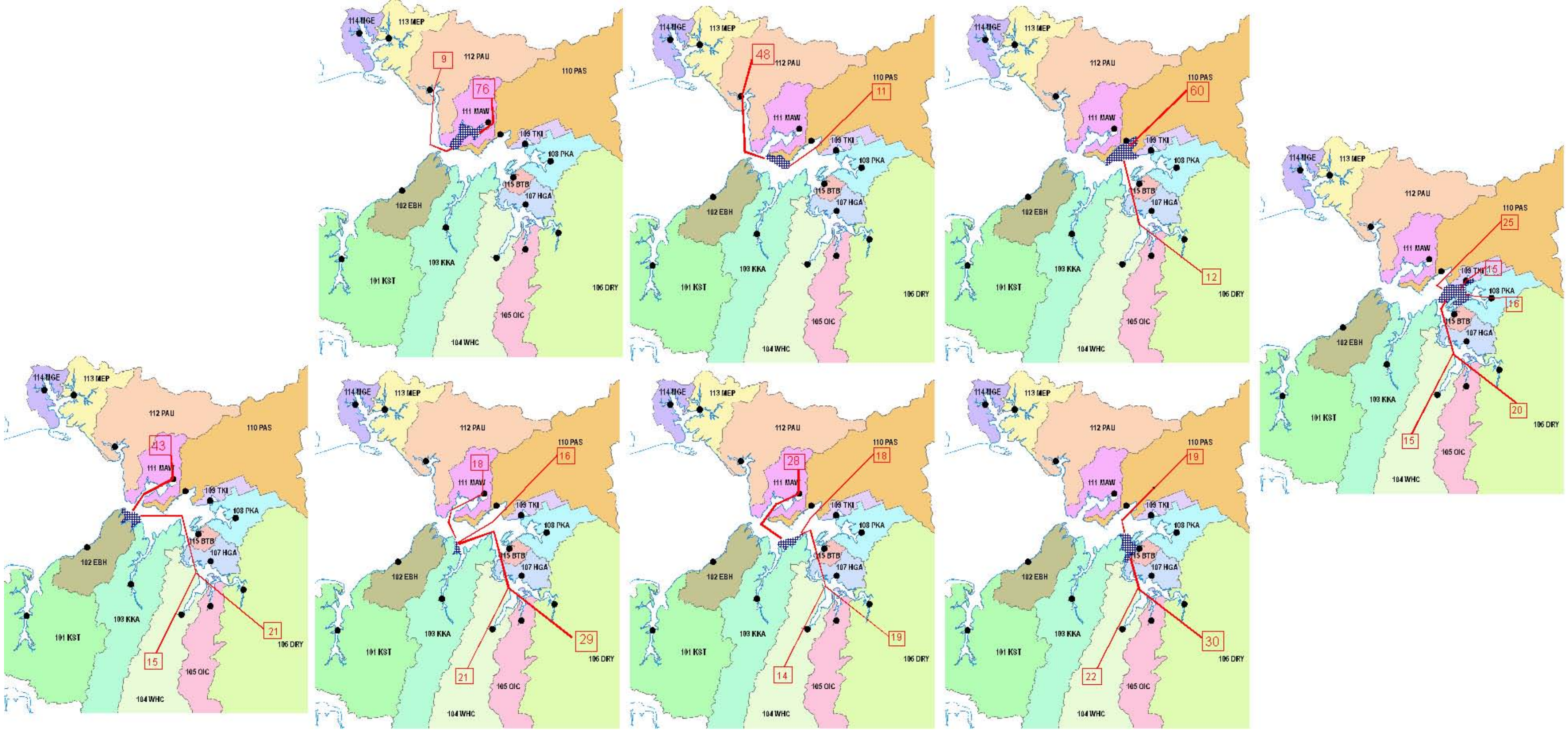



\cop5\f1\run\out\copper source map c1b manuaku.odg

**Figure 4.23:**

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

## SOURCE – Copper (Pahurehure Inlet)

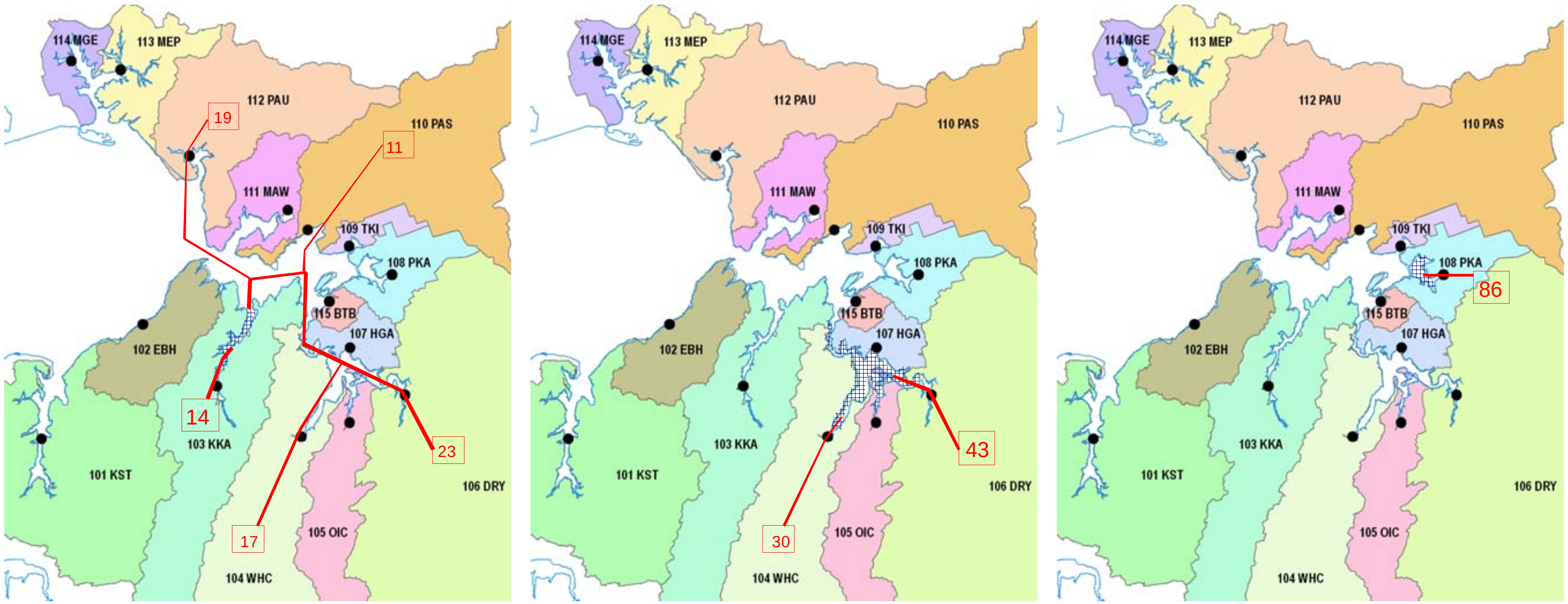


\cop5\f1\run\out\copper source map z1b inlet.odg

**Figure 4.24:**

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

## SOURCE – Copper (tidal creeks & basin, Pahurehure Inlet)




\cop5\f1\run\out\copper source map c1b tidal creeks-basin.odg

**Figure 4.25:**

Predicted annual sedimentation rate in each subestuary averaged over the future period. The annual-average sedimentation rate hindcast for the historical period by Green (2008) is shown for comparison, as are measured sedimentation rates reported by Reed et al. (2008) from radioisotopic analysis of sediment cores.


\zin5\f1\run\out\sedimentation map z1b.odg

**Figure 4.26:**

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

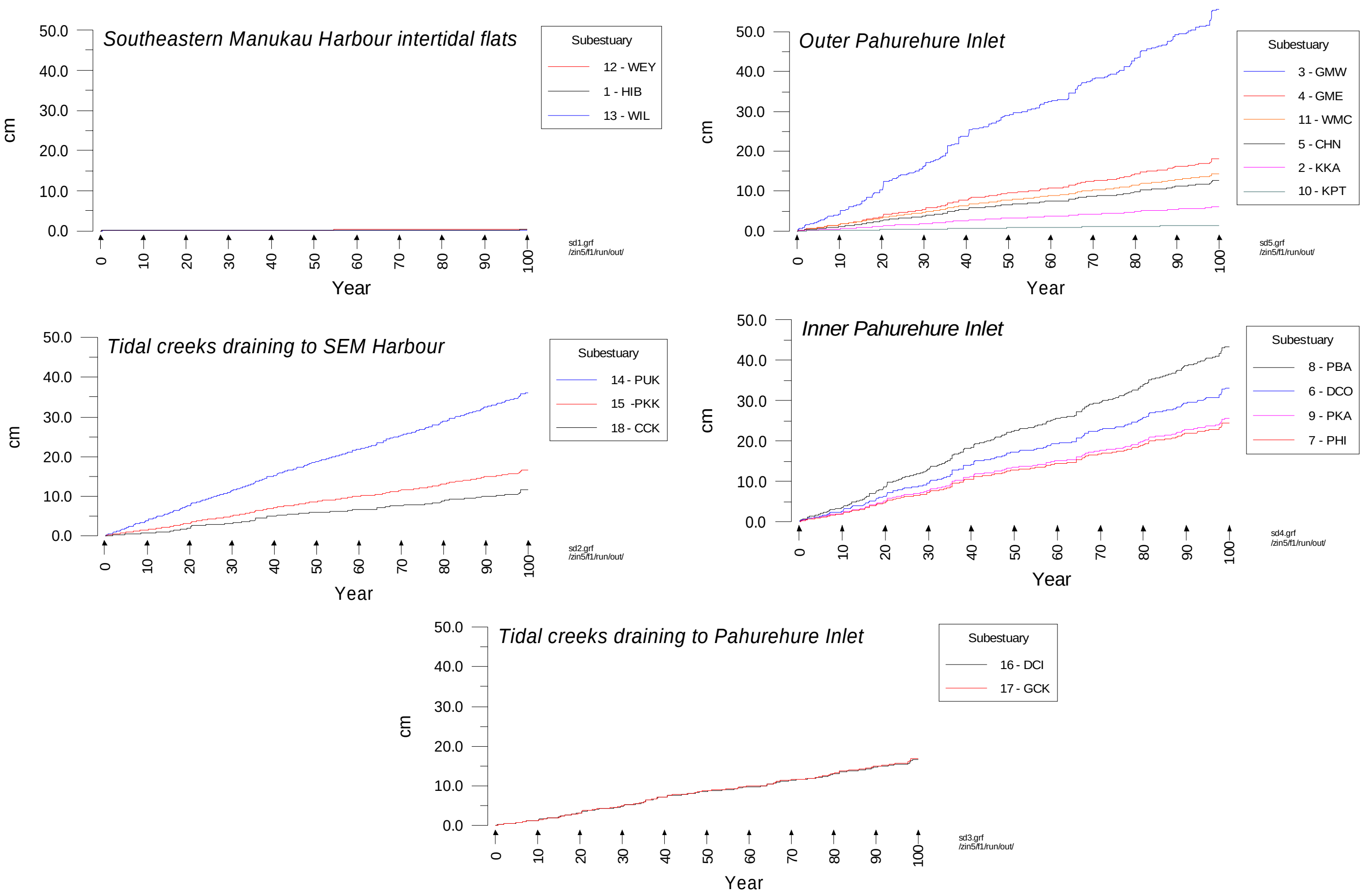
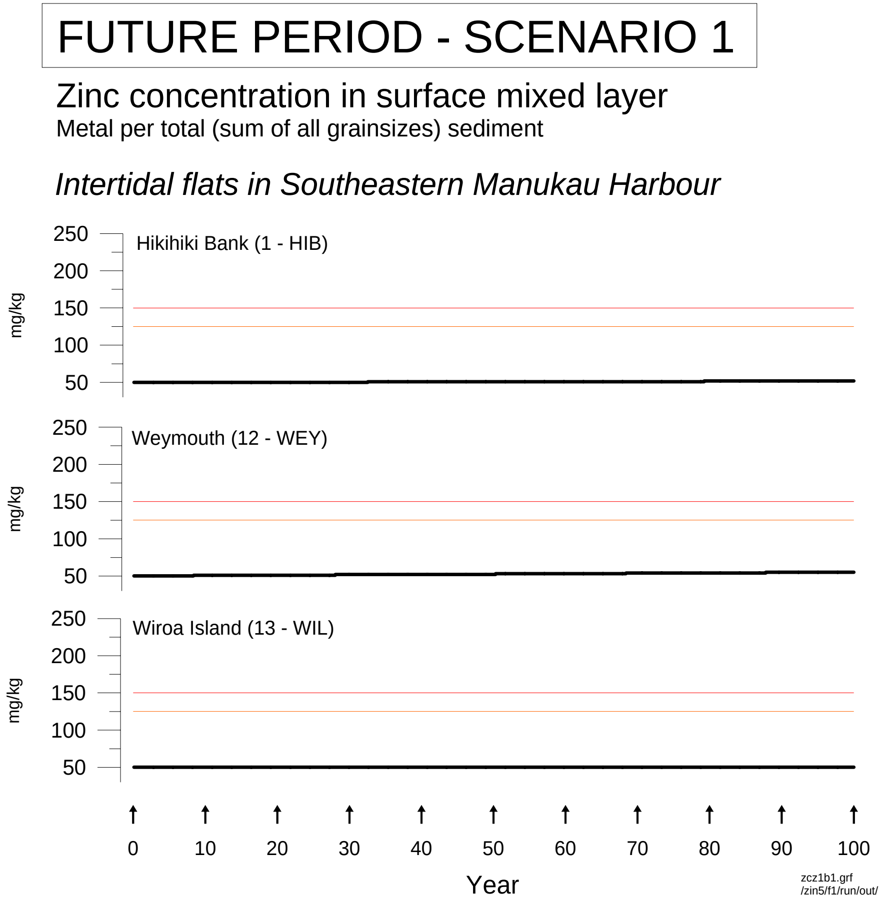


Figure 4.27:

Predicted change in zinc and copper concentration for the future period under Scenario 1 for intertidal flats in Southeastern Manukau Harbour. Year 1 is 2001 and year 100 is 2100. Metal concentration is total metal per total sediment in the surface mixed layer.



