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Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study: Predictions of Sediment, Zinc and Copper Accumulation Under Future Development Scenarios 2, 3 and 4

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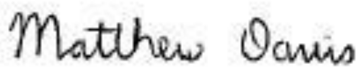

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Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study: Predictions of Sediment, Zinc and Copper Accumulation Under Future Development Scenarios 2, 3 and 4

Malcolm Green

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.

Scenario	Source control	Stormwater treatment
1	None	No additional
2	Zinc	No additional
3	None	Additional realistic

Predictions for Scenarios 2, 3 and 4 are reported herein. Predictions for Scenario 1, for which there is no zinc source control of industrial areas and stormwater treatment is at current levels of service, have already been reported[1].

The total sediment runoff is the sum of sediment from rural sources and sediment from urban sources. Sediment from urban sources only (not rural sources) is affected by stormwater treatment. Zinc source control has no effect on sediment runoff.

- In the four rural subcatchments (Kingseat, Elletts Beach, Karaka and Oira Creek), which all lie to the south of Pahurehure Inlet, total sediment runoff is not changed by improved stormwater treatment.
- In the remaining subcatchments, additional realistic stormwater treatment reduces total sediment runoff by 2–29% compared to no additional stormwater treatment.

The total metal runoff is the sum of metal from anthropogenic sources and metal from natural sources (i.e., soil). 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. Anthropogenic zinc only is affected by zinc source control.

[1] Green, M. (2008). Southeastern Manukau Harbour / Pahurehure Inlet Contaminant Study: Predictions of Sediment, Zinc and Copper Accumulation Under Future Development Scenario 1. NIWA Client Report HAM2008–141.

Anthropogenic metal plus that component of the natural metal that is associated with soil from urban sources is affected by stormwater treatment.

- In the four rural subcatchments, total metal runoff is not changed by mitigation measures.
- In the remaining subcatchments additional realistic stormwater treatment reduces total zinc by 8–20% compared to no additional stormwater treatment. The corresponding reduction in copper is 12–21%.
- On its own, zinc source control of industrial areas is a lot less effective than improved stormwater treatment on its own is, with zinc source control delivering reductions of just 0–1% in total zinc compared to no source control.
- Zinc source control combined with additional realistic stormwater treatment of course delivers the greatest reduction in zinc, but the difference between that reduction and the reduction under improved stormwater treatment alone is barely discernible.

The improved stormwater treatment reduces sedimentation in the harbour by 0–9%. This is, in broad terms, less than the reduction in total sediment runoff in those subcatchments with at least some urban areas (2–29%), and more than the reduction in total sediment runoff in the four rural subcatchments (0%). The reason is that most subestuaries deposit sediment from a number of subcatchments, including some that are exclusively rural and others that contain urban areas.

An ideal land-management strategy may seek to do two things: (1) reduce the concentration at which metals arrive at the base-of-catchment (BOC) in freshwater runoff; (2) reduce the sedimentation rate in the harbour.

- For the four rural subcatchments, the concentrations at which metals are delivered to BOC are exactly the same under all four scenarios.
- The subcatchments that are all or nearly all urbanised (Takanini, Manurewa / Weymouth and Bottle Top Bay) actually see metal (zinc and copper) concentration at BOC increase as a result of improved stormwater treatment. The reason is that improved stormwater treatment, as implemented in the Contaminant Load Model, removes proportionately more urban sediment than anthropogenic metal from the freshwater runoff.
- In all of the other subcatchments, which are urbanised to various degrees, the metal concentration at BOC is typically reduced by the improved stormwater treatment. This occurs even though the improved stormwater treatment removes proportionately more urban sediment than anthropogenic metal from the freshwater runoff. The reason for this, which is actually quite subtle, is explained and explored.
- Unlike improved stormwater treatment, zinc source control of industrial areas always reduces the concentration at which total zinc is delivered to BOC in the freshwater runoff. But, compared to the best reductions in zinc concentration at BOC achieved by improved stormwater treatment, the reduction due to zinc source control is minor. Furthermore, zinc source control of industrial areas has only a

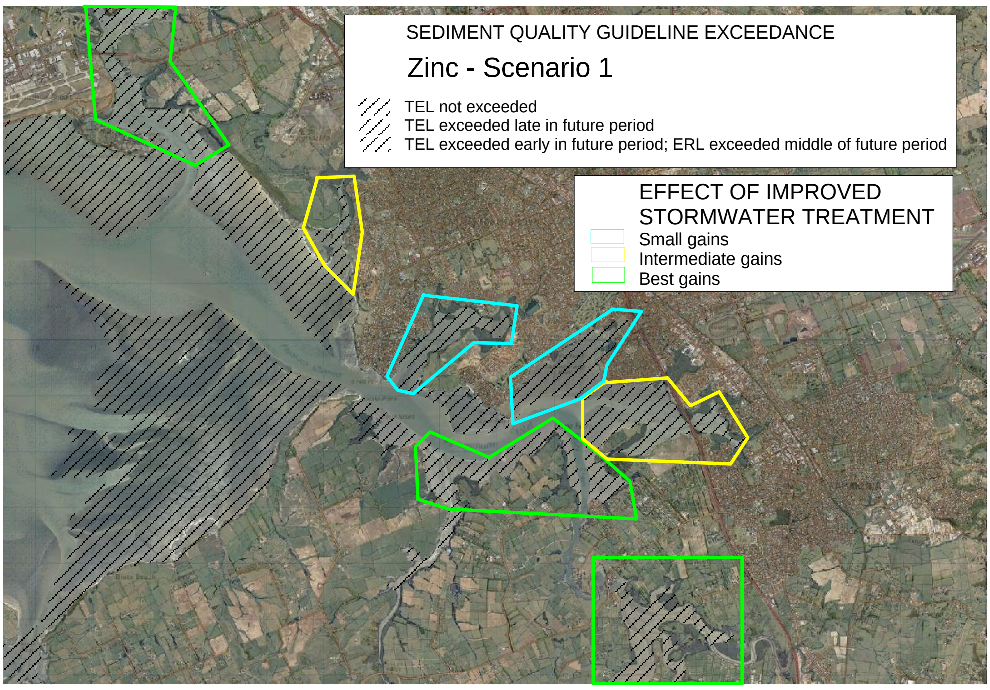
limited effect in time, but improved stormwater treatment has an effect throughout most of the future period.

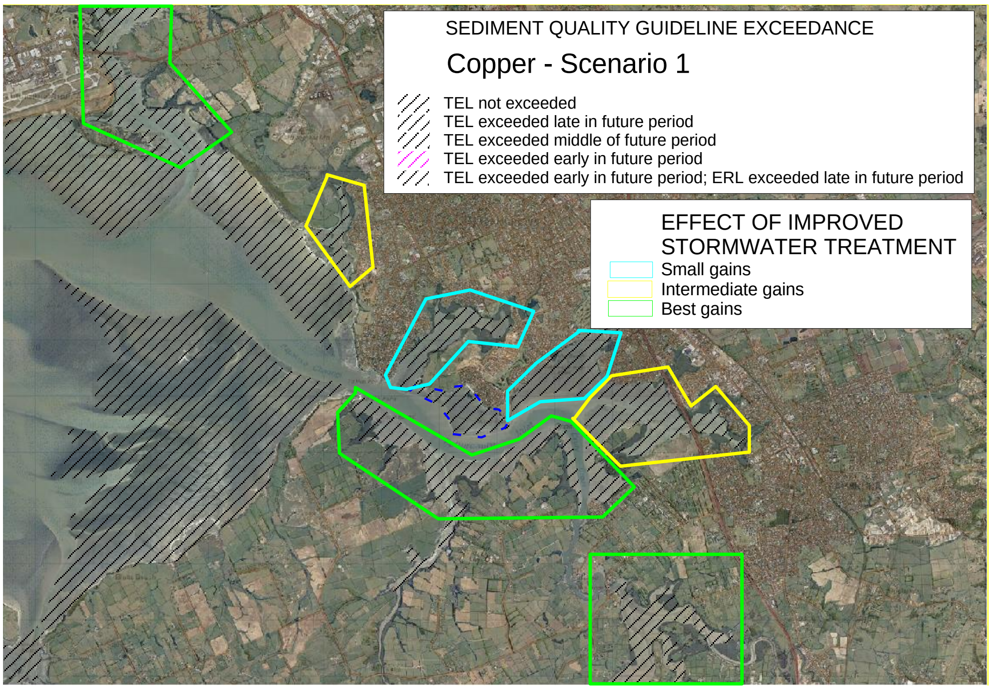
To sum up: zinc source control and stormwater treatment in some subcatchments decrease the concentration at which metals will be delivered to the harbour compared to Scenario 1, and in other subcatchments the delivery concentrations are increased. Since most subestuaries deposit sediment and metal from a number of subcatchments, it is not clear *a priori* how zinc source control of industrial areas and stormwater treatment will actually change the rate at which metals accumulate in the harbour bed sediments compared to Scenario 1. Of course, the purpose of the USC-3 model is to sort this out.

The figure below provides a summary of how the additional realistic stormwater treatment depicted in Scenarios 3 and 4 is predicted by the USC-3 model to improve on the no additional stormwater treatment depicted in Scenario 1.

- There are no gains to be had in subestuaries which either have a small sedimentation rate or that deposit sediment and metal mainly from rural subcatchments. This includes the intertidal flats of Southeastern Manukau Harbour (Hikihiki Bank, Weymouth and Wiroa Island), Glassons Creek tidal creek, Clarks Creek tidal creek, and Kauri Point. However, there is also no threat on the horizon for these subestuaries.
- The best gains are to be had for subestuaries that deposit sediment and metal from mixed rural–urban subcatchments, where metal concentration in freshwater runoff is most reduced by improved stormwater treatment. This includes the subestuaries that are 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 for these subestuaries is already low.
- Intermediate gains are seen for the inner, sheltered reaches of Pahurehure Inlet (Pahurehure Inner and Pahurehure Basin) and for Puhinui Creek. The threat is heightened in these subestuaries.
- The smallest gains are seen in Papakura and Waimahia Creek, where the threat is also heightened. The reason is that these subestuaries deposit sediment and metal that derives mainly from highly urbanised subcatchments, for which improved stormwater treatment increases the metal concentration in the freshwater runoff.

Zinc source control is predicted to have little effect on metal concentrations in the harbour bed sediments.


SEDIMENT QUALITY GUIDELINE EXCEEDANCE
Zinc - Scenario 1
TEL not exceeded
TEL exceeded late in future period
TEL exceeded early in future period; ERL exceeded middle of future period
EFFECT OF IMPROVED STORMWATER TREATMENT
Small gains
Intermediate gains
Best gains


SEDIMENT QUALITY GUIDELINE EXCEEDANCE
Copper - Scenario 1
TEL not exceeded
TEL exceeded late in future period
TEL exceeded middle of future period
TEL exceeded early in future period
TEL exceeded early in future period; ERL exceeded late in future period
EFFECT OF IMPROVED STORMWATER TREATMENT
Small gains
Intermediate gains
Best gains

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 or additional stormwater treatment.

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

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

(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.

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. 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.

Predictions for Scenarios 2, 3 and 4 are reported herein. Predictions for Scenario 1 have been reported in Green (2008b); these results are reproduced here where they add to the discussion.

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	Zinc source control applied to anthropogenic metal generation in industrial areas	Stormwater treatment applied to urban areas
1	Future population growth and urban development	None	No additional
2	Future population growth and urban development	Zinc source control	No additional
3	Future population growth and urban development	None	Additional realistic
4	Future population growth and urban development	Zinc source control	Additional realistic

- Scenarios 2, 3 and 4 differ from each other and from Scenario 1 only by anthropogenic metal (as opposed to the "natural" metals that are present in the soils of the catchment) runoff, and urban (as opposed to rural) sediment runoff.
- The "no additional" stormwater treatment modelled in Scenarios 1 and 2 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.
- The "additional realistic" stormwater treatment modelled in Scenarios 3 and 4 includes the treatment in Scenarios 1 and 2 plus: raingardens or multimedia filters on all large roads (>20,000 vehicles per day); silt fences or similar on all residential infill construction sites; raingardens or multimedia filters on all industrial paved areas; and ponds or wetlands at the bottom of all catchments treating 20% of the catchment stormwater.
- The source control modelled in Scenarios 2 and 4 applies to zinc only (not copper), and consists only of painting all unpainted and poorly painted industrial galvanised steel roofs.

Further details of scenarios are provided in Moores et al. (2008).

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 on 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, 2008a).

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. Each subcatchment discharges through one outlet to the harbour.

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

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

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

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

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

- For the injection into the harbour of sediment that is eroded from the land when it rains the model timestep is 2 complete tidal cycles (referred to herein as "one day").
- For the resuspension of estuarine bed sediments by waves and tidal currents the model timestep is also one day.
- Each day an injection and/or resuspension event may occur, or no event may occur. The rainfall, wind and tide range on the day govern whether or not an event occurs. The rainfall, wind and tide range on each day are determined by the long-term weather sequence that drives the model.
- The rainfall, wind and tide range on the day govern the way land-derived sediment is injected into the harbour. At the end of the day on which injection occurs, land-derived sediment may be settled onto the bed in any part of the harbour, may be in suspension in any part of the harbour, or may be lost to sinks. 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 all of the constituent particle sizes, including the finer fractions, which otherwise might be very mobile.

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

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

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

Because model predictions are sensitive to sequences of events (as just described), a series of 100-year simulations is run, with each simulation in the series driven by a different, randomly-chosen weather sequence. The predictions from the series of simulations are averaged to yield one average prediction of contaminant accumulation over the 100-year duration. Each weather sequence in the series is constructed so that long-term weather statistics are recovered.

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

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

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

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

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

3.2.1 Comparison with the USC-2 model

The USC-2 model allowed for erosion of bed sediment by waves and currents between rainfall events, but only in a limited way. In effect, only sediment / contaminant that was deposited in the immediately-previous rainfall event was allowed to be eroded and redispersed/redeposited throughout the harbour in any given between-rainfall period. This had the effect of "ratcheting up" deposition, as sediment deposited during previous events became sequestered, which is appropriate in sheltered basins. This will not be 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 (2008a), 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 (2008a), 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.

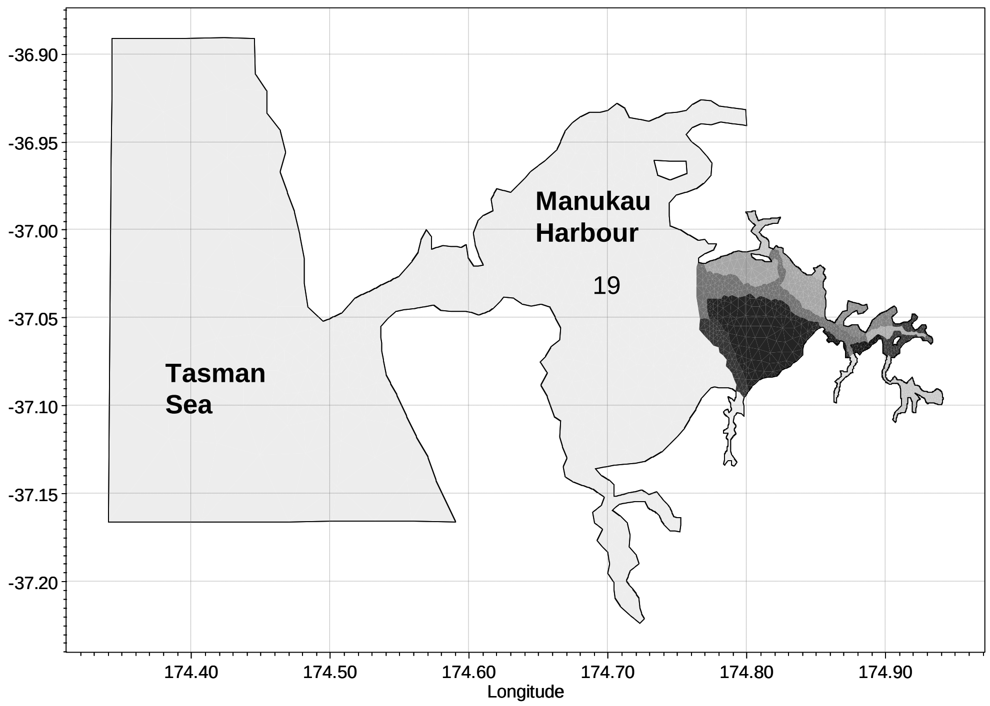
The subdivision of the catchment surrounding Southeastern Manukau Harbour / Pahurehure Inlet into subcatchments for the purposes of application of the USC-3 model is shown in Table 3.2 and Figure 3.2.

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.



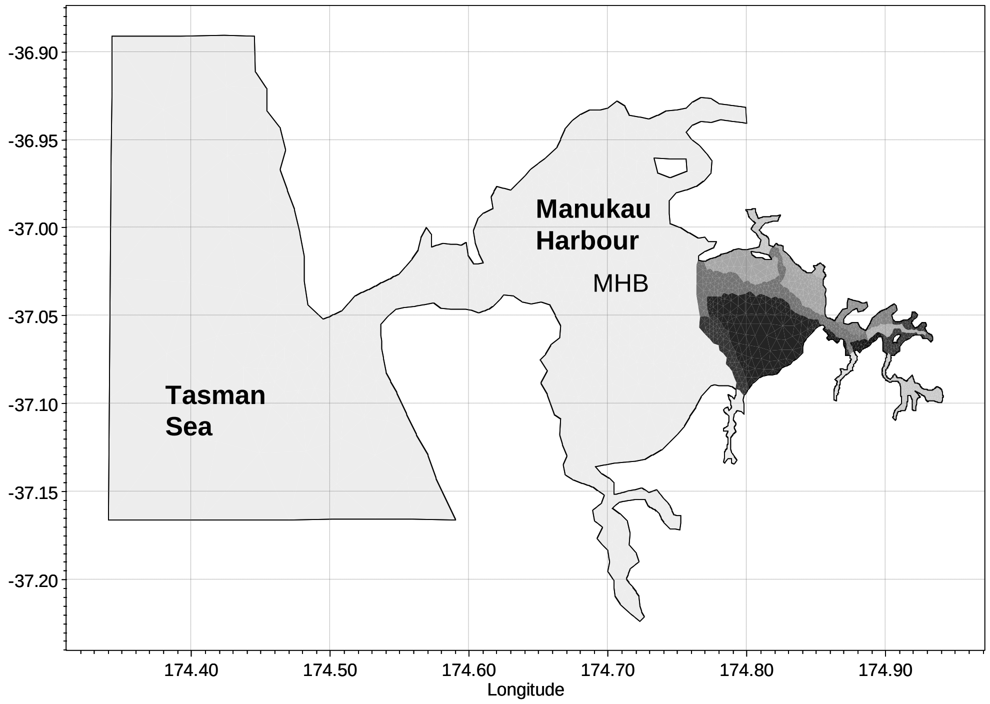
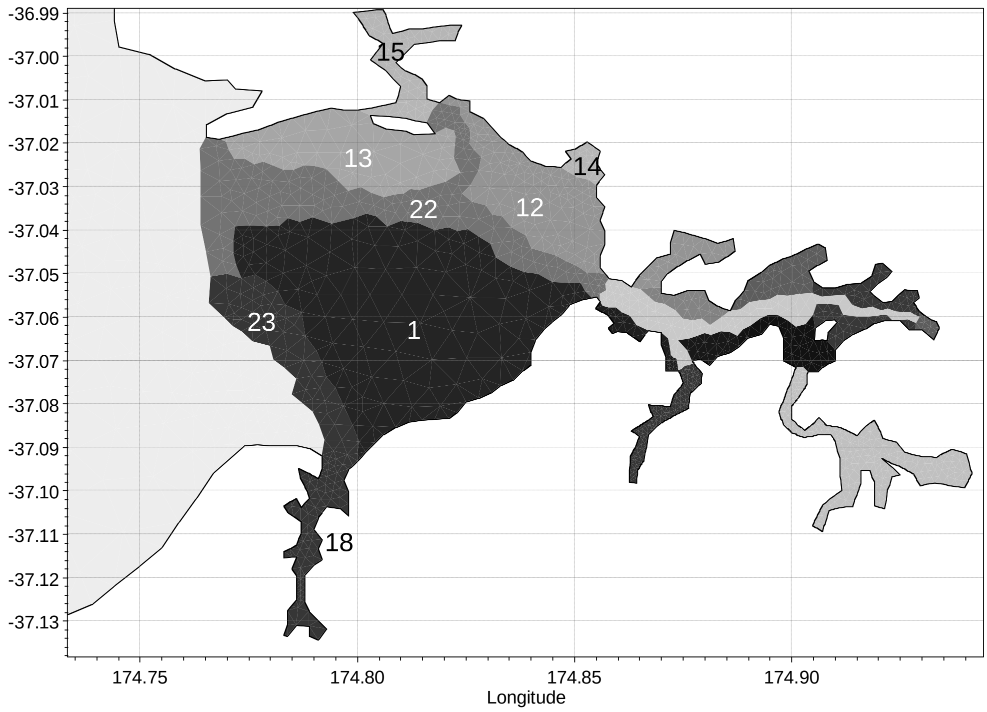


Figure 3.1: (continued)
Division of Southeastern Manukau Harbour / Pahurehure Inlet into subestuaries for the purposes of application of the USC-3 model.



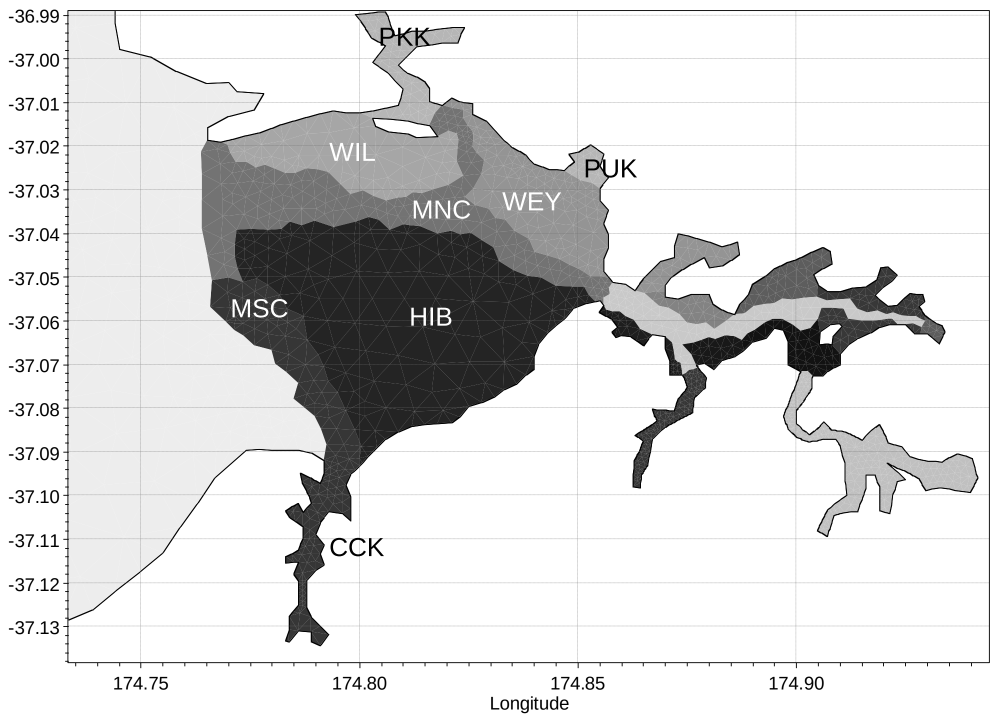


Figure 3.1: (continued)
Division of Southeastern Manukau Harbour / Pahurehure Inlet into subestuaries for the purposes of application of the USC-3 model.

