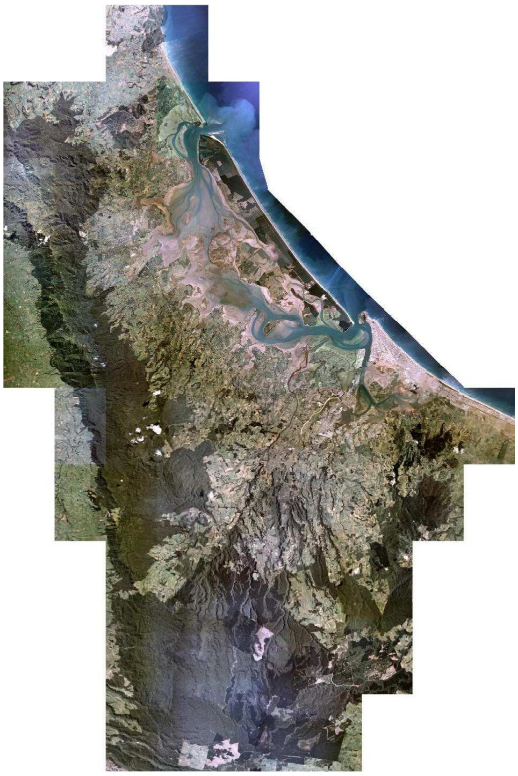
Tauranga Harbour Sediment Study: Catchment Model Results



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Prepared for

Environment Bay of Plenty

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Executive Summary

This report presents the results of the GLEAMS-TAU catchment model which simulated sediment loading to the southern Tauranga Harbour from the surrounding catchment. The land use and climate change scenarios for the study are established in a separate report (Parshotam et al. 2008). The model description and comparison with measurements are presented in a separate report (Parshotam et al. 2009).

Key results of the modelling were:

- Land slope, soil type, rainfall, and land use all have a significant impact on sediment yields, which leads to a complex spatial pattern of sediment generation. The highest yields occur for pasture areas, steep slopes, and soils which are less well-drained. A band of higher yield occurs between the coast and the ranges, which is mostly a result of pasture land use on moderate slopes.

- Pasture, which covers 33.5% of the catchment, makes the largest contribution to the sediment load (tonnes per year) from the catchment into streams (62.5% of the total). Although bush, scrub and native forest cover 44% of the catchment and are generally in steeper, higher-rainfall parts of the catchment, they contribute only 27.3% of the total sediment load.

- Uncontrolled earthworks have the highest sediment yield. However, controls on urban earthworks were predicted to reduce the sediment yield markedly. Such controls, in conjunction with the small areas of urban earthworks, were predicted to reduce the sediment load (mass per year, t y^{-1}) from earthworks to 0.5% of the total load to the stream system.

- Orchards and cropland were predicted to make a small contribution to the sediment load to the estuary. Bare earth associated with cropland made only a small contribution to the total sediment load, because the areas were small.

- Generally speaking, the sediment load to the harbour from a subcatchment increases with the area of the subcatchment. Here, a subcatchment is defined as the land area associated with an input point to the estuary sedimentation model. Most of the sediment entering the southern harbour enters through the Wairoa subcatchment (45.6% of the total load to the southern harbour). The Matakana 1 subcatchment has the lowest yield, due to the pine land use and well-drained soils. The Apata subcatchment has highest yield, due to the pasture land use, moderate slopes, and moderate rainfall.

- By the year 2050, the mean annual sediment load to the harbour was predicted to decrease by 0.7%, because pasture land use will be replaced by lower-yielding urban land use. Land use changes other than urbanisation were not assessed in this study. The contribution from urban earthworks was predicted to decrease over time from the current level of 0.5%, because the rate of urbanisation is predicted to decrease in the future.

- Future climate change was predicted to increase the sediment load to the harbour by 42.8% by 2051. Averaged over the period from the present until 2051, climate change was predicted to increase the sediment load by 19.4%. Mean annual rainfall was predicted to increase by 4.4%, but the rainfall from events with a long return period, were predicted to increase by 10 to 20%. Such events contribute the bulk of the sediment load to the harbour. Moreover, sediment load is sensitive to rainfall in large events; an increase of 10% in event rainfall results in an increase of approximately 30% in event sediment load. The increase in rainfall from large rainfall events, in conjunction with the large sensitivity of erosion to increased rainfall in large events, results in a substantial increase in sediment load to the harbour. These predictions were somewhat on the conservative (high) side in that a ‘wettest’ climate model was selected from a range of climate models and the method of calculating the distribution of rainfall depths allocates more rain to less frequent events. To obtain an improved representation of uncertainties in the effect of climate change on sediment loads, it is recommended that the catchment model be run with a range of climate models.

Potential areas of improvement in the assessment of sediment loads to the estuary include: assessment and modelling of stream bank erosion; collection of longer-term monitoring data to better characterise the distribution of event sediment loads and the relation between rainfall and loads; assessment of predictions of sediment deposition in streams in relation to measurements; assessment of current or potential future prevalence of slips in the catchment; and further monitoring to refine model parameters related to the effect of land use.

Predictions of sediment loads from the catchment model will be fed into the estuarine sedimentation model to predict the effects of current and future sediment loading on the rates of sediment accumulation in different parts of the harbour. The results of the estuary model are presented in a separate report.

1. Introduction

1.1 Background

Environment Bay of Plenty (Environment BOP) seeks to understand sedimentation in Tauranga Harbour in order to appropriately manage growth and development in the harbour catchment now and in the future. This will also assist Environment BOP to adapt management rules and practices appropriately and to 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.

Environment BOP contracted NIWA to conduct the Tauranga Harbour Sediment Study. The study began in April 2007 and was scheduled to run for 3 years. The main aim of the study was 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 the harbour entrance at Mount Maunganui (see Figure 1). The time frame for predictions is 50 years from the present day (2001-2051).

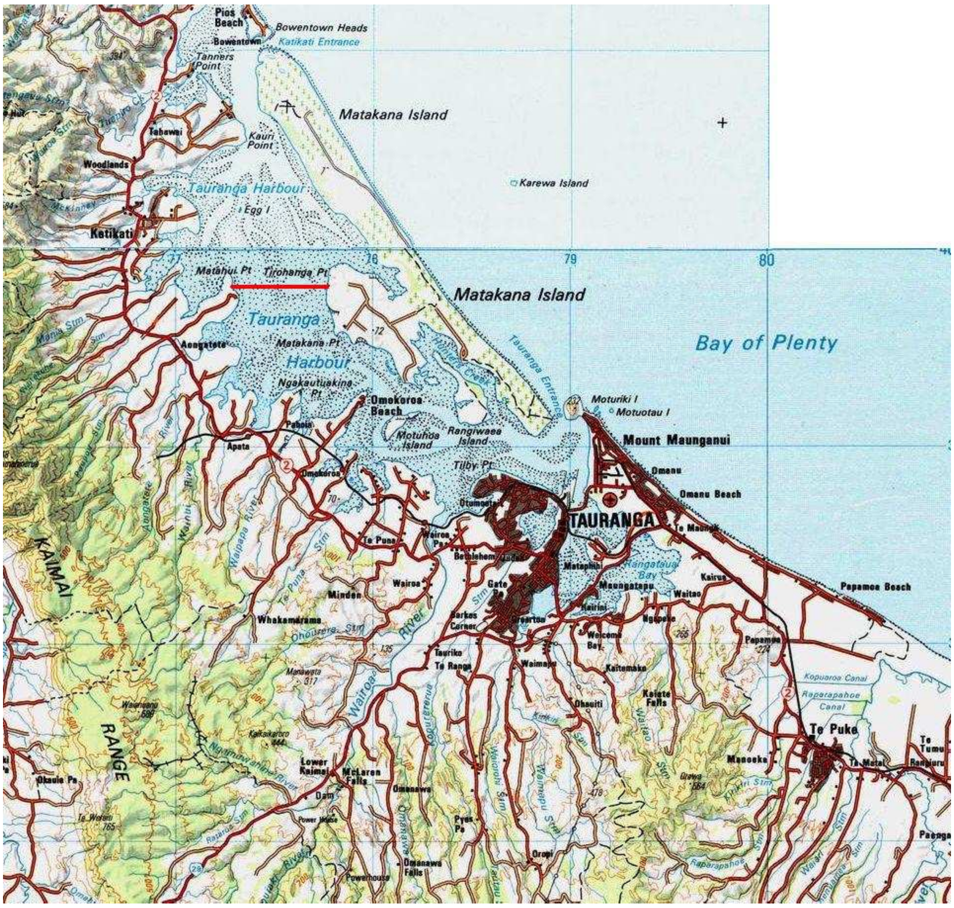

Figure 1: Tauranga Harbour, showing the study area from the South of the red line extending from Matahui Point to the harbour entrance at Mount Maunganui.

