Tauranga Harbour Sediment Study: Predictions of Harbour Sedimentation under Future Scenarios

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Tauranga Harbour Sediment Study: Predictions of Harbour Sedimentation under Future Scenarios

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Prepared for

Environment Bay of Plenty

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Executive Summary

This report describes predictions by the USC-3 model of sedimentation in southern Tauranga Harbour over the “planning timescale”, which is decades and greater. The model is physically based, and is intended to support decision-making by predicting various changes in the harbour bed sediments associated with catchment development scenarios that will cause changes in sediment runoff from the catchment. 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 grainsize.

The USC-3 model was run for the period 2001–2051 under three future scenarios. Scenario 1 has present-day (2001) landuse and present-day weather. This scenario is intended as a baseline against which comparisons can be made. Scenario 2 has landuse as provided for in SmartGrowth, and present-day weather. Scenario 3 has the same landuse as Scenario 2, but the weather incorporates anticipated effects of climate change.

A random block-sampling scheme was applied to the GLEAMS-TAU model predictions of sediment runoff from the catchment to produce daily land-derived sediment loads at the base of each subcatchment for each of Scenarios 1, 2 and 3. The GLEAMS-TAU model predictions are assumed to represent a fine-sediment suspended load. For all but the three largest subcatchments (those drained by the Wairoa River, Kopurererua Stream and Waimapu Stream), the coarse-sediment bedload was assumed to be zero. Bedload from the three largest subcatchments was estimated as 0.45 of the fine-sediment suspended load.

With one exception, subcatchment sediment runoff under landuse change will typically reduce slightly or not change at all. The exception is the Matua subcatchment, which will undergo significant urbanisation, resulting in significant reduction of sediment runoff. In contrast, climate change is predicted to increase sediment runoff from every subcatchment.

Sediment-transport patterns in the harbour are described in order to provide background for understanding how changes in sediment runoff from the land get translated into changes in sedimentation in the harbour. Fine-sediment loss to the ocean is greatest from those subcatchments that discharge close to the (southern) mouth of the harbour. Nearly all (95%) of the fine sediment discharged from Wairoa River, which has the largest freshwater discharge and sediment runoff of any subcatchment, is lost to the ocean. Compared to the loss of fine sediment, the loss of coarse sediment to the ocean is much smaller. This is because the coarser sediment grains are heavier, and therefore less easily dispersed and resuspended by waves and currents. The fate of fine sediment discharged from each subcatchment and the source of fine sediment deposited in each subestuary are described.

Two important general findings concerning the change in sedimentation under landuse/climate change are:

- In general, there is not an exact correspondence between change in sedimentation rate in any given subestuary and change in sediment runoff from the subcatchment that is the largest source of sediment to that subestuary. There are two reasons. Firstly, subestuaries typically deposit sediment from more than one subcatchment, and the changes in sediment runoff under the various scenarios are usually different for each subcatchment. Secondly, the patterns of sediment transport in the harbour can be changed by changes in sediment runoff from the catchment, which can alter the relationships between sources and sinks. This is a hallmark of a nonlinear model, which can throw up unexpected results.

- A typical response in the harbour is that there is an increase in subestuary sedimentation rate that is greater than the corresponding increase in sediment runoff from the primary source of sediment to that subestuary, which is called here a “positive imbalance”. A possible likely explanation is that harbour resuspension processes, which otherwise are quite effective at scouring fine sediment, resulting in loss of sediment to the coastal ocean, get overwhelmed by the larger sediment runoff from the catchment.

For all subestuaries, the dominant driver of change is climate change (as opposed to landuse change). This always results in an increase in sedimentation which, furthermore, is “positively imbalanced”.

The seabed composition will become progressively altered where fine sediments deposit on a relatively coarser pre-existing bed, and vice versa. A description of changes in seabed composition under landuse change and climate change is presented, drawing together the predictions of sedimentation by the USC–3 model, and information on present-day bed sediment composition.

Some preliminary interpretations of the results in terms of risk to estuarine ecology are presented. The next phase of the Tauranga Harbour Sediment Study is to discuss more fully, in a workshop setting, the implications of the findings for the ecology and management of the harbour.

1. Introduction

1.1 Background

Environment Bay of Plenty (EBOP) seeks to understand sedimentation in Tauranga Harbour in order to understand sediment sources and fate sufficiently to appropriately manage growth and development now and in the future. This will also assist EBOP to adapt management rules and practices appropriately and be able to make decisions concerning development of the harbour and catchment with full understanding of likely sedimentation effects. This need stems from section 5 of the Tauranga Harbour Integrated Management Study (THIMS), which describes the many effects of sediments. Although these changes are to a large extent driven by historical events when there was little control on development, there is increasing public concern about sediment-related issues, and these are expected to escalate as the catchment continues to develop and climate change becomes increasingly felt. The THIMS recommended a review of the drivers and consequences of sedimentation, including analysis of sediment yields from all sources in the catchment, peak flow monitoring, projection of sediment yields under proposed development scenarios, assessment of sediment effects in the harbour including cumulative effects, analysis of current best practices, and recommendations on how to address the findings, including appropriate policy.

EBOP contracted NIWA to conduct the Tauranga Harbour Sediment Study. The study began in April 2007 and is scheduled to run for 3 years. The main aim of the study is to develop a model or models to be used to: (1) assess relative contributions of the various sediment sources in the catchment surrounding Tauranga Harbour, (2) assess the characteristics of significant sediment sources, and (3) investigate the fate (dispersal and deposition) of catchment sediments in Tauranga Harbour. The project area is defined as the southern harbour, extending from Matahui Point to Rangataua Bay in the south. The timeframe for predictions is 50 years from the present day (2001).

1.2 Study outline and modules

The study consists of 6 modules:

Module A: Specification of scenarios – Defines landuse and weather information that is required for driving the various models. Three scenarios are defined in terms of landuse, which includes earthworks associated with any development, and weather. The weather is described in terms of magnitude and frequency of storms and wind climate, and needs to be specified to a degree that is sufficient for driving models. The third scenario incorporates anticipated effects of climate change.

Module B: Catchment sediment modelling – (1) Uses the GLEAMS model to predict time series of daily sediment yields from each subcatchment under each scenario. (2) Summarises these predictions to identify principal sources of sediment in the catchment in order to compare sources of sediment under present-day landuse and under future development scenarios and to assess sediment characteristics of significant sources. (3) Provides sediment loads to the USC-3 model for prediction of harbour sedimentation over the decadal scale.

Module C: Harbour bed sediments – (1) Develops a description of the harbour bed sediments to provide sediment grainsize and composition information required for running the harbour sediment-transport model and for initialising the USC-3 model. (2) Provides information on sedimentation rates over the past 50 years for end-of-chain model validation.

Module D: Harbour modelling – (1) Uses the DHI FM (Flexible Mesh) hydrodynamic and sediment models and the SWAN wave model to develop predictions of sediment dispersal and deposition at the "snapshot" or event scale, including during and between rainstorms and under a range of wind conditions. (2) Provides these event predictions to the USC-3 model for prediction of harbour sedimentation over decadal scales.

Module E: USC-3 model – Uses the USC-3 model to make predictions of sedimentation, bed-sediment composition and linkages between sources and sinks, based on division of the catchment into subcatchments and the estuary into subestuaries. An end-of-chain model validation will consist of comparing USC-3 model hindcasts of annual-average sedimentation rate to measurements, where the measurements derive from Module C.

Module F: Assessment of predictions for management – Assesses and synthesises information developed in the modelling components of the study using an expert panel approach. It will address matters including: (1) Which catchments are more important as priority areas for focusing resources to reduce sedimentation in the harbour? (2) What are the likely effects of existing and future urban development on the harbour? (3) How can the appropriate regulatory agencies (EBOP, WBPDC and TCC) most effectively address sedimentation issues, and what management intervention could be appropriate? (4) Are there any reversal methods, such as mangrove control and channel dredging, that may be effective in managing sedimentation issues?

1.3 This report

This report describes predictions of sedimentation in southern Tauranga Harbour by the USC-3 model under three future scenarios. It is Technical Report E2 in Module E of the study, and completes Milestone M10.

1.4 Scenarios

The three scenarios are defined in terms of landuse (which includes earthworks associated with any development) and weather (see Parshotam et al. 2008, for details). The weather is described in terms of magnitude and frequency of rainfall and wind.

Scenario 1: 2001 to 2051, with present-day (2001) landuse, and present-day weather. This scenario is intended as a baseline against which comparisons can be made.

Scenario 2: 2001 to 2051, with landuse as provided for in SmartGrowth and Change No. 2 (Growth Management) to the Regional Policy Statement Change in the Western Bay of Plenty sub-region, and present-day weather.

Scenario 3: As Scenario 2, but with weather incorporating anticipated effects of climate change.

A summary of scenarios is provided in Table 1.1.

Table 1.1: Scenarios defined with respect to landuse and weather.

Scenario	Landuse	Weather
1	Present-day (2001)	Present-day
2	SmartGrowth	Present-day
3	SmartGrowth	Climate change

1.5 USC-3 model

The USC-3 model is described fully by Green (2009). The 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. This is much longer than “standard” estuary sediment-transport models. In the implementation of the model for southern Tauranga Harbour, it predicts sedimentation only. The model is physically based, and is intended to support decision-making by predicting various changes in the harbour bed sediments associated with catchment development scenarios that will cause changes in sediment runoff from the catchment. 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 grainsize. The model predicts sedimentation in different parts of the estuary, which may be compared and used in an assessment of sediment effects, and change in bed composition over time, which reflects degradation of habitat (e.g., change of sandy substrate to silt), and which may bring associated ecological degradation (e.g., mangrove spread, loss of shellfish beds). In addition, the model provides an explicit analysis of the links between sediment sources in the catchment and sediment sinks in the estuary. This type of analysis effectively links “subestuary effects” to “subcatchment causes”, thus showing where best management practices on the land can be most effectively focused. Without an understanding of the link between source and sink, assessment of sediment sources on the land lacks any effects context.

The implementation of the USC-3 model for southern Tauranga Harbour was described by Green (2009). Implementation consisted of defining subestuaries and subcatchments, evaluating the various terms that control sediment transport and deposition inside the harbour, defining the way land-derived sediments are to be fed into the harbour at the subcatchment outlets, and assembling weather time series for driving the model.

Model calibration, also described by Green (2009), was achieved by running the model for the 58-year historical period 1943 to 2001, with sediment 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 hindcasts of sedimentation over the historical period came to match observations from that same period. Calibration resulted in a set of annual-average sedimentation rates throughout the model domain that could be interpreted sensibly in broad, physical terms, and that could be reconciled with six reliable measurements of sedimentation rate reported by Hancock et al. (2009). Because of that, the model calibration was deemed to be satisfactory.

2. Overview of Model Implementation

The implementation of the USC-3 model for southern Tauranga Harbour consisted of defining subestuaries and subcatchments, evaluating the various terms that control sediment transport and deposition inside the harbour, defining the way land-derived sediments are to be fed into the harbour at the subcatchment outlets, and assembling weather time series for driving the model.

Green (2009) describes the model implementation in full; an overview is provided here.

2.1 Subestuaries

Subestuaries are shown in Figure 2.1, and further information is given in Table 2.1. Green (2009) provides the rationale for the definition of subestuaries.

2.1.1 Northern sector of (southern) Tauranga Harbour

- Subestuary 16–MHR is the middle-harbour sandbanks.

- Subestuary 15–AGR is the embayment at the mouth of the Aongatete River. Sediment discharged from the river is prograding into the embayment, and being colonised by mangroves.

- Subestuary 14–WNR is a dual embayment at the mouth of the Wainui River. The inner embayment is largely choked with mangroves. The outer embayment features complicated sandbanks and islands.

- Subestuary 13–PAH is a sheltered embayment accessed from Pahoia Beach Road. The inner part of the embayment is largely occupied by a centrally-located stand of mangroves, but the mouth of the embayment is open.

- Subestuary 12–WAI is at the mouth of the Waipapa River. There is a depositional lobe associated with the river, and the inner reaches are filled with mangroves.

- Subestuary 23-OMO is the open intertidal flats between the mouth of the Waipapa River and the western shore of Omokoroa Peninsula.

2.1.2 Central sector of (southern) Tauranga Harbour

- Subestuary 24–OMI is the sandbank between the eastern shore of Omokoroa Peninsula and the western shore of Motuhoa Island.

- Subestuary 22–MOT is a mid-harbour sandbank that lies to the east of Motuhoa Island.

- Subestuary 11–MGO is Mangawhai Bay Outer, which runs along the east of Omokoroa Peninsula. This is open and flat, and exposed to winds and strong tidal currents.

- Subestuary 20–MGI is Mangawhai Bay Inner. This is enclosed by the East Coast Main Trunk rail line embankment, and is virtually disconnected from the adjoining outer embayment (i.e., 11–MGO, to the east of the rail line). It is an effective sediment trap.

- Subestuary 10–TPO (Te Puna Outer) is partially enclosed by a spit complex at the mouth, and is being colonised by mangroves.

- Subestuary 26–TPI (Te Puna Inner) is the inner pocket of Te Puna estuary that is enclosed by the East Coast Main Trunk rail line embankment. The pocket is reached via Jess Road. It is virtually disconnected from its adjoining outer embayment (to the east of the rail line), and is an effective sediment trap.

- Subestuary 9–WKA is Waikaraka estuary. Like 10–TPO, it is partially enclosed by a spit complex at the mouth, and is being colonised by mangroves.

2.1.3 Mouth of Wairoa River

- Subestuary 21–OIK is a mid-harbour sandbank that lies off Oikimoke Point.

- Subestuary 8–WAR is at the mouth of the Wairoa River. This is an area of extensive, exposed sandflats.

- Subestuary 25–MAT is a small embayment near the mouth of the Wairoa River, formed by the Matua peninsula. It is open but fringed with mangroves.

2.1.4 Waikareao

- Subestuary 7–WKE is Waikareao estuary, which receives runoff from Kopurererua Stream.

2.1.5 Southern sector of Tauranga Harbour

- Subestuary 4–WMA is Waimapu estuary, which receives runoff from Waimapu Stream and which is enclosed at the mouth by the SH2 embankment.

- Subestuary 5–TAC is the intertidal flats that run along the Tauranga City foreshore.

- Subestuary 6–WPB is Waipu Bay, which lies across the main channel from the Tauranga City foreshore.

- Subestuary 3–WEL is Welcome Bay. This is fringed by mangroves.

- Subestuary 2–RNC is the central reaches of Rangataua Bay. This receives runoff from a number of streams (including Waitao) and is fringed by mangroves.

- Subestuary 1–SPE is the northeastern intertidal flats of Rangataua Bay, adjacent to the speedway. This is fringed by mangroves, which are thick in places.

2.1.6 Matakana Island

- Subestuary 19–HCK is Hunters Creek, which penetrates the southern end of Matakana Island.

- Subestuary 18–RGI lies on the opposite (western) side of Rangiwaea Island from Hunters Creek.

- Subestuary 17–MKI is the intertidal flats that run along the western, central section of Matakana Island.

2.1.7 Ocean

- Subestuary 27–SPO is the South Pacific Ocean, which is a sink. This designation as a sink is based on the assumption that the bulk of any sediment transported through the mouth of the harbour is dispersed widely. By virtue of its designation as a sink, the offshore region is also prevented from eroding and supplying sediment to southern Tauranga Harbour.

2.1.8 Deep channels

- Subestuaries 28–DCS, 29–DCC and 30–DCN are deep, subtidal channels that convey rapid currents. They can neither accumulate sediment nor supply sediment to the rest of the model domain below the initial "basement" level.

2.2 Subcatchments

The subdivision of the catchment surrounding southern Tauranga Harbour into subcatchments for the purposes of application of the USC-3 model is shown in Table 2.2 and Figure 2.2. The approximate association of subcatchments with subestuaries is also shown in Figure 2.1. Note that the subcatchments used in this report differ from the subcatchment codes used in the GLEAMS-TAU modelling reports (Parshotam et al. 2009; Elliott et al. 2009) by a value of 100. That is, subcatchment 2 in Parshotam et al. (2009) and Elliott et al. (2009) is subcatchment 102 in this report. This change has been made to more readily distinguish between subestuaries and subcatchments.

2.3 Sediment transport in the harbour

Sediment transport in the harbour was evaluated using the DHI estuary model suite, which comprises the DHI Water and Environment (DHI) MIKE3 FM hydrodynamic model, the DHI MIKE3 MT sediment flocculation/transport model, and the SWAN wave model. Together, these simulate tidal propagation within the harbour, tide- and wind-driven currents, freshwater mixing, waves, and sediment flocculation, transport and deposition. SWAN uses the water levels and current fields predicted by the MIKE3 FM model in predicting wind-generated waves. The predicted wave heights, periods and directions are in turn used to quantify wave-induced bed shear stress, which then transports sediments in the MIKE3 MT model.

The DHI model implementation and calibration for Tauranga Harbour are described in Pritchard and Gorman (2009).

The DHI model suite was used to create a library or database of sediment-transport patterns in the harbour, which the USC-3 model then looks up as it does its calculations. For creating that library, the calibrated MIKE3 MT model was used to simulate the resuspension, transport and redeposition of four sediment grainsizes: 4, 12, 40 and 125 μm. These grainsizes represent: sediment washload / slowly-settling, low-density sediment flocs; fine silt; coarse silt; and fine sand, respectively. Fall speeds of 0.0001 m/s, 0.001 m/s and 0.01 m/s were assigned to the 12, 40 and 125 μm fractions, respectively. These are Stokes fall speeds assuming sediment density of 2.65 g/m^3 (quartz). Hence, the 12, 40 and 125 μm fractions are implied to be, as a result, in an unaggregated state. The fall speed for the 4 μm fraction was set at 0.00001 m/s to represent sediment washload and slowly-settling, low-density sediment flocs. 4 μm is a nominal size for this fraction.