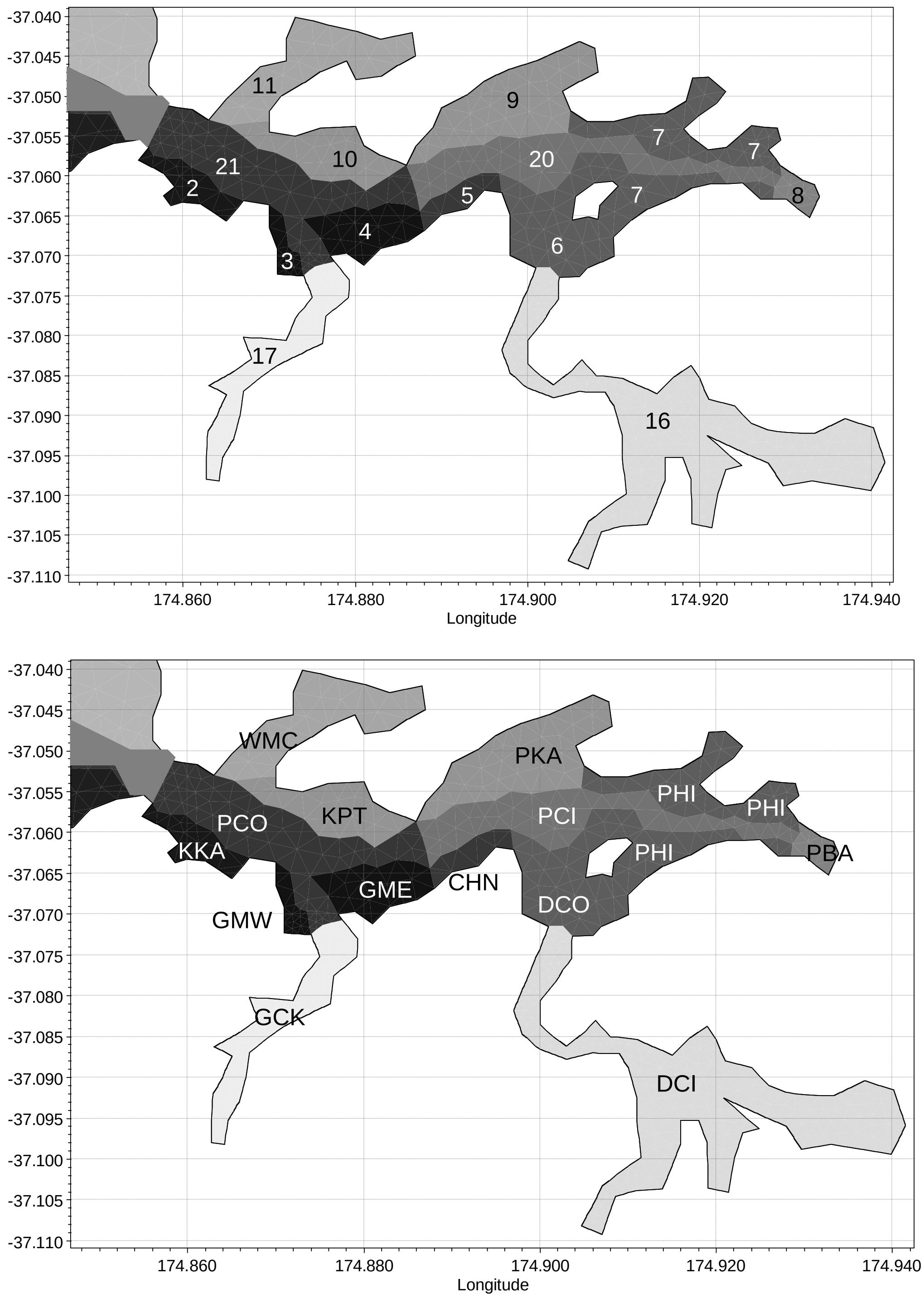
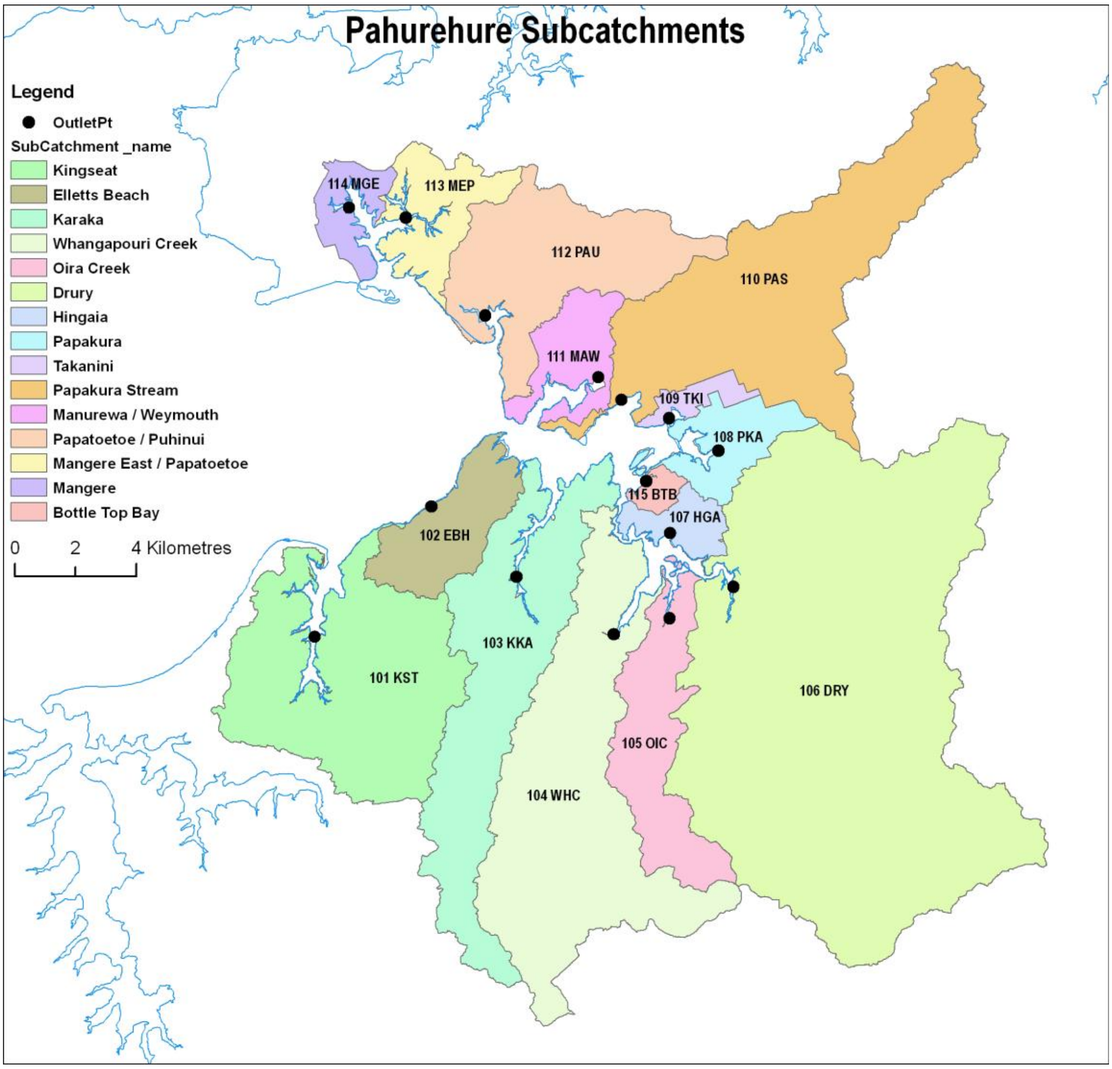


Table 3.2:

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 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 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 (2008a), 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 – Scenarios 2, 3 and 4

Scenarios 2, 3 and 4 all address future population growth and urban development in the catchment of Southeastern Manukau Harbour / Pahurehure Inlet. Each scenario covers 100 years into the future from the present day, which is defined as 2001. (Scenario 1 also addressed this same population growth and urban development.)

Scenarios 2, 3 and 4 differ from each other and from Scenario 1 only by anthropogenic metal (as opposed to the "natural" metals that are present in the soils of the catchment) runoff, and urban (as opposed to rural) sediment runoff, both of which are predicted by the Contaminant Load Model (CLM).

A summary of the way scenarios differ from each other is given in Table 2.1.

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 industrial zinc source control and stormwater treatment (Table 2.1).
- The CLM predictions of urban sediment runoff for the future period, which do vary by scenario, are presented in detail by Moores and Timperley (2008). 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

For each scenario, 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, 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 (2008a). 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 the same as that applied in the analysis of Scenario 1 (see Green, 2008b). This split was predicted by GLEAMS for the year 2001 and applied throughout the future period. 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, 2008a).

4.2.2 Sediment inputs from urban sources

For each scenario, 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. For each scenario, 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 is the same as that applied in the analysis of Scenario 1 (see Green, 2008b). This split was calculated by the CLM. 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, 2008a).

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, for each scenario, 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.

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

For each scenario, the CLM was used to predict annual anthropogenic zinc and copper loads at the bottom of each subcatchment for each year during the future period. The assignment of the anthropogenic metal load from each subcatchment to the sediment constituent particle sizes 12, 40 and 125 μm is the same as that applied in the analysis of Scenario 1 (see Green, 2008b). This assignment was calculated by the CLM. Note that one-half of the 12 μm metal load is assigned to the 4 μm particle size sediment (washload / low-density, slowly-settling flocs), which was determined during the calibration process (Green, 2008a).

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.

4.4 Estuarine bed sediments at the start of the future period

The split of the bed sediment in each subestuary amongst the constituent particle sizes at the start of the future period is the same split used in the analysis of Scenario

1 by Green (2008b). This split was based on observations reported by Reed et al. (2008).

The metal concentrations in the surface mixed layer of each subestuary at the start of the future period are also the same as those used by Green (2008b) in the analysis of Scenario 1. Again, these were based on observations by Reed et al. (2008).

4.5 Note

Understanding the division of the total sediment runoff between urban and rural sources in each subcatchment under Scenario 1, which was described in detail by Green (2008b), is crucial to understanding the effectiveness of stormwater treatment in reducing total sediment runoff to the harbour. Green's (2008b) analysis for Scenario 1 is reproduced in full in Appendix A. This should be consulted by the reader before proceeding.

Similarly, understanding the division of the total metal runoff between anthropogenic and natural sources in each subcatchment under Scenario 1, which was also described in detail by Green (2008b), is crucial to understanding the effectiveness of both zinc source control of industrial areas and stormwater treatment in reducing total metal runoff to the harbour. Green's (2008b) analysis for Scenario 1 is reproduced in full in Appendix B. Again, this should also be consulted by the reader before proceeding.

4.6 Results

4.6.1 Sediment runoff

Table 4.1 shows the total (rural plus urban) sediment runoff, summed over the future period, from each subcatchment under each scenario.

Figures 4.1 to 4.7 show how urban and total (rural plus urban) sediment runoff differ under each scenario during each year in the future period.

- The total sediment runoff is the sum of sediment from rural sources and sediment from urban sources. Sediment from urban sources only (not rural sources) is affected by stormwater treatment. Zinc source control of industrial areas has no effect on sediment runoff. Hence, total sediment runoff is the same under Scenarios 1 and 2 (both have no additional stormwater treatment, and Scenario 2 has zinc source control but Scenario 1 does not), and it is the same under Scenarios 3 and 4 (both have additional realistic stormwater treatment, and Scenario 4 has zinc source control but Scenario 3 does not). Total sediment runoff will be the same under all scenarios in subcatchments that have no urban sources of sediment. On the other hand, stormwater treatment will have the greatest effect on total sediment runoff in subcatchments where there are no rural sources of sediment.

- Four subcatchments have no urban areas: Kingseat (101); Elletts Beach (102); Karaka (103); and Oira Creek (105) (Appendix A), which all lie to the south of Pahurehure Inlet. For each of these subcatchments, total sediment runoff is the same under all four scenarios, as explained above.
- In all the other subcatchments, which do have urban areas, additional realistic stormwater treatment reduces total sediment runoff by 2–29% compared to no additional stormwater treatment. The largest reduction in total sediment runoff (29%) is achieved for Takanini subcatchment, for which 99% of the total sediment runoff derived from urban sources under Scenario 1 (Appendix A). The next largest reductions (22% for Bottle Top Bay and 18% for Manurewa / Weymouth) also correspond to highly urbanised subcatchments (100% in both cases). On the other hand, sparsely urbanised subcatchments see only a small reduction in total sediment runoff associated with improved stormwater treatment (e.g., Drury sees a reduction of only 2%, with 21% of the total sediment runoff deriving from urban sources under Scenario 1). A similar result holds for Mangere subcatchment (2% reduction, with 25% of total sediment runoff deriving from urban sources under Scenario 1).
- Urban sediment runoff is seen to reduce (compared to Scenario 1) smoothly throughout the future period from about 2116, which reflects the way the additional realistic stormwater treatment is applied in the CLM. Total sediment runoff does not always correspondingly smoothly decrease, however. The reason is that the rural sediment runoff, which is predicted by GLEAMS, fluctuates randomly from year to year. The random fluctuations are most pronounced in sparsely urbanised subcatchments (e.g., Drury), and absent in fully urbanised subcatchments (e.g., Manurewa / Weymouth).

4.6.2 Zinc runoff

Table 4.2 shows anthropogenic and total (anthropogenic plus natural) zinc runoff, summed over the future period, from each subcatchment under each scenario.

Figures 4.1 to 4.7 show how anthropogenic and total (anthropogenic plus natural) zinc runoff differ under each scenario during each year in the future period.

- The total zinc runoff is the sum of zinc from anthropogenic sources and zinc from natural sources (i.e., soil). Anthropogenic zinc (not natural zinc) is affected by zinc source control of industrial areas. Anthropogenic zinc plus that component of the natural zinc that is associated with soil from urban sources is affected by stormwater treatment. Total zinc runoff will be the same under all scenarios in subcatchments that have no urban areas. On the other hand, stormwater treatment and zinc source control will have the greatest effect on total zinc runoff in highly urbanised subcatchments.
- Four subcatchments have no anthropogenic zinc and all of the sediment is from rural sources: Kingseat (101); Elletts Beach (102); Karaka (103); and Oira Creek (105) (Appendix A), which all lie to the south of Pahurehure Inlet. For each of these

subcatchments, total zinc runoff is the same under all four scenarios, as explained above.

- In all the other subcatchments, which do have urban areas, additional realistic stormwater treatment reduces total zinc by 8–20% compared to no additional stormwater treatment. The largest reduction in total zinc (20%) is achieved for subcatchment 107 (Hingaia), for which 94% of the total zinc under Scenario 1 was anthropogenic (Appendix B). Subcatchments 109 (Takanini) and 112 (Papatoetoe / Puhinui) see the next-largest reduction (18%) (99% and 97%, respectively, of total zinc under Scenario 1 was anthropogenic). The smallest reductions are seen in subcatchments 113 (Mangere East / Papatoetoe) (8%) (89% of total zinc was anthropogenic under Scenario 1) and 114 (Mangere) (11%) (84% of total zinc was anthropogenic under Scenario 1).
- Compared to the percent reductions in total zinc, the percent reductions in anthropogenic zinc achieved by improved stormwater treatment are a little greater (9–21% compared to 8–20%), which is expected.
- On its own, zinc source control of industrial areas is a lot less effective than improved stormwater treatment on its own is, with source control delivering reductions of just 0–1% in both total zinc and anthropogenic zinc compared to no source control.
- Zinc source control of industrial areas combined with additional realistic stormwater treatment of course delivers the greatest reduction in zinc, but the difference between that reduction and the reduction under improved stormwater treatment alone is barely discernible. The reason is that zinc source control of industrial areas is barely effective, as already noted.
- Anthropogenic zinc is seen to reduce (compared to Scenario 1) smoothly throughout the future period from about 2116, which reflects the way both zinc source control of industrial areas and the additional realistic stormwater treatment are applied in the Contaminant Load Model. Total zinc does not always correspondingly smoothly decrease, however. The reason is that natural zinc, which derives from the rural sediment runoff, which in turn is predicted by GLEAMS, fluctuates randomly from year to year. The random fluctuations are most pronounced in sparsely urbanised subcatchments (e.g., Drury), and absent in fully urbanised subcatchments (e.g., Manurewa / Weymouth).

4.6.3 Copper runoff

Table 4.3 shows anthropogenic and total (anthropogenic plus natural) copper runoff, summed over the future period, from each subcatchment under each scenario.

Figures 4.1 to 4.7 show how anthropogenic and total (anthropogenic plus natural) copper runoff differ under each scenario during each year in the future period.

- The total copper runoff is the sum of copper from anthropogenic sources and copper from natural sources (i.e., soil). Zinc source control has no effect on copper. Anthropogenic copper plus that component of the natural copper that is associated with soil from urban sources is affected by stormwater treatment. Total copper runoff will be the same under all scenarios in subcatchments that have no urban areas. On the other hand, stormwater treatment will have the greatest effect on total copper runoff in highly urbanised subcatchments.

- Four subcatchments have no anthropogenic copper: Kingseat (101); Elletts Beach (102); Karaka (103); and Oira Creek (105) (Appendix A), which all lie to the south of Pahurehure Inlet. For each of these subcatchments, total copper runoff is the same under all four scenarios, as explained above.
- In all the other subcatchments, which do have urban areas, additional realistic stormwater treatment reduces total copper by 12–21% compared to no additional stormwater treatment. The largest reduction in total copper (21%) is achieved for subcatchment 112 (Papatoetoe / Puhinui), for which 96% of the total copper under Scenario 1 was anthropogenic (Appendix B). Subcatchments 109 (Takanini) and 107 (Hingaia) see the next-largest reduction (19%) (99% and 95%, respectively, of total copper under Scenario 1 was anthropogenic). The smallest reductions are seen in subcatchments 113 (Mangere East / Papatoetoe) (12%) (86% of total copper was anthropogenic under Scenario 1) and 114 (Mangere) (13%) (80% of total copper was anthropogenic under Scenario 1).
- Compared to the percent reductions in total copper, the percent reductions in anthropogenic copper achieved by improved stormwater treatment are a little greater (14–22% compared to 12–21%), which is expected.
- Anthropogenic copper is seen to reduce (compared to Scenario 1) smoothly throughout the future period from about 2116, which reflects the way the additional realistic stormwater treatment is applied in the Contaminant Load Model. Total copper does not always correspondingly smoothly decrease, however. The reason is that natural copper, which derives from the rural sediment runoff, which in turn is predicted by GLEAMS, fluctuates randomly from year to year. The random fluctuations are most pronounced in sparsely urbanised subcatchments (e.g., Drury), and absent in fully urbanised subcatchments (e.g., Manurewa / Weymouth).

4.6.4 Sedimentation

Table 4.4 shows the predicted sedimentation rate (averaged over the future period) under no additional stormwater treatment (Scenarios 1 and 2) and under additional realistic stormwater treatment (Scenarios 3 and 4).

The improved stormwater treatment reduces sedimentation by 0–9% across all subestuaries. This is, in broad terms, less than the reduction in total sediment runoff in those subcatchments with at least some urban areas (2–29%), and more than the reduction in total sediment runoff in the four subcatchments with no urban areas (0%). The reason is that most subestuaries deposit sediment from a number of subcatchments, including some that are exclusively rural and others that contain urban areas. The subestuary with the smallest reduction (Clarks Creek) (0%) deposits sediment virtually exclusively from the adjacent Kingseat subcatchment, which contains no urban areas and which sees no reduction in sediment runoff from the improved stormwater treatment as a result. Conversely, the greatest reduction in sedimentation (9%) is in Waimahia Creek, which deposits sediments mostly from urbanised subcatchments, where the improved stormwater treatment has the most effect.

4.6.5 Concentration at which metals are delivered to the harbour

The concentration at which metals are delivered to the harbour in freshwater runoff is a key driver of the harbour response to runoff from the catchment, as Green (2007) explained. The harbour can be viewed simply as a bucket that contains sediment and metal, and sediment and metal from another bucket – the catchment – gets tipped into the harbour bucket as time goes by. If metal is present in the catchment bucket at the same concentration that it is present in the harbour bucket, then the concentration in the harbour bucket will not change. On the other hand, if metal is present in the catchment at a greater (lesser) concentration, then the concentration in the harbour bucket will increase (decrease) over time. If there is enough time and if the metal concentration in the catchment bucket does not change, then the concentration in the harbour bucket will eventually attain the same concentration as in the catchment bucket, which is termed "equilibrium" (The term "equilibrium" applies strictly to closed systems, such as the buckets being described here, but for open systems, such as estuaries, the correct term is "steady state").

An ideal land-management strategy may seek to do two things: (1) reduce the concentration at which metals arrive at the base-of-catchment (BOC) in freshwater runoff; (2) reduce the sedimentation rate in the harbour. The reduction in metal concentration at BOC will slow the increase in metal concentrations in the harbour, as explained by the bucket analogy. The reduction in sedimentation rate will achieve the same result 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, thus reducing concentration in the surface mixed layer (This strategy of course has the additional benefit of reducing adverse effects associated purely with sediments). These two goals may be achieved in a number of ways. For instance, unilaterally reducing the sediment runoff will reduce the sedimentation rate. At the same time, this would increase the metal concentration in the freshwater runoff at BOC, which may counteract the effect of the reduced sedimentation rate. Jointly reducing sediment and metal runoff by, for instance, improved stormwater treatment, may cause surprising changes in metal concentration at BOC, as explained in Appendix C:

- In a rural catchment, stormwater treatment cannot change metal concentration in freshwater runoff at BOC.
- In an urban catchment, the way metal concentrations at BOC are changed by improved stormwater treatment depends entirely on the relative removal of sediment and anthropogenic metal. Specifically, when proportionately more sediment than metal is removed by improved stormwater treatment, the metal concentration at BOC is increased. This would not be the desired result from improving stormwater treatment. Conversely, when proportionately more metal

than sediment is removed by the improved stormwater treatment, the metal concentration at BOC is decreased. This would be the desired result from improving stormwater treatment.

- In a mixed urban–rural catchment, the removal of more sediment than metal by improved stormwater treatment can actually result in a decrease in the metal concentration in freshwater at BOC. Unlike the case of the urban catchment, therefore, this still delivers the desired result from improving stormwater treatment.

These comments relate only to the effect of stormwater treatment on metal concentration at BOC. At least two other factors need to be considered when translating these effects into changes in metal concentrations in harbour bed sediments. Firstly, the sedimentation rate is also a factor, as previously explained. Secondly, any given subestuary typically receives sediment from more than one subcatchment, so increases in metal concentration at BOC in one subcatchment may be offset by decreases in other subcatchments, and vice versa.

Figures 4.1 to 4.7 show how the concentrations at which total (anthropogenic plus natural) metals delivered to the harbour differ under each scenario during each year in the future period.

- For the four subcatchments that do not have any urban areas (Kingseat, Elletts Beach, Karaka and Oira Creek), and which as a result produce no anthropogenic metals and no urban sediments, the concentrations at which metals are delivered to BOC are exactly the same under all four scenarios. The reason is that neither improved stormwater treatment nor zinc source control of industrial areas has any effect in these purely rural subcatchments.
- The subcatchments that are all or nearly all urbanised (Takanini, Manurewa / Weymouth and Bottle Top Bay) actually see metal (zinc and copper) concentration at BOC increase as a result of improved stormwater treatment. The reason is that improved stormwater treatment, as implemented in the CLM, removes proportionately more urban sediment than anthropogenic metal from the freshwater runoff and freshwater runoff in these subcatchments carries mainly urban sediment and anthropogenic metal (as opposed to rural sediment and natural metal, respectively).
- In all of the other subcatchments, which are urbanised to various degrees, the metal concentration at BOC is typically reduced by the improved stormwater treatment. This occurs even though the improved stormwater treatment removes proportionately more urban sediment than anthropogenic metal from the freshwater runoff, as explained in Appendix C.
- Note that there can be considerable variability from year to year in the metal concentration at BOC in the partially urbanised subcatchments, with most years seeing a reduction in concentration due to the improved stormwater treatment, but other years seeing an increase. The variability is driven by the rural sediment runoff, which is predicted by GLEAMS, and which fluctuates randomly from year to year. The random fluctuations are most pronounced in the most sparsely urbanised subcatchments (e.g., Drury).

- Unlike improved stormwater treatment, zinc source control of industrial areas always reduces the concentration at which total zinc is delivered to BOC in freshwater. The reason is that zinc source control only affects zinc runoff, not sediment runoff. (Stormwater treatment affects metal and sediment runoff.) Compared to the best reductions in zinc concentration at BOC achieved by improved stormwater treatment, the reduction due to zinc source control of industrial areas is minor. Furthermore, zinc source control has only a limited effect in time, but improved stormwater treatment has an effect throughout most of the future period.

To sum up what is shown in Figures 4.1 to 4.7: zinc source control of industrial areas and stormwater treatment in some subcatchments decrease the concentration at which metals will be delivered to BOC compared to Scenario 1, and in other subcatchments the BOC concentrations are increased. Since most subestuaries deposit sediment and metal from a number of subcatchments, it is not clear *a priori* how zinc source control of industrial areas and stormwater treatment will actually change the rate at which metals accumulate in the harbour bed sediments compared to Scenario 1. In addition, the sedimentation rate is a factor. In some places and at some times the rate at which metals accumulate in the harbour bed sediments compared to Scenario 1 may be increased, and in other places and at other times the rate may be decreased. Of course, the purpose of the USC-3 model is to sort this out.

It is noteworthy in this regard that metal concentrations in the freshwater discharge from Drury subcatchment, which is the largest supplier of sediment to the harbour (Green, 2008b), are reduced by improved stormwater treatment and zinc source control of industrial areas. Similarly, metal concentrations in the freshwater discharge from Papatoetoe / Puhinui subcatchment, which is the largest supplier of zinc and copper to the harbour (Green, 2008b), are also reduced by improved stormwater treatment and zinc source control. These reductions, and the (small) reductions in sedimentation rate, may dominate the harbour response, causing an overall decrease in the rate at which metals accumulate in the harbour bed sediments.

4.6.6 Metal concentration in estuarine bed sediments

Figures 4.8 to 4.13 show the predicted change in zinc concentration in the surface mixed layer of the estuarine bed sediments for the future period under all scenarios, including Scenario 1 (from Green, 2008b). Figures 4.14 to 4.19 show the same for copper. Metal concentration 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).

Tables 4.5 to 4.8 show a tabulation of the times at which sediment-quality guideline threshold values are predicted to be first exceeded in the future period under all scenarios, including Scenario 1 for comparison (from Green, 2008b). 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.

Tables 4.9 to 4.13 show a comparison of the sediment-quality guideline threshold exceedance under each scenario. In each of these tables, the differences in years-to-exceedance between scenarios are presented, as follows:

- Table 4.9: Scenario 3 – Scenario 1, shows effect of additional realistic stormwater treatment (zinc and copper).
- Table 4.10: Scenario 4 – Scenario 2, shows effect of additional realistic stormwater treatment (zinc and copper).
- Table 4.11: Scenario 2 – Scenario 1, shows effect of zinc source control (zinc only).
- Table 4.12: Scenario 4 – Scenario 3, shows effect of zinc source control (zinc only).
- Table 4.13: Scenario 4 – Scenario 1, shows effect of additional realistic stormwater treatment and zinc source control (zinc only).

For context and to develop a better understanding of the predictions, the information in Tables 4.5 to 4.8 (sediment-quality guideline threshold exceedance) and Tables 4.9 to 4.13 (differences in sediment-quality guideline threshold exceedance) should be considered together with the trends shown in Figures 4.8 to 4.19.

The discussion of Scenario 1 results presented by Green (2008b) is reproduced in the following in italics, and this is followed by comments on how those Scenario 1 results are changed by stormwater treatment and zinc source control of industrial areas (Scenarios 2, 3 and 4).

Summary figures will be presented in the Conclusions.

Intertidal flats in Southeastern Manukau Harbour (Figure 4.8 for zinc and Figure 4.14 for copper)

- *Hikihiki Bank (1–HIB), Weymouth (12–WEY) and Wiroa Island (13–WIL) are predicted to experience only a very slow increase in zinc and copper concentrations in the future period 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. It is noteworthy that sediment and metal is supplied to Hikihiki Bank, Weymouth, Wiroa Island at a similar proportion at which it comes off the greater catchment. This implies that sediment and metal runoff from the individual subcatchments is well-mixed together in the Southeastern Manukau.*

Neither zinc source control of industrial areas nor improved stormwater treatment has any discernible effect on metal accumulation on these intertidal flats. Any effect of zinc source control and/or improved stormwater treatment is hidden by the very slow increase in metal concentrations in the future period.