1.2 Study outline and modules

The Tauranga Harbour Sediment Study consists of 6 modules:

Module A: Specification of scenarios – Defines land use and weather that are required for driving the various models. Three scenarios are defined in terms of land use, 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 loads from each sub-catchment under each scenario. (2) Summarises these predictions to identify principal sources of sediment in the subcatchment; to compare sources of sediment under present-day land use and under future development scenarios; and to assess sediment characteristics of significant sources. (3) Provides sediment loads to the USC-3 model for extrapolation of harbour sedimentation over the decadal scale. In addition, historical sediment loads are estimated, for use in validation of the harbour model.

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, and (2) 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 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, and (2) Provide these event predictions to the USC-3 model for extrapolation of harbour sedimentation over decadal scales.

Module E: USC-3 model **-** Uses the USC-3 sedimentation model to make predictions of sedimentation, bed-sediment composition and linkages between sources and sinks at decadal scales, 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 predictions 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 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 (Environment BOP, WBPDC and TCC) most effectively address sedimentation issues, and what management intervention could be appropriate? and (4) Are there any reversal methods, such as mangrove control and channel dredging, that may be effective?

1.3 This report

This report summarises predictions of sediment loads to the harbour, and is part of Module B. A description of the catchment model and its implementation is presented in a separate report (Parshotam et al. 2009), along with a comparison between predicted and measured loads. The land use and climate change scenarios for the study are established in a separate report (Parshotam et al. 2008). This report provides information to help address the following questions:

- Which land uses (for example, urban, pastoral, cropping) contribute the most to sediment to the harbour?
- Which soil types contribute the most to the sediment load?
- What is the contribution of urban earthworks to the sediment load?
- Which locations within the catchment produce most sediment?
- Which streams have the highest sediment load to the harbour?
- How will the sediment loads increase in the future as parts of the catchment urbanise?
- To what extent will sediment loads increase as a result of climate change?
- What is the combined effect of climate change and catchment development?

In this report we also discuss how the predictions of sediment loads could be improved by modifying the model or collecting further data.

This report summarises the results from a large number of detailed simulation. For each scenario, calculations were made for each day over a 50 y period for 1,103,461 30 m by 30 m grid cells in the 994 km^2 catchment. Calculations were conducted for each of 6 decadal land use scenarios, and for 4 climate periods.

The predictions from GLEAMS-TAU will be passed to an estuarine sedimentation model (USC-3) to enable forecasting of sedimentation in the harbour.

2. Contribution of different land uses to the sediment load

2.1 Contribution of different land uses to the total load delivered to the stream network

The contribution of different land uses to the total sediment load (t y^{-1}) to the stream network is shown in Figure 2 and Table 1, based on the current land use with digitised earthworks areas. These values do not take stream deposition into account. The contribution of a particular land use to the total sediment load to the stream depends not only on the yield (t ha^{-1} y^{-1}), but also the extent of the land use and the soils, slopes, and climate that the land use occurs upon. The relative yields for different land uses compared to pasture for a common slope, rainfall, and soil, are given in Section 2.2.

Pasture made the largest contribution to the predicted sediment load (62.5%) because pasture is 33.5% of the catchment and the yield from pasture was higher than that from the other main land uses in the catchment (for the same slope, rain, and soils, as explained in Section 2.2).

Bush, scrub and native forest made the next largest contribution to the sediment load (27.3%). While these land uses had a relatively low yield compared to pasture (for the same slope, soil and rainfall) they have a large area (44% of the catchment) and tend to occur on steeper slopes and in higher-rainfall areas. Hence these land uses still made a substantial contribution to the total load.

Exotic forest contributed 4.8% of the total load. The exotic forest class includes open and closed canopy pine, afforestation, and harvested forest. While the harvested areas had a relatively high yield compared with mature pine forest, they occupy only 0.46% of the catchment compared with the 10.2% of the catchment that is in exotic forest. Hence the contribution from the harvesting was modest (0.4%). The relative areas of harvested and unharvested pine forest are consistent with a harvesting cycle of 25 to 30 years.

Orchards and cropland made a small contribution to the sediment load (0.3%). While the area of orchards and cropland is 5% of the catchment, the yields for these land uses are relatively low as these land uses tend to occur on areas that are less prone to erosion (lower slopes, better-drained soils, lower rainfall). In the model, the parameters for orchards and cropland include good ground cover. Bare soil, which might be associated with market gardens or crop establishment, is included in the agricultural bare-earth land-cover category and is only bare for part of the year.

Urban earthworks contributed only 0.5% to the total sediment load, based on the digitised earthworks areas in 2007/8. Although controlled earthworks had a yield comparable to pasture, the area of earthworks is small. The rate of earthworks in 2007/8 was comparable to the 2001-2010 decadal average (Parshotam et al. 2009), so the average sediment load for the current decade was also a small part of the overall load. The predictions were based on 88% of the urban earthworks areas having siltation ponds, as determined by examination of high-resolution aerial photographs[1]. If there were no earthworks controls or siltation ponds, then the urban earthworks load would increase to approximately 2.4% of the load from the catchment, highlighting the benefits of the current earthworks controls. Even if the treatment efficiencies of the ponds were worse than modelled, urban earthworks would make only a minor contribution to the total load. If there were complete earthworks controls including siltation ponds on all urban earthworks, then the contribution from urban earthworks would be reduced to 0.05%.

Urban land use and roads contributed a relatively small fraction of the load to the harbour. The urban and roads class includes all roads (strategic-arterial, rural and urban roads), industrial, commercial and residential areas (along with urban grassland). Even though this land use class constitutes 6.5% of the catchment, the yield from this land use class is relatively low, a result of the low sediment concentrations from impervious areas and the low yield from urban grasslands. The load from urban areas was potentially under-estimated because the contribution from stream-bank erosion was not included in the model. We do not have information on the extent of channel widening associated with urbanisation in the Tauranga area. It would be desirable to assess this in follow-up studies.

The contribution of various ‘other bare earth’ land uses to the total load to the stream network is shown in Table 3. The area of agricultural bare earth, which includes tilled soil for part of the year, is sufficiently small that its contribution to the total load was small. Quarrying and surface mines contributed 2.7% of the sediment load, although there is considerable uncertainty regarding this figure due to uncertainties about the exposed soil types and extent, and the configuration and efficiency of sediment control measures.

The analysis above relates to the contribution of various land uses to the sediment load to the stream network; a comparable breakdown of sediment load to the estuary is not available, as the sediment masses from different land uses are not tracked separately in

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[1] In Parshotam et al. (2009), the area of urban earthworks without ponds was assessed to be 29% of the total urban earthworks. Re-examination of the aerial photographs has identified that a larger percentage of the earthworks (88%) do have ponds. There are still some small areas of earthworks where siltation ponds are not currently required or used.

the stream routing model. Stream deposition could alter the contribution of different land uses to the sediment load to the estuary, because some land uses may be associated with parts of the catchment with a particularly large or small sediment delivery ratio. Nevertheless the contributions to the stream network give a reasonable estimate of relative importance of different land uses to sediment loads to the estuary, because sediment delivery ratios do not vary widely between subcatchments (Section 4.2) and the correlation between land use and delivery ratio is not expected to be strong.