Resuspension of estuarine bed sediments is described in the USC-3 model by the terms *ED50*, *R5*, *R5SUSP* and *RFS* (see Green, 2009, for definitions). Dispersal and deposition in the estuary of sediment eroded from the catchment by rainfall and delivered to the harbour in freshwater runoff is described in the USC-3 model by the terms *R*, *RSUSP* and *RFS* (Green, 2009).

2.4 Evaluation of land-derived sediment loads

The GLEAMS-TAU model (Parshotam et al. 2009; Elliott et al. 2009) provides daily land-derived sediment loads at the base of each subcatchment (BOC) split by constituent grainsize. A random block-sampling scheme (described by Green, 2009) is used to assemble these loads for input to the USC-3 model. The advantage to this block-sampling scheme, which is significant, is that the effects on sediment generation of antecedent rainfall and rainfall intensity on the day of generation, both of which can create large variability in the response of the catchment to rainfall, can be captured. For example, sediment yield (sediment generation per unit rainfall) may be higher under intense rainfall after an extended period of dry weather compared to less intense rainfall when the ground is partly saturated. These effects are captured in GLEAMS-TAU, and they get transferred to the USC-3 model by using sequences of GLEAMS-TAU output to drive the USC-3 model.

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 50-year future period, where *N* is of the order 10^2. The *N* sets of predictions are averaged to give one set of "average" predictions for the future period, and it is these average predictions that are delivered to the user. Each of the *N* runs of the model is driven by a different time series of sediment runoff from rural sources, randomly constructed by the block-sampling scheme. The set of N simulations, constructed in this way, will properly account for extreme events, so long as N is “large”.

For the implementation of the model for southern Tauranga Harbour, N was set at 100.

2.5 Evaluation of weather time series

The daily rainfall is determined as a by-product of the same block-sampling scheme used to create the daily sediment runoff from the GLEAMS-TAU model output. In effect, each time a daily GLEAMS-TAU sediment runoff is picked out by the sampling scheme, the corresponding daily rainfall is also picked out. The daily wind (speed and direction) is determined by random sampling from a distribution of winds, which vary according to whether or not it is raining.

Table 2.1: Characteristics of subestuaries for the purposes of application of the USC-3 model. The area shown in the table is the total subestuary area.

Code	Subestuary	Area (m^2)	Sink	Deep Channel
1 – SPW	Speedway	2,300,000		
2 – RNC	Rangataua Bay	5,000,000		
3 – WEL	Welcome Bay	1,500,000		
4 – WMA	Waimapu	1,500,000		
5 – TAC	Tauranga City foreshore	3,600,000		
6 – WPB	Waipu Bay	3,200,000		
7 – WKE	Waikareao	2,600,000		
8 – WAR	Mouth of Wairoa River	3,234,013		
9 – WKA	Waikaraka	800,000		
10 – TPO	Te Puna (outer)	829,639		
11 – MGO	Mangawhai Bay (outer)	1,926,783		
12 – WAI	Mouth of Waipapa River	1,400,000		
13 – PAH	Pahoia Beach Road	1,300,000		
14 – WNR	Mouth of Wainui River	3,600,000		
15 – AGR	Mouth of Aongatete River	3,400,000		
16 – MHR	Middle-harbour sandbanks	16,400,000		
17 – MKI	Matakana Island	4,800,000		
18 – RGI	Rangiwaea Island	2,400,000		
19 – HCK	Hunters Creek	6,300,000		
20 – MGI	Mangawhai Bay (inner)	473,217		
21 – OIK	Oikimoke Point	3,500,000		
22 – MOT	Sandbank east of Motuhoa Island	1,900,000		
23 – OMO	West of Omokoroa Peninsula	2,600,000		
24 – OMI	Sandbank east of Omokoroa Peninsula	900,000		
25 – MAT	Matua	700,000		
26 – TPI	Te Puna (inner)	770,361		
27 – SPO	Ocean	n/a	✓	
28 – DCS	Deep channel south	n/a		✓
29 – DCC	Deep channel central	n/a		✓
30 – DCN	Deep channel north	n/a		✓

Table 2.2: Division of the catchment into subcatchments for the purposes of application of the USC-3 model. The subcatchment codes shown in this figure are taken from the GLEAMS-TAU modelling reports (Parshotam et al. 2009; Elliott et al. 2009) and they differ from the subcatchment codes used in this report by a value of 100. That is, subcatchment 2 in Parshotam et al. (2009) and Elliott et al. (2009) is subcatchment 102 in this report. This change has been made to more readily distinguish between subestuaries and subcatchments.

Code	Subcatchment
101 – MKE	Matakana 1
102 – MMI	Mount Maunganui
103 – PAP	Papamoa
104 – WTO	Waitao
105 – KMK	Kaitemako
106 – WMP	Waimapu
107 – KOP	Kopurererua
108 – WAR	Wairoa
109 – OTU	Oturu
110 – TPU	Te Puna
111 – MGW	Mangawhai
112 – WAI	Waipapa
113 – APA	Apata
114 – WNR	Wainui
115 – AGR	Aongatete
116 – MAT	Matua
117 – MKW	Matakana 2

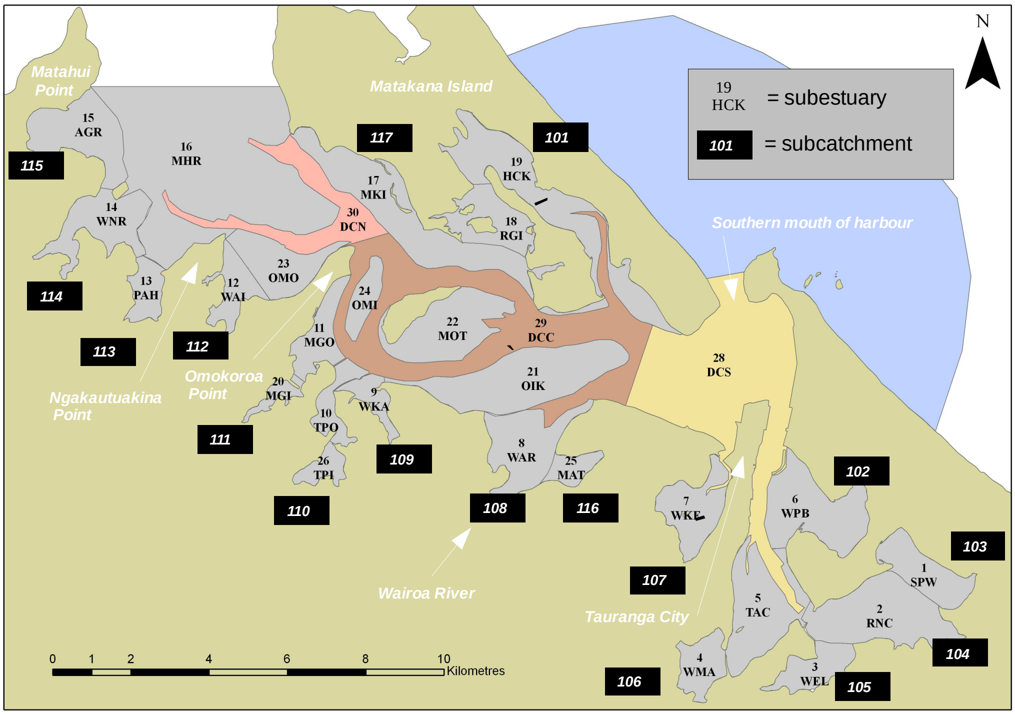

Figure 2.1: Subdivision of the harbour into subestuaries for the purposes of application of the USC-3 model. Also shown is the approximate association of subcatchments with subestuaries, and some place names.

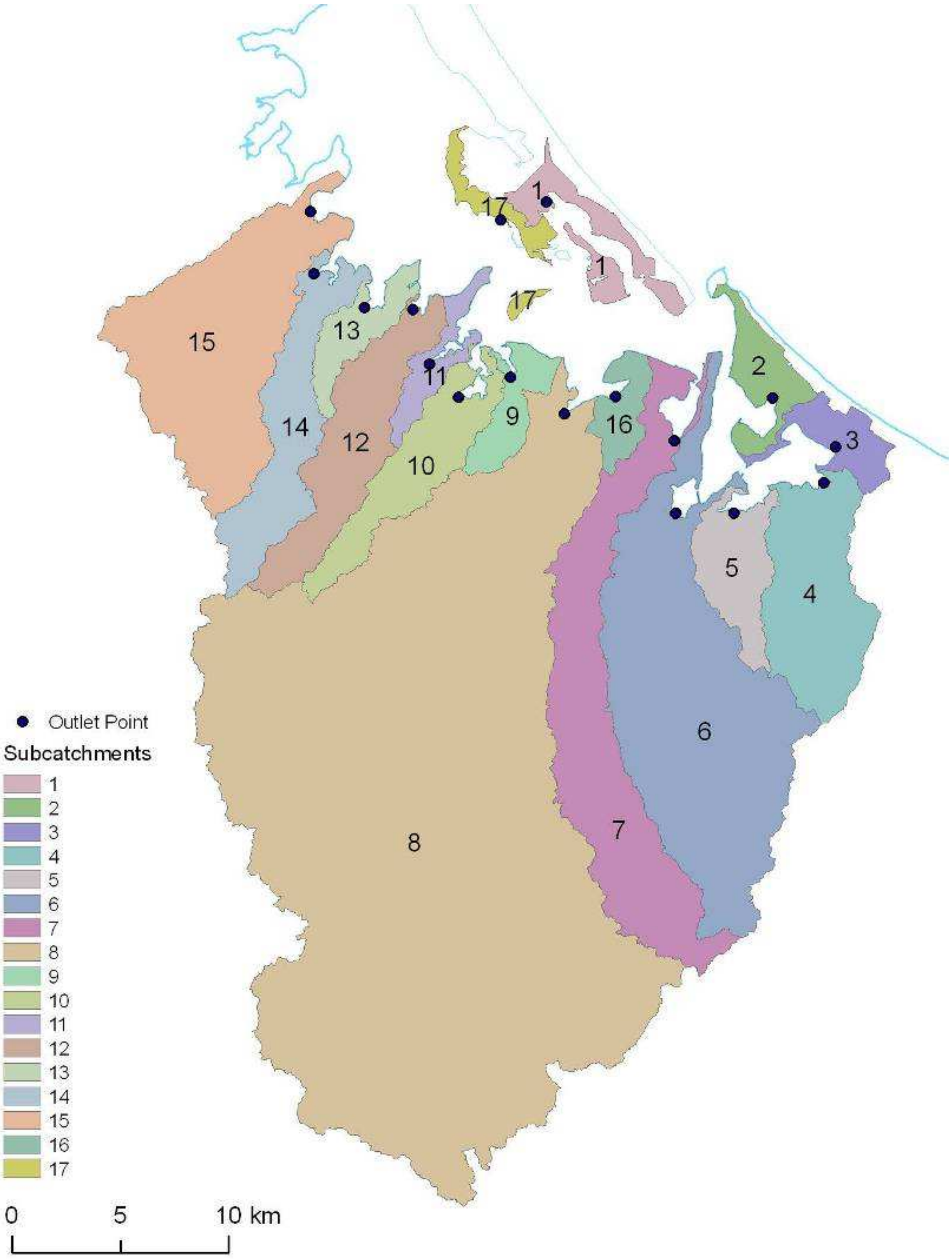

Figure 2.2: Division of the catchment of southern Tauranga Harbour into subcatchments for the purposes of application of the USC-3 model. The subcatchment codes shown in this figure are taken from the GLEAMS-TAU modelling reports (Parshotam et al. 2009; Elliott et al. 2009) and they differ from the subcatchment codes used in this report by a value of 100. That is, subcatchment 2 in Parshotam et al. (2009) and Elliott et al. (2009) is subcatchment 102 in this report. This change has been made to more readily distinguish between subestuaries and subcatchments.

3. Overview of Model Calibration

The USC-3 model was run for the 58-year historical period 1943 to 2001, with sediment 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.

Green (2009) describes the model calibration in full; an overview is provided here.

3.1 Sediment inputs

The random block-sampling scheme described by Green (2009) was applied to the 2001 GLEAMS-TAU model output[1] to produce the daily land-derived sediment loads at the base of each subcatchment for the 58-year historical period (1943–2001).

The split of the GLEAMS-TAU sediment loads by constituent grainsize was based on analysis of samples that were collected from a range of locations in the Kopurererua catchment during a heavy rainfall event on 30–31 July 2008.

The sediment runoff from every subcatchment except 108–WAR, 107–KOP and 106–WMP was deemed to consist exclusively of “fine sediment”. For 108–WAR, 107–KOP and 106–WMP, which are the three largest subcatchments, a coarse bedload component was added. Following Bell et al. (2006), the (coarse) bedload was contrived to be 31% of the total load.

3.2 Grainsize composition of subestuary bed sediments

The present-day grainsize composition described by Hancock et al. (2009) was used to initialise the model at the start of the historical period.

3.3 Results

Although it was possible to adjust more in the calibration process, just one parameter needed to be adjusted in this case to achieve calibration. This was the erosion depth (*ED50*), which was reduced for all values of D_{50} by approximately half across the model domain to achieve a reasonably good match between the set of measured annual-average sedimentation rates provided by Hancock et al. (2009) and the set of

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[1] Green (2009) explained why the 1943, 1959 and 1973 GLEAMS-TAU hindcasts were not used in the calibration.

hindcast (1943–2001) annual-average sedimentation rates. Green (2009) provided a brief discussion of the hindcast sedimentation rates. It was noted that a more comprehensive discussion and analysis requires taking account of sediment-transport pathways, sediment runoff from the land, and proportion of the sediment runoff that gets lost to the coastal ocean, amongst other things. This comprehensive analysis, including the influence of all of these factors, is given in this report, in the context of predictions of sedimentation for the future period.

4. Predictions

4.1 Sediment runoff from the catchment

The random block-sampling scheme described by Green (2009) was applied to the GLEAMS-TAU model predictions to produce the daily land-derived sediment loads at the base of each subcatchment for each of Scenarios 1, 2 and 3 for the 50-year future period (2001–2051).

Following the calibration procedure, the split of the GLEAMS-TAU sediment loads by constituent grainsize was based on analysis of samples that were collected from a range of locations in the Kopurererua catchment during a heavy rainfall event on 30–31 July 2008. This results in a split of the GLEAMS-TAU sediment loads at the base of each subcatchment by constituent grainsize as follows.

For every subcatchment except 108–WAR (Wairoa), 107–KOP (Kopurererua) and 106–WMP (Waimapu), the average Kopurererua distribution in the size classes <8 μm and 8–25 μm was equated with the constituent grainsizes 4 μm and 12 μm, respectively. Then, the average Kopurererua distributions in the size classes 25–100 μm and >100 μm were added together and the sum was equated with the constituent grainsize 40 μm. The 125 μm constituent grainsize was set to zero. This results in splitting the GLEAMS-TAU sediment loads at the base of every subcatchment except 108–WAR, 107–KOP and 106–WMP into 18.8% / 17.5% / 63.9% / 0% for the 4, 12, 40 and 125 μm constituent grainsizes. The three constituent grainsizes 4, 12 and 40 μm will be referred to collectively throughout the remainder of this report just as “fine sediment”. The sediment runoff from every subcatchment except 108–WAR, 107–KOP and 106–WMP therefore consists exclusively of “fine sediment”. This will make the interpretation of results considerably simpler.

Also following the calibration procedure, a coarse, bedload component was added to the sediment runoff from the three largest subcatchments, as follows.

Bell et al. (2006) reported bedload as a percentage of suspended sediment as being 45% for five divisions of the catchment that drains to Tauranga Harbour. That is, bedload is 31% of the total load. The Kopurererua sampling is biased towards the suspended-sediment load, and the GLEAMS-TAU model does not treat bedload at all. Following Bell et al. a method was developed to include a bedload component in the sediment runoff from just the three largest subcatchments (108–WAR, 107–KOP and 106–WMP). The GLEAMS-TAU loads at the base of each of these subcatchments is assumed to be just the load in suspension. Following Bell et al. the total load is then given by 1.45×*G*, where *G* represents the GLEAMS-TAU (suspended) load, and 0.45×*G* is the bedload. Hence, the bedload is 0.45/1.45 = 0.31 of the total load; the suspended load is 1.00/1.45 = 0.69 of the total load; and the bedload is 0.45/1.00 = 0.45 of the suspended load. Based on this calculation, 1.00×*G* is assigned to the three constituent grainsizes 4, 12 and 40 μm ("fine sediment", travelling in suspension) as before, and 0.45×*G* is assigned to the 125 μm constituent grainsize ("coarse sediment", travelling as bedload). This gives a total sediment runoff of 1.45×*G* (sum of suspended load and bedload) for 108–WAR, 107–KOP and 106–WMP.

Table 4.1 shows the predicted annual-average fine-sediment runoff from each subcatchment for each scenario. This is an annual-average over the duration of each 50-year simulation and over all 100 simulations in the Monte Carlo package. Also shown in Table 4.1 is the change in sediment runoff from scenario to scenario. This is expressed as a percentage change, where a positive change signifies an increase and a negative change signifies a decrease[2].

- Comparing Scenario 2 to Scenario 1 shows the change in sediment runoff predicted to occur under future landuse compared to under 2001 landuse.

  With one exception, in subcatchments where SmartGrowth calls for urbanisation, sediment runoff is predicted to reduce by a few percent. The exception is subcatchment 116 (Matua), which will undergo significant urbanisation, resulting in significant reduction (-23.8%) of sediment runoff. (The reasons are described in detail in Elliott et al., 2009.) In the remainder of the subcatchments there is no change in sediment runoff. For the subcatchment that supplies (by far) the largest sediment load to the harbour (subcatchment 108), there is no change in sediment runoff. This subcatchment discharges into the central reaches of southern Tauranga Harbour. For the subcatchments that supply the next three largest loads to the harbour (subcatchments 106, 107 and 104), sediment runoff is predicted to decrease by -0.5%, -2.2% and -0.7%, respectively. All of these subcatchments discharge to the southernmost sector of the harbour. For the subcatchments that discharge into the northernmost subestuaries (subcatchments 113, 114, 115), sediment runoff does not change under landuse change.

