Auckland Regional Council
TE RAUHĪTANGA TAIAO

Central Waitemata Harbour Contaminant Study

Predictions of Sediment, Zinc and Copper Accumulation under Future Development Scenarios 2, 3 and 4

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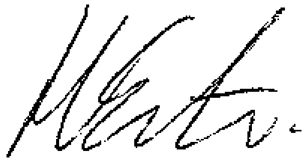	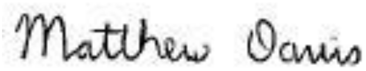
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Central Waitemata Harbour Contaminant Study. Predictions of Sediment, Zinc and Copper Accumulation under Future Development Scenarios 2, 3 and 4

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Preface

The Waitemata Harbour is comprised of tidal creeks, embayments and the central basin. The harbour receives sediment and stormwater chemical contaminant run-off from urban and rural land from a number of subcatchments, which can adversely affect the ecology. An earlier study examined long-term accumulation of sediment and stormwater chemical contaminants in the Upper Waitemata Harbour. However, previously little was known about the existing and long-term accumulation of sediment and stormwater chemical contaminants in the central harbour. The Central Waitemata Harbour Contaminant Study was commissioned to improve understanding of these issues. This study is part of the 10-year Stormwater Action Plan to increase knowledge and improve stormwater management outcomes in the region. The work was undertaken by the National Institute of Water and Atmospheric Research (NIWA).

The scope of the study entailed:

1) field investigation,

2) development of a suite of computer models for

    a. urban and rural catchment sediment and chemical contaminant loads,

    b. harbour hydrodynamics and

    c. harbour sediment and contaminant dispersion and accumulation,

3) application of the suite of computer models to project the likely fate of sediment, copper and zinc discharged into the central harbour over the 100-year period 2001 to 2100, and

4) conversion of the suite of computer models into a desktop tool that can be readily used to further assess the effects of different stormwater management interventions on sediment and stormwater chemical contaminant accumulation in the central harbour over the 100-year period.

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

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

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

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

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

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

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

The three general stormwater management intervention scenarios evaluated were:

1) source control of zinc by painting existing unpainted and poorly painted galvanised steel industrial building roofs;

2) additional stormwater treatment, including:

    - raingardens on roads carrying more than 20,000 vehicles per day and on paved industrial sites,
    - silt fences and hay bales for residential infill building sites and
    - pond / wetland trains treating twenty per cent of catchment area; and

3) combinations of the two previous scenarios.

International Peer Review Panel

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

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

Key Findings of the Study

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

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

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

- Central Waitemata Harbour bed sediment concentrations of copper and zinc are not expected to reach toxic levels based on current assumptions of future trends in urban landuse and activities.

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

- Given that the modelling approach used large-scale depositional zones and long timeframes, differences can be expected from the modelling projections and stormwater management interventions contained within these reports versus consideration of smaller depositional areas and local interventions. (For example, whereas the study addresses the Whau River as a whole, differences exist within parts of the Whau River that may merit a different magnitude or type of intervention than may be inferred from considering the Whau River and its long-term contaminant trends as a whole.) As a consequence, these local situations may merit further investigation and assessment to determine the best manner in which to intervene and make improvements in the short and long terms.

Research and Investigation Questions

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

- Sediment and chemical contaminant dynamics within tidal creeks.

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

- The fate of other contaminants derived from urban sources.

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

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

Technical reports

The study has produced a series of technical reports:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Contents

1 Executive Summary

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

This report describes predictions that have been made by the USC-3 ("Urban Stormwater Contaminant") model, which has been developed specifically for the study. The model, which functions as a decision-support scheme, predicts sedimentation and accumulation of contaminants (including zinc and copper) in the bed sediments of estuaries on the "planning timescale", which is decades and greater.

Predictions are to be made for a number of development scenarios, where scenarios differ from each other only by anthropogenic metal (as opposed to the "natural" metals that are present in the soils of the catchment) run-off, and urban (as opposed to rural) sediment run-off. Each scenario covers 100 years into the future from the present day, which is defined as 2001.

- The "no additional" stormwater treatment modelled in Scenarios 1 and 2 consists of specific stormwater treatment devices (data provided by Auckland, Waitakere and North Shore City Councils) in addition to sediment 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 "moderate" stormwater treatment modelled in Scenarios 3 and 4 includes the treatment in Scenarios 1 and 2 plus: rain gardens or multimedia filters on all large roads (>20,000 vehicles per day); silt fences or similar on all residential infill construction sites; rain gardens or multimedia filters on all industrial paved areas; and ponds or wetlands at the bottom of all catchments treating 20 % of the catchment stormwater. Urban sediment run-off is reduced under the "moderate" stormwater treatment compared to the "no additional" stormwater treatment.
- "No additional" zinc source control of industrial roofs is modelled in Scenarios 1 and 3. 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. Anthropogenic zinc run-off is reduced under the source control. In effect, there is no Scenario 2 or 4 for copper.

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

Under all scenarios, Henderson Creek sub-catchment is predicted to be the principal sediment source to the harbour, and the Upper Waitemata Harbour sub-catchment and the Whau River sub-catchment are the next largest sources. For all sub-catchments except Henderson Creek, sediment run-off from rural sources is a very small fraction of the total sediment run-off. This reflects the urbanisation of the catchment.

The sediment run-off under Scenario 3 is identical to the sediment run-off under Scenario 4, and the sediment run-off under both of these scenarios is, in turn, smaller than the sediment run-off under Scenarios 1 and 2. This is expected since Scenarios 3 and 4 have the same "moderate" stormwater treatment, which is more effective than the "no additional" stormwater treatment applied in Scenarios 1 and 2.

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

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

Zinc run-off under Scenarios 2 and 4 is only very slightly smaller than under Scenarios 1 and 3, respectively, which indicates that the zinc source control applied in Scenarios 2 and 4, which is painting of industrial galvanised steel roofs, is not very effective. The reason is that industrial roofs contribute only a minor proportion of the zinc generated by roof run-off. By 2025 all industrial galvanised steel roofs will disappear anyway, to be replaced by zincalume roofs, after which time this method of source control as a result becomes irrelevant.

On the other hand, zinc run-off under Scenarios 3 and 4 is significantly smaller than under Scenarios 1 and 2. This is because the "moderate" stormwater treatment applied in Scenarios 3 and 4 is more effective than the "no additional" stormwater treatment applied in Scenarios 1 and 2. The "moderate" stormwater treatment is applied to run-off from large roads (>20,000 vehicles per day), which are a major source of zinc. Copper run-off under Scenario 3 is also significantly smaller than under Scenario 1, for the same reasons.

Under all scenarios, concentrations at which total (anthropogenic plus natural) zinc is delivered to the harbour generally decrease for the first 15–20 years into the future period, and then they approximately level off. This is driven primarily by a decrease in anthropogenic zinc loads, which in turn is due mainly to a reduction in galvanised steel roofs in the catchment. The decrease in total sediment loads that is also predicted to occur over the next 15–20 years slows the decrease in metal concentrations. In contrast, concentrations at which total (anthropogenic plus natural) copper is delivered to the harbour generally increase steadily from 2001, reflecting an increase in anthropogenic copper loads over the future period, which in turn is due to increasing vehicle traffic and increasing use of copper sheet roofing. The increase in copper loads combines with the decrease in sediment loads to accelerate the change in concentration.

In both cases (zinc and copper), the concentrations at which total metals are predicted to be delivered to the harbour under all scenarios are much higher than the present-day concentrations in the estuarine bed sediments.

Zinc source control of industrial roofs and stormwater treatment combine in some sub-catchments and under some scenarios to decrease the concentration at which metals will be delivered to the harbour compared to Scenario 1, and in other sub-catchments and under other scenarios the delivery concentrations are increased. Hence, it is not possible to always know *a priori* how zinc source control and stormwater treatment will change metal concentrations in the harbour compared to Scenario 1. That is, they may be better or worse under the other scenarios.

The fate of sediments from each sub-catchment is substantially the same as that described by Green (2008b) for Scenario 1, which in turn is substantially the same as that described by Green (2008b) for the historical period, 1940–2001. The fate of zinc and copper mirrors almost exactly the fate of sediment. The origin of sediment and contaminant deposited in each subestuary is also substantially the same as that described in Green (2008b) for Scenario 1.

The predicted sedimentation rates in the harbour under all scenarios are smaller than Green's (2008b) hindcast sedimentation rates for the historical period 1940–2001, which is due to less sediment run-off in the future period.

The "moderate" stormwater treatment is predicted to reduce sedimentation rates in the harbour by about 10 % compared to the "no additional" stormwater treatment. This roughly reflects the reduction in sediment run-off achieved by the extra stormwater treatment in the sub-catchments that are the main suppliers of sediment to the CWH, these being the Henderson Creek and Whau River sub-catchments.

Green (2008b) provided a detailed discussion of how sedimentation is predicted to change in response to the decrease in sediment run-off from the catchment over the next 15–20 years under Scenario 1, for which there is "no additional" stormwater treatment. In the intertidal parts of the main body of the harbour, sedimentation is predicted to reduce at the time sediment run-off reduces. The subtidal part of the main body of the harbour will also experience a reduction in sedimentation, after which a new transportational regime (approximately zero sedimentation) will be established. The subestuaries that lie to the west of Te Tokaroa reef in the transition between the throat and the main body of the harbour (Waterview Flats, Point Chevalier and Meola subestuaries) will erode for a time, after which a new transportational regime is established. In contrast, in Motions subestuary, which lies to the east of Te Tokaroa reef, sedimentation will decline significantly, but will remain positive thereafter. For the tidal creeks, sedimentation will not obviously be affected, and sediment will continue to accumulate. Sedimentation in Shoal Bay will also not obviously be affected. The same picture applies to the case of "moderate" stormwater treatment

(Scenarios 3 and 4), with just two exceptions: the Western Intertidal subestuary and Motions Creek subestuaries are also predicted to become transportational in the response to the reduction in catchment sediment run-off 15–20 years into the future.

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

Zinc and copper concentrations are predicted to rise continuously in subestuaries that will experience virtually constant sedimentation throughout the future period. This includes the Henderson Creek and Whau River tidal creeks; the Waterview Embayment and Hobsons Bay sheltered embayments; Limeburners Bay, which acts like an extension of Henderson Creek; and Shoal Bay. In all cases, zinc source control of industrial roofs is predicted to have virtually no effect on the rise in zinc concentrations. In contrast, the more effective "moderate" stormwater treatment retards the accumulation of both zinc and copper compared to "no additional" stormwater treatment.

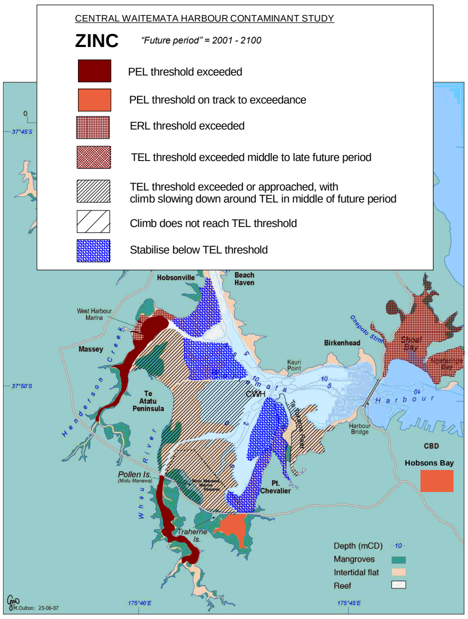
For subestuaries that will become transportational partway through the future period (Meola, Point Chevalier, Waterview Flats and Central Subtidal) the situation is different. Zinc and copper concentrations reach an equilibrium partway through the future period. This is a response to the change in sedimentation regime – from depositional to transportational – that also occurs at this time, and which in turn is a response to the reduction in sediment run-off from the catchment. Although an equilibrium concentration is attained, in the sense that the concentration becomes steady, it is more the case that these subestuaries become "moribund" (or "stagnant") when deposition switches off. Zinc source control of industrial roofs is predicted to have virtually no effect on the rise in zinc concentrations. Furthermore, the "moderate" stormwater treatment has no effect on the zinc and copper concentrations since the concentrations are stabilised – that is, become unchangeable – when the transportational regime is reached, which is before the "moderate" stormwater really starts to have an effect.

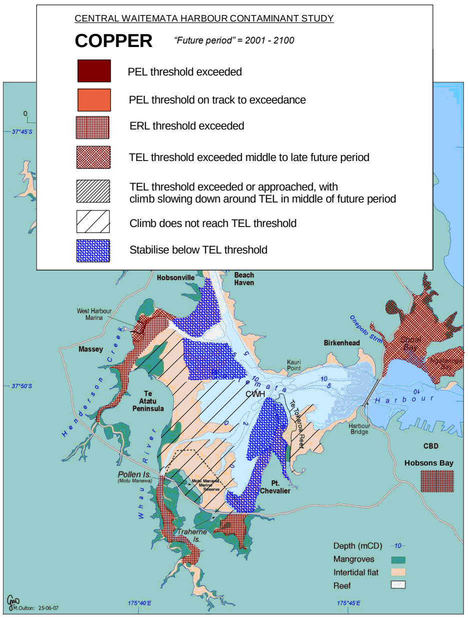
For the intertidal subestuaries in the main body of the harbour, which will remain depositional but with a decrease in sedimentation rate partway through the future period, zinc and copper concentrations do not stabilise when sediment run-off from the catchment reduces, although the rate at which they continue to climb drops significantly. As above, industrial roof source control has virtually no effect on the rise in zinc concentrations, and the more effective "moderate" stormwater treatment retards the accumulation of both zinc and copper compared to "no additional" stormwater treatment.

Finally, the sedimentation rate in Motions Creek subestuary under Scenarios 1 and 2 with "no additional" stormwater treatment reduces partway through the future period in response to the reduction in catchment sediment run-off. The rise in metal concentrations (zinc and copper) is retarded as a result, but not fully arrested. Under

Scenarios 3 and 4 with “moderate” stormwater treatment, Motions Creek subestuary becomes transportational in response to the reduction in catchment sediment run-off, and zinc and copper concentrations as a result are stabilised.

The times in the future at which sediment quality guideline threshold levels are predicted to be exceeded are tabulated. The zinc source control has virtually no effect on the zinc sediment-quality guideline threshold exceedance times. The more effective “moderate” stormwater treatment depicted in Scenarios 3 and 4 generally extends the zinc and copper threshold exceedance times by around 10 years or less compared to Scenarios 1 and 2 with the “no additional” stormwater treatment. However, it is also noteworthy that the more effective “moderate” stormwater treatment generally does not prevent any thresholds from being exceeded. That is, all subestuaries that exceed a threshold under the less effective “no additional” stormwater treatment exceed that same threshold (albeit a little later) under the more effective “moderate” stormwater treatment. Because of this, the schematic summaries of zinc and copper sediment-quality guideline threshold exceedances presented by Green (2008b) for Scenario 1 also apply to Scenarios 2, 3 and 4. These summaries are reproduced in Figure 20 and Figure 21 below (see Section 5):



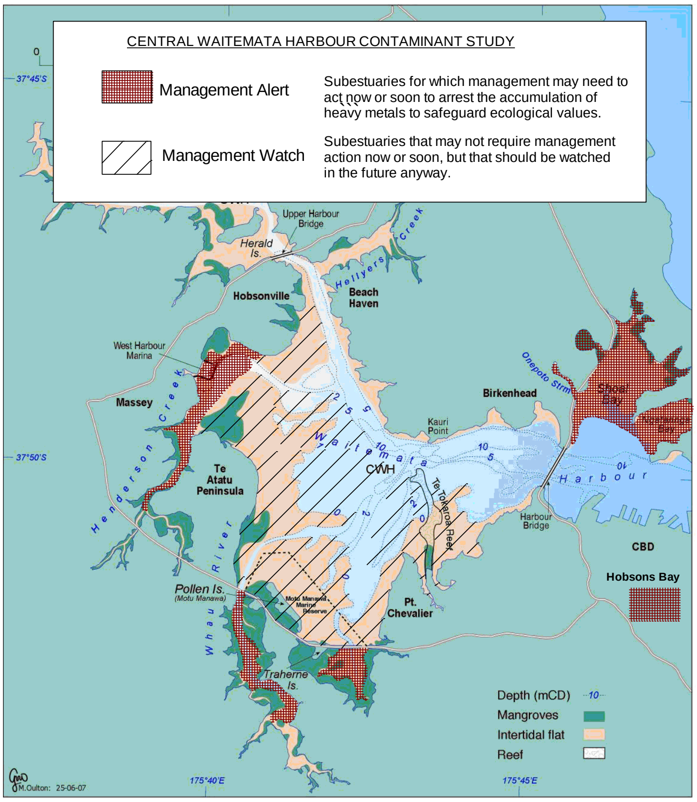


The analysis of Scenario 1 by Green (2008b) culminated in a high-level, simplified summary. In this view, subestuaries were classified as either “Management Alert” or “Management Watch”. The classification was based on zinc only, since zinc is predicted to accumulate in greater concentrations than copper.

- Subestuaries assigned to Management Alert are the tidal creeks around the fringes of the harbour (Henderson Creek and the associated Limeburners Bay, Whau River, Waterview Embayment), Shoal Bay and Hobsons Bay. Management may need to act now or soon to arrest the accumulation of heavy metals to safeguard ecological values in these subestuaries. The rationale is that ERL (Effects Range Low) thresholds either already have been or soon will be exceeded, and in some cases PEL (Probable Effects Level) thresholds will be exceeded.

- Management Watch includes all the other subestuaries in the harbour. These may not require management action now or soon, but they should be watched in the future anyway. The rationale is that the TEL (Threshold Effects Level) threshold is either not predicted to be exceeded or, if it is, it will be exceeded decades into the future, in many cases when the rate at which metals are building up is reducing anyway.

Green's (2008b) high-level summary for Scenario 1, which is captured in the figure below (Figure 22, Section 5), also applies to Scenarios 2, 3 and 4.



2 Introduction

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

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

2.1 Study aims

The study aims to:

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

2.2 Model suite

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

- The GLEAMS sediment-generation model, which predicts sediment erosion from the land and transport down the stream channel network. Predictions of sediment supply are necessary because, ultimately, sediment eroded from the land dilutes the concentration of contaminants in the bed sediments of the harbour, making them less harmful to biota[1].
- The CLM contaminant/sediment-generation model, which predicts sediment and contaminant concentrations (including zinc, copper) in stormwater at a point source, in urban streams, or at end-of-pipe where stormwater discharges into the receiving environment.
- The USC-3 (Urban Stormwater Contaminant) contaminant/sediment accumulation model, which predicts sedimentation and accumulation of contaminants (including zinc, copper) in the bed sediments of the estuary. Underlying the USC-3 model is yet another model: an estuarine sediment-transport model, which simulates the dispersal of contaminants/sediments by physical processes such as tidal currents and waves.

2.3 This report

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

The model, which functions as a decision-support scheme, predicts sedimentation and accumulation of contaminants (including zinc and copper) in the bed sediments of estuaries on the "planning timescale", which is decades and greater.

The predictions reported herein are the culmination of the study. Table 1 shows the scenarios for which predictions are to be made, where scenarios differ by zinc source control applied industrial roofs in urban areas, and stormwater treatment applied in urban areas.

The four scenarios are:

1. Scenario 1 is the existing scenario and includes all existing stormwater treatment such as catchpits for all roads, all urban paved and all pervious surfaces; ponds for commercial and industrial construction sites; and specific installed devices.
2. Scenario 2 is the source-control scenario and includes the existing stormwater treatment from Scenario 1 plus painting of presently-unpainted galvanised steel roofs on industrial buildings.

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

3. Scenario 3 applies moderate additional stormwater treatement and includes the existing stormwater treatment from Scenario 1 plus raingardens (in addition to catchpits) for all roads carrying >20,000 vpd; hay bales and silt fences (in addition to catchpits) for residential infill construction sites; raingardens or multimedia filters (in addition to catchpits) for industrial paved surfaces; and pond/wetland systems for treating 20% of the stormwater in each Stormwater Management Unit.
4. Scenario 4 is a combination of Scenario 2 and Scenario 3.

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

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

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

- 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) run-off, and urban (as opposed to rural) sediment run-off.
- The "no additional" stormwater treatment modelled in Scenarios 1 and 2 consists of specific stormwater treatment devices (data provided by Auckland, Waitakere and North Shore City Councils) 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 "moderate" stormwater treatment modelled in Scenarios 3 and 4 includes the treatment in Scenarios 1 and 2 plus: rain gardens or multimedia filters on all large roads (>20,000 vehicles per day); silt fences or similar on all residential infill construction sites; rain gardens 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. To keep this clear, the source control will be referred to throughout this report as "Painting IGSR".

Further details of scenarios are provided in Timperley and Reed (2008a).

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

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

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

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

The USC-3 model requires as inputs:

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

Parameters required by the model include:

- bed-sediment mixing depth in the harbour; and
- bed-sediment active layer thickness in the harbour.

Patterns of sediment transport and deposition in the harbour, including the way land-derived sediments are discharged and dispersed in the harbour during and following rainstorms, need to be known.

Model initial conditions include:

- present-day particle size distribution of harbour bed sediments; and
- present-day metal concentrations on harbour bed sediments.

Assumptions need to be made regarding the association of heavy metals with sediment particulate matter.

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

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

The model has been calibrated against annual-average sedimentation rates in the harbour and metal concentrations in harbour bed sediments (Green, 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 sub-catchments on a similar scale. Each sub-catchment discharges through one outlet to the harbour.

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

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

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

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

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

- Determine from the model predictions the relative contributions of sediment and contaminant from individual sub-catchments and local authorities.
- 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 sub-catchments and various subestuaries each time it rains (according to the rules), and between the various subestuaries to account for the action of waves of tidal currents (again, according to the rules).

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

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

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

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

For example, the erosion rate is determined by a weighted-mean particle size of the bed sediment that reflects the combined presence of the constituent particle sizes. This has a profound consequence: if the weighted-mean particle size of the bed sediment increases, it becomes more difficult to erode, and so becomes "armoured" as a whole. This reduces the erosion of **all** of the constituent particle sizes, including the finer fractions, which otherwise might be very mobile.

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

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

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

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

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

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

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

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

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

3.2.1 Comparison with the USC-2 model

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

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

3.3 Model details

Model details have been given in Green (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 the Central Waitemata Harbour 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 sub-catchments, specifying the weather time series used to drive the model, defining the way land-derived sediments and associated heavy metals are to be fed into the harbour at the sub-catchment outlets, evaluating the various terms that control sediment and associated heavy-metal transport and deposition inside the harbour, defining the way heavy-metal concentration in the estuarine bed-sediment surface mixed layer is to be evaluated, and specifying the mixing depth. Other information required to drive the model, including harbour bed-sediment initial conditions (eg, particle size, metal concentration in the surface mixed layer) and sub-catchment sediment and metal loads, varies depending on the particular scenario being addressed. This information is not treated as part of the model implementation; instead, it is reported where the scenario model runs are reported.

Some useful information is now recapped.

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

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

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

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

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

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

Five subestuaries are designated as deep channels. Since sediment is not allowed to deposit in or erode from deep channels, predictions of sediment and contaminant accumulation are not made in these subestuaries. Green (2008a) provides further justification and discussion of this designation.

Figure 1

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

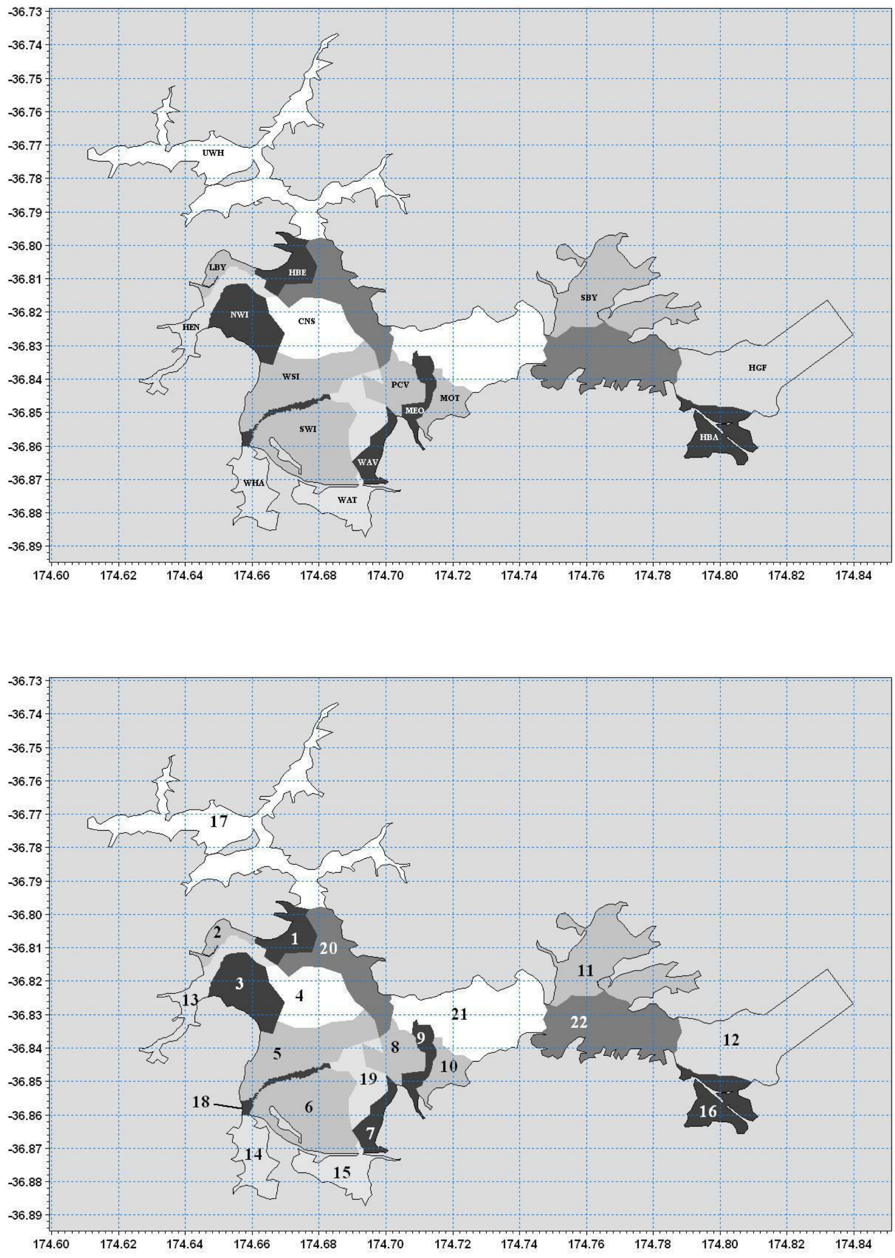


Table 2
Characteristics of subestuaries for the purposes of application of the USC-3 model. The area shown in the table is the total subestuary area.

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

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

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

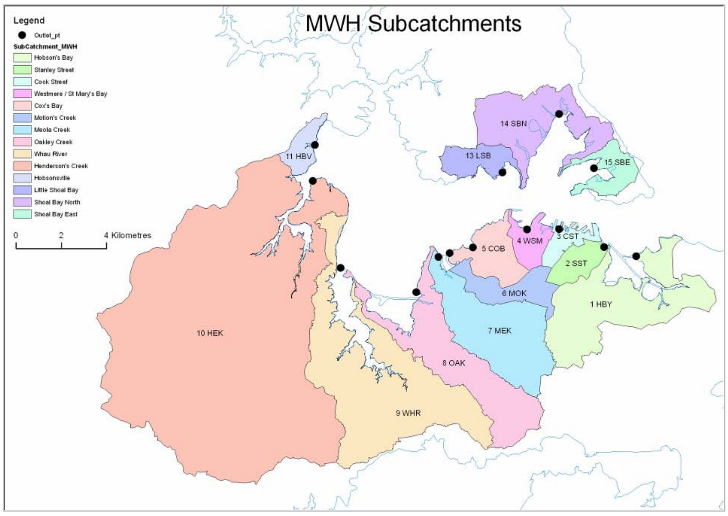


Table 3
Division of the catchment of the Central Waitemata Harbour into sub-catchments for the purposes of application of the USC-3 model.

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

The GLEAMS model provides daily land-derived sediment loads at the bottom of each sub-catchment split by constituent particle size. For this implementation, GLEAMS predicts sediments from all of the rural areas in each sub-catchment. Hence, "GLEAMS sediments" is synonymous with "sediments from sources in rural areas". Even though the daily GLEAMS timestep matches the one-day timestep in the USC-3 model associated with injection of land-derived material into the harbour, there is still some manipulation required to assemble these loads for input into the USC-3 model. This is done with a "random block sampling" scheme, which is intended to capture the effects on sediment generation of antecedent rainfall and rainfall intensity on the day of generation, both of which can create large variability in the response of the catchment to rainfall.

The CLM model predicts annual urban sediment loads, split by constituent particle size, that derive from all of the urban areas in each sub-catchment. Hence "CLM sediments" is synonymous with "sediments from sources in urban areas". The urban (CLM) sediment loads need to be added to the rural (GLEAMS) sediment loads, but because the annual timestep of the CLM does not match the daily timestep in the USC-3 model associated with injection of land-derived material into the harbour, the CLM loads need to be further manipulated before they can be added to the GLEAMS loads and used in the USC-3 model. Each annual load of urban sediment is fully distributed over the days in that year such that no part of the annual load is "carried over" into a succeeding year. Specifically, the annual urban load emanating from each sub-catchment is broken down into daily loads over that same year in proportion to the daily GLEAMS sediment loads.

The CLM also provides annual anthropogenic metal (zinc and copper) loads at the bottom of each sub-catchment, split by sediment constituent particle size that carries the load. Because the annual timestep of the CLM does not match the daily timestep in the USC-3 model associated with injection of land-derived material into the harbour, these loads need to be further manipulated before they can be used in the USC-3 model. Each annual anthropogenic load of metal is fully distributed over the days in that year such that no part of the annual load is "carried over" into a succeeding year. Specifically, the annual anthropogenic metal load emanating from each sub-catchment is broken down into daily loads over that same year in proportion to the daily GLEAMS sediment loads. Using this scheme, the annual-average concentration (mass of metal per mass of sediment) at which anthropogenic heavy metals are carried to the harbour will vary from year-to-year, since the annual anthropogenic heavy metal load may vary independently of the annual sediment load.

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

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

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

Mixing on the one hand moves sediments (and attached heavy metals) near the surface of the sediment column deeper into the sediment column, and on the other hand moves sediments deeper in the sediment column towards the surface. Mixing therefore has the net effect of reducing gradients in heavy-metal concentrations in the bed sediment. For example, a recently deposited layer carrying heavy metals at a concentration greater than in the underlying bed sediment will get mixed downwards, obliterating the concentration gradient between the recently deposited layer and the underlying bed sediment, and slightly raising the concentration in the mixed layer (which now includes the recently deposited layer) as a whole. If the recently deposited layer carries metal at a concentration less than the underlying bed sediment, then concentration in the mixed layer will be reduced. For the application of the USC-3 model in the Central Waitemata Harbour, mixing acts uniformly over a depth of 5 cm, which is based, primarily, on radioisotopic and x-ray analysis of sediment cores reported by Swales et al. (2008).

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

The model is run by time series of daily sediment and metal run-off from the catchment, and daily rainfall and wind. To ensure that extreme sediment-generation events get captured in the USC-3 model, it is run in a “Monte Carlo package”. Specifically, the USC-3 model is run N times to create N sets of predictions for the 100-year future period, where N is of the order 10^2. The N sets of predictions are averaged to give one set of “average” predictions for the future period, and it is these average predictions that are reported here.

3.5 Model behaviour

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

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

3.6 Model calibration

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

Model calibration was achieved by running the model for the historical period 1940 to 2001, with sediment and metal (zinc, copper) inputs from the catchment appropriate to that period. The aim of the calibration process was to adjust various terms in the USC-3 model so that its hindcasts ("backward-looking predictions") during the historical period came to match observations from that same period.

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

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

4 Model Predictions – Scenarios 2, 3 and 4

Scenarios 2, 3 and 4 all address future population growth and urban development in the catchment of the Central Waitemata Harbour. 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) run-off, and urban (as opposed to rural) sediment run-off, both of which are predicted by the Contaminant Load Model (CLM). Full details of how urban areas are depicted in each scenario are provided in Timperley and Reed (2008a).