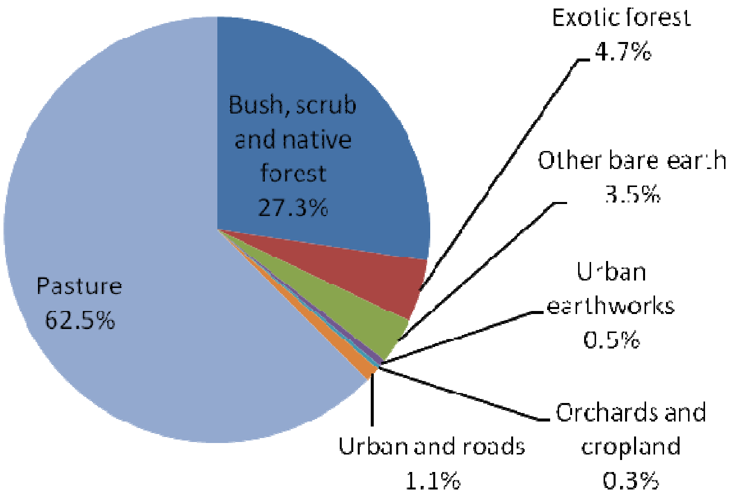

Figure 2: Proportions of total sediment entering the stream network by land use.

Table 1: Sediment load and sediment yield from various land uses, for the current climate and distribution of land use. These values are before sediment deposition in the stream network. The yields in this table are averaged over the range of slopes, soils and climate that occur for the particular land use.

Land use	Total load ($t\ y^{-1}$)	Fraction of total load (%)	Total area (ha)	Fraction of total area (%)	Yield ($t\ ha^{-1}\ y^{-1}$)
Pasture	119696	62.5	33262	33.7	3.60
Bush, scrub and native forest	52291	27.3	43595	43.9	1.20
Exotic forest	9079	4.7	10098	10.2	0.90
Other bare earth	3227	3.5	121	0.1	26.66
Urban earthworks	992	0.5	186	0.2	5.33
Urban and roads	2162	1.1	6416	6.5	0.34
Orchard and cropland	579	0.3	4963	5.0	0.12

Table 2: Contribution of various ‘other bare earth’ land use classes to the total sediment loss from the catchment.

Land use	Contribution (%)
Agricultural bare earth	0.22
Land slips	0.22
Metal roads	0.32
Quarry with pond	0.72
Quarry and surface mines	1.98
Unpaved yards	0.03

2.2 Relative sediment yields to the stream network for different land uses, for the same soil, slope, and rainfall

The yields for different land uses are compared to the yield for pasture in Table 2 for the same soil type (Ka), slope class (10.5 degrees), and rainfall region (RR1). This comparison gives and insight into the effect of land use on sediment yield. The values were obtained by setting up GLEAMS model for single cells with the particular combination of soil, slope, and climate, and land use of interest. The slope class of 10.5 degrees was chosen as the basis of comparison as the mean slope of the catchment is 11 degrees. The yields here are the yields to the stream network, before stream deposition processes are taken into account.

Pine, indigenous forest, and scrub had the lowest relative yields. The yields for mature tree cover were predicted to be 0.04 to 0.05 of the yield for pasture, for soil type Ka. For other soils, the relative yield was between 0.19 and 0.02. These relative yields are broadly consistent with values in the literature (e.g., Blaschke et al. 2008).

Harvested forest had approximately 9 times the sediment yield of mature pine land use. This is broadly consistent with literature values (e.g., Hicks 1989).

Uncontrolled urban earthworks increased the predicted sediment yield by a factor of 43 compared with pasture, which is consistent with literature values (e.g., Hicks 1994). Limiting the period of earthworks reduced the sediment yield by a factor of 4.7. Erosion control ponds reduced the yield by a further factor of 10.6 (that is, the pond efficiency was 90.6%). This removal efficiency is somewhat high in relation to values measured in Auckland (e.g., Moores and Pattinson 2008), and it would be desirable to collect data to establish the performance of siltation ponds in the Tauranga area and to refine the parameters used in the pond component of the model.

Agricultural bare earth also increased the sediment yield considerably beyond what would be expected for pasture, but not to the same extent as urban earthworks where topsoil was removed.

Orchards and cropland had a low sediment yield compared with pasture. This is because this land use was modelled with good ground cover and soil drainage, and bare earth associated with tilling was included in the model separately.

The relative yields reflect the processes in the model and the parameters selected for the model. In the model, sediment transport is driven by rainfall dislodging sediment, sediment being entrained in overland flow, and sediment depositing at the base of the hill slope. Pasture has a larger yield than the forested land uses in the model because:

- bare ground is exposed by animal grazing, so there is more exposed ground for sediment dislodgment and entrainment. The exposed ground is represented in the model with a ground cover coefficient. At present, the model is not set up to take account of details of grazing intensity, stock type, grazing management, and grass sward type;

- grazing leads to more soil compaction and reduced evapotranspiration, leading to more runoff generation in storms, greater entrainment in overland flow and less settling of sediment.

Grazing can also lead to increased bank erosion and increased prevalence of slips, but these processes are not included in the GLEAMS model.

The yield from urban earthworks with no controls is relatively large, because more runoff is produced and there is little ground cover.

The contribution of different land uses to the total load to the streams depends not only on the relative yield, but also the extent of the land uses and the soils, slopes and rainfall associated with the land use. These factors were taken into account in the previous section.

Table 3: Sediment yields to the stream for various land uses, relative to the yield for pasture, for a 10.5 degree slope, soil type Ka, and rainfall region RR1.

Land use	Yields relative to pasture yield
Open canopy pine	0.02
Indigenous forest	0.03
Closed canopy pine	0.04
Bush and scrub	0.05
Orchard and cropland	0.05
Harvested forest	0.19
Urban grassland	0.41
Afforestation	1.0
Pasture	1
Quarry with treatment pond	3.2
Agricultural bare earth	8.6
Urban earthworks with seasonal control and treatment pond	0.86
Urban earthworks with seasonal control and no treatment pond	9.1
Urban earthworks with no seasonal control and no treatment pond	43.3
Bare earth on land slips	47.8

3. Effect of soil type, slope, and rainfall

3.1 Effect of soil type

The sediment yield for each soil type is given in Table 4 for a slope of 10.5 degrees and pasture land use. These results are based on single-cell GLEAMS runs, and do not take stream deposition into account. Certain soil types tend to be associated with certain slopes or land uses, but a common slope and land use are used in the table to highlight the effect of soil type. A map of soil types is included in Parshotam et al. (2009). The differences in predicted yields for different soils relate to different surface runoff generation rates and differences in soil erodibility. The soil erodibility relates to soil characteristics such as texture, organic matter, and structure.

The highest sediment yields were from Pahoia silt loam (Pa) and Waiari silt loam (Wi). These are acid gley soils with poor drainage. They cover only a small proportion of the catchment and generally occur on flatter areas.

The pumice soils in the southeast of the catchment (Oropi sand (Or) and Oropi hill soils (OrH)) have moderate erodibility but very rapid drainage, giving rise to little runoff generation and relatively low erosion rates.

The Orthic Allophanic Soils, which comprise 56% of the catchment, had a low to moderate yield compared with other soils. They have moderate erodibility. Some of these soils (such as Katikati sandy loam (Ka)) produce little runoff, and hence produced little sediment. Other soils (such as Katikati hill soils (KaH)) have a higher erodibility due to the poorer drainage.