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[2] Note that Elliott et al. (2009) reported change in sediment runoff from scenario to scenario in the same way, in two different tables (Table 6 and Table 7 of Elliott et al.). The changes reported here in Table 5.1 are most similar to the changes Elliott et al. reported in their Table 7; these were calculated as an average over the simulation period, as they are here. Nevertheless, the numbers are not identical, because of the random block-sampling technique used to derive sediment loads (for driving the USC-3 model) from the GLEAMS-TAU predictions.

- Comparing Scenario 3 to Scenario 2 shows the change in sediment runoff predicted to occur under climate change compared to under present-day climate. Both of these scenarios assume future landuse.

  Climate change is predicted to increase sediment runoff from every subcatchment. Elliott et al. (2009) provide a detailed discussion of how this arises. The predicted increase ranges from +14.4% to +29.3%. Sediment runoff from subcatchment 108 (by far the largest sediment supplier; discharges into central reaches of southern Tauranga Harbour) is predicted to increase by +22.1%. Sediment runoff from the next three largest suppliers (subcatchments 106, 107 and 104; all discharge into the southernmost sector of the harbour) is predicted to increase by +20.6%, +21.4% and +25.8%, respectively. Sediment runoff from the northern subcatchments 113, 114 and 115 is predicted to increase by +23.5%, +21.8% and +26.6%, respectively.

- Comparing Scenario 3 to Scenario 1 shows the change in sediment runoff predicted to occur under climate change and future landuse compared to under present-day climate and 2001 landuse.

  In all subcatchments except one, the combined effects of landuse change and climate change result in an increase in sediment runoff. The exception is subcatchment 116 (Matua) where the decrease under landuse change (-23.8%) outweighs the increase under climate changes (22.3%), which results in a total change of -6.8%.

Table 4.2 shows the predicted annual-average coarse-sediment runoff from each subcatchment for each scenario. This is an annual-average over the duration of each 50-year simulation and over all 100 simulations in the Monte Carlo package. Also shown in Table 4.2 is the change in sediment runoff from scenario to scenario. As above, this is expressed as a percentage change, where a positive change signifies an increase and a negative change signifies a decrease.

- The coarse-sediment runoff from the three subcatchments (108–WAR, 107–KOP and 106–WMP) deemed to supply coarse sediment to the harbour was contrived to be 0.45 times the respective fine-sediment runoff shown in Table 4.1, which is confirmed by comparing Table 4.2 to Table 4.1. Because of this contrivance, the percentage changes in fine-sediment runoff under the various scenarios shown in Table 4.1 also apply to the coarse-sediment runoff.

Before showing how these predicted changes in sediment runoff from the land get translated into changes in sedimentation throughout the harbour, sediment-transport patterns in the harbour will be described. This will provide the background information needed to understand the sedimentation predictions.

4.2 Sediment transport patterns in the harbour

4.2.1 Loss of fine sediment to coastal ocean

Figure 4.1 shows the loss of fine sediment to the coastal ocean from each subcatchment. The loss is expressed as a percentage of the total load from each subcatchment, where that percentage is an average over all 100 simulations in the Monte Carlo package for Scenario 1.

- Fine-sediment loss to the ocean is greatest from those subcatchments that discharge in the middle reaches of southern Tauranga Harbour, close to the (southern) mouth of the harbour, which favours sediment loss. In addition to that, freshwater discharge from three of the subcatchments in this group is also high, which also favours sediment loss. Nearly all (95%) of the fine sediment discharged from Wairoa River (subcatchment 108), which has the largest freshwater discharge of any subcatchment, is lost. Subcatchments 106 and 107 are secondary in area only to subcatchment 108, and accordingly have high freshwater discharge. The loss of fine sediment from subcatchments 106 and 107 is therefore also high, at 81% and 80%, respectively. Freshwater runoff from subcatchment 102 is not large, but this subcatchment does discharge very close to the (southern) harbour mouth, and the loss is high (87%) accordingly.

- Fine-sediment loss is much higher from subcatchment 104 (67%) compared to subcatchments 103 (15%) and 105 (23%), both of which have much smaller freshwater discharge, and both of which discharge around the sheltered edges of Rangataua Bay, compared to 104.

- Fine-sediment loss from subcatchments 109 and 110 is small (both 26%). Both of these subcatchments are very small, with small freshwater discharge, and both drain into a sheltered part of the harbour. Subcatchment 111 is also small and drains into a sheltered part of the harbour, but the loss is somewhat higher (41%). This may be because sediment from subcatchment 111 that escapes from the inner part of Mangawhai Bay (20–MGI) is not deposited in any significant way in the outer part of Mangawhai Bay (11–MGO), whereas sediment from subcatchment 110 that escapes from the inner part of Te Puna estuary (26–TPI) does deposit in the outer part (110–TPO).

- In the northern part of southern Tauranga Harbour, loss of fine sediment tends to decrease with increasing distance from the (southern) mouth (subcatchments 112, 113, 114 and 115 lose 53%, 41%, 32% and 40%, respectively). Subcatchment 115 does not quite follow the pattern, which may be because this is the largest of these subcatchments, with the largest freshwater runoff.

- Fine-sediment loss from subcatchment 117 is very high (88%). Although freshwater runoff from Matakana Island is low, this subcatchment discharges directly into a part of the harbour with strong tidal currents that follow a direct pathway to the (southern) mouth of the harbour. Loss from subcatchment 101, which discharges into a more sheltered part of Matakana Island, is considerably less (42%).

4.2.2 Loss of coarse sediment to coastal ocean

Figure 4.2 shows the loss of coarse sediment to the coastal ocean from each of the three subcatchments that are deemed to supply coarse sediment to the harbour (108–WAR, 107–KOP and 106–WMP). The loss is expressed as a percentage of the total load from each subcatchment, where that percentage is an average over all 100 simulations in the Monte Carlo package for Scenario 1.

- Compared to the loss of fine sediment, the loss of coarse sediment is much smaller. This is because the coarser sediment grains are heavier, and therefore less easily dispersed and resuspended by waves and currents.

4.2.3 Fate of fine sediment discharged from subcatchments

Figure 4.3 shows the primary fate of fine sediment discharged from each subcatchment, which can be thought of as primary transport pathways for terrigenous fine sediment that result in deposition. (Note that the lines simply connect source and sink; they do not imply an actual route the sediment follows between source and sink.) Broad patterns are shown in this figure, and they apply to every scenario. Not shown in this figure is loss of fine sediment to the coastal ocean, which has already been described.

Northern sector of (southern) Tauranga Harbour

- Fine sediment discharged from the three northernmost subcatchments (115, 114 and 113) deposits in each respective adjacent subestuary (that is, sediment from subcatchment 115 deposits in subestuary 15–AGR, sediment from 114 deposits in 14–WNR, and sediment from 113 deposits in 13–PAH). In addition to that, fine sediment from these subcatchments is exchanged amongst these subestuaries. Hence, these three subcatchments and three subestuaries can be viewed as a group. This group of three subestuaries is bound by Matahui Point (to the north) and Ngakautuakina Point (to the south) (see Figure 2.1 for place names).

- Fine sediment from subcatchment 112 deposits in its respective adjacent subestuary (12–WAI). There is no significant exchange around Ngakautuakina Point with the group of three subestuaries to the north that results in deposition, and there is also no significant exchange with subestuaries to the south of Omokoroa Point that results in deposition. Presumably, sediment that passes to the south of Omokoroa Point is entrained by the strong tidal currents in that part of the harbour and lost to the coastal ocean.

Central sector of (southern) Tauranga Harbour

- Subcatchments 111, 110 and 109 all deposit fine sediment in their respective adjacent subestuaries (20–MGI and 11–MGO for subcatchment 111; 26–TPI and 10–TPO for subcatchment 110; 9–WKA for subcatchment 109).

Mouth of Wairoa River

- Fine sediment from subcatchment 108 is dispersed widely throughout the central reaches of southern Tauranga Harbour, between the (southern) harbour mouth and Omokoroa Point. Omokoroa Point evidently acts as something of a barrier to fine sediment from southern sources passing into the northern reaches of the harbour. Fine sediment from the Wairoa River is also dispersed into the southern part of the harbour, spreading around the Tauranga City peninsula and as far afield as Waikareao estuary (7–WKE) and Waipu Bay (6–WPB). Widespread dispersal of fine sediment from subcatchment 108 is consistent with the central location of the Wairoa River mouth, and the river’s high freshwater discharge.

- Fine sediment from subcatchment 116, which discharges into the embayment (25–MAT) beside the mouth of the Wairoa River, tends to deposit primarily in that embayment. However, some is dispersed as widely as sediment that discharges from the Wairoa River, but its presence is swamped by the relatively much greater sediment runoff from the Wairoa River subcatchment.

Waikareao

- Fine sediment from subcatchment 107 is mainly deposited in the adjacent subestuary (Waikareao, 7–WKE) or lost to the coastal ocean. Presumably this is because Waikareao is very close to the (southern) harbour mouth, and there is a direct route from there to the coastal ocean.

Southern sector of Tauranga Harbour

- The subestuaries and subcatchments to the south of the Tauranga City peninsula tend to function as a unit in the same way that the northernmost group of subcatchments/subestuaries function. That is, fine sediment is deposited in respective adjacent subestuaries, but there is also considerable exchange amongst the group of subestuaries. It is notable that fine sediment from these southern subcatchments does not disperse, in general, into the central reaches of the harbour beyond the Tauranga City peninsula[3], but fine sediment from the Wairoa River, which discharges into the central reaches, does make its way into the southern harbour.

Matakana Island

- Fine sediment from subcatchment 101, which discharges from Matakana Island into the sheltered confines of Hunters Creek, either deposits there or is lost to the coastal ocean, but fine sediment from subcatchment 117, which discharges from Matakana Island into the open, central reaches of the harbour, is widely dispersed.

4.2.4 Fate of coarse sediment discharged from subcatchments

The predicted fate of coarse sediment from the three subcatchments deemed to supply coarse sediment to the harbour (108–WAR, 107–KOP and 106–WMP) is very simple:

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[3] The source analysis, to follow, reveals that that is not completely true: subcatchment 106, for instance, is a source of deposited fine sediment in some parts of the central reaches.

what is not lost to the coastal ocean is deposited in the respective adjacent subestuary. Coarse sediment from subcatchment 108 is also deposited in 25–MAT, which lies adjacent to 108–WAR at the mouth of the Wairoa River.

4.2.5 Source of fine sediment deposited in subestuaries

Figure 4.4 shows the principal sources of fine sediment deposited in each subestuary. These are broad patterns, and they apply to every scenario. In Figure 4.4, there is one thick, red line that connects each subestuary to a subcatchment. This denotes the principal source of sediment to that subestuary. The thin, black lines that connect to other subcatchments show secondary sources. It is important to recognise that, in general, it is not possible to infer sources from an analysis of fate (of the sort shown in Figure 4.3). The reason is that the constitution of deposited sediment depends on both transport pathways (fate) and the relative sizes of the catchment sediment supplies. For example, a subestuary may deposit all of the sediment from a small catchment supply and only a very small fraction of the sediment from a very much larger catchment supply. In that case, an analysis of fate may not show a transport pathway between the second (larger) supply and the subestuary in question, but that second supply will be dominant in the source analysis. Therefore, the patterns in Figure 4.3 (fate) will not necessarily mirror the patterns in Figure 4.4 (source).

Northern sector of (southern) Tauranga Harbour

- Each of the three northernmost subestuaries (15–AGR, 14–WNR and 13–PAH) deposits sediment principally from the respective adjacent subcatchment (115, 114 and 113). However, there is also a significant amount of exchange amongst subcatchments and subestuaries in this group, which was also inferred from the fate analysis. (A small amount of sediment from subcatchment 112 also does escape around Ngakautuakina Point to the north to deposit in subestuary 14–WNR.).

- Subestuary 12–WAI deposits fine sediment principally from its adjacent subcatchment (112). It is isolated from the northernmost grouping of sources by Ngakautuakina Point, and from southern sources by Omokoroa Point, which was also inferred from the fate analysis.

Central sector of (southern) Tauranga Harbour

- The enclosed, sheltered subestuaries 20–MGI and 26–TPI deposit sediment from their respective adjacent subcatchments (111 and 110, respectively), and from subcatchment 108, which is the largest supplier of sediment to the harbour (it was explained previously how source of deposited sediments depends on transport pathways and the relative sizes of catchment supplies)

- Subestuary 10–TPO, which is the outer part of Te Puna estuary, and neighbouring subestuary 9–WKA both deposit sediment primarily from their respective adjacent subcatchments (110 and 109, respectively), and from subcatchment 108, which is the largest supplier of sediment to the harbour.

Mouth of Wairoa River

- The principal source of sediment to subestuary 25–MAT is subcatchment 108, not the adjacent subcatchment 116, even though there is a more direct connection with subcatchment 116. The reason is that subcatchment 108 is a much larger supplier of sediment to the harbour than subcatchment 116. Note, too, that subcatchment 107 is also a source of sediment to subestuary 25–MAT, even though no primary transport pathway connects these two in Figure 4.3. As explained previously, this is because subcatchment 107 is one of the largest suppliers of sediment to the harbour. Subestuaries 25–MAT, 6–WPB, 18–RGI and 19–HCK (to be described) are all dominated by sediment from subcatchment 108 which, in all cases, is not the adjacent source.

Waikareao

- The principal source of sediment to subestuary 7–WKE is subcatchment 107. This is expected, as subcatchment 107 is not only adjacent but is also a large supplier of sediment to the harbour. It is notable that sediment from subcatchment 108, the largest supplier of sediment to the harbour, also deposits in 7–WKE.

Southern sector of Tauranga Harbour

- The principal source of sediment to subestuary 6–WPB is subcatchment 108, not the adjacent subcatchment 102, even though there is a more direct connection with subcatchment 102. This is exactly the same situation as subestuary 25–MAT: the largest sediment supplier (subcatchment 108) over-rides, as it were, the more direct connection with the adjacent subcatchment. Subestuaries 6–WPB, 25–MAT, 18–RGI and 19–HCK are all dominated by sediment from subcatchment 108 which, in all cases, is not the adjacent source. Subestuary 102–WPB also deposits sediments from subcatchment 107, which is a large supplier, and from nearly all of the subcatchments that drain into the harbour south of the Tauranga City peninsula (subcatchments 106, 105 and 104). Sediments from all of these subcatchments pass by the mouth of 6–WPB on an ebbing tide; presumably some fraction of that load is drawn into Waipu Bay as it passes by and is sequestered.

- The principal source of sediment to subestuary 4–WMA is subcatchment 106. This is expected, as subcatchment 106 is not only adjacent but is also a large supplier of sediment to the harbour.

- Subcatchment 104 is the largest source of sediment to the eastern (1–SPW) and central (2–RNC) sectors of Rangataua Bay. However, Welcome Bay (3–WEL), in the western sector, primarily deposits sediment from adjacent subcatchment 105. It is notable that all of these subestuaries also deposit sediment from the three largest suppliers of sediment to the harbour (subcatchments 108, 107 and 106).

Matakana Island

- Both subestuaries 18–RGI and 19–HCK deposit sediment principally from subcatchment 108, the largest supplier of sediment to the harbour, rather than from their respective adjacent subcatchments. This puts them in the same category as 25–MAT and 6–WPB.

Mangawhai, outer

- Finally, subestuary 11–MGO deposits fine sediment primarily from the largest supplier of sediment to the harbour (subcatchment 108), but it also receives some sediment from virtually every other subcatchment. This is an interesting result, and at first glance seems contrary to some previous comments about barriers to fine-sediment dispersal in the harbour, and the implied divisions of the harbour into sectors. Subestuary 11–MGO is different to most of the subestuaries that accumulate sediment, in that it is in an exposed, central part of the harbour. In this location, it receives sediments that have been mixed together from a wide range of sources. As a result, the breakdown of sediment that deposits in 11–MGO by subcatchment loosely matches the ranking of subcatchments by sediment runoff. This indicates that sedimentation at this location is not particularly influenced by proximity of any particular subcatchment. Although sedimentation is zero throughout the central, exposed parts of the (southern) harbour (11–MGO is the exception), analysis of the sediment that passes through (as opposed to deposits in) these areas, shows that this is generally also the case in these parts.

4.3 Sedimentation rates

4.3.1 Fine sediment – Scenario 1

The predicted fine-sediment sedimentation rates under Scenario 1 are shown in Figure 4.5 and Table 4.3. These are practically identical to the rates hindcast for the historical period (Green, 2009), which is to be expected, since both Scenario 1 and the historical period use GLEAMS sediment loads based on the 2001 catchment landuse. The following comments on sedimentation rates are reproduced from Green (2009), which in turn make reference to Hancock et al.'s (2009) measurements of sedimentation rate from radioisotopic analysis of sediment cores.

- Hindcast [predicted under Scenario 1] fine-sediment sedimentation in the central reaches of the harbour to the north of the harbour mouth is zero (8–WAR, 21–OIK, 22–MOT, 24–OMI, 23–OMO, 16–MHR and 17–MKI). These reaches are scoured by tidal currents and are exposed to locally-generated windwaves that frequently resuspend bed sediments. This prevents the accumulation of fine sediments, and the seabed in these areas is typically hard-packed, clean, rippled sand. The hindcast [predicted under Scenario 1] sedimentation rate of zero in 8–WAR is consistent with Hancock et al.'s (2009) conclusion that the core data from 8–WAR indicate "a highly wave-exposed intertidal flat, with negligible long-term accumulation of fine sediments". The core data from 23–OMO are also consistent with an exposed area where, according to Hancock et al. "long-term accumulation of fine sediments is negligible".

- The hindcast [predicted under Scenario 1] fine-sediment sedimentation rate in subestuary 11–MGO is small. The seabed in this area is also hard-packed sand and it is exposed to winds and strong tidal currents. Hence, it is functionally similar to the central reaches of the harbour.