A handy summary of the way scenarios differ from each other is given in Table 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 Land use

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

4.2 Sediment inputs

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

- The GLEAMS predictions of rural sediment run-off for the future period are presented in detail by Parshotam (2008). For these predictions, GLEAMS used the future-period land use data described in Parshotam and Wadhwa (2008a). The implementation of GLEAMS for the Central Waitemata Harbour Study is documented by Parshotam and Wadhwa (2008b). Note that the rural sediment run-off is the same under all scenarios (1, 2, 3 and 4), because the scenarios differ only by urban zinc source control and stormwater treatment (Table 1), neither of which affects rural sediment run-off.
- The CLM predictions of urban sediment run-off for the future period, which do vary by scenario, are presented in detail by Timperley and Reed (2008a). For these predictions, the CLM used the future-period land use data described in Parshotam and Wadhwa (2008a). The implementation of the CLM for the Central Waitemata Harbour Study is documented by Timperley and Reed (2008b).

4.2.1 Sediment inputs from rural sources

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

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

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

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

4.2.2 Sediment inputs from urban sources

For each scenario, 50 time series, each covering the future period 2001–2100, of daily urban sediment run-off from each sub-catchment are required (as before, one time series for each USC model run in the Monte Carlo package).

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

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

4.2.3 Sediment inputs from the Upper Waitemata Harbour

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

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

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

4.2.4 Total (rural plus urban) sediment inputs

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

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

Figure 3 shows the annual sediment run-off under all scenarios.

- The sediment run-off under Scenario 2 is identical to the sediment run-off under Scenario 1, since these scenarios have the same stormwater treatment. Likewise, the sediment run-off under Scenario 4 is identical to the sediment run-off under Scenario 3, since these scenarios have the same stormwater treatment.

Referring to Figure 3, for all scenarios:

- For all sub-catchments except sub-catchment 10 – HEK (Henderson Creek), the sediment run-off from rural sources is a very small fraction of the total sediment run-off. This trend developed during the historical period (1940 to 2001; reported in Green, 2008a), which showed the proportion of the total sediment run-off from rural sources decreasing over time in the historical period, and the proportion of the sediment run-off from urban sources correspondingly increasing. This, of course, reflects the increasing urbanisation of the catchment over time.

- For sub-catchment 10 – HEK (Henderson Creek), which is the principal source of sediment to the harbour, rural sources still constitute a significant fraction of the total sediment run-off.

- Sediment loads from the Upper Waitemata Harbour (12 – UWH) are relatively more significant in the future period than they were in the historical period. This may be due to the lag in urbanisation of the catchment surrounding the Upper Waitemata Harbour compared to urbanisation of the catchment of the Central Waitemata Harbour.

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

Table 6 shows the total (urban plus rural) sediment run-off under each scenario.

- The sediment run-off under Scenario 1 is identical to the sediment run-off under Scenario 2. This is expected since these scenarios have the same stormwater treatment (different stormwater treatment would have caused different urban sediment run-off). Note that these scenarios do have different zinc source control applied to industrial roofs in urban areas, but this does not affect urban sediment generation.

- The sediment run-off under Scenario 3 is identical to the sediment run-off under Scenario 4, and the sediment run-off under both of these scenarios is, in turn, smaller than the sediment run-off under Scenarios 1 and 2. This is expected since Scenarios 3 and 4 have the same stormwater treatment (so-called "moderate" – see Table 1) which in turn is more effective than the stormwater treatment under Scenarios 1 and 2 (so-called "no additional" – see Table 1).

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

Figure 4 shows just the annual urban sediment run-off under each scenario. This confirms that the scenarios differ by urban sediment run-off.

4.3 Metal inputs

4.3.1 Natural metal inputs

Table 7 shows the concentration at which zinc is carried on soils in the sub-catchments of the Central Waitemata Harbour, which is taken from Reed (2007). Table 8 shows the concentration at which copper is carried on soils in the sub-catchments of the Central Waitemata Harbour, also from Reed (2007).

To calculate daily inputs of natural metals to the harbour:

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

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

4.3.2 Anthropogenic metal inputs

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

Figure 5 shows the anthropogenic zinc run-off, and Table 9 shows how the zinc run-off is carried on the sediment constituent particle sizes.

Figure 6 shows the anthropogenic copper run-off, and Table 10 shows how the copper run-off is carried on the sediment constituent particle sizes.

- Note that copper run-off is shown only for Scenario 1 and Scenario 3. This is because Scenario 2 differs from Scenario 1, and Scenario 4 differs from Scenario

3, only by zinc source control, which does not affect copper generation. This means, in effect, there is no Scenario 2 or 4 for copper.

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

4.3.3 Metal inputs from the Upper Waitemata Harbour

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

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

4.3.4 Total (anthropogenic plus natural) metal inputs

As explained in Green (2008b), each annual anthropogenic load of metal is fully distributed over the days in that year such that no part of the annual load is "carried over" into a succeeding year. Specifically, the annual anthropogenic heavy-metal load emanating from each sub-catchment is broken down into daily loads over that same year in proportion to the daily GLEAMS sediment loads.

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

For zinc (Table 11):

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

- Zinc run-off under Scenario 2 is only very slightly smaller than under Scenario 1, which indicates that the zinc source control applied in Scenario 2 is not very effective. (Likewise, zinc run-off under Scenario 4 is only very slightly smaller than under Scenario 3. This is expected, since the zinc source control applied in Scenario 4 is the same source control applied in Scenario 2.) The zinc source control modelled in Scenarios 2 and 4 is painting of industrial galvanised steel roofs. The reason that this is not very effective is that industrial roofs contribute only a minor proportion of the zinc generated by roof run-off. By 2025 all industrial galvanised steel roofs will disappear anyway, to be replaced by zincalume roofs, after which time this method of source control as a result becomes irrelevant. Further details are provided in Timperley and Reed (2008a).
- On the other hand, zinc run-off under Scenarios 3 and 4 is significantly smaller than under Scenarios 1 and 2. This is because the "moderate" stormwater treatment applied in Scenarios 3 and 4 is more effective than the "no additional" stormwater treatment applied in Scenarios 1 and 2. The "moderate" stormwater treatment is applied to run-off from "large" roads (>20,000 vehicles per day), which are a major source of zinc. Further details are provided in Timperley and Reed (2008a).
- Note that the urban sediment removed by stormwater treatment also holds natural zinc. Hence, stormwater treatment removes both anthropogenic and natural zinc. In the least urbanised sub-catchment (Henderson Creek), more of the total zinc load under Scenario 3 is natural compared to under Scenario 1, indicating that proportionately more anthropogenic zinc is removed by the improved stormwater treatment. In some of the highly urbanised sub-catchments, the opposite is true.

For copper (Table 12):

- Under all scenarios, sub-catchment 10 – HEK (Henderson Creek) and sub-catchment 9 – WHR (Whau River) are the principal sources of copper to the harbour. Sub-catchment 8 – OAK (Oakley Creek) and sub-catchment 14 – SBN (Shoal Bay North) contribute the next largest loads.
- Under all scenarios, the proportion of the total copper load that is due to natural sources is typically slightly greater than the proportion of the total zinc load that is due to natural sources. For sub-catchment 10 – HEK (Henderson Creek), which is the largest source of copper and sediment to the harbour, anthropogenic copper makes up 76 % of the total load. For all other sub-catchments the proportion is greater than 90 %.
- Copper run-off under Scenario 3 is significantly smaller than under Scenario 1. This is because the "moderate" stormwater treatment applied in Scenario 3 is more effective than the "no additional" stormwater treatment applied in Scenario 1. The "moderate" stormwater treatment is applied to run-off from "large" roads (>20,000 vehicles per day), which are a major source of copper. Further details are provided in Timperley and Reed (2008a).

- Note that the urban sediment removed by stormwater treatment also holds natural copper. Hence, stormwater treatment removes both anthropogenic and natural copper. In the least urbanised sub-catchment (Henderson Creek), more of the total copper load under Scenario 3 is natural compared to under Scenario 1, indicating that proportionately more anthropogenic copper is removed by the improved stormwater treatment. In some of the highly urbanised sub-catchments, the opposite is true.

4.4 Concentration at which metals are delivered to the harbour

The concentrations at which total (anthropogenic plus natural) metals are delivered to the harbour over the future period are shown in Figures 7 and 8.

Under Scenarios 2, 3 and 4, concentrations of total (anthropogenic plus natural) zinc generally decrease for the first 15–20 years into the future period, and then they approximately level off. This was also the case under Scenario 1. The trend is driven primarily by a decrease in anthropogenic zinc loads (Figure 5)[2], although there is also a decrease in total sediment loads around that same time (Figure 3), which slows the decrease in metal concentrations that would have occurred if the sediment loads had not also reduced. As was the case with Scenario 1, the decrease in total sediment loads will also be seen (below) to have a significant effect on sedimentation rates.

In contrast, under Scenario 3 the concentrations of total (anthropogenic plus natural) copper generally increase steadily from 2001, reflecting an increase in anthropogenic copper loads over the future period (Figure 6)[3]. This was also the case for Scenario 1. The increase in copper loads combines with the decrease in sediment loads, to accelerate the change in concentration.

In both cases (that is, zinc and copper), the concentrations at which total metals are predicted to be delivered to the harbour over the future period under all scenarios are much higher than the present-day concentrations in the estuarine bed sediments. Mixing will retard the rise in metal concentrations in the estuarine bed sediments, thus conferring an "inertia" to the system. This occurs through mixing of highly contaminated sediments that arrive during rainstorms from the catchment down into the "ballast" of less contaminated estuarine sediments, which has the effect of reducing metal concentrations in the surface mixed layer compared to the concentrations at which they left the catchment.

Figure 9 shows a comparison by scenario of the concentrations at which zinc will be delivered to the harbour over the future period.

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

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

- For most sub-catchments the concentration is reduced in Scenario 2 compared to Scenario 1, but only for a time and only by less than 10 %. The reduction is due entirely to the zinc source control (painting of industrial galvanised steel roofs) applied in the CLM, since the sediment run-off under these two scenarios is identical (both scenarios have the same level of stormwater treatment, ie, "no additional"). The reduction in concentration only for a short time early in the future period is consistent with the expected disappearance of those same roofs by 2025, explained previously.
- Comparison of Scenario 3 with Scenario 1 sees an increase in concentration at which zinc is delivered to the harbour in some sub-catchments and a decrease in concentration in others. The increase in concentration occurs where the "moderate" stormwater treatment applied in Scenario 3 removes proportionately more sediment than zinc compared to the "no additional" stormwater treatment in Scenario 1. On the other hand, the decrease in concentration occurs where the "moderate" stormwater treatment removes proportionately less sediment than zinc compared to the "no additional" stormwater treatment. At this point it is not clear how zinc concentrations in the harbour will behave in response to these mixed increases and decreases of concentration in the various sub-catchment discharges. However, it is noteworthy in this regard that the concentration decreases in the discharge from Henderson Creek sub-catchment, which is the largest supplier of sediment and zinc to the harbour. This may dominate the harbour response.
- Comparison of Scenario 4 with Scenario 1 yields very nearly the same picture as the comparison of Scenario 3 with Scenario 1. This is expected, since Scenario 4 zinc run-off is only slightly less than Scenario 3 zinc run-off (Scenario 4 has zinc source control and Scenario 3 does not), and the sediment run-off under these two scenarios is identical.
- Finally, the comparison of Scenario 4 with Scenario 3 is very nearly the same as the comparison of Scenario 2 with Scenario 1. This is expected since Scenario 4 differs from Scenario 3, and Scenario 2 differs from Scenario 1, by the same zinc source control of industrial roofs.

Figure 10 shows a comparison by scenario of the concentrations at which copper will be delivered to the harbour over the future period.

- The comparison of copper Scenario 3 with copper Scenario 1 is very similar to the comparison of zinc Scenario 3 with zinc Scenario 1, and for the same reasons. That is, there is a mixture of increases and decreases in copper concentration across the sub-catchments; the differences are due entirely to the different stormwater treatments; and it is not clear at this point how the harbour will respond. As was the case with zinc, it is noteworthy that the concentration decreases in the discharge from Henderson Creek sub-catchment, which is the largest supplier of sediment and copper to the harbour. This may dominate the harbour response.

To sum up what is shown in Figure 9 and 10: zinc source control of industrial roofs and stormwater treatment combine in some sub-catchments and under some scenarios to decrease the concentration at which metals will be delivered to the harbour compared to Scenario 1, and in other sub-catchments and under other scenarios the delivery concentrations are increased. Hence, it is not possible to always know *a priori* how zinc source control and stormwater treatment will change metal concentrations in the Central Waitemata Harbour compared to Scenario 1. That is, they may be better or worse under the other scenarios.

4.5 Estuarine bed sediments at the start of the future period

The split of the bed sediment amongst the constituent particle sizes and the metal concentrations in the surface mixed layer of each subestuary need to be specified at the start of the future period. These constitute the USC-3 model initial conditions. The way the initial conditions were specified for Scenario 1 is explained in Green (2008b). Exactly the same initial conditions were used for Scenarios 2, 3 and 4.

4.6 Results

4.6.1 Patterns of sediment and contaminant dispersal

4.6.1.1 Fate

The fate of sediments from each sub-catchment is substantially the same as that described by Green (2008b) for Scenario 1, which in turn is substantially the same as that described by Green (2008b) for the historical period, 1940–2001. This is not surprising, as the fate of sediments depends to a large extent on circulation patterns in the harbour, which are not expected to change between the historical and future periods, and amongst the various future-period scenarios. A detailed discussion of sediment fate is provided by Green (2008b) for Scenario 1.

The fate of zinc and copper mirrors almost exactly the fate of sediment. This is not surprising, since zinc and copper are carried (in the model) by sediments.

4.6.1.2 Origin

The origin of sediment and contaminant deposited in each subestuary is also substantially the same as that described in Green (2008b) for Scenario 1.

4.6.2 Sedimentation

The predicted sedimentation rate in each subestuary is shown in Table 13, organised by "no additional" stormwater treatment (Scenarios 1 and 2) and "moderate" stormwater treatment (Scenarios 3 and 4).

The harbour-wide pattern of sedimentation for Scenarios 2, 3 and 4 is substantially the same as that described for Scenario 1 by Green (2008b). That description is now recapped here.

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

The sedimentation rates predicted for the future period (Table 13) show the same patterns that were observed by Swales et al. (2008) and hindcast by Green (2008b) for the 1940–2001 historical period.

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

- Finally, the predicted sedimentation rates in the three tidal creeks (Henderson Creek, Whau River and Hobsons Bay) exceeded the predicted sedimentation rates at all places outside of the tidal creeks. This concurs with previous observations of sedimentation in tidal creeks in the Auckland region (eg, Vant et al. 1993; Oldman and Swales, 1999; Swales et al. 1997; Swales et al. 2002).

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

Green's (2008b) predicted sedimentation rates for the future period under Scenario 1 were smaller (by about one half or more) than the hindcast sedimentation rates for the historical period. Green (2008b) explained that this was due to a reduction in sediment run-off in the future period under Scenario 1, which in turn was due to increasing urbanisation that "hardens" the landscape. That same reduction in sediment run-off relative to the historical period also occurs under Scenarios 2, 3 and 4.

The "moderate" stormwater treatment is seen to reduce sedimentation rates in the harbour by about 10 % compared to the "no additional" stormwater treatment (Table 13). This is an interesting result, as the sediment run-off is reduced by much more than that in most sub-catchments (see Table 6, the column headed "S3/S1"). This apparent anomaly is explained by the fact that Henderson Creek sub-catchment is, by far, the largest source of sediment to the harbour (see Table 6), and the "moderate" stormwater treatment in that sub-catchment only reduces the sediment run-off to 96 % of the "no additional" treatment run-off. Sediment run-off is not changed at all in the catchment of the Upper Waitemata Harbour by the more effective stormwater treatment, which is the second largest supplier of sediment to the Central Waitemata Harbour. Furthermore, sediment run-off from the Whau River sub-catchment (the third largest supplier of sediment to the CWH) under the "moderate" stormwater treatment is 90 % of the sediment run-off under the "no additional" treatment. Hence, the harbour-wide reduction in sedimentation of about 10 % roughly reflects the reduction in sediment run-off achieved by the extra stormwater treatment in the sub-catchments that are the main suppliers of sediment to the CWH. This makes sense.

The sedimentation rate over the future period is shown in Figure 11, organised by "no additional" stormwater treatment (Scenarios 1 and 2) and "moderate" stormwater treatment (Scenarios 3 and 4). The purpose of this figure is to show an important detail: sedimentation rates drop, and in some cases reverse (the subestuary erodes) 15–25 years into the future period. This was also noted by Green (2008b) in the analysis of the Scenario 1 predictions, and was attributable to a corresponding decrease in sediment run-off over the next 15–20 years, which occurs as urbanisation proceeds and rural sources of sediment, primarily in the Henderson Creek sub-catchment, correspondingly decline (see Figure 3).

Green (2008b) provided a detailed discussion of the predicted sedimentation rates for Scenario 1, which corresponds to "no additional" stormwater treatment. That discussion is now recapped here, with further comments on how the "moderate" stormwater treatment changes sedimentation.

- In the intertidal parts of the main body of the harbour (Northwestern Intertidal, Western Intertidal, Southwestern Intertidal subestuaries) under "no additional" stormwater treatment (Scenarios 1 and 2), sedimentation reduces at the time sediment run-off reduces, but remains positive thereafter until the end of the simulation. The reduction in sedimentation is greatest for the Western Intertidal subestuary – in fact, it nearly enters a new transportational (approximately zero sedimentation) regime. This subestuary lies between the respective outlets of the Henderson Creek and Whau River sub-catchments. Compared to that, the reduction in sedimentation is less for the Northwestern Intertidal subestuary, which is close to the outlet of the Henderson Creek sub-catchment, and the Southwestern Intertidal subestuary, which is close to the outlet of the Whau River sub-catchment. Sedimentation is reduced overall under the more effective "moderate" stormwater treatment (Scenarios 3 and 4). Note that, under the "moderate" stormwater treatment, the reduction of sedimentation in the Western Intertidal subestuary due to the reduction in sediment run-off over the next 15–20 years shifts that subestuary into a new transportational (approximately zero sedimentation) regime.
- The subtidal part of the main body of the harbour (Central Subtidal subestuary) under "no additional" stormwater treatment (Scenarios 1 and 2) experiences a reduction in sedimentation when sediment run-off reduces, after which a new transportational regime (approximately zero sedimentation) is established. The same happens under "moderate" stormwater treatment (Scenarios 3 and 4).
- For the subestuaries that lie to the west of Te Tokaroa reef in the transition between the throat and the main body of the harbour (Waterview Flats, Point Chevalier and Meola subestuaries) under "no additional" stormwater treatment (Scenarios 1 and 2), sedimentation goes negative (the subestuary erodes) when sediment run-off reduces until a new transportational regime is established. The same happens under "moderate" stormwater treatment (Scenarios 3 and 4).
- In contrast, for the Motions subestuary, which lies to the east of Te Tokaroa reef in the transition between the throat and the main body of the harbour, sedimentation declines significantly under "no additional" stormwater treatment (Scenarios 1 and 2) when sediment run-off reduces, but remains positive until the end of the simulation. Under "moderate" stormwater treatment (Scenarios 3 and 4), sedimentation is reduced when sediment run-off reduces to the point that a new transportational regime is established. This is an interesting result, which is explained as follows. Sediment that deposits in Motions Creek subestuary primarily comes from Coxs Bay (26 %) and Motions Creek (29 %) sub-catchments, with a lesser contribution from Henderson Creek sub-catchment (16 %) and the Upper Waitemata Harbour (14 %). The "moderate" stormwater treatment reduces sediment run-off to 88 % of "no additional" run-off from Coxs Bay sub-catchment and to 49 % of "no additional" run-off from Motions Creek sub-catchment (Table

6, column "S3/S1"). This results in decreased sedimentation over the duration of the simulation period of 71 % of the "no additional" sedimentation (Table 13). This is a greater reduction in sedimentation compared to subestuaries that are supplied with sediment principally from the Henderson Creek, Upper Waitemata Harbour and Whau River sub-catchments, where the sediment run-off reduces by about 10 % under "moderate" stormwater treatment.

- For the tidal creeks under "no additional" stormwater treatment (Scenarios 1 and 2), sedimentation is not obviously affected by the reduction in sediment run-off over the next 15–20 years, and sediment continues to accumulate. Sedimentation is reduced overall under the more effective "moderate" stormwater treatment (Scenarios 3 and 4).
- Sedimentation in Shoal Bay subestuary (11 – SBY) under "no additional" stormwater treatment (Scenarios 1 and 2) is also not obviously affected by the reduction in sediment run-off over the next 15–20 years. Sedimentation is reduced overall under the more effective "moderate" stormwater treatment (Scenarios 3 and 4).

Figures 12 and 13 summarise from the preceding discussion the change in sedimentation that is due to the reduction in sediment run-off from the catchment over the next 15–20 years. Green (2008b) noted that these changes in sedimentation will have profound effects on heavy-metal concentrations in the harbour in the future, for the following reasons. A reduction in sediment run-off from the land accompanied by an increase in heavy-metal run-off will obviously cause the concentration at which metals are delivered to the harbour to increase. As noted previously, this increase will drive a corresponding increase in metal concentration in the bed sediments of the harbour. However, and this is the point, this can only occur in those areas of the harbour where sediments (and attached metals) actually deposit. For subestuaries that become erosional (negative sedimentation) or transportational (zero sedimentation), metal concentrations will be unaffected by the changes in concentration at which metals are being delivered from the land. In essence, the reduction in sediment run-off causes the **behaviour** of these subestuaries to fundamentally change, that is, to switch from depositional to erosional/transportational. It is worth noting that in more sheltered harbours (such as the Upper Waitemata Harbour), where erosion of estuary bed sediments is never significant, this change in behaviour is not possible, and the metal concentration in the bed sediment is driven entirely by the disequilibrium between the concentration at which metals are delivered from the land and concentration at which metals are present in the bed sediments.

Figure 14 summarises from the preceding discussion the comparison of sedimentation under "no additional" stormwater treatment with sedimentation under "moderate" stormwater treatment.

4.6.3 Metal concentration in estuarine bed sediments

Figures 15 to 19 show the predicted change in metal concentration in the surface mixed layer of the estuarine bed sediments for the future period under all scenarios, including Scenario 1 (from Green, 2008b). These show the total metal concentration, which is defined as the metal carried on all sediment particle sizes divided by the total (sum of all particle sizes) sediment. Predicted metal concentrations are subestuary averages. In the main body of the harbour, concentrations will tend to be uniform across subestuaries, but in the side 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).

Green (2008b) showed that the change in metal concentrations through the future period is principally controlled by the sedimentation regime.

Green (2008b) also provided a detailed discussion of the predicted metal concentrations for Scenario 1, which corresponds to "no additional" zinc source control and "no additional" stormwater treatment. That discussion is now recapped here, with further comments relating to Scenarios 2, 3 and 4.

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

- Figure 15: Under all scenarios, zinc and copper concentrations in the bed sediments of the tidal creeks/sinks (Henderson Creek, Whau River, Waterview Embayment and Hobsons Bay subestuaries) rise continuously through the future period under a sedimentation rate that remains positive and virtually constant through the period. It is noteworthy that this continuous rise occurs for zinc, even though the concentration at which zinc is delivered to the harbour tends to stabilise around one-third of the way through the future period (Figure 7). This shows that zinc concentrations in the bed sediments of these subestuaries do not reach an equilibrium with the input zinc concentrations by the end of the future period. The concentration at which copper is delivered to the harbour does not stabilise in the future period (ie, it increases throughout the future; see Figure 8), hence copper concentrations cannot attain equilibrium. Source control is predicted to have virtually no effect on the rise in zinc concentrations (compare Scenario 2 with Scenario 1 and Scenario 4 with Scenario 3). This accords with Figure 9, which shows that zinc source control has only a minor effect on the concentration at which zinc is delivered to the harbour. Furthermore, the effect is only for a limited time. In contrast, the more effective "moderate" stormwater treatment retards the accumulation of both zinc and copper compared to "no additional" stormwater treatment (compare Scenario 3 with 1 and Scenario 4 with Scenario 2).
- Figure 15: Limeburners Bay subestuary, with a large sedimentation rate, acts like an extension of Henderson Creek subestuary. As a consequence, zinc and copper concentrations rise continuously throughout the future period. Zinc source control

has virtually no effect on the rise in zinc concentrations. In contrast, the more effective “moderate” stormwater treatment retards the accumulation of both zinc and copper compared to “no additional” stormwater treatment.

- Figure 15: Zinc and copper concentrations in Shoal Bay under a sedimentation rate that also remains positive and virtually constant throughout the future period behave in the same way as zinc and copper concentrations in the tidal creeks/sinks, and for the same reasons. So, zinc and copper concentrations both rise throughout the future period, and this occurs even though the concentration at which zinc is being delivered from the sub-catchment stabilises. As in the case of tidal creeks/sinks, this indicates that zinc concentration in the estuarine bed sediments does not equilibrate with the input concentration. Again, zinc source control has virtually no effect on the rise in zinc concentration. In contrast, the more effective “moderate” stormwater treatment retards the accumulation of both zinc and copper compared to “no additional” stormwater treatment.

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

- Figure 16: In Motions subestuary, which lies to the east of Te Tokaroa reef in the transition zone between the harbour throat and the main body of the harbour, zinc and copper concentrations under the “no additional” stormwater treatment (Scenarios 1 and 2) do not stabilise when sediment run-off from the catchment reduces 15–20 years into the future, although the rate at which they continue to climb drops significantly. This is due to the reduction in sedimentation rate (previously described): under the reduced sedimentation, mixing brings together proportionately more pre-existing sediment (with lower metal concentrations) with newly-deposited sediment (with higher metal concentrations) into the surface mixed layer, which retards the rise in metal concentration in the surface mixed layer. Under the “moderate” stormwater treatment (Scenarios 3 and 4), the subestuary becomes transportational (described previously: this is a response to reduced sediment inputs compared to “no additional” stormwater treatment). When the subestuary becomes transportational the zinc and copper concentrations stabilise , with even a slight sign of reversal. Zinc source control has virtually no effect on the rise in zinc concentrations.

- Figure 17: Under the “no additional” stormwater treatment (Scenarios 1 and 2), the rise in zinc and copper concentrations in the Northwestern Intertidal, Western Intertidal and Southwestern Intertidal subestuaries in the main body of the harbour: becomes retarded when the sedimentation rates drop, but because these subestuaries do not become transportational, that rise is not fully arrested. Under the “moderate” stormwater treatment (Scenarios 3 and 4), the Northwestern Intertidal and Southwestern Intertidal subestuaries remain depositional but with a reduced sedimentation rate, and the rise in zinc and copper concentrations is correspondingly retarded. The Western Intertidal subestuary becomes transportational under the “moderate” stormwater treatment, and the zinc and copper concentrations stabilise. Zinc source control has virtually no effect on the rise in zinc concentrations.

The following comments relate to subestuaries that become transportational partway through the future period:

- Figure 18: Zinc and copper concentrations in the subestuaries that are situated to the west of Te Tokaroa reef in the transition zone between the harbour throat and the main body of the harbour (Meola, Point Chevalier, Waterview Flats subestuaries) reach an equilibrium partway through the future period under the "no additional" stormwater treatment (Scenarios 1 and 2). This is a response to the change in sedimentation regime – from depositional to transportational – that also occurs at this time, and which in turn is a response to the reduction in sediment run-off from the catchment, as previously described. Although an equilibrium concentration is attained, in the sense that the concentration becomes steady, it is more the case that these subestuaries become "moribund" (or "stagnant") when deposition switches off. The "moderate" stormwater treatment (Scenarios 3 and 4) has no effect on the zinc and copper concentrations since the concentrations are stabilised – that is, not changeable – when the transportational regime is reached, which is before the "moderate" stormwater really starts to have an effect.

  Green (2008b) pointed out that it is noteworthy that, early in the future period, before going moribund, metal (both zinc and copper) concentrations in the Waterview Flats and Point Chevalier subestuaries rise at approximately the same rate as the metal concentrations in the Southwestern Intertidal subestuary (see Figure 18), which is adjacent to the west. In contrast, metal concentrations in the Meola subestuary rise at about the same rate as in Motions subestuary, which is adjacent to the east, before going moribund (also shown in Figure 18).

  Figure 18: The same thing occurs in the Central Subtidal subestuary, ie, metal concentrations stabilise when the subestuary becomes moribund under a change in sedimentation regime from depositional to transportational, which in turn is a response to the reduction in sediment run-off from the catchment. Prior to becoming moribund, metal concentrations tend to rise at about the same rate as in the Western Intertidal subestuary, which is adjacent. The "moderate" stormwater treatment has no effect, and neither does the zinc source control.

For Hobsonville subestuary, which had a doubtful (very small) predicted sedimentation rate, zinc and copper concentrations are predicted to rise only very slowly in the future period (Figure 19).

4.6.4 Exceedance of sediment-quality guideline threshold values

Tables 14 (Scenario 1), 15 (Scenario 2), 16 (Scenario 3) and 17 (Scenario 4) show a tabulation of the times at which sediment-quality guideline threshold values are predicted to be first exceeded in the future period. 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).

Tables 18 (a comparison of Scenario 3 with Scenario 1) and 19 (a comparison of Scenario 4 with Scenario 2) show that, generally, the exceedance of sediment-quality guideline thresholds is delayed somewhat under the "moderate" stormwater treatment compared to under the "no additional" stormwater treatment.

Tables 20 (a comparison of Scenario 2 with Scenario 1) and 21 (a comparison of Scenario 4 with Scenario 3) show that, generally, the exceedance of sediment-quality guideline thresholds is hardly changed by the zinc source control.

Green (2008b) noted that a more informed appreciation of threshold exceedances is to be gained by studying the predicted trends in metal concentrations (shown in this report in Figures 15 to 19) – understanding the trends provides the necessary context for interpreting the threshold exceedance times. Green (2008b) provided comments on Scenario 1, which are now recapped here. Following this, some comments on threshold exceedance under Scenarios 2, 3 and 4 will be made.

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

  ERL threshold exceedance tends to occur earlier in the case of the tidal creeks/sinks, which begin the future period with higher metal concentrations. In the case of the Henderson Creek and Whau River subestuaries, the future period began with the zinc and copper ERL thresholds already exceeded.

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

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

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

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

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

The "moderate" stormwater treatment in Scenario 3 delays the threshold exceedance times for zinc by around 10 years or less compared to Scenario 1 with the "no additional" stormwater treatment (see Table 18)[4]. The exception is the Western Intertidal subestuary, where the TEL exceedance is delayed by 25 years. This is rather misleading, however, since zinc concentrations actually stabilise right around the TEL concentration as the subestuary transitions from a depositional to a transportational regime. Waterview Embayment subestuary is the only subestuary where the threshold exceedance (in this case, ERL) time does not change under the more effective stormwater treatment. This exceedance time is only 15 years beyond 2001. The "moderate" stormwater treatment in Scenario 3 also delays the threshold exceedance times for copper by around 10 years or less compared to Scenario 1 with the "no additional" stormwater treatment (see Table 18). The Southwestern Intertidal subestuary does not exceed the TEL under the more effective stormwater treatment (although it is on track to exceed the TEL shortly past the end of the simulation), whereas it did exceed the TEL (86 years beyond 2001) under the less effective stormwater treatment. The ERL exceedance in Henderson Creek and Whau River subestuaries is unchanged by the more effective stormwater treatment – these exceedances occur early in the future period (10 years for Henderson Creek and 15 years for Whau River), before the stormwater treatment really takes effect.

[4] The comments that are about to be made apply equally to the comparison of Scenario 4 ("moderate" stormwater treatment) with Scenario 2 ("no additional" stormwater treatment) (see Table 19).

In contrast to the stormwater treatment, the zinc source control has virtually no effect on the zinc threshold exceedance times (Table 20 and Table 21).

Table 4

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

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

Table 5

Average (over the simulation and all scenarios) fraction of the urban sediment load assigned to each constituent particle size (12, 40, 125 and 180 μm), calculated by the CLM.

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

Table 6
Total (rural plus urban) sediment run-off, 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 the sediment run-off under Scenario 2 divided by the sediment run-off under Scenario 1, and so on.