The Orthic Podzols, which are on the western and southern ranges of the catchment, had low to moderate yields compared with other soils. The variation again relates to the amount of runoff generated.

The soil type Mamaku loamy sand (M) on the southern hills had a moderately high yield due to the slow permeability.

The effect of soil type was insensitive to the slope or land use (results not shown). That is, the same pattern of yields would have been found if a different slope or land use had been used instead of the 10.5 degree slope and pasture soil.

The relative yields for different soils are summarised by NZ Soil Order in Table 5. The values for each soil type in Table 4 were averaged by NZ Soil Order, taking the area of each soil type into account. Gley soils had the largest yield, but they constitute only a small part of the catchment. Orthic Allophanics and Orthic Podzols, which are the predominant soils in the catchment, had moderate sediment yields compared with other soils. Pumice soils had lower yields relative to the other main soils types.

The contribution of various soils to the total sediment load entering the stream network is shown in Table 6. This takes into account the area of the different soils and the slopes, land-uses, and rainfall regions that are associated with each soil. The Orthic Allophanic Soils made the highest contribution to the load because this soil had the largest area and a moderate relative yield. Orthic Podzols also have a large area and a moderate yield, but they did not make as large a contribution to the load as Orthic Allophanics because they tend to occur in areas with tree cover. Pumice soils contributed approximately 5% of the total load.

Table 4: Sediment yields for different soil types in the catchment assuming pasture with a 10.5 degree slope and rainfall region RR1.

Soil	NZ Soil Order	Sediment yields ($t\ ha^{-1}\ year^{-1}$)	Area of soil type in the catchment (%)
AS	Orthic Podzol	0.71	2.34
Ka	Orthic Allophanic Soils	1.05	16.05
KaH	Orthic Allophanic Soils	3.56	6.51
KaR	Orthic Allophanic Soils	1.10	15.25
Kh	Orthic Podzol	0.73	<0.1
Ki	Orthic Podzol	0.49	1.66
M	Orthic Podzol	4.55	9.06
Mg	Orthic Podzol	0.47	0.01
MH	Orthic Podzol	0.83	0.28
MM	Truncated Anthropic Soils	1.34	0.82
MN	Fluvial Recent Soils	4.94	0.11
Mu	Gley Raw Soils	5.48	0.57
Oa	Tephric Recent Soils	1.02	0.12
Oe	Sandy Raw Soils	1.18	0.29
Or	Pumice	0.91	6.57
OrH	Pumice	0.63	1.11
OS	Orthic Allophanic Soils	3.09	14.73
Pa	Acid Gley Soils	12.33	0.95
Pp	Sandy Recent Soils	0.50	0.12
Pt	Mesic organic	6.34	0.03
Rp	Orthic gley	3.09	0.13
Tk	Orthic Allophanic Soils	1.05	0.13
TkH	Orthic Allophanic Soils	4.01	1.19
TkR	Orthic Allophanic Soils	0.95	2.34
TM	Fluvial Recent Soils	3.14	0.91
TP	Acid Gley Soils	0.26	0.28
Whar	Sandy Brown Soils	4.70	0.10
Wi	Acid Gley Soils	15.05	0.16
Wk	Orthic Podzol	0.89	7.46
WkH	Orthic Podzol	1.51	4.45
WkR	Orthic Podzol	0.70	4.85

Table 5: Weighted average of sediment yields grouped by NZ soil orders in the catchment, assuming pasture with a 10.5 degree slope and rainfall region RR1.

NZ Soil Order	Sediment yields (t ha^{-1} year^{-1})	Area of soil in the catchment (%)
Acid Gley Soils	10.21	1.39
Fluvial Recent Soils	3.33	1.02
Gley Raw Soils	5.48	0.57
Mesic Organic Soils	6.34	0.03
Orthic Allophanic Soils	1.95	56.2
Orthic Gley Soils	3.09	0.13
Orthic Podzols	2.02	30.11
Pumice Soils	0.87	7.68
Sandy Brown Soils	4.70	0.1
Sandy Raw Soils	1.18	0.29
Sandy Recent Soils	0.50	0.12
Tephric Recent Soils	1.02	0.12
Truncated Anthropic Soils	1.34	0.82

Table 6: Proportions of total sediment entering the stream network by NZ soil order.

NZ Soil Order	Contribution (%)
Acid Gley Soils	1.19
Fluvial Recent Soils	0.43
Gley Raw Soils	0.03
Mesic Organic Soils	<0.01
Orthic Allophanic Soils	80.27
Orthic Gley Soils	0.02
Orthic Podzols	12.91
Pumice Soils	4.94
Sandy Brown Soils	0.01
Sandy Raw Soils	<0.01
Sandy Recent Soils	<0.01
Tephric Recent Soils	<0.01
Truncated Anthropic Soils	0.17

3.2 Slope effect

Sediment yield increased with slope, as illustrated in Figure 3 for a single soil, rainfall zone, and land use. A similar effect of slope applied for other soils, rainfall zones, and land uses. A map of slopes is included in Parshotam et al. (2009). This result means that there will be higher erosion in the steeper areas in the ranges, and also in steep gully sides, if other factors are constant.

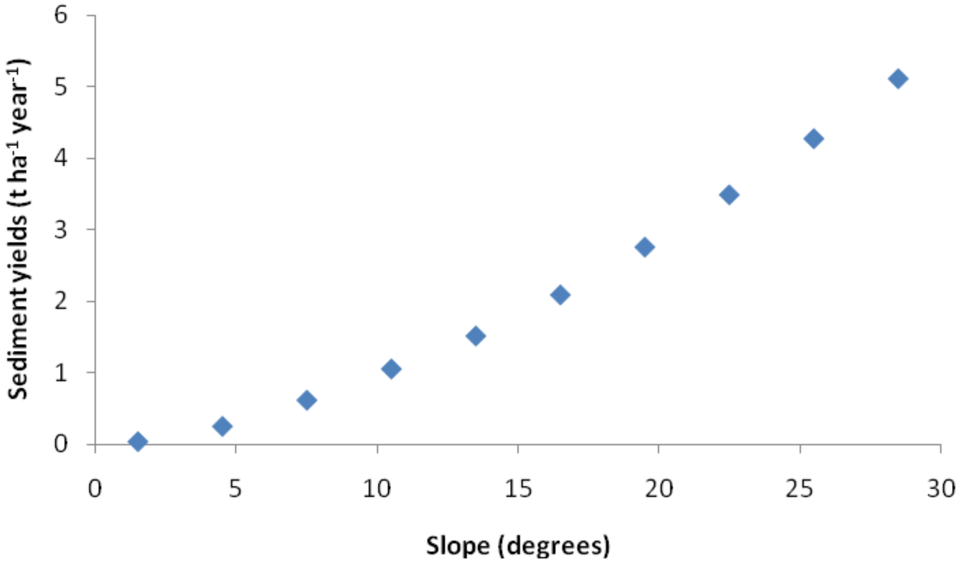

Figure 3: Sediment yield for soil type Ka, pasture land use, and rainfall region 1.

3.3 Rain effect

Sediment generation increased with mean annual rainfall, as demonstrated by the increase in erosion rate across the rainfall regions (Figure 4). The daily rainfalls in regions RR2 and RR3 were determined from the daily rainfalls in region RR1 by multiplying the values in RR1 by a factor. The model is run on a daily basis, and does not take account of sub-daily variations in rainfall intensity.

Higher-rainfall areas such as the Kaimai Ranges produced more sediment than the coastal area, if other factors such as soil type were equal. Maps of mean annual rainfall are presented in Parshotam et al. (2009). The effect of rainfall on sediment yield depends on soil type. The yield increased by a factor 4.8 going from RR1 (1258 mm/y rain) to RR3 (1975 mm/y) for soil type Ka, but by a factor of 3.7 for the relatively poorly-drained soil KaH.