<u>Tidal creeks draining along southern shoreline (Figure 4.9 for zinc and Figure 4.15 for copper)</u>

- *Zinc concentration is predicted to very slowly increase over the future period in Clarks Creek tidal creek (18–CCK), and no sediment-quality guideline threshold is predicted to be exceeded. Copper is not predicted to exceed any sediment-quality guideline threshold. Most of the sediment, zinc and copper that deposits in Clarks Creek is sourced from the Kingseat (101) subcatchment, which the tidal creek drains.*

  Neither zinc source control of industrial areas nor improved stormwater treatment is able to reduce the concentration at which metals are delivered to the base of the Kingseat subcatchment, which is rural. Therefore, both zinc source control of industrial areas and improved stormwater treatment have virtually no effect on metal accumulation in Clarks Creek.

  Drury Creek Inner tidal creek (16-DCI), which drains to the southern shoreline inside Pahurehure Inlet, is predicted to experience a slow rise in metal concentrations. Sediment deposited here comes mainly from the Drury subcatchment (106), which it drains. In addition, a significant fraction comes from Papakura Stream subcatchment (110), which is a principal sediment generator, and sediment from many other subcatchments does in fact deposit in Drury Creek Inner. This highlights the role of tidal creeks as sediment traps. Zinc and copper deposited in Drury Creek Inner come mainly from the Drury subcatchment. This is expected since the Drury subcatchment is a large generator of metal. Zinc and copper concentrations are predicted to exceed the TEL threshold late in the future period.

  The rise in both zinc concentration and copper concentration in the future period is noticeably retarded by the additional realistic stormwater treatment. The zinc TEL is not exceeded by the end of the future period (whereas it was exceeded 90–91 years into the future period under the no additional stormwater treatment), and the exceedance of the copper TEL is delayed by 13 years. These changes can be traced back primarily to the decrease in concentrations at which metals are delivered to the base of Drury subcatchment, which is the primary supplier of sediment and metals to Drury Creek Inner tidal creek. Zinc source control of industrial areas delays the zinc TEL exceedance by only 1 year.

  Glassons Creek Inner tidal creek (17–GCK), which also drains to the southern shoreline inside Pahurehure Inlet, is predicted to experience a slow rise in metal *concentrations. They do not, however, rise close to the TEL. Glassons Creek Inner 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 Glassons Creek Inner rise.*

Neither zinc source control of industrial areas nor improved stormwater treatment is able to reduce the concentration at which metals are delivered to the base of the rural Karaka subcatchment. Therefore, neither zinc source control nor improved stormwater treatment have any significant effect on metal accumulation.

<u>Tidal creeks draining along northern shoreline (Figure 4.10 for zinc and Figure 4.16 for copper)</u>

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

  Puhinui Creek tidal creek (14–PUK) receives most of its sediment and metal from the adjacent subcatchment 112 (Papatoetoe / Puhinui), which is highly urbanised. 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.

  The additional realistic stormwater treatment delays the zinc TEL exceedance by only four years, but the flattening of the zinc concentration trajectory causes the zinc ERL exceedance to be delayed by 10 years. The copper TEL exceedance is delayed by six years. Zinc source control delays both the zinc TEL and ERL exceedances by only two years. As expected, zinc source control together with additional realistic stormwater treatment delivers the best result for zinc: delay of TEL exceedance by six years and delay of ERL exceedance by 12 years.

  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 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.

  The additional realistic stormwater treatment delays both the zinc TEL exceedance and the copper TEL exceedance by 14 years. Zinc source control delays the zinc TEL exceedance by only a year.

<u>Subestuaries along the southern shoreline of the outer reaches of Pahurehure Inlet (Figure 4.11 for zinc and Figure 4.17 for copper)</u>

- *In Karaka (2–KKA), Glassons Mouth West (3–GMW), Glassons Mouth East (4–GME) and Cape Horn (5–CHN), the copper TEL is predicted to be exceeded very late in the future period. 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.*

Some significant delays in both zinc and copper exceedance times are achieved for these subestuaries by improved stormwater treatment. For instance, the zinc TEL exceedance is delayed by 17 years and the copper TEL exceedance is delayed by 13 years in Glassons Mouth East under Scenario 3 compared to under Scenario 1. For Glassons Mouth West, the zinc TEL, which was exceeded 90 years into the future period under Scenario 1, is not exceeded under Scenario 3, and the copper TEL exceedance is delayed by 16 years. For Cape Horn, both the zinc TEL and the copper TEL are not exceeded under Scenario 3, whereas they were under Scenario 1 (at 94 and 85 years into the future period, respectively). Zinc source control has little effect.

<u>Subestuaries in the inner reaches of Pahurehure Inlet (Figure 4.12 for zinc and Figure 4.18 for copper)</u>

- *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. Copper concentrations are predicted to exceed the TEL.*

For Pahurehure Basin (8–PBA) and Pahurehure Inner (7–PHI), 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 (6–DCO), 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 respective outlets, which drives a corresponding relatively rapid rise in metal concentrations in the estuary.

Additional realistic stormwater treatment delays the zinc TEL exceedance in Drury Creek Outer by 16–17 years. The copper TEL exceedance is delayed by 13 years.

In Pahurehure Inner, the zinc TEL exceedance is delayed by improved stormwater treatment by six years, but the flattening zinc concentration trajectory delays the zinc ERL exceedance by 16 years. The copper TEL exceedance is delayed by eight years.

Similarly, in Pahurehure Basin, although the zinc TEL exceedance not changed by improved stormwater treatment, but the zinc ERL exceedance is delayed by 10–11 years. The copper TEL exceedance is delayed by six years.

Zinc source control has little effect on threshold exceedances.

Embayments along the northern shoreline of the outer reaches of Pahurehure Inlet (Figure 4.13 for zinc and Figure 4.19 for copper)

- *Embayments along the northern shoreline of the outer reaches of Pahurehure Inlet are predicted to exceed sediment-quality guideline thresholds. For both Papakura (9–PKA) and Waimahia Creek (11–WMC), 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.*

  Improved stormwater treatment delays the zinc and copper TEL exceedances by just a few years in both Papakura and Waimahia Creek, but the delay in zinc ERL exceedance is better (6–9 years). It is worth noting that Waimahia Creek, in particular, is supplied with sediment and metal principally from the urbanised Manurewa / Weymouth subcatchment (111), which sees additional realistic stormwater treatment increase metal concentrations in freshwater at the base of subcatchment. This explains why the improved stormwater treatment has reduced effect compared to some other subestuaries.

  Zinc source control has little effect on threshold exceedances.

  Metal concentrations at Kauri Point 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.

  Any effect of zinc source control of industrial areas and/or improved stormwater treatment is hidden by the very slow increase in metal concentrations in the future period.

Table 4.1:

Total (rural plus urban) sediment runoff, summed over the simulation. This is the sum of all particle sizes, and is for just one USC model run in the Monte Carlo package of 50 USC model runs. "S2/S1" denotes percent reduction in total sediment runoff under Scenario 2 compared to Scenario 1, and so on.

Subcatchment	No additional stormwater treatment			Additional realistic stormwater treatment				Rank
	Scenario 1 (kg)	Scenario 2 (kg)	S2/S1	Scenario 3 (kg)	S3/ S1	Scenario 4 (kg)	S4/ S1	
101 - KST	63,769,180	63,769,180	0	63,769,180	0	63,769,180	0	6
102 - EBH	44,930,228	44,930,228	0	44,930,228	0	44,930,228	0	9
103 - KKA	56,944,496	56,944,496	0	56,944,496	0	56,944,496	0	7
104 - WHC	83,984,552	83,984,552	0	81,258,776	3	81,258,776	3	4
105 - OIC	24,406,112	24,406,112	0	24,406,112	0	24,406,112	0	11
106 - DRY	322,938,656	322,938,656	0	317,570,048	2	317,570,048	2	1
107 - HGA	10,007,908	10,007,908	0	8,958,373	10	8,958,373	10	13
108 - PKA	49,737,656	49,737,656	0	46,605,068	6	46,605,068	6	8
109 - TKI	3,572,033	3,572,033	0	2,547,347	29	2,547,347	29	14
110 - PAS	148,333,488	148,333,488	0	142,412,640	4	142,412,640	4	2
111 - MAW	23,217,994	23,217,994	0	19,052,794	18	19,052,794	18	12
112 - PAU	122,685,472	122,685,472	0	105,520,320	14	105,520,320	14	3
113 - MEP	67,823,080	67,823,080	0	65,989,352	3	65,989,352	3	5
114 - MGE	27,903,770	27,903,770	0	27,248,154	2	27,248,154	2	10
115 - BTB	1,616,428	1,616,428	0	1,263,377	22	1,263,377	22	15

Table 4.2:

Zinc runoff. 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. "S2/S1" denotes percent reduction in metal runoff under Scenario 2 compared to Scenario 1, and so on.

	Sum over simulation of anthropogenic zinc (kg)							
Stormwater treatment	No additional			Additional realistic				
Source control	None	Zinc		None		Zinc		
Subcatchment	Scenario 1	Scenario 2	S2/S1	Scenario 3	S3/S1	Scenario 4	S4/S3	S4/S1
101 - KST	0	0	0	0	0	0	0	0
102 - EBH	0	0	0	0	0	0	0	0
103 - KKA	0	0	0	0	0	0	0	0
104 - WHC	23,969	23,767	1	20,358	15	20,156	1	16
105 - OIC	0	0	0	0	0	0	0	0
106 - DRY	42,951	42,671	1	36,044	16	35,765	1	17
107 - HGA	5,801	5,796	0	4,590	21	4,584	0	21
108 - PKA	34,312	34,203	0	29,288	15	29,179	0	15
109 - TKI	10,515	10,444	1	8,625	18	8,554	1	19
110 - PAS	46,832	46,602	0	38,636	18	38,408	1	18
111 - MAW	32,597	32,513	0	27,956	14	27,872	0	14
112 - PAU	124,212	122,758	1	101,958	18	100,508	1	19
113 - MEP	18,241	18,133	1	16,572	9	16,466	1	10
114 - MGE	5,194	5,175	0	4,554	12	4,536	0	13
115 - BTB	2,901	2,901	0	2,483	14	2,483	0	14

	Sum over simulation of total (anthropogenic plus natural) zinc (kg)							
Stormwater treatment	No additional			Additional realistic				
Source control	None	Zinc		None		Zinc		
Subcatchment	Scenario 1	Scenario 2	S2/S1	Scenario 3	S3/S1	Scenario 4	S4/S3	S4/S1
101 - KST	2,206	2,206	0	2,206	0	2,206	0	0
102 - EBH	1,555	1,555	0	1,555	0	1,555	0	0
103 - KKA	1,970	1,970	0	1,970	0	1,970	0	0
104 - WHC	26,875	26,673	1	23,170	14	22,968	1	15
105 - OIC	844	844	0	844	0	844	0	0
106 - DRY	54,124	53,844	1	47,032	13	46,753	1	14
107 - HGA	6,148	6,142	0	4,899	20	4,894	0	20
108 - PKA	36,033	35,924	0	30,900	14	30,791	0	15
109 - TKI	10,639	10,567	1	8,713	18	8,642	1	19
110 - PAS	51,964	51,734	0	43,564	16	43,335	1	17
111 - MAW	33,400	33,317	0	28,615	14	28,531	0	15
112 - PAU	128,457	127,003	1	105,609	18	104,159	1	19
113 - MEP	20,587	20,480	1	18,855	8	18,749	1	9
114 - MGE	6,159	6,141	0	5,497	11	5,478	0	11
115 - BTB	2,957	2,957	0	2,526	15	2,526	0	15

Table 4.3:

Copper runoff. 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. "S2/S1" denotes percent reduction in metal runoff under Scenario 2 compared to Scenario 1, and so on.

	Sum over simulation of anthropogenic copper (kg)		
Stormwater treatment	No additional	Additional realistic	
Source control	None		
Subcatchment	Scenario 1	Scenario 3	S3/S1
101 - KST	0	0	0
102 - EBH	0	0	0
103 - KKA	0	0	0
104 - WHC	5,709	4,922	14
105 - OIC	0	0	0
106 - DRY	6,417	5,025	22
107 - HGA	1,224	986	19
108 - PKA	7,171	6,143	14
109 - TKI	2,083	1,685	19
110 - PAS	8,377	6,776	19
111 - MAW	6,967	6,000	14
112 - PAU	20,062	15,725	22
113 - MEP	2,832	2,444	14
114 - MGE	758	639	16
115 - BTB	460	376	18

	Sum over simulation of total (anthropogenic plus natural) copper (kg)		
Stormwater treatment	No additional	Additional realistic	
Source control		None	
Subcatchment	Scenario 1	Scenario 3	S3/S1
101 - KST	441	441	0
102 - EBH	311	311	0
103 - KKA	394	394	0
104 - WHC	6,291	5,484	13
105 - OIC	169	169	0
106 - DRY	8,652	7,222	17
107 - HGA	1,293	1,048	19
108 - PKA	7,515	6,466	14
109 - TKI	2,108	1,702	19
110 - PAS	9,403	7,762	17
111 - MAW	7,127	6,131	14
112 - PAU	20,910	16,455	21
113 - MEP	3,302	2,900	12
114 - MGE	951	828	13
115 - BTB	471	384	18

Table 4.4:

Predicted sedimentation rate in each subestuary averaged over the future period. These are all average values over the 50 model runs in the Monte Carlo package. The Scenario 1 predictions are described fully in Green (2008b).

Subestuary	Sedimentation rate No additional stormwater treatment (Scenarios 1 and 2) mm/yr	Additional realistic stormwater treatment (Scenarios 3 and 4) mm/yr	Additional realistic / No additional
1 – HIB	0.03	0.02	0.96
2 – KKA	0.62	0.60	0.97
3 – GMW	5.57	5.48	0.98
4 – GME	1.82	1.75	0.96
5 – CHN	1.27	1.23	0.97
6 – DCO	3.30	3.21	0.97
7 – PHI	2.45	2.37	0.97
8 – PBA	4.34	4.10	0.95
9 – PKA	2.56	2.47	0.97
10 – KPT	0.15	0.14	0.95
11 – WMC	1.44	1.31	0.91
12 – WEY	0.04	0.04	0.92
13 – WIL	0.01	0.01	0.95
14 – PUK	3.61	3.20	0.89
15 – PKK	1.67	1.61	0.97
16 – DCI	1.66	1.61	0.97
17 – GCK	1.69	1.65	0.98
18 – CCK	1.17	1.16	1.00

Table 4.5:

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

SCENARIO 1

	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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	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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Table 4.6:

Times (years from 2001) at which sediment-quality guideline threshold values are predicted to be first exceeded in the future period under Scenario 2. "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.

SCENARIO 2

	Zinc		
Subestuary	TEL	ERL	PEL
1-HIB	-	-	-
2-KKA	-	-	-
3-GMW	91	-	-
4-GME	81	-	-
5-CHN	94	-	-
6-DCO	73	-	-
7-PHI	38	69	-
8-PBA	18	63	-
9-PKA	26	53	-
10-KPT	-	-	-
11-WMC	27	51	-
12-WEY	-	-	-
13-WIL	-	-	-
14-PUK	37	59	-
15-PKK	79	-	-
16-DCI	91	-	-
17-GCK	-	-	-
18-CCK	-	-	-

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	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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Table 4.7:

Times (years from 2001) at which sediment-quality guideline threshold values are predicted to be first exceeded in the future period under Scenario 3. "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.

SCENARIO 3

	Zinc		
Subestuary	TEL	ERL	PEL
1-HIB	-	-	-
2-KKA	-	-	-
3-GMW	-	-	-
4-GME	97	-	-
5-CHN	-	-	-
6-DCO	89	-	-
7-PHI	43	84	-
8-PBA	18	73	-
9-PKA	27	60	-
10-KPT	-	-	-
11-WMC	28	57	-
12-WEY	-	-	-
13-WIL	-	-	-
14-PUK	39	67	-
15-PKK	92	-	-
16-DCI	-	-	-
17-GCK	-	-	-
18-CCK	-	-	-

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	Copper		
Subestuary	TEL	ERL	PEL
1-HIB	-	-	-
2-KKA	-	-	-
3-GMW	88	-	-
4-GME	89	-	-
5-CHN	-	-	-
6-DCO	80	-	-
7-PHI	59	-	-
8-PBA	59	-	-
9-PKA	41	-	-
10-KPT	-	-	-
11-WMC	37	-	-
12-WEY	-	-	-
13-WIL	-	-	-
14-PUK	48	-	-
15-PKK	97	-	-
16-DCI	79	-	-
17-GCK	-	-	-
18-CCK	-	-	-

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Table 4.8:

Times (years from 2001) at which sediment-quality guideline threshold values are predicted to be first exceeded in the future period under Scenario 4. "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.

SCENARIO 4

	Zinc		
Subestuary	TEL	ERL	PEL
1-HIB	-	-	-
2-KKA	-	-	-
3-GMW	-	-	-
4-GME	99	-	-
5-CHN	-	-	-
6-DCO	89	-	-
7-PHI	44	85	-
8-PBA	18	73	-
9-PKA	27	61	-
10-KPT	-	-	-
11-WMC	29	58	-
12-WEY	-	-	-
13-WIL	-	-	-
14-PUK	41	69	-
15-PKK	93	-	-
16-DCI	-	-	-
17-GCK	-	-	-
18-CCK	-	-	-

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	Copper		
Subestuary	TEL	ERL	PEL
1-HIB	-	-	-
2-KKA	-	-	-
3-GMW	88	-	-
4-GME	89	-	-
5-CHN	-	-	-
6-DCO	80	-	-
7-PHI	59	-	-
8-PBA	59	-	-
9-PKA	41	-	-
10-KPT	-	-	-
11-WMC	37	-	-
12-WEY	-	-	-
13-WIL	-	-	-
14-PUK	48	-	-
15-PKK	97	-	-
16-DCI	79	-	-
17-GCK	-	-	-
18-CCK	-	-	-

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Table 4.9:

Difference between times (years from 2001) at which sediment-quality guideline threshold values are predicted to be first exceeded in the future period under Scenario 3 compared to 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 in either scenario. An integer denotes the threshold is exceed that many years later under Scenario 3. A zero denotes the threshold is exceeded at the same time under both scenarios. A "*" denotes that the threshold is not exceeded under Scenario 3, but it is exceeded under Scenario 1, and the number in brackets shows the tine when the threshold is exceeded under Scenario 1. "TEL" denotes Threshold Effects level. "ERL" denotes Effects Range Low. "PEL" denotes Probable Effects Level.

SCENARIO 3 – SCENARIO 1 (Effect of Stormwater Treatment)

Subestuary	Zinc			Copper		
	TEL	ERL	PEL	TEL	ERL	PEL
1 – HIB	–	–	–	–	–	–
2 – KKA	–	–	–	*(93)	–	–
3 – GMW	*(90)	–	–	16	–	–
4 – GME	17	–	–	13	–	–
5 – CHN	*(94)	–	–	*(85)	–	–
6 – DCO	17	–	–	13	–	–
7 – PHI	6	16	–	8	–	–
8 – PBA	0	11	–	6	–	–
9 – PKA	2	9	–	4	–	–
10 – KPT	–	–	–	–	–	–
11 – WMC	1	6	–	3	*(93)	–
12 – WEY	–	–	–	–	–	–
13 – WIL	–	–	–	–	–	–
14 – PUK	4	10	–	6	–	–
15 – PKK	13	–	–	14	–	–
16 – DCI	*(90)	–	–	13	–	–
17 – GCK	–	–	–	–	–	–
18 – CCK	–	–	–	–	–	–

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Table 4.10:

Difference between times (years from 2001) at which sediment-quality guideline threshold values are predicted to be first exceeded in the future period under Scenario 4 compared to Scenario 2. "X" denotes the future period began with the threshold exceeded. "–" denotes the threshold is not exceeded by the end of the future period in either scenario. An integer denotes the threshold is exceed that many years later under Scenario 4. A zero denotes the threshold is exceeded at the same time under both scenarios. A "*" denotes that the threshold is not exceeded under Scenario 4, but it is exceeded under Scenario 2, and the number in brackets shows the tine when the threshold is exceeded under Scenario 2. "TEL" denotes Threshold Effects level. "ERL" denotes Effects Range Low. "PEL" denotes Probable Effects Level.

SCENARIO 4 – SCENARIO 2 (Effect of Stormwater Treatment)

Subestuary	Zinc			Copper		
	TEL	ERL	PEL	TEL	ERL	PEL
1 – HIB	–	–	–	–	–	–
2 – KKA	–	–	–	*(93)	–	–
3 – GMW	*(91)	–	–	16	–	–
4 – GME	18	–	–	13	–	–
5 – CHN	*(94)	–	–	*(85)	–	–
6 – DCO	16	–	–	13	–	–
7 – PHI	6	16	–	8	–	–
8 – PBA	0	10	–	6	–	–
9 – PKA	1	8	–	4	–	–
10 – KPT	–	–	–	–	–	–
11 – WMC	2	7	–	3	*(93)	–
12 – WEY	–	–	–	–	–	–
13 – WIL	–	–	–	–	–	–
14 – PUK	4	10	–	6	–	–
15 – PKK	14	–	–	14	–	–
16 – DCI	*(91)	–	–	13	–	–
17 – GCK	–	–	–	–	–	–
18 – CCK	–	–	–	–	–	–

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Table 4.11:

Difference between times (years from 2001) at which sediment-quality guideline threshold values are predicted to be first exceeded in the future period under Scenario 2 compared to 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 in either scenario. An integer denotes the threshold is exceed that many years later under Scenario 2. A zero denotes the threshold is exceeded at the same time under both scenarios. A "*" denotes that the threshold is not exceeded under Scenario 2, but it is exceeded under Scenario 1, and the number in brackets shows the tine when the threshold is exceeded under Scenario 1. "TEL" denotes Threshold Effects level. "ERL" denotes Effects Range Low. "PEL" denotes Probable Effects Level.

SCENARIO 2 – SCENARIO 1 (Effect of Zinc Source Control)

Subestuary	Zinc		
	TEL	ERL	PEL
1 – HIB	–	–	–
2 – KKA	–	–	–
3 – GMW	1	–	–
4 – GME	1	–	–
5 – CHN	0	–	–
6 – DCO	1	–	–
7 – PHI	1	1	–
8 – PBA	0	1	–
9 – PKA	1	2	–
10 – KPT	–	–	–
11 – WMC	0	0	–
12 – WEY	–	–	–
13 – WIL	–	–	–
14 – PUK	2	2	–
15 – PKK	0	–	–
16 – DCI	1	–	–
17 – GCK	–	–	–
18 – CCK	–	–	–

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Table 4.12:

Difference between times (years from 2001) at which sediment-quality guideline threshold values are predicted to be first exceeded in the future period under Scenario 4 compared to Scenario 3. "X" denotes the future period began with the threshold exceeded. "–" denotes the threshold is not exceeded by the end of the future period in either scenario. An integer denotes the threshold is exceed that many years later under Scenario 4. A zero denotes the threshold is exceeded at the same time under both scenarios. A "*" denotes that the threshold is not exceeded under Scenario 4, but it is exceeded under Scenario 3, and the number in brackets shows the tine when the threshold is exceeded under Scenario 3. "TEL" denotes Threshold Effects level. "ERL" denotes Effects Range Low. "PEL" denotes Probable Effects Level.

SCENARIO 4 – SCENARIO 3 (Effect of Zinc Source Control)

Subestuary	Zinc		
	TEL	ERL	PEL
1 – HIB	–	–	–
2 – KKA	–	–	–
3 – GMW	–	–	–
4 – GME	2	–	–
5 – CHN	–	–	–
6 – DCO	0	–	–
7 – PHI	1	1	–
8 – PBA	0	0	–
9 – PKA	0	1	–
10 – KPT	–	–	–
11 – WMC	1	1	–
12 – WEY	–	–	–
13 – WIL	–	–	–
14 – PUK	2	2	–
15 – PKK	1	–	–
16 – DCI	–	–	–
17 – GCK	–	–	–
18 – CCK	–	–	–

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Table 4.13:

Difference between times (years from 2001) at which sediment-quality guideline threshold values are predicted to be first exceeded in the future period under Scenario 4 compared to 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 in either scenario. An integer denotes the threshold is exceed that many years later under Scenario 4. A zero denotes the threshold is exceeded at the same time under both scenarios. A "*" denotes that the threshold is not exceeded under Scenario 4, but it is exceeded under Scenario 1, and the number in brackets shows the tine when the threshold is exceeded under Scenario 1. "TEL" denotes Threshold Effects level. "ERL" denotes Effects Range Low. "PEL" denotes Probable Effects Level.