	"No additional" stormwater treatment			"Moderate" stormwater treatment			
Sub-catchment	Scenario 1 (kg)	Scenario 2 (kg)	S2/ S1	Scenario 3 (kg)	S3/ S1	Scenario 4 (kg)	S4/ S1
1 – HBY	41,800,244	41,800,244	1.00	36,000,272	0.86	36,000,272	0.86
2 – SST	14,837,731	14,837,731	1.00	8,821,842	0.59	8,821,842	0.59
3 – CST	3,088,220	3,088,220	1.00	2,759,919	0.89	2,759,919	0.89
4 – WSM	13,919,330	13,919,330	1.00	8,054,465	0.58	8,054,465	0.58
5 – COB	16,392,245	16,392,245	1.00	14,437,755	0.88	14,437,755	0.88
6 – MOK	21,211,056	21,211,056	1.00	10,312,518	0.49	10,312,518	0.49
7 – MEK	27,221,628	27,221,628	1.00	23,734,494	0.87	23,734,494	0.87
8 – OAK	49,153,744	49,153,744	1.00	40,048,372	0.81	40,048,372	0.81
9 – WHR	100,566,352	100,566,352	1.00	90,627,952	0.90	90,627,952	0.90
10 – HEK	513,099,808	513,099,808	1.00	494,699,232	0.96	494,699,232	0.96
11 – HBV	9,916,956	9,916,956	1.00	7,847,275	0.79	7,847,275	0.79
12 – UWH	104,819,688	104,819,688	1.00	104,819,688	1.00	104,819,688	1.00
13 – LSB	10,314,576	10,314,576	1.00	9,374,302	0.91	9,374,302	0.91
14 – SBN	38,011,480	38,011,480	1.00	28,596,800	0.75	28,596,800	0.75
15 – SBE	9,438,470	9,438,470	1.00	8,341,710	0.88	8,341,710	0.88

Table 7

Concentration (mg kg^{-1}) at which zinc is carried on soils in the sub-catchments of the Central Waitemata Harbour, from Reed (2007).

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

Table 8

Concentration (mg kg^{-1}) at which copper is carried on soils in the sub-catchments of the Central Waitemata Harbour, from Reed (2007).

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

Table 9
Average (over the simulation and all scenarios) fraction of anthropogenic zinc load carried by each sediment constituent particle size (12, 40, 125 and 180 µm), predicted by the CLM.

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

Table 10

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

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

\implement\metal loads\future 1\Future loads from CLM.xls

Table 11
Total (anthropogenic plus natural) zinc run-off and how the total run-off is 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. "S2/S1" denotes Scenario 2 divided by Scenario 1, and so on.

Sum over simulation of anthropogenic zinc (kg)							
Stormwater treatment	"No additional"			"Moderate"			
Zinc source control	"No additional"	Painting IGSR		"No additional"		Painting IGSR	
Sub-catchment	Scenario 1	Scenario 2	S2/S1	Scenario 3	S3/S1	Scenario 4	S4/S3
1 – HBY	74,104	73,940	0.998	64,610	0.872	64,462	0.870
2 – SST	41,033	40,890	0.997	30,694	0.748	30,551	0.745
3 – CST	10,435	10,435	1.000	9719	0.931	9719	0.931
4 – WSM	46,220	45,872	0.992	33,919	0.734	33,572	0.726
5 – COB	26,856	26,765	0.997	23,365	0.870	23,274	0.867
6 – MOK	67,428	67,161	0.996	48,000	0.712	47,732	0.708
7 – MEK	46,150	46,010	0.997	40,128	0.870	39,988	0.866
8 – OAK	108,751	108,067	0.994	89,354	0.822	88,670	0.815
9 – WHR	174,029	173,309	0.996	154,131	0.886	153,477	0.882
10 – HEK	268,130	267,254	0.997	235,600	0.879	233,320	0.870
11 – HBV	17,626	17,626	1.000	14,792	0.839	14,792	0.839
12 – UWH	–	–	–	–	–	–	–
13 – LSB	17,390	17,358	0.998	15,837	0.911	15,804	0.909
14 – SBN	86,396	86,375	1.000	71,048	0.822	71,027	0.822
15 – SBE	19,188	19,123	0.997	16,987	0.885	16,921	0.882

Table 11 (cont.)

Total (anthropogenic plus natural) zinc run-off and how the total run-off is 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. "S2/S1" denotes Scenario 2 divided by Scenario 1, and so on.

Sum over simulation of total (anthropogenic plus natural) zinc (kg)							
Stormwater treatment	"No additional"			"Moderate"			
Zinc source control	"No additional"	Painting IGSR		"No additional"		Painting IGSR	
Sub-catchment	Scenario 1	Scenario 2	S2/S1	Scenario 3	S3/S1	Scenario 4	S4/S3
1 – HBY	76,888	76,725	0.998	67,008	0.871	66,860	0.870
2 – SST	42,375	42,232	0.997	31,492	0.743	31,349	0.740
3 – CST	10,714	10,714	1.000	9969	0.930	9969	0.930
4 – WSM	47,479	47,131	0.993	34,648	0.730	34,300	0.722
5 – COB	28,092	28,002	0.997	24,454	0.870	24,363	0.867
6 – MOK	69,778	69,510	0.996	49,142	0.704	48,874	0.700
7 – MEK	47,276	47,136	0.997	41,109	0.870	40,969	0.867
8 – OAK	112,089	111,404	0.994	92,073	0.821	91,389	0.815
9 – WHR	180,057	179,337	0.996	159,563	0.886	158,909	0.883
10 – HEK	298,885	298,009	0.997	265,302	0.888	262,972	0.880
11 – HBV	18,220	18,220	1.000	15,262	0.838	15,262	0.838
12 – UWH	70,970	70,970	1.000	70,970	1.000	70,970	1.000
13 – LSB	17,817	17,784	0.998	16,224	0.911	16,192	0.909
14 – SBN	87,967	87,946	1.000	72,230	0.821	72,209	0.821
15 – SBE	20,042	19,976	0.997	17,741	0.885	17,676	0.882

Table 11 (cont.)
Total (anthropogenic plus natural) zinc run-off and how the total run-off is 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. "S2/S1" denotes Scenario 2 divided by Scenario 1, and so on.

Fraction of total zinc due to anthropogenic							
Stormwater treatment	"No additional"			"Moderate"			
Zinc source control	"No additional"	Painting IGSR		"No additional"		Painting IGSR	
Sub-catchment	Scenario 1	Scenario 2	S2/S1	Scenario 3	S3/S1	Scenario 4	S4/S1
1 – HBY	0.96	0.96	1.00	0.96	1.00	0.96	1.00
2 – SST	0.97	0.97	1.00	0.97	1.01	0.97	1.01
3 – CST	0.97	0.97	1.00	0.97	1.00	0.97	1.00
4 – WSM	0.97	0.97	1.00	0.98	1.01	0.98	1.01
5 – COB	0.96	0.96	1.00	0.96	1.00	0.96	1.00
6 – MOK	0.97	0.97	1.00	0.98	1.01	0.98	1.01
7 – MEK	0.98	0.98	1.00	0.98	1.00	0.98	1.00
8 – OAK	0.97	0.97	1.00	0.97	1.00	0.97	1.00
9 – WHR	0.97	0.97	1.00	0.97	1.00	0.97	1.00
10 – HEK	0.90	0.90	1.00	0.89	0.99	0.89	0.99
11 – HBV	0.97	0.97	1.00	0.97	1.00	0.97	1.00
12 – UWH	–	–	–	–	–	–	–
13 – LSB	0.98	0.98	1.00	0.98	1.00	0.98	1.00
14 – SBN	0.98	0.98	1.00	0.98	1.00	0.98	1.00
15 – SBE	0.96	0.96	1.00	0.96	1.00	0.96	1.00

Table 11 (cont.)
Total (anthropogenic plus natural) zinc run-off and how the total run-off is 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. "S2/S1" denotes Scenario 2 divided by Scenario 1, and so on.

Fraction of total zinc due to natural							
Stormwater treatment	"No additional"			"Moderate"			
Zinc source control	"No additional"	Painting IGSR		"No additional"		Painting IGSR	
Sub-catchment	Scenario 1	Scenario 2	S2/S1	Scenario 3	S3/S1	Scenario 4	S4/S1
1 – HBY	0.04	0.04	1.00	0.04	0.99	0.04	0.99
2 – SST	0.03	0.03	1.00	0.03	0.80	0.03	0.80
3 – CST	0.03	0.03	1.00	0.03	0.96	0.03	0.96
4 – WSM	0.03	0.03	1.01	0.02	0.79	0.02	0.80
5 – COB	0.04	0.04	1.00	0.04	1.01	0.04	1.02
6 – MOK	0.03	0.03	1.00	0.02	0.69	0.02	0.69
7 – MEK	0.02	0.02	1.00	0.02	1.00	0.02	1.01
8 – OAK	0.03	0.03	1.01	0.03	0.99	0.03	1.00
9 – WHR	0.03	0.03	1.00	0.03	1.02	0.03	1.02
10 – HEK	0.10	0.10	1.00	0.11	1.09	0.11	1.10
11 – HBV	0.03	0.03	1.00	0.03	0.94	0.03	0.94
12 – UWH	–	–	–	–	–	–	–
13 – LSB	0.02	0.02	1.00	0.02	1.00	0.02	1.00
14 – SBN	0.02	0.02	1.00	0.02	0.92	0.02	0.92
15 – SBE	0.04	0.04	1.00	0.04	1.00	0.04	1.00

Table 12

Total (anthropogenic plus natural) copper run-off and how the total run-off is 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. "S2/S1" denotes Scenario 2 divided by Scenario 1, and so on.

	Sum over simulation of anthropogenic copper (kg)		
Stormwater treatment	"No additional"	"Moderate"	
Zinc source control	"No additional"		
Sub-catchment	Scenario 1	Scenario 3	S3/S1
1 – HBY	13,823	12,093	0.875
2 – SST	7409	5600	0.756
3 – CST	6003	5874	0.979
4 – WSM	7190	4902	0.682
5 – COB	5422	4737	0.874
6 – MOK	10,373	7181	0.692
7 – MEK	9264	8104	0.875
8 – OAK	18,654	14,906	0.799
9 – WHR	32,398	28,480	0.879
10 – HEK	49,708	43,714	0.879
11 – HBV	3373	2899	0.859
12 – UWH	–	–	–
13 – LSB	3385	3099	0.915
14 – SBN	14,942	12,482	0.835
15 – SBE	3895	3488	0.896

Table 12 (cont.)
Total (anthropogenic plus natural) copper run-off and how the total run-off is 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. "S2/S1" denotes Scenario 2 divided by Scenario 1, and so on.

	Sum over simulation of total (anthropogenic plus natural) copper (kg)		
Stormwater treatment	"No additional"	"Moderate"	
Zinc source control	"No additional"		
Sub-catchment	Scenario 1	Scenario 3	S3/S1
1 – HBY	14,591	12,754	0.874
2 – SST	7,825	5,848	0.747
3 – CST	6,089	5,952	0.977
4 – WSM	7,580	5,128	0.676
5 – COB	5,800	5,070	0.874
6 – MOK	11,117	7,543	0.678
7 – MEK	9,533	8,338	0.875
8 – OAK	20,612	16,502	0.801
9 – WHR	35,506	31,280	0.881
10 – HEK	65,563	59,026	0.900
11 – HBV	3,680	3,141	0.854
12 – UWH	7,659	7,659	1.000
13 – LSB	3,487	3,192	0.915
14 – SBN	15,317	12,764	0.833
15 – SBE	4,159	3,722	0.895

Table 12 (cont.)

Total (anthropogenic plus natural) copper run-off and how the total run-off is 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. "S2/S1" denotes Scenario 2 divided by Scenario 1, and so on.

	Fraction of total copper due to anthropogenic		
Stormwater treatment	"No additional"	"Moderate"	
Zinc source control	"No additional"		
Sub-catchment	Scenario 1	Scenario 3	S3/S1
1 – HBY	0.95	0.95	1.00
2 – SST	0.95	0.96	1.01
3 – CST	0.99	0.99	1.00
4 – WSM	0.95	0.96	1.01
5 – COB	0.93	0.93	1.00
6 – MOK	0.93	0.95	1.02
7 – MEK	0.97	0.97	1.00
8 – OAK	0.91	0.90	1.00
9 – WHR	0.91	0.91	1.00
10 – HEK	0.76	0.74	0.98
11 – HBV	0.92	0.92	1.01
12 – UWH	–	–	–
13 – LSB	0.97	0.97	1.00
14 – SBN	0.98	0.98	1.00
15 – SBE	0.94	0.94	1.00

Table 12 (cont.)

Total (anthropogenic plus natural) copper run-off and how the total run-off is 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. "S2/S1" denotes Scenario 2 divided by Scenario 1, and so on.

	Fraction of total copper due to natural		
Stormwater treatment	"No additional"	"Moderate"	
Zinc source control	"No additional"		
Sub-catchment	Scenario 1	Scenario 3	S3/S1
1 – HBY	0.05	0.05	0.99
2 – SST	0.05	0.04	0.80
3 – CST	0.01	0.01	0.91
4 – WSM	0.05	0.04	0.86
5 – COB	0.07	0.07	1.01
6 – MOK	0.07	0.05	0.72
7 – MEK	0.03	0.03	1.00
8 – OAK	0.09	0.10	1.02
9 – WHR	0.09	0.09	1.02
10 – HEK	0.24	0.26	1.07
11 – HBV	0.08	0.08	0.93
12 – UWH	–	–	–
13 – LSB	0.03	0.03	0.99
14 – SBN	0.02	0.02	0.90
15 – SBE	0.06	0.06	0.99

Table 13
Predicted sedimentation rate in each subestuary 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^{-1}	"Moderate" stormwater treatment (Scenarios 3 and 4) mm yr^{-1}	"Moderate"/ "No additional"
1 – HBE	0.03	0.02	0.84
2 – LBY	1.8	1.7	0.95
3 – NWI	1.0	0.9	0.93
4 – CNS	0.1	0.1	0.93
5 – WSI	0.3	0.2	0.90
6 – SWI	0.5	0.4	0.88
7 – WAV	0.2	0.2	0.99
8 – PCV	0.2	0.2	1.00
9 – MEO	0.2	0.2	1.00
10 – MOT	0.2	0.2	0.71
11 – SBY	1.2	1.0	0.87
12 – HGF	–	–	–
13 – HEN	3.4	3.3	0.96
14 – WHA	1.0	0.9	0.90
15 – WAT	0.4	0.3	0.82
16– HBY	1.9	1.6	0.88
17 – UWH	–	–	–

Table 14

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

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

Table 15
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

Subestuary	Zinc			Copper		
	TEL	ERL	PEL	TEL	ERL	PEL
1 – HBE	–	–	–	–	–	–
2 – LBY	67	–	–	62	–	–
3 – NWI	–	–	–	–	–	–
4 – CNS	–	–	–	–	–	–
5 – WSI	37	–	–	–	–	–
6 – SWI	74	–	–	86	–	–
7 – WAV	–	–	–	–	–	–
8 – PCV	–	–	–	–	–	–
9 – MEO	–	–	–	–	–	–
10 – MOT	–	–	–	–	–	–
11 – SBY	39	61	–	58	–	–
12 – UWH	N/A	N/A	N/A	N/A	N/A	N/A
13 – HEN	X	X	59	X	10	–
14 – WHA	X	X	61	X	15	–
15 – WAT	X	15	–	X	55	–
16 – HBA	34	48	–	33	76	–

Table 16
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

Subestuary	Zinc			Copper		
	TEL	ERL	PEL	TEL	ERL	PEL
1 – HBE	–	–	–	–	–	–
2 – LBY	76	–	–	70	–	–
3 – NWI	–	–	–	–	–	–
4 – CNS	–	–	–	–	–	–
5 – WSI	62	–	–	–	–	–
6 – SWI	86	–	–	–	–	–
7 – WAV	–	–	–	–	–	–
8 – PCV	–	–	–	–	–	–
9 – MEO	–	–	–	–	–	–
10 – MOT	–	–	–	–	–	–
11 – SBY	42	70	–	65	–	–
12 – UWH	N/A	N/A	N/A	N/A	N/A	N/A
13 – HEN	X	X	66	X	10	–
14 – WHA	X	X	67	X	15	–
15 – WAT	X	15	–	X	65	–
16 – HBA	35	53	–	35	85	–

Table 17
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

Subestuary	Zinc			Copper		
	TEL	ERL	PEL	TEL	ERL	PEL
1 – HBE	–	–	–	–	–	–
2 – LBY	77	–	–	70	–	–
3 – NWI	–	–	–	–	–	–
4 – CNS	–	–	–	–	–	–
5 – WSI	64	–	–	–	–	–
6 – SWI	86	–	–	–	–	–
7 – WAV	–	–	–	–	–	–
8 – PCV	–	–	–	–	–	–
9 – MEO	–	–	–	–	–	–
10 – MOT	–	–	–	–	–	–
11 – SBY	42	70	–	65	–	–
12 – UWH	N/A	N/A	N/A	N/A	N/A	N/A
13 – HEN	X	X	67	X	10	–
14 – WHA	X	X	68	X	15	–
15 – WAT	X	15	–	X	65	–
16 – HBA	36	54	–	35	85	–

Table 18

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 – HBE	–	–	–	–	–	–
2 – LBY	10	–	–	8	–	–
3 – NWI	–	–	–	–	–	–
4 – CNS	–	–	–	–	–	–
5 – WSI	25	–	–	–	–	–
6 – SWI	12	–	–	* (86)	–	–
7 – WAV	–	–	–	–	–	–
8 – PCV	–	–	–	–	–	–
9 – MEO	–	–	–	–	–	–
10 – MOT	–	–	–	–	–	–
11 – SBY	3	9	–	7	–	–
12 – UWH	N/A	N/A	N/A	N/A	N/A	N/A
13 – HEN	X	X	8	X	0	–
14 – WHA	X	X	7	X	0	–
15 – WAT	X	0	–	X	10	–
16 – HBA	2	5	–	2	9	–

Table 19

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 – HBE	–	–	–	–	–	–
2 – LBY	10	–	–	8	–	–
3 – NWI	–	–	–	–	–	–
4 – CNS	–	–	–	–	–	–
5 – WSI	27	–	–	–	–	–
6 – SWI	12	–	–	* (86)	–	–
7 – WAV	–	–	–	–	–	–
8 – PCV	–	–	–	–	–	–
9 – MEO	–	–	–	–	–	–
10 – MOT	–	–	–	–	–	–
11 – SBY	3	9	–	7	–	–
12 – UWH	N/A	N/A	5	N/A	N/A	N/A
13 – HEN	X	X	8	X	0	–
14 – WHA	X	X	7	X	0	–
15 – WAT	X	0	–	X	10	–
16 – HBA	2	5	–	2	9	–

Table 20

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 – HBE	–	–	–
2 – LBY	1	–	–
3 – NWI	–	–	–
4 – CNS	–	–	–
5 – WSI	0	–	–
6 – SWI	0	–	–
7 – WAV	–	–	–
8 – PCV	–	–	–
9 – MEO	–	–	–
10 – MOT	–	–	–
11 – SBY	0	0	–
12 – UWH	N/A	N/A	N/A
13 – HEN	X	X	1
14 – WHA	X	X	1
15 – WAT	X	0	–
16 – HBA	0	0	–

Table 21

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 – HBE	–	–	–
2 – LBY	1	–	–
3 – NWI	–	–	–
4 – CNS	–	–	–
5 – WSI	2	–	–
6 – SWI	0	–	–
7 – WAV	–	–	–
8 – PCV	–	–	–
9 – MEO	–	–	–
10 – MOT	–	–	–
11 – SBY	0	0	–
12 – UWH	N/A	N/A	N/A
13 – HEN	X	X	1
14 – WHA	X	X	1
15 – WAT	X	0	–
16 – HBA	1	1	–

Figure 3

Annual sediment run-off. This is the sum of all particle sizes, as it appears for just one USC model run in the Monte Carlo package of 50 USC model runs. This figure shows the urban component of the total load, and the total load. The rural component of the total load is the difference between those two. Year 1 is 2001 and year 100 is 2100.

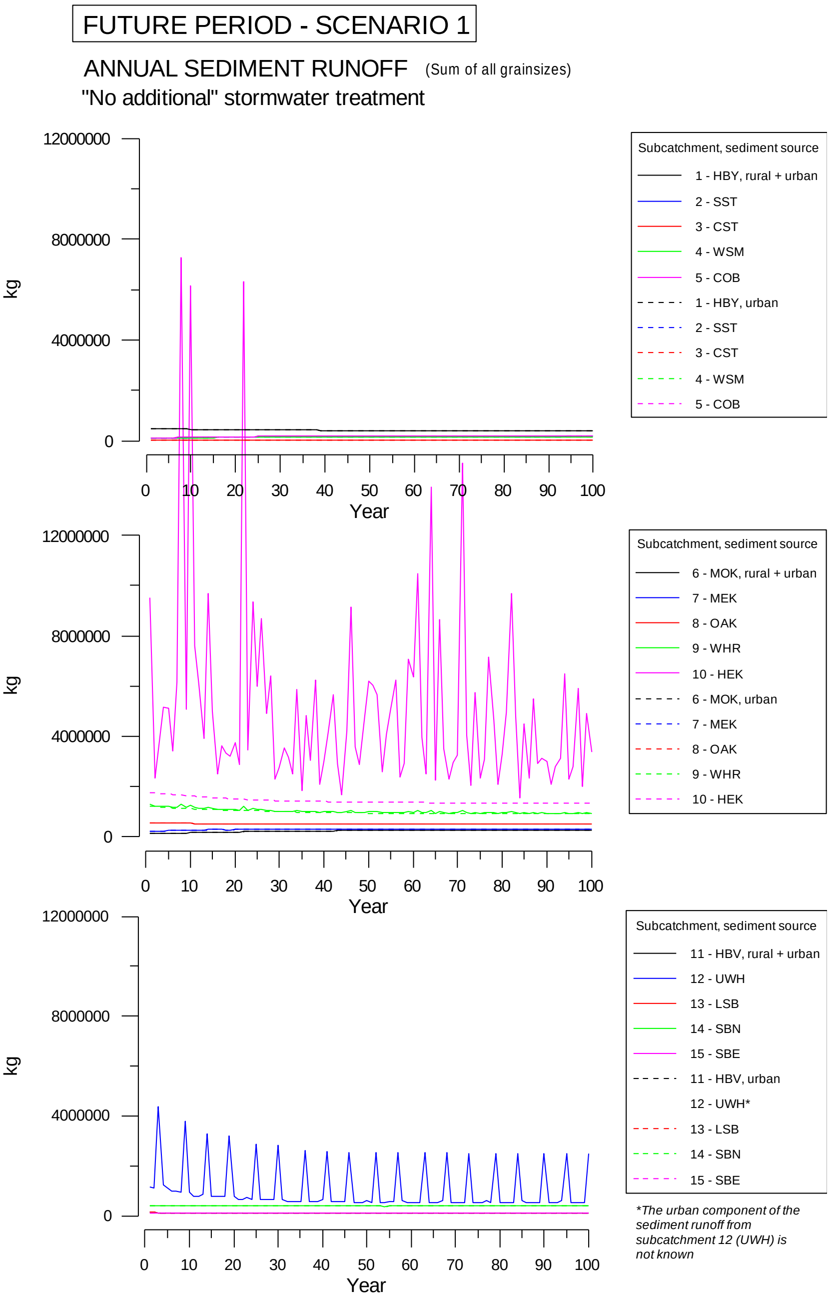


Figure 3 (cont.)

Annual sediment run-off. This is the sum of all particle sizes, as it appears for just one USC model run in the Monte Carlo package of 50 USC model runs. This figure shows the urban component of the total load, and the total load. The rural component of the total load is the difference between those two. Year 1 is 2001 and year 100 is 2100.

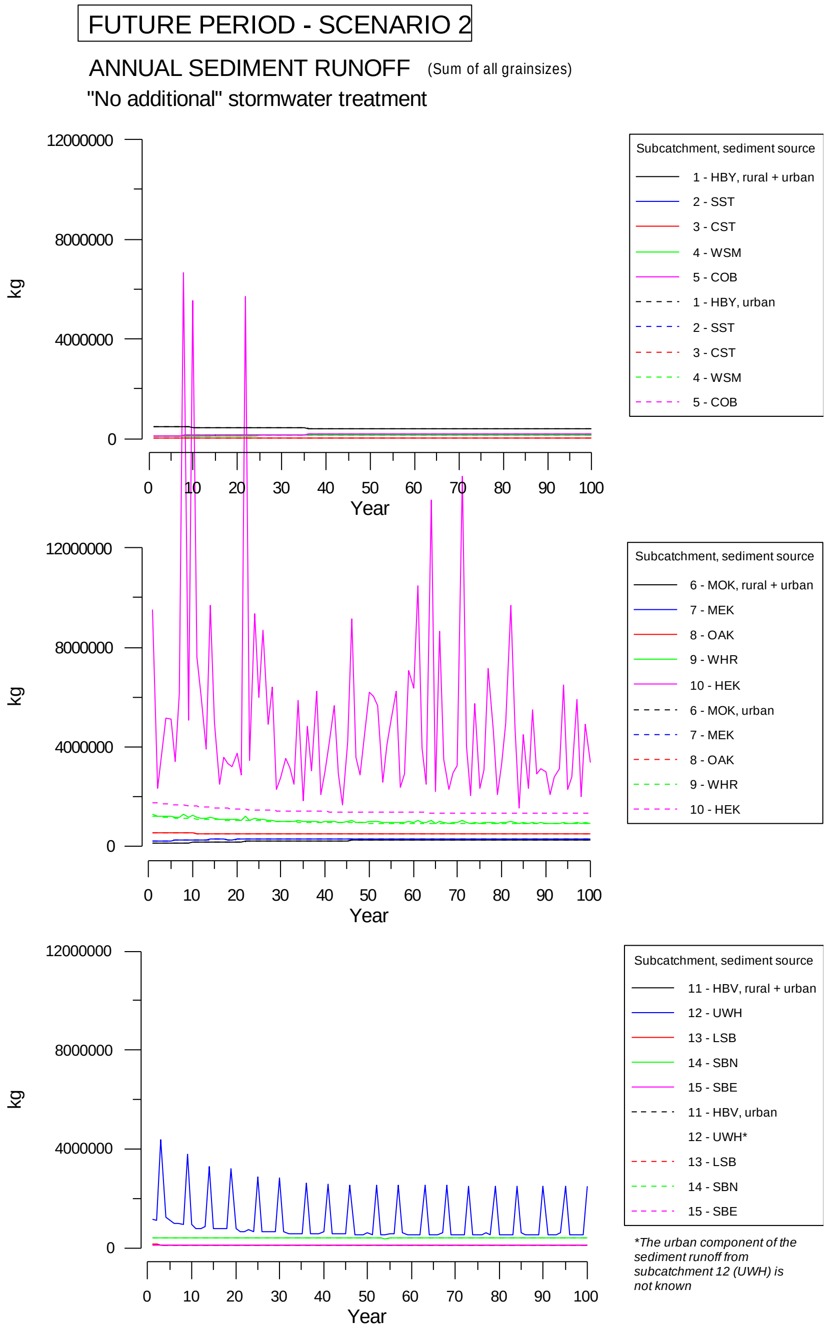


Figure 3 (cont.)

Annual sediment run-off. This is the sum of all particle sizes, as it appears for just one USC model run in the Monte Carlo package of 50 USC model runs. This figure shows the urban component of the total load, and the total load. The rural component of the total load is the difference between those two. Year 1 is 2001 and year 100 is 2100.

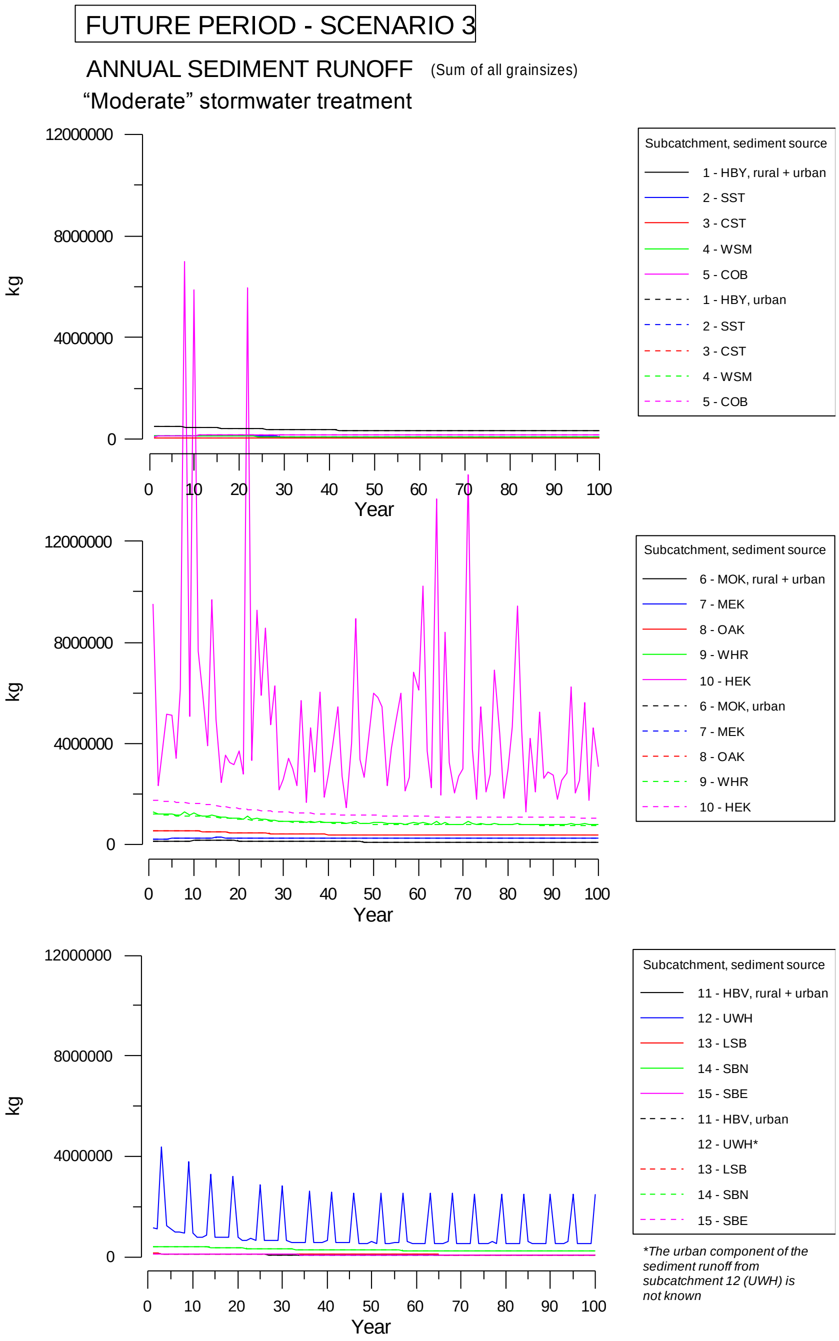


Figure 3 (cont.)

Annual sediment run-off. This is the sum of all particle sizes, as it appears for just one USC model run in the Monte Carlo package of 50 USC model runs. This figure shows the urban component of the total load, and the total load. The rural component of the total load is the difference between those two. Year 1 is 2001 and year 100 is 2100.

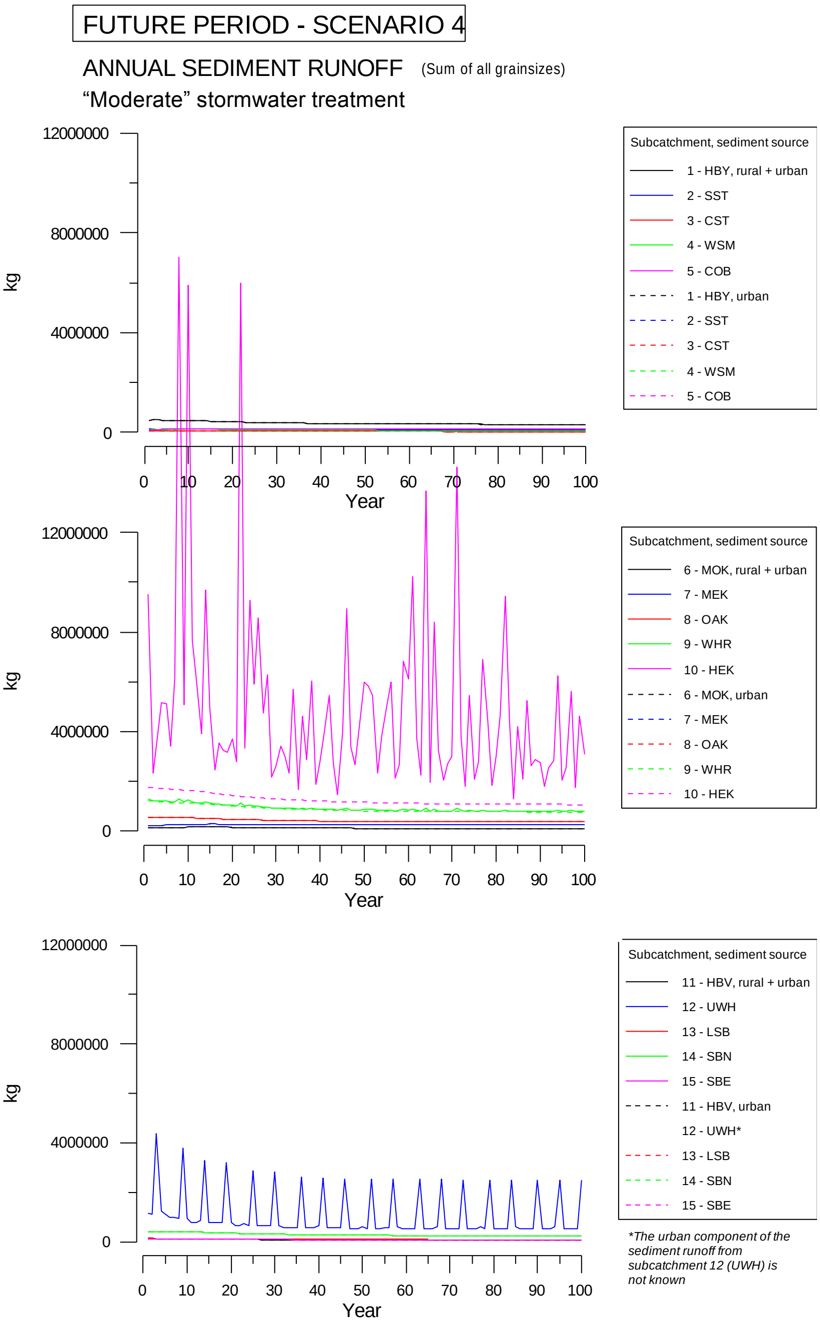


Figure 4

Annual urban sediment run-off (sum of all particle sizes) for each scenario. Year 1 is 2001 and year 100 is 2100.