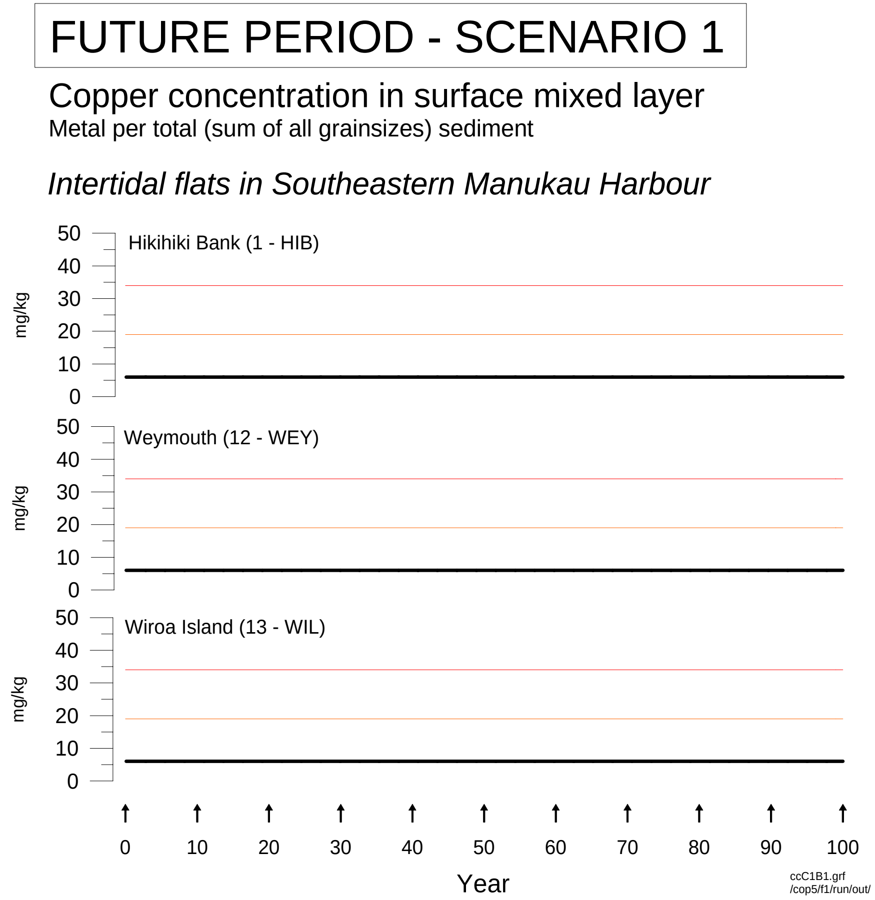
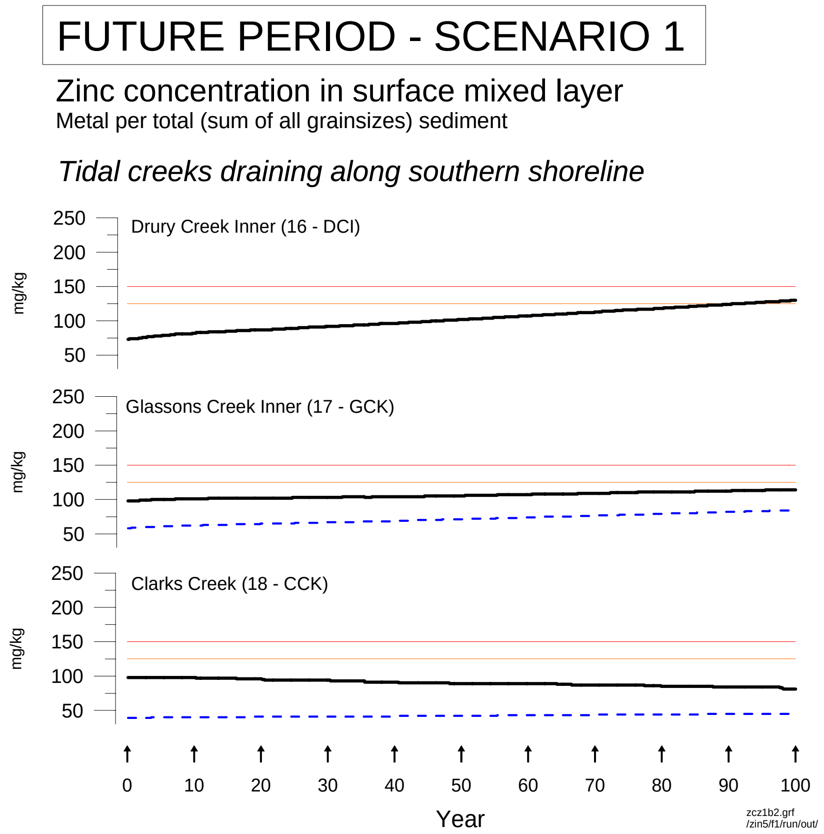



Figure 4.28:

Predicted change in zinc and copper concentration for the future period under Scenario 1 for tidal creeks that drain along the southern shoreline. Year 1 is 2001 and year 100 is 2100. Metal concentration is total metal per total sediment in the surface mixed layer. Refer to the text for the explanation of the blue lines.



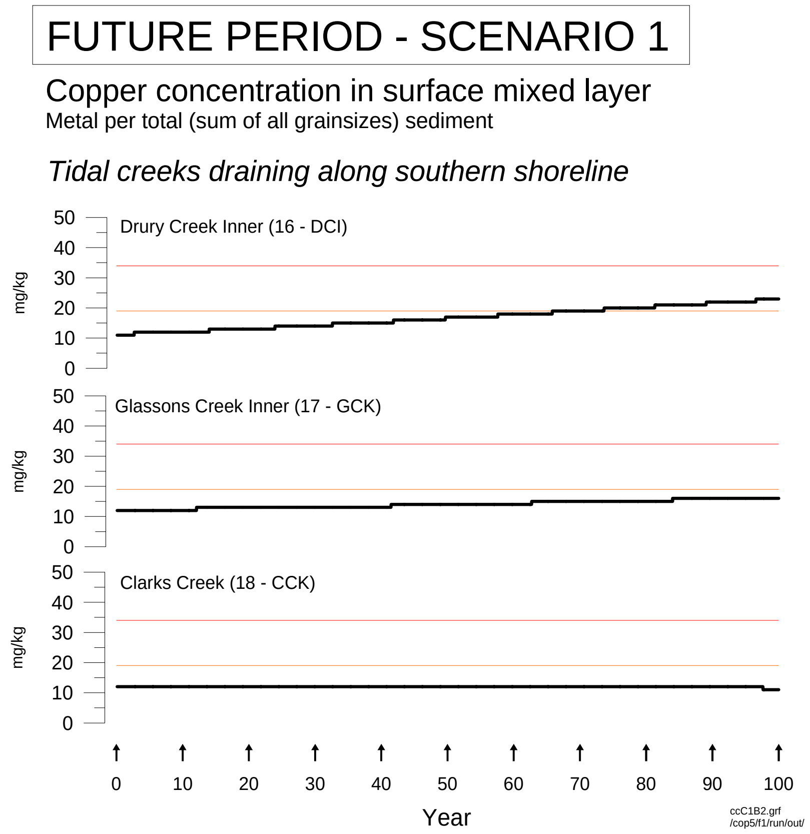
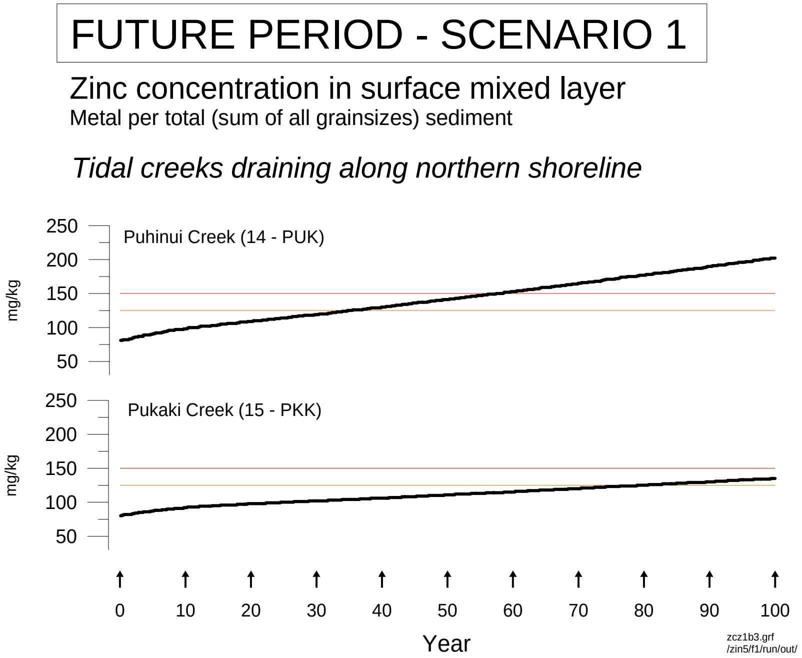



Figure 4.29:

Predicted change in zinc and copper concentration for the future period under Scenario 1 for tidal creeks that drain along the northern shoreline.  Year 1 is 2001 and year 100 is 2100.  Metal concentration is total metal per total sediment in the surface mixed layer.



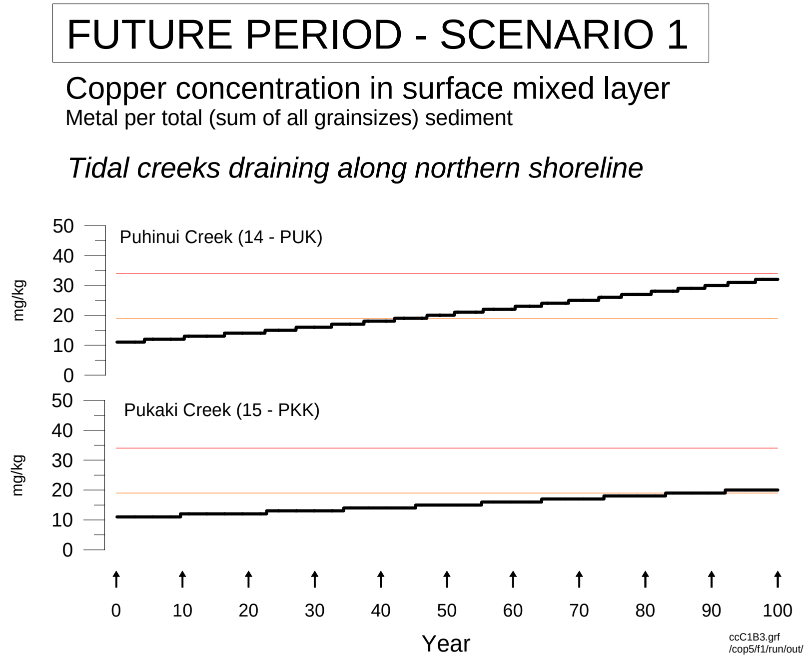
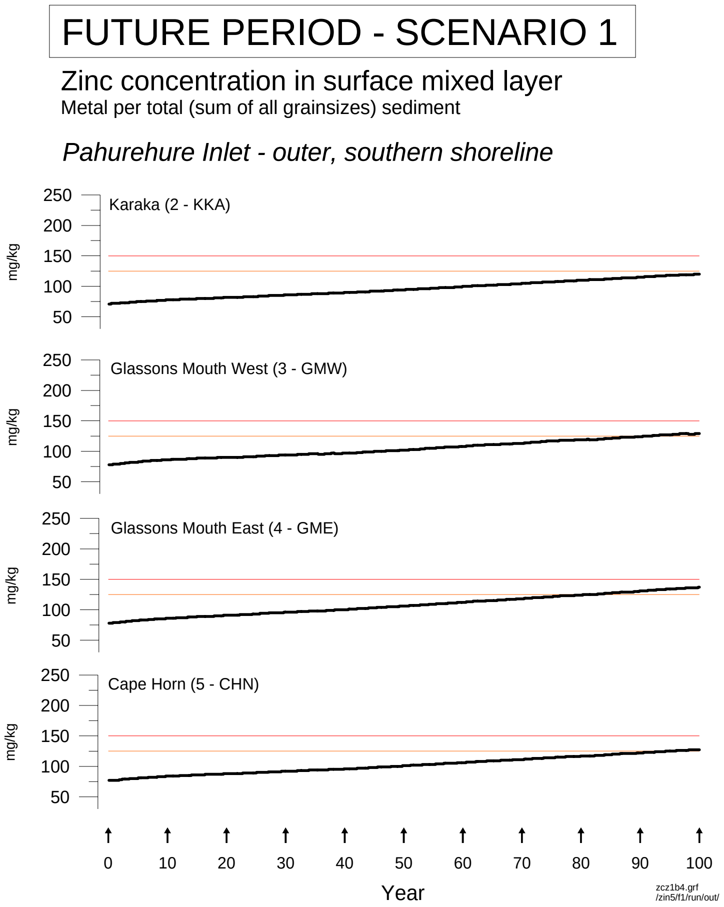



Figure 4.30:

Predicted change in zinc and copper concentration for the future period under Scenario 1 for subestuaries in outer Pahurehure Inlet, along the southern shoreline. Year 1 is 2001 and year 100 is 2100. Metal concentration is total metal per total sediment in the surface mixed layer.