- Hindcast [predicted under Scenario 1] fine-sediment sedimentation in the central reach of the harbour to the south of the harbour inlet (5–TAC) is also zero. This area is swept by strong tidal currents and the seabed is sandy. The long axis of this area presents a long fetch to northeasterly winds, which generate waves that scour the bed of fine sediments.

- Hindcast [predicted under Scenario 1] fine-sediment sedimentation in 6–WPB is very small. This is close to the mouth of the harbour, which favours loss of fine sediment to the coastal ocean, and it drains a catchment (102) with a very small sediment yield.

- Both 4–WMA and 7–WKE have, on the face of it, surprisingly low hindcast [predicted under Scenario 1] sedimentation rates given that they are virtually impounded and that the sediment runoff from the respective adjacent subcatchments is quite high. However, the respective catchments are also quite large, which means that freshwater runoff will be large and therefore capable of flushing the embayments[4]. Furthermore, both embayments are close to the mouth of the harbour, which favours loss of fine sediment to the coastal ocean. In both 4–WMA and 7–WKE, the hindcast [predicted under Scenario 1] fine-sediment sedimentation rate is similar to Hancock et al.'s reported measured sedimentation rate.

- Hindcast [predicted under Scenario 1] fine-sediment sedimentation in the central, more exposed reaches of Rangataua Bay (2–RNC) is smaller than in the more sheltered fringes, which have experienced rapid mangrove spread in recent years (1–SPW and 3–WEL). Rangataua Bay drains subcatchment 104, which has a high sediment runoff.

- The four northernmost subestuaries in the model (15–AGR, 14–WNR, 13–PAH and 12–WAI) have similar hindcast [predicted under Scenario 1] sedimentation rates, which are high compared to elsewhere in the model domain. In each case they deposit sediment mainly from the adjacent subcatchment, as a group they are far from the mouth of the harbour, and tidal currents in this central part of the harbour are relatively weak, all of which favour retention of fine sediment. The measured sedimentation rate reported by Hancock et al. in this region (1.6 mm/year) is similar to but somewhat smaller than the hindcast [predicted under Scenario 1] sedimentation rate in the closest subestuary (2.4 mm/year in 14–WNR). However, Hancock et al.'s core was taken near the boundary of 14–WNR and 16–MHR, where the sedimentation rate can be expected to be smaller. Hancock et al. note that where the core was taken, the radioisotope profiles are "consistent with a wave-exposed intertidal flat environment".

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[4] Hancock et al. (2009) suggested that sedimentation in 4–WMA is caused by low sediment inputs from the catchment and energetic wave resuspension of bed sediments. However, the GLEAMS-TAU hindcasts do not support the former claim (subcatchment 106, which drains into subestuary 4–WMA, has the second-largest sediment runoff of all subcatchments in the historical period), and the embayment is small and enclosed, which will limit the growth of waves.

- The hindcast [predicted under Scenario 1] fine-sediment sedimentation rate in 20–MGI is similar to that in the four northernmost subestuaries. However, this subestuary is virtually enclosed by the East Coast Main Trunk rail line and so it is not functionally similar to that group of subestuaries. Subestuary 26–TPI is also enclosed by the rail line, and this subestuary features the highest hindcast [predicted under Scenario 1] sedimentation rate.

- Subestuary 10–TPO and 9–WKA are both partially enclosed by a spit complex at the mouth, are both small, and both drain small catchments. The hindcast [predicted under Scenario 1] fine-sediment sedimentation rate is intermediate between the sedimentation rate in the respective impounded headwaters and the sedimentation rate in the central reaches.

- The hindcast [predicted under Scenario 1] fine-sediment sedimentation rate in the two subestuaries enclosed by Matakana Island (18–RGI and 19–HCK) is small. The sediment runoff from the respective adjacent subcatchments (117 and 101) is small. Hancock et al.'s core data indicate a sedimentation rate of 1.3 mm/year, which is much larger than the hindcast [predicted under Scenario 1] fine-sediment sedimentation rate. A possible explanation is that the core was taken in a localised depositional sink, although care was taken in the sampling to avoid that situation. A more likely conclusion is that the model is not performing well in this area.

4.3.2 Coarse sediment – Scenario 1

The predicted coarse-sediment sedimentation rates under Scenario 1 are shown in Figure 4.6 and Table 4.4. As was the case for the fine sediments, these are practically identical to the rates hindcast for the historical period (Green, 2009). As explained, this is to be expected, since both Scenario 1 and the historical period use GLEAMS sediment loads based on the 2001 catchment landuse. The following comments on sedimentation rates are reproduced from Green (2009), which in turn make reference to Hancock et al.'s (2009) measurements of sedimentation rate from radioisotopic analysis of sediment cores.

- The hindcast [predicted under Scenario 1] coarse-sediment sedimentation rate was 3.2 [3.4] mm/year in subestuary 8–WAR at the mouth of the Wairoa River, and 2.4 [2.6] mm/year in subestuary 25–MAT, which is immediately adjacent. Hancock et al. were not able to establish a sedimentation rate there (although they did conclude that fine sediments do not accumulate in this region, which is consistent with the hindcast fine-sediment sedimentation rate of zero). Given that this part of the harbour is the principal coarse-sediment depositional lobe associated with the Wairoa River [inferred from geomorphological setting] the hindcast [predicted under Scenario 1] coarse-sediment sedimentation rate does not seem unreasonable.

- The hindcast [predicted under Scenario 1] coarse-sediment sedimentation rate was 3.7 [3.6] mm/year in 4–WMA. This is much greater than Hancock et al.'s measured value of 0.8 mm/year. However, Hancock et al. did note that their dating was applied to a "low-density mud layer", and so their result can be interpreted as a fine-sediment sedimentation rate. If that is the case, then it is pleasing that the hindcast [predicted under Scenario 1] fine-sediment sedimentation of 1.1 [1.2] mm/year is similar to Hancock et al.'s measured value of 0.8 mm/year.

- The hindcast [predicted under Scenario 1] coarse-sediment sedimentation rate was 1.0 [1.0] mm/year in 7–WKE, which is the Waikareao estuary at the mouth of the Kopurererua River. Added to the hindcast [predicted under Scenario 1] fine-sediment rate of 0.9 [1.0] mm/year, this gives a total hindcast sedimentation rate of nearly 2 mm/year, which is twice the measured value reported by Hancock et al. The measured rate reported by Hancock et al. in 107–WKE was derived by Burggraaf et al. (1994) by analysis of DDT measurements, and should apply to the total (sum of fine and coarse sediment). Hence, the model is overpredicting the total (fine plus coarse) sedimentation rate by about a factor of two. It may be that the coarse-sediment runoff from the Kopurererua subcatchment is being over-estimated in the model.

4.3.3 Fine sediment – effects of landuse change and climate change

Figure 4.7 and Table 4.3 show the predicted change in fine-sediment sedimentation rate due to landuse change. This is expressed as a percentage change under Scenario 2 compared to Scenario 1. Also shown in Figure 4.7 is the corresponding percentage change in predicted annual-average fine-sediment runoff from each subcatchment, which is taken from Table 4.1. A pink line is drawn between each subcatchment and its respective principal source of sediment, which is taken from Figure 4.4.

Figure 4.8 and Table 4.3 show, in the same way, the predicted change in fine-sediment sedimentation rate due to climate change, assuming the same landuse (Scenario 3 compared to Scenario 2).

In general, there is not an exact correspondence between change in sedimentation rate in any given subestuary and change in sediment runoff from the subcatchment that is the largest source of sediment to that subestuary. There are two reasons. Firstly, subestuaries typically deposit sediment from more than one subcatchment, and the changes in sediment runoff under the various scenarios are usually different for each subcatchment. Secondly, the patterns of sediment transport in the harbour can be changed by changes in sediment runoff from the catchment, which can alter the relationships between sources and sinks. This is the hallmark of a nonlinear model, which can throw up unexpected results. In a few instances, as are discussed now, that is the case here.

Northern sector of (southern) Tauranga Harbour

- For the group of three northernmost subestuaries (15–AGR, 14–WNR and 13–PAH), there is no change in sedimentation under landuse change, and there is no change in sediment runoff from the respective main sources (subcatchments 115, 114 and 113). Under climate change, the change in sediment runoff from subcatchments 115, 114 and 113 ranges from +21.8% to +26.6%, and the change in sedimentation in subestuaries 15–AGR, 14–WNR and 13–PAH ranges from +36.6% to +55.5%. This "positive imbalance" (meaning, positive change in sedimentation rate that is greater than corresponding positive change in sediment runoff from the principal sediment source) will be seen to be a typical outcome under the climate change scenario. It occurs because of a change in sediment-transport patterns that results in less sediment being lost to the coastal ocean. For example, under Scenario 2, 40% of fine sediment from subcatchment 115 is lost to the coastal ocean, but under Scenario 3 (climate change) this reduces to a 35% loss. It is not entirely clear why the model is doing this (this being a nonlinear model, it can be difficult to always know how changes in one variable translate through into changes in another). A possible likely explanation is that harbour resuspension processes, which otherwise are quite effective at scouring fine sediment, resulting in loss to the coastal ocean, are becoming overwhelmed by the larger sediment inputs under climate change. However, the model may well be overestimating the increase in sedimentation rate under climate change, for two reasons. Firstly, it is not accounting for the reduction in sediment "accommodation space" which will occur as the harbour continues to fill with sediment. This will promote loss of sediment to the coastal ocean. Secondly, it may not be accounting for the increased flushing that might occur under the increased freshwater runoff that is associated with climate change. Hence, the positive imbalance under the climate-change projections may be over-estimated.

- There is a very small (0.2%) increase in sediment runoff from subcatchment 112 under landuse change, which translates into a very small (0.5%) increase in sedimentation rate in adjacent subestuary 12–WAI, which is the primary sink for sediment from that source. Under climate change, sediment runoff from subcatchment 112 is increased by +22.6% and there is an increase of +67.9% in the sedimentation rate in adjacent subestuary 12–WAI, which is the same kind of positive imbalance noted in the three subestuaries to the north under climate change.

Central sector of (southern) Tauranga Harbour

- In the two enclosed, sheltered subestuaries 20–MGI and 26–TPI, which deposit sediment mainly from their respective adjacent subcatchments (111 and 110, respectively), there is a close correspondence between change in sediment runoff and change in sedimentation under both landuse change and climate change. This is an interesting result, as it implies that the harbour "self-cleansing" processes are not being overwhelmed here. A likely explanation is that, in these very enclosed reaches, the self-cleansing processes are not actually operative at all (and therefore cannot be overwhelmed). This lends credence to the explanation for the positive imbalance.

- A slight decrease in sediment runoff from subcatchment 110 under landuse change translates into a slight decrease in sedimentation rate in subestuary 10–TPO, which is the outer part of Te Puna estuary, and which deposits sediment primarily from adjacent subcatchment 110. There is a positive imbalance under climate change (+24.3% increase in sediment runoff from 110; +73.0% increase in sedimentation in 10–TPO).

- In subestuary 9–WKA, which deposits sediment primarily from subcatchment 109, sedimentation rate reduces very slightly under landuse change even though there is no reduction in sediment runoff from subcatchment 109. This reflects the influence of distant sediment sources. Under climate change, there is a slight positive imbalance (+27.6% increase in sediment runoff from subcatchment 109, and +38.5% increase in sedimentation rate in 9–WKA).

- In subestuary 11–MGO, sedimentation rate decreases by –3.0% under landuse change, but sediment runoff from its major source (subcatchment 108) is unchanged. This result is explainable by a change in sediment-transport patterns in the harbour under landuse change, keeping in mind that 11–MGO does in fact deposit sediment from virtually every other subcatchment. Under climate change, there is a positive imbalance when comparing change in sediment runoff from subcatchment 108 (+22.1%) with change in sedimentation in 11–MGO (>80%). As explained previously, this also is indicative of a change in harbour sediment-transport patterns.

Mouth of Wairoa River

- The change in sedimentation in subestuary 25–MAT under landuse change is not well correlated with the change in sediment runoff from its adjacent subcatchment (116), however, subcatchment 116 is not the principal source of sediment to 25–MAT. Under landuse change, sediment runoff from adjacent subcatchment 116 reduces by -23.8% while sediment runoff from principal source subcatchment 108 does not change. Combined, this results in a decrease in sedimentation in 25–MAT of -8.9%. There is the characteristic positive imbalance under climate change.

Waikareao

- In subestuary 7–WKE, which deposits sediment principally from subcatchment 107, there is a close correspondence between change in sediment runoff and sedimentation rate under landuse change (–2.2% decrease in sediment runoff from subcatchment 107; –2.7% decrease in sedimentation in subestuary 7–WKE). Under climate change, however, there is a very strong positive imbalance (+21.4% increase in sediment runoff; +69.7% increase in sedimentation). The same pattern is seen in subestuary 4–WMA, which also deposits sediment mainly from its adjacent subcatchment (106): under landuse change there is close correspondence between change in sediment runoff and change in sedimentation, and under climate change there is a strong positive imbalance (+20.6% increase in sediment runoff from 106; +88.8% increase in sedimentation in 4–WMA). In both cases (that is, 7–WKE and 4–WMA), the strong imbalance arises, at least partly, because of a reduction in loss of sediment to the coastal ocean. However, it is notable that this reduction is only slight: from 79% to 72% in the case of subcatchment 107, and from 81% to 75% in the case of subcatchment 106.

Southern sector of Tauranga Harbour

- In subestuary 3–WEL, there is a close correspondence between change in sedimentation and change in sediment runoff from its main source (adjacent subcatchment 105) under landuse change, but there is a positive imbalance under climate change. In neighbouring subestuary 2–RNC, there is a close correspondence between change in sedimentation rate and change in sediment runoff from its main source (subcatchment 104) under both landuse change and climate change. In subestuary 1–SPW, sedimentation is increased by +0.1% under landuse change, even though sediment runoff from the adjacent source (103) is increased by much more than that (+3.5%). However, the main source is actually subcatchment 104, where sediment runoff is reduced by -0.7% under landuse change. Hence, change in sedimentation in this case is responding to the combined influence of subcatchments 103 and 104. Under climate change, there is a close correspondence between change in sedimentation rate in subestuary 1–SPW and change in sediment runoff from both subcatchments 104 and 103.

- The principal source of sediment to subestuary 6–WPB is subcatchment 108, not the adjacent subcatchment 102. Hence, changes in sedimentation are driven by changes in sediment runoff from 108 as well as 102. There is little change under landuse change. Under climate change, there is the by-now familiar positive imbalance.

Matakana Island

- For the two subestuaries that are adjacent to Matakana Island (18–RGI and 19–HCK), the sedimentation rate under landuse change is slightly reduced even though sediment runoff from the main source (subcatchment 108) is unchanged. Under climate change, the increase in sedimentation in 19–HCK very closely matches the increase in sediment runoff from 108, but the increase in sedimentation in 18–RGI is not quite as large.

Figure 4.9 and Table 4.3 show the predicted change in fine-sediment sedimentation rate due to both landuse change and climate change (Scenario 3 compared to Scenario 1). The main driver(s) of change (climate change or landuse change, or both) is identified in Table 4.5.

- For all subestuaries, the dominant driver of change is climate change, which, furthermore, always results in an increase in sedimentation rate.

4.3.4 Coarse sediment – effects of landuse change and climate change

Figure 4.10 and Table 4.4 show the predicted change in coarse-sediment sedimentation rate due to landuse change. This is expressed as a percentage change under Scenario 2 compared to Scenario 1. Also shown in Figure 4.10 is the corresponding percentage change in predicted annual-average coarse-sediment runoff from each subcatchment, which is taken from Table 4.2. A pink line is drawn between each subcatchment and its respective principal source of sediment.

Figure 4.11 and Table 4.4 show, in the same way, the predicted change in coarse-sediment sedimentation rate due to climate change, assuming the same landuse (Scenario 3 compared to Scenario 2).

- Small or zero reductions in coarse-sediment runoff from subcatchments 106, 107 and 108 under landuse change translate into correspondingly small or zero reductions in sedimentation rate in respective adjacent subestuaries.

- Changes in coarse-sediment runoff are all positive (increases) under climate change. There is a positive imbalance in subestuary 8–WAR (+51.9% change in sedimentation rate, compared to +22.1% increase in sediment runoff from subcatchment 108, which is the main source). In contrast, in subestuaries 7–WKE and 4–WMA there is a fairly close correspondence between change in sedimentation rate and change in sediment runoff from the respective main source subcatchment.

Figure 4.12 and Table 4.4 show the predicted change in coarse-sediment sedimentation rate due to both landuse change and climate change (Scenario 3 compared to Scenario 1). The main driver(s) of change (climate change or landuse change, or both) is identified in Table 4.6.

- In all subestuaries that deposit coarse sediment from the catchment, the dominant driver of change is climate change, which, furthermore, always results in an increase in sedimentation rate.

4.4 Bed composition

The seabed composition will become progressively altered where fine sediments deposit on a relatively coarser pre-existing bed, and vice versa. The USC–3 model does make explicit predictions of the change through time in the bed-sediment surface-mixed-layer median grainsize (D_{50}). However, this requires a good estimate of the mixing depth, which is not known for Tauranga Harbour with any degree of certainty.

For an alternative analysis of the change in bed-sediment composition through time, a narrative is presented here, drawing together the predictions of sedimentation by the USC–3 model, and information on present-day bed-sediment composition (primarily mean grainsize and percentage mud), presented by Hancock et al. (2009).

Figure 4.13 accompanies the narrative. In this figure, the predicted fine-sediment sedimentation rate under the combined influence of landuse change and climate change (i.e., Scenario 3) is classified into a "traffic light" system: red signifies a high sedimentation rate (>1.0 mm/year); amber signifies a moderate sedimentation rate (0.30–1.0 mm/year); and green signifies a low sedimentation rate (<0.30 mm/year). The present-day mud content of the bed is also shown, classified into "traffic lights": red signifies high mud content (>20%); amber signifies moderate mud content (10–20%); and green signifies low mud content (<10%). The intent with this dual traffic-light classification is to show which subestuaries are most likely to experience ecologically significant changes in bed-sediment composition. For example, a high fine-sediment sedimentation rate (red) combined with an already-high mud content (red) will cause the bed to become muddier. However, the mud content is already high, and so ecological effects may be minor. A high fine-sediment sedimentation rate (red) combined with an already-low mud content (green) will also cause the bed to become muddier, however, the ecological effects in this case may be significant as the bed shifts from sandy to muddy.