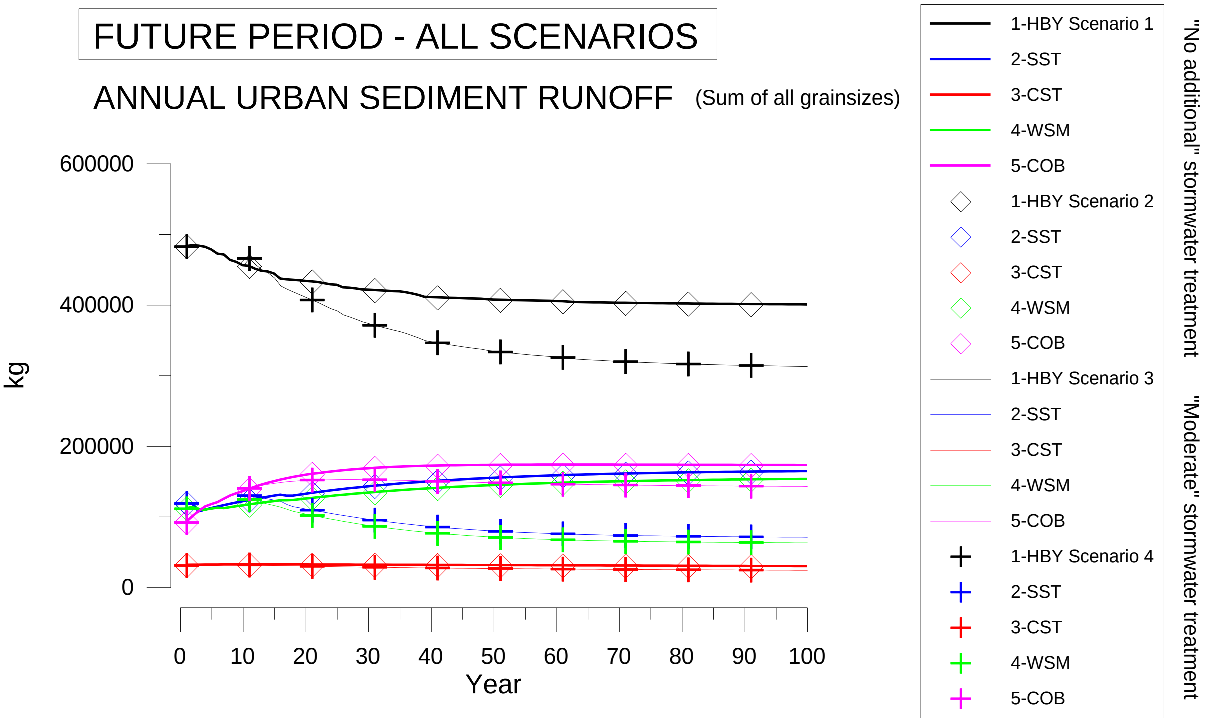


Figure 4 (cont.)

Annual urban sediment run-off (sum of all particle sizes) for each scenario. Year 1 is 2001 and year 100 is 2100.

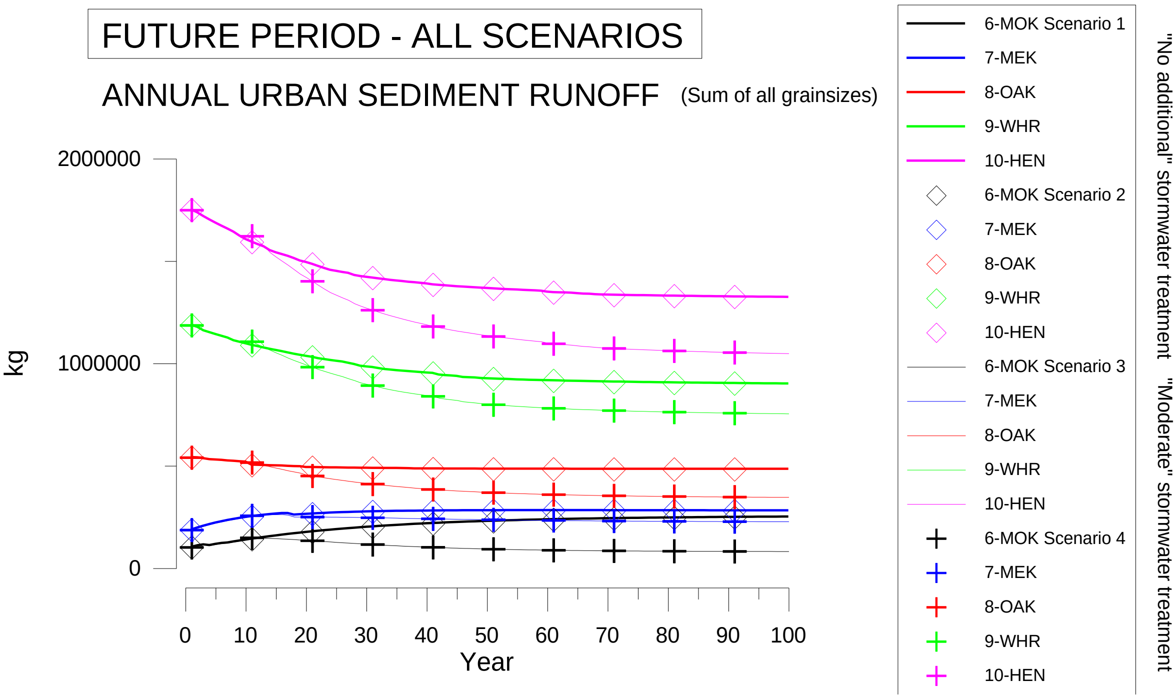


Figure 4 (cont.)

Annual urban sediment run-off (sum of all particle sizes) for each scenario. Year 1 is 2001 and year 100 is 2100.

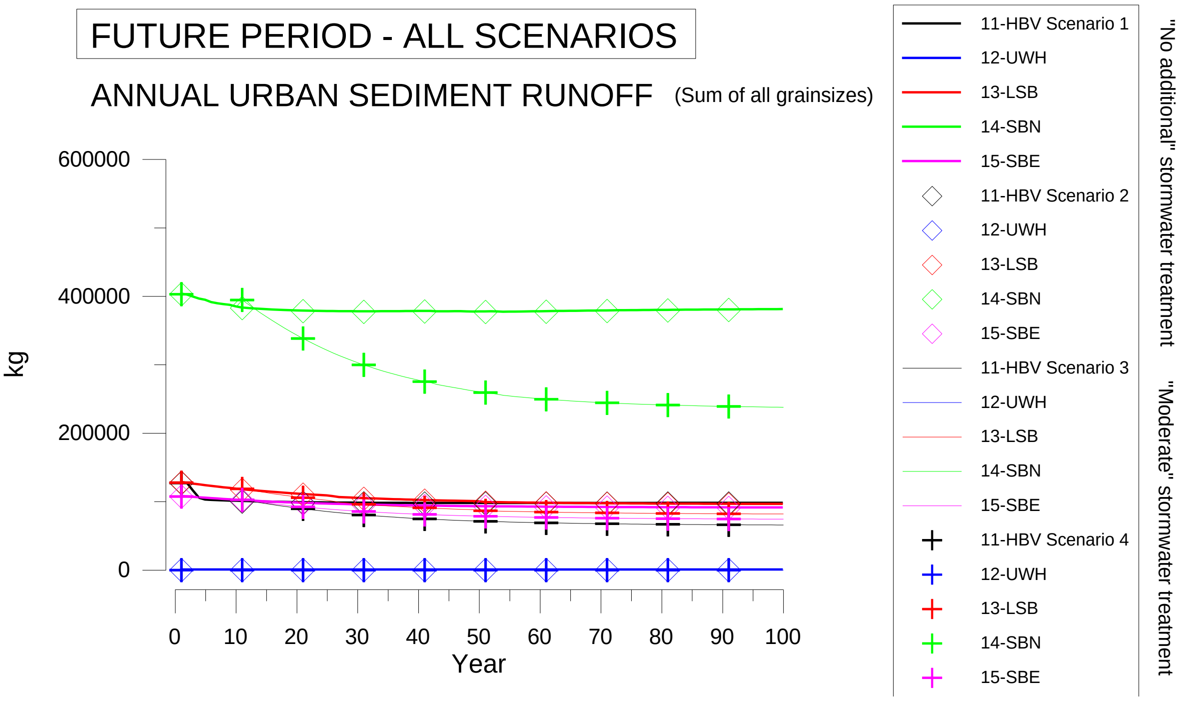


Figure 5

Anthropogenic zinc run-off (total carried by all sediment constituent particle sizes). Year 1 is 2001 and year 100 is 2100.

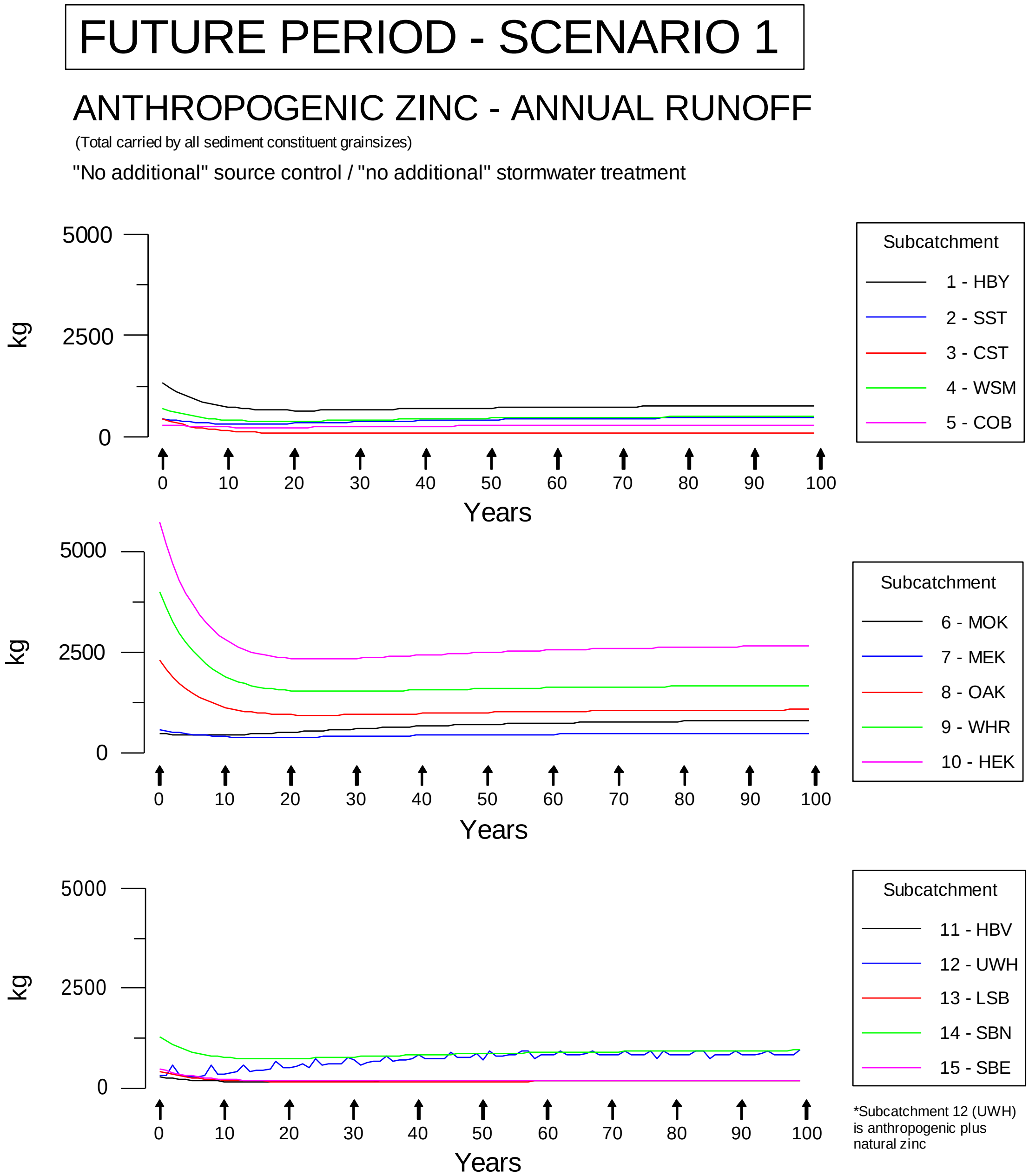


Figure 5 (cont.)

Anthropogenic zinc run-off (total carried by all sediment constituent particle sizes). Year 1 is 2001 and year 100 is 2100.

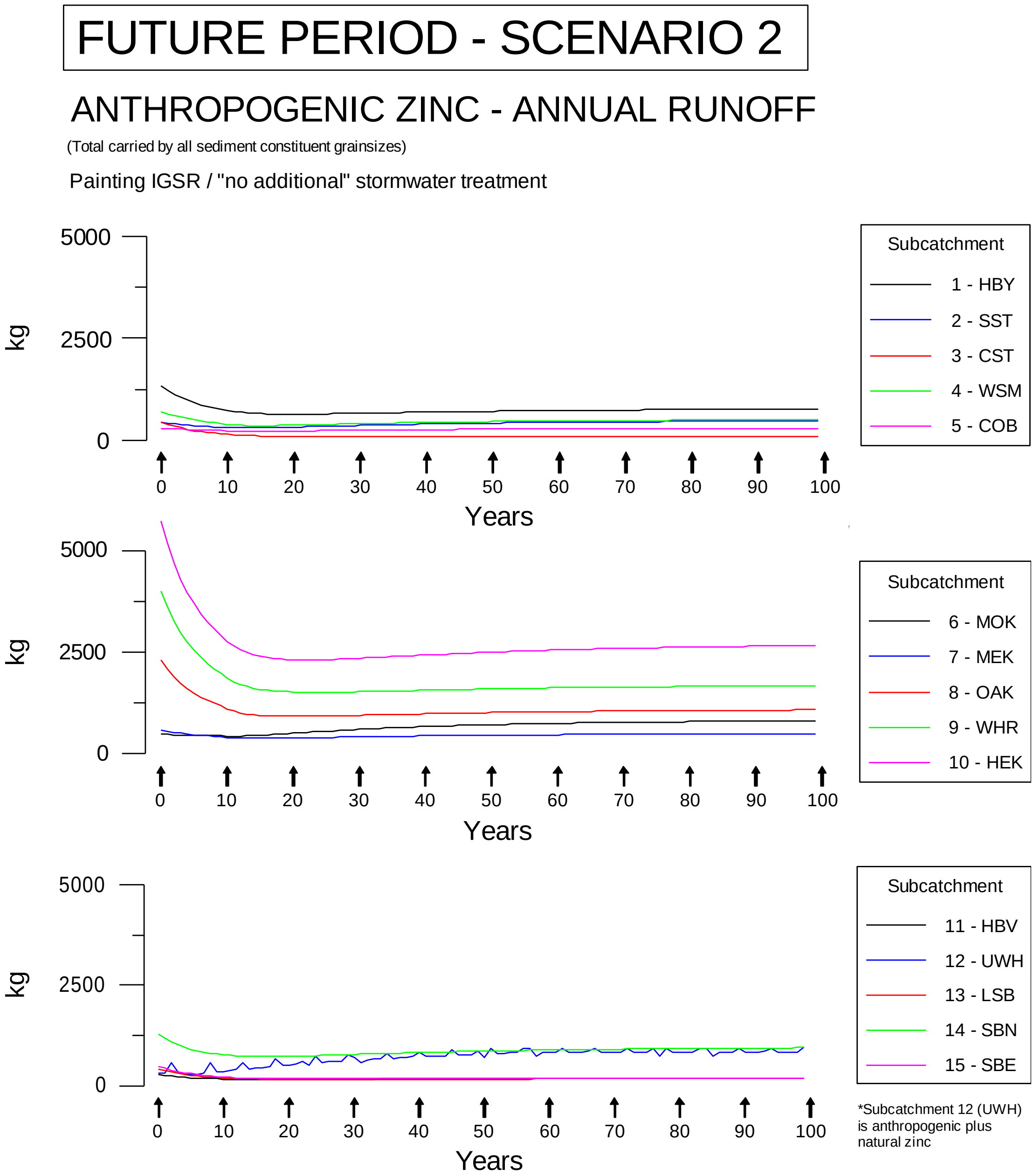


Figure 5 (cont.)

Anthropogenic zinc run-off (total carried by all sediment constituent particle sizes). Year 1 is 2001 and year 100 is 2100.

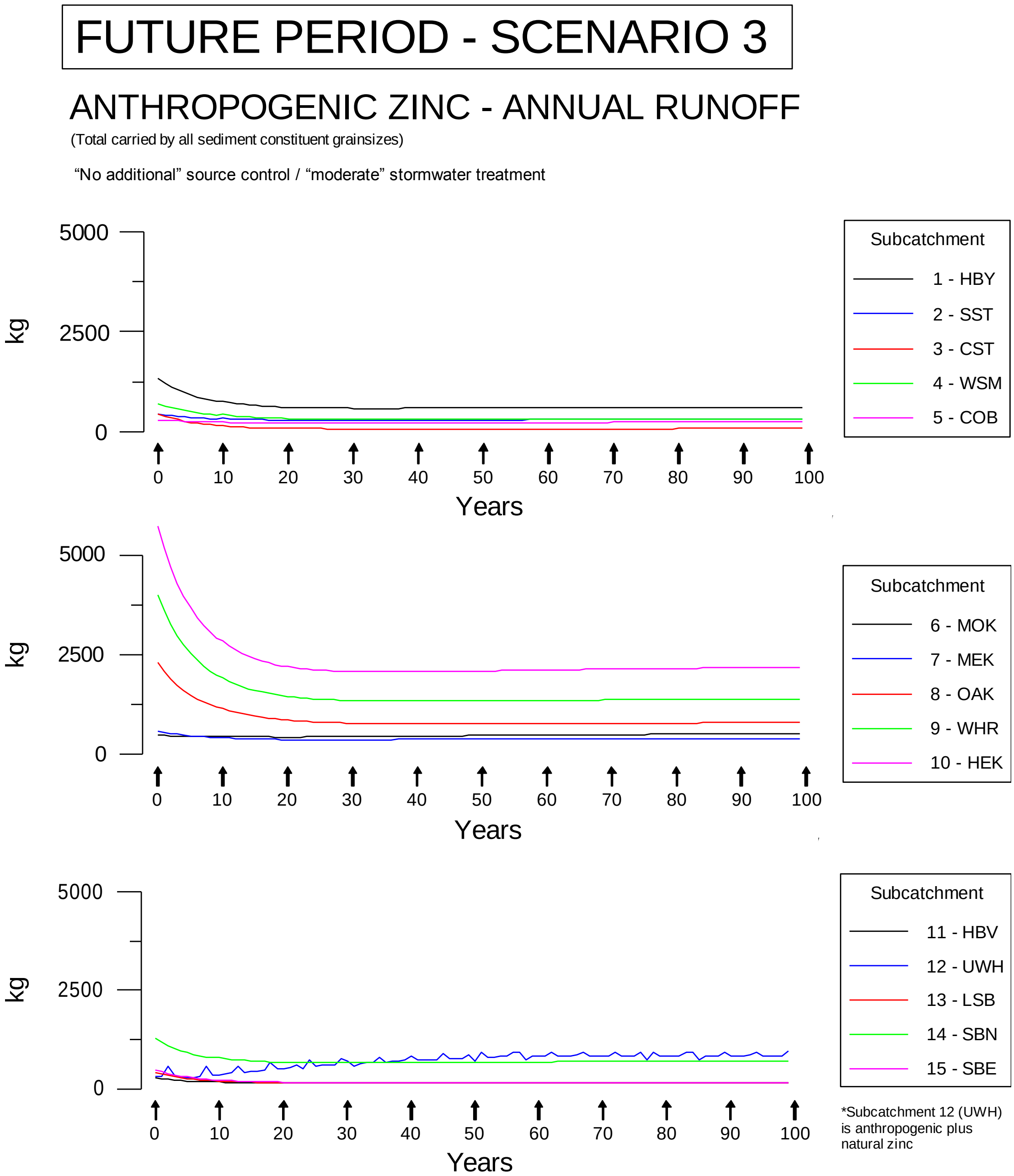


Figure 5 (cont.)

Anthropogenic zinc run-off (total carried by all sediment constituent particle sizes). Year 1 is 2001 and year 100 is 2100.

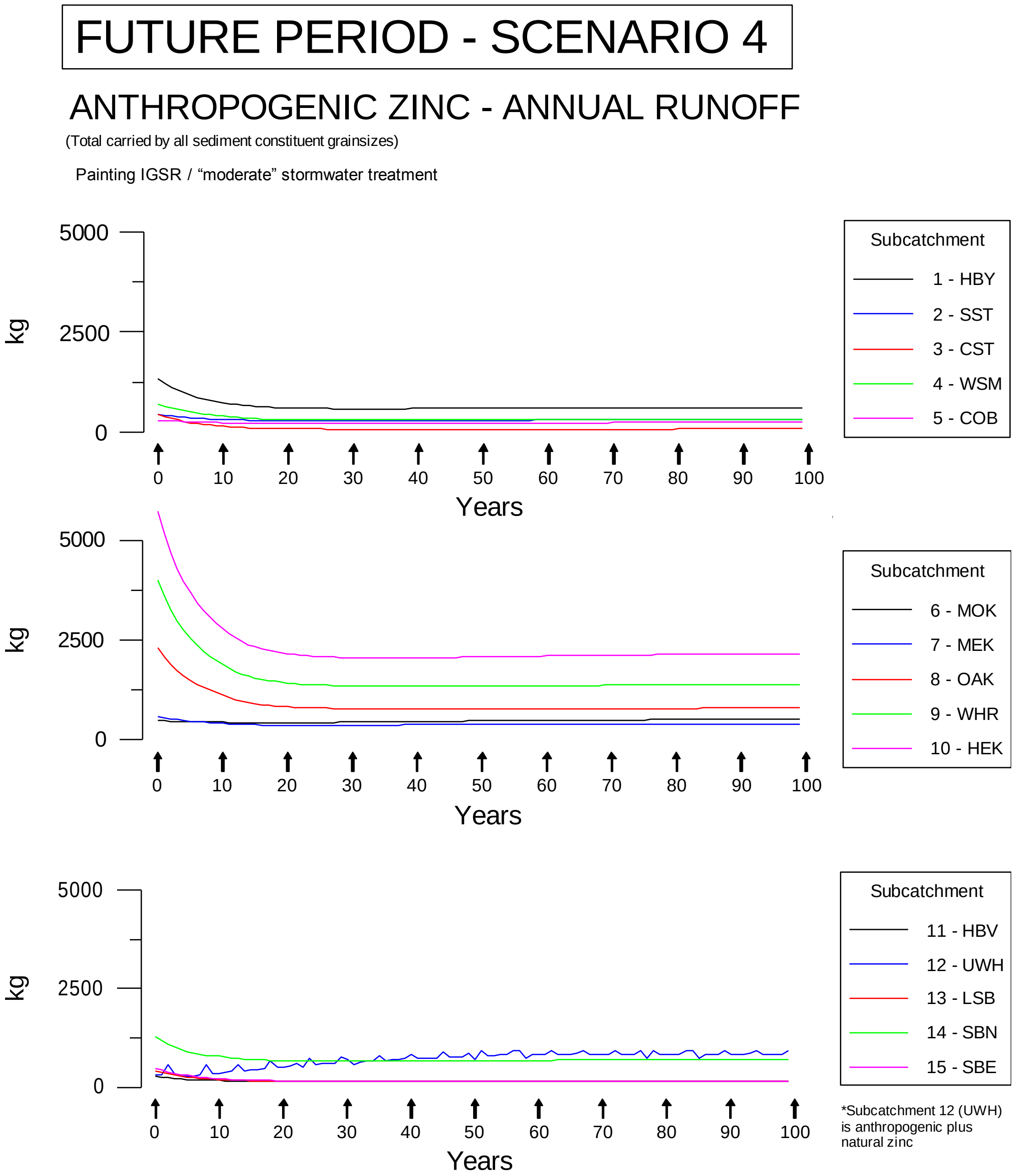


Figure 6

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

FUTURE PERIOD - SCENARIO 1

ANTHROPOGENIC COPPER - ANNUAL RUNOFF

(Total carried by all sediment constituent grainsizes)

"No additional" source control / "no additional" stormwater treatment

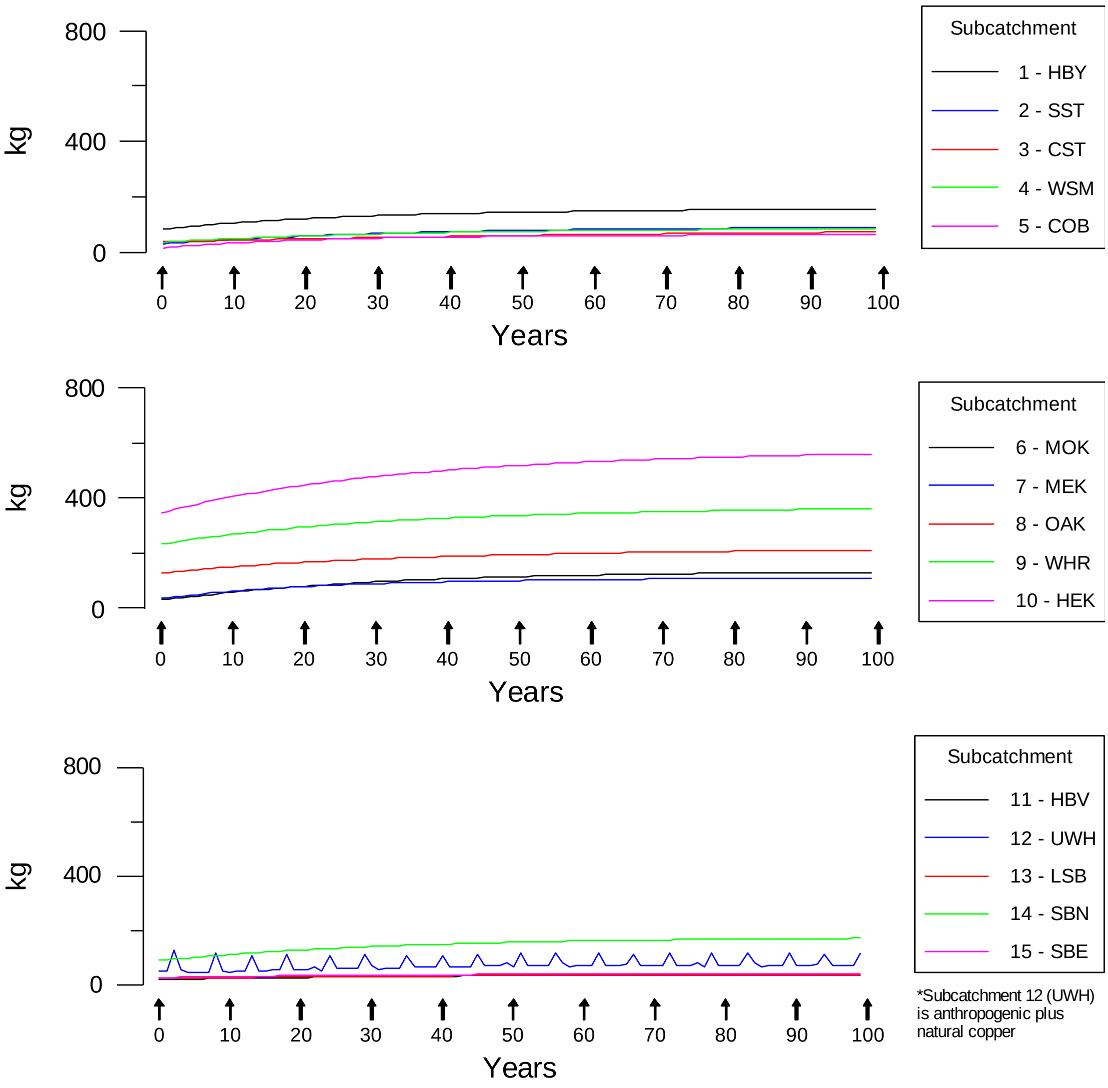


Figure 6 (cont.)

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

FUTURE PERIOD - SCENARIO 3

ANTHROPOGENIC COPPER - ANNUAL RUNOFF

(Total carried by all sediment constituent grainsizes)

"No additional" source control / "moderate" stormwater treatment

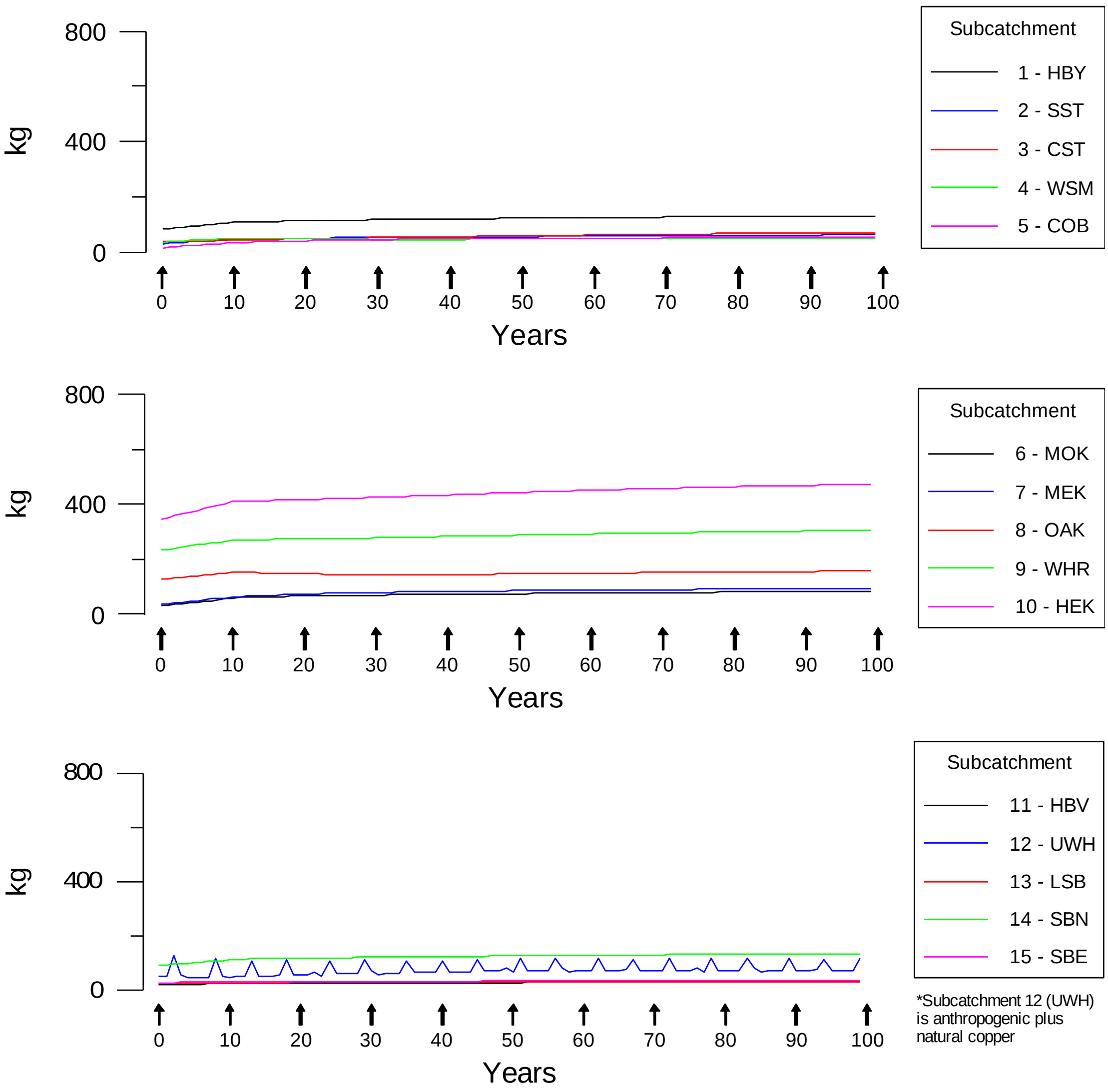


Figure 7

Concentrations at which total (anthropogenic plus natural) zinc is delivered to the harbour over the future period. Concentration is defined here as the total (anthropogenic plus natural) metal carried by all sediment particle sizes divided by the total (rural plus urban) sediment summed over all particle sizes. These figures are for just one USC model run in the Monte Carlo package of 50 USC model runs. Year 1 is 2001 and year 100 is 2100.