SCENARIO 4 – SCENARIO 1
(Effect of Zinc Source Control and Stormwater Treatment)

Subestuary	Zinc		
	TEL	ERL	PEL
1 – HIB	–	–	–
2 – KKA	–	–	–
3 – GMW	*(90)	–	–
4 – GME	19	–	–
5 – CHN	*(94)	–	–
6 – DCO	17	–	–
7 – PHI	7	17	–
8 – PBA	0	11	–
9 – PKA	2	10	–
10 – KPT	–	–	–
11 – WMC	2	7	–
12 – WEY	–	–	–
13 – WIL	–	–	–
14 – PUK	6	12	–
15 – PKK	14	–	–
16 – DCI	*(90)	–	–
17 – GCK	–	–	–
18 – CCK	–	–	–

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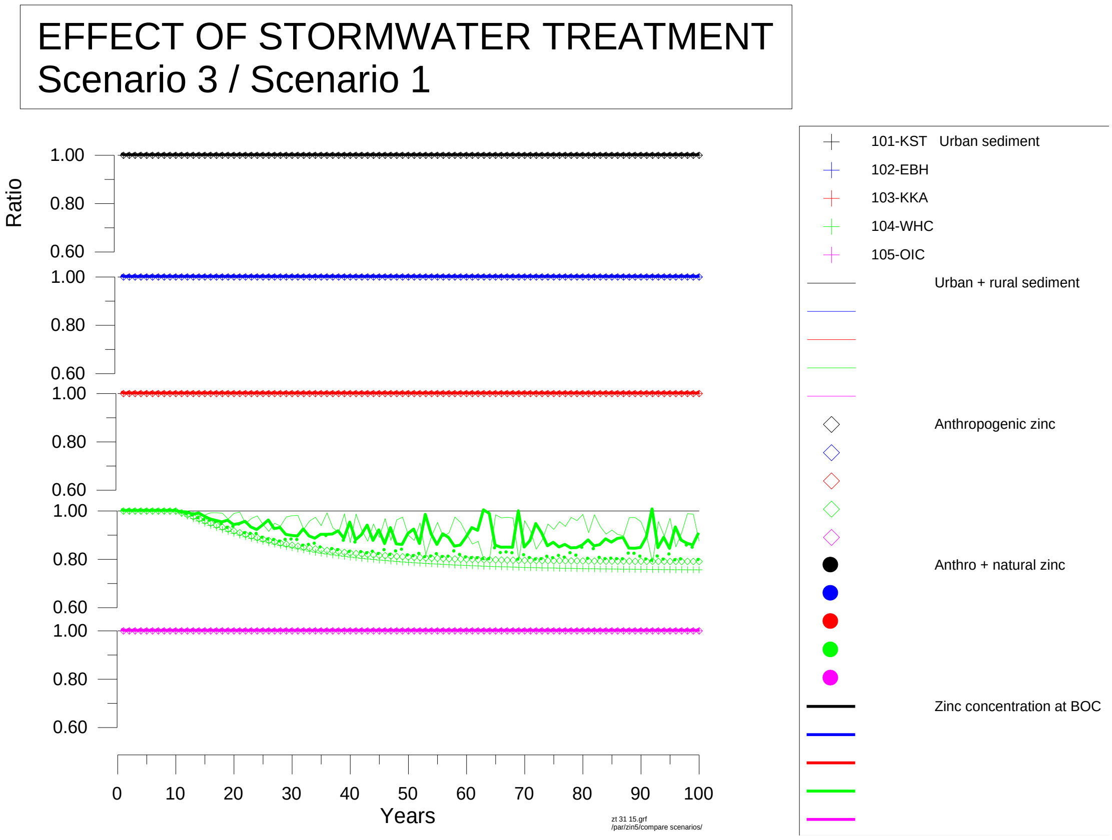
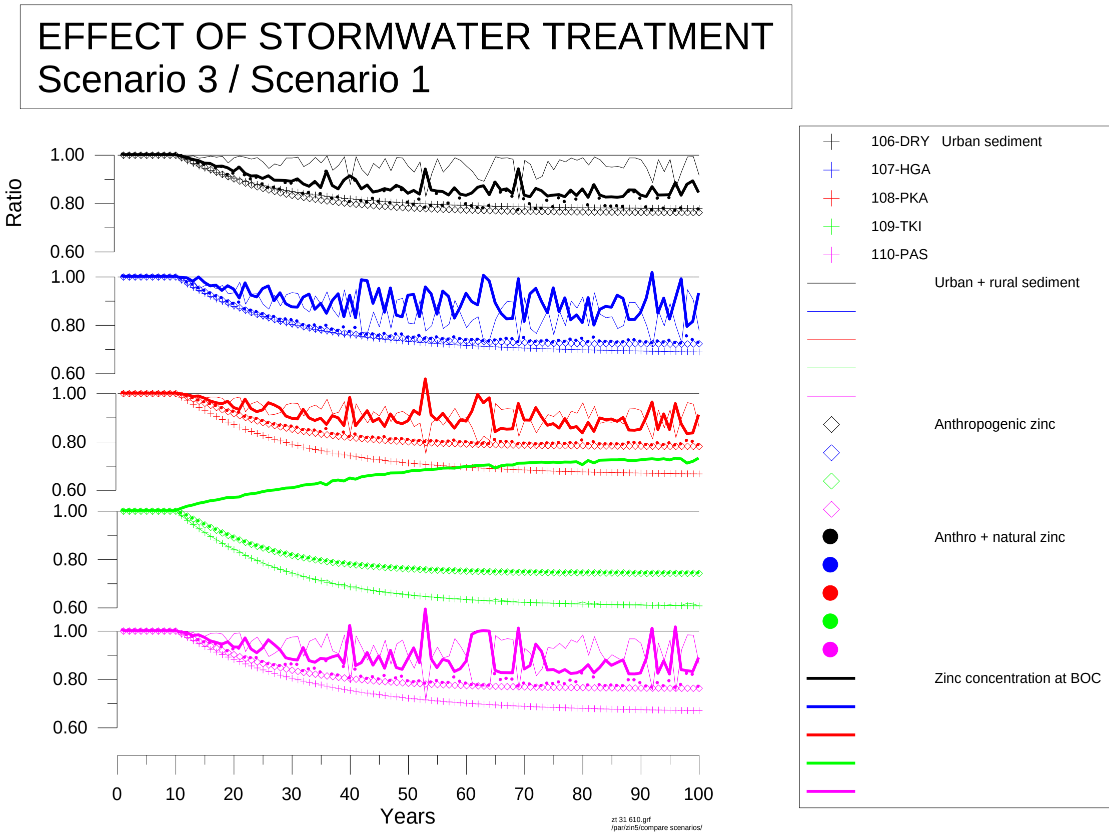
EFFECT OF MITIGATION MEASURES ON ZINC GENERATION AND DELIVERY TO HARBOUR

EFFECT OF MITIGATION MEASURES ON ZINC GENERATION AND DELIVERY TO HARBOUR

Figure 4.1:

Effect of stormwater treatment on urban sediment runoff, total (urban plus rural) sediment runoff, anthropogenic metal runoff, total (anthropogenic plus natural) metal runoff, and concentration at which metal is delivered to the harbour at the base of subcatchment (BOC). Year 1 is 2001 and year 100 is 2100. "Ratio" is the ratio of the first scenario to the second scenario. The metal shown is zinc.




EFFECT OF STORMWATER TREATMENT
Scenario 3 / Scenario 1
Ratio
1.00
0.80
0.60
0 10 20 30 40 50 60 70 80 90 100
Years
106-DRY Urban sediment
107-HGA
108-PKA
109-TKI
110-PAS
Urban + rural sediment
Anthropogenic zinc
Anthro + natural zinc
Zinc concentration at BOC

EFFECT OF MITIGATION MEASURES ON ZINC GENERATION AND DELIVERY TO HARBOUR

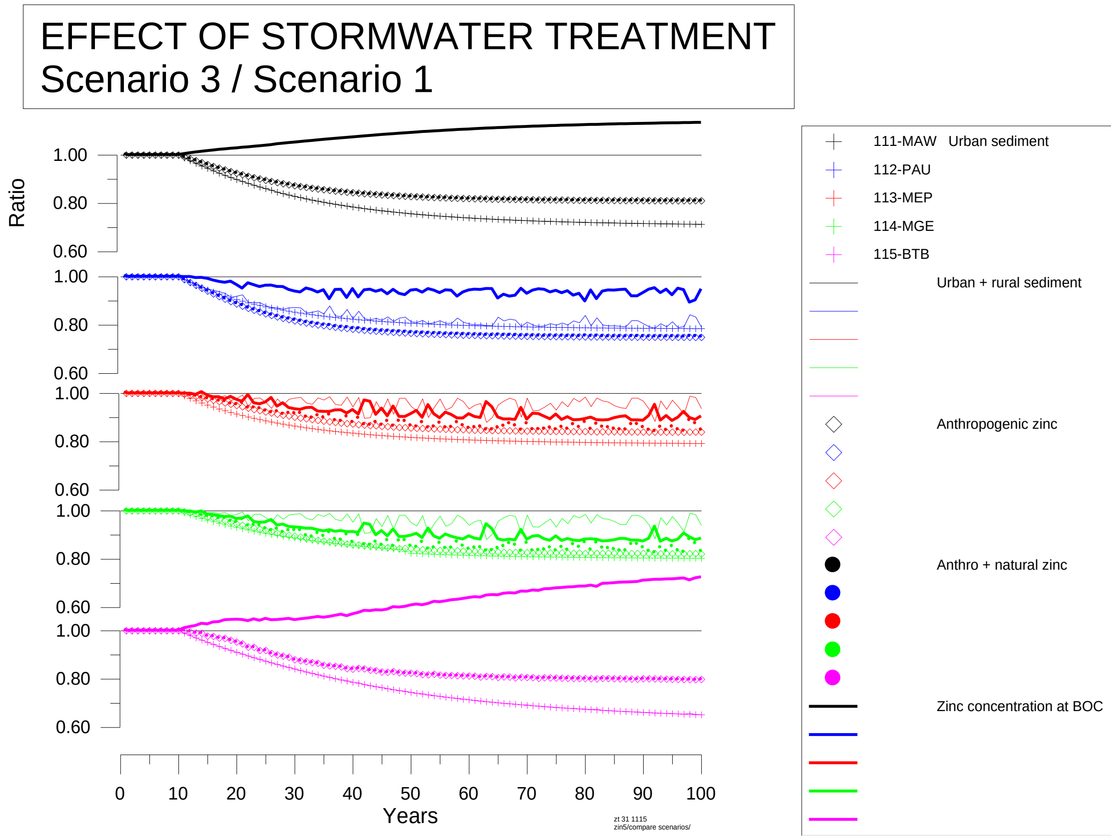
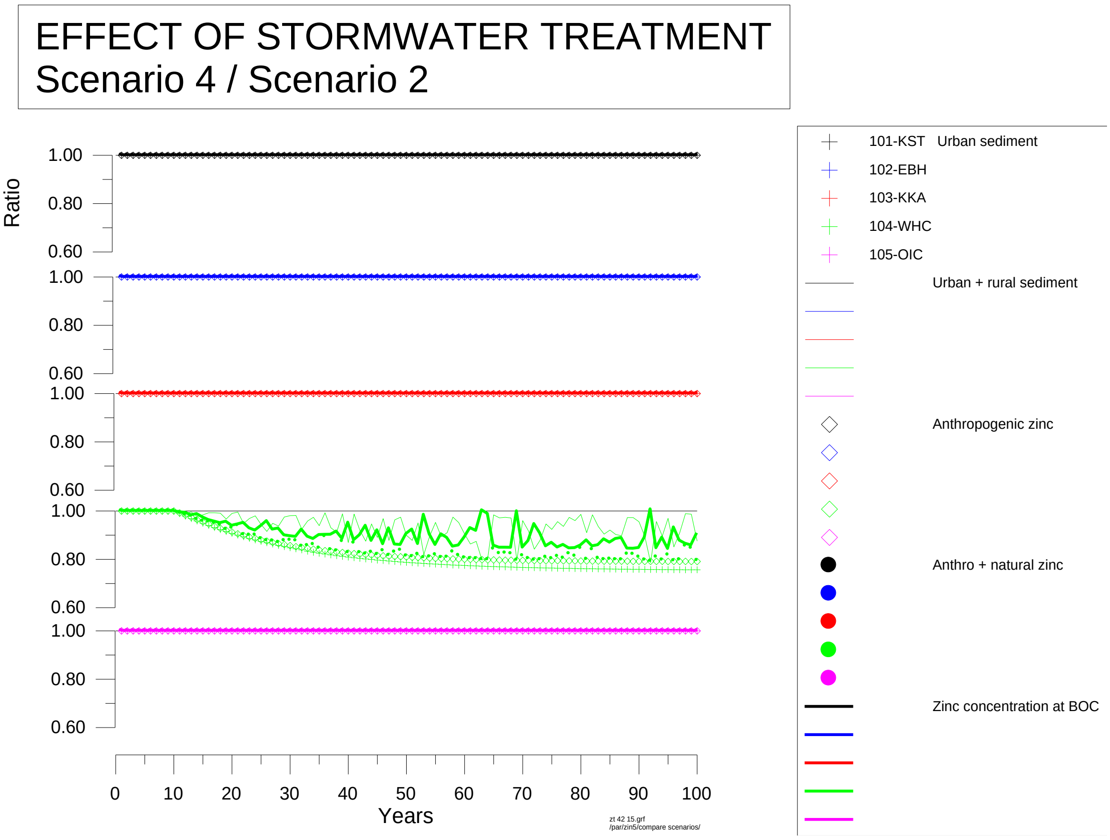


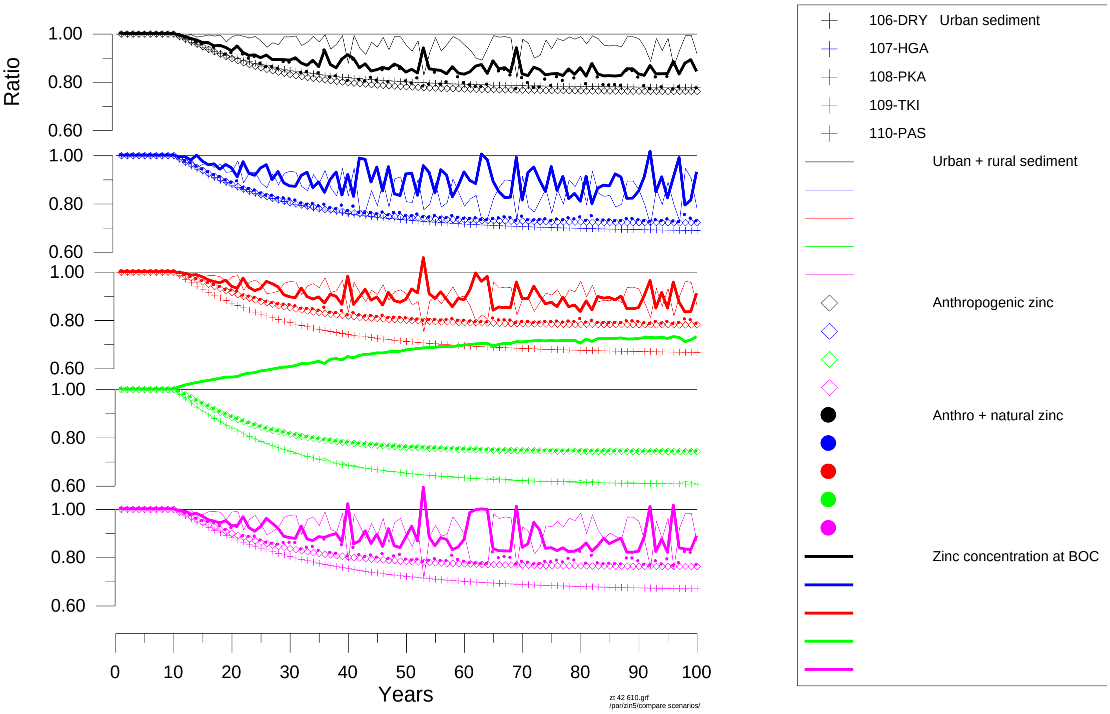
Figure 4.2:

Effect of stormwater treatment on urban sediment runoff, total (urban plus rural) sediment runoff, anthropogenic metal runoff, total (anthropogenic plus natural) metal runoff, and concentration at which metal is delivered to the harbour at the base of subcatchment (BOC). Year 1 is 2001 and year 100 is 2100. "Ratio" is the ratio of the first scenario to the second scenario. The metal shown is zinc.



EFFECT OF MITIGATION MEASURES ON ZINC GENERATION AND DELIVERY TO HARBOUR

EFFECT OF STORMWATER TREATMENT
Scenario 4 / Scenario 2



EFFECT OF MITIGATION MEASURES ON ZINC GENERATION AND DELIVERY TO HARBOUR

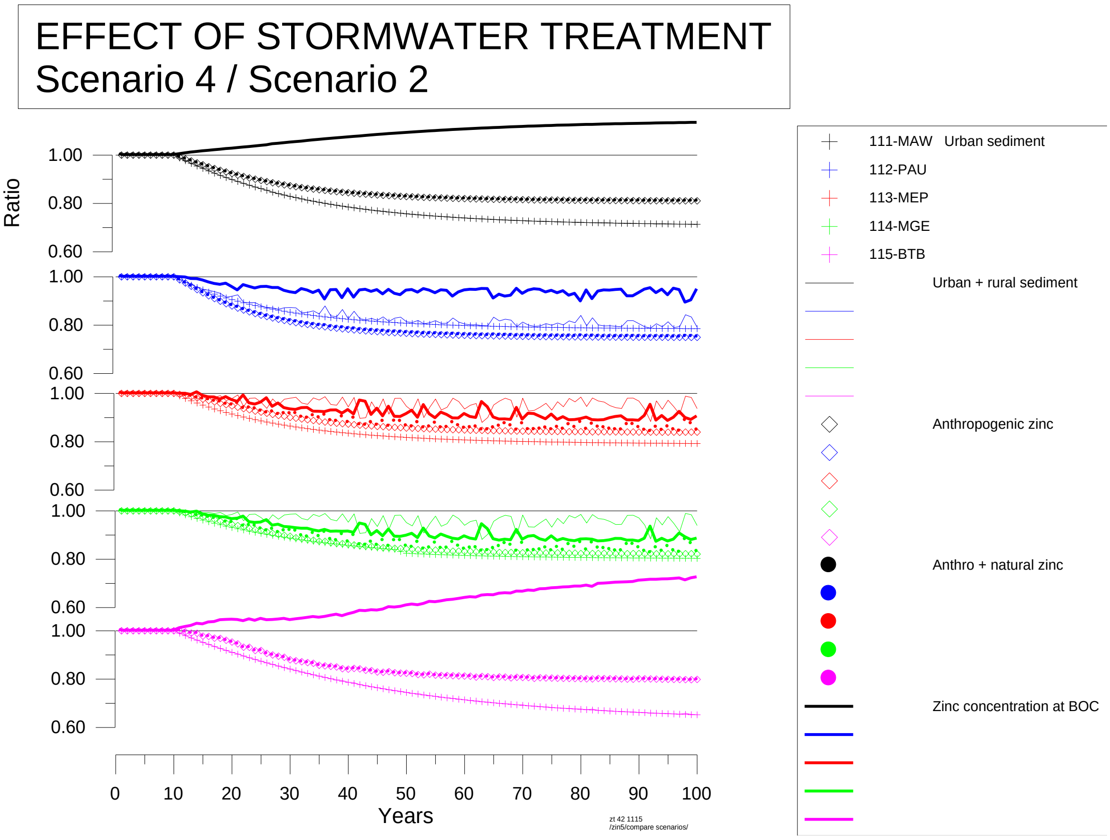
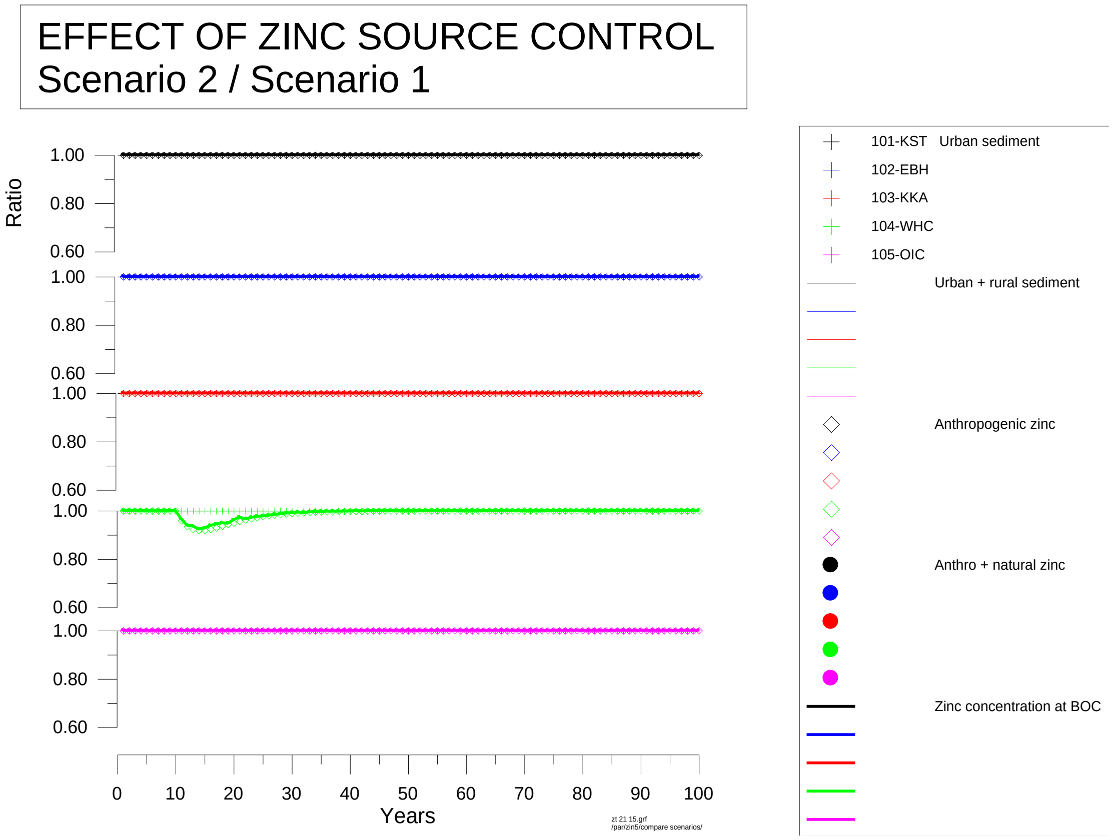
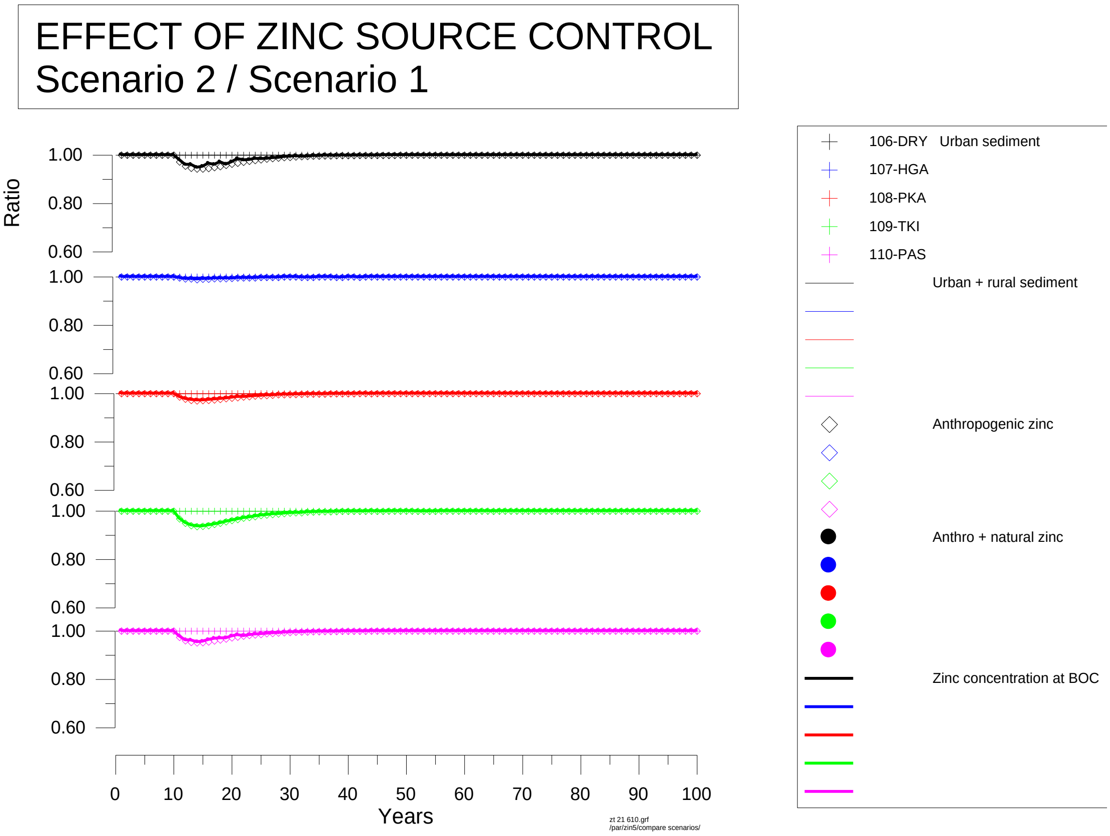


Figure 4.3:

Effect of zinc source control on urban sediment runoff, total (urban plus rural) sediment runoff, anthropogenic metal runoff, total (anthropogenic plus natural) metal runoff, and concentration at which metal is delivered to the harbour at the base of subcatchment (BOC). Year 1 is 2001 and year 100 is 2100. “Ratio” is the ratio of the first scenario to the second scenario. The metal shown is zinc.