Following this kind of reasoning, also shown in Figure 4.13 are "ecology alerts". These very roughly indicate parts of the harbour where the ecology may be at risk due to fine-sediment deposition, and should be regarded as preliminary interpretations only. They are explained in the narrative that follows.

Northern sector of (southern) Tauranga Harbour

- The model predicts that fine sediments will not accumulate on the middle-harbour sandbanks (16–MHR).
- The fine-sediment sedimentation rate in subestuary 15–AGR at the mouth of the Aongatete River is predicted to increase substantially (+36.6%, to 2.22 mm/year) under the combined influence of landuse change and climate change. The mud content of the seabed here is already 27.1% on average, which will increase in time. This is likely to occur through further

encroachment of fine sediment beyond the mouth of the river, towards 16–MHR, causing habitat change and continued mangrove spread.

- The situation is very similar for subestuary 14–WNR at the mouth of the Wainui River, where the fine-sediment sedimentation rate is predicted to increase substantially (+36.7%, to 3.22 mm/year) under the combined influence of landuse change and climate change. The mud content of the seabed here is already 43.7% on average, which will increase in time. Since the mud content of the seabed is already high, there may not be further significant ecological effects. However, fine sediment will also encroach into the outer embayment, into the area that currently features complicated sandbanks and islands, and towards 16–MHR.

- Subestuary 13–PAH is predicted to experience a large increase of +55.4% in fine-sediment sedimentation rate under the combined influence of landuse change and climate change, to 3.69 mm/year. As was the case in 14–WNR to the north, the mud content of the seabed here is already high (48.1%), which will increase in time. The ecological effects will possibly be limited, given that the seabed is already quite muddy. However, fine sediment will also encroach into the mouth of the embayment, which currently features sandier habitats.

- Subestuary 12–WAI also experiences a large increase (68.8%) in fine-sediment sedimentation rate under the combined influence of landuse change and climate change, to 4.50 mm/year. Hancock et al. report a low mud content for the bed sediments here (only 6.3%), although this estimate is biased towards the outer, sandier, parts of the subestuary. Continued deposition of fine sediment will encroach on to these outer areas, altering habitat and fostering the spread of mangroves.

- The model predicts that fine sediments will not accumulate in the open intertidal flats between the mouth of the Waipapa River and the western shore of Omokoroa Peninsula (23–OMO). Nevertheless, fine sediment deposited within 12–WAI, which lies adjacent, will encroach in this direction.

Central sector of (southern) Tauranga Harbour

- The model predicts that fine sediments will not accumulate on the sandbank between the eastern shore of Omokoroa Peninsula and the western shore of

Motuhoa Island (24–OMI). The mud content here is presently moderate at 14.1%.

- Predicted fine-sediment sedimentation rate is low in 11–MGO (0.47 mm/year under the combined influence of landuse change and climate change), which suggests that bed-sediment mud content will increase and mean grainsize will decrease only slowly. The present-day mud content of >20% in this region seems somewhat at odds with that prediction; an explanation may be that this subestuary is rather poorly defined, stretching as it does from the East Coast Main Trunk rail line embankment, which is sheltered, to Omokoroa Point, which is exposed. Because of this, traffic lights are not applied in 11–MGO in Figure 4.13. However, an ecological alert is placed at the sheltered end of 11–MGO, where fine sediment may escape from 20–MGI (enclosed by the rail line embankment) and deposit.

- The two subestuaries enclosed by the East Coast Main Trunk rail line embankment (20–MGI and 26–TPI) are already choked with mud. Further deposition of fine sediment here will continue to push these subestuaries towards the end stages of stabilisation by vegetation.

- Subestuary 10–TPO is partially enclosed by a spit complex at the mouth. The predicted sedimentation rate under the combined influence of landuse change and climate change is small compared to subestuaries to the north (1.22 mm/year, compared to 2–3 mm/year). However, this represents a large change relative to the baseline sedimentation rate (+72.4%), so it is still a matter of concern, especially given the recent history of mangrove spread here and the high amenity values. Should the spit complex at the mouth continue to prograde, the embayment enclosed by the spit may become a more effective sediment trap.

- Subestuary 9–WKA is similar to 10–TPO: the predicted fine-sediment sedimentation rate under the combined influence of landuse change and climate is relatively small (1.07 mm/year), but it, too, has a recent history of mangrove spread, and a high amenity value. Climate change is predicted to cause a significant increase in sedimentation here. As was the case for 10–TPO, should the spit complex at the mouth of 9–WKA continue to prograde, the embayment enclosed by the spit may become a more effective sediment trap.

Mouth of Wairoa River

- Fine-sediment is not predicted to accumulate at the mouth of the Wairoa River in subestuary 8–WAR, because it is exposed and subject to flushing flows. In addition to that, coarse sediment brought down by the Wairoa River in flood deposits in this area. Hence, the already sandy bed (just 3.5% mud content) will not become muddier.

- Subestuary 25–MAT is also at the mouth of the Wairoa River, and it also receives some coarse sediment brought down by the Wairoa River in flood. However, the fine-sediment sedimentation rate is moderate (0.74 mm/year under the combined influence of landuse change and climate change). The seabed will become muddier as fine sediment spreads from the inner edges of the embayment, where mangroves have already established.

Waikareao

- The mud content of the seabed in subestuary 7–WKE is currently 20.8% and this will increase under a fine-sediment sedimentation rate of 1.66 mm/year under the combined influence of landuse change and climate change. This will be manifest as spreading of mud into the relatively sandier central reaches and the reaches near the outlet of the embayment. Any increase in mud content may be mitigated by deposition of coarse sediment brought down by the Kopurererua Stream in flood. However, Green (2009) thought that the coarse-sediment runoff from the Kopurererua subcatchment is being over-estimated in the model.

Southern sector of Tauranga Harbour

- The model predicts that fine sediments will not accumulate on the intertidal flats that run along the Tauranga City foreshore (5–TAC).

- The seabed in subestuary 4–WMA is currently 30.3% mud and this will further increase under the combined influence of landuse change and climate change with a fine-sediment sedimentation rate of 2.16 mm/year. This will be manifest as spreading of mud into the relatively sandier central reaches and the reaches near the outlet of the embayment. Any increase in mud content may be mitigated by deposition of coarse sediment brought down by the Waimapu Stream in flood.

- Rangataua Bay, which encompasses subestuaries 3–WEL, 2–RNC and 1–SPW, is presently muddier around the fringes and in localised embayments, (the seabed mud content in Welcome Bay and Speedway is currently 31.4% and 14.0%, respectively). The muddy fringes will expand into the central reaches (currently 6.9% mud) under high fine-sediment sedimentation rates (3.23 mm/year for 3–WEL and 1.93 mm/year for 1–SPW, under the combined influence of landuse change and climate change). This will foster a corresponding spread of mangroves.

- Predicted fine-sediment sedimentation rate is low in 6–WPB (0.33 mm/year under the combined influence of landuse change and climate change). Bed-sediment mean grainsize is presently large at 0.32 mm and the mud content is low at 8.1%. These will only change slowly.

Matakana Island

- Predicted fine-sediment sedimentation rate in both 18–RGI and 19–HCK is small (0.08 mm/year and 0.24 mm/year, respectively). In both of these subestuaries the bed-sediment mean grainsize is large (0.32 mm in both) and the mud content is low (10.8% and 8.5%, respectively). These will only change slowly.

Central reaches

- The model predicts that fine sediments will not accumulate in the central reaches of the (southern) harbour (21–OIK, 22–MOT), or on the intertidal flats that run along the western, central section of Matakana Island (17–MKI).

FINE SEDIMENT

Subcatchment	Annual-average load (kg/year)			% change		
	Scenario 1 Current (2001) landuse No climate change	**Scenario 2** Future landuse No climate change	**Scenario 3** Future landuse Climate change	**Landuse change** (S2/S1)	**Climate change** (S3/S2)	**Both** (S3/S1)
101	53,138	53,225	68,834	0.2	29.3	29.5
102	329,689	327,826	374,944	-0.6	14.4	13.7
103	275,049	284,679	353,042	3.5	24.0	28.4
104	7,160,301	7,111,379	8,945,375	-0.7	25.8	24.9
105	1,776,815	1,731,510	2,203,496	-2.5	27.3	24.0
106	14,649,806	14,578,067	17,578,178	-0.5	20.6	20.0
107	7,302,388	7,140,506	8,669,131	-2.2	21.4	18.7
108	44,183,562	44,178,484	53,931,825	0.0	22.1	22.1
109	390,134	390,132	497,815	0.0	27.6	27.6
110	3,819,758	3,817,694	4,745,218	-0.1	24.3	24.2
111	1,123,502	1,071,829	1,318,969	-4.6	23.1	17.4
112	4,228,386	4,237,168	5,196,643	0.2	22.6	22.9
113	2,682,534	2,682,429	3,313,085	0.0	23.5	23.5
114	4,433,307	4,433,179	5,399,622	0.0	21.8	21.8
115	4,068,928	4,067,793	5,149,544	0.0	26.6	26.6
116	225,350	171,649	209,990	-23.8	22.3	-6.8
117	278,707	278,707	354,671	0.0	27.3	27.3

Table 4.1: Predicted annual-average fine-sediment runoff from each subcatchment for each scenario. This is an annual-average over the duration of each 50-year simulation and over all 100 simulations in the Monte Carlo package. The change in sediment runoff from scenario to scenario is expressed as a percentage change, where a positive change signifies an increase and a negative change signifies a decrease.

COARSE SEDIMENT

Subcatchment	Annual-average load (kg/year)			% change		
	Scenario 1 Current (2001) landuse No climate change	**Scenario 2** Future landuse No climate change	**Scenario 3** Future landuse Climate change	**Landuse change** (S2/S1)	**Climate change** (S3/S2)	**Both** (S3/S1)
101	-	-	-	-	-	-
102	-	-	-	-	-	-
103	-	-	-	-	-	-
104	-	-	-	-	-	-
105	-	-	-	-	-	-
106	6,567,944	6,532,739	7,881,409	-0.5	20.6	20.0
107	3,266,525	3,186,785	3,873,156	-2.4	21.5	18.6
108	19,878,656	19,875,687	24,264,358	0.0	22.1	22.1
109	-	-	-	-	-	-
110	-	-	-	-	-	-
111	-	-	-	-	-	-
112	-	-	-	-	-	-
113	-	-	-	-	-	-
114	-	-	-	-	-	-
115	-	-	-	-	-	-
116	-	-	-	-	-	-
117	-	-	-	-	-	-

Table 4.2: Predicted annual-average coarse-sediment runoff from each subcatchment for each scenario. This is an annual-average over the duration of each 50-year simulation and over all 100 simulations in the Monte Carlo package. The change in sediment runoff from scenario to scenario is expressed as a percentage change, where a positive change signifies an increase and a negative change signifies a decrease.

FINE SEDIMENT

Subestuary	**Annual-average sedimentation rate (mm/year)**			**% change**		
	Scenario 1 Current (2001) landuse No climate change	**Scenario 2** Future landuse No climate change	**Scenario 3** Future landuse Climate change	**Landuse change** (S2/S1)	**Climate change** (S3/S2)	**Both** (S3/S1)
1	1.48	1.48	1.93	0.1	30.2	30.4
2	0.50	0.50	0.59	-0.5	18.0	17.4
3	2.11	2.04	3.23	-3.5	58.6	53.0
4	1.15	1.14	2.16	-1.0	88.8	87.0
5	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
6	0.22	0.22	0.33	-1.0	49.2	47.7
7	1.01	0.98	1.66	-2.7	69.7	65.1
8	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
9	0.77	0.77	1.07	-0.2	38.5	38.3
10	0.71	0.71	1.22	-0.3	73.0	72.4
11	0.25	0.25	0.47	-3.0	88.7	83.1
12	2.67	2.68	4.50	0.5	67.9	68.8
13	2.38	2.38	3.69	0.0	55.5	55.4
14	2.36	2.36	3.22	0.0	36.7	36.7
15	1.63	1.63	2.22	0.0	36.6	36.6
16	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
17	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
18	0.06	0.06	0.08	-0.4	17.6	17.2
19	0.19	0.19	0.24	-0.3	26.8	26.5
20	2.55	2.47	2.93	-3.2	18.8	15.0
21	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
22	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
23	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
24	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
25	0.60	0.55	0.74	-8.9	36.1	24.1
26	6.51	6.50	8.03	-0.1	23.4	23.4

Table 4.3: Predicted annual-average fine-sediment sedimentation rate, all scenarios. For each scenario, this is the average over all years in the simulation and over all USC-3 model runs in the Monte Carlo package. Also shown is the change in sedimentation rate from scenario to scenario, expressed as a percentage change, where a positive change signifies an increase and a negative change signifies a decrease.

COARSE SEDIMENT

Subestuary	Annual-average sedimentation rate (mm/year)			% change		
	Scenario 1 Current (2001) landuse No climate change	**Scenario 2** Future landuse No climate change	**Scenario 3** Future landuse Climate change	**Landuse change** (S2/S1)	**Climate change** (S3/S2)	**Both** (S3/S1)
1	-	-	-	-	-	-
2	-	-	-	-	-	-
3	-	-	-	-	-	-
4	3.59	3.58	4.19	-0.3	16.9	16.5
5	-	-	-	-	-	-
6	-	-	-	-	-	-
7	0.95	0.93	1.15	-2.2	24.3	21.6
8	3.35	3.34	5.08	-0.1	51.9	51.8
9	-	-	-	-	-	-
10	-	-	-	-	-	-
11	-	-	-	-	-	-
12	-	-	-	-	-	-
13	-	-	-	-	-	-
14	-	-	-	-	-	-
15	-	-	-	-	-	-
16	-	-	-	-	-	-
17	-	-	-	-	-	-
18	-	-	-	-	-	-
19	-	-	-	-	-	-
20	-	-	-	-	-	-
21	-	-	-	-	-	-
22	-	-	-	-	-	-
23	-	-	-	-	-	-
24	-	-	-	-	-	-
25	2.57	2.57	2.59	0.0	0.8	0.8
26	-	-	-	-	-	-

Table 4.4: Predicted annual-average fine-sediment sedimentation rate, all scenarios. For each scenario, this is the average over all years in the simulation and over all USC-3 model runs in the Monte Carlo package. Also shown is the change in sedimentation rate from scenario to scenario, expressed as a percentage change, where a positive change signifies an increase and a negative change signifies a decrease.

FINE SEDIMENT

Main source subcatchment	Subestuary	Main driver of change
104	1	Climate change and landuse change additive (increase)
104	2	Climate change dominant (increase)
105	3	Climate change dominant (increase)
106	4	Climate change dominant (increase)
-	5	-
108	6	Climate change dominant (increase)
107	7	Climate change dominant (increase)
-	8	-
109	9	Climate change dominant (increase)
110	10	Climate change dominant (increase)
108	11	Climate change dominant (increase)
112	12	Climate change and landuse change additive (increase)
113	13	Climate change dominant (increase)
114	14	Climate change dominant (increase)
115	15	Climate change dominant (increase)
-	16	-
-	17	-
108	18	Climate change dominant (increase)
108	19	Climate change dominant (increase)
111	20	Climate change dominant (increase)
-	21	-
-	22	-
-	23	-
-	24	-
108	25	Climate change dominant (increase)
110	26	Climate change dominant (increase)

Table 4.5: Summary of the main drivers of change of fine-sediment sedimentation rate. Refer to text for explanation.

COARSE SEDIMENT

Main source subcatchment	Subestuary	Main driver of change
-	1	-
-	2	-
-	3	-
106	4	Climate change dominant (increase)
-	5	-
-	6	-
107	7	Climate change dominant (increase)
108	8	Climate change dominant (increase)
-	9	-
-	10	-
-	11	-
-	12	-
-	13	-
-	14	-
-	15	-
-	16	-
-	17	-
-	18	-
-	19	-
-	20	-
-	21	-
-	22	-
-	23	-
-	24	-
108	25	Climate change dominant (increase)
-	26	-

Table 4.6: Summary of the main drivers of change of coarse-sediment sedimentation rate. Refer to text for explanation.

Figure 4.1: Loss of fine sediment to the coastal ocean from each subcatchment, expressed as a percentage of the total load from each subcatchment, where that percentage is an average over all 100 simulations in the Monte Carlo package for Scenario 1.