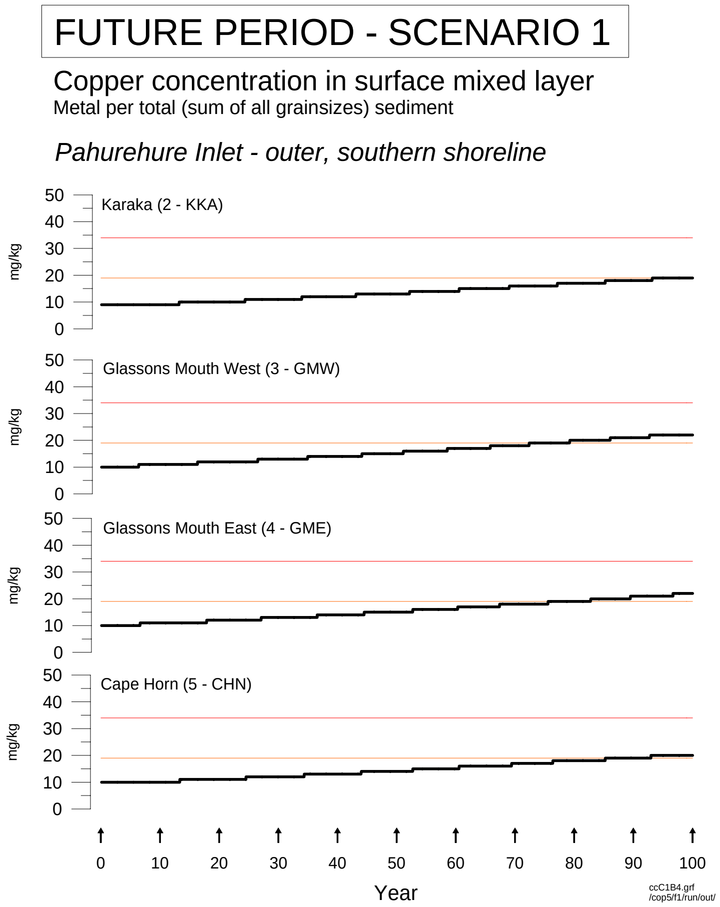
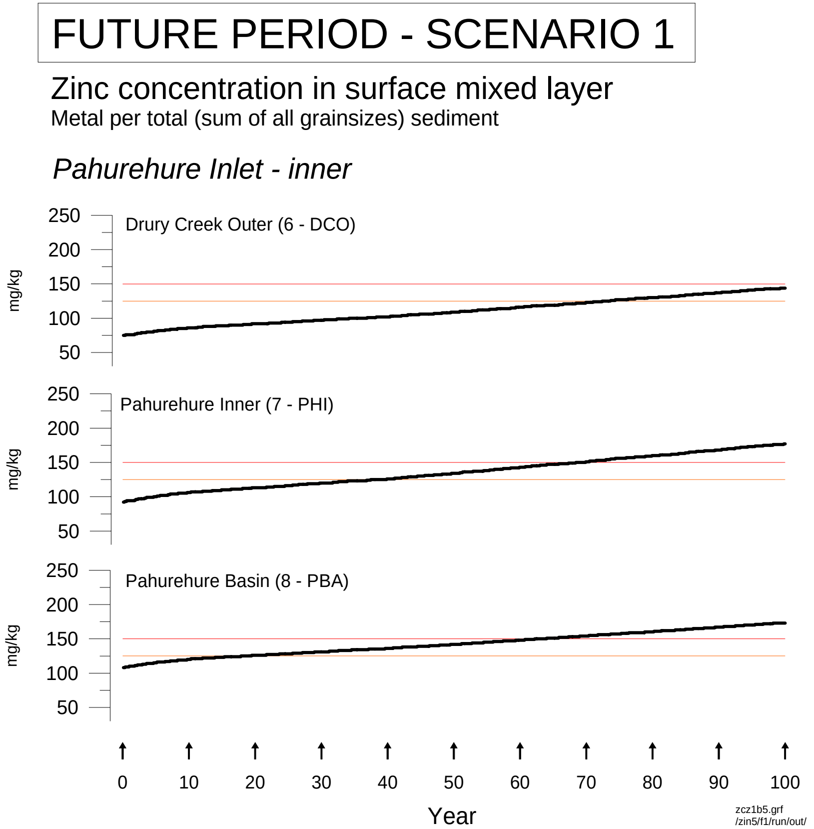



Figure 4.31:

Predicted change in zinc and copper concentration for the future period under Scenario 1 for subestuaries in inner Pahurehure Inlet. Year 1 is 2001 and year 100 is 2100. Metal concentration is total metal per total sediment in the surface mixed layer.



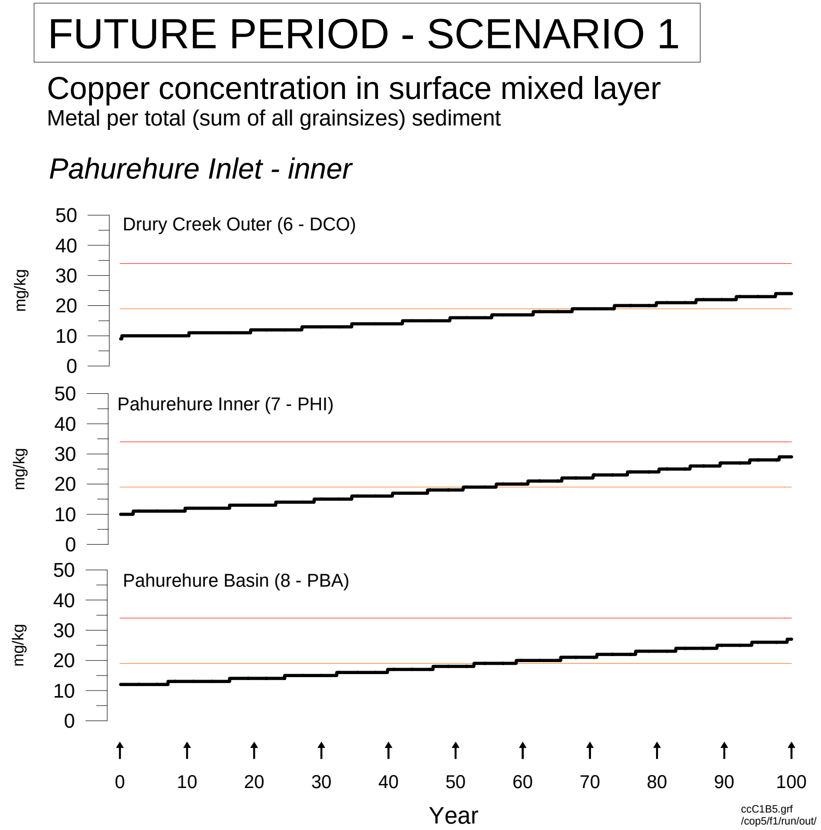
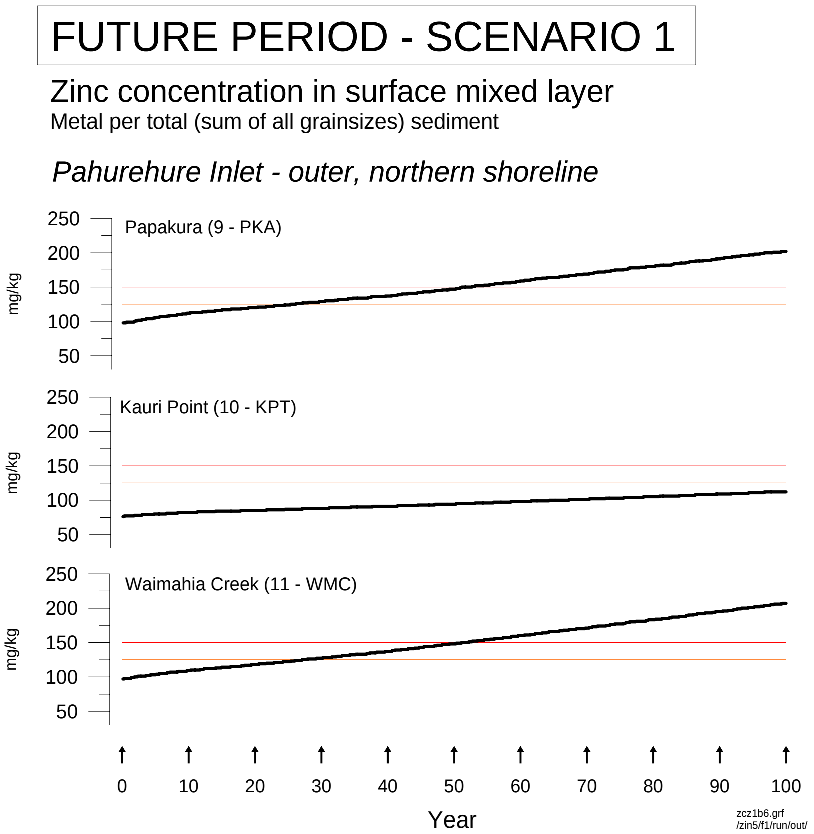



Figure 4.32:

Predicted change in zinc and copper concentration for the future period under Scenario 1 for subestuaries in outer Pahurehure Inlet, along the northern shoreline. Year 1 is 2001 and year 100 is 2100. Metal concentration is total metal per total sediment in the surface mixed layer.



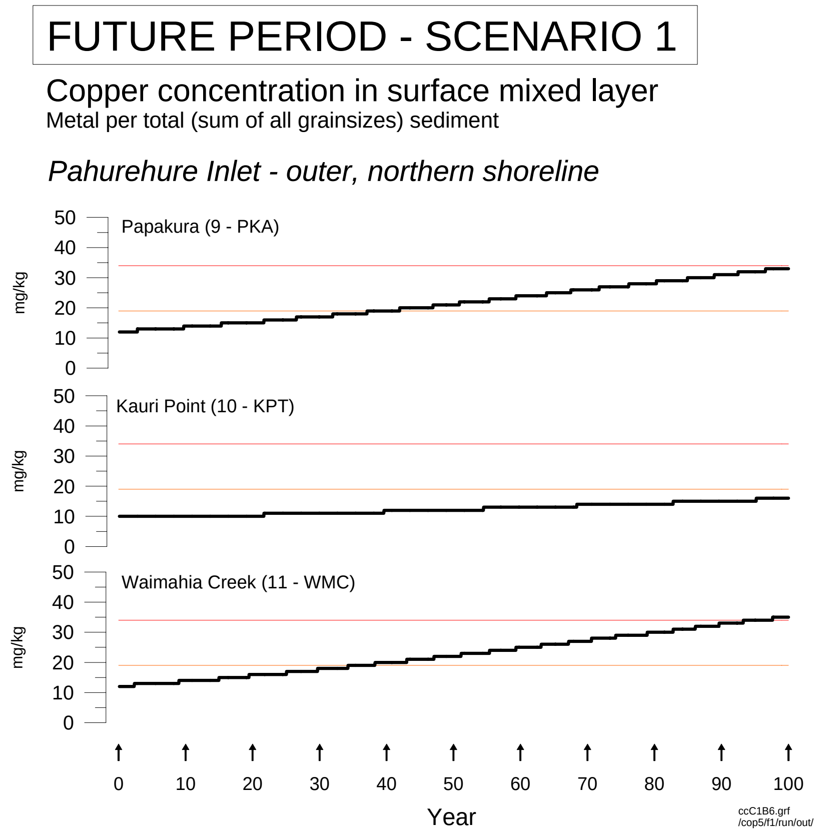
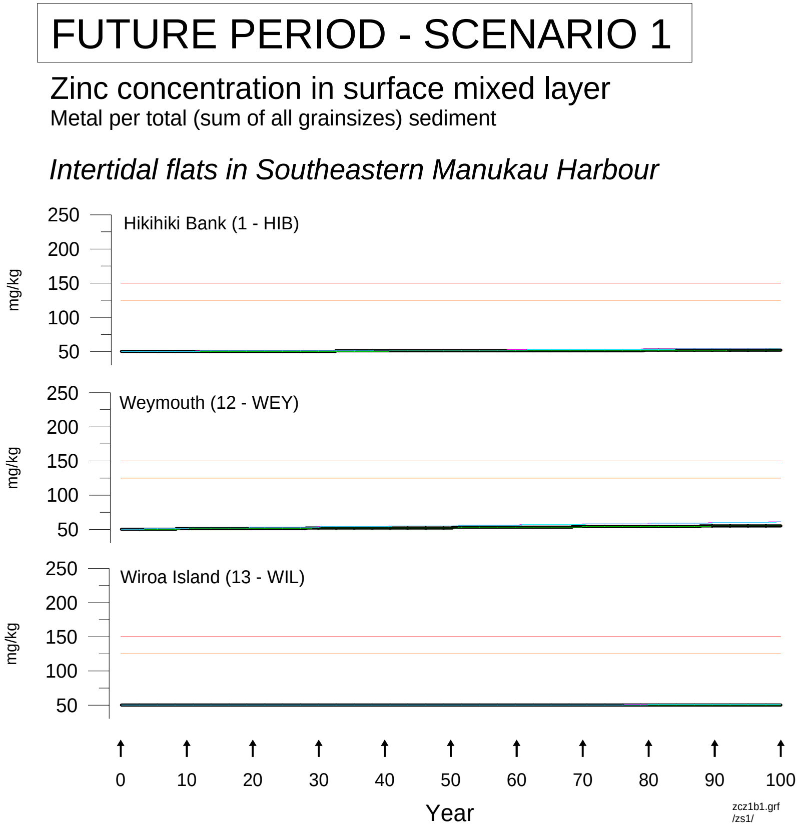
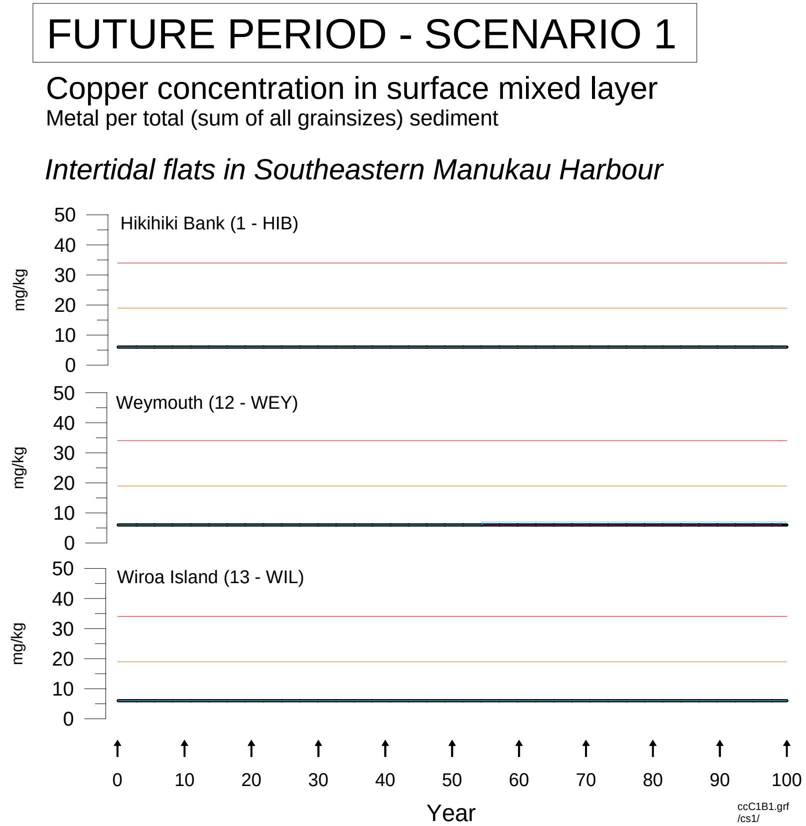



Figure 4.33:

Sensitivity of Scenario 1 predictions to various combinations of doubling the sediment and metal runoff. Year 1 is 2001 and year 100 is 2100. Metal concentration is total metal per total sediment in the surface mixed layer.