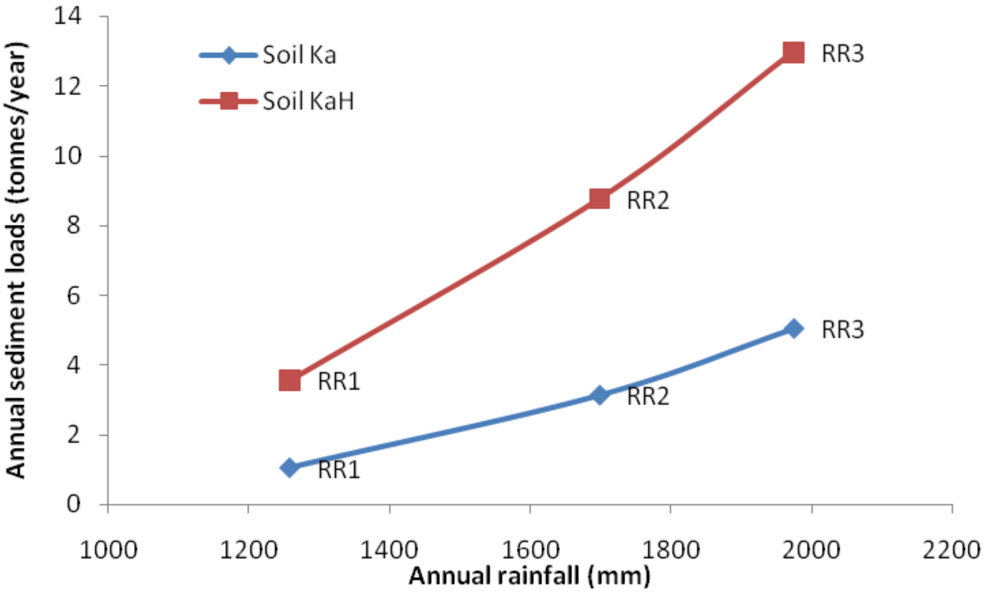

Figure 4: Effect of mean annual rainfall on mean annual sediment yield for two soil types, pasture land use, and a slope of 10.5 percent. The mean annual rainfall points correspond to the three rainfall regions.

A time series of rainfall and runoff (Figure 5) shows that there was considerable variability in runoff and sediment yield from event to event. The sequencing and variability of events is taken into account in the estuary deposition model.

The mass of sediment entering the harbour from a rainfall event generally increased with rain depth (Figure 6). There was some variability in this relationship, due to the effect of antecedent moisture conditions on runoff generation.

The daily sediment load varied with daily rainfall in a non-linear fashion (Figure 6 and Figure 7). For reference, the rainfall depths for 3-month, 6-month, 1-year, 2-year and 5-year return intervals are 46, 63, 78, 97, and 124 mm in rainfall region RR1. Doubling the rainfall more than doubled the amount of sediment generated. For events larger than 50 mm (which contribute most of the sediment load, as explained later), the sediment load to the harbour varied approximately with rainfall to the power of 3. This is a sensitive response. This sensitivity to rainfall in region RR1 will also apply for the catchment average rainfall because the rainfall from the other regions is a multiple of the rainfall in RR1. From empirical regional regression studies in New Zealand (Elliott et al. 2008), the mean annual load increases with mean annual rainfall to the power of 2. The model suggests that individual events have a larger sensitivity to rainfall than indicated by the mean annual sensitivity. The relationship between measured concentrations and flows show that concentration increases with flow to the power of approximately 1 to 1.5 (Parshotam et al. 2009), so the sediment transport rate increases with flow to the power of 2 to 2.5 (the sediment transport rate is the concentration times the flow). If flow increases in proportion to rainfall (which has not been established from measurements, but is not unreasonable as a first approximation), then the sediment transport rate would increase with rainfall to the power of 3 to 3.5. Hence, the sediment model sensitivity (a power of 3) does not seem unreasonable. This is an approximate argument to check that the model predictions are not unreasonable.

The contribution of various rainfall depths in RR1 to the total sediment load to the harbour is shown in Figure 8. Rare large rainfall amounts resulted in considerable erosion. For example, the largest event in the 50-year simulation period (18 May 2005) had a rainfall of 240.6 mm (in RR1) and a sediment load to the harbour of 551000 t, which was 5 times the mean annual load of 110500 t and 10% of the load over the 50-year simulation period. Events less than 50 mm (in RR1) contributed less than 10% of the sediment load.

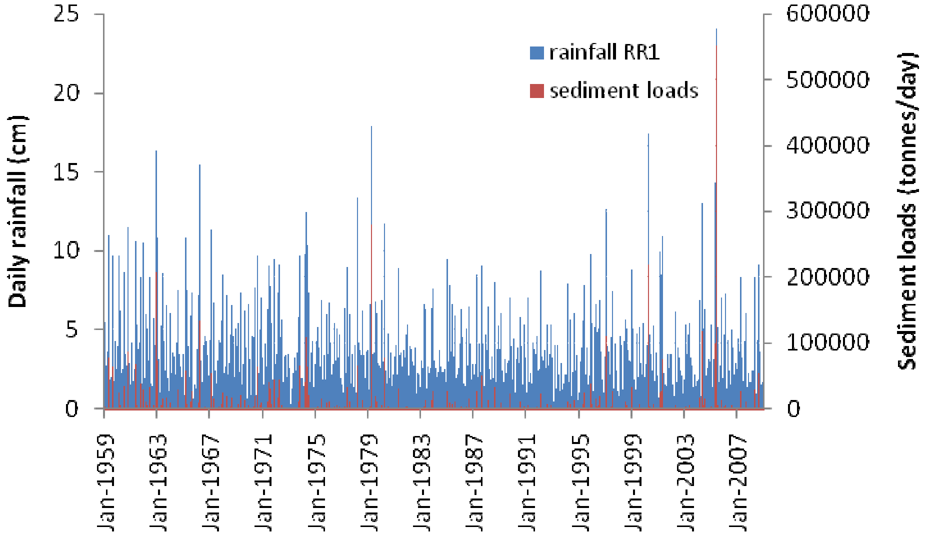

Figure 5: Time series of daily rainfall depth and sediment load to the harbour. The rainfall values are from the RR1 rainfall zone.

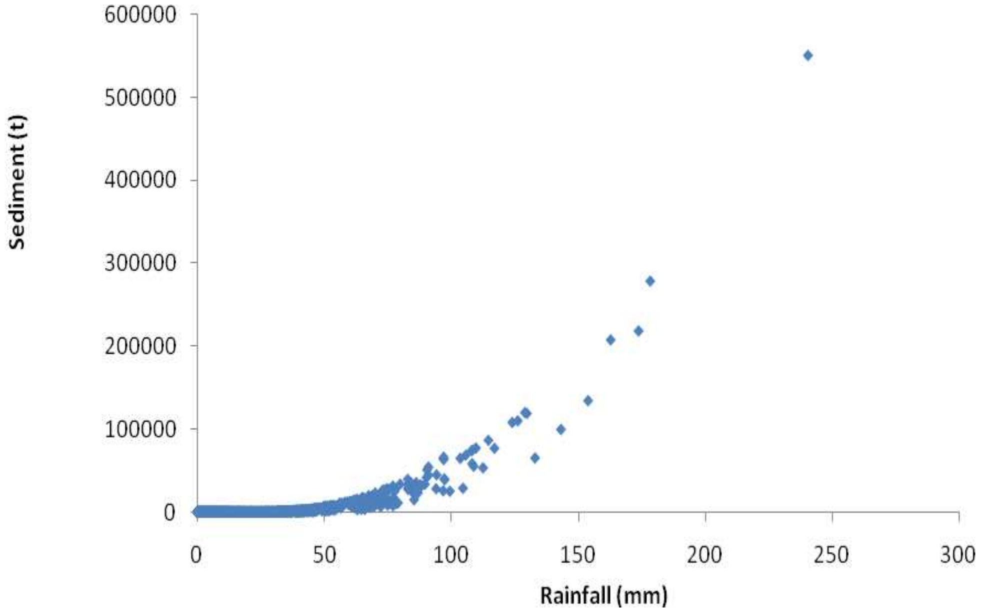

Figure 6: Variation of sediment load to the harbour with daily rainfall depth (in RR1).