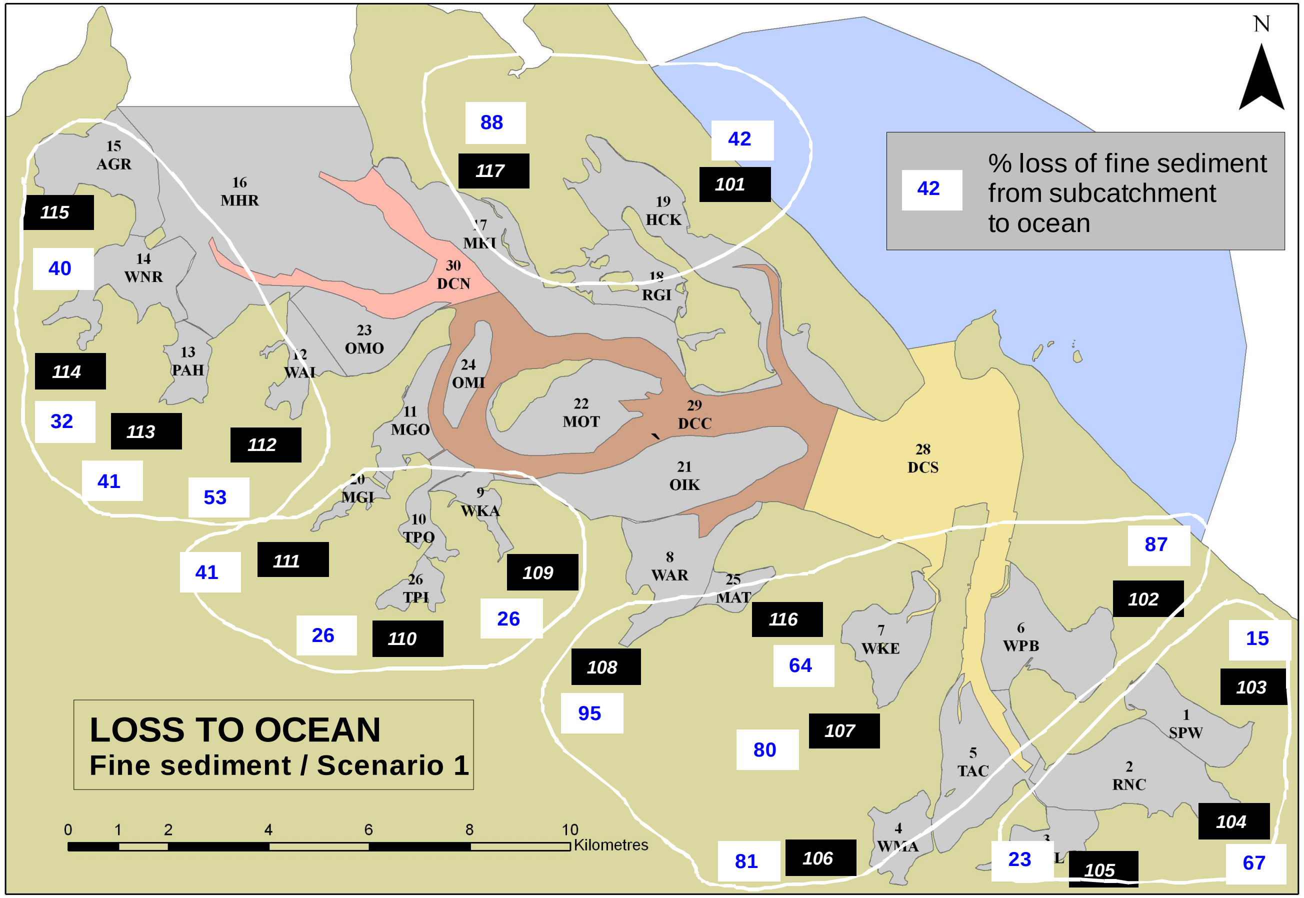


Figure 4.2: Loss of coarse sediment to the coastal ocean from each subcatchment, expressed as a percentage of the total load from each subcatchment, where that percentage is an average over all 100 simulations in the Monte Carlo package for Scenario 1.

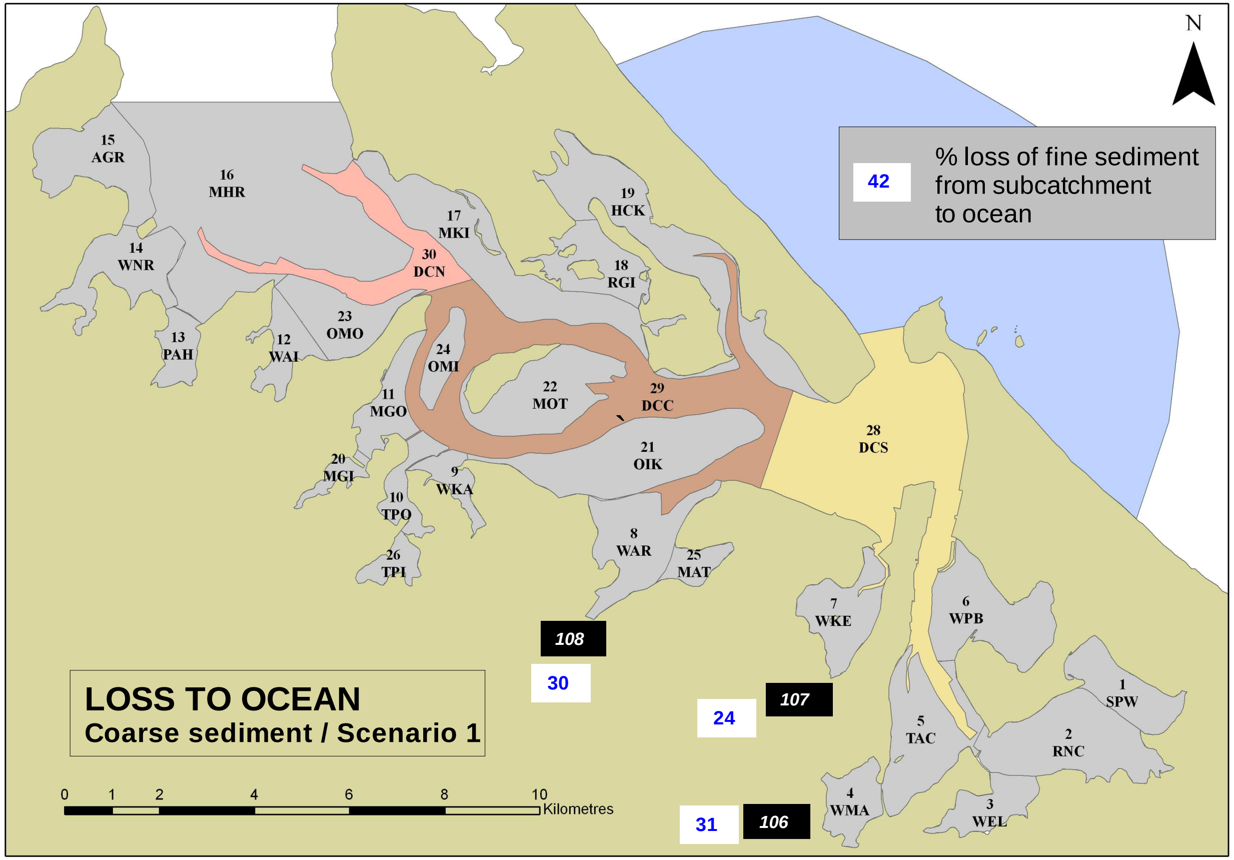


Figure 4.3: Primary fate of fine sediment discharged from each subcatchment. These are broad patterns, applicable to every scenario. These can be thought of as primary transport pathways for terrigenous fine sediment that result in deposition. (Note that the lines simply connect source and sink; they do not imply an actual route the sediment follows between source and sink.) Not shown is loss of sediment to the coastal ocean.

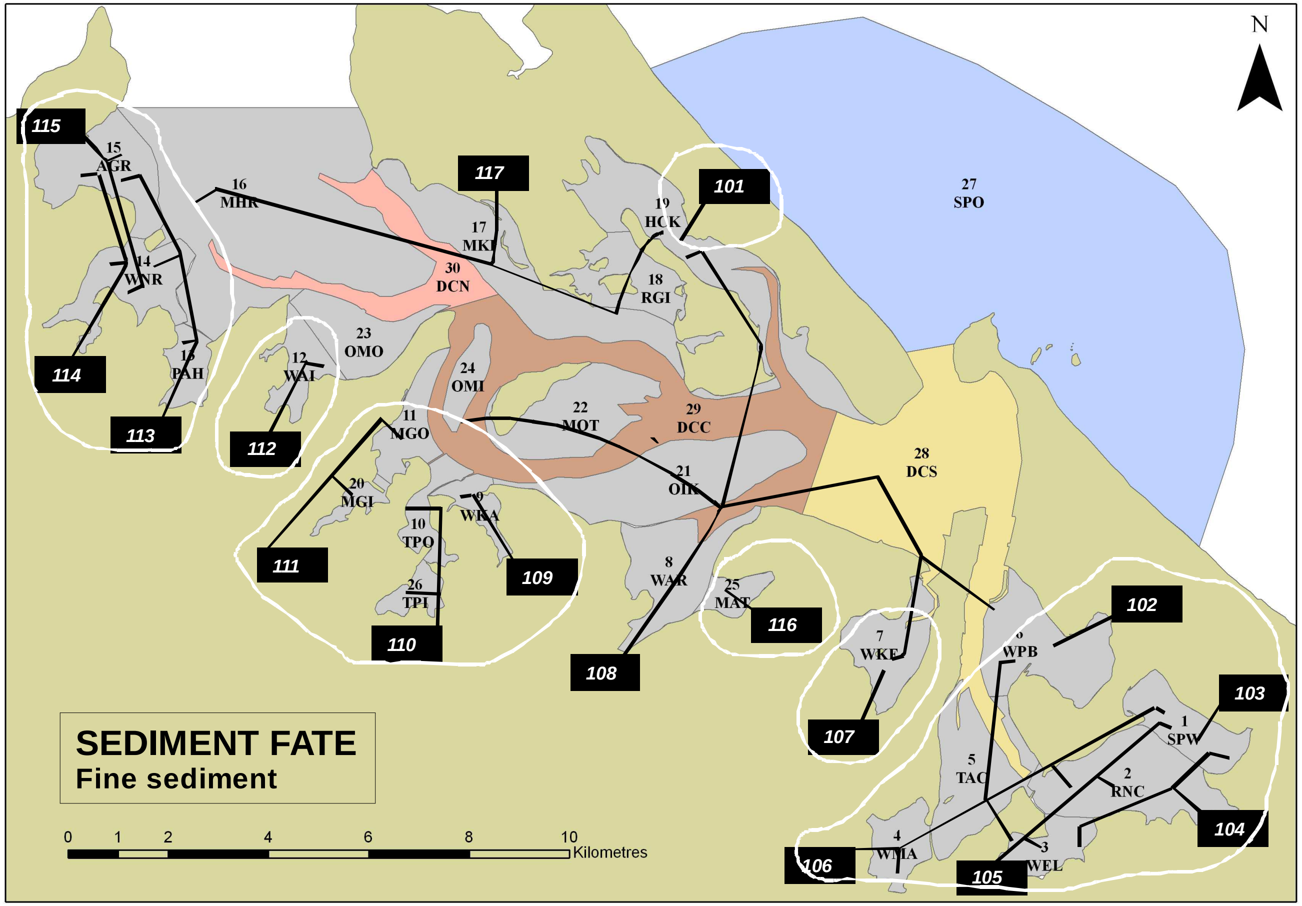


Figure 4.4: Principal sources of fine sediment deposited in each subestuary. These are broad patterns, and they apply to every scenario. There is one thick, red line that connects each subestuary to a subcatchment. This denotes the principal source of sediment to that subestuary. The thin, black lines that connect to other subcatchments show secondary sources.

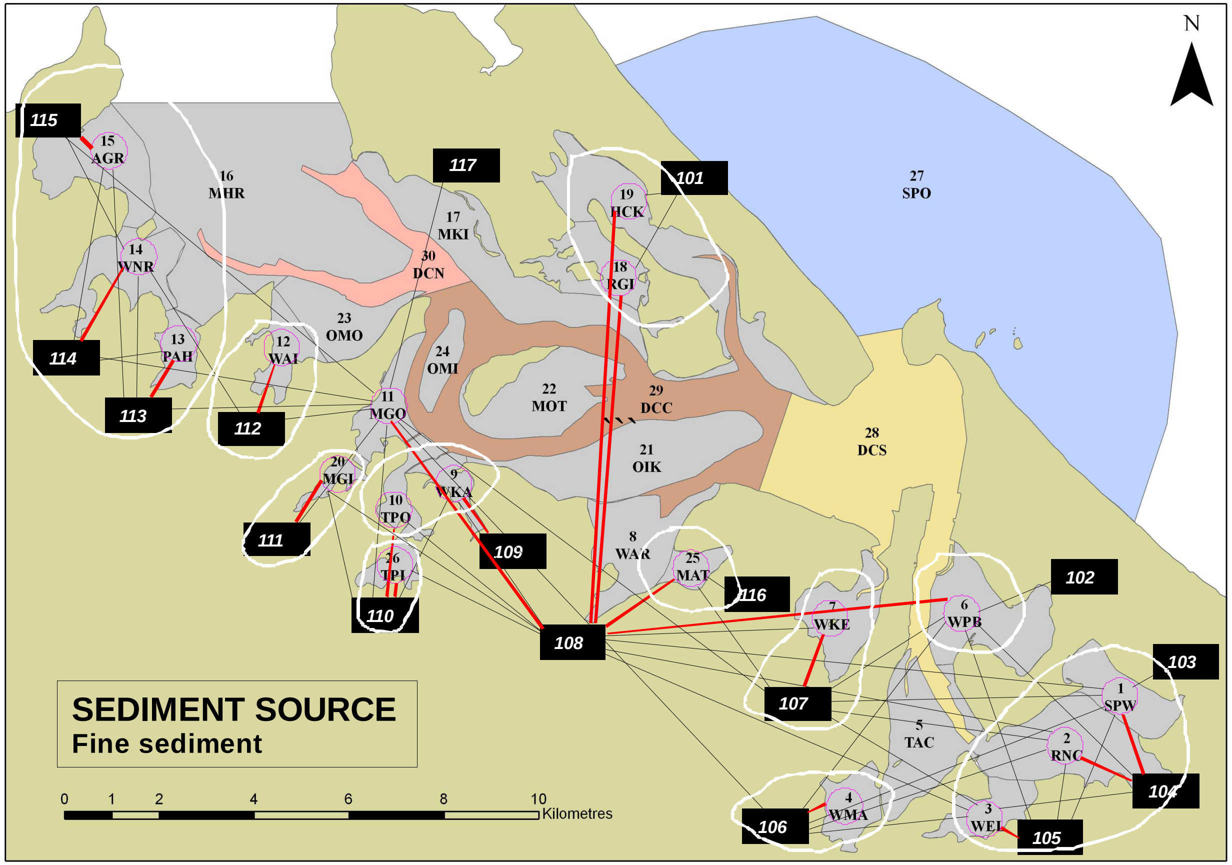


Figure 4.5: Predicted annual-average fine-sediment sedimentation rate, Scenario 1. This is the average over all years in the simulation and over all USC-3 model runs in the Monte Carlo package. Also shown are the measured values reported by Hancock et al. (2009).

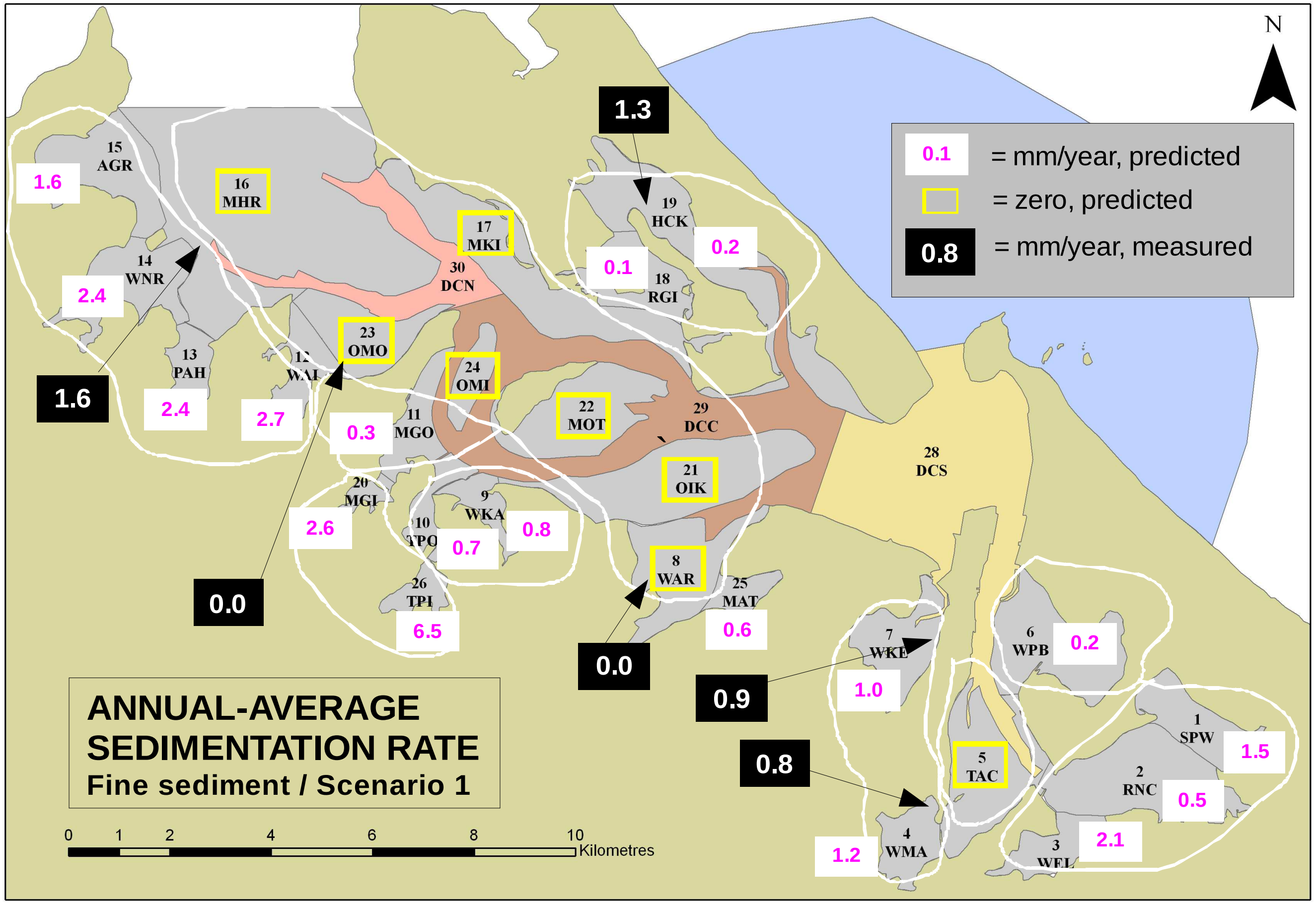


Figure 4.6: Predicted annual-average coarse-sediment sedimentation rate, Scenario 1. This is the average over all years in the simulation and over all USC-3 model runs in the Monte Carlo package. Also shown are the measured values reported by Hancock et al. (2009).