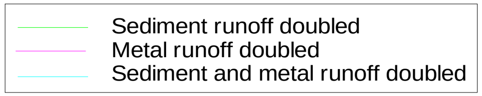
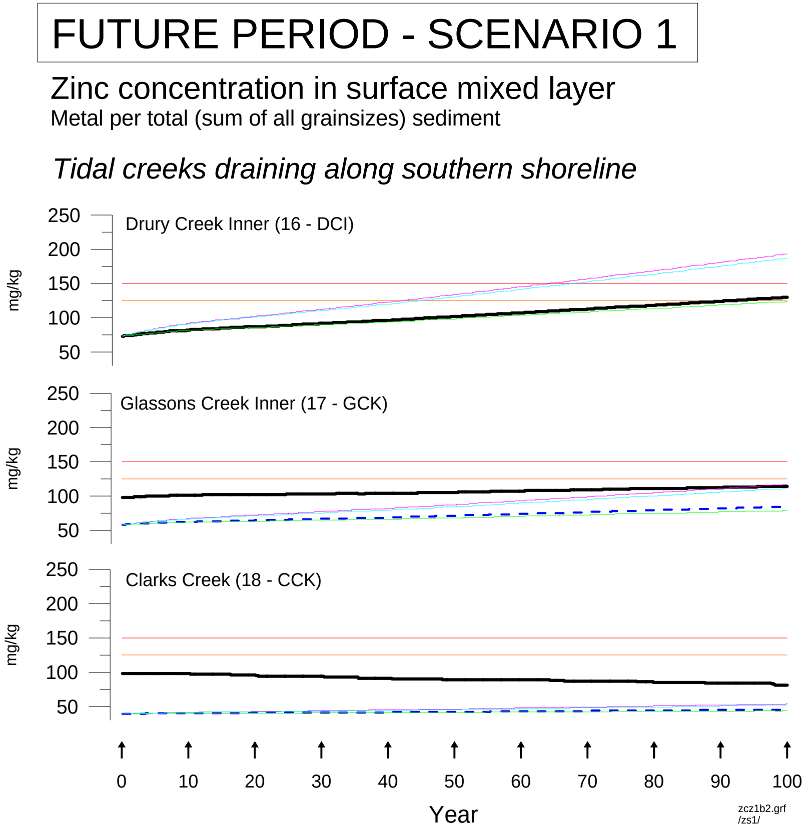
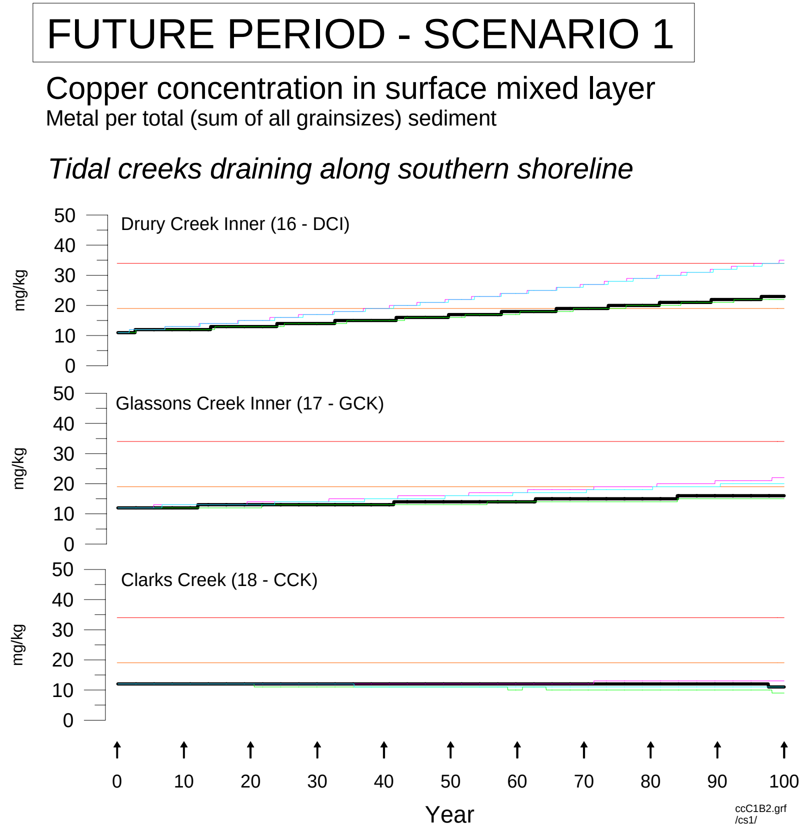



Figure 4.34

Sensitivity of Scenario 1 predictions to various combinations of doubling the sediment and metal runoff. Year 1 is 2001 and year 100 is 2100. Metal concentration is total metal per total sediment in the surface mixed layer.



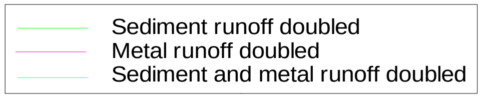



Figure 4.35

Sensitivity of Scenario 1 predictions to various combinations of doubling the sediment and metal runoff. Year 1 is 2001 and year 100 is 2100. Metal concentration is total metal per total sediment in the surface mixed layer.

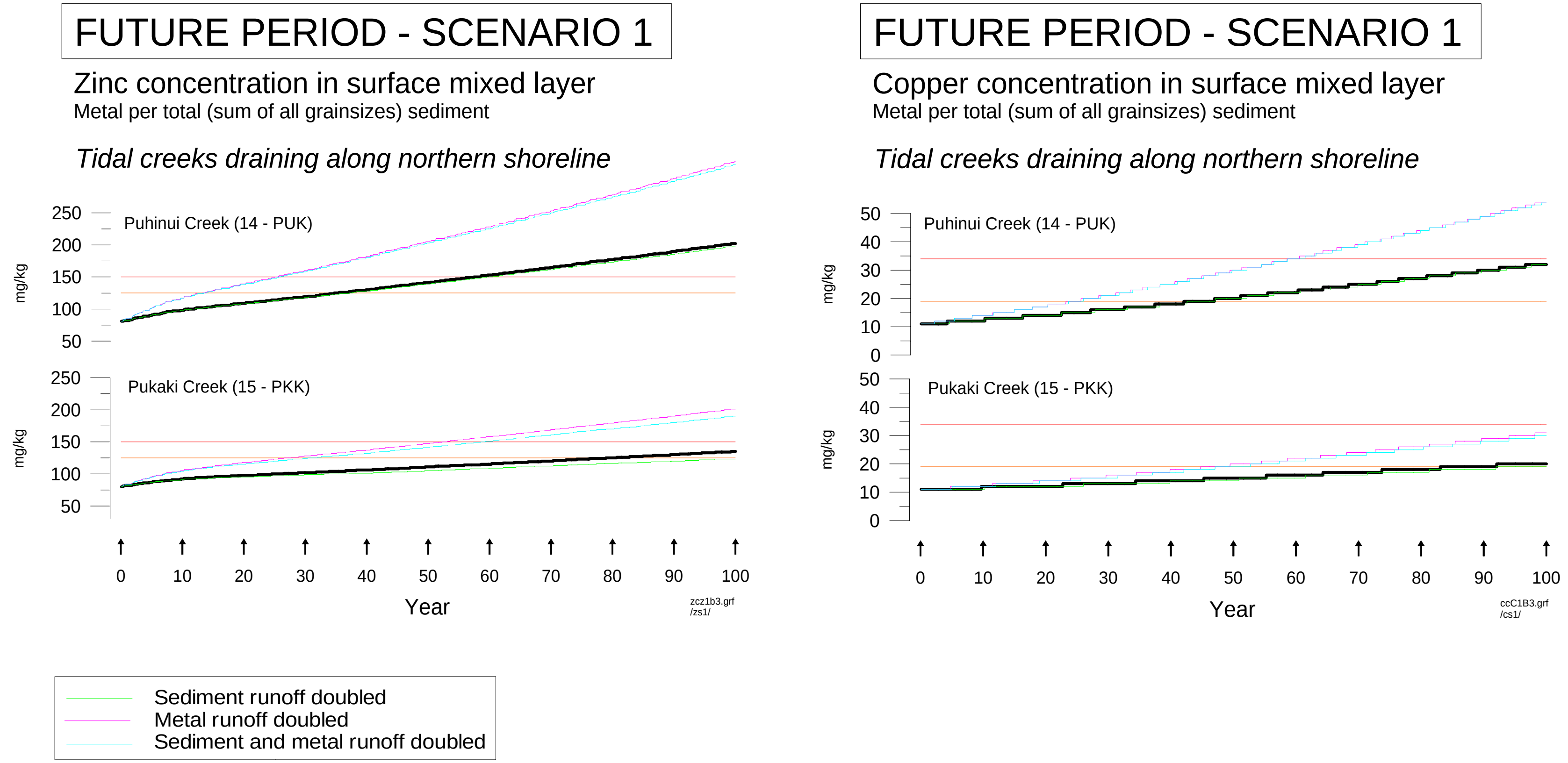


Figure 4.36

Sensitivity of Scenario 1 predictions to various combinations of doubling the sediment and metal runoff. Year 1 is 2001 and year 100 is 2100. Metal concentration is total metal per total sediment in the surface mixed layer.

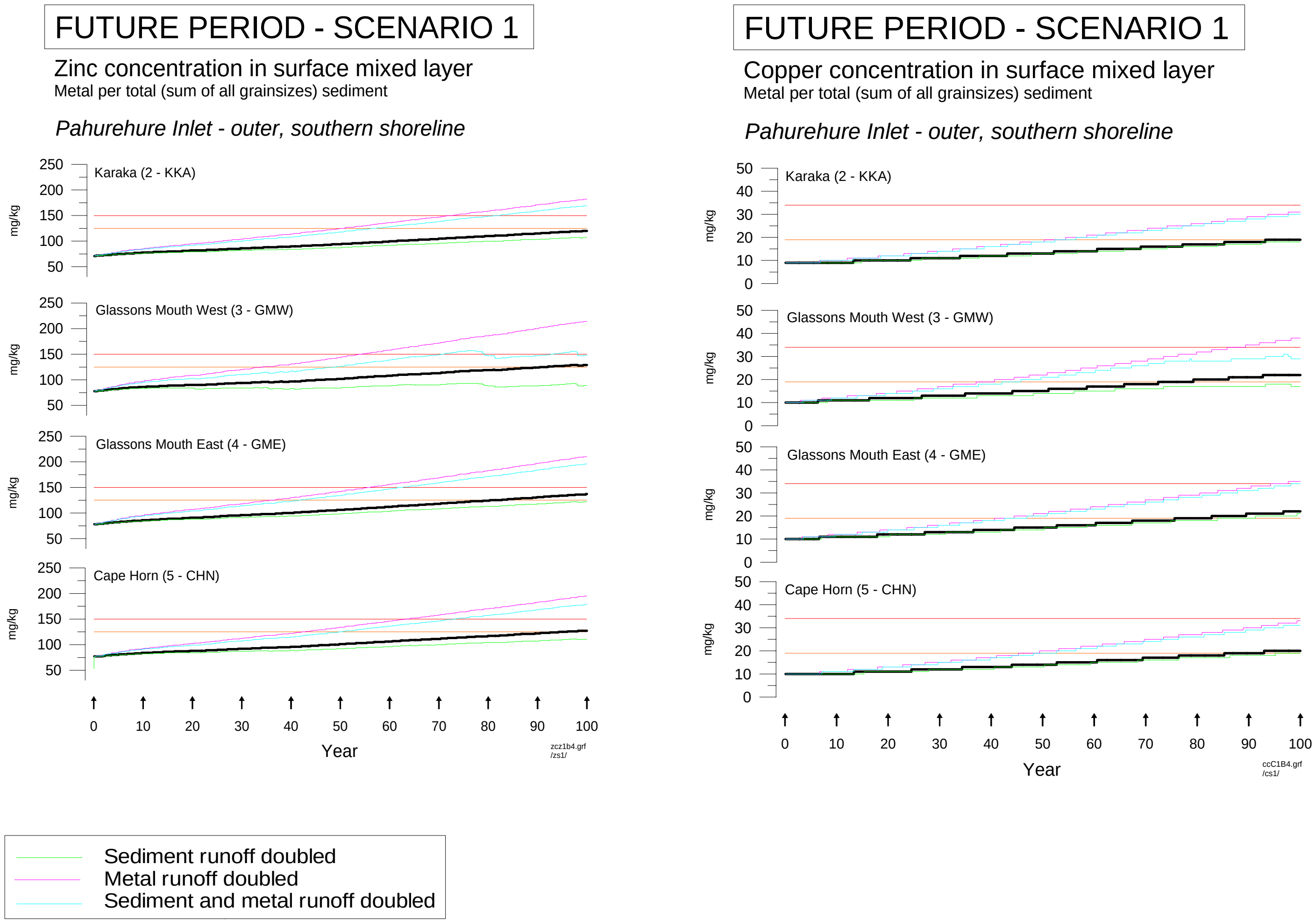


Figure 4.37

Sensitivity of Scenario 1 predictions to various combinations of doubling the sediment and metal runoff.  Year 1 is 2001 and year 100 is 2100.  Metal concentration is total metal per total sediment in the surface mixed layer.

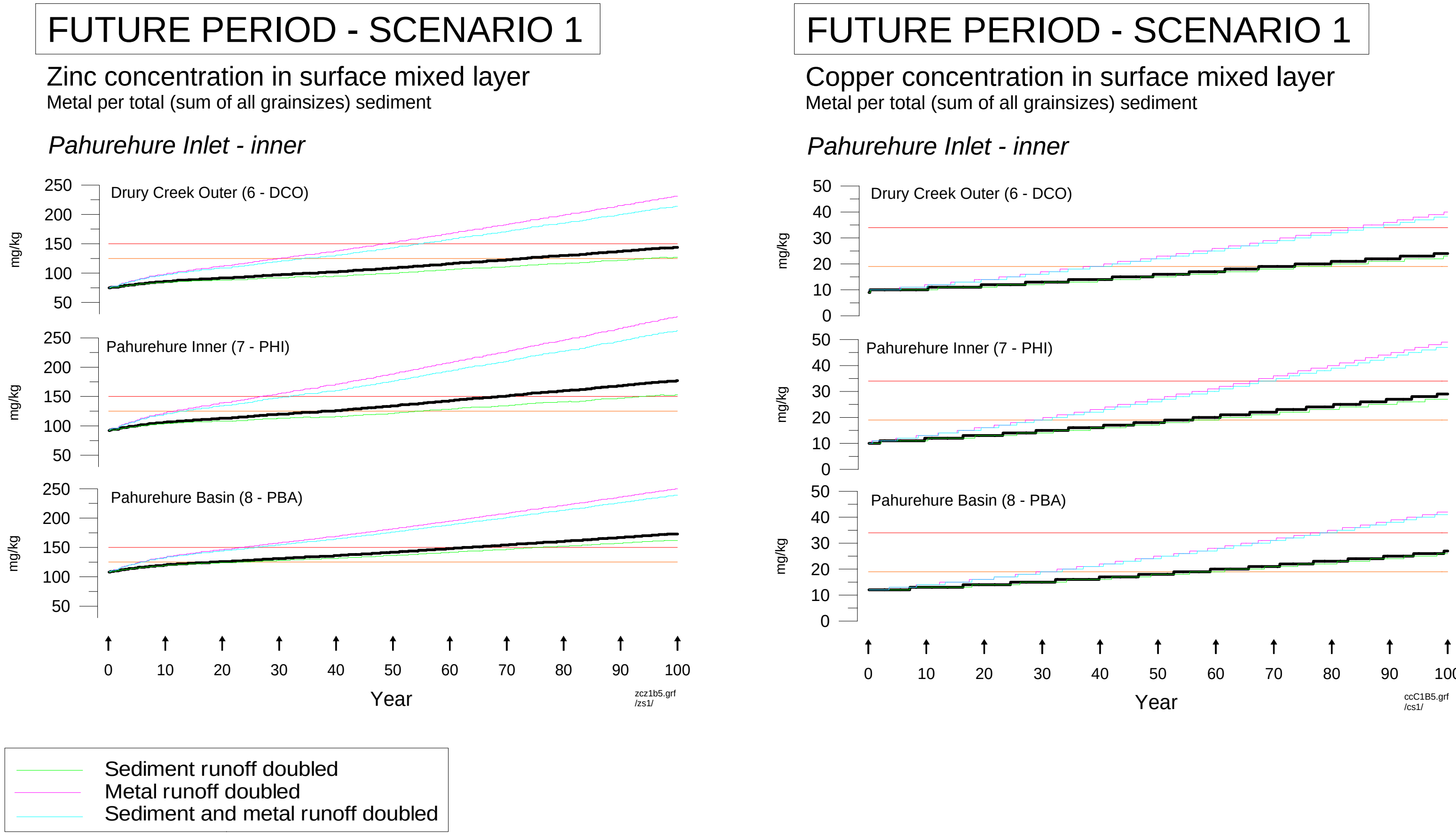


Figure 4.38

Sensitivity of Scenario 1 predictions to various combinations of doubling the sediment and metal runoff. Year 1 is 2001 and year 100 is 2100. Metal concentration is total metal per total sediment in the surface mixed layer.