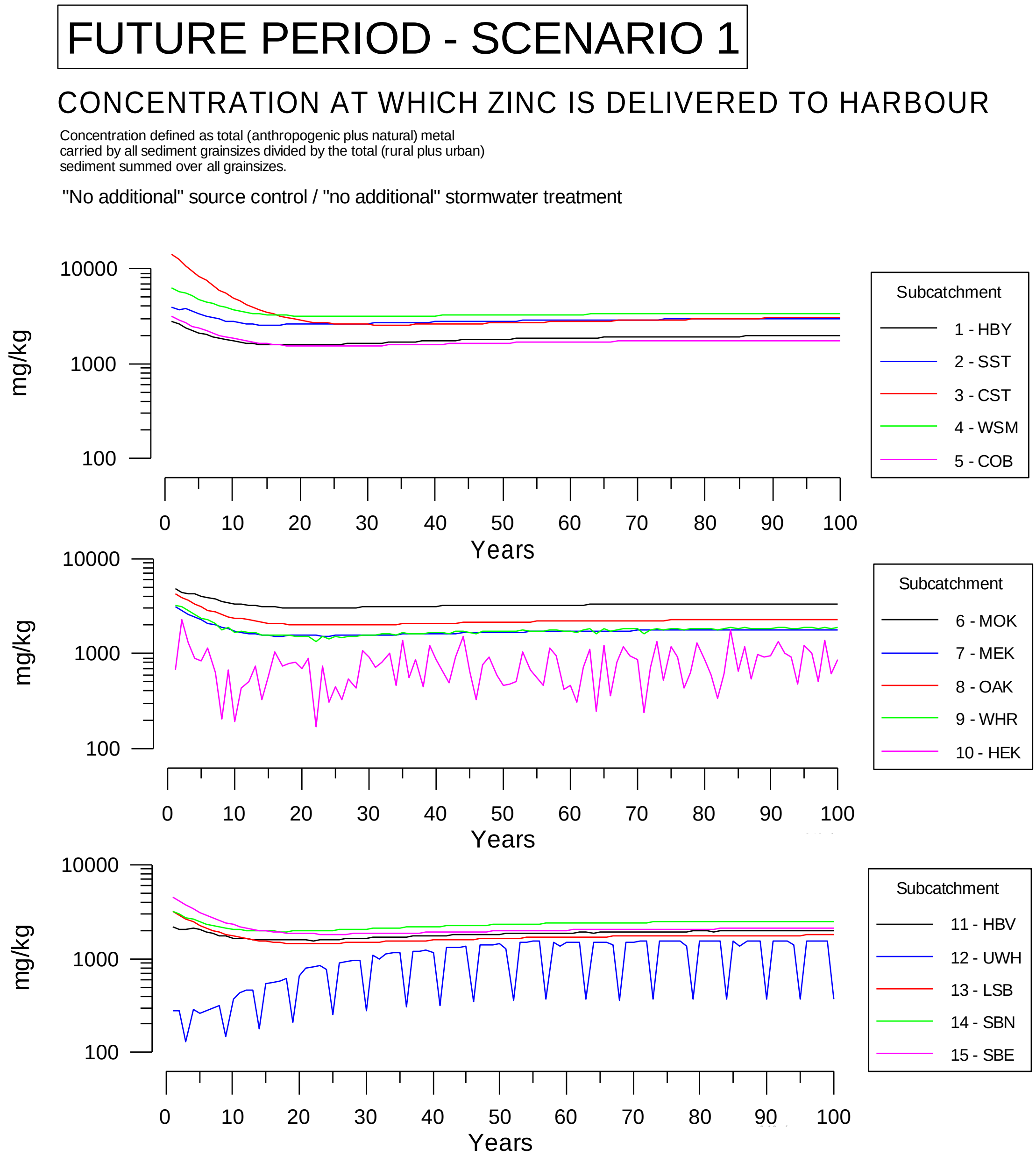


Figure 7 (cont.)

Concentrations at which total (anthropogenic plus natural) zinc is delivered to the harbour over the future period. Concentration is defined here as the total (anthropogenic plus natural) metal carried by all sediment particle sizes divided by the total (rural plus urban) sediment summed over all particle sizes. These figures are for just one USC model run in the Monte Carlo package of 50 USC model runs. Year 1 is 2001 and year 100 is 2100.

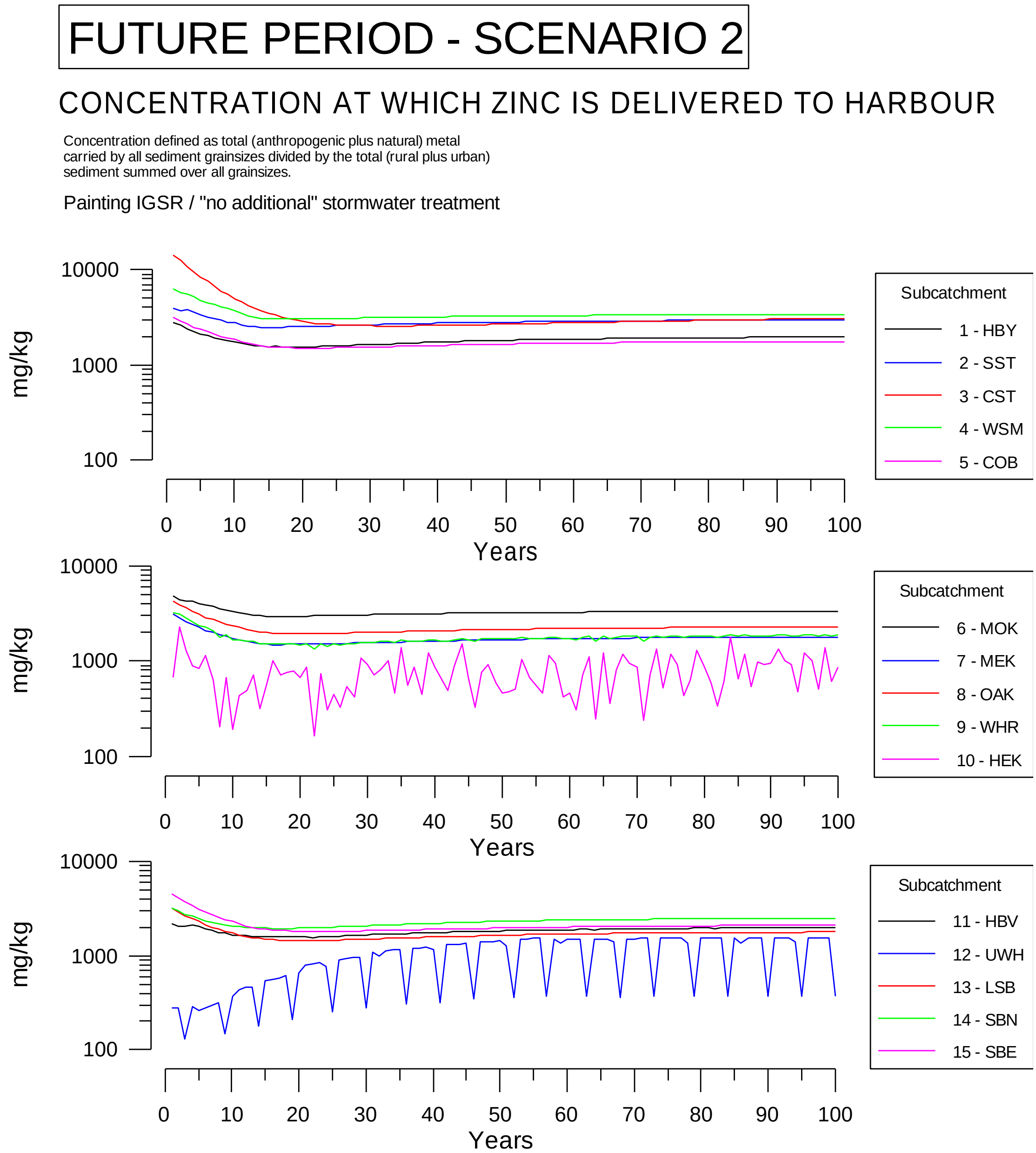


Figure 7 (cont.)

Concentrations at which total (anthropogenic plus natural) zinc is delivered to the harbour over the future period. Concentration is defined here as the total (anthropogenic plus natural) metal carried by all sediment particle sizes divided by the total (rural plus urban) sediment summed over all particle sizes. These figures are for just one USC model run in the Monte Carlo package of 50 USC model runs. Year 1 is 2001 and year 100 is 2100.

FUTURE PERIOD - SCENARIO 3

CONCENTRATION AT WHICH ZINC IS DELIVERED TO HARBOUR

Concentration defined as total (anthropogenic plus natural) metal
carried by all sediment grainsizes divided by the total (rural plus urban)
sediment summed over all grainsizes.

"No additional" source control / "moderate" stormwater treatment

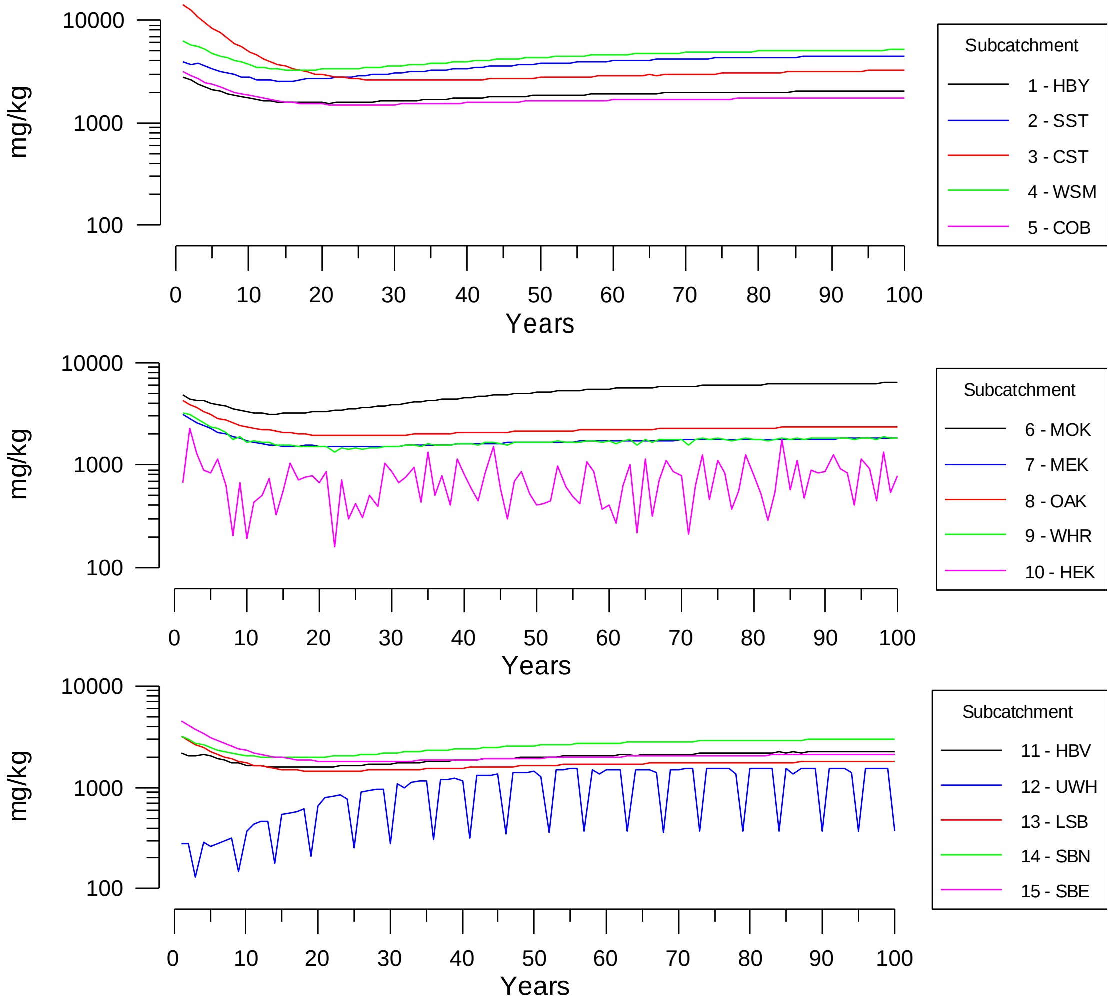


Figure 7 (cont.)

Concentrations at which total (anthropogenic plus natural) zinc is delivered to the harbour over the future period. Concentration is defined here as the total (anthropogenic plus natural) metal carried by all sediment particle sizes divided by the total (rural plus urban) sediment summed over all particle sizes. These figures are for just one USC model run in the Monte Carlo package of 50 USC model runs. Year 1 is 2001 and year 100 is 2100.

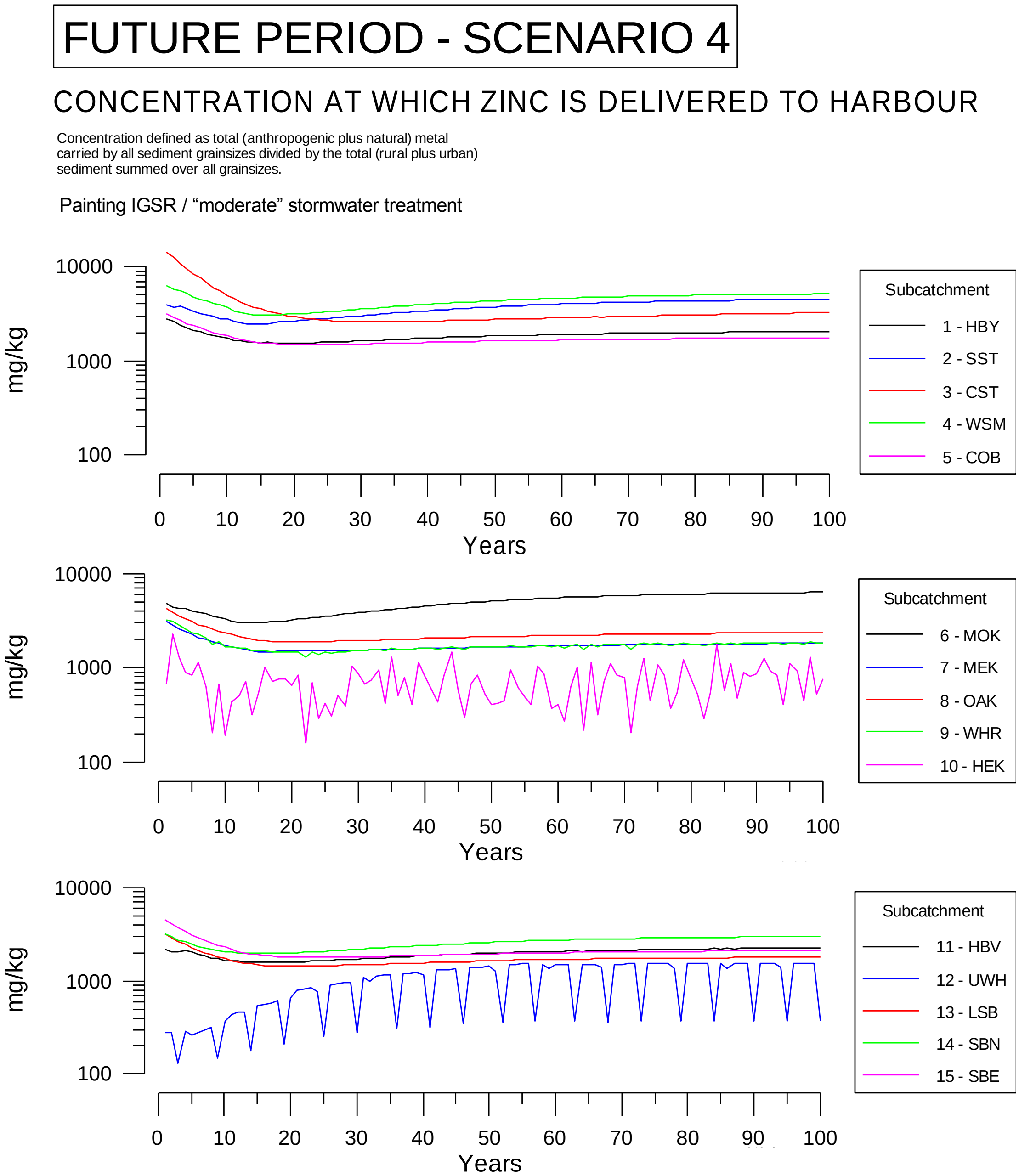


Figure 8
Concentrations at which total (anthropogenic plus natural) copper is delivered to the harbour over the future period. Concentration is defined here as the total (anthropogenic plus natural) metal carried by all sediment particle sizes divided by the total (rural plus urban) sediment summed over all particle sizes. These figures are for just one USC model run in the Monte Carlo package of 50 USC model runs. Year 1 is 2001 and year 100 is 2100.

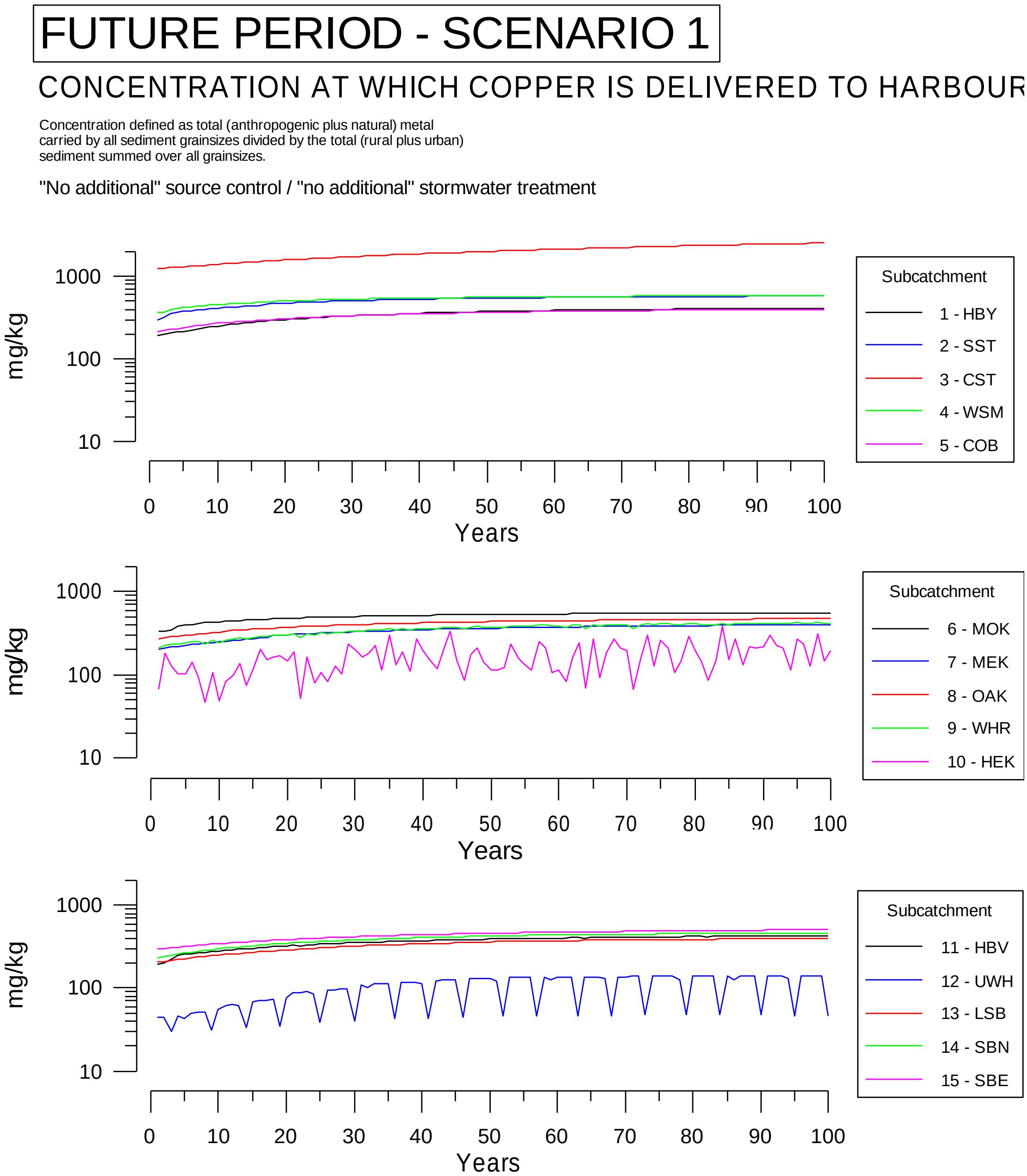


Figure 8 (cont.)

Concentrations at which total (anthropogenic plus natural) copper is delivered to the harbour over the future period. Concentration is defined here as the total (anthropogenic plus natural) metal carried by all sediment particle sizes divided by the total (rural plus urban) sediment summed over all particle sizes. These figures are for just one USC model run in the Monte Carlo package of 50 USC model runs. Year 1 is 2001 and year 100 is 2100.

FUTURE PERIOD - SCENARIO 3

CONCENTRATION AT WHICH COPPER IS DELIVERED TO HARBOUR

Concentration defined as total (anthropogenic plus natural) metal carried by all sediment grainsizes divided by the total (rural plus urban) sediment summed over all grainsizes.

"No additional" source control / "moderate" stormwater treatment

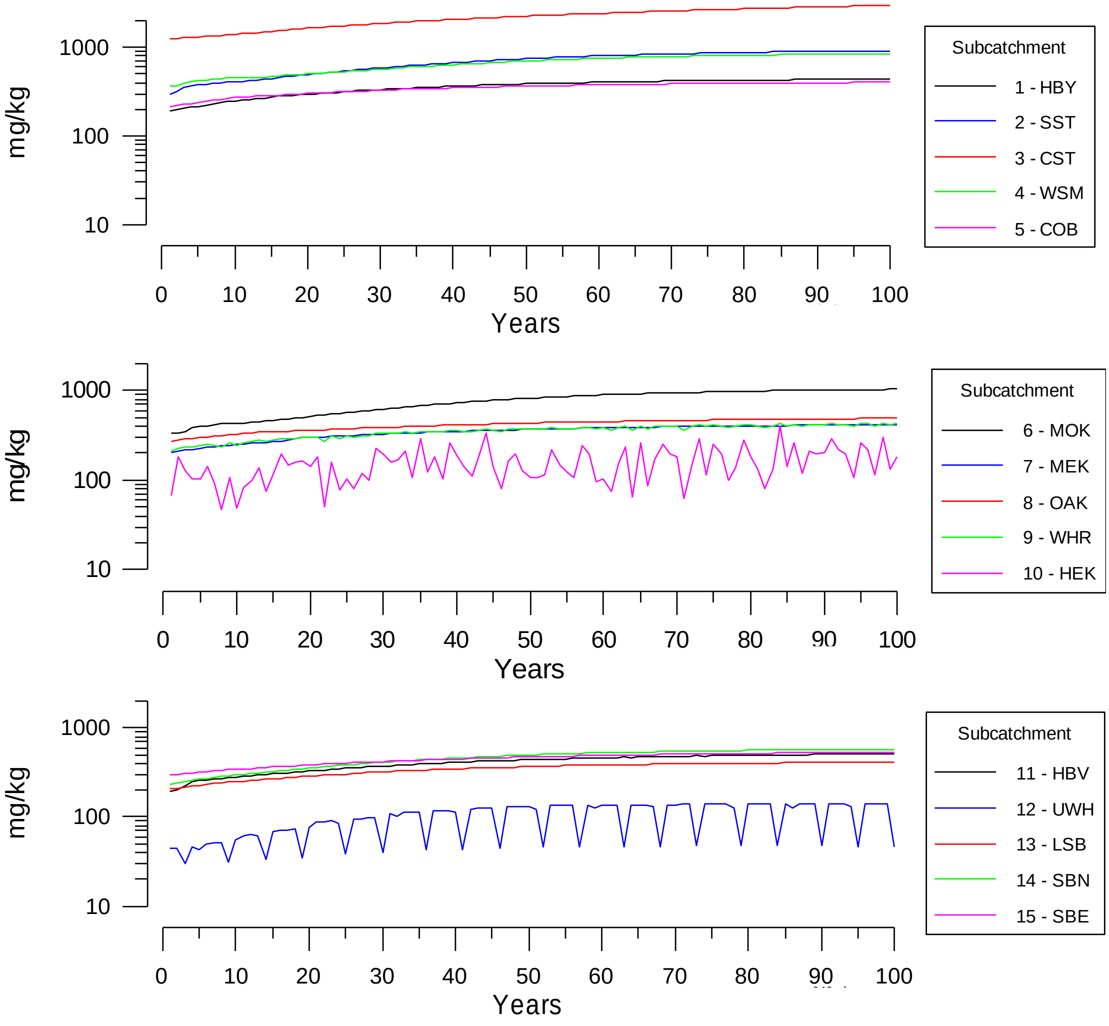


Figure 9

Comparison by scenario of the concentrations at which total (anthropogenic plus natural) zinc is delivered to the harbour over the future period. Concentration is defined here as the total (anthropogenic plus natural) metal carried by all sediment particle sizes divided by the total (rural plus urban) sediment summed over all particle sizes. These figures are for just one USC model run in the Monte Carlo package of 50 USC model runs. Year 1 is 2001 and year 100 is 2100.

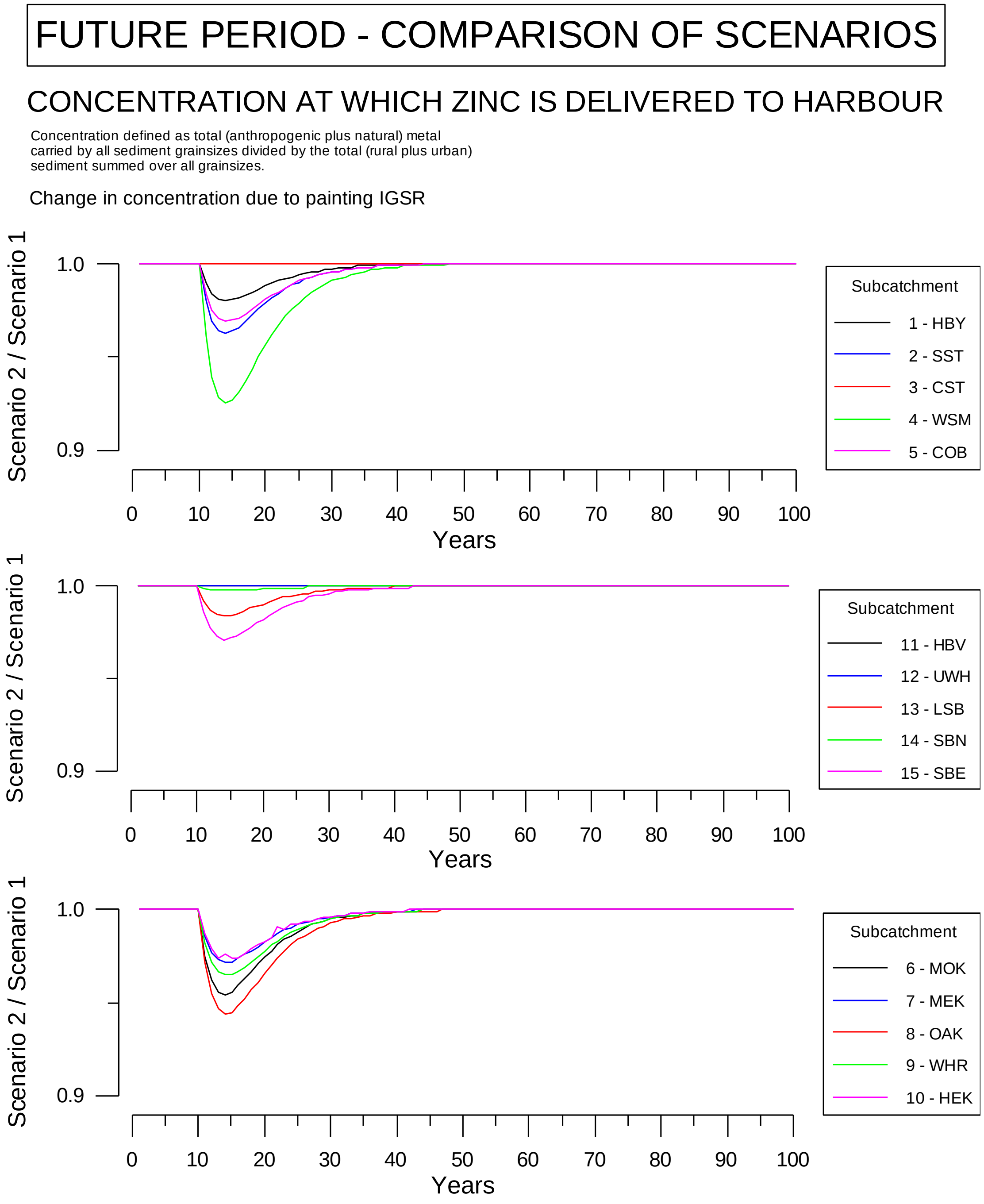


Figure 9 (cont.)

Comparison by scenario of the concentrations at which total (anthropogenic plus natural) zinc is delivered to the harbour over the future period. Concentration is defined here as the total (anthropogenic plus natural) metal carried by all sediment particle sizes divided by the total (rural plus urban) sediment summed over all particle sizes. These figures are for just one USC model run in the Monte Carlo package of 50 USC model runs. Year 1 is 2001 and year 100 is 2100.

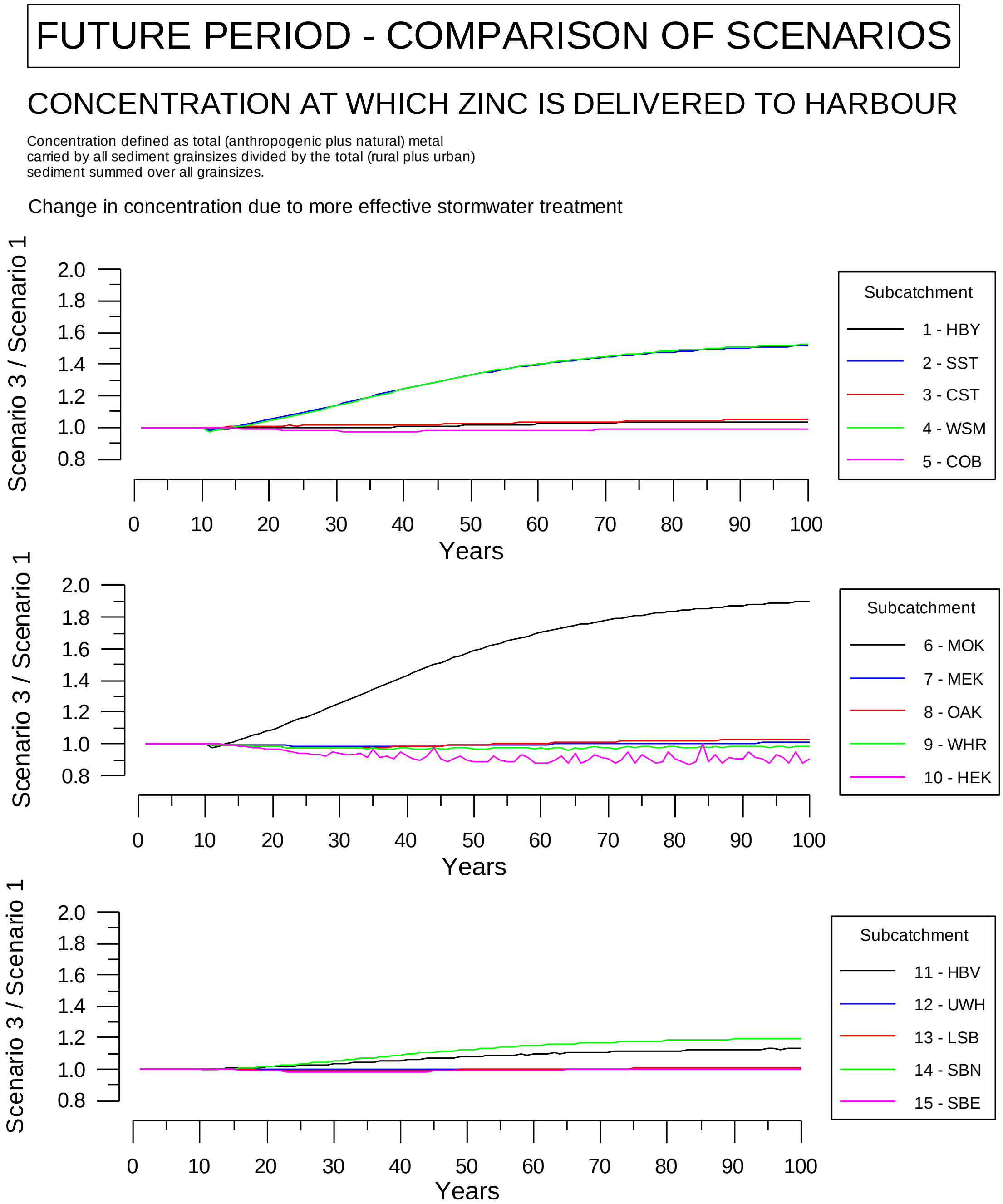


Figure 9 (cont.)