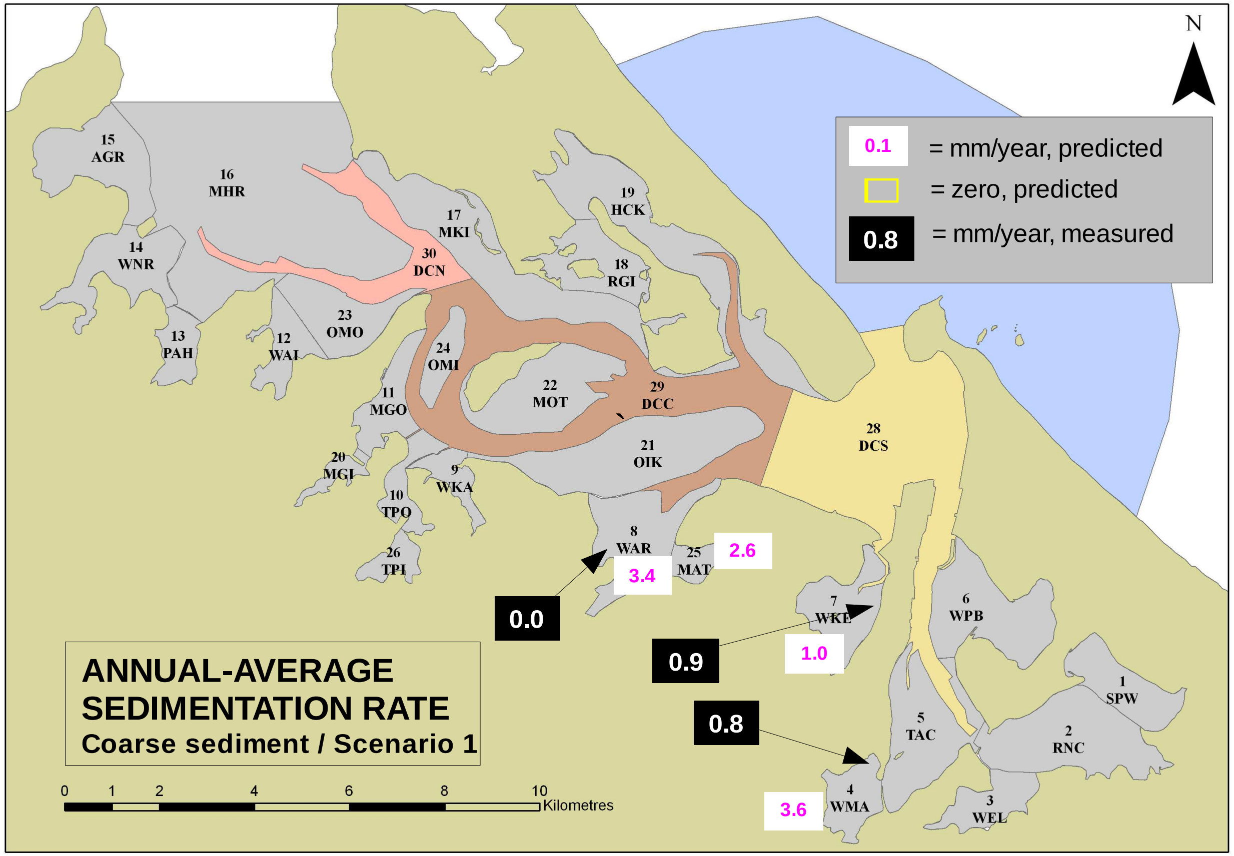


Figure 4.7: Predicted change in fine-sediment sedimentation rate due to landuse change, expressed as a percentage change under Scenario 2 compared to Scenario 1. Also shown is the corresponding percentage change in predicted annual-average fine-sediment runoff from each subcatchment. A pink line is drawn between each subcatchment and its respective principal source of sediment,

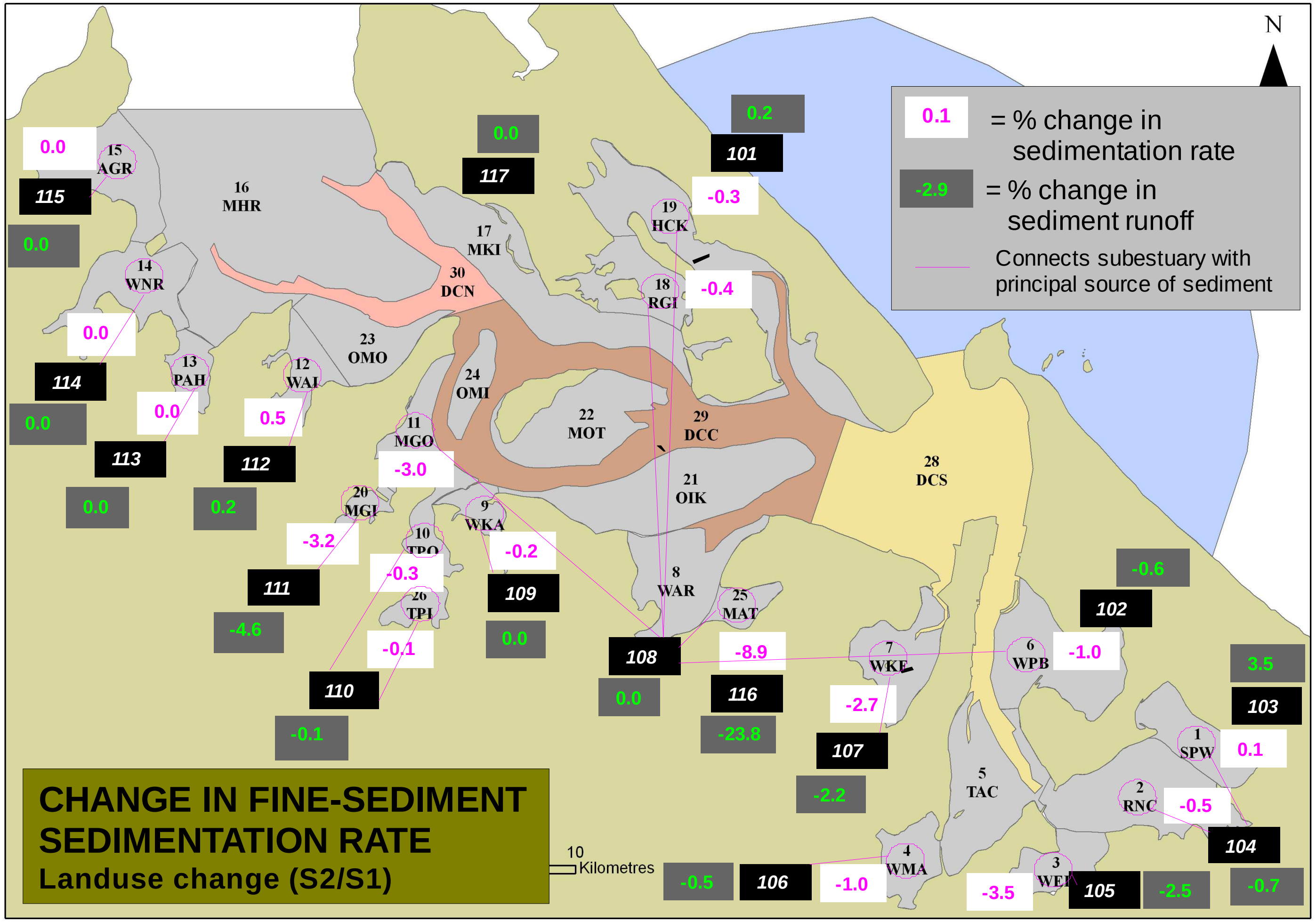


Figure 4.8: Predicted change in fine-sediment sedimentation rate due to climate change, expressed as a percentage change under Scenario 3 compared to Scenario 2. Also shown is the corresponding percentage change in predicted annual-average fine-sediment runoff from each subcatchment. A pink line is drawn between each subcatchment and its respective principal source of sediment.

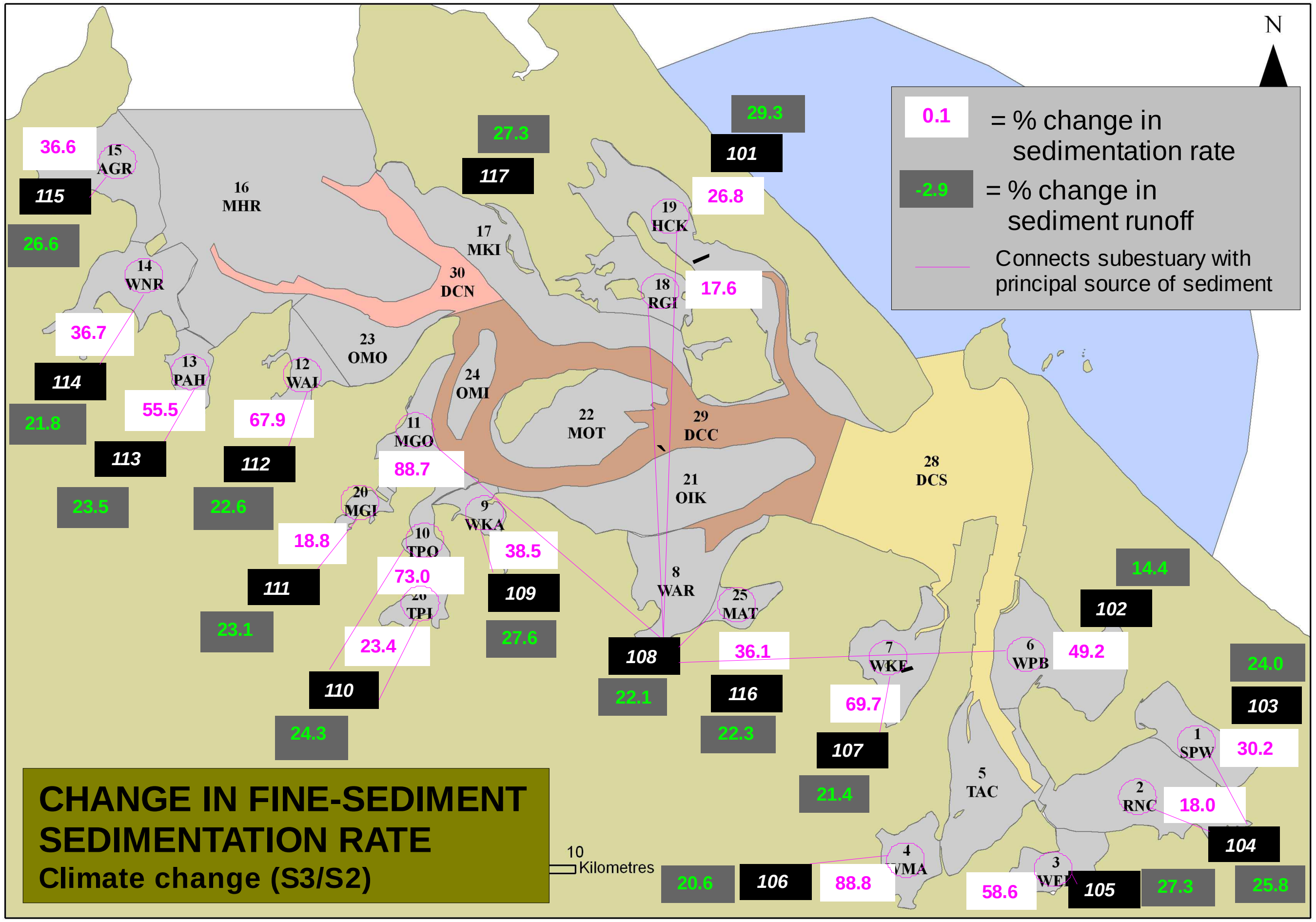


Figure 4.9: Predicted change in fine-sediment sedimentation rate due to both landuse change and climate change, expressed as a percentage change under Scenario 3 compared to Scenario 1. Also shown is the corresponding percentage change in predicted annual-average fine-sediment runoff from each subcatchment. A pink line is drawn between each subcatchment and its respective principal source of sediment.

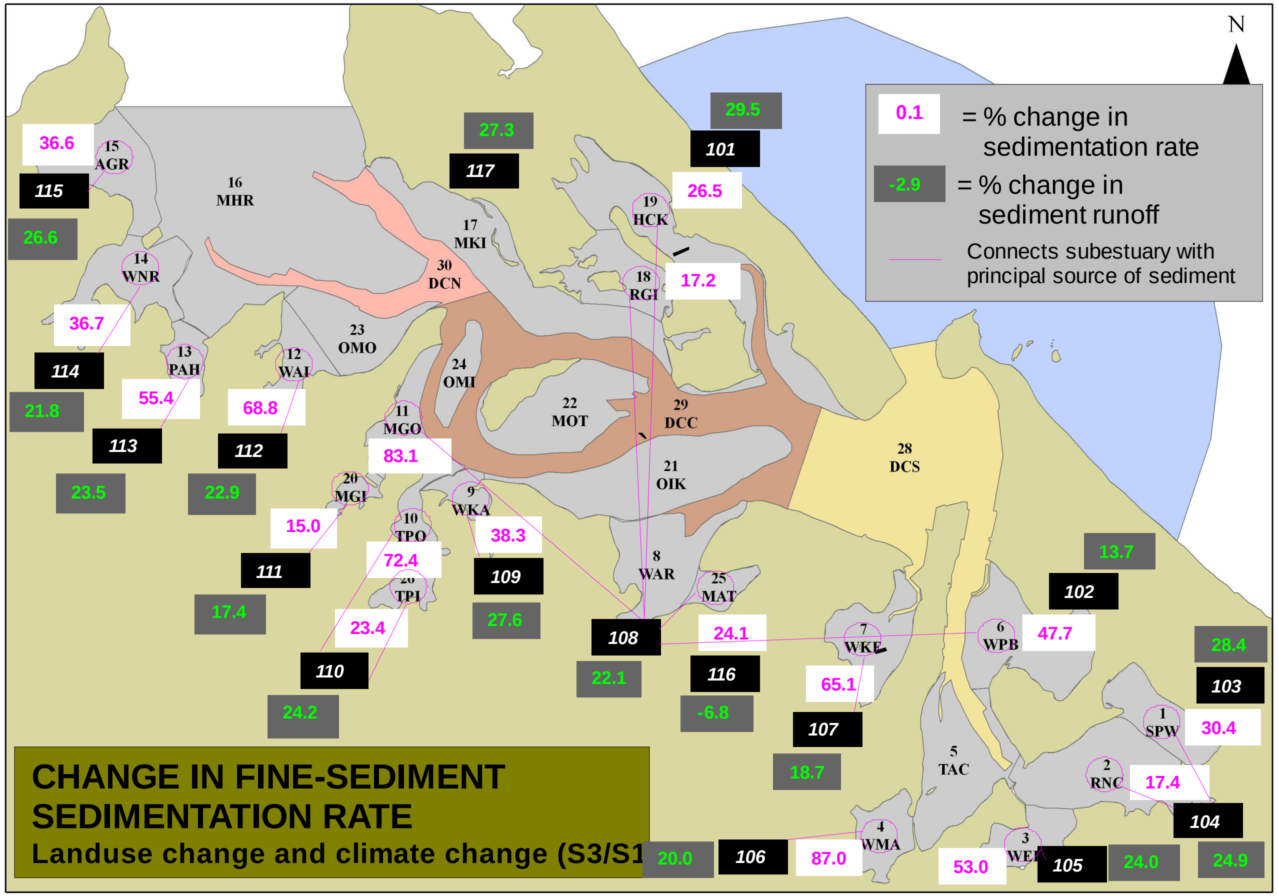


Figure 4.10: Predicted change in coarse-sediment sedimentation rate due to landuse change, expressed as a percentage change under Scenario 2 compared to Scenario 1. Also shown is the corresponding percentage change in predicted annual-average fine-sediment runoff from each subcatchment. A pink line is drawn between each subcatchment and its principal source of sediment.

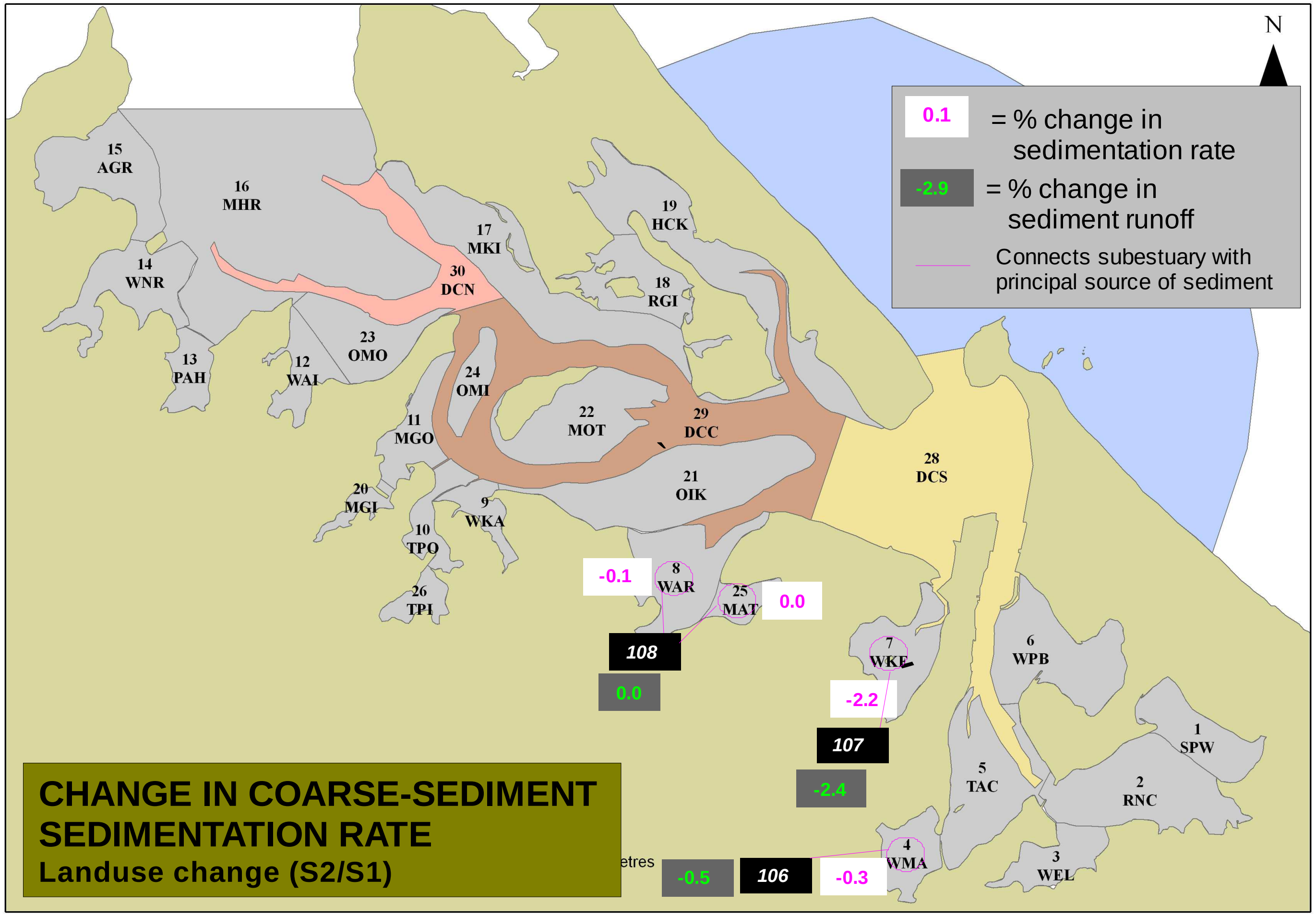


Figure 4.11: Predicted change in coarse-sediment sedimentation rate due to climate change, expressed as a percentage change under Scenario 3 compared to Scenario 2. Also shown is the corresponding percentage change in predicted annual-average fine-sediment runoff from each subcatchment. A pink line is drawn between each subcatchment and its principal source of sediment.