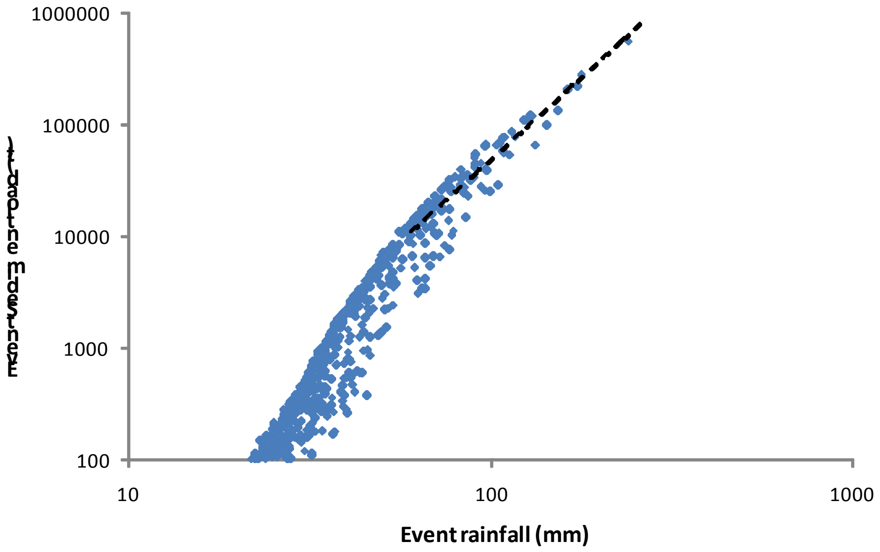

Figure 7: Variation of sediment load to the harbour with daily rainfall depth in RR1, plotted on a log-log scale for events with sediment load greater than 100 t. The dashed line shows that the sediment load increases approximately with daily rainfall to the power of 3 for events larger than 50 mm.

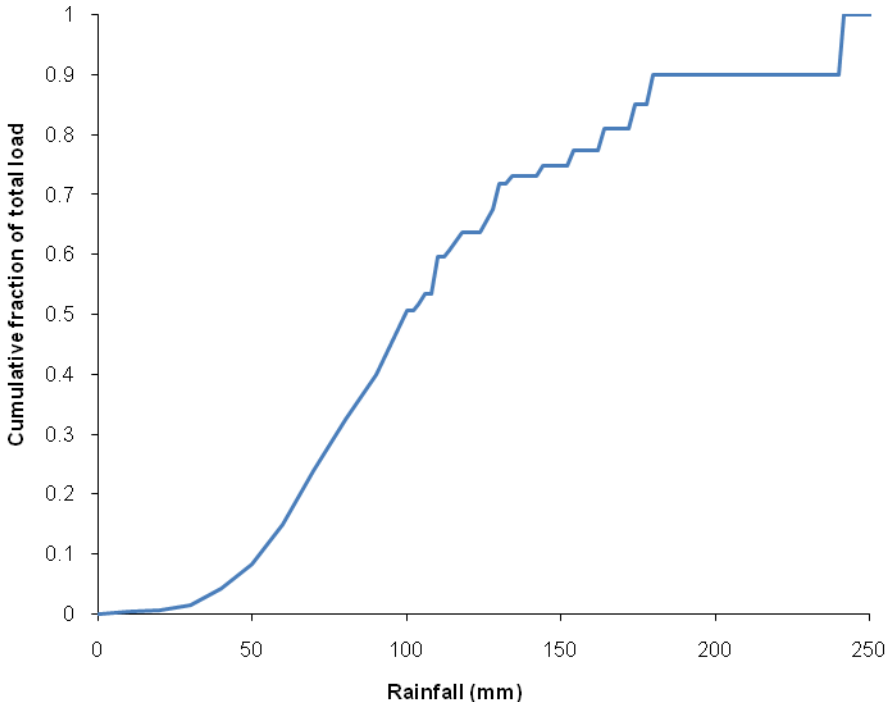

Figure 8: Contribution of various rainfall depths to the total sediment load to the harbour. The rainfall is based on rainfall region RR1. The vertical axis is the fraction of the total sediment load to the harbour that occurs with rainfall depths less than or equal to the rainfall value on the horizontal axis. For example, 0.5 of the sediment load comes from daily rainfall events less than 100 mm.

4. Contributions from different parts of the catchment

4.1 Sediment generation patterns

There was considerable variation of predicted sediment yield across the catchment (Figure 9). Differences in sediment yield due to land use, soil type, slope, and rainfall combined to give a fairly complex spatial pattern of sediment yield. There were relatively low yields around the ranges on the western slopes of the catchment. Even though the rainfall is higher in those areas and the slopes are generally steep, there is also native bush and pines in those areas, which counteracts the effect of high rain and slope. In the southern ranges, the soils are more erodible, giving rise to higher erosion than in the western ranges. In the areas around the coast, the slopes and rainfall are generally lower, so that the predicted yield was relatively low. There were also low yields around the coast associated with mature urban areas. In a band between the ranges and the coast, there were relatively high yields due to the pasture land use and moderately high rainfall. The yields were large in gully areas due to the high slopes. The highest yields were in small uncontrolled earthworks on the fringes of the built-up areas, and in quarrying areas in the east of the catchment.

Figure 9: Sediment yields (t ha^{-1} y^{-1}) for the current land use, mapped for every 30m x 30m model cell (over 1.1 million cells in total). The yields do not take sediment routing into account, which would reduce the load entering the harbour.

4.2 Contribution from different subcatchments

The load of sediment to the harbour from the various subcatchments is shown in Figure 10 and Table 7, based on the current land use with the random areas of earthworks representing a decadal average earthworks rate. A subcatchment is the land area associated with a point of input of sediment to the harbour model.

The area of a subcatchment is obviously a key influence on the sediment load. The Wairoa catchment, which has the largest area, also had the largest sediment load (45.6% of the total load to the estuary). However, there was also a variation in the yield (Figure 11 and Table 7), so that some subcatchments contributed disproportionately to the load. The Matakana 1 subcatchment, for example, has a low yield due to the well-drained soils and pine land use, so that the load from that subcatchment was disproportionately small in relation to the area of the subcatchment. The Apata subcatchment had a large yield due to the relatively high rainfall in conjunction with the pasture land use and moderate slopes. The urban catchments had relatively low yields, as discussed in Section 2.1.