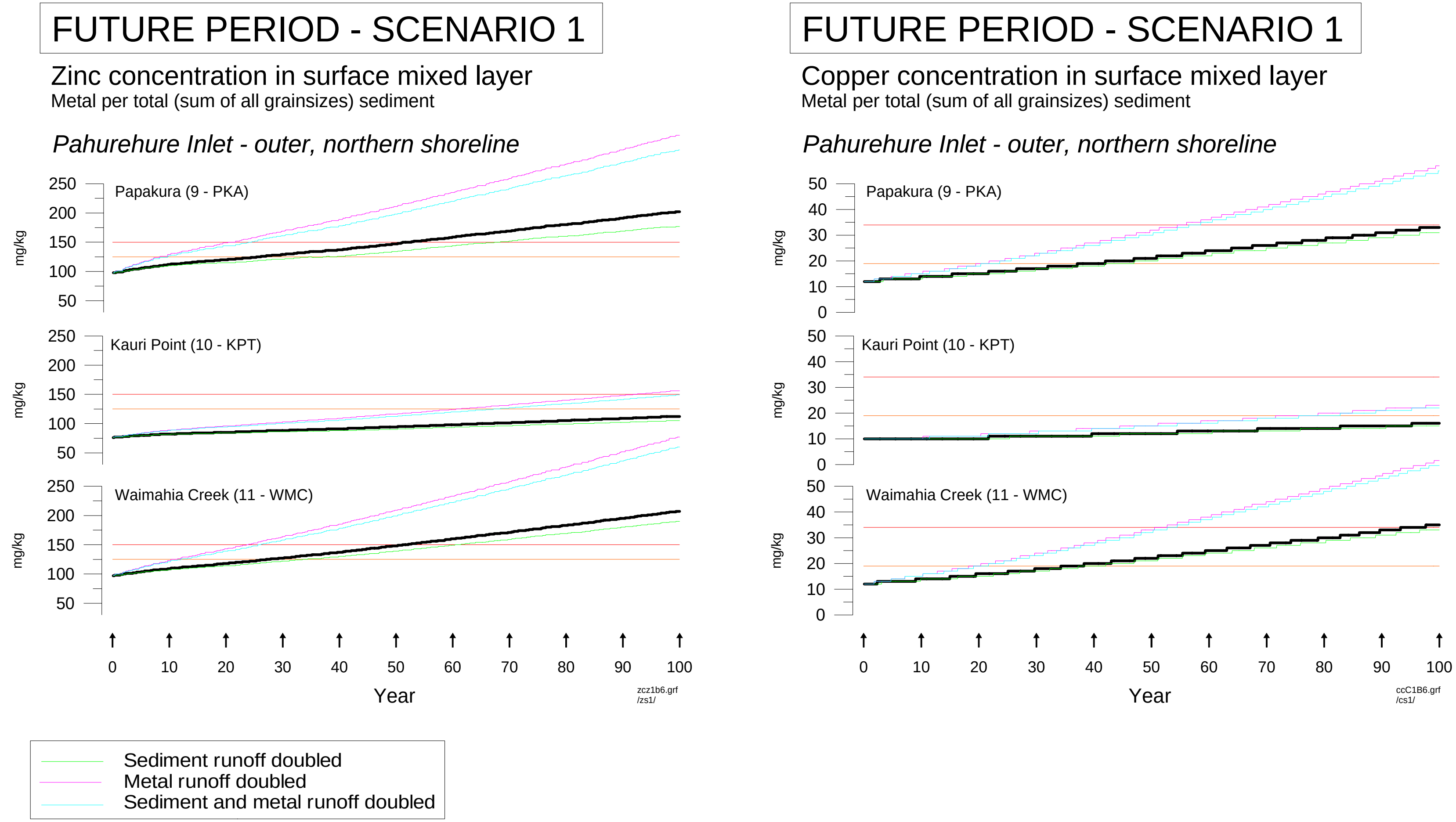


Figure 4.39

Sensitivity of Scenario 1 predictions to various combinations of halving the sediment and metal runoff. Year 1 is 2001 and year 100 is 2100. Metal concentration is total metal per total sediment in the surface mixed layer.

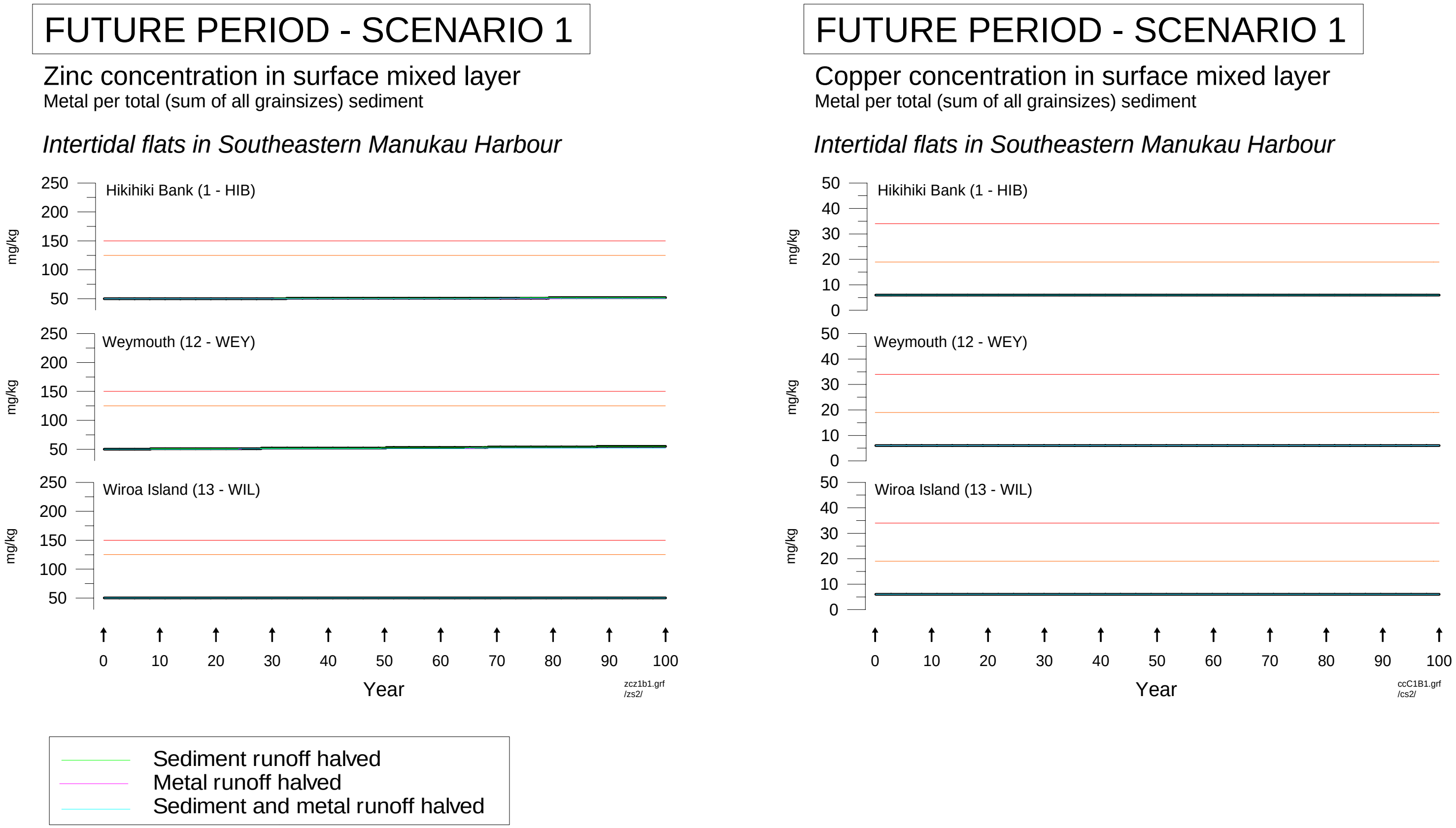


Figure 4.40

Sensitivity of Scenario 1 predictions to various combinations of halving the sediment and metal runoff.  Year 1 is 2001 and year 100 is 2100.  Metal concentration is total metal per total sediment in the surface mixed layer.

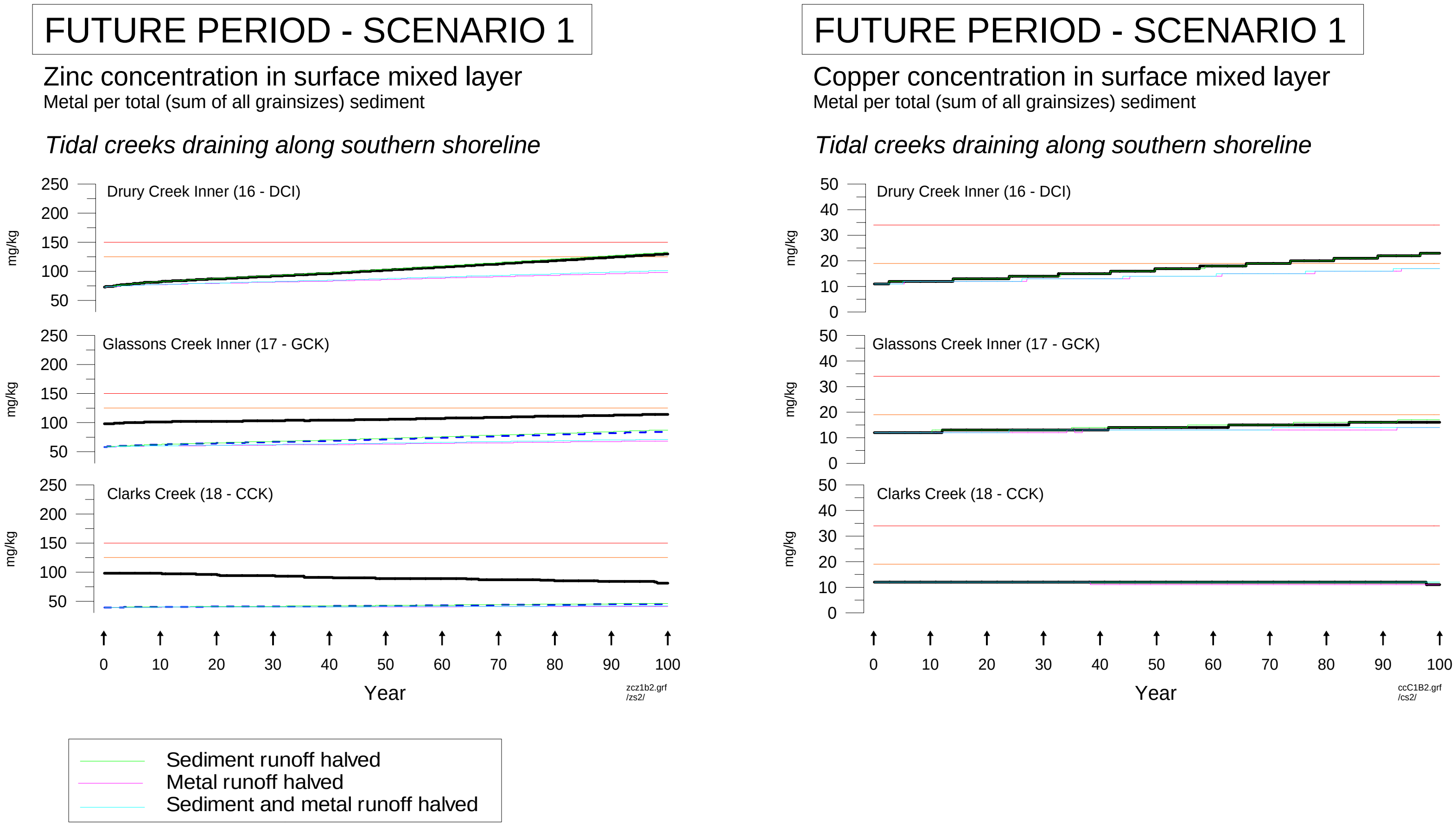


Figure 4.41

Sensitivity of Scenario 1 predictions to various combinations of halving the sediment and metal runoff.  Year 1 is 2001 and year 100 is 2100.  Metal concentration is total metal per total sediment in the surface mixed layer.