Comparison by scenario of the concentrations at which total (anthropogenic plus natural) zinc is delivered to the harbour over the future period. Concentration is defined here as the total (anthropogenic plus natural) metal carried by all sediment particle sizes divided by the total (rural plus urban) sediment summed over all particle sizes. These figures are for just one USC model run in the Monte Carlo package of 50 USC model runs. Year 1 is 2001 and year 100 is 2100.

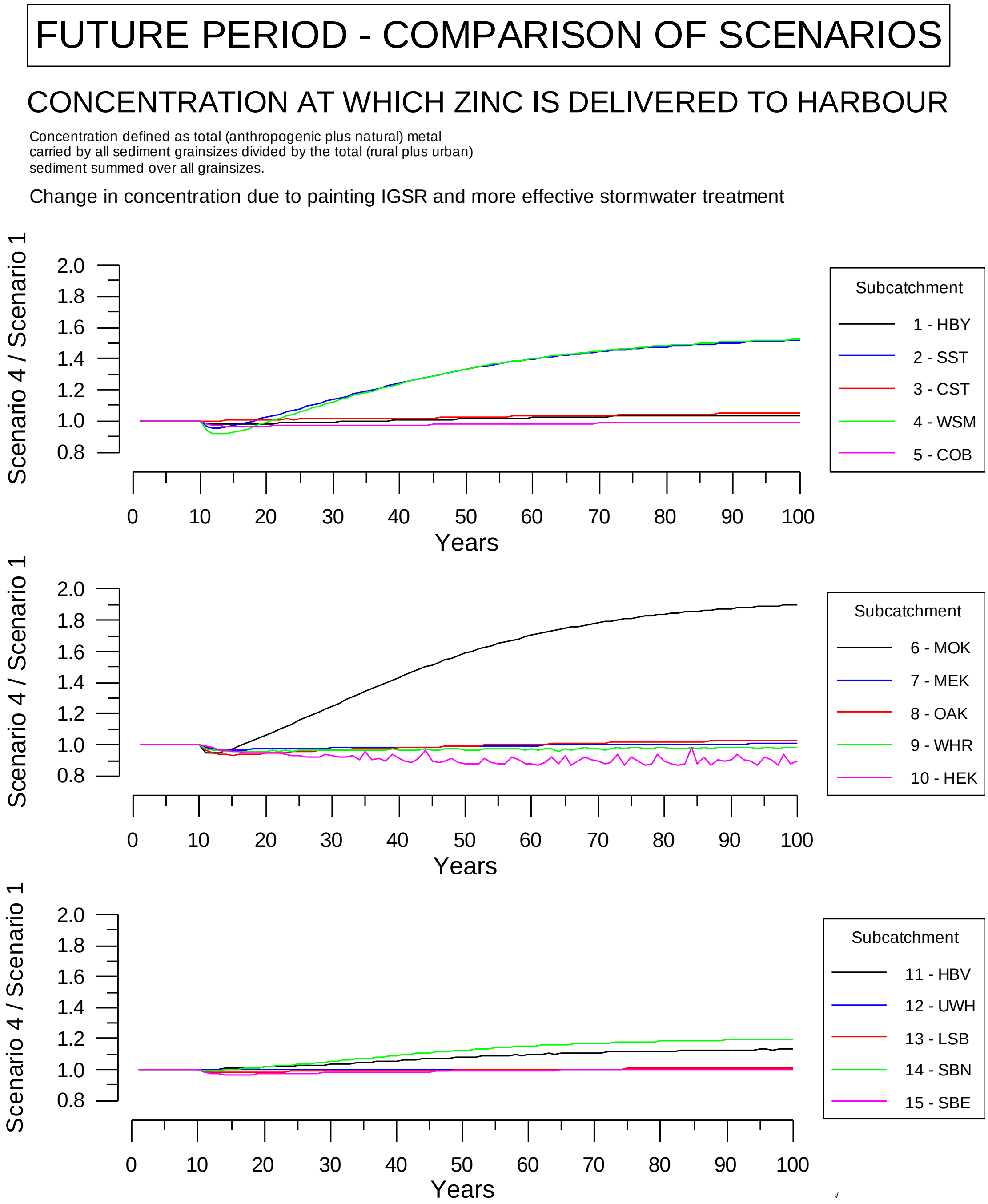


Figure 9 (cont.)

Comparison by scenario of the concentrations at which total (anthropogenic plus natural) zinc is delivered to the harbour over the future period. Concentration is defined here as the total (anthropogenic plus natural) metal carried by all sediment particle sizes divided by the total (rural plus urban) sediment summed over all particle sizes. These figures are for just one USC model run in the Monte Carlo package of 50 USC model runs. Year 1 is 2001 and year 100 is 2100.

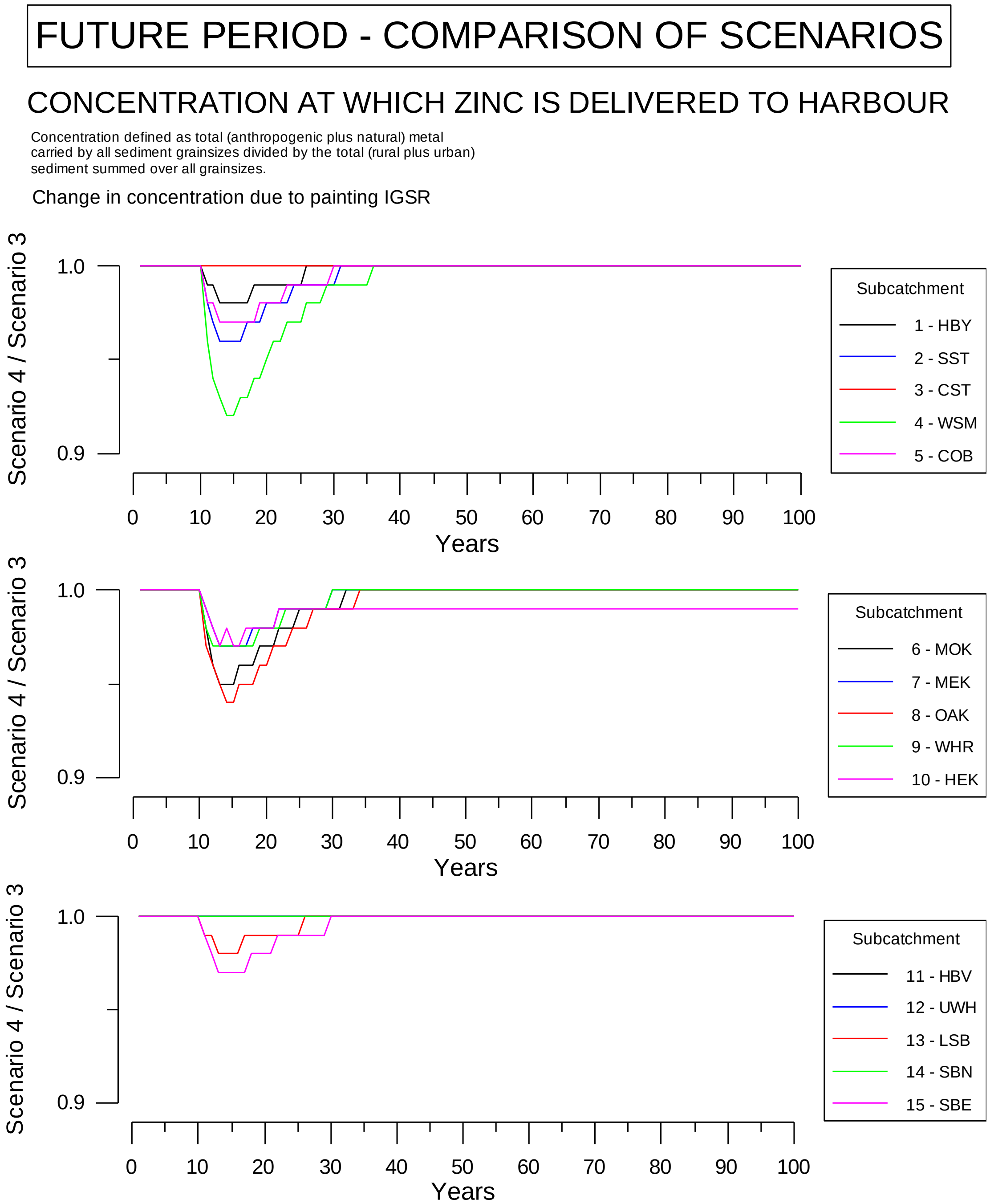


Figure 10

Comparison by scenario of the concentrations at which total (anthropogenic plus natural) zinc is delivered to the harbour over the future period. Concentration is defined here as the total (anthropogenic plus natural) metal carried by all sediment particle sizes divided by the total (rural plus urban) sediment summed over all particle sizes. These figures are for just one USC model run in the Monte Carlo package of 50 USC model runs. Year 1 is 2001 and year 100 is 2100.

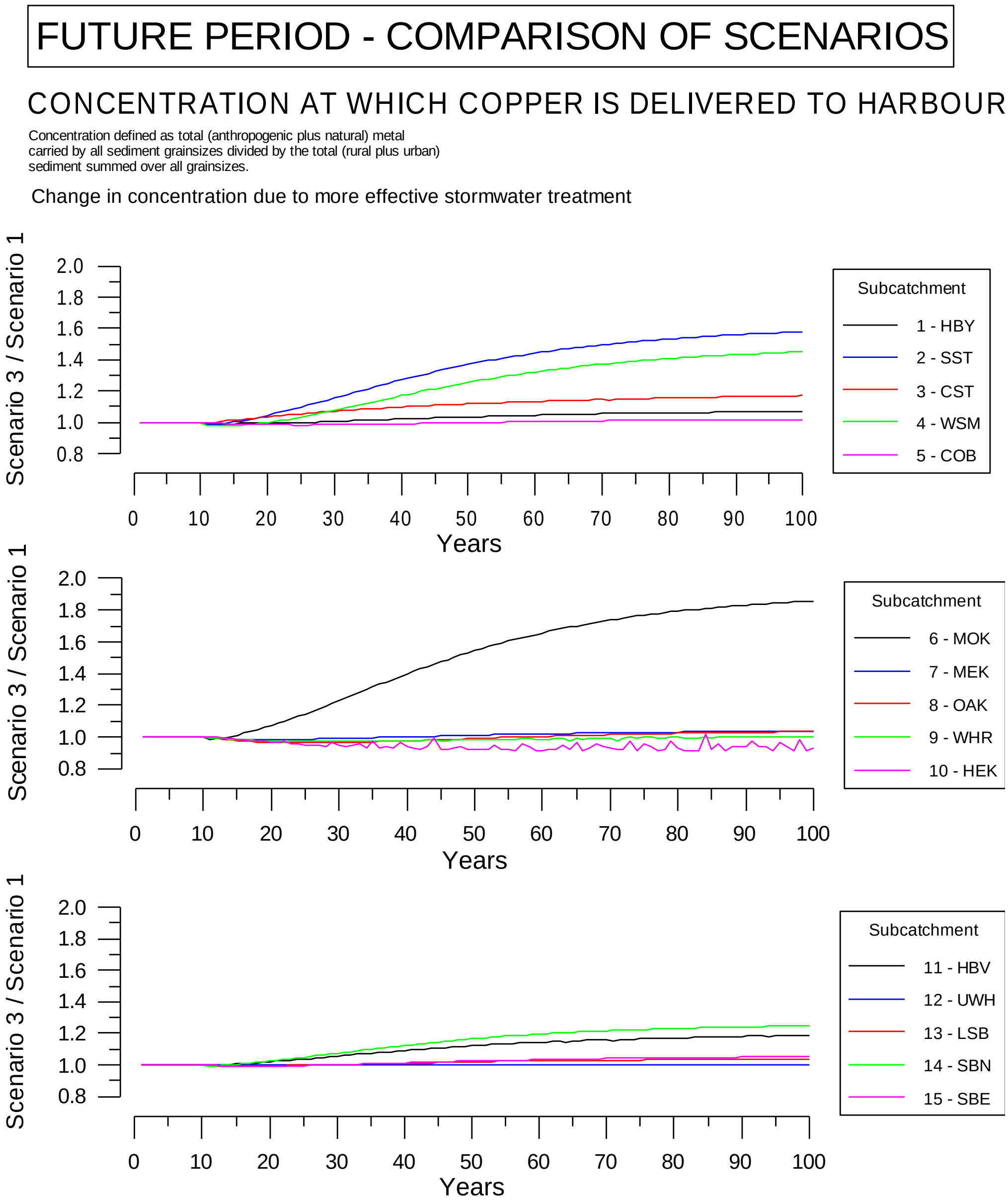


Figure 11

Sedimentation (change in height of bed sediment) in each subestuary over the future period. This is the average over 50 model runs in the Monte Carlo package. The Scenario 1 predictions are described fully in Green (2008b).

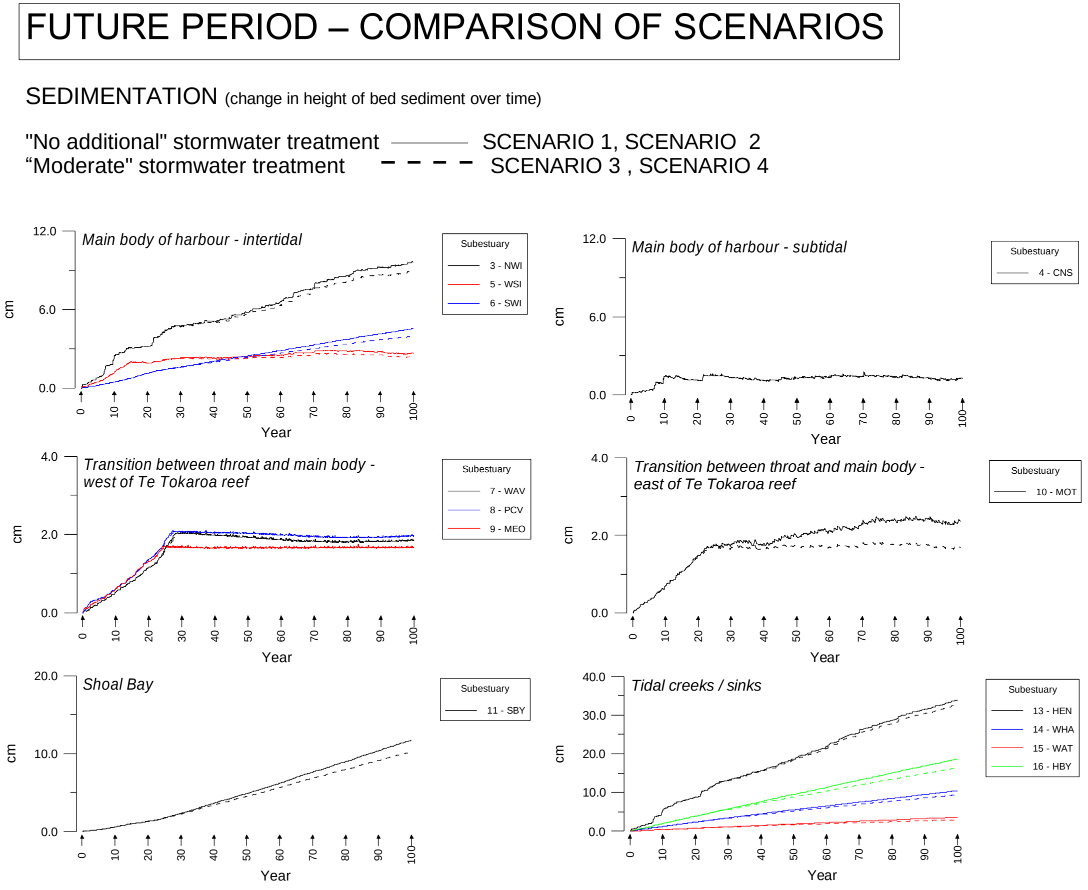


Figure 12

Schematic showing the change in sedimentation due to a widespread reduction in sediment run-off from the catchment over the next 15–20 years under "no additional" stormwater treatment (Scenarios 1 and 2).

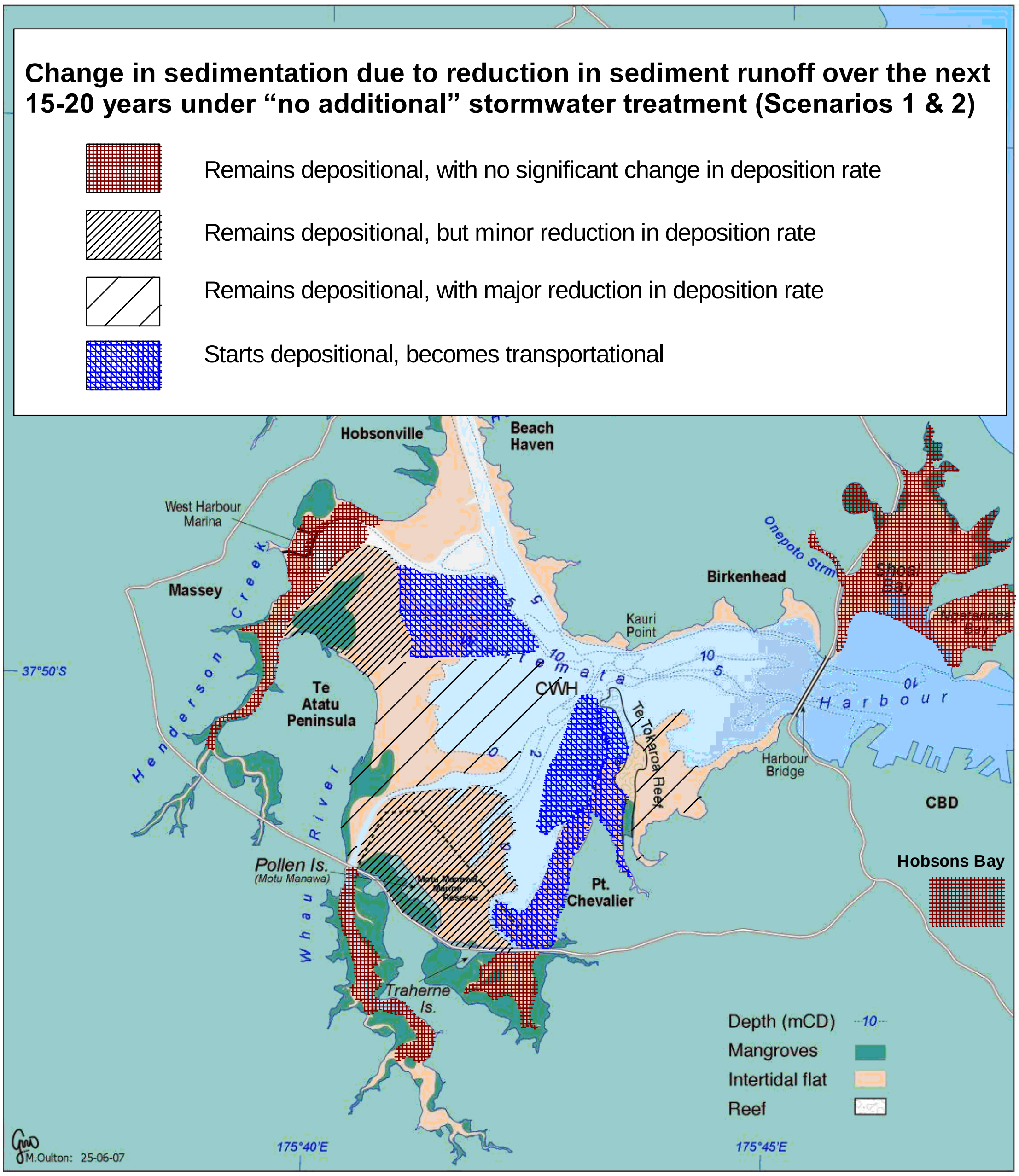


Figure 13
Schematic showing the change in sedimentation due to a widespread reduction in sediment run-off from the catchment over the next 15–20 years under "moderate" stormwater treatment (Scenarios 1 and 2).

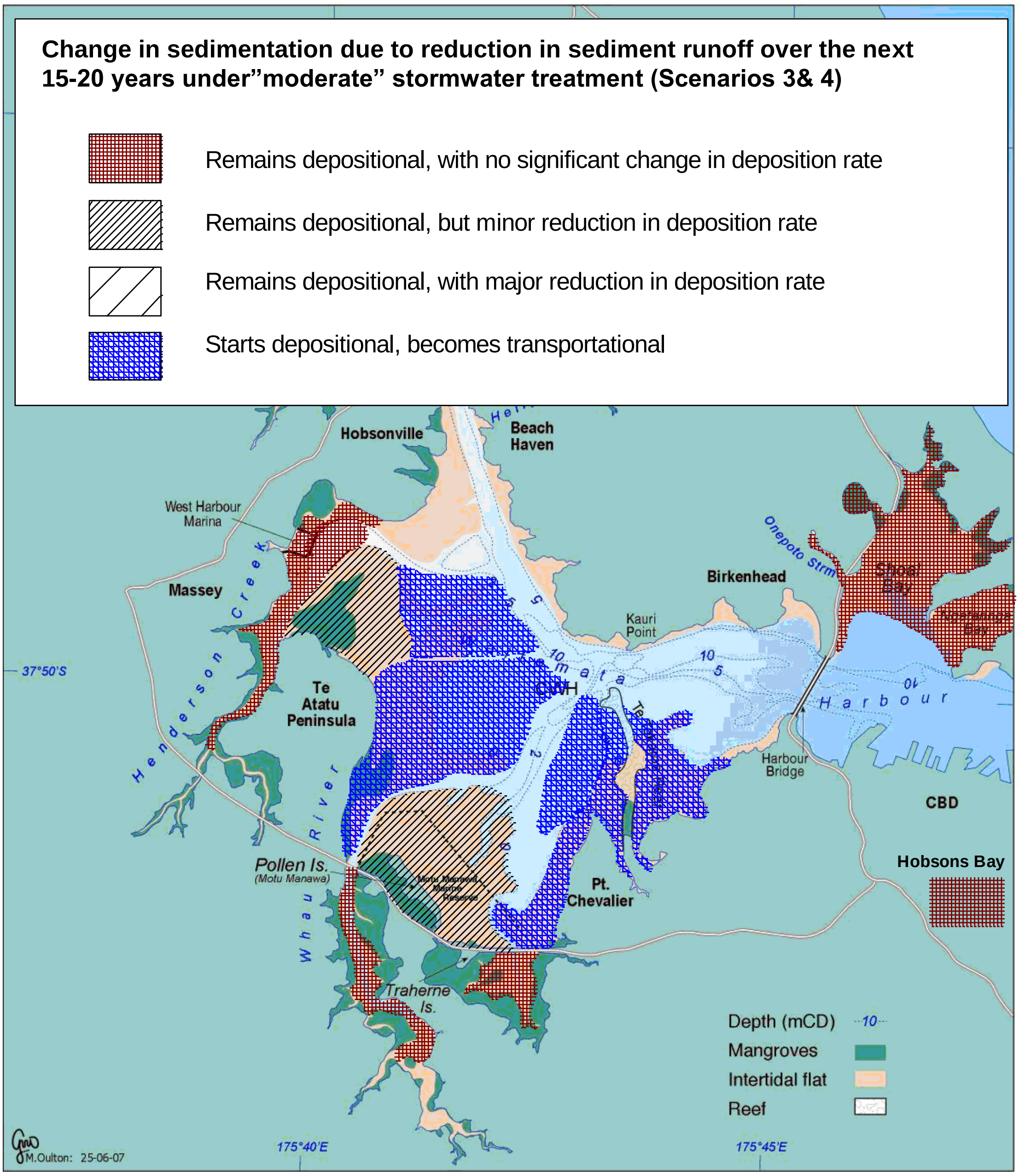


Figure 14

Schematic showing differences in sedimentation under "moderate" stormwater treatment (Scenarios 3 and 4) compared to under "no additional" stormwater treatment (Scenarios 1 and 2).

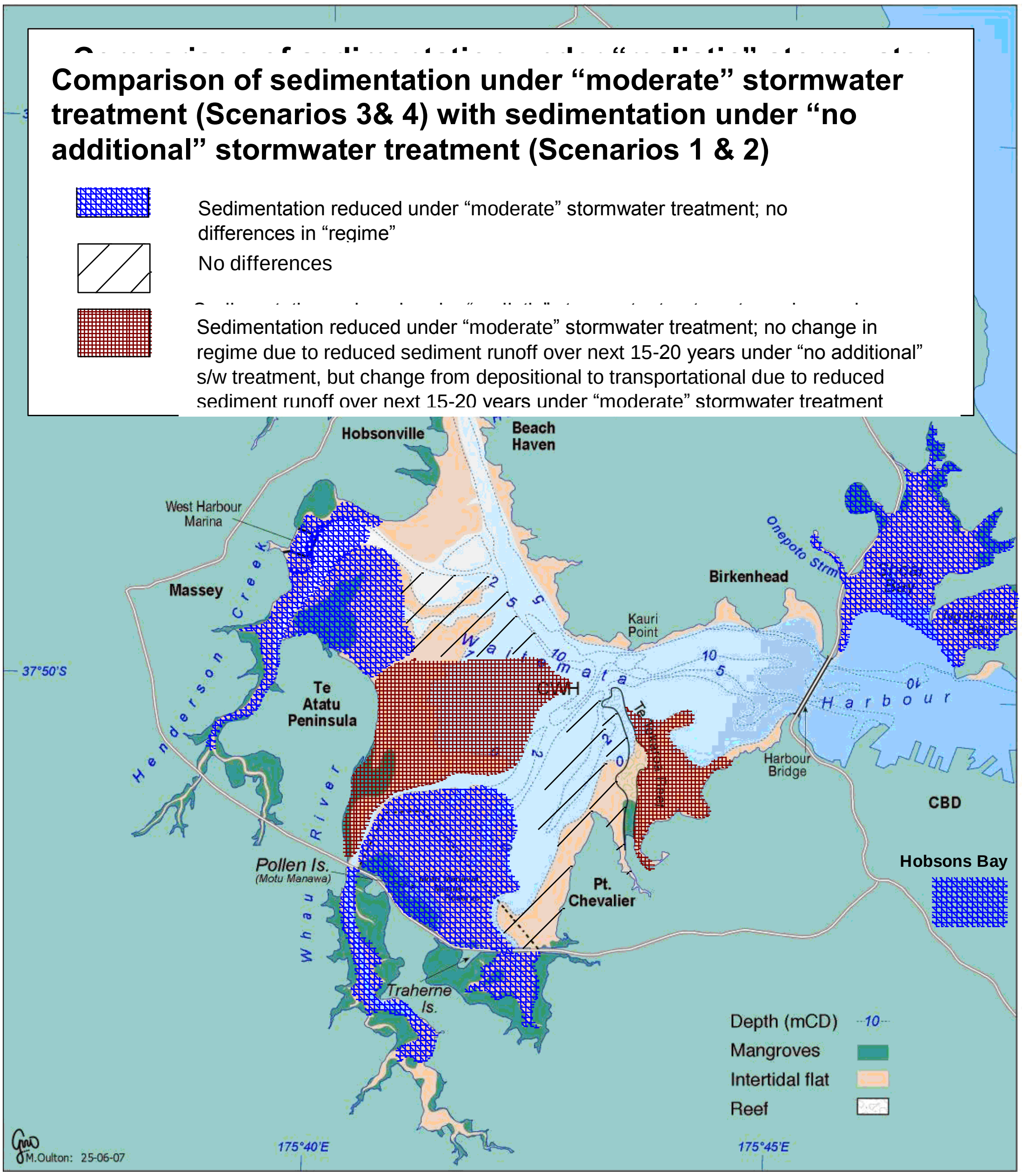


Figure 15

Predicted change in metal concentration for the future period for subestuaries that experience a virtually constant sedimentation rate throughout the period. Year 1 is 2001 and year 100 is 2101. Metal concentration is total metal per total sediment in the surface mixed layer. "Paint IGSR" denotes zinc source control by painting all unpainted and poorly painted industrial galvanised steel roofs.

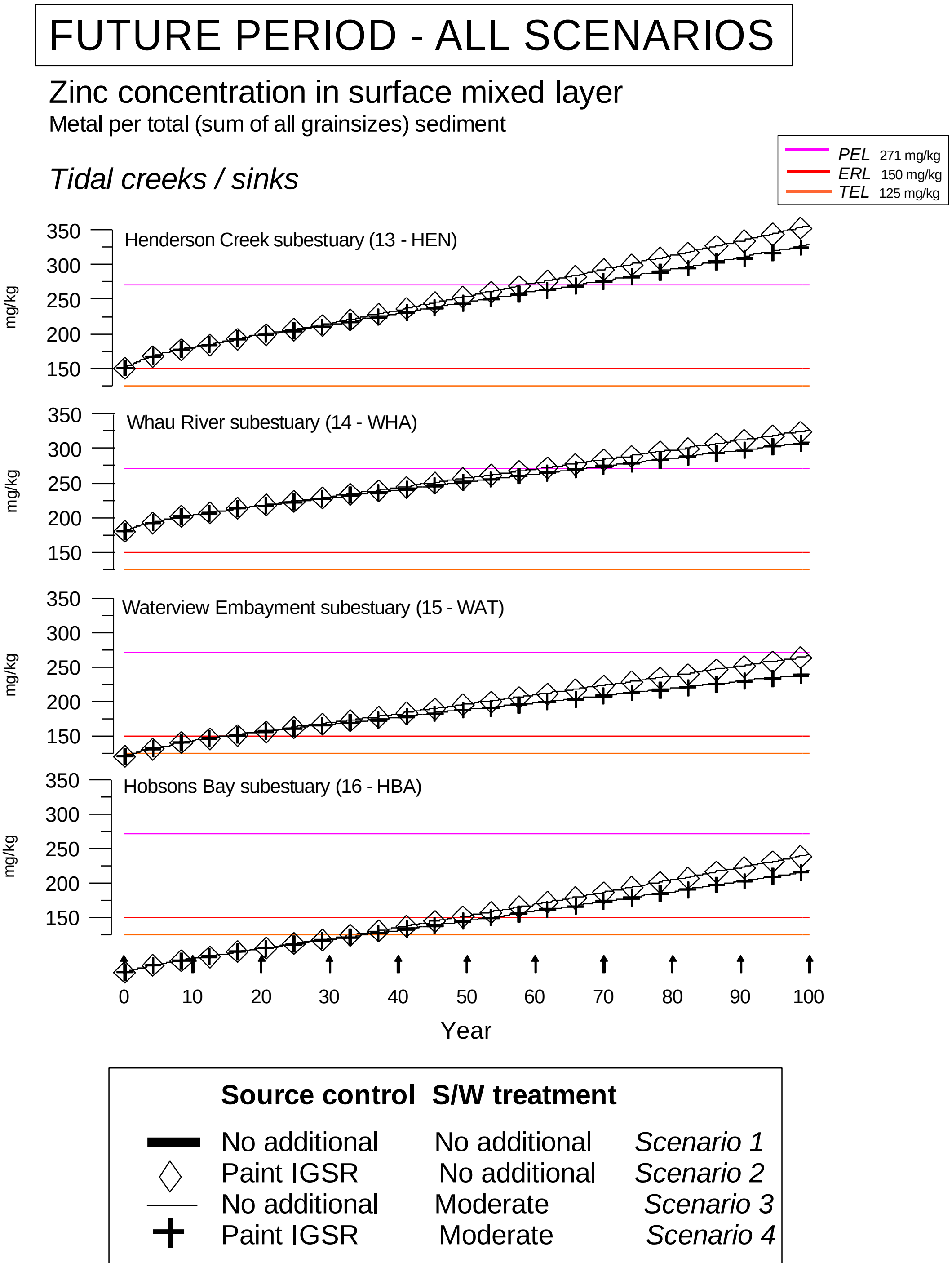


Figure 15 (cont.)