EFFECT OF MITIGATION MEASURES ON ZINC GENERATION AND DELIVERY TO HARBOUR



EFFECT OF MITIGATION MEASURES ON <u>ZINC</u> GENERATION AND DELIVERY TO HARBOUR

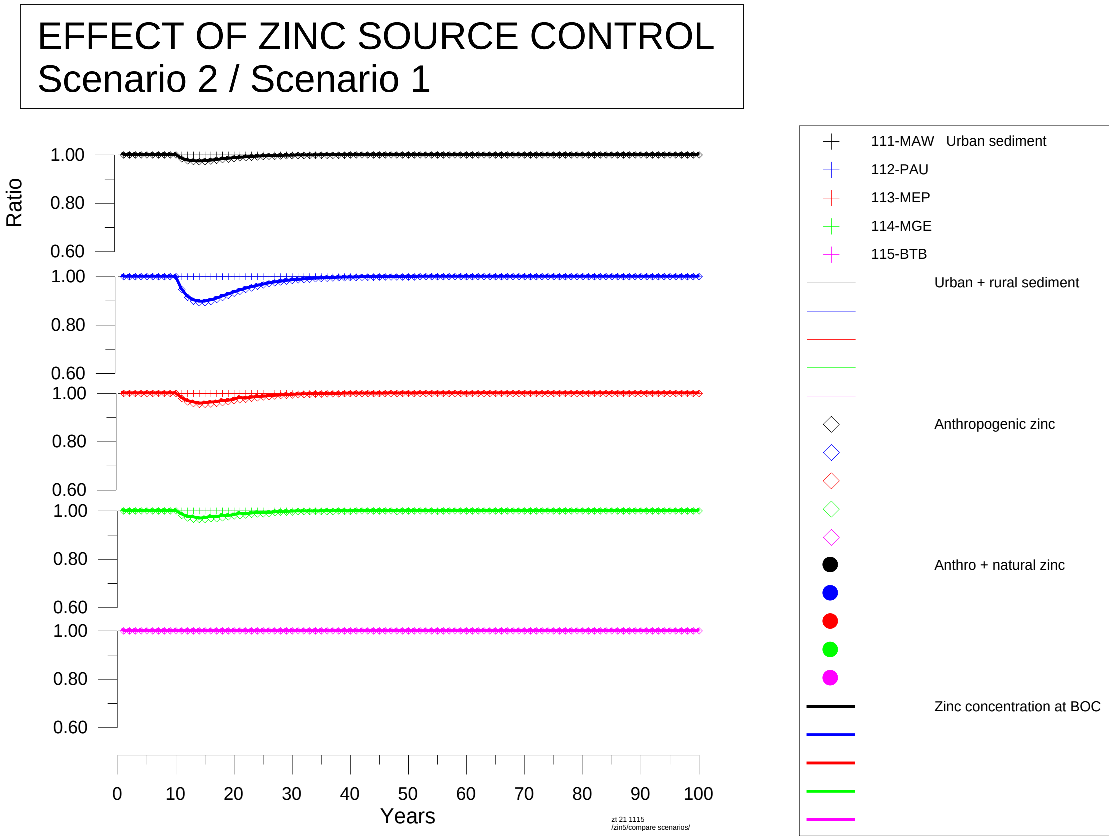
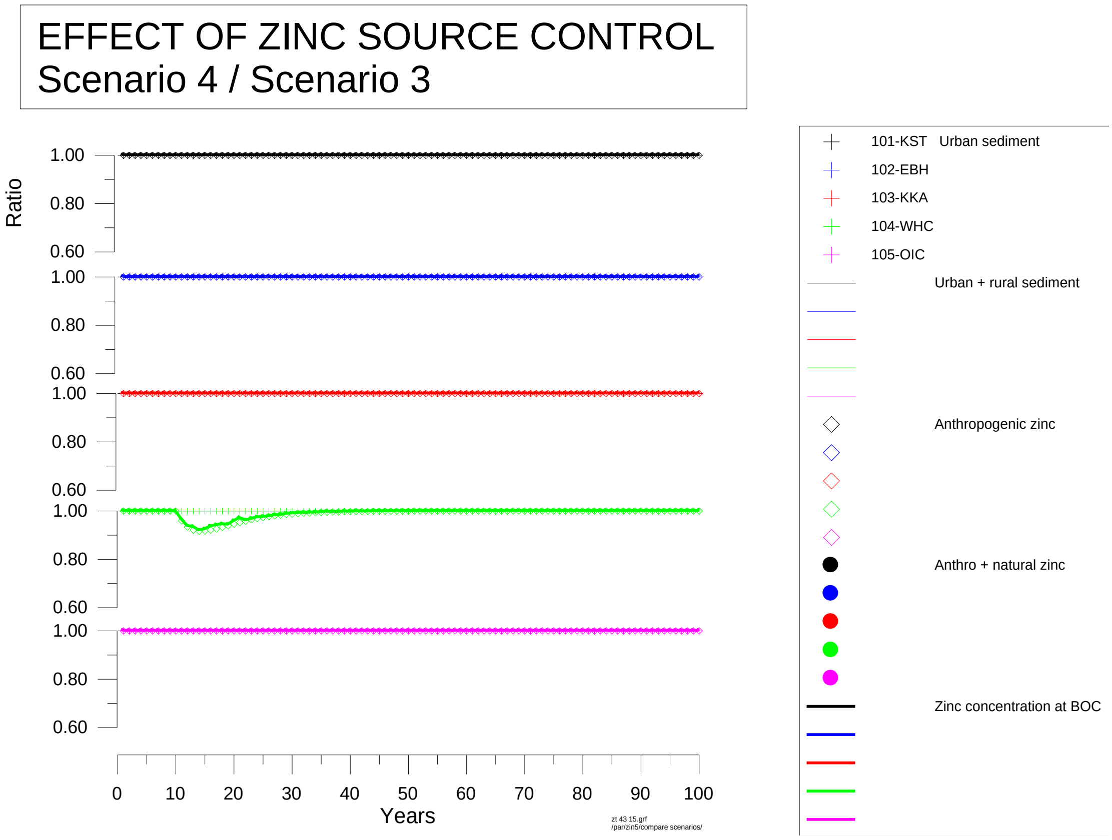
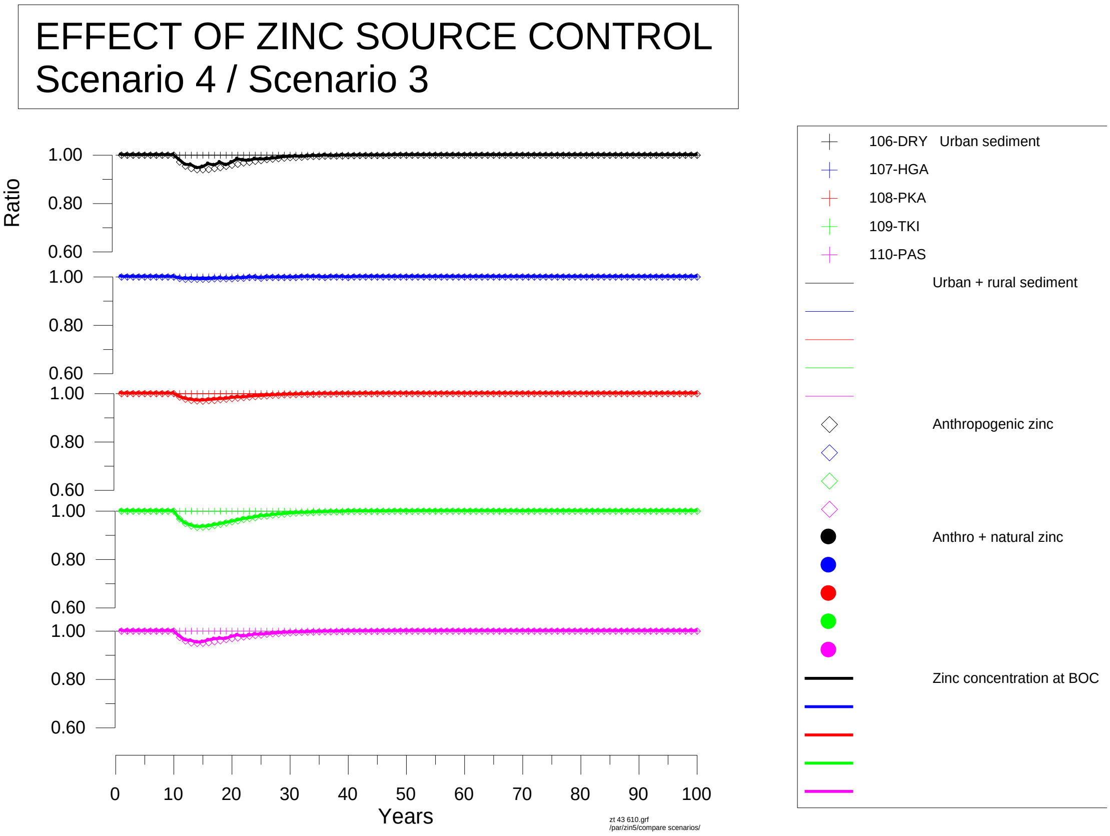


Figure 4.4:

Effect of zinc source control on urban sediment runoff, total (urban plus rural) sediment runoff, anthropogenic metal runoff, total (anthropogenic plus natural) metal runoff, and concentration at which metal is delivered to the harbour at the base of subcatchment (BOC). Year 1 is 2001 and year 100 is 2100. "Ratio" is the ratio of the first scenario to the second scenario. The metal shown is zinc.



EFFECT OF MITIGATION MEASURES ON ZINC GENERATION AND DELIVERY TO HARBOUR



EFFECT OF MITIGATION MEASURES ON ZINC GENERATION AND DELIVERY TO HARBOUR

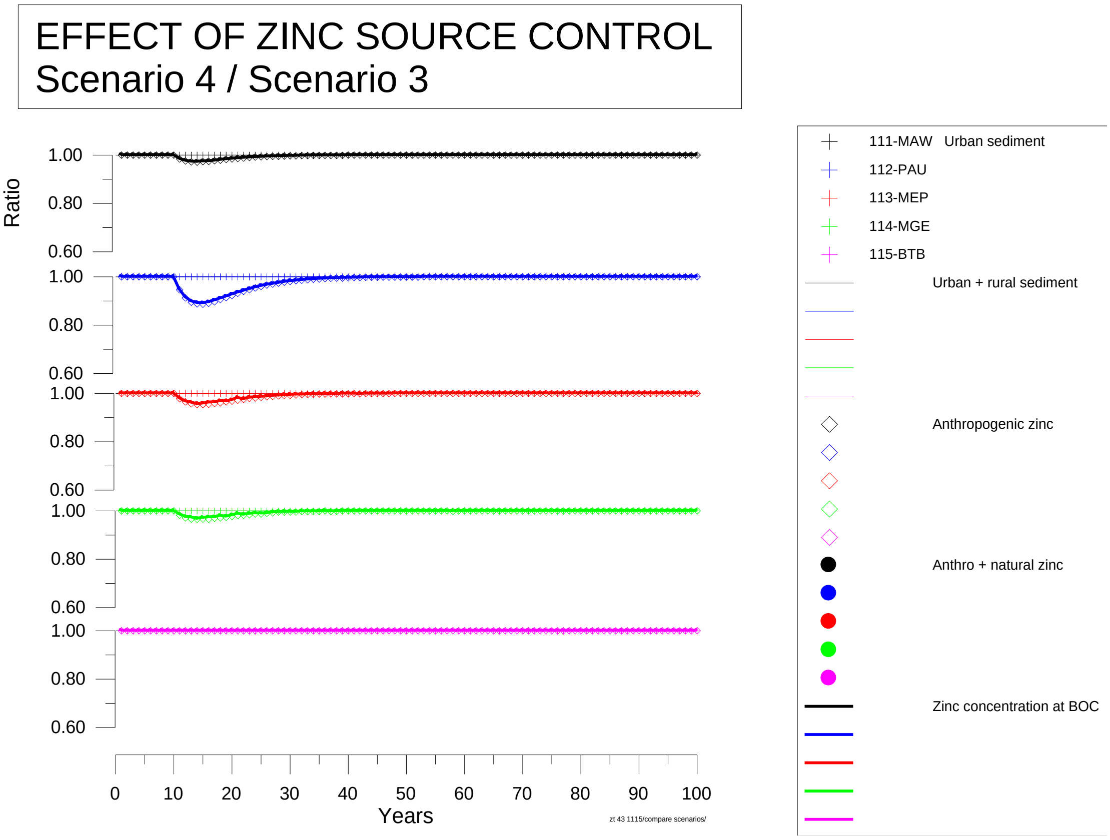
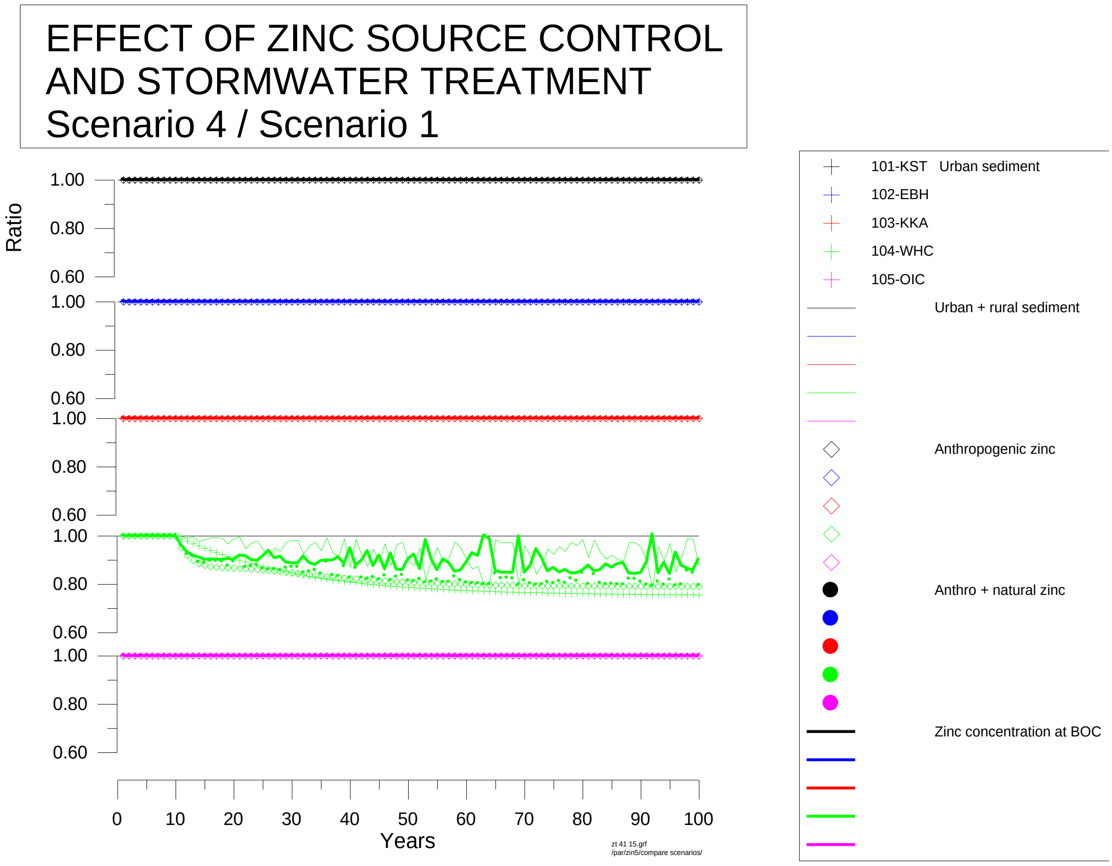
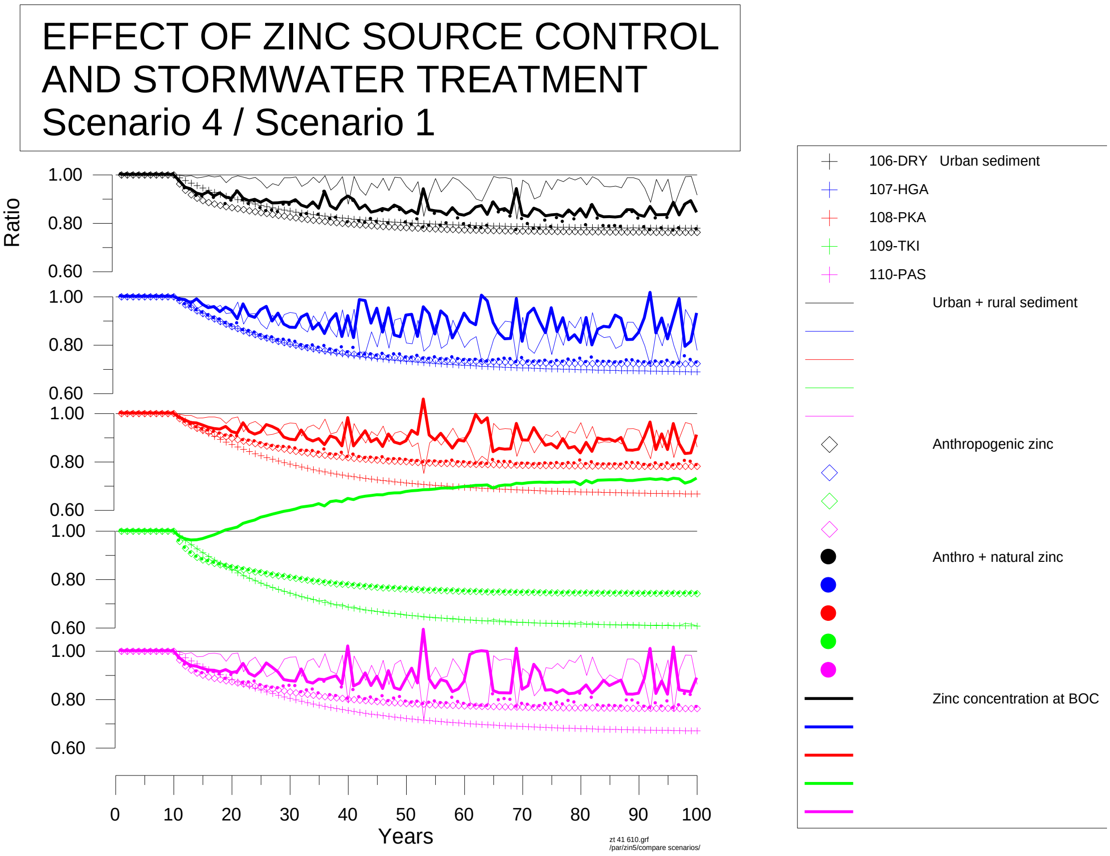


Figure 4.5:

Effect of zinc source control and stormwater treatment on urban sediment runoff, total (urban plus rural) sediment runoff, anthropogenic metal runoff, total (anthropogenic plus natural) metal runoff, and concentration at which metal is delivered to the harbour at the base of subcatchment (BOC). Year 1 is 2001 and year 100 is 2100. “Ratio” is the ratio of the first scenario to the second scenario. The metal shown is zinc.

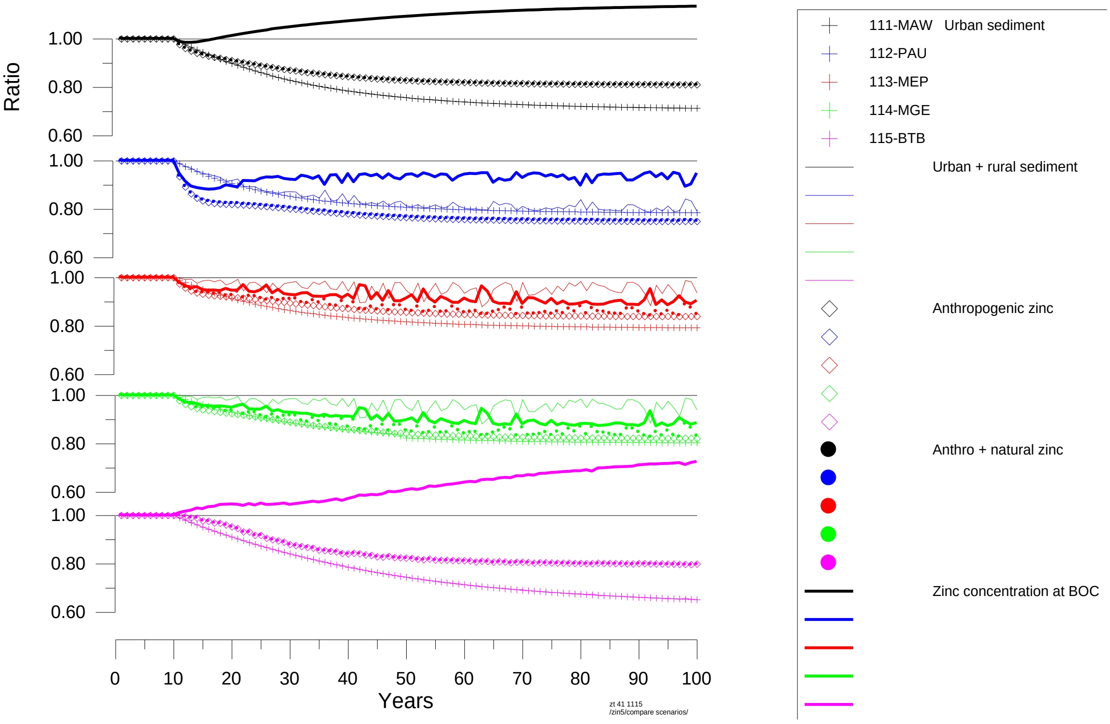


EFFECT OF MITIGATION MEASURES ON ZINC GENERATION AND DELIVERY TO HARBOUR



EFFECT OF MITIGATION MEASURES ON ZINC GENERATION AND DELIVERY TO HARBOUR

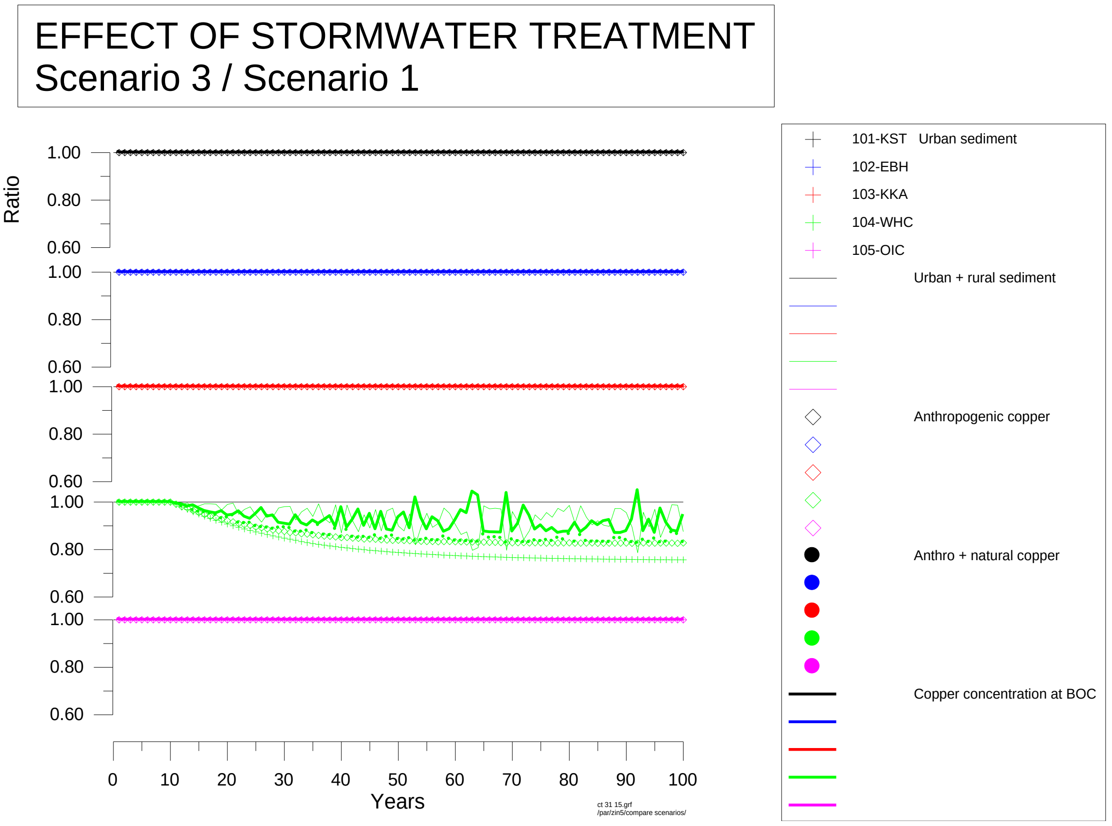
EFFECT OF ZINC SOURCE CONTROL AND STORMWATER TREATMENT
Scenario 4 / Scenario 1



EFFECT OF MITIGATION MEASURES ON COPPER DELIVERY TO HARBOUR

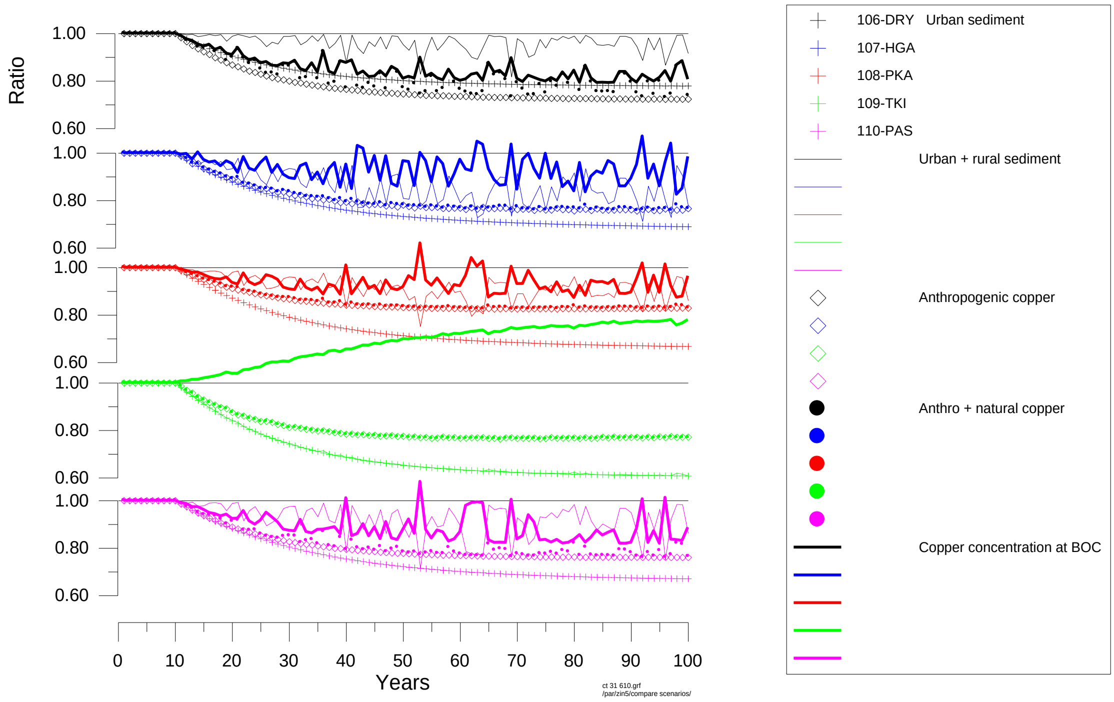
Figure 4.6:

Effect of stormwater treatment on urban sediment runoff, total (urban plus rural) sediment runoff, anthropogenic metal runoff, total (anthropogenic plus natural) metal runoff, and concentration at which metal is delivered to the harbour at the base of subcatchment (BOC). Year 1 is 2001 and year 100 is 2100. "Ratio" is the ratio of the first scenario to the second scenario. The metal shown is copper.