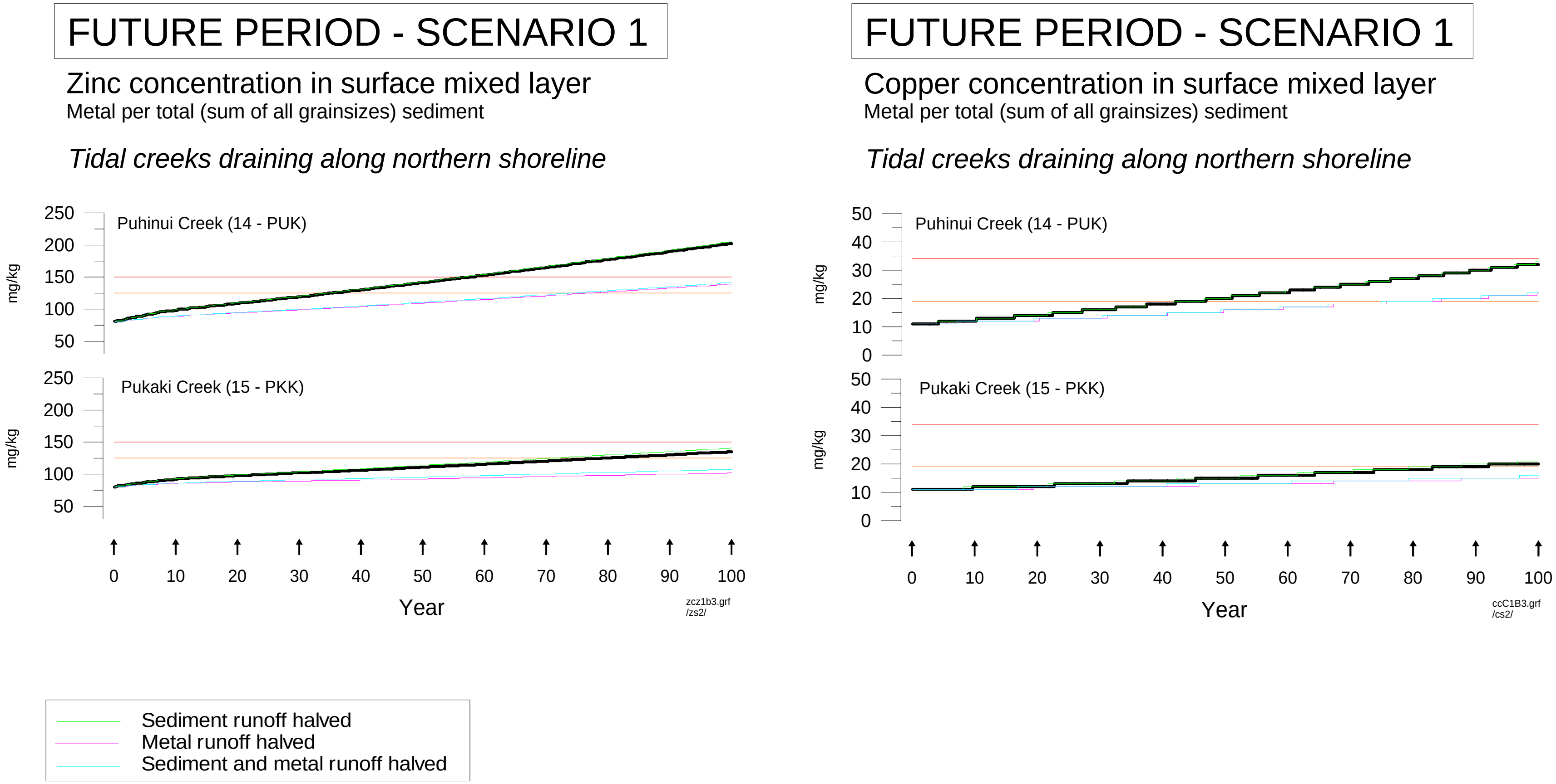


Figure 4.42

Sensitivity of Scenario 1 predictions to various combinations of halving the sediment and metal runoff. Year 1 is 2001 and year 100 is 2100. Metal concentration is total metal per total sediment in the surface mixed layer.

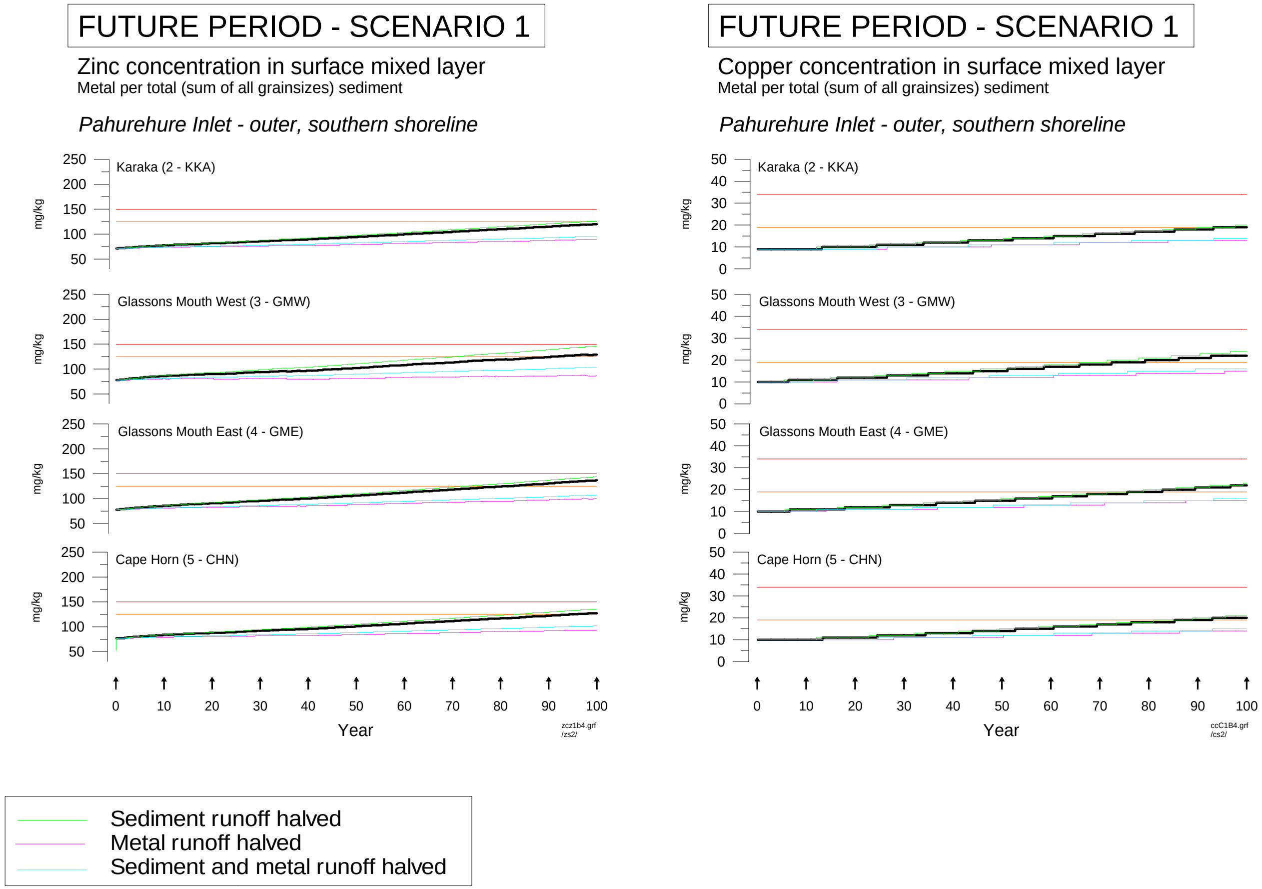


Figure 4.43

Sensitivity of Scenario 1 predictions to various combinations of halving the sediment and metal runoff.  Year 1 is 2001 and year 100 is 2100.  Metal concentration is total metal per total sediment in the surface mixed layer.

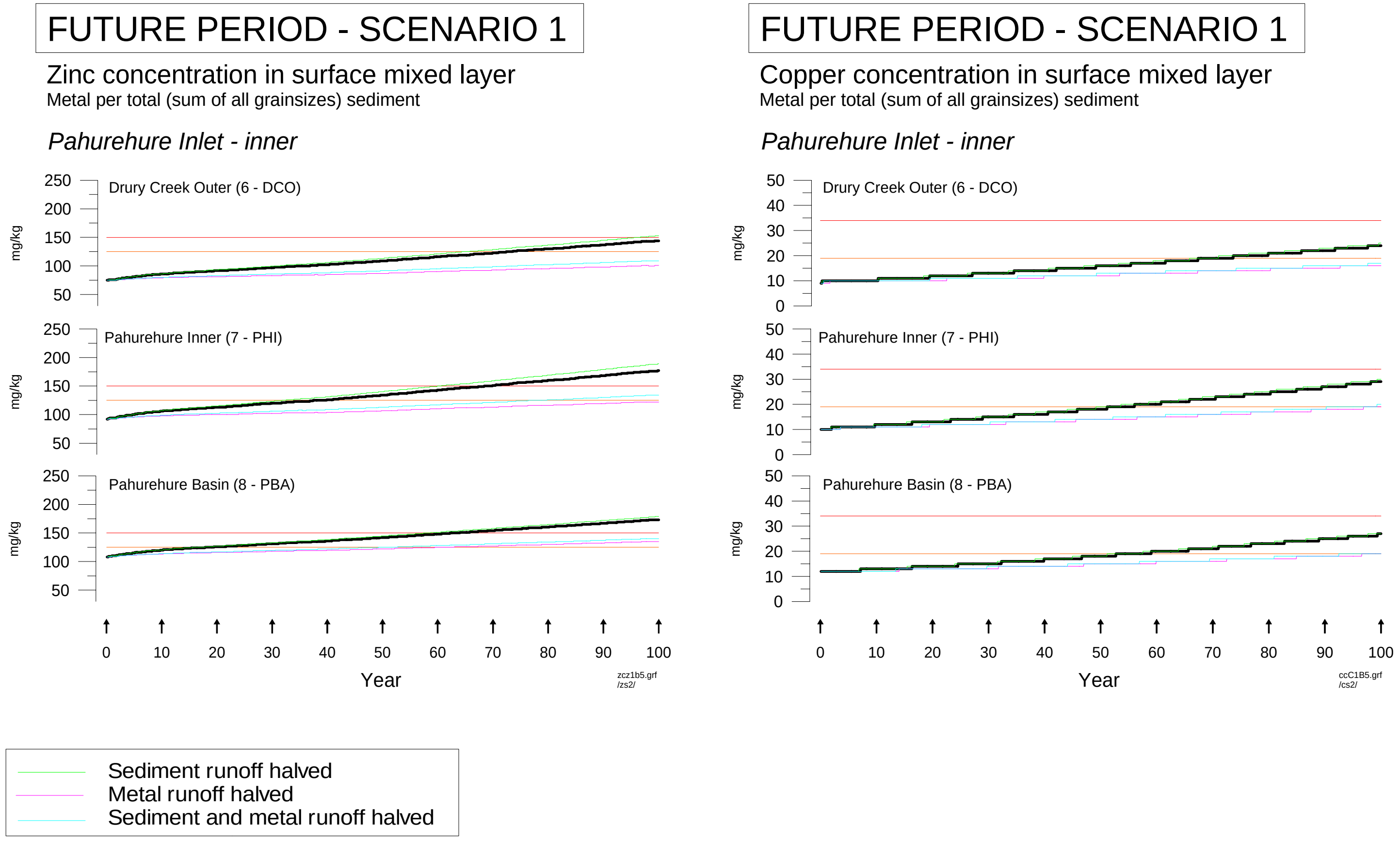


Figure 4.44

Sensitivity of Scenario 1 predictions to various combinations of halving the sediment and metal runoff.  Year 1 is 2001 and year 100 is 2100.  Metal concentration is total metal per total sediment in the surface mixed layer.

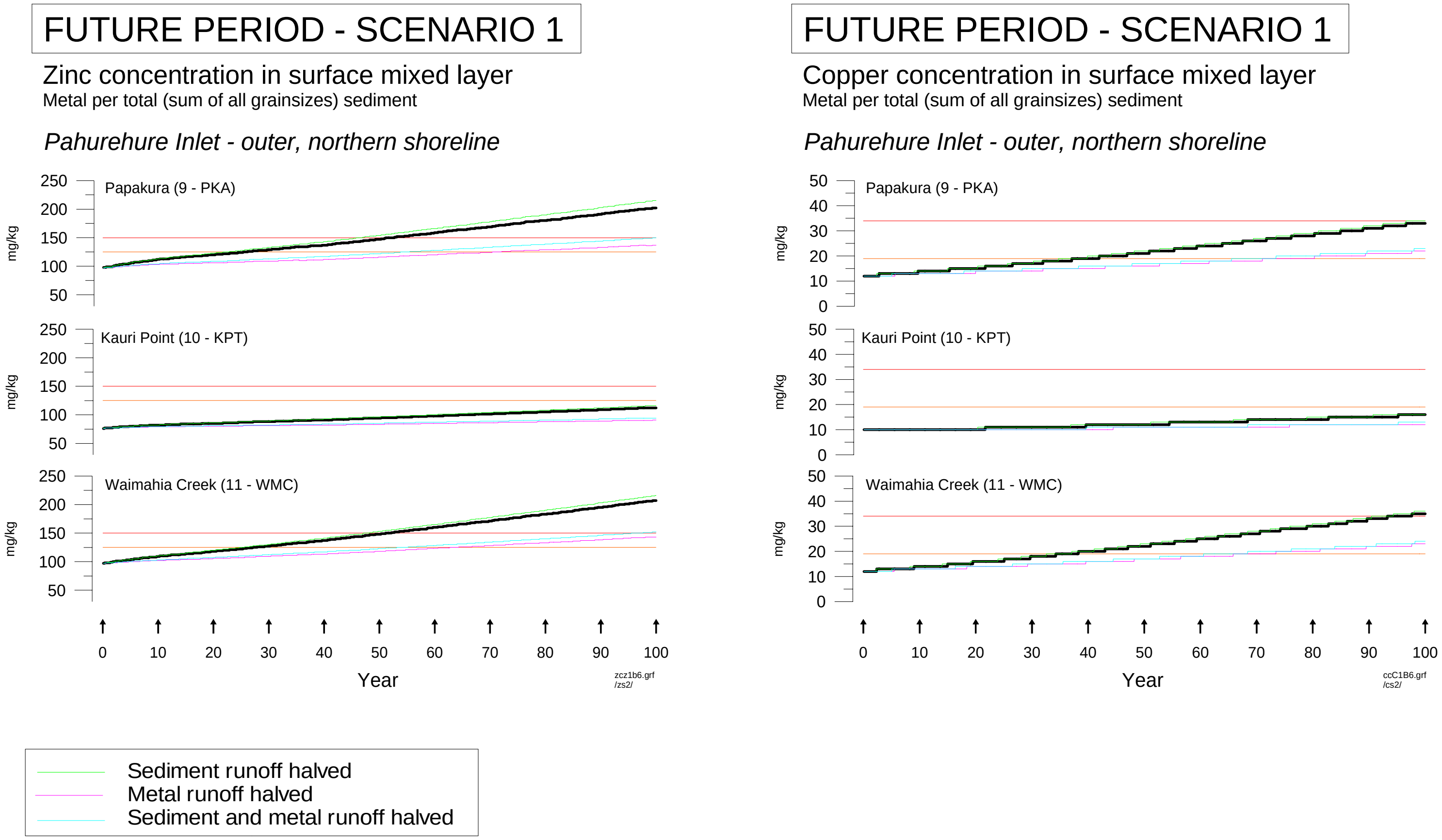
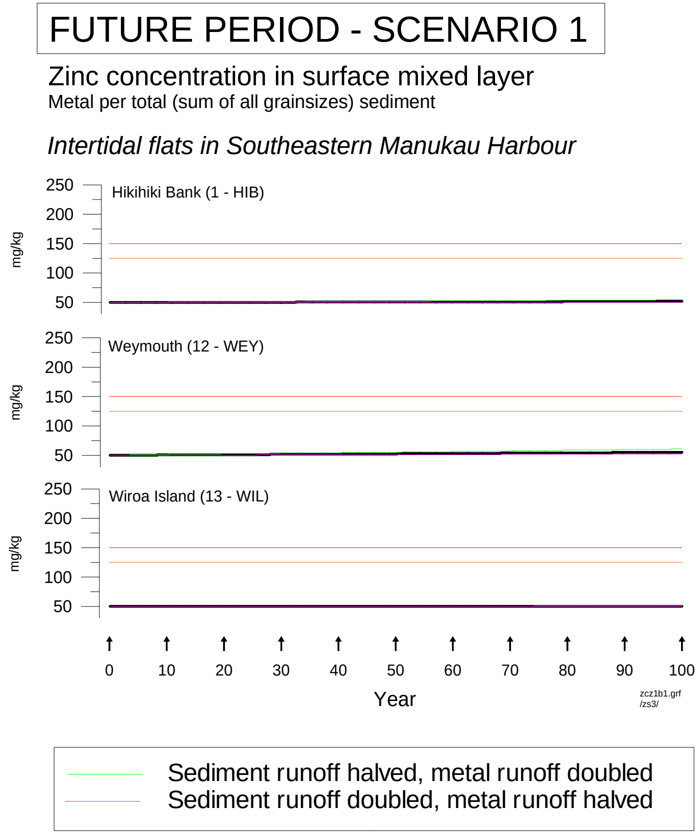


Figure 4.45

Sensitivity of Scenario 1 predictions to various combinations of halving and doubling the sediment and metal runoff. Year 1 is 2001 and year 100 is 2100. Metal concentration is total metal per total sediment in the surface mixed layer.