Predicted change in metal concentration for the future period for subestuaries that experience a virtually constant sedimentation rate throughout the period. Year 1 is 2001 and year 100 is 2101. Metal concentration is total metal per total sediment in the surface mixed layer. "Paint IGSR" denotes zinc source control by painting all unpainted and poorly painted industrial galvanised steel roofs.

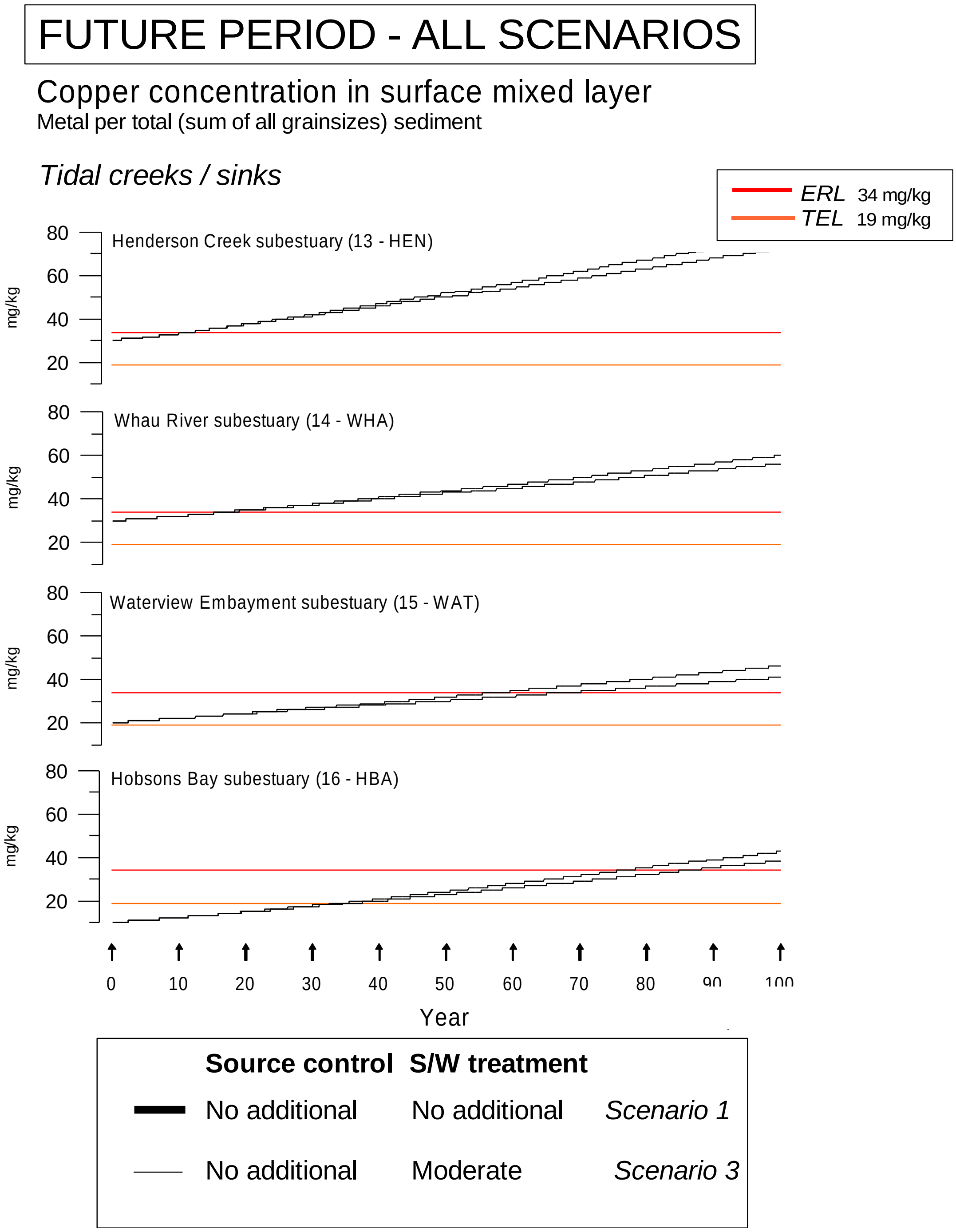


Figure 15 (cont.)

Predicted change in metal concentration for the future period for subestuaries that experience a virtually constant sedimentation rate throughout the period. Year 1 is 2001 and year 100 is 2101. Metal concentration is total metal per total sediment in the surface mixed layer. "Paint IGSR" denotes zinc source control by painting all unpainted and poorly painted industrial galvanised steel roofs.

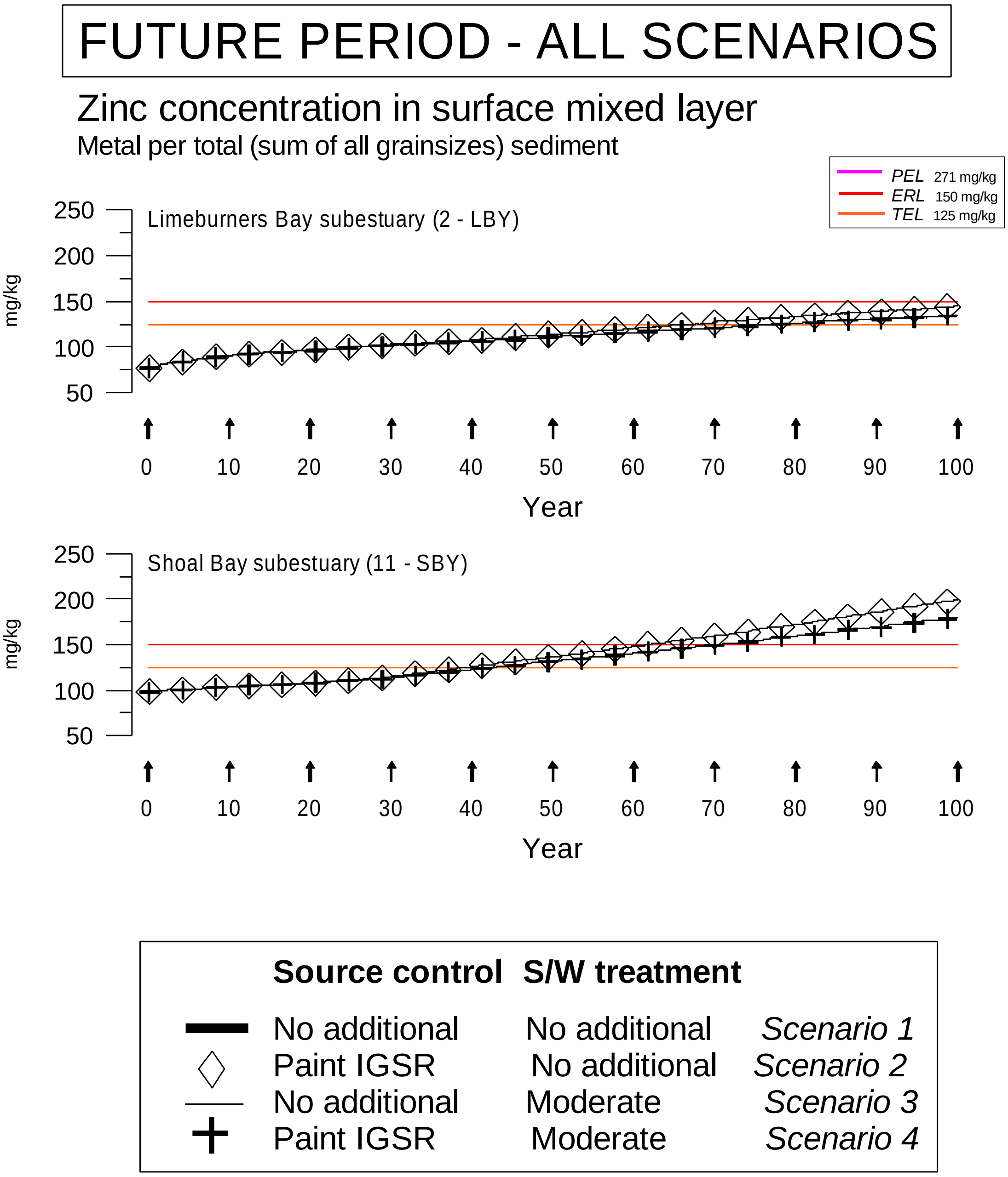


Figure 15 (cont.)
Predicted change in metal concentration for the future period for subestuaries that experience a virtually constant sedimentation rate throughout the period. Year 1 is 2001 and year 100 is 2101. Metal concentration is total metal per total sediment in the surface mixed layer. "Paint IGSR" denotes zinc source control by painting all unpainted and poorly painted industrial galvanised steel roofs.

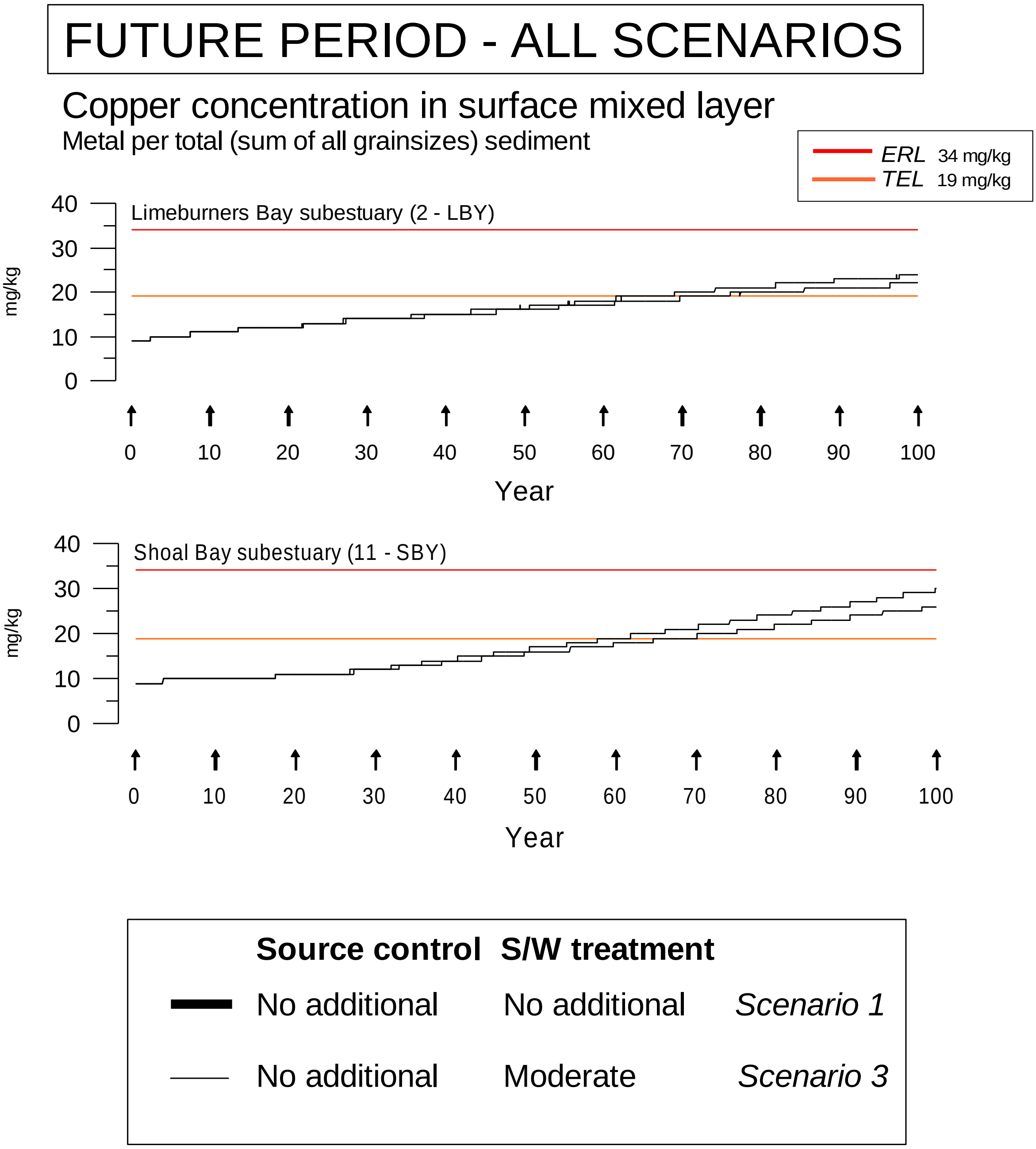


Figure 16

Predicted change in metal concentration for the future period for subestuaries that remain depositional but experience a decrease in sedimentation rate partway through the period. Year 1 is 2001 and year 100 is 2101. Metal concentration is total metal per total sediment in the surface mixed layer. "Paint IGSR" denotes zinc source control by painting all unpainted and poorly painted industrial galvanised steel roofs.

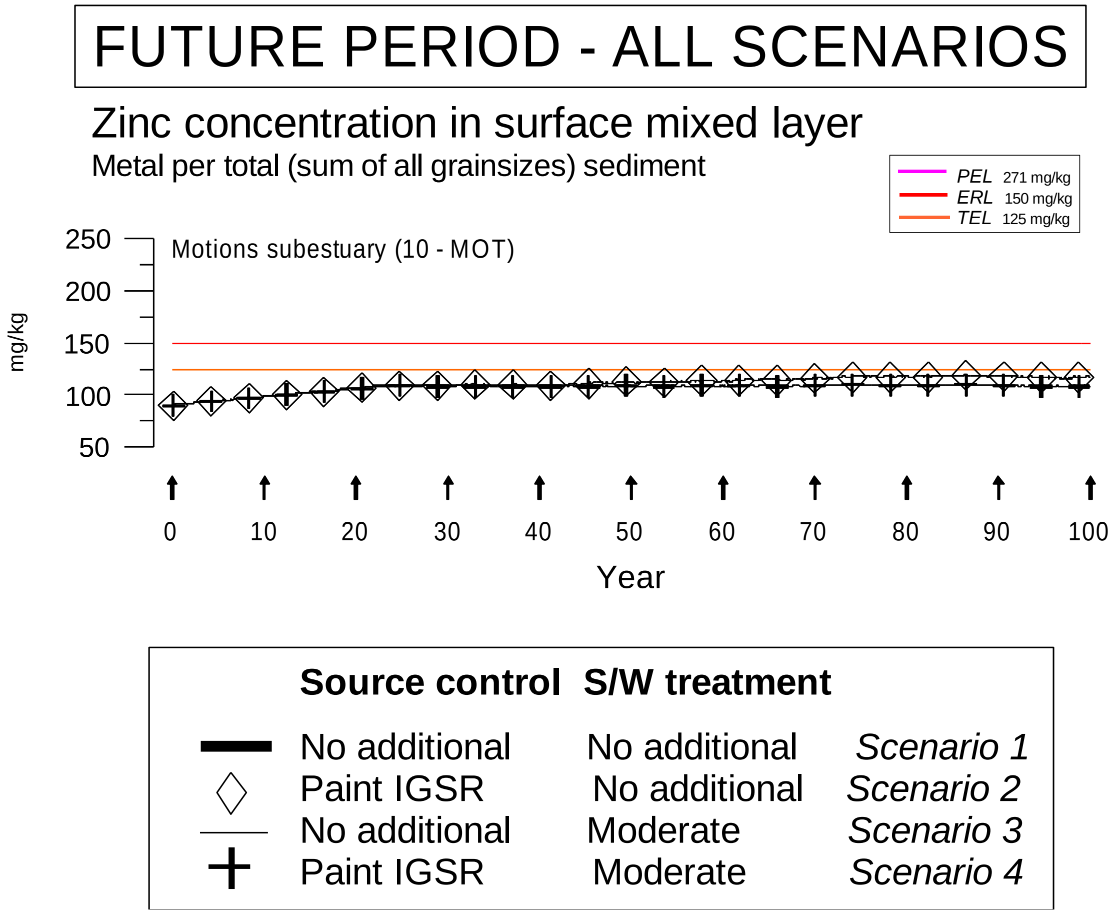


Figure 16 (cont.)

Predicted change in metal concentration for the future period for subestuaries that remain depositional but experience a decrease in sedimentation rate partway through the period. Year 1 is 2001 and year 100 is 2101. Metal concentration is total metal per total sediment in the surface mixed layer. "Paint IGSR" denotes zinc source control by painting all unpainted and poorly painted industrial galvanised steel roofs.

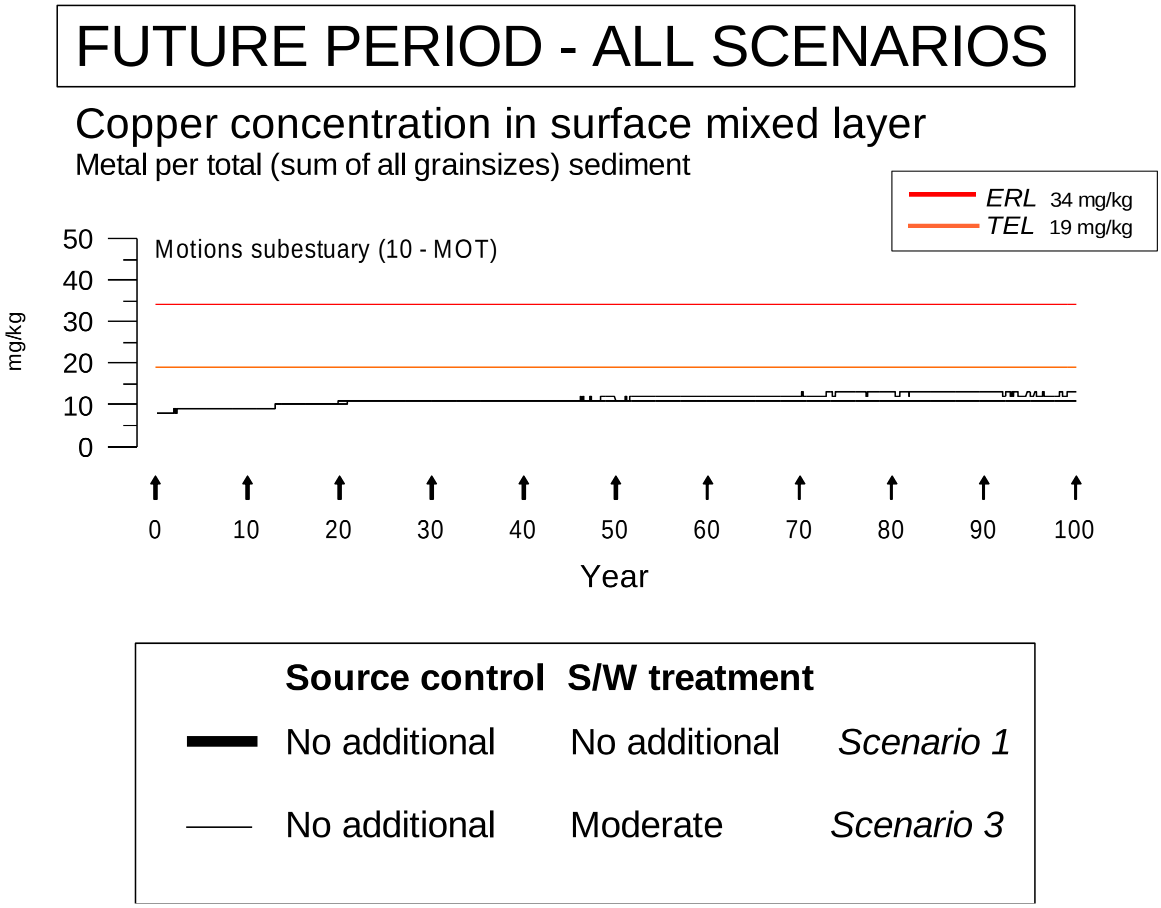


Figure 17
Predicted change in metal concentration for the future period for subestuaries that remain depositional but experience a decrease in sedimentation rate partway through the period. Year 1 is 2001 and year 100 is 2101. Metal concentration is total metal per total sediment in the surface mixed layer. "Paint IGSR" denotes zinc source control by painting all unpainted and poorly painted industrial galvanised steel roofs.

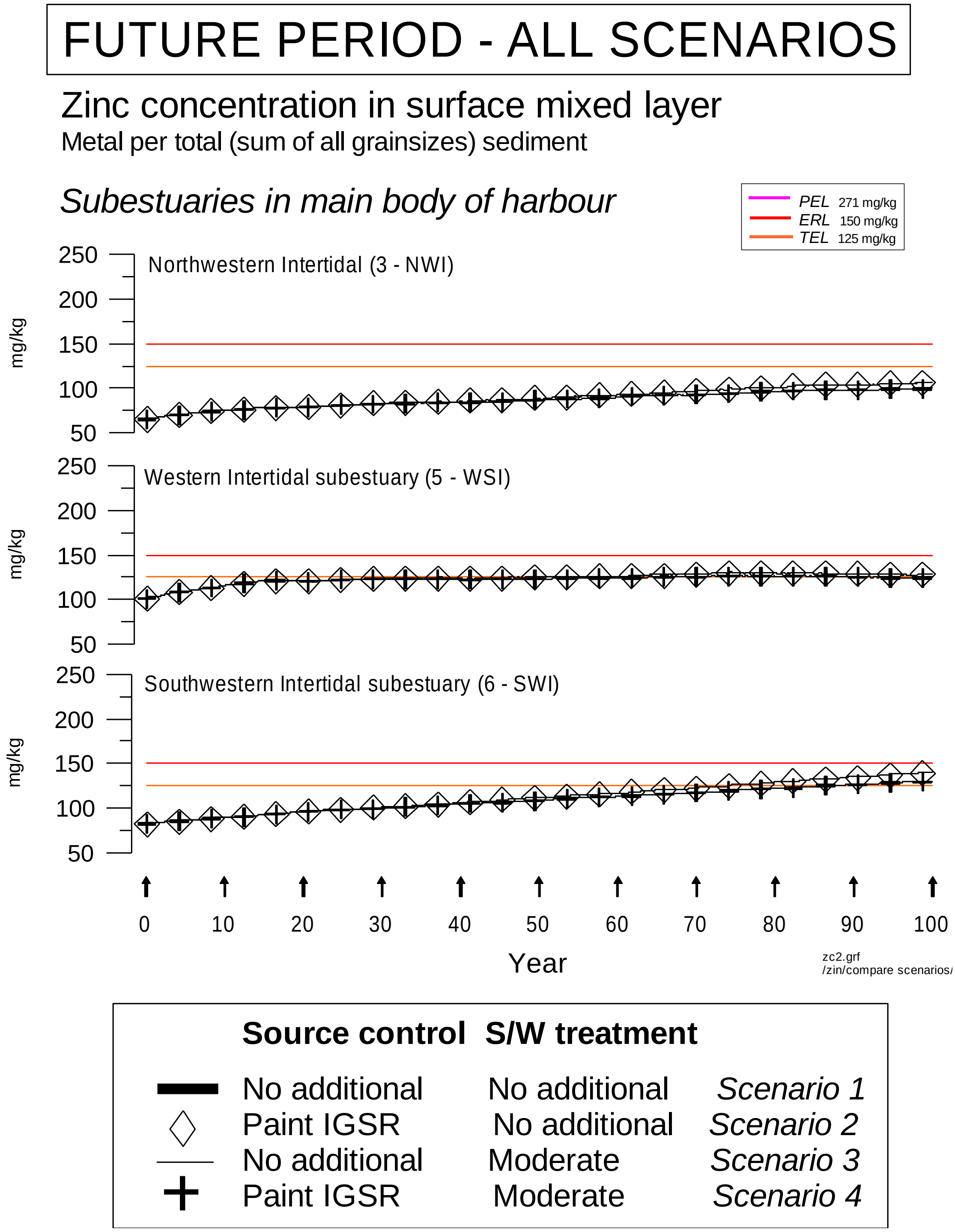


Figure 17 (cont.)
Predicted change in metal concentration for the future period for subestuaries that remain depositional but experience a decrease in sedimentation rate partway through the period. Year 1 is 2001 and year 100 is 2101. Metal concentration is total metal per total sediment in the surface mixed layer. "Paint IGSR" denotes zinc source control by painting all unpainted and poorly painted industrial galvanised steel roofs.

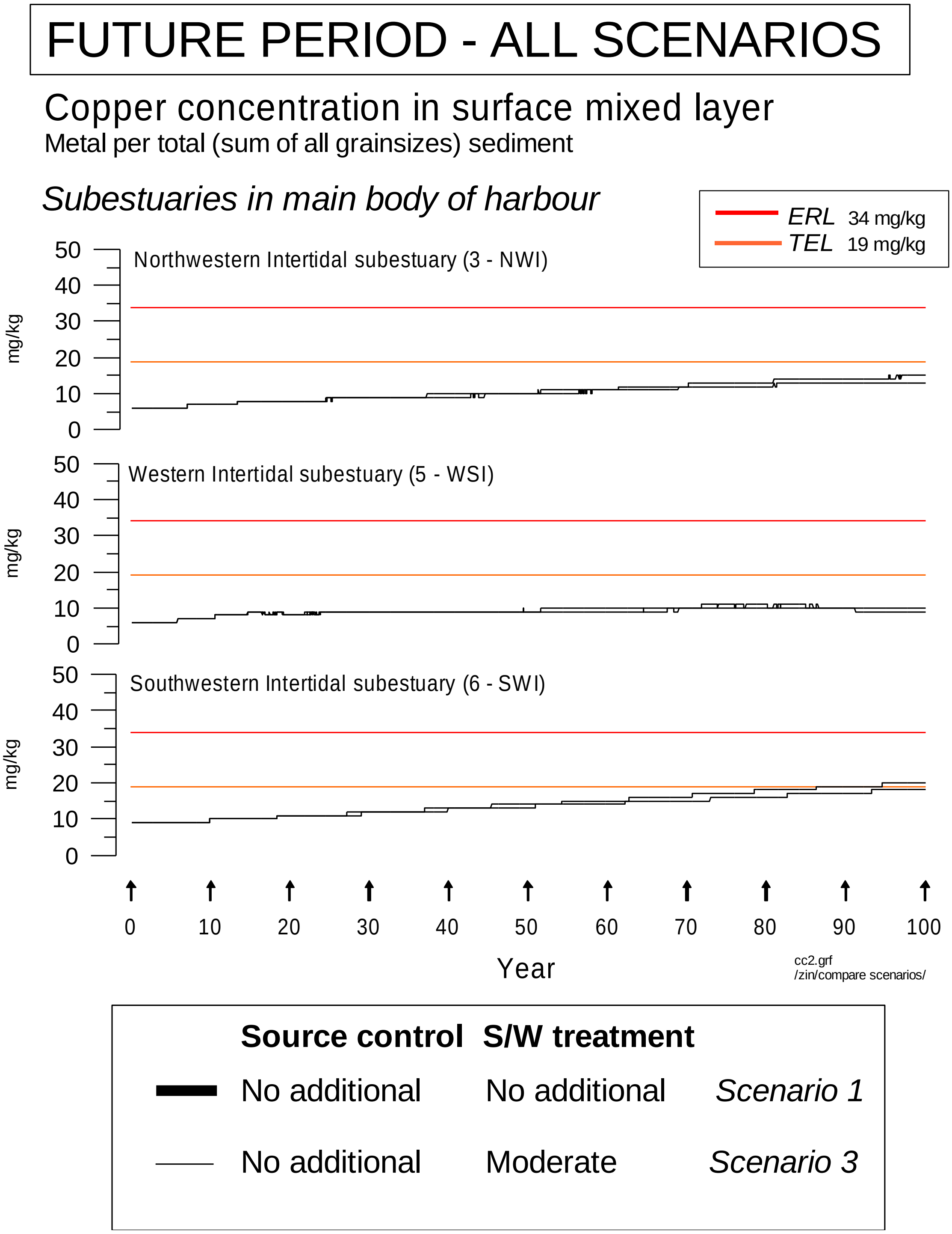


Figure 18

Predicted change in metal concentration for the future period for subestuaries that become transportational partway through the period. Year 1 is 2001 and year 100 is 2101. Metal concentration is total metal per total sediment in the surface mixed layer. "Paint IGSR" denotes zinc source control by painting all unpainted and poorly painted industrial galvanised steel roofs.

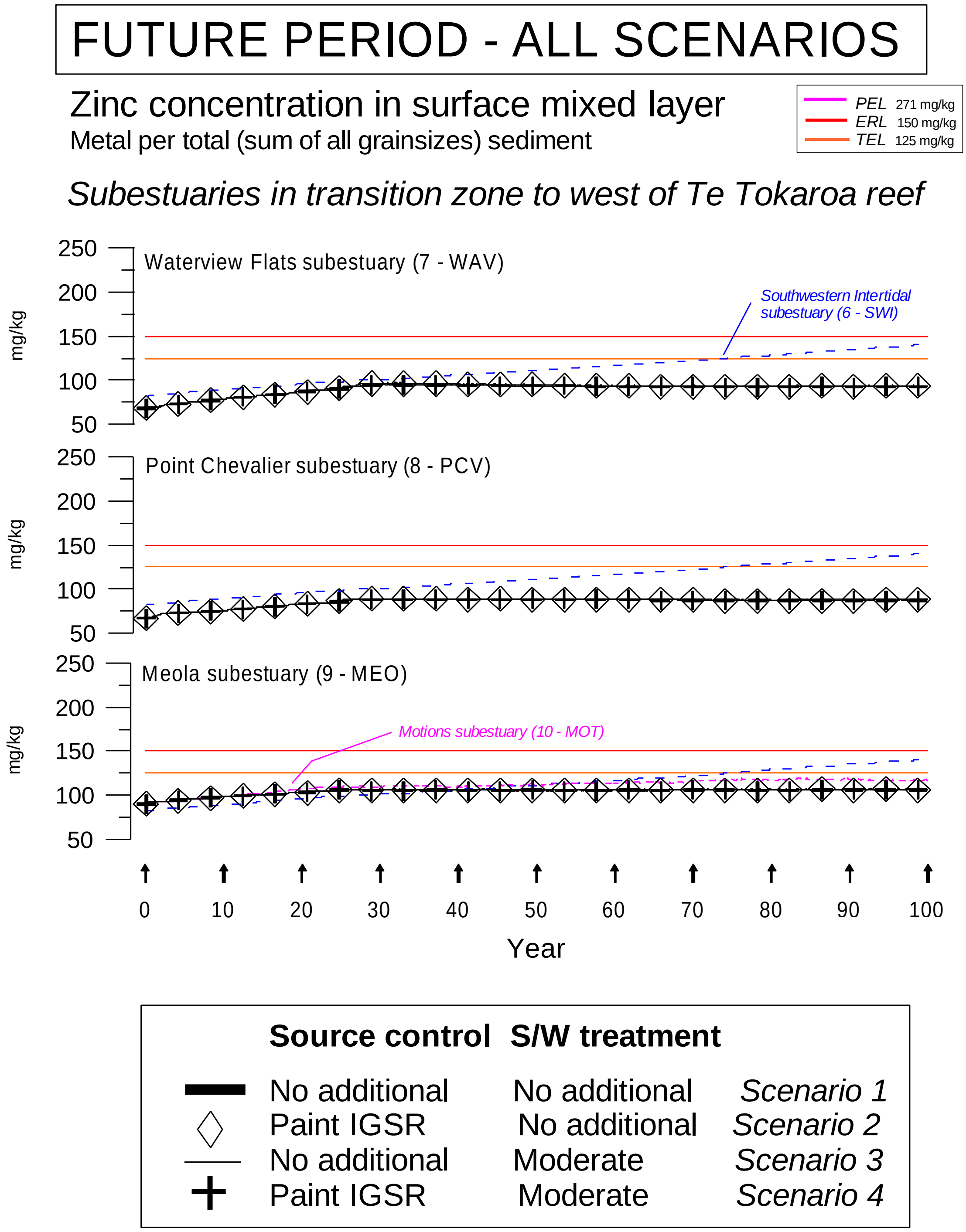


Figure 18 (cont.)
Predicted change in metal concentration for the future period for subestuaries that become transportational partway through the period. Year 1 is 2001 and year 100 is 2101. Metal concentration is total metal per total sediment in the surface mixed layer. "Paint IGSR" denotes zinc source control by painting all unpainted and poorly painted industrial galvanised steel roofs.