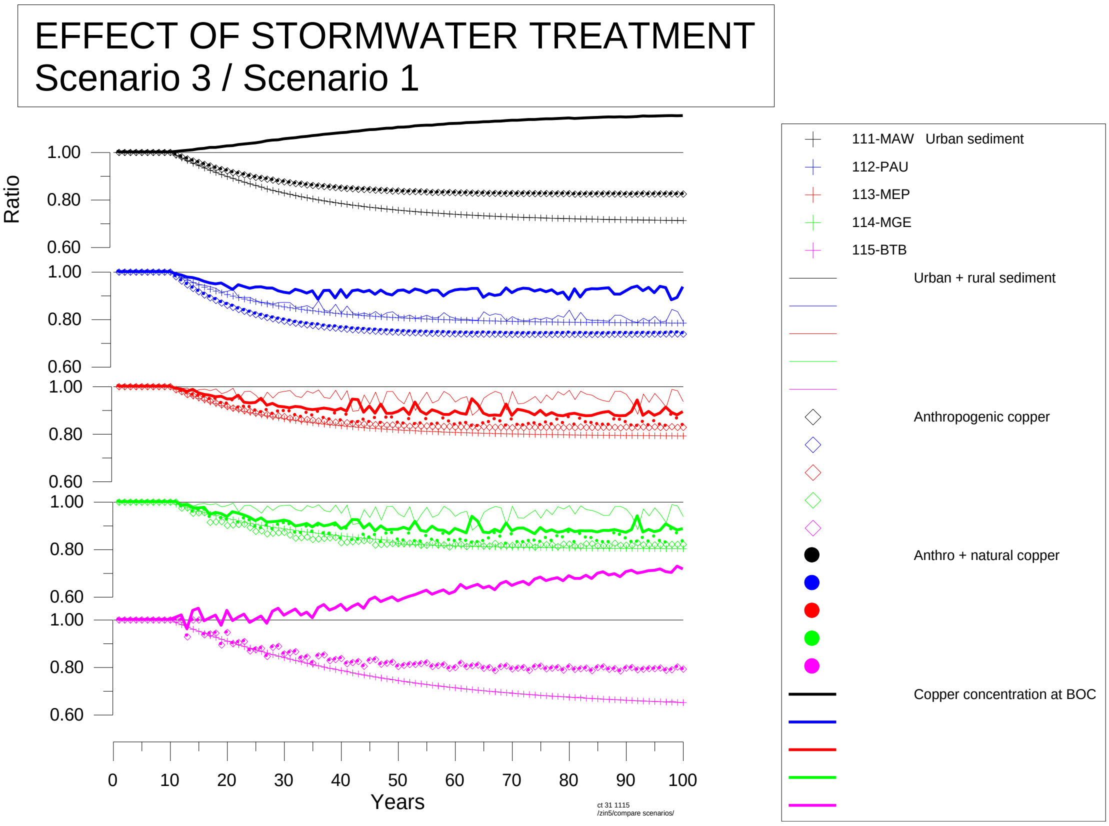


EFFECT OF MITIGATION MEASURES ON <u>COPPER</u> DELIVERY TO HARBOUR

EFFECT OF STORMWATER TREATMENT
Scenario 3 / Scenario 1



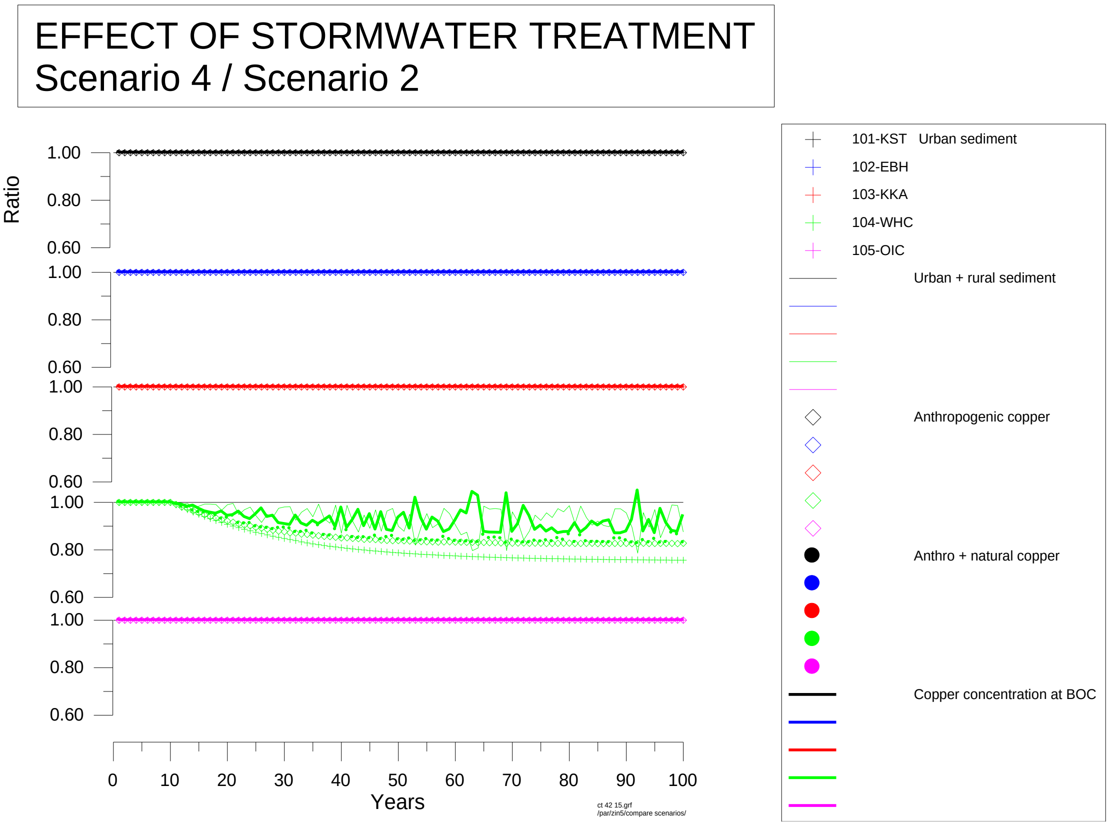
EFFECT OF MITIGATION MEASURES ON COPPER DELIVERY TO HARBOUR



EFFECT OF MITIGATION MEASURES ON COPPER DELIVERY TO HARBOUR

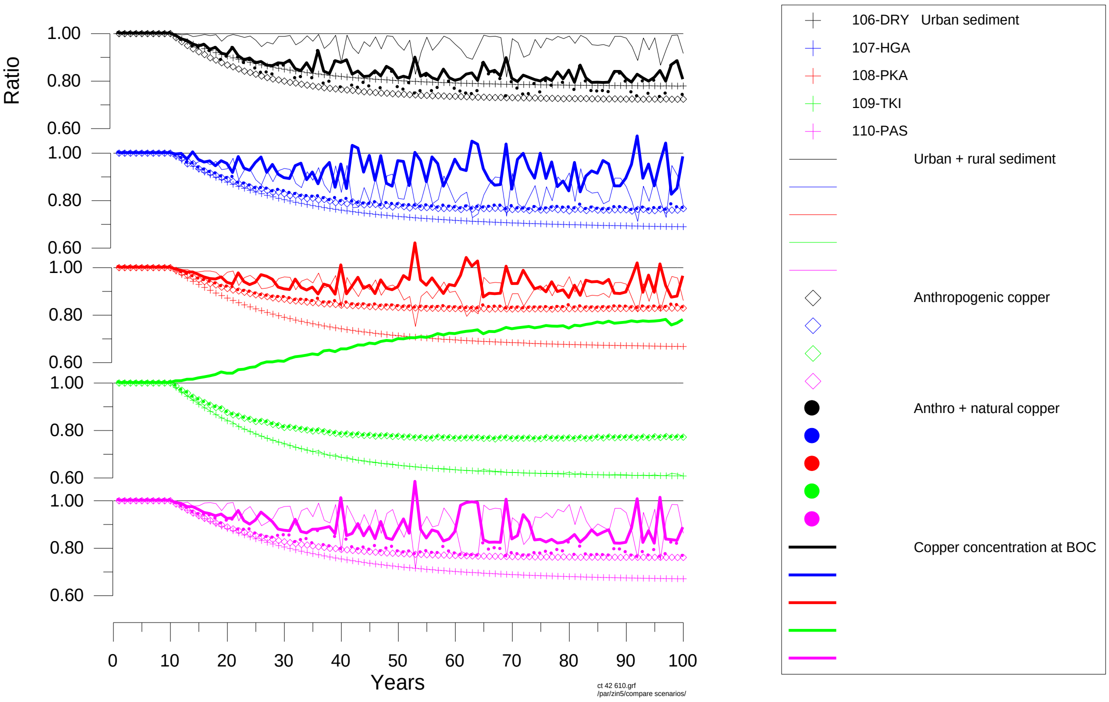
Figure 4.7:

Effect of stormwater treatment on urban sediment runoff, total (urban plus rural) sediment runoff, anthropogenic metal runoff, total (anthropogenic plus natural) metal runoff, and concentration at which metal is delivered to the harbour at the base of subcatchment (BOC). Year 1 is 2001 and year 100 is 2100. "Ratio" is the ratio of the first scenario to the second scenario. The metal shown is copper.

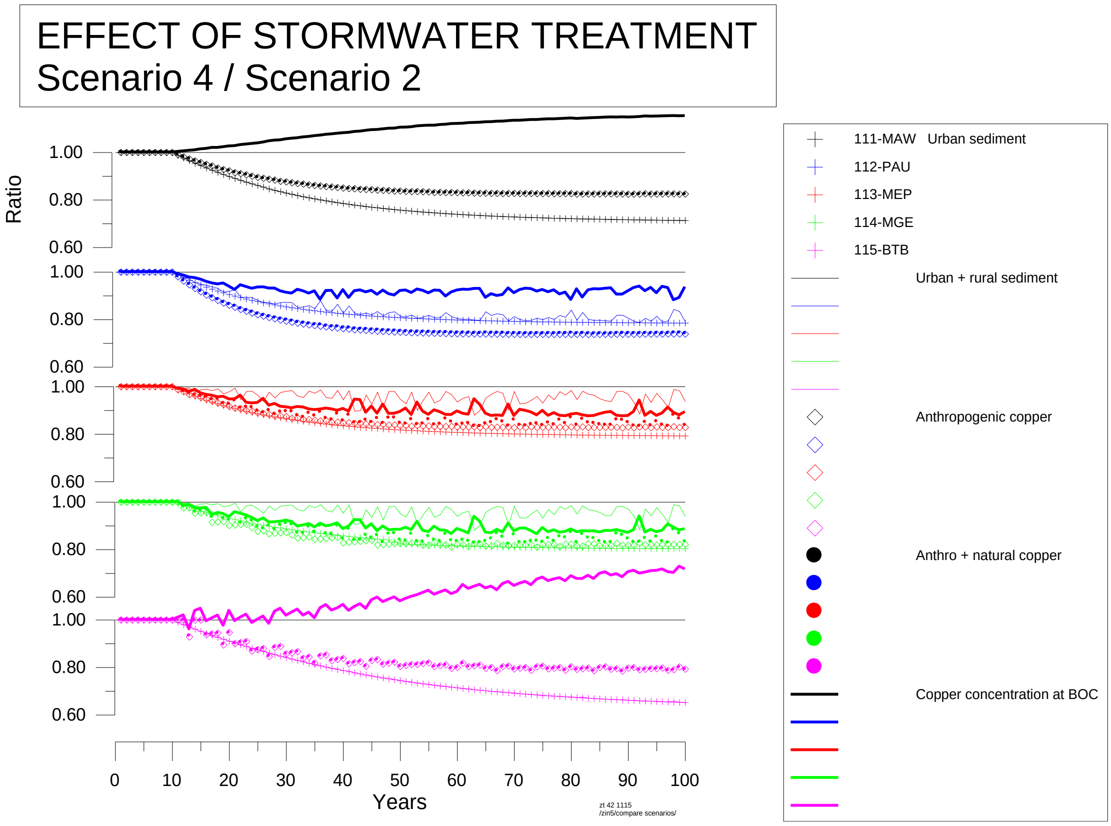


EFFECT OF MITIGATION MEASURES ON COPPER DELIVERY TO HARBOUR

EFFECT OF STORMWATER TREATMENT
Scenario 4 / Scenario 2



EFFECT OF MITIGATION MEASURES ON COPPER DELIVERY TO HARBOUR



EFFECT OF MITIGATION MEASURES ON ZINC ACCUMULATION IN HARBOUR BED SEDIMENTS

Figure 4.8:

Predicted change in zinc concentration for the future period under all scenarios 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.

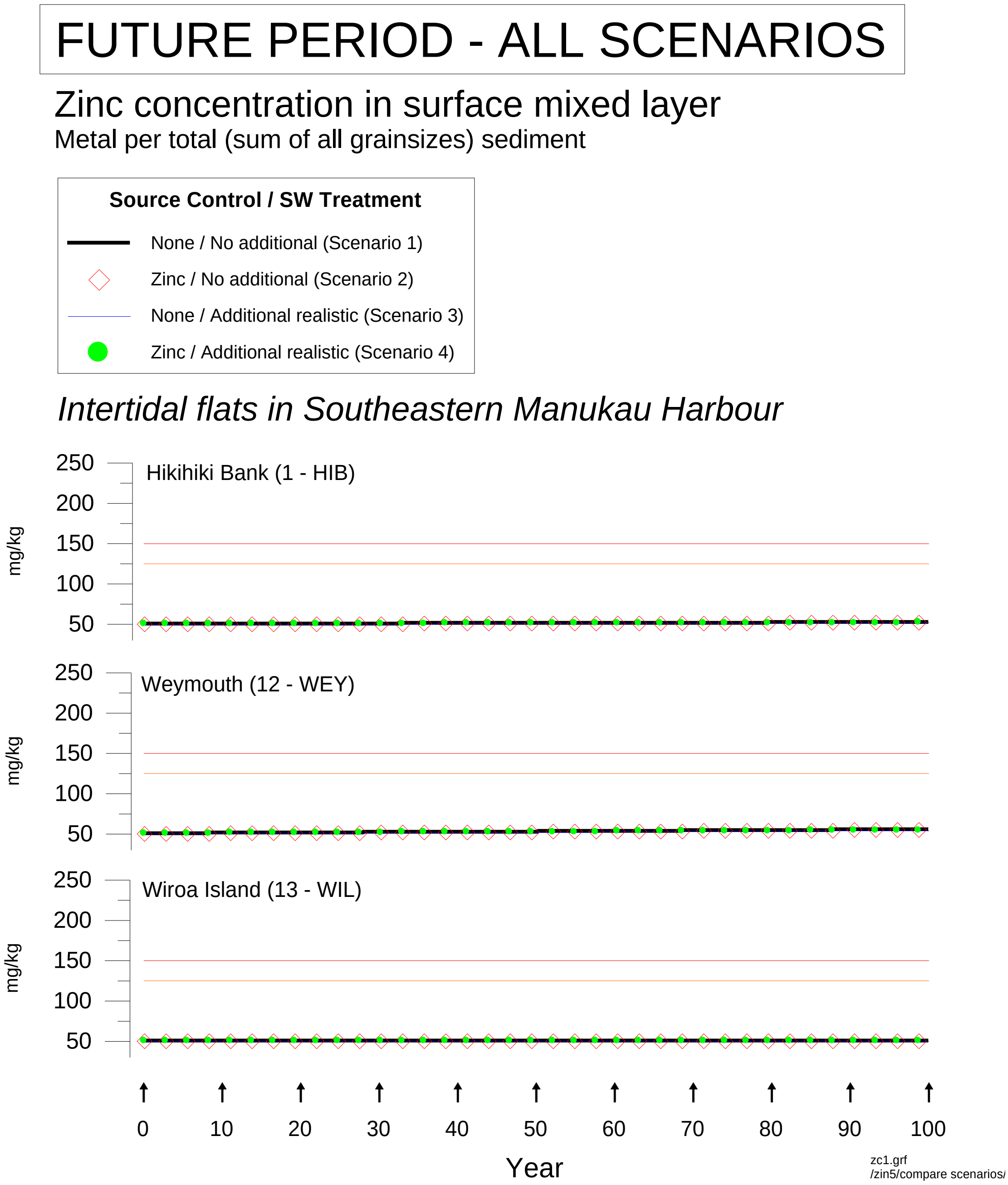


Figure 4.9:

Predicted change in zinc concentration for the future period under all scenarios 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.

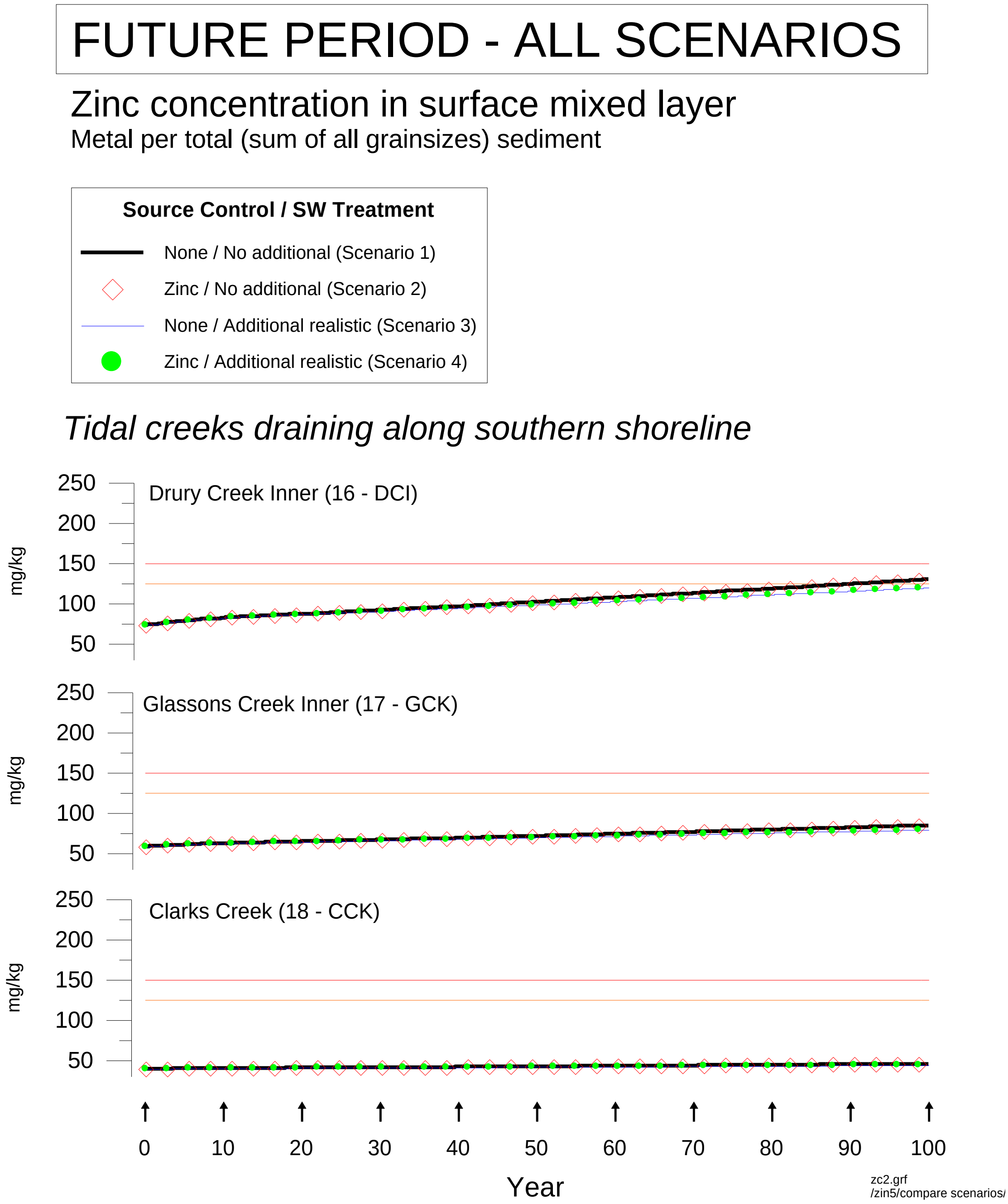


Figure 4.10:

Predicted change in zinc concentration for the future period under all scenarios 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.

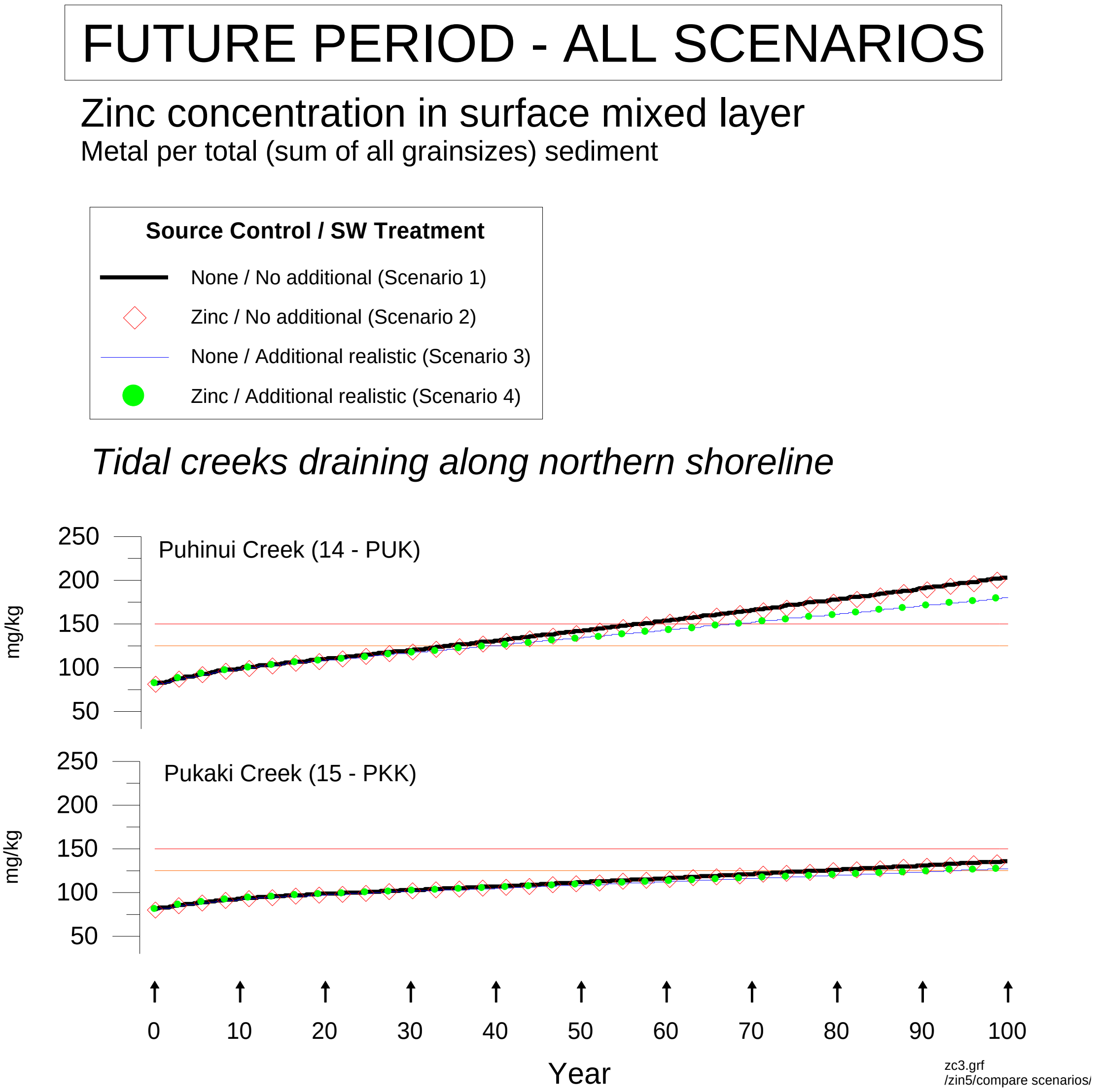


Figure 4.11:

Predicted change in zinc concentration for the future period under all scenarios 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.

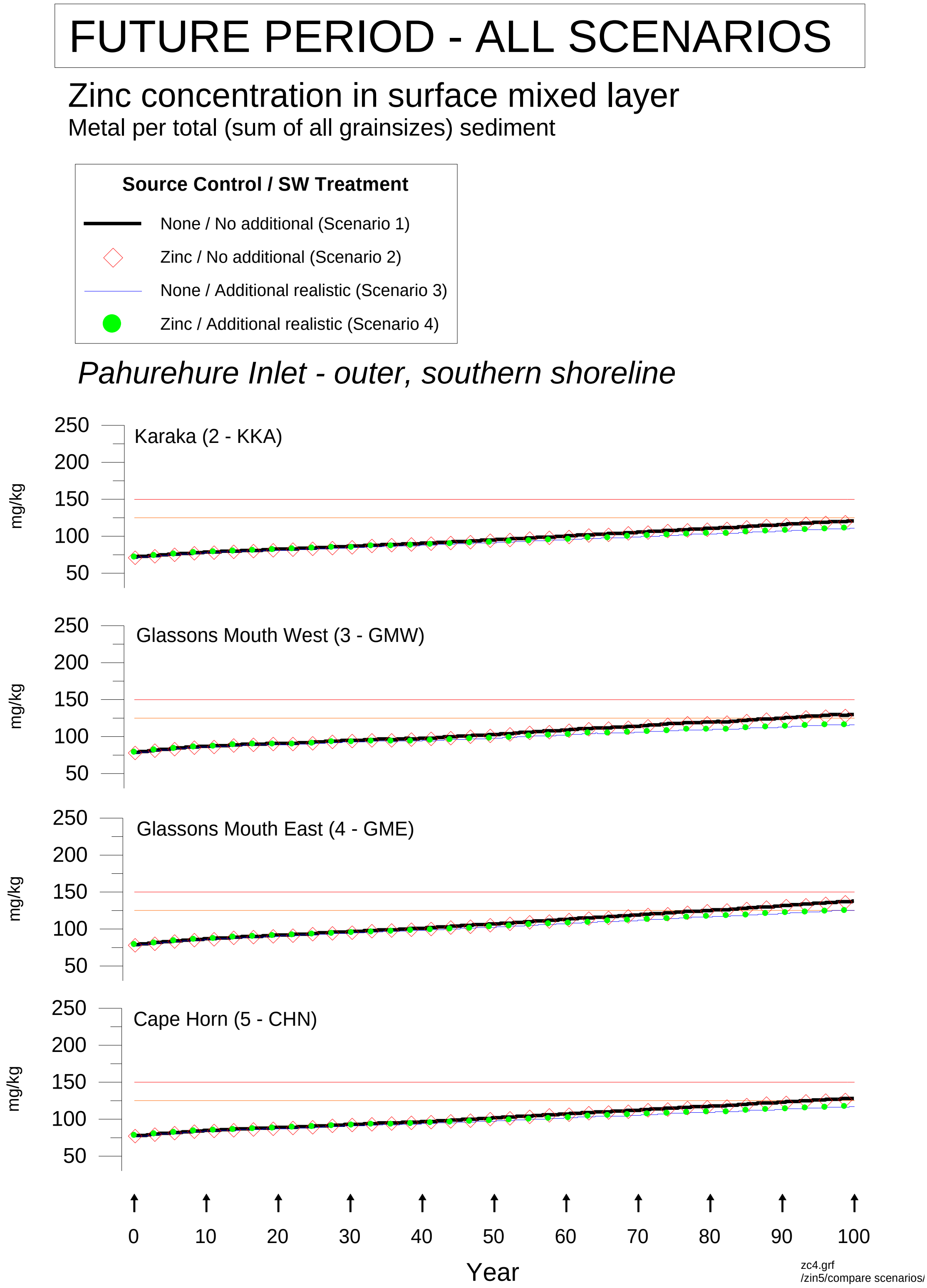


Figure 4.12:

Predicted change in zinc concentration for the future period under all scenarios 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.