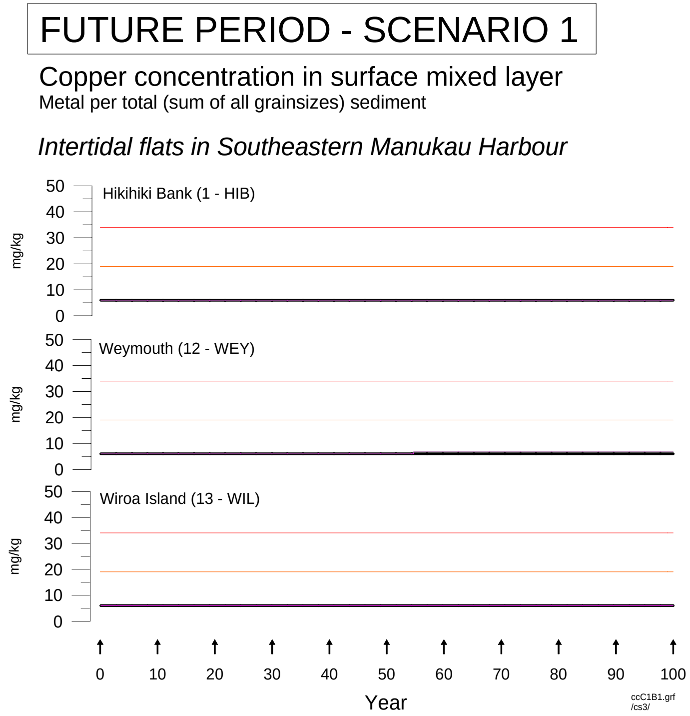



Figure 4.46

Sensitivity of Scenario 1 predictions to various combinations of halving and doubling the sediment and metal runoff.  Year 1 is 2001 and year 100 is 2100.  Metal concentration is total metal per total sediment in the surface mixed layer.

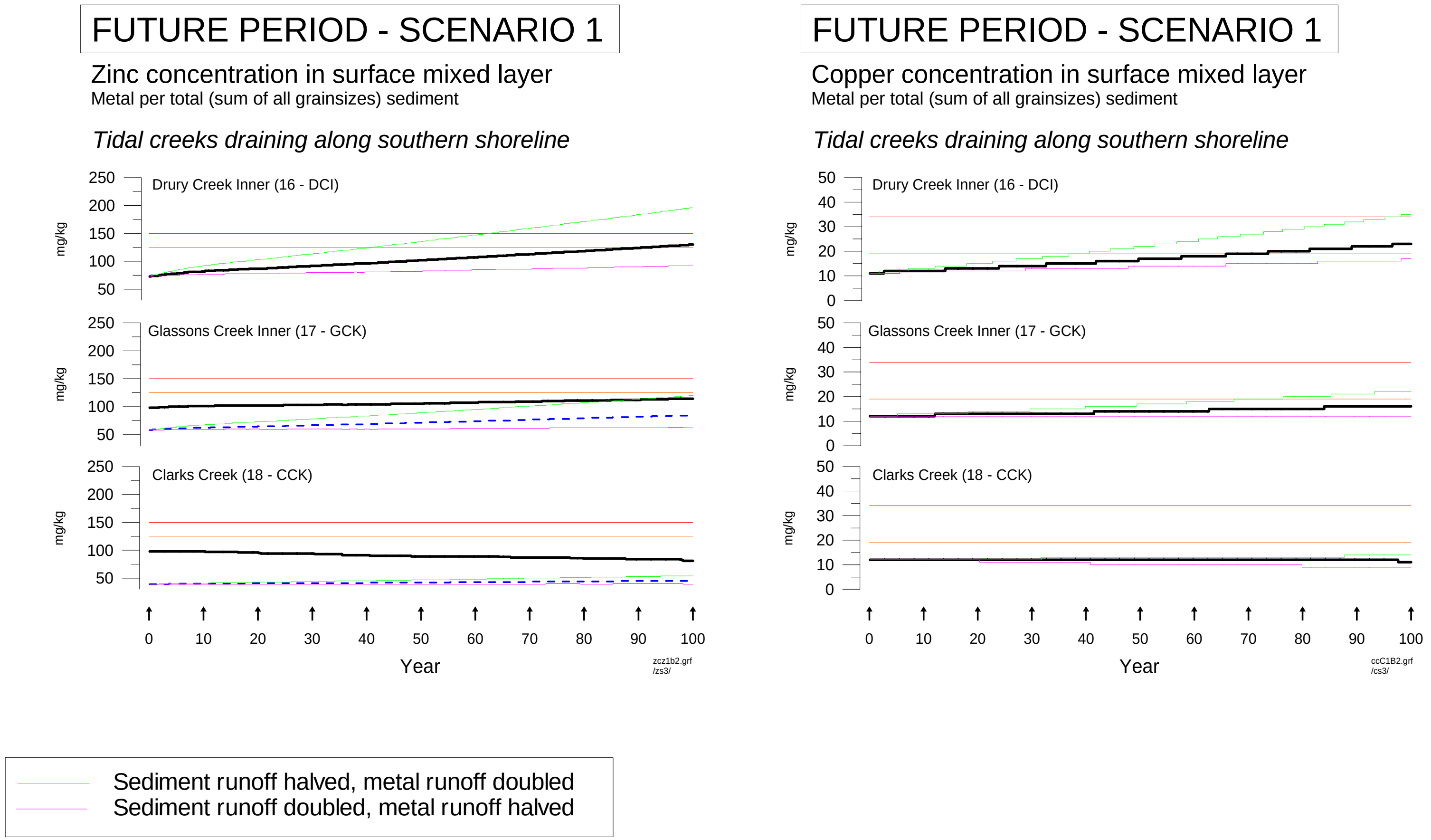
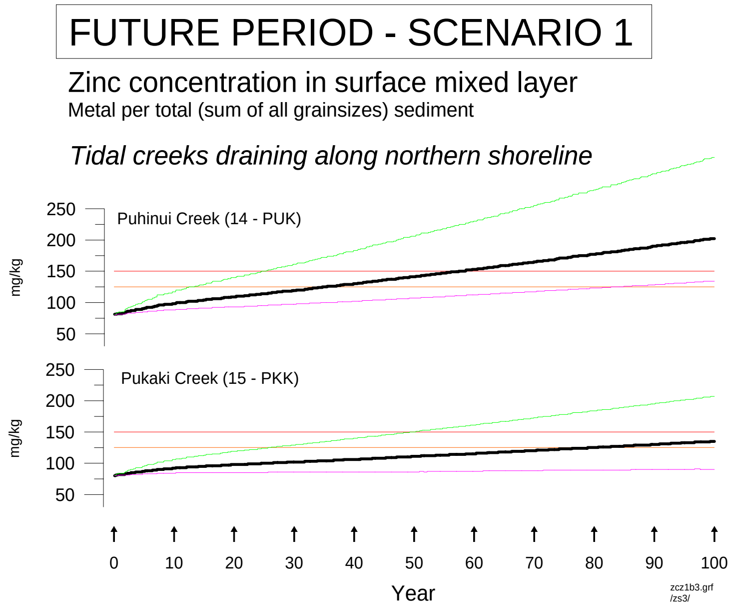
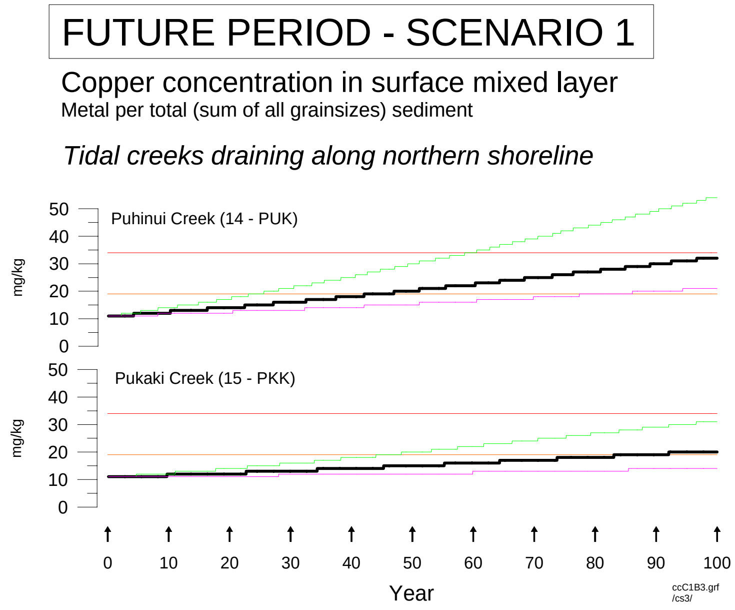


Figure 4.47

Sensitivity of Scenario 1 predictions to various combinations of halving and doubling the sediment and metal runoff. Year 1 is 2001 and year 100 is 2100. Metal concentration is total metal per total sediment in the surface mixed layer.




Sediment runoff halved, metal runoff doubled
Sediment runoff doubled, metal runoff halved

Figure 4.48

Sensitivity of Scenario 1 predictions to various combinations of halving and doubling the sediment and metal runoff. Year 1 is 2001 and year 100 is 2100. Metal concentration is total metal per total sediment in the surface mixed layer.

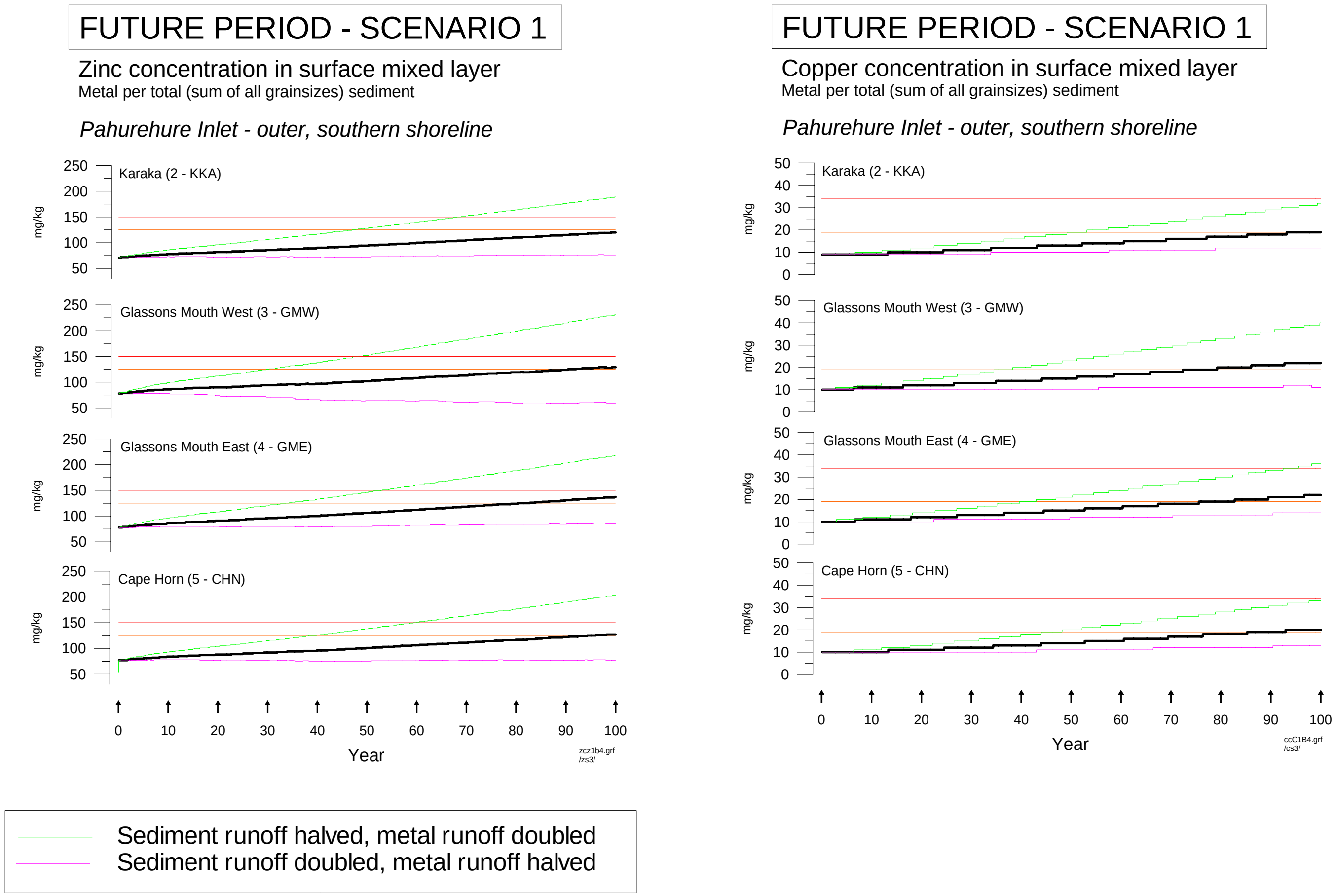
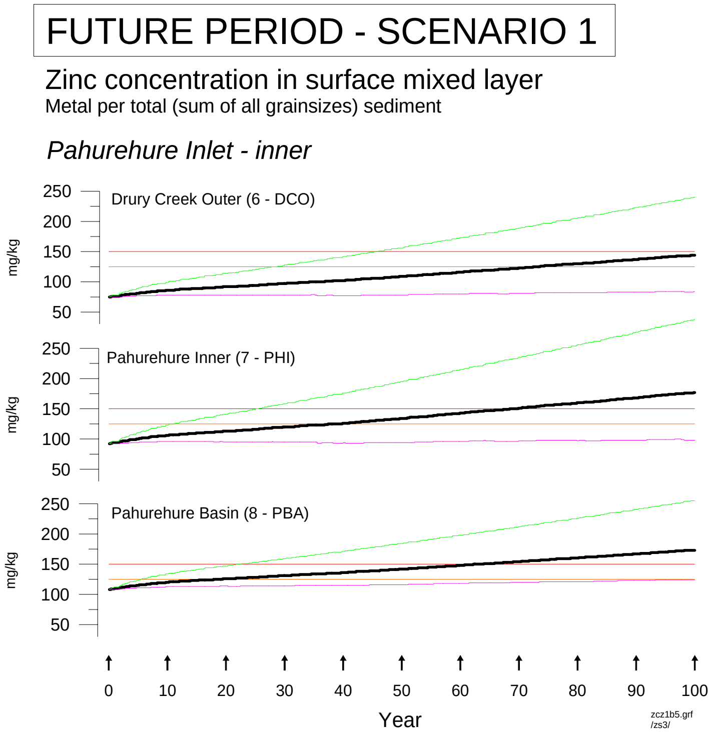
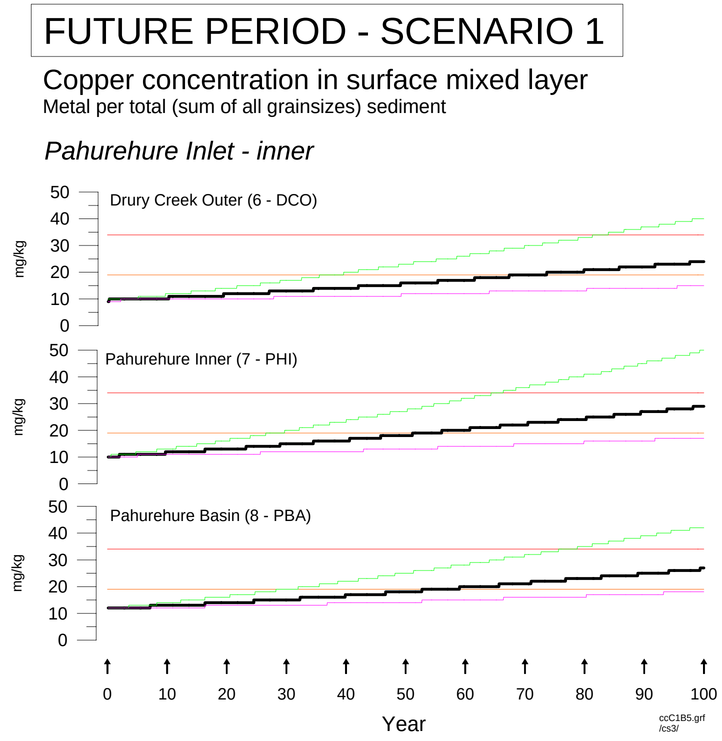