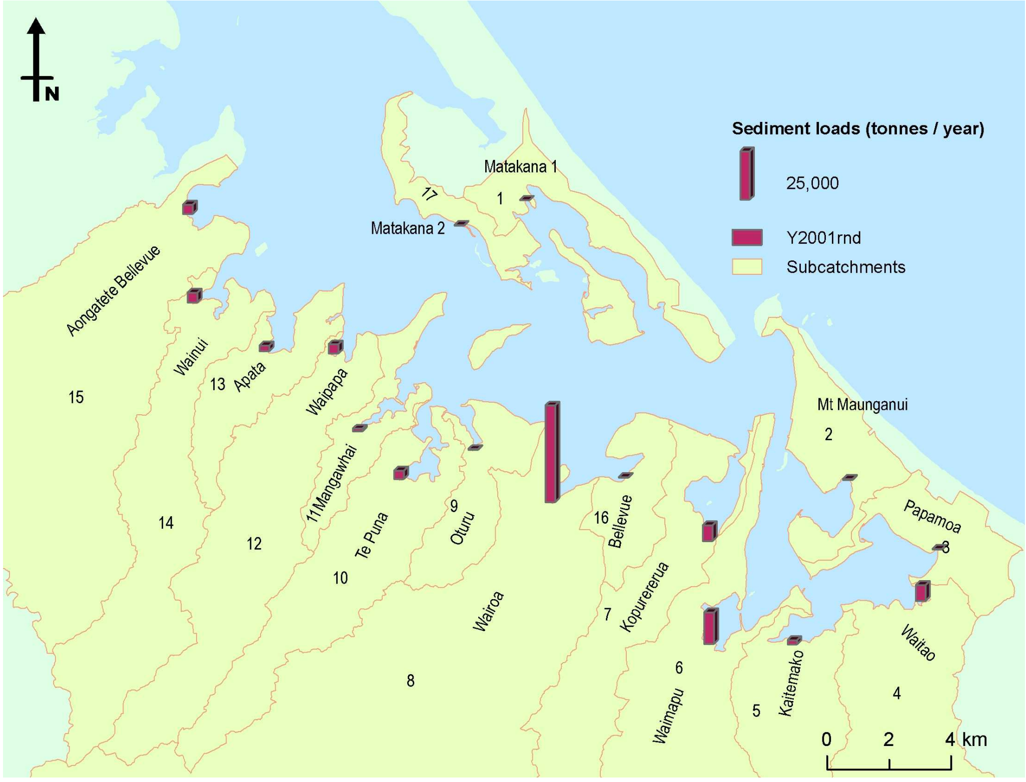

Figure 10: Sediment load from subcatchments to the harbour.

Table 7: Sediment load to the harbour, yield, and sediment delivery ratio (SDR) for each subcatchment. The yield in this table is the load from the subcatchment to the estuary, divided by the subcatchment area.

Outlet ID	Name	Area (ha)	Load ($t\ y^{-1}$)	Fraction of total load (%)	Yield ($t\ ha^{-1}\ y^{-1}$)	SDR (%)
1	Matakana 1	1409	62	0.1	0.04	85
2	Mt Maunganui	1299	393	0.4	0.30	83
3	Papamoa	1182	318	0.3	0.27	59
4	Waitao	4332	8078	7.4	1.86	64
5	Kaitemako	1989	2045	1.9	1.03	66
6	Waimapu	11824	16262	15.0	1.38	61
7	Kopurererua	7879	8113	7.5	1.03	60
8	Wairoa	46534	49641	45.6	1.07	54
9	Oturu	1158	453	0.4	0.39	60
10	Te Puna	2799	4274	3.9	1.53	57
11	Mangawhai	957	1251	1.2	1.31	75
12	Waipapa	3680	4722	4.3	1.28	55
13	Apata	1240	2955	2.7	2.38	67
14	Wainui	3523	4891	4.5	1.39	54
15	Aongatete Bellevue	7854	4717	4.3	0.60	50
16	Bellevue	950	267	0.2	0.28	80
17	Matakana 2	755	316	0.3	0.42	87
Total		99366	108758	100	1.09	57

4.3 Sediment delivery ratios

The sediment delivery ratio (SDR) is the load of sediment exiting the subcatchment after stream routing divided by the load entering the stream network. The SDR values are summarised in Table 7. The values ranged from 50% to 87%, and overall 57% of the sediment generated within the catchment was delivered to the estuary. The modelled SDR values varied due to differences in catchment size, particle size, and stream slopes. The SDR estimates imply a considerable degree of deposition in the stream network. It would be of some interest to examine the streams and terraces for evidence of deposition.

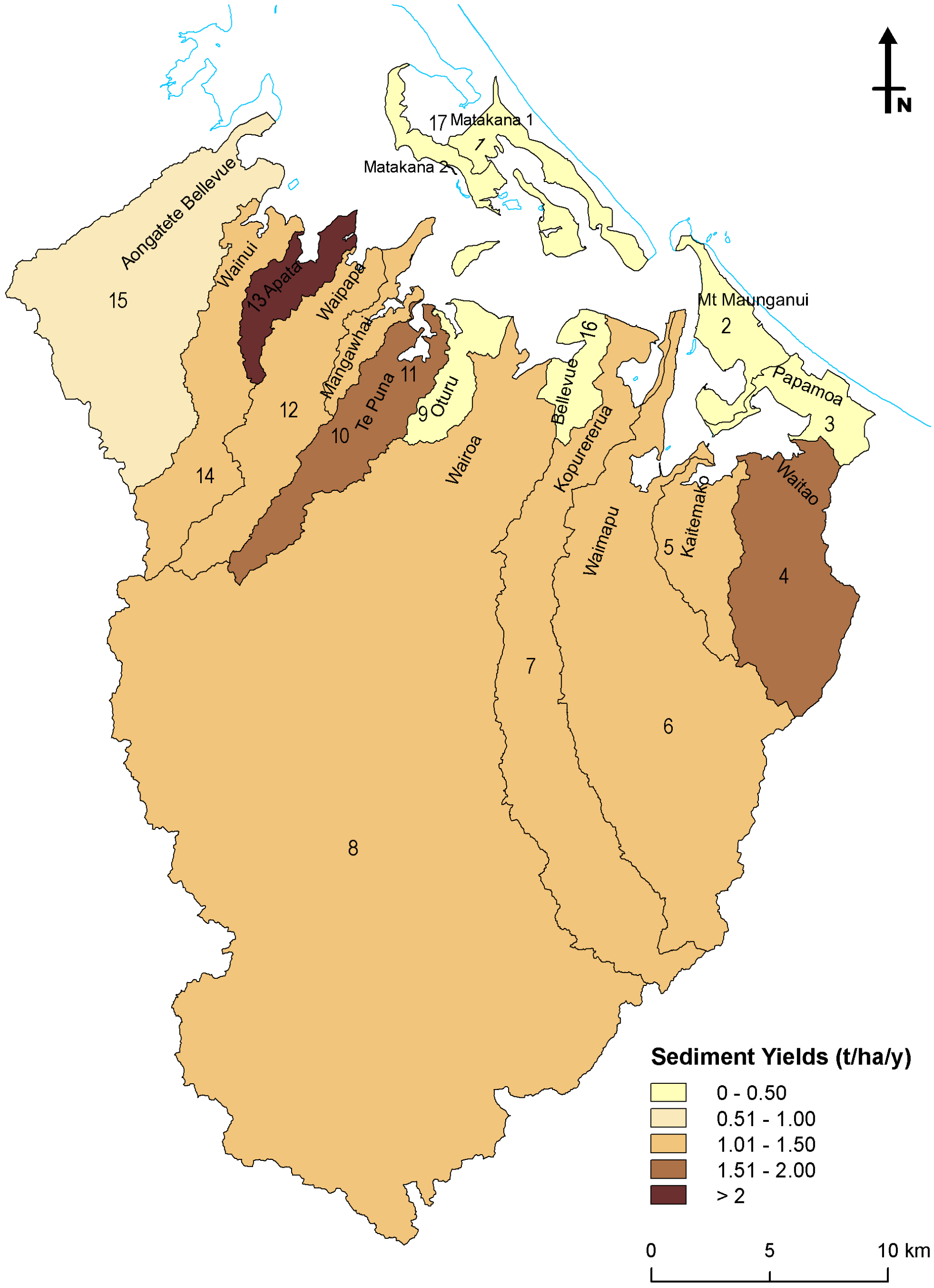

Figure 11: Sediment yield summarised by subcatchment. The yield in this table is the load to the estuary from the catchment divided by the subcatchment area.

5. Effect of future land use change

Future land use change was predicted to decrease the mean annual load of sediment to the harbour (Figure 12, Table 8). By 2051, the load to the harbour was predicted to decrease by 0.7%. The only land use change was urban expansion, while the rural part of the catchment remained in the current land use. When the urban area expands, pasture is replaced by urban areas with a smaller sediment yield, reducing the total load.