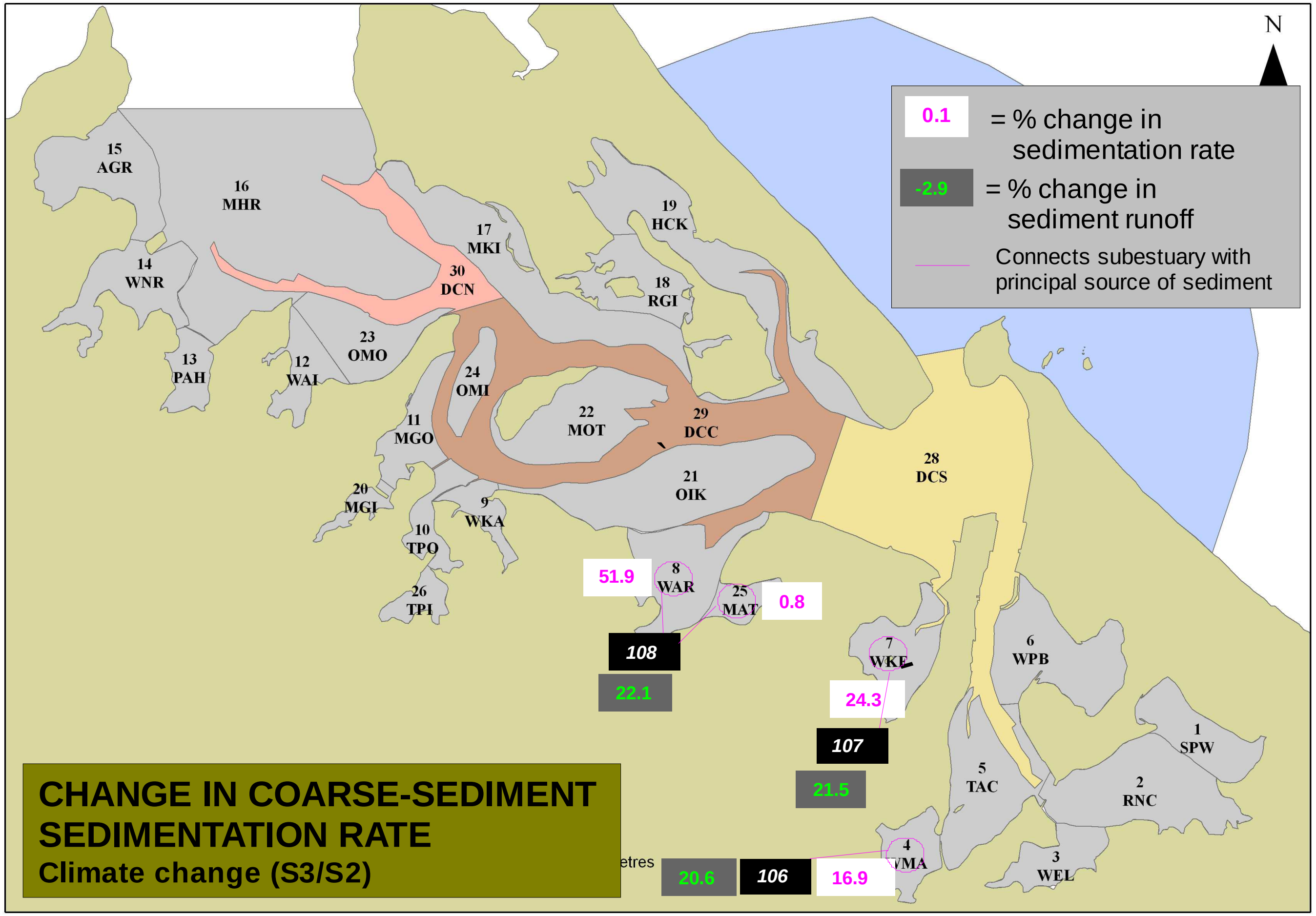


Figure 4.12: Predicted change in coarse-sediment sedimentation rate due to both landuse change and climate change, expressed as a percentage change under Scenario 3 compared to Scenario 1. Also shown is the corresponding percentage change in predicted annual-average fine-sediment runoff from each subcatchment. A pink line is drawn between each subcatchment and its respective principal source of sediment.

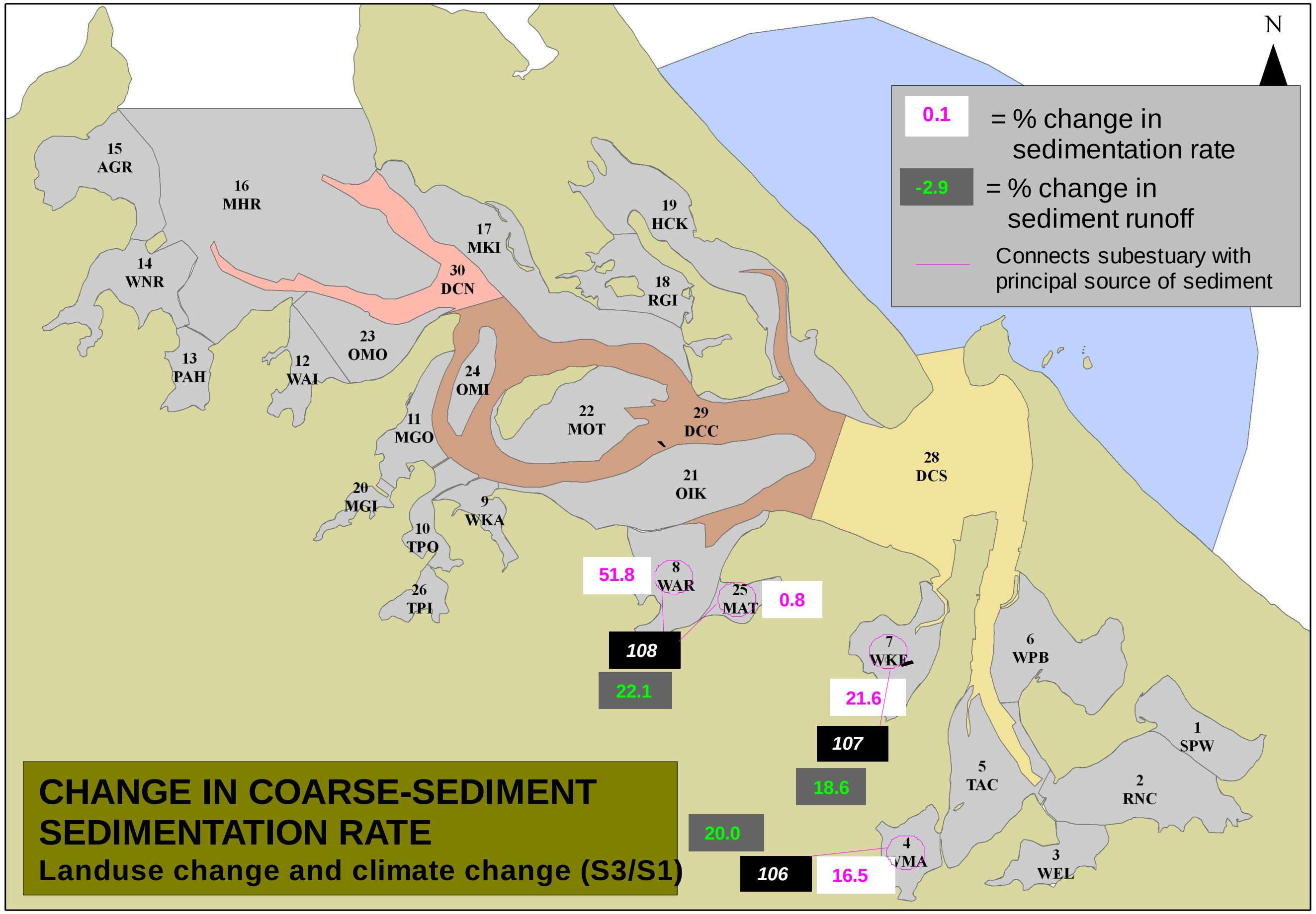
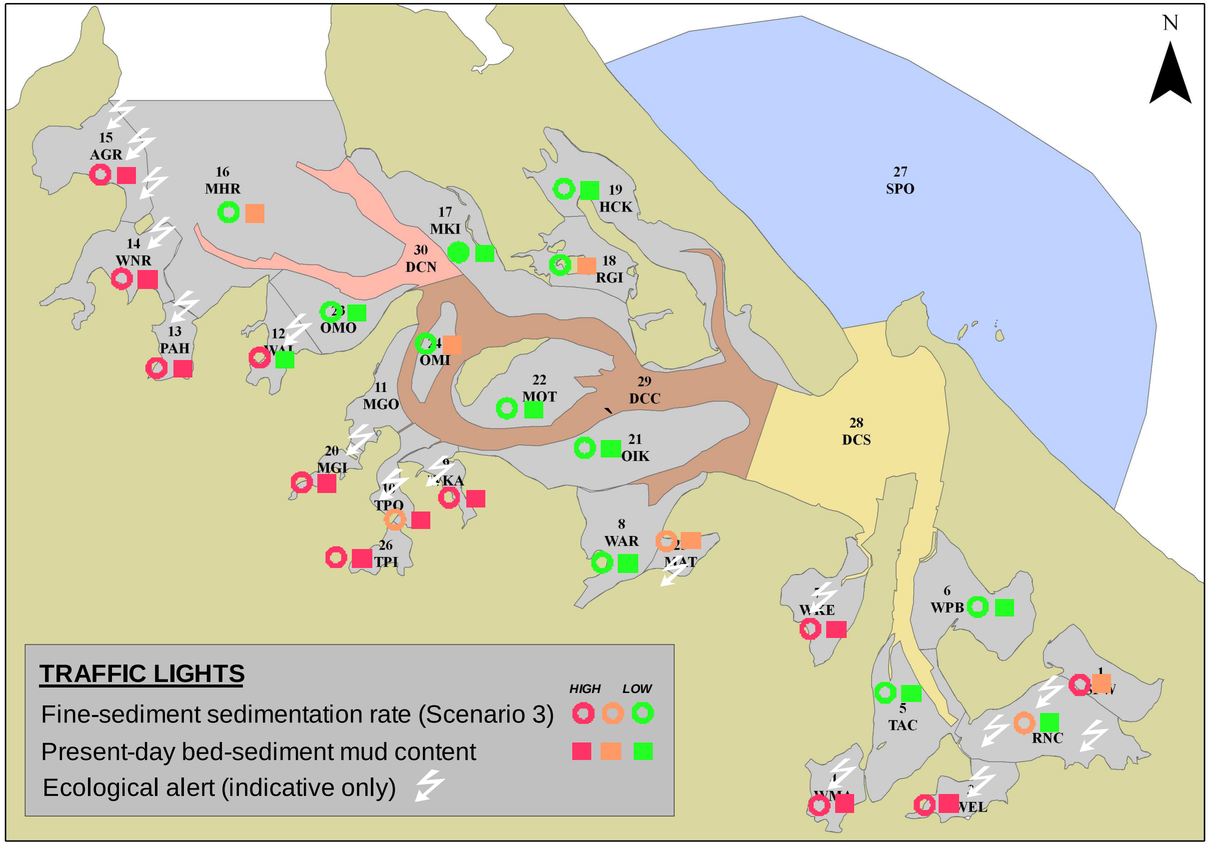


Figure 4.13: Fine-sediment sedimentation rate under the combined influence of landuse change and climate change (i.e., Scenario 3) classified into a "traffic light" system: red signifies a high sedimentation rate (>1.0 mm/year); amber signifies a moderate sedimentation rate (0.30–1.0 mm/year); and green signifies a low sedimentation rate (<0.30 mm/year). The present-day mud content of the bed is also shown, classified into "traffic lights": red signifies high mud content (>20%); amber signifies moderate mud content (10–20%); and green signifies low mud content (<10%). "Ecology alerts" very roughly indicate parts of the harbour where the ecology may be at risk due to fine-sediment deposition. They are explained in the text.



5. Conclusions

The analysis of sediment-transport patterns and sedimentation illustrates "how the harbour works". A brief recap follows:

- The three northernmost subestuaries (between Matahui Point and Ngakautuakina Point) can be viewed as a group, as they are morphologically similar, they exchange sediments amongst each other, they lose similar amounts of fine sediment to the ocean, and they have similar sedimentation rates.

- The subestuary at the mouth of the Wainui River, between Ngakautuakina Point and Omokoroa Point, is not connected by transport pathways to the group to the north, and sediment that passes to the south of Omokoroa Point is entrained by the strong tidal currents in that part of the harbour and lost to the coastal ocean.

- Mangawhai Bay is divided by the East Coast Main Trunk rail line into a very sheltered inner embayment that is rapidly filling with sediment from its adjacent subcatchment, and an outer part that a has a low sedimentation rate. Te Puna estuary is also divided by the East Coast Main Trunk rail line into a very sheltered inner embayment that is rapidly filling with sediment from its adjacent subcatchment, and an outer part. The outer part is morphologically similar to Waikaraka estuary just to the south, both being partially enclosed by a spit complex at the mouth. These both lose a similar amount of fine sediment to the ocean, and they both have a fine-sediment sedimentation rate that is intermediate between the sedimentation rate in the respective impounded headwaters and the sedimentation rate in the central reaches of the harbour.

- Fine sediment is not predicted to accumulate at the mouth of the Wairoa River, because it is exposed and subject to flushing flows. In addition to that, coarse sediment brought down by the Wairoa River in flood deposits in this area.

- Waikareao estuary and Waimapu estuary are both sinks for sediment primarily from their respective adjacent subcatchment.

- The primary source of sediment to Rangataua Bay is the Waitao River. Sedimentation in the central, more exposed reaches of Rangataua Bay is smaller than in the more sheltered fringes (which includes Welcome Bay), which have experienced rapid mangrove spread in recent years.

- Several parts of the harbour do not deposit sediment from the adjacent subcatchment. Instead, the largest sediment supplier (Wairoa River) over-rides the more direct connection with the adjacent subcatchment. These parts include Waipu Bay (opposite Tauranga City), the small embayment at the mouth of the Wairoa River, and subcatchments adjacent to Matakana Island.

- The central reaches of the (southern) harbour and the intertidal flats along the Tauranga City foreshore are too exposed to accumulate fine sediments.

This understanding greatly enhances the interpretation of the sedimentation predictions.

Two important general findings concerning the change in sedimentation under landuse/climate change are:

- In general, there is not an exact correspondence between change in sedimentation rate in any given subestuary and change in sediment runoff from the subcatchment that is the largest source of sediment to that subestuary. There are two reasons. Firstly, subestuaries typically deposit sediment from more than one subcatchment, and the changes in sediment runoff under the various scenarios are usually different for each subcatchment. Secondly, the patterns of sediment transport in the harbour can be changed by changes in sediment runoff from the catchment, which can alter the relationships between sources and sinks.

- A typical response in the harbour is that there is an increase in subestuary sedimentation rate that is greater than the corresponding increase in sediment runoff from the primary source of sediment to that subestuary, which is called here a “positive imbalance”. A possible likely explanation is that harbour resuspension processes, which otherwise are quite effective at scouring fine sediment, resulting in loss of sediment to the coastal ocean, get overwhelmed by the larger sediment runoff from the catchment.

For all subestuaries, the dominant driver of change is climate change. This always results in an increase in sedimentation which, furthermore, is “positively imbalanced”. That is, the increase in subestuary sedimentation rate is greater than the corresponding increase in sediment runoff from that subestuary’s main source subcatchment.

The seabed composition will become progressively altered where fine sediments deposit on a relatively coarser pre-existing bed, and vice versa. A description of changes in seabed composition under landuse change and climate change has been presented, drawing together the predictions of sedimentation by the USC–3 model, and information on present-day bed sediment composition.

Some preliminary interpretations of the results in terms of risk to estuarine ecology have been presented. The next phase of the Tauranga Harbour Sediment Study is to discuss more fully, in a workshop setting, the implications of the findings for the ecology and management of the harbour.

6. References

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