Figure 4.49

Sensitivity of Scenario 1 predictions to various combinations of halving and doubling the sediment and metal runoff.  Year 1 is 2001 and year 100 is 2100.  Metal concentration is total metal per total sediment in the surface mixed layer.

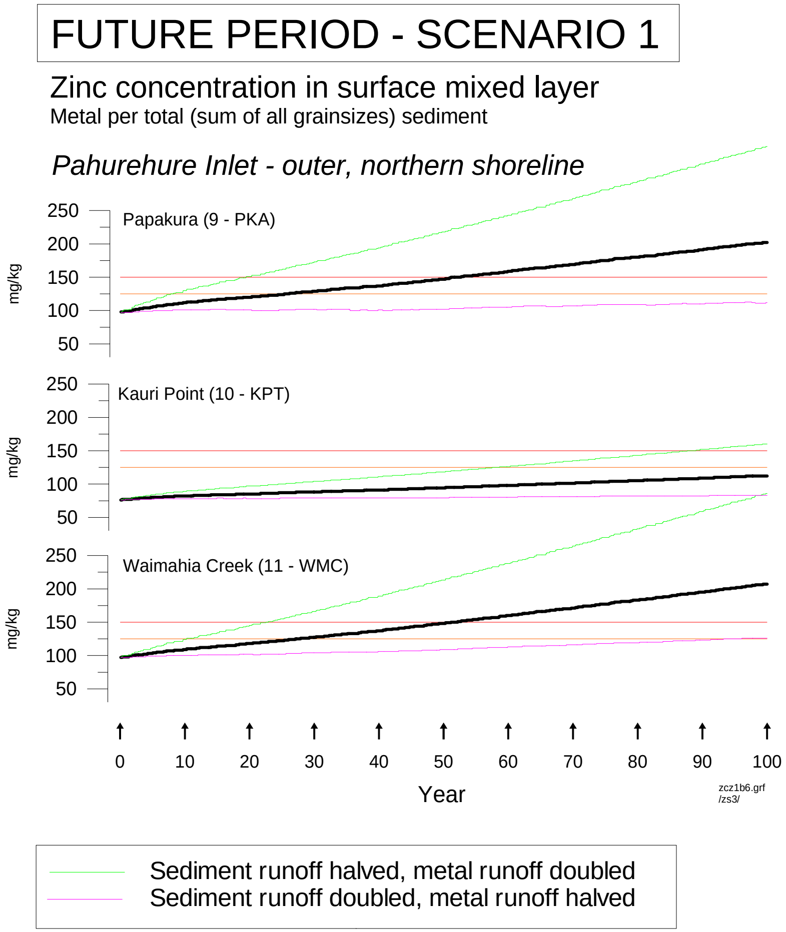


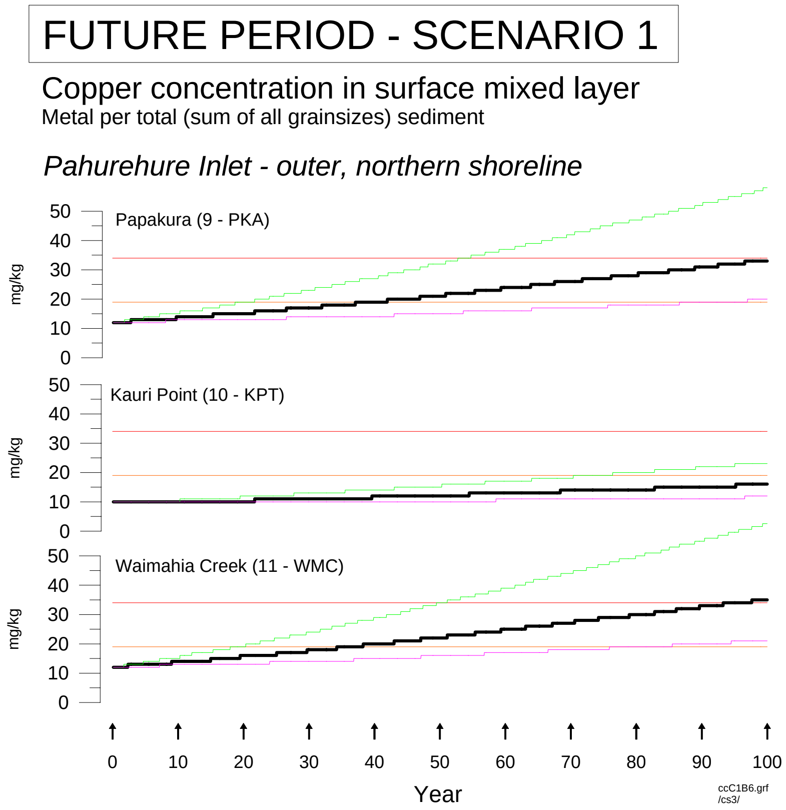




Sediment runoff halved, metal runoff doubled
Sediment runoff doubled, metal runoff halved

Figure 4.50

Sensitivity of Scenario 1 predictions to various combinations of halving and doubling the sediment and metal runoff. Year 1 is 2001 and year 100 is 2100. Metal concentration is total metal per total sediment in the surface mixed layer.



# 5 Conclusions

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 runoff, dispersal and accumulation in a complex, energetic receiving environment must be acknowledged. Ongoing monitoring is required to test and support the modelling.

Figures 6.1 provides a summary of the metal-concentration predictions for Scenario 1. In very general terms:

- There is no threat on the horizon for subestuaries designated “TEL not exceeded”.

  These subestuaries are the intertidal flats of Southeastern Manukau Harbour (Hikihiki Bank, Weymouth and Wiroa Island); Glassons Creek tidal creek and Clarks Creek tidal creek, which drain predominantly rural subcatchments; and Kauri Point, in an exposed location in the middle of Pahurehure Inlet.

  There is some uncertainty concerning measurements of zinc concentration in present-day surface sediments in both Glassons Creek and Clarks Creek. Unexpected high measured concentrations suggest a source of zinc that is not being accounted for in the modelling. This needs to be resolved.

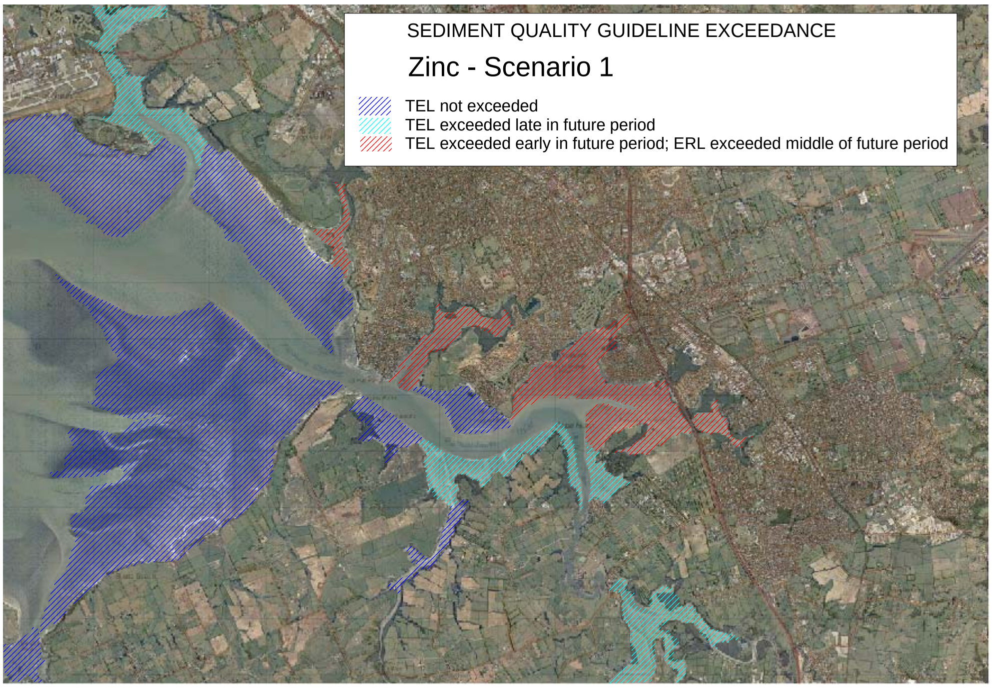
- The threat is low for subestuaries designated “TEL exceeded late in future period”.

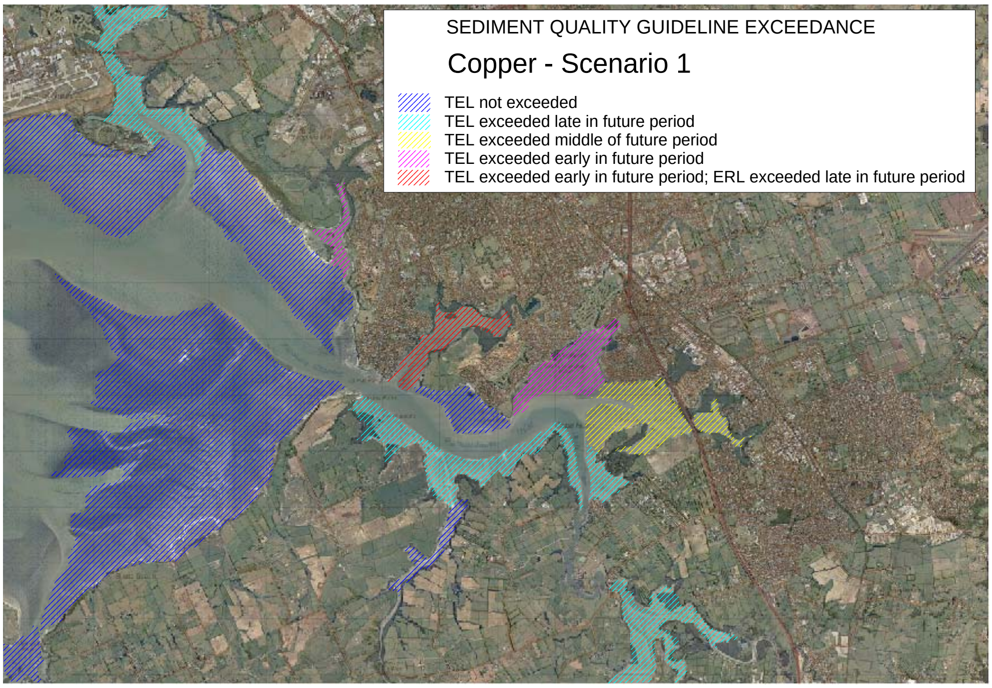
  These subestuaries are those clustered around the mouth of Glassons Creek on the southern side of the Inlet (Karaka, Glassons Mouth West, Glassons Mouth East, Cape Horn and Drury Creek Outer); Drury Creek Inner tidal creek, which drains the semi-rural Drury subcatchment; and Pukaki Creek tidal creek.

- The threat is heightened in the remaining subestuaries, in which the zinc TEL is predicted to be exceeded early in the future period, and the zinc ERL is predicted to be exceeded in the middle of the future period. Exceedance of copper sediment-quality guideline thresholds is predicted to be somewhat delayed relative to zinc. Management may need to act now or soon to safeguard ecological values in these areas.

  These subestuaries are Puhinui Creek tidal creek, subestuaries in the inner, sheltered reaches of Pahurehure Inlet (Pahurehure Inner and Pahurehure Basin), and the sheltered embayments along the northern shoreline of Pahurehure Inlet (Papakura and Waimahia Creek), all of which drain major urban centres.

**Figure 6.1:**
A high-level, simplified summary of the results for Scenario 1. Refer to the text for explanation.



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