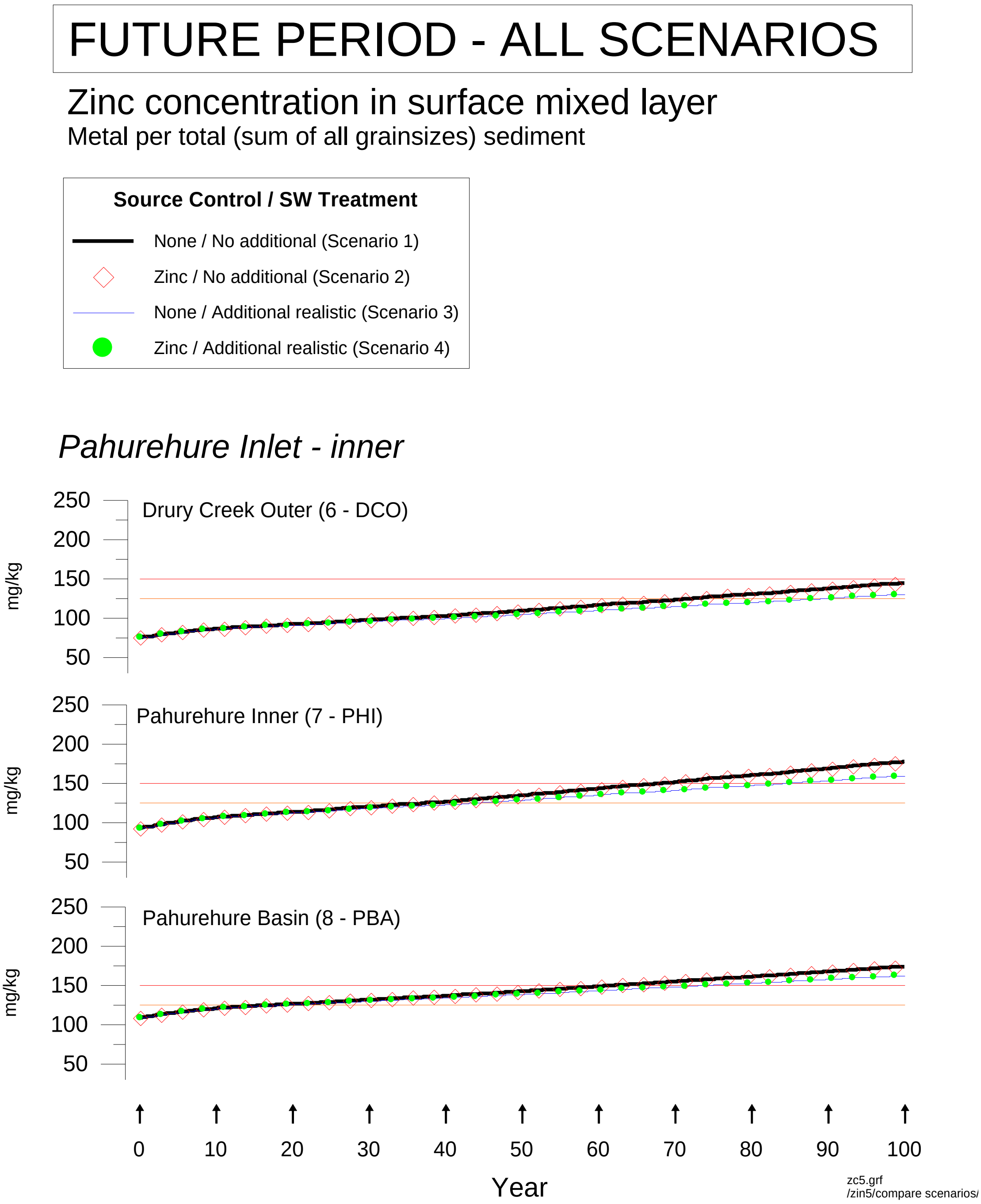
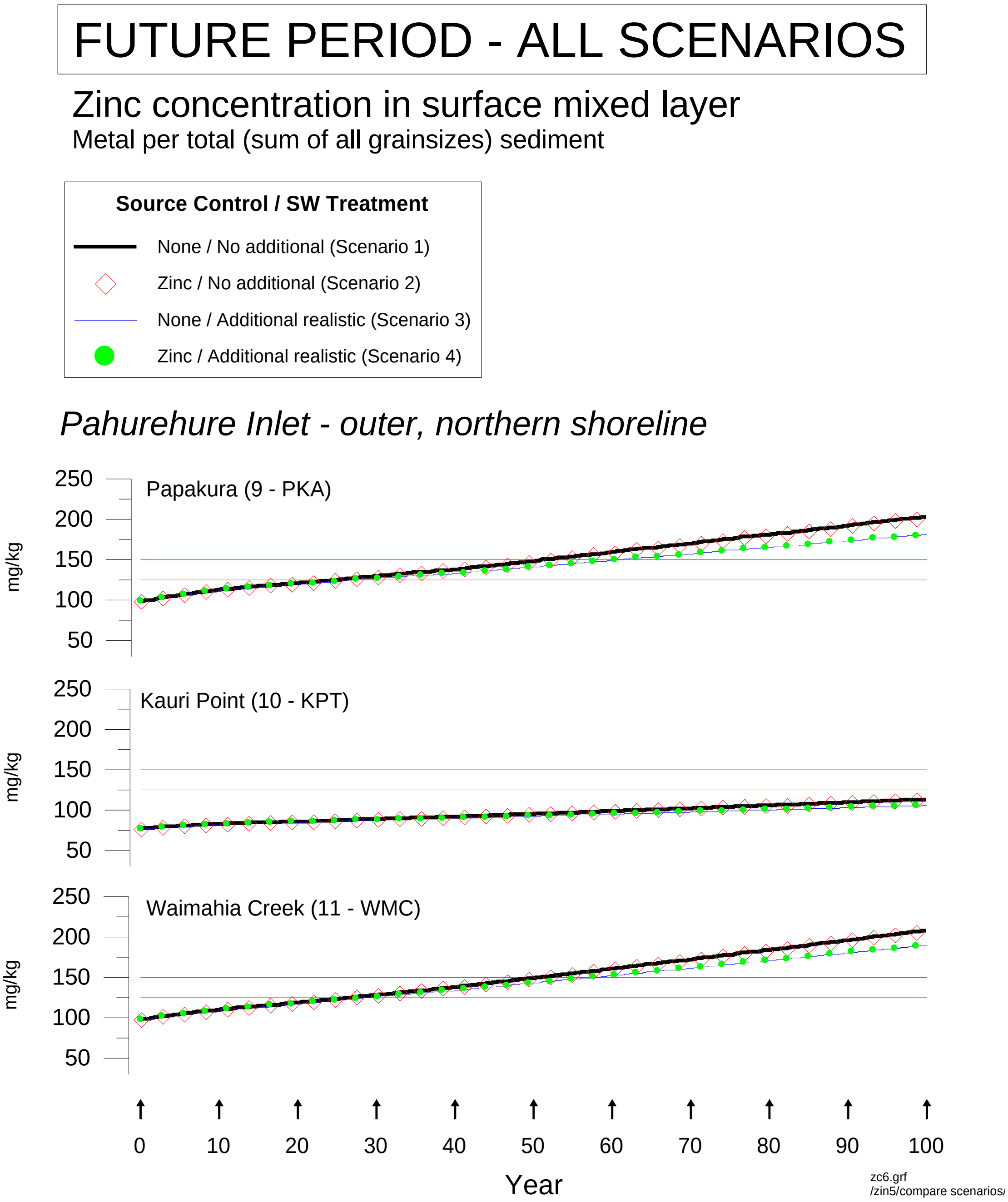


Figure 4.13:

Predicted change in zinc concentration for the future period under all scenarios 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.



EFFECT OF MITIGATION MEASURES ON COPPER ACCUMULATION IN HARBOUR BED SEDIMENTS

Figure 4.14:

Predicted change in copper concentration for the future period under all scenarios 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.

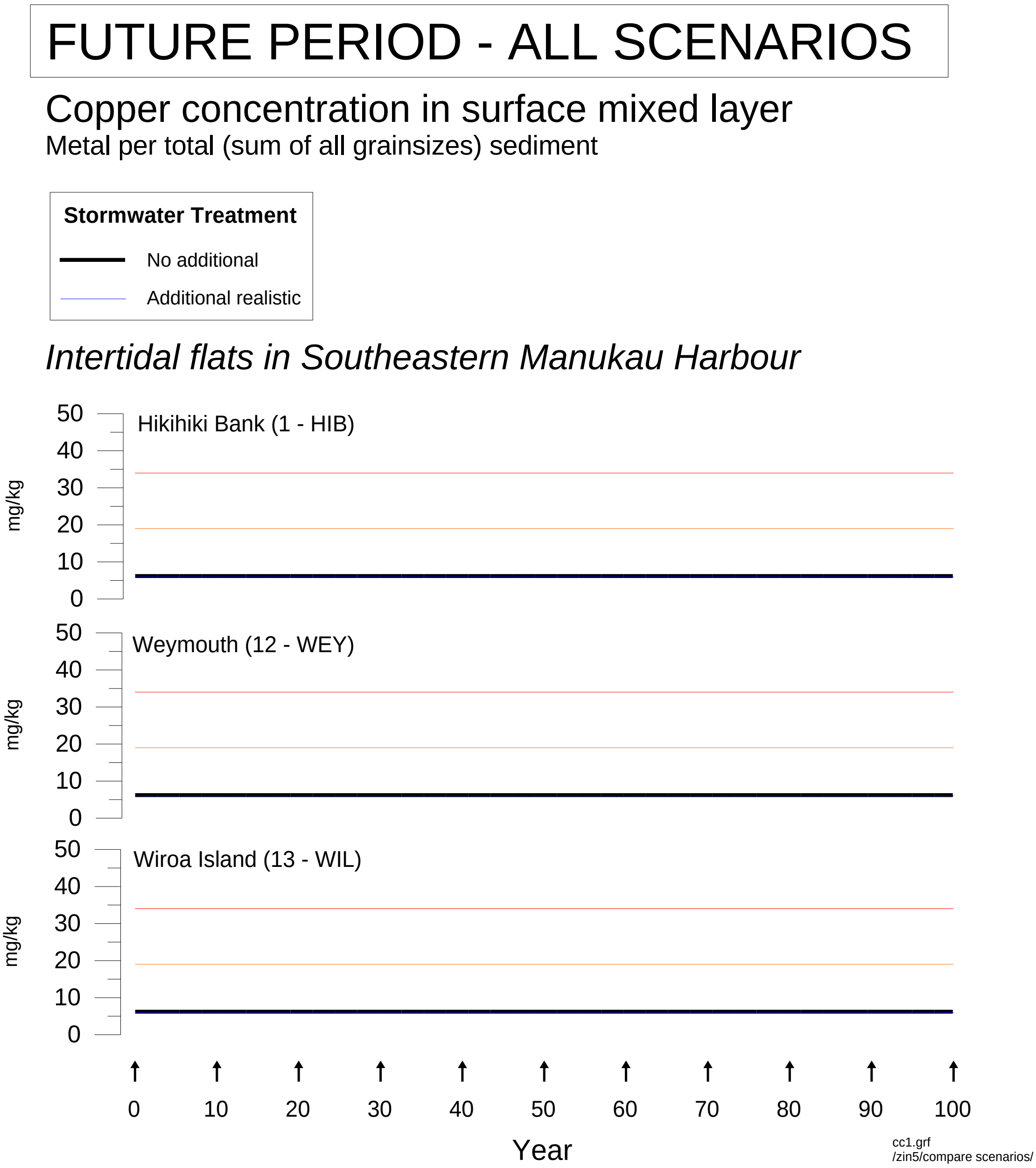


Figure 4.15:

Predicted change in copper concentration for the future period under all scenarios 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.

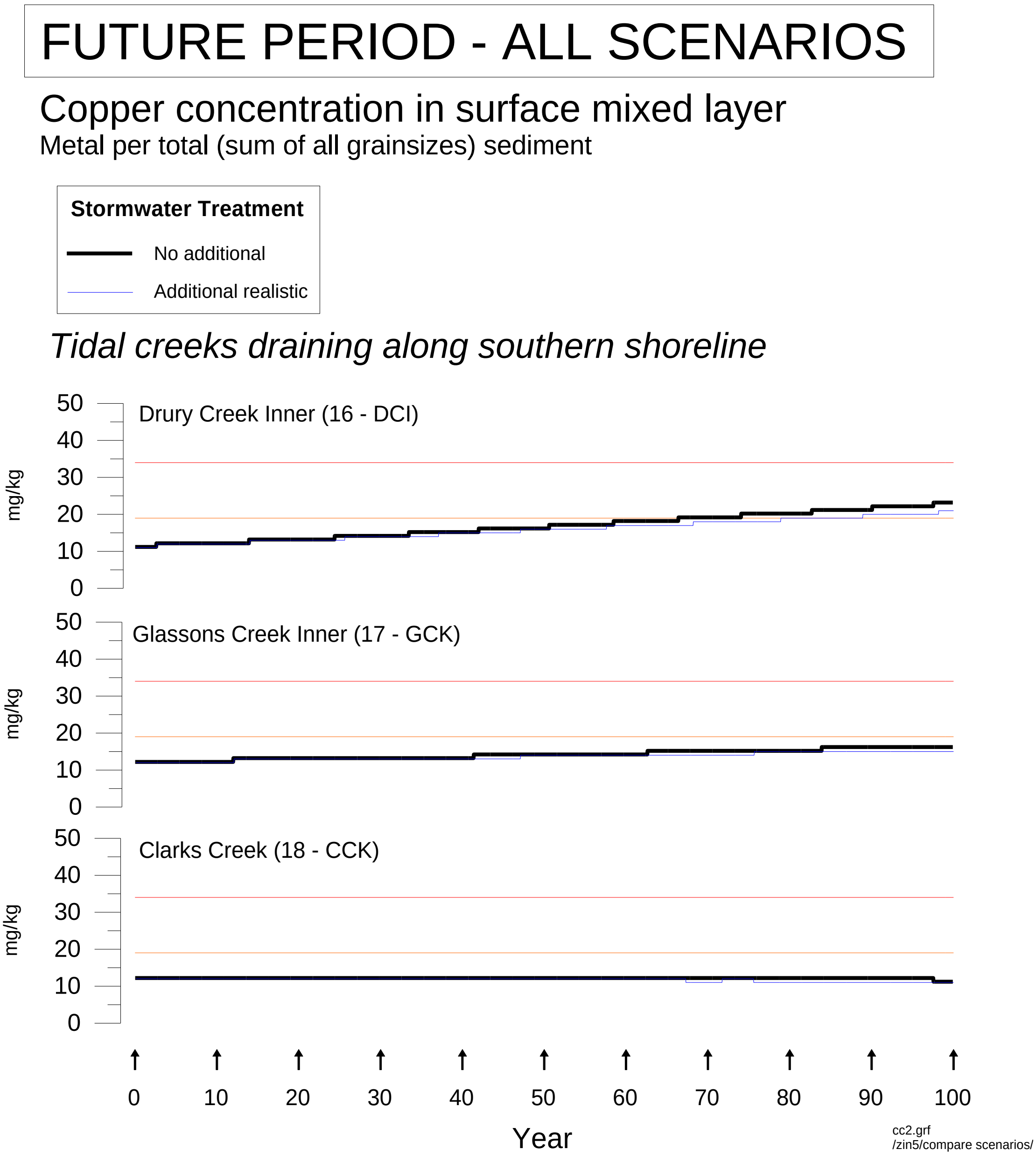


Figure 4.16:

Predicted change in copper concentration for the future period under all scenarios 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.

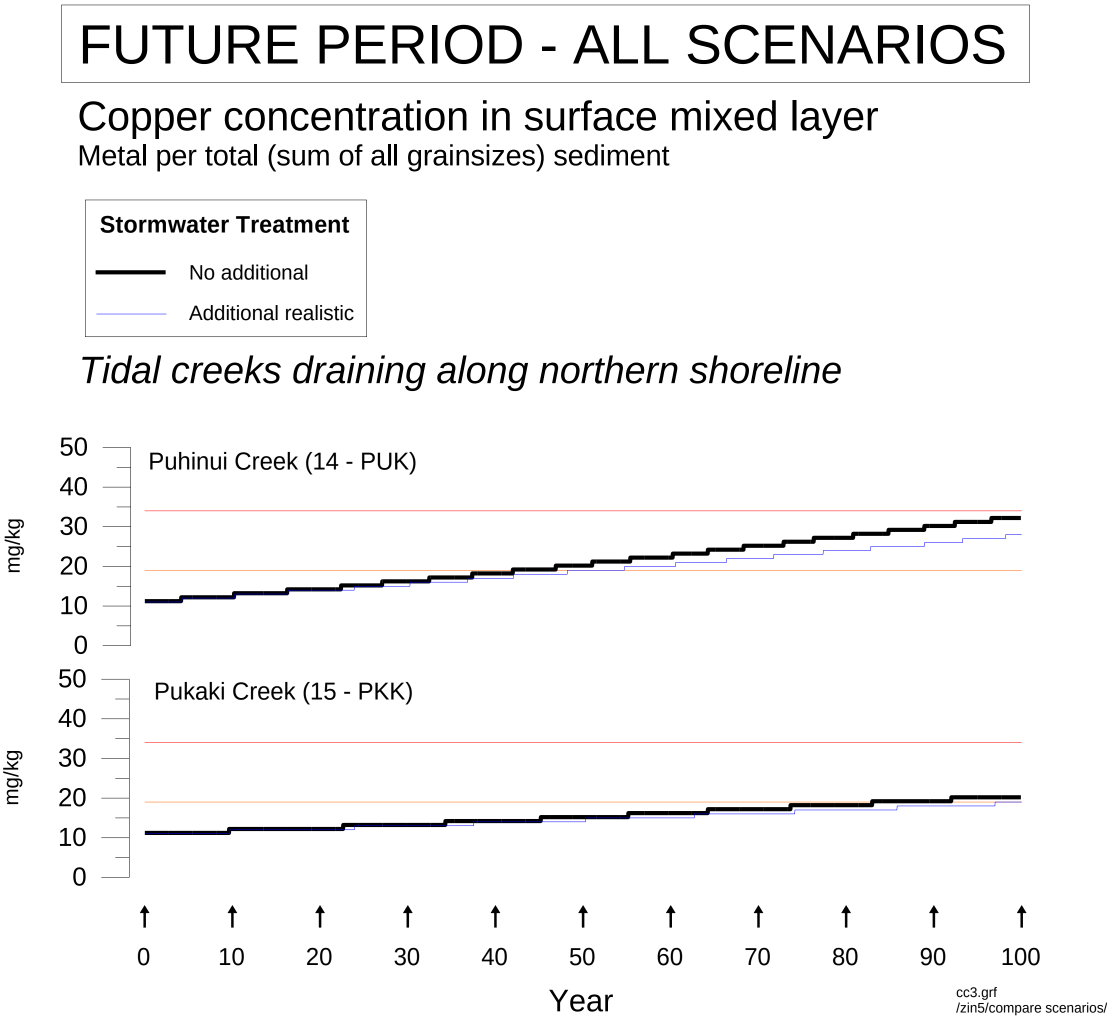


Figure 4.17:

Predicted change in copper concentration for the future period under all scenarios 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.

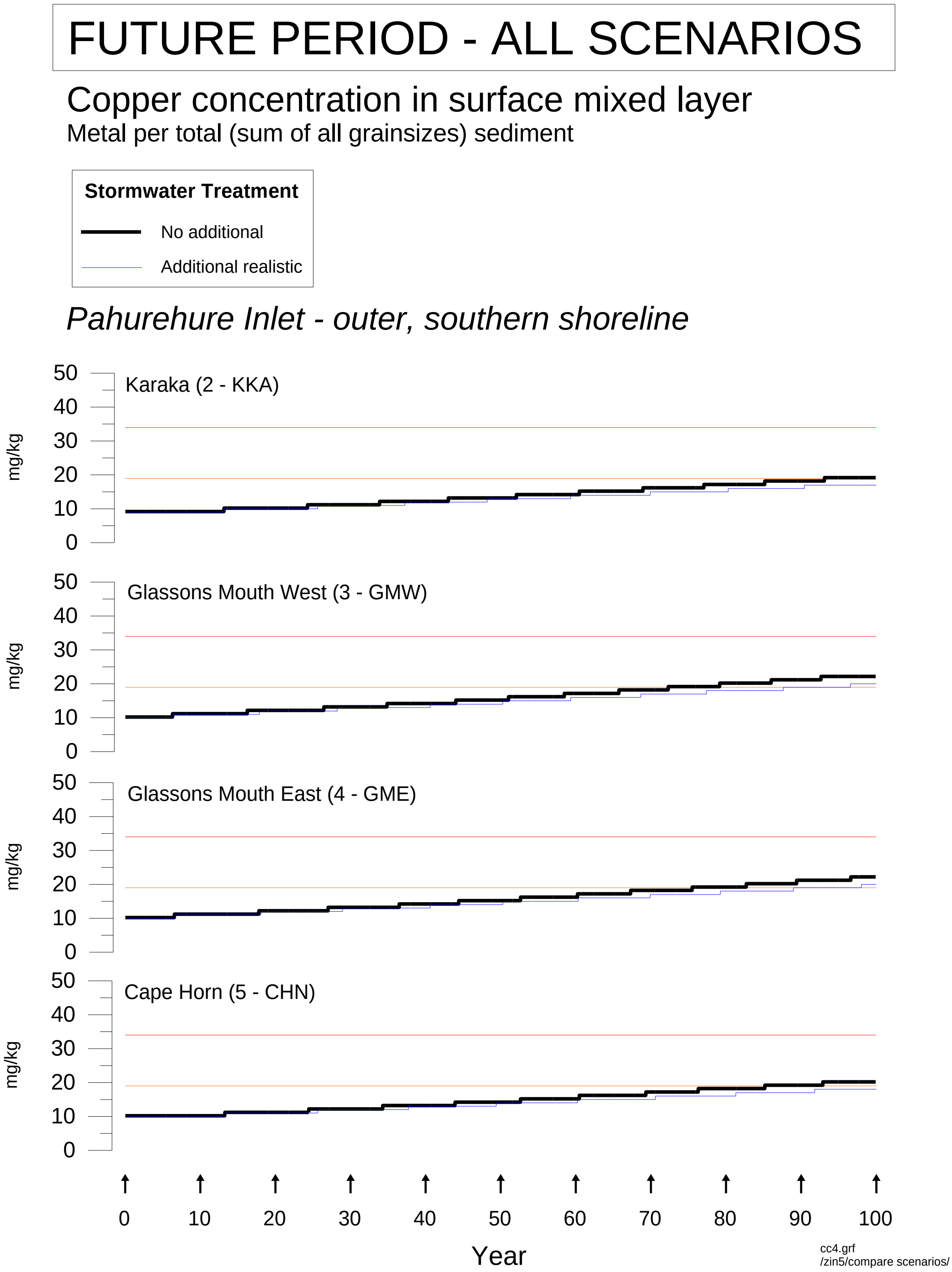


Figure 4.18:

Predicted change in copper concentration for the future period under all scenarios 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.