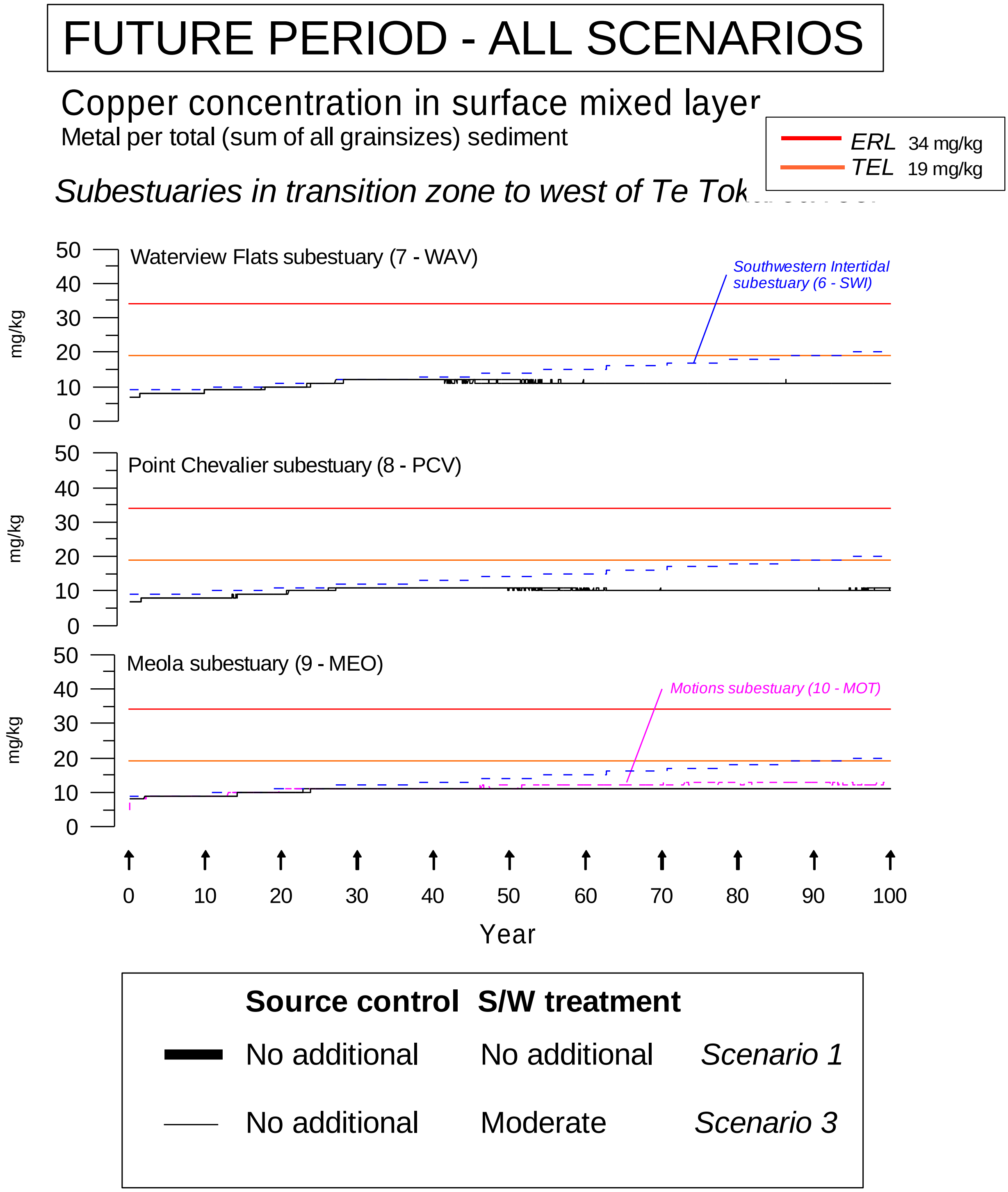


Figure 18 (cont.)

Predicted change in metal concentration for the future period for subestuaries that become transportational partway through the period. Year 1 is 2001 and year 100 is 2101. Metal concentration is total metal per total sediment in the surface mixed layer. "Paint IGSR" denotes zinc source control by painting all unpainted and poorly painted industrial galvanised steel roofs.

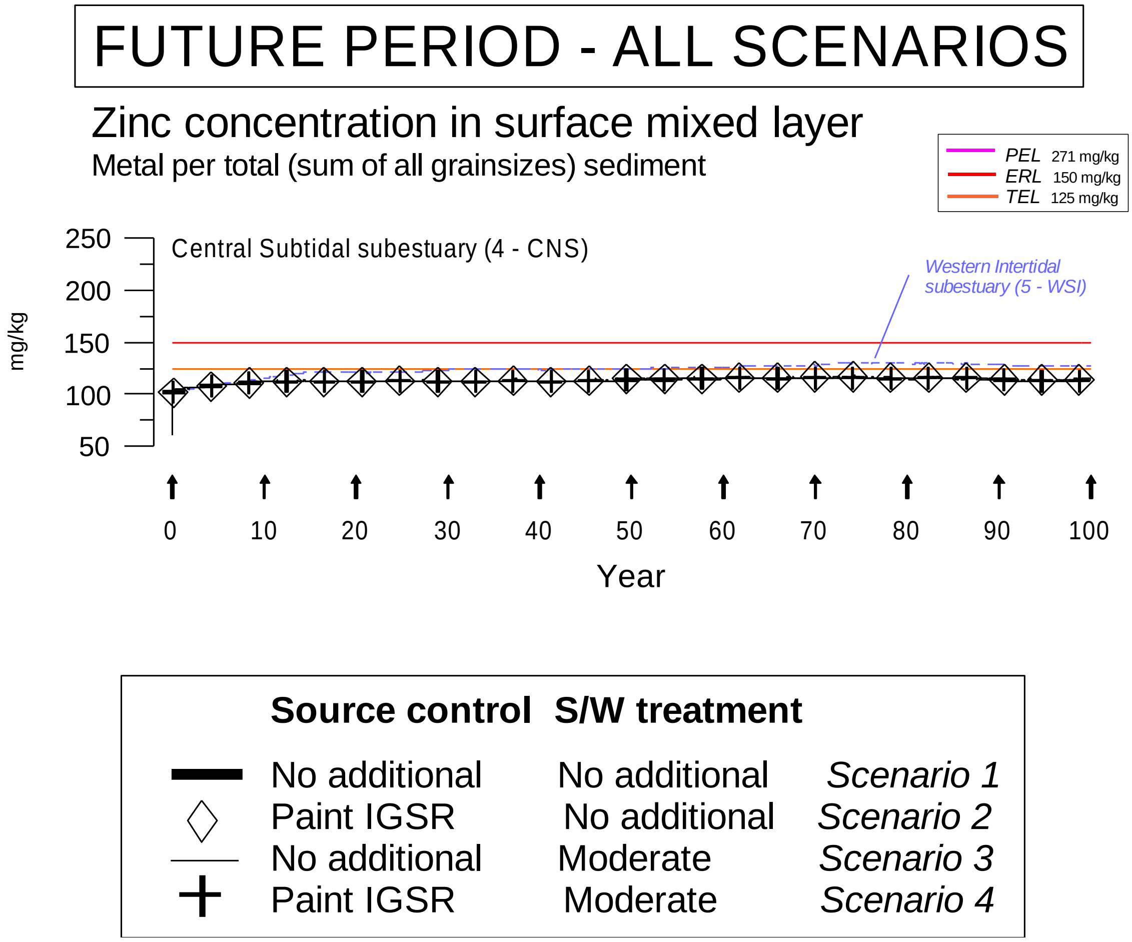


Figure 18 (cont.)
Predicted change in metal concentration for the future period for subestuaries that become transportational partway through the period. Year 1 is 2001 and year 100 is 2101. Metal concentration is total metal per total sediment in the surface mixed layer. "Paint IGSR" denotes zinc source control by painting all unpainted and poorly painted industrial galvanised steel roofs.

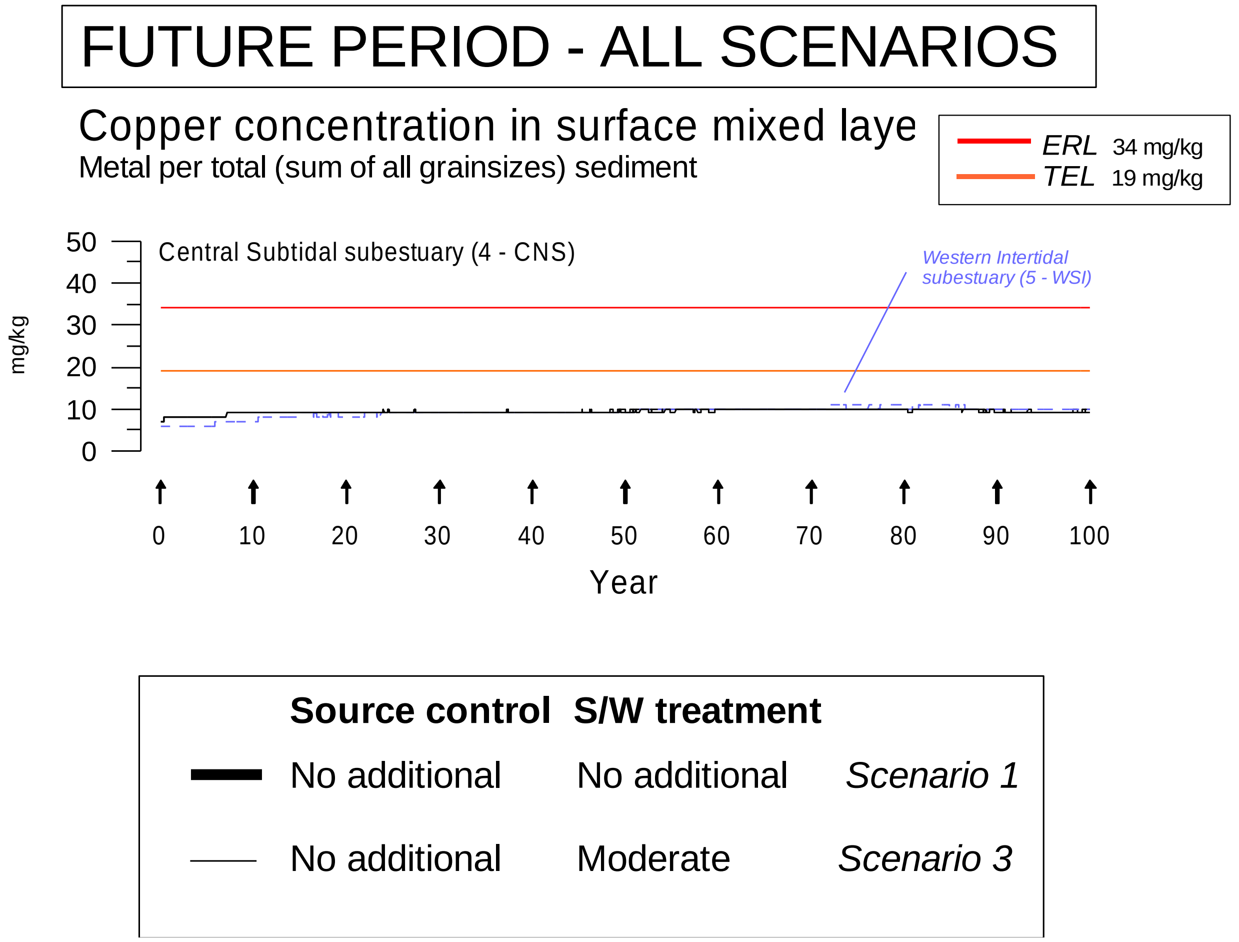


Figure 19

Predicted change in metal concentration for the future period for Hobsonville subestuary. Year 1 is 2001 and year 100 is 2101. Metal concentration is total metal per total sediment in the surface mixed layer. "Paint IGSR" denotes zinc source control by painting all unpainted and poorly painted industrial galvanised steel roofs.

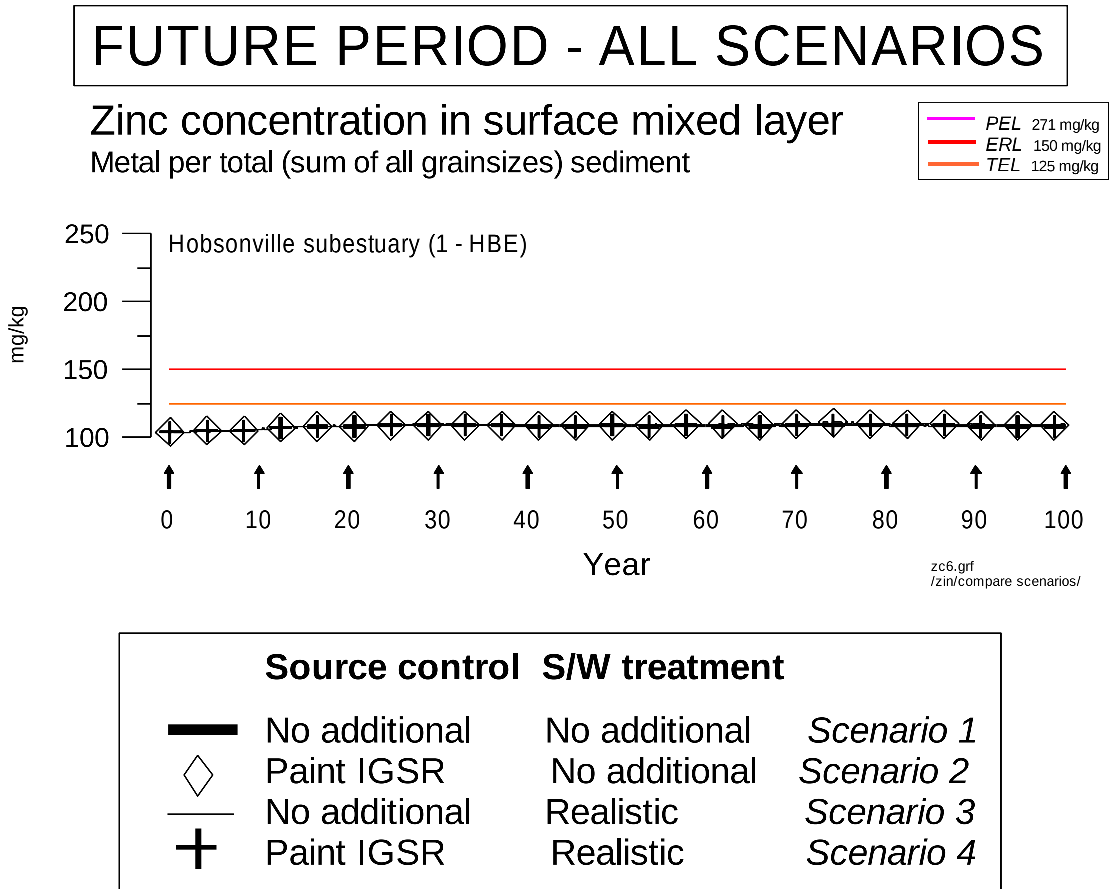
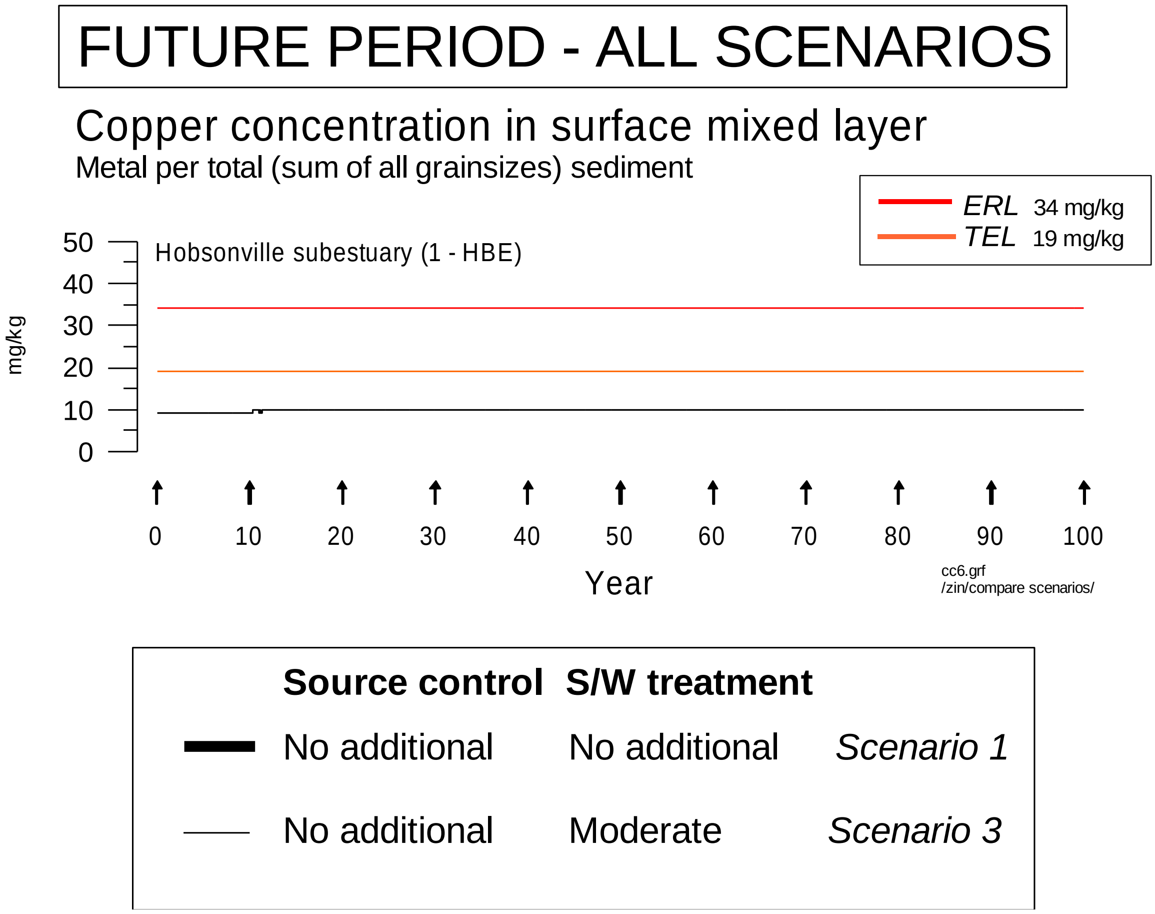


Figure 19 (cont.)

Predicted change in metal concentration for the future period for Hobsonville subestuary. Year 1 is 2001 and year 100 is 2101. Metal concentration is total metal per total sediment in the surface mixed layer. "Paint IGSR" denotes zinc source control by painting all unpainted and poorly painted industrial galvanised steel roofs.



5 Conclusions

The zinc source control has virtually no effect on the zinc sediment-quality guideline threshold exceedance times. The more effective "moderate" stormwater treatment depicted in Scenarios 3 and 4 generally extends the zinc and copper threshold exceedance times by around 10 years or less compared to Scenarios 1 and 2 with the "no additional" stormwater treatment. However, it is also noteworthy that the more effective "moderate" stormwater treatment generally does not prevent any thresholds from being exceeded. That is, all subestuaries that exceed a threshold under the less effective "no additional" stormwater treatment exceed that same threshold (albeit a little later) under the more effective "moderate" stormwater treatment. Because of this, the schematic summaries of zinc and copper sediment-quality guideline threshold exceedances presented by Green (2008b) for Scenario 1 also apply to Scenarios 2, 3 and 4. These summaries are reproduced from Green (2008b) in Figures 20 and 21.

Green (2008b) also provided a high-level, simplified summary of the results for Scenario 1, which is reproduced here in Figure 22. In this view, subestuaries were classified as either "Management Alert" or "Management Watch". The classification was based on zinc only, since zinc is predicted to accumulate in greater concentrations than copper.

- Management Alert includes the categories "PEL threshold exceeded", "PEL threshold on track to exceedance" and "ERL threshold exceeded" shown in Figure 20. This denotes subestuaries for which management may need to act now or soon to arrest the accumulation of heavy metals to safeguard ecological values. The rationale is that ERL thresholds either already have been or soon will be exceeded, and in some cases PEL thresholds will be exceeded. Subestuaries assigned to Management Alert are the tidal creeks around the fringes of the harbour (Henderson Creek and the associated Limeburners Bay, Whau River, Waterview Embayment), Shoal Bay and Hobsons Bay.
- Management Watch includes all the other categories shown in Figure 20. This denotes subestuaries that may not require management action now or soon, but that should be watched in the future anyway. The rationale is that the TEL threshold is either not predicted to be exceeded or, if it is, it is decades into the future, in many cases when the rate at which metals are building up is reducing anyway.

Green's (2008b) high-level summary also applies to Scenarios 2, 3 and 4.

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

Figure 20

Green's (2008b) schematic summary of zinc sediment-quality guideline threshold exceedance throughout the harbour for Scenario 1. Because none of the mitigation measures investigated in Scenarios 2, 3 and 4 prevent thresholds from being exceeded, the same general picture applies to Scenarios 2, 3 and 4.

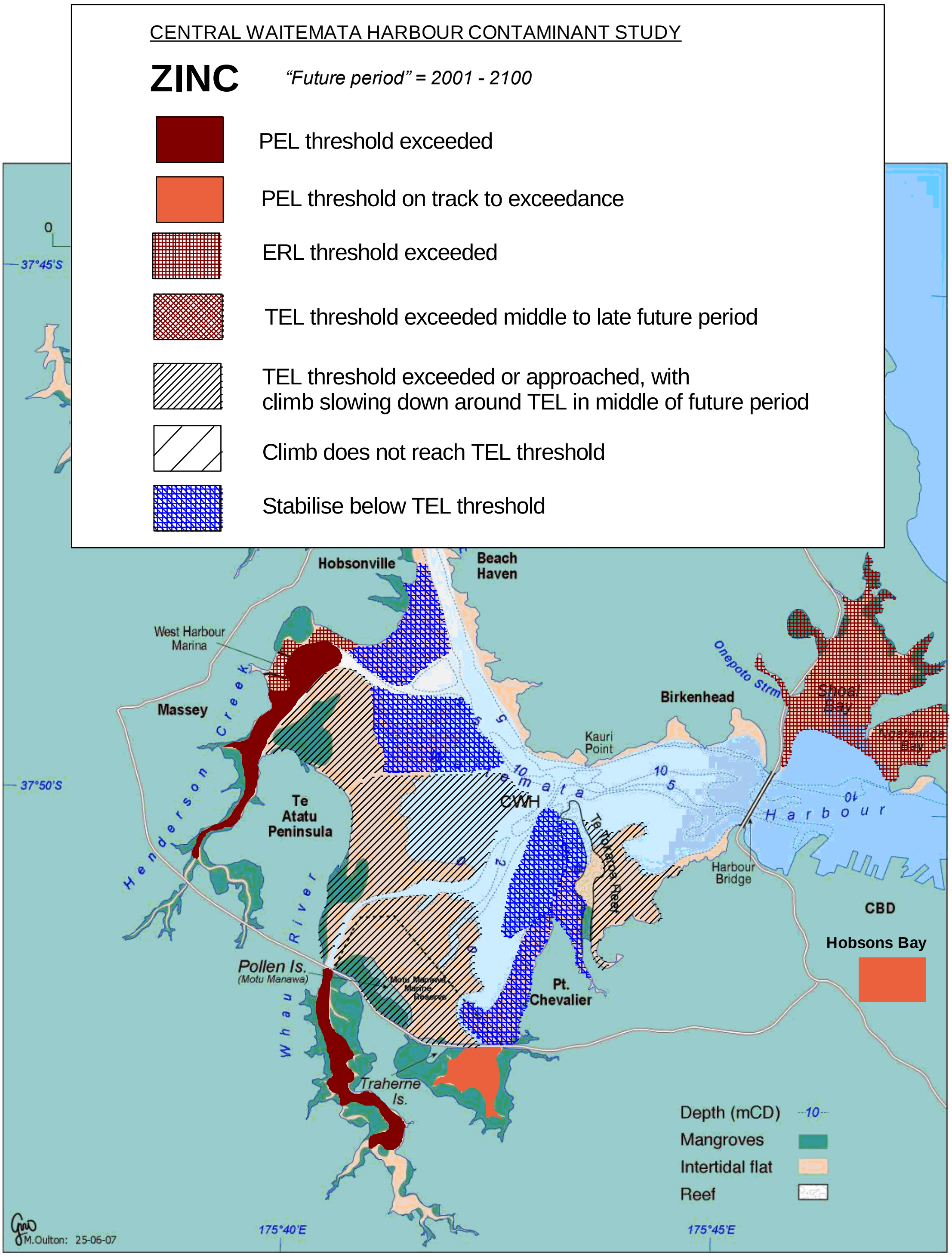


Figure 21

Green's (2008b) schematic summary of copper sediment-quality guideline threshold exceedance throughout the harbour. Because none of the mitigation measures investigated in Scenarios 2, 3 and 4 prevent thresholds from being exceeded, the same general picture applies to Scenarios 2, 3 and 4.

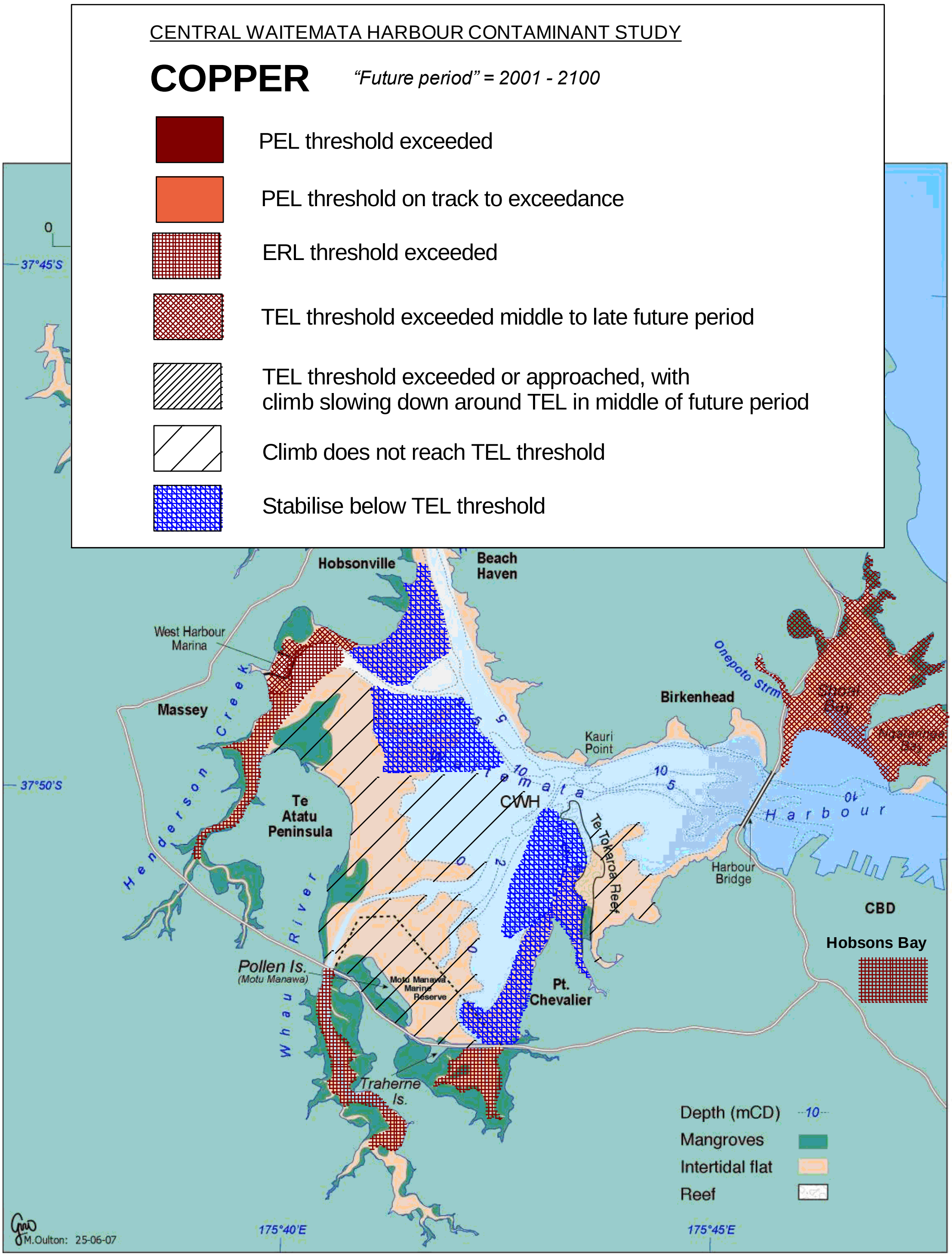
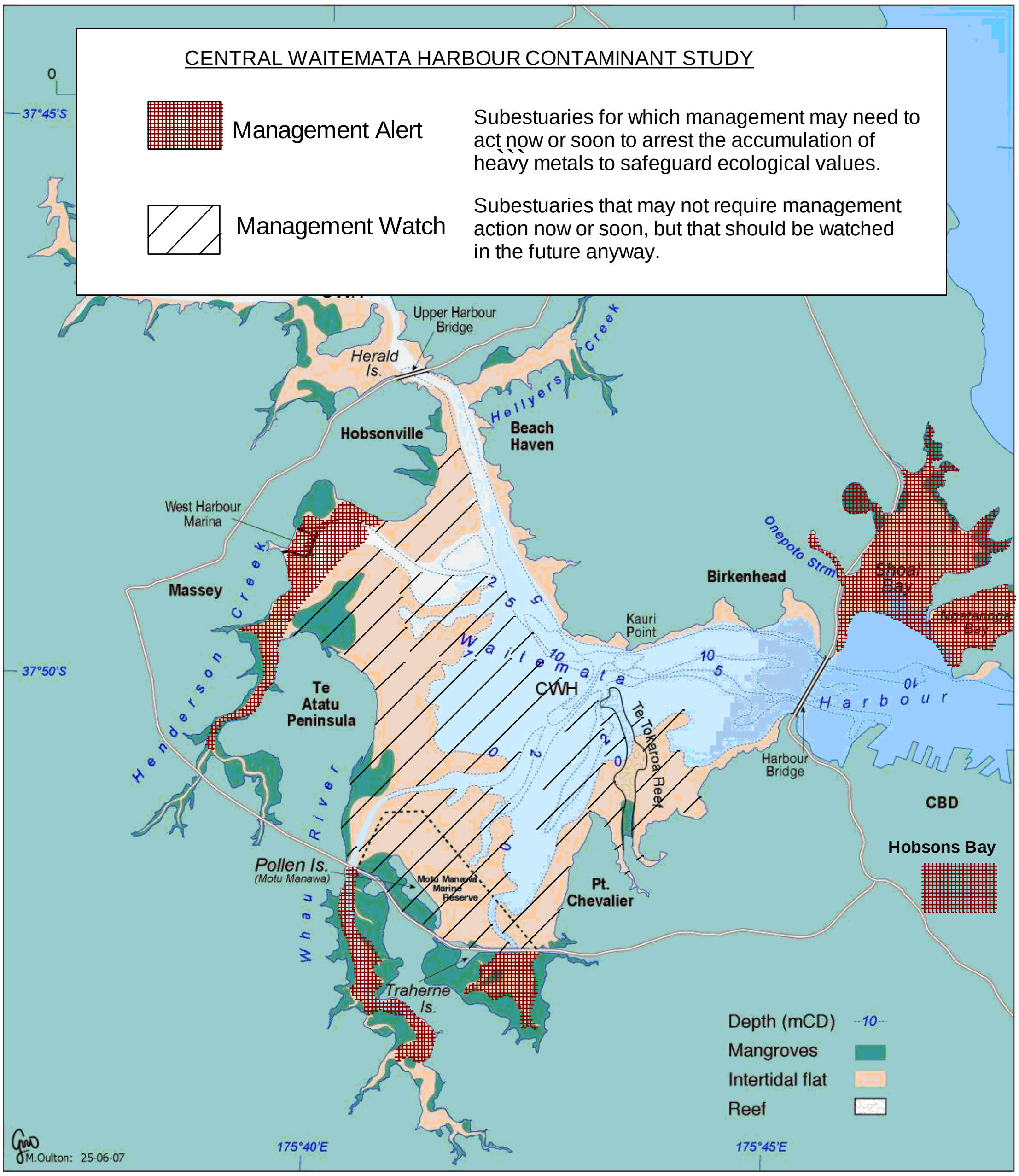


Figure 22

Green's (2008b) high-level, simplified summary of the results for Scenario 1. Refer to the text for explanation. The same summary applies to Scenarios 2, 3 and 4.



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