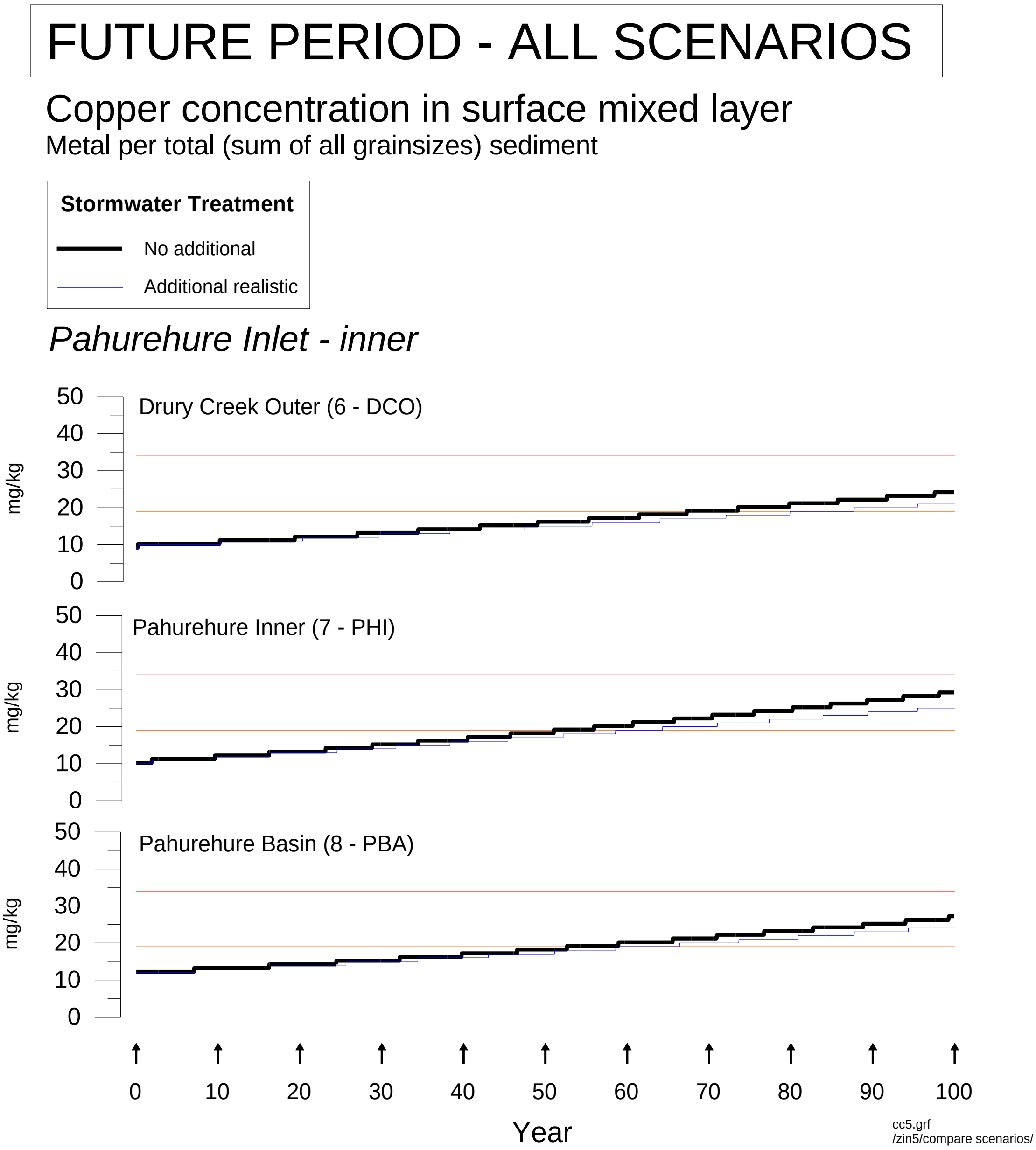
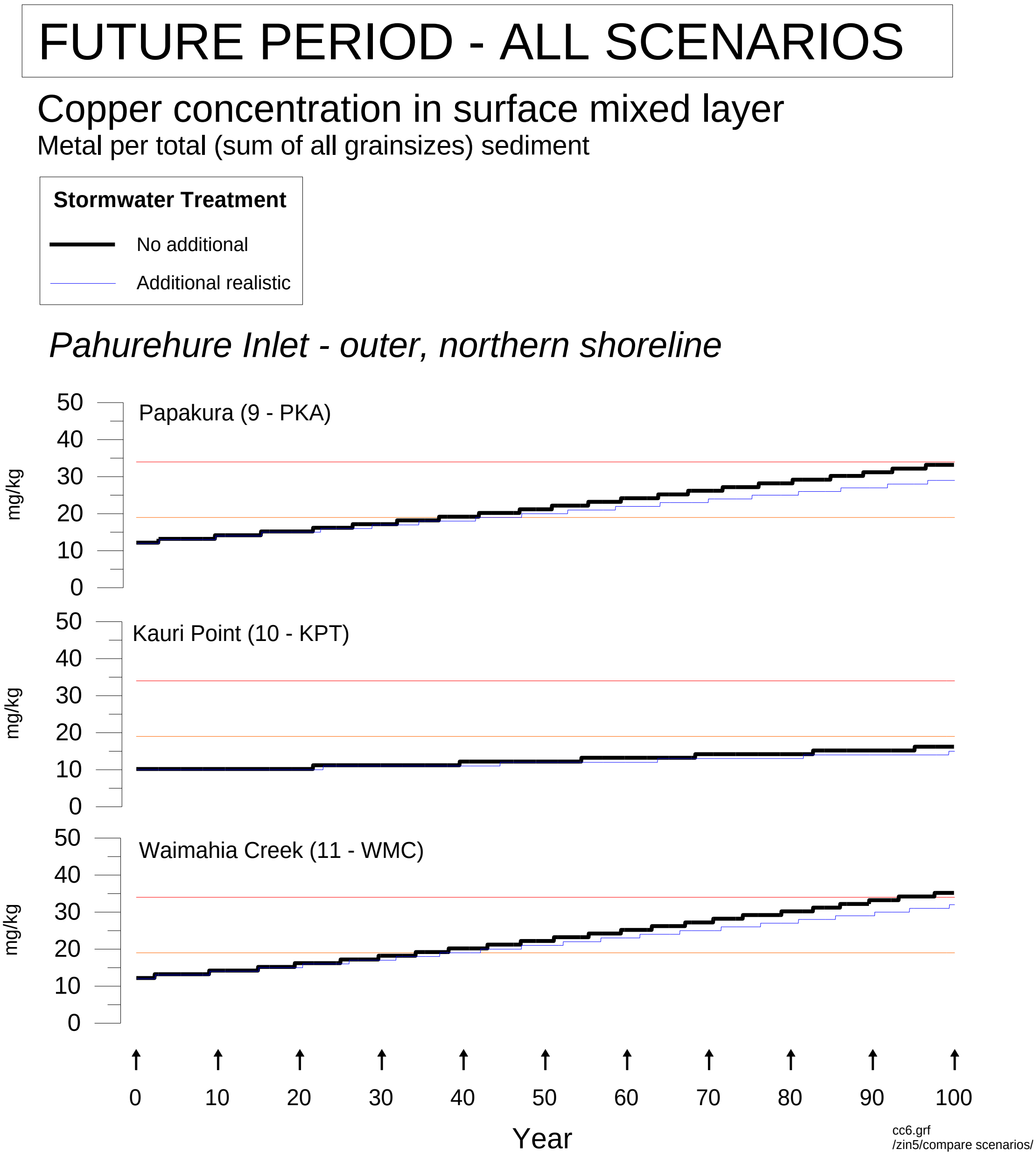


Figure 4.19:

Predicted change in copper concentration for the future period under all scenarios 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.



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6 References

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8 Appendix A – Division of Total Sediment Runoff Between Urban and Rural Sources Under Scenario 1

Understanding the division of the total sediment runoff between urban and rural sources in each subcatchment under Scenario 1, which was described in detail by Green (2008b), is crucial to understanding the effectiveness of stormwater treatment in reducing total sediment runoff to the harbour.

Green's (2008b) analysis for Scenario 1 is reproduced here.

Table A.1 (Table 4.4 of Green, 2008b) 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 A.1 (Figure 4.4 of Green, 2008b) shows how the rural–urban split for each subcatchment varies over time during the future period, and Figure A.2 (Figure 4.5 of Green, 2008b) 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.

Table A.1 (Table 4.4 of Green, 2008b):

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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Figure A.1 (Figure 4.4 of Green, 2008b):

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.

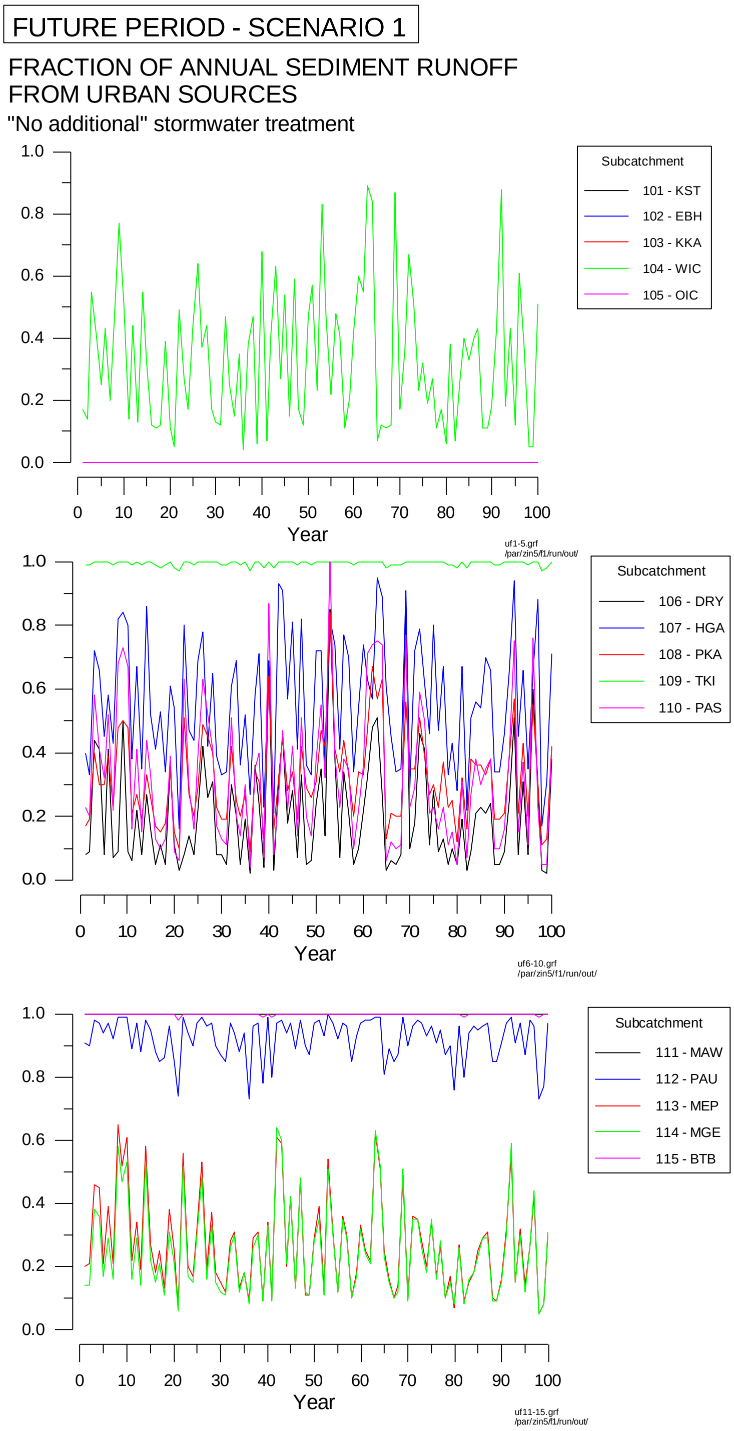
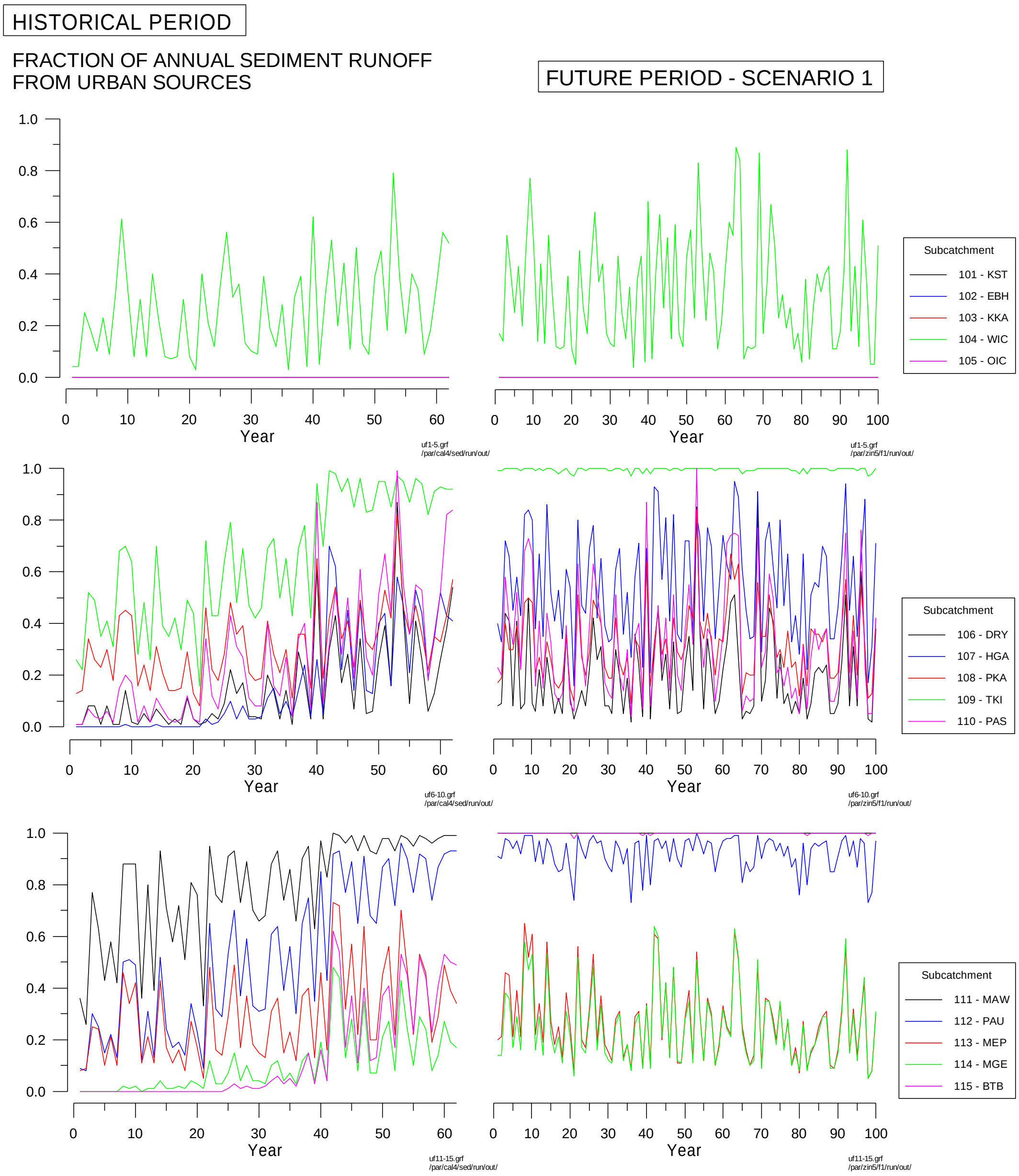


Figure A.2 (Figure 4.5 of Green, 2008b):

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).



9 Appendix B – Division of Total Metal Runoff Between Anthropogenic and Natural Sources Under Scenario 1

Understanding the division of the total metal runoff between anthropogenic and natural sources in each subcatchment under Scenario 1, which was described in detail by Green (2008b), is crucial to understanding the effectiveness of both zinc source control and stormwater treatment in reducing total metal runoff to the harbour.

Green's (2008b) analysis for Scenario 1 is reproduced here.

Table B.1 (Table 4.7 of Green, 2008b) and Table B.2 (Table 4.8 of Green, 2008b) 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.

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%).

Table B.1 (Table 4.7 of Green, 2008b):

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 B.2 (Table 4.8 of Green, 2008b):

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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10 Appendix C – Analysis of Change in Metal Delivery Concentration due to Improved Stormwater Treatment

Why does the USC-3 model predict that improved stormwater treatment can change the concentration at which metals are delivered to the base-of-catchment (BOC) differently in fully urbanised catchments compared to partially urbanised catchments? For instance, the model predicts that, in a fully urbanised catchment, metal delivery concentration is increased when improved stormwater treatment removes proportionately more sediment than metal from the freshwater runoff (and vice versa). But, in a partially urbanised catchment, those same conditions can cause metal delivery concentration to decrease. Understanding the reason for this is relevant to management, since metal delivery concentration is one factor that drives the rate and the direction of change of metal concentration in the estuary bed sediments. (Sedimentation rate is another factor.)

For this analysis, let Scenario 1 have “standard” stormwater treatment and Scenario 2 have “improved” stormwater treatment.

The total sediment runoff under Scenario 1 is

$$TS = US + RS$$

where *US* is the urban sediment runoff and *RS* is the rural sediment runoff. The total metal runoff is:

$$TM = AM + (C*US) + (C*RS)$$

where *AM* is the anthropogenic metal runoff and *C* is the concentration at which natural metal is attached to the sediment. The concentration at which metal is delivered to the estuary under Scenario 1 is:

$$CONC1 = [AM + (C*US) + (C*RS)]/(US + RS)$$

Under Scenario 2, the total sediment runoff is changed to:

$$TS = (US*SWS) + RS$$

where *SWS* is the fraction of the urban sediment runoff that passes through the stormwater treatment facility and is delivered to BOC. Note that stormwater treatment does not change the rural sediment runoff. The total metal runoff is changed to:

$$TM = (AM*SWM) + (C*US*SWS) + (C*RS)$$

where *SWM* is the fraction of the anthropogenic metal runoff that passes through the stormwater treatment facility and is delivered to BOC. The concentration at which metal is delivered to the estuary under Scenario 2 is:

$$CONC2 = [(AM * SWM) + (C * US * SWS) + (C * RS)]/[(US * SWS) + RS]$$

Case 1 – *AM* = 0 and US = 0

This case corresponds to a fully rural catchment. With no anthropogenic metal and no urban sediment:

$$CONC1 = (C * RS) / RS$$

$$CONC2 = (C * RS) / RS$$

and so *CONC2* = *CONC1*. In this case, stormwater treatment can have no effect on the metal delivery concentration. Furthermore, metal is delivered to BOC at the concentration at which natural metal is attached to sediment.

Stormwater treatment cannot change metal delivery concentration in a rural catchment.

Case 2 – *AM* = 0

When there is no anthropogenic metal runoff:

$$CONC1 = \frac{C * (US + RS)}{US + RS} = C$$

$$CONC2 = \frac{C * [(US * SWS) + RS]}{(US * SWS) + RS} = C$$

and so

$$CONC2 = CONC1$$

This shows that, firstly, metal is delivered to BOC at the concentration at which natural metal is attached to sediment. This of course must be the case, since there is no anthropogenic metal. Secondly, stormwater treatment cannot change that concentration, since it removes sediment and (natural) metal proportionately from the runoff. It is interesting that this is the same result as Case 1, which is the fully rural catchment. This shows that the Case 1 result is in fact dependent on the absence of anthropogenic metal, not the absence of urban sediment.

In fact, the condition that needs to hold for stormwater treatment to be ineffective (i.e., unable to change metal delivery concentration) is just that there is no anthropogenic metal load.

Case 3 – *US* = 0

When there is no urban sediment:

$$CONC1 = \frac{AM + (C * RS)}{RS}$$

$$CONC2 = \frac{(AM * SWM) + (C * RS)}{RS}$$

and so

$$\frac{CONC2}{CONC1} = \frac{(AM * SWM) + (C * RS)}{AM + (C * RS)}$$

This is now a very different result than Case 1 for the fully rural catchment.

- For *SWM* = 1, *CONC2* = *CONC1*. In this case, there is no urban sediment for the stormwater to remove, and no anthropogenic metal is removed. Hence the metal delivery concentration under Scenario 2 cannot be changed.
- As *SWM*→0, *CONC2*/*CONC1* decreases. This equates to unilateral removal of anthropogenic metal from the runoff, which reduces the delivery concentration under Scenario 2.
- AS *AM*→∞, *CONC2*/*CONC1*→1. All other things being held constant, as the anthropogenic metal runoff increases it becomes more difficult to change the delivery concentration under Scenario 2.

<u>Case 4 – *RS* = 0</u>

This is the case of the fully urbanised catchment.

$$CONC1 = \frac{AM + (C * US)}{US}$$

$$CONC2 = \frac{(AM * SWM) + (C * US * SWS)}{(US * SWS)}$$

and so

$$\frac{CONC2}{CONC1} = \frac{\frac{SWM}{SWS} * \frac{AM}{US} + C}{\frac{AM}{US} + C}$$

- If *SWM*/*SWS*>1 then *CONC2* will exceed *CONC1*. This happens because more sediment than metal is removed by the stormwater treatment. This would <u>not</u> be the desired result from improving stormwater treatment.
- Conversely, if *SWM*/*SWS*<1 then *CONC2* will be less than *CONC1*. This happens because more metal than sediment is removed by the stormwater treatment. This would be the desired result from improving stormwater treatment.

Thus, in a fully urbanised catchment, the direction of change in metal delivery concentration depends on the ratio of metal to sediment removed by stormwater treatment.

Note also the modifying role of C (the natural metal concentration). The larger this becomes, the more difficult it is to change the delivery concentration under Scenario 2.

Case 5 – General

Now,

$$CONC1 = \frac{AM}{US + RS} + C$$

$$CONC2 = \frac{(AM * SWM)}{(US * SWS) + RS} + C$$

Equating *CONC2* with *CONC1* yields

$$\frac{RS}{SWM} + \frac{US * SWS}{SWM} = US + RS$$

This is actually a surprisingly complex system, which we will now explore in just a little detail. In the following discussion, *TERM1* refers to the lefthand side of the above equation, and *TERM2* refers to the righthand side.

The analysis hinges on the recognition that *RS/SWM* is always greater than or equal to *RS*, since *SWM* is less than or equal to 1.

- The first case is when (*US** *SWS*)/*SWM* exceeds *US* by the same amount that *RS/SWM* exceeds *RS*. In this case, *TERM1* = *TERM2* and *CONC2*=*CONC1*. This indicates that improved stormwater treatment has no effect.
- The second case is when (*US** *SWS*)/*SWM* exceeds *US* by less than *RS/SWM* exceeds *RS*. In this case, *TERM1* is less than *TERM2*, and *CONC2* exceeds *CONC1*, which indicates that the improved stormwater treatment increases the metal delivery concentration.
- The third case is the converse, and is when (*US** *SWS*)/*SWM* exceeds *US* by more than *RS/SWM* exceeds *RS*. In this case, *TERM1* is greater than *TERM2*, and *CONC2* is less *CONC1*, which indicates that the improved stormwater treatment reduces the metal delivery concentration.

The surprising result from this set of equations is shown by the pink stippled region in Figure C-1, which is that **in a mixed urban–rural catchment the removal of more sediment than metal by improved stormwater treatment can result in a <u>decrease</u> in the metal delivery concentration.** This is the result that was thrown up the USC-3 model and which led to the question that is posed at the start of Appendix C.

A few other things to note from Figure C-1:

- Removal of more sediment than metal by improved stormwater treatment can also result in an <u>increase</u> in metal delivery concentration.
- When there is no rural sediment (ratio of rural to urban sediment = 0 in the graph), the effect of improved stormwater treatment is governed purely by the relative removal of sediment and anthropogenic metal. When more sediment than metal is removed by the improved stormwater treatment then the delivery concentration is increased, and vice versa. This result has already been established in Case 4 (urban catchment), above.

- As the rural sediment gets larger, improved stormwater treatment has progressively less effect regardless of the relative removal of metal and sediment.

Figure C-1 actually shows the ratio of *CONC2* to *CONC1*, not *CONC2-CONC1*. The anthropogenic metal load *AM* affects CONC2/CONC2, as suggested in Figure C-2. This gives a hint of the real complexity of the system, the further exploration of which is beyond the scope of this report.

Figure C-1:
The bottom graph shows the ratio *CONC2/CONC1*, where *CONC2* is the metal delivery concentration in freshwater at BOC after applying improved stormwater treatment and *CONC1* is delivery concentration under standard stormwater treatment. There is a range of *US/RS* where the delivery concentration is reduced even though more sediment than metal is removed by the stormwater treatment. The top graph shows *TERM1* and *TERM2*. Note that where *TERM2=TERM1*, *CONC2/CONC1* = 1. Parameters are *US* = 1000, *SWM* = 0.6, *AM* = 100.

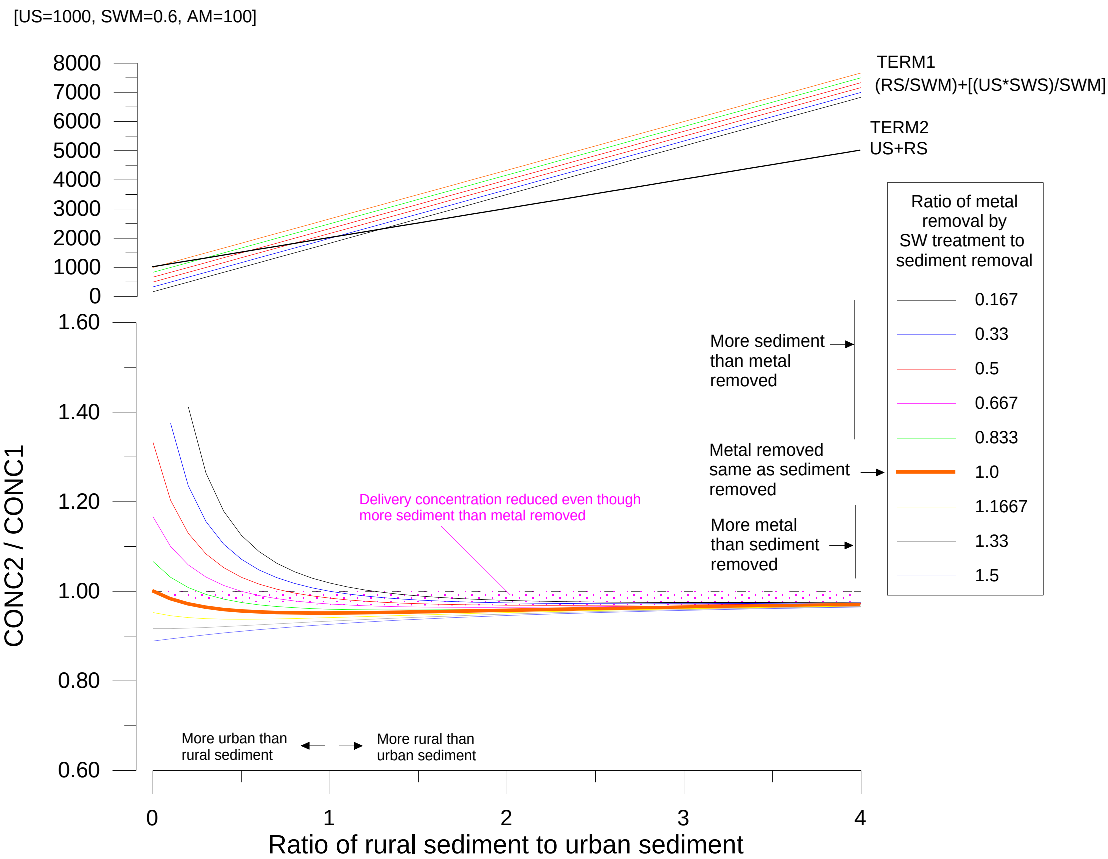

Figure C-2:

As Figure C-1, except *AM* = 1000 (*AM* was 100 in Figure C-1).