Urban earthworks accompany urbanisation, and since uncontrolled urban earthworks have a relatively large sediment yield, there is the potential for earthworks to increase the sediment load to the harbour. However, earthwork controls reduced the sediment load substantially, and the rate of urban earthworks in the model was small, so that earthworks contributed only 0.5% of the current load to the harbour for the current land use scenario. The rate of urbanisation is projected to decrease over time (Figure 13), and earthworks will be conducted on slopes and soils similar to the current earthworks, so the future earthworks sediment load will be even less than 0.5% of the total load to the harbour. Also, we assume that future earthworks sites larger than 0.3 ha will all have ponds in the future, which reduces the load from earthworks further.

The temporal progression of sediment loads from each subcatchment is shown in Figure 14 and is tabulated in Appendix 1. In rural subcatchments, the sediment load was predicted to remain the same over time, because the rural land use was constant. In subcatchments with urbanisation, the predicted mean annual sediment load dropped slightly over time, as explained above for the whole catchment.

The distribution of sediment yield over the catchment in 2041 very similar to the map for the current land use (Figure 9), except for the reduction in new urban areas, such as in the vicinity of Tauranga.

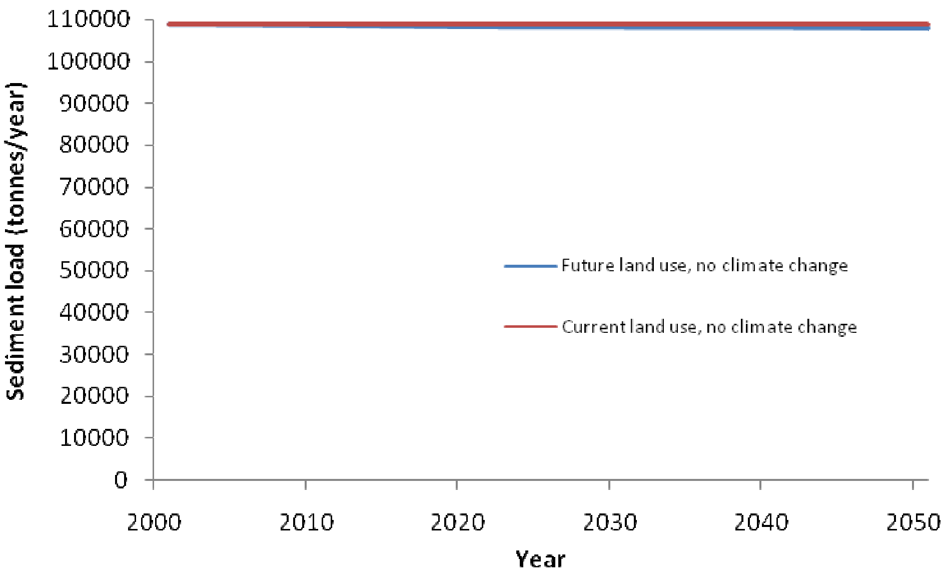

Figure 12: Effect of land use change on the mean annual sediment load entering the southern harbour from the catchment, for the current climate. The current land use is based on the decadal average urbanisation rates (2001rnd land use scenario).

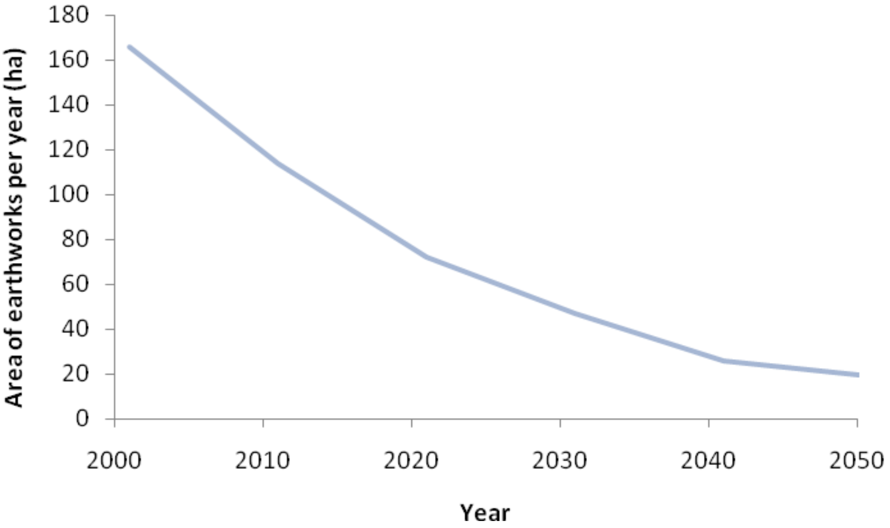

Figure 13: Predicted rate of urban earthworks. The current earthworks rate is based on the decadal average urbanisation rates (2001rnd land use scenario).

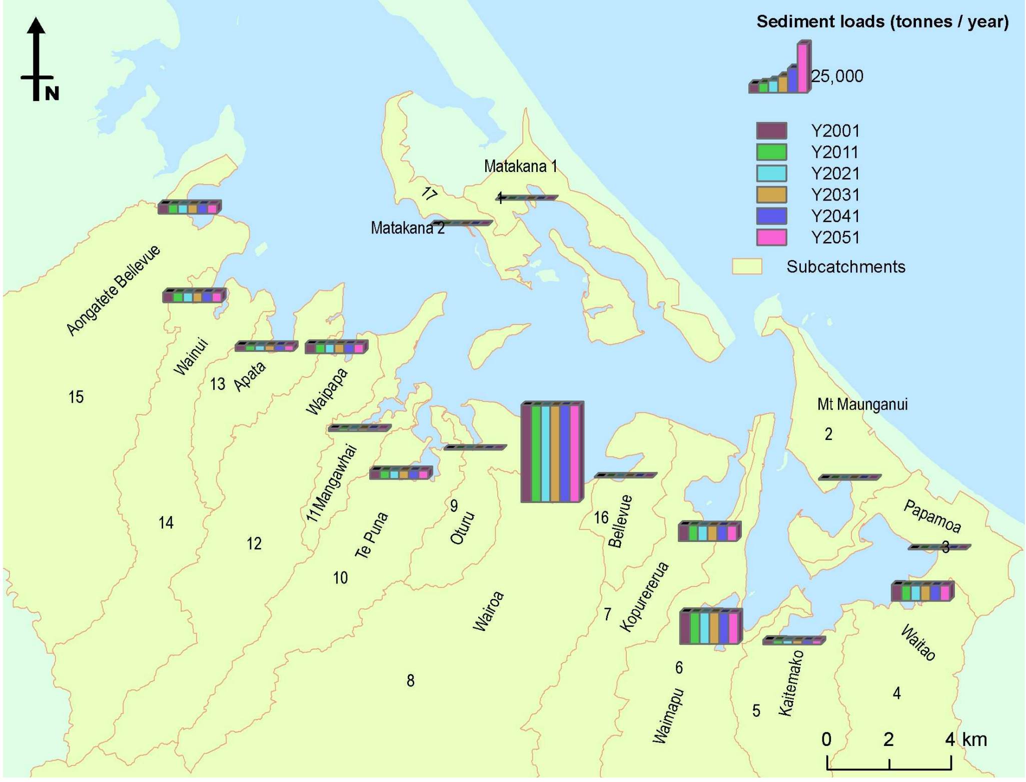

Figure 14: Effect of land use change on loads from each subcatchment, for the current climate.

6. Effect of climate change

Future climate projections were generated for 2020, 2030, 2040, and 2050, and the GLEAMS model was run for each of these climate periods, as described in Parshotam et al. (2009). For the climate projections, a medium greenhouse gas emissions scenario (A1B) was used, and the ‘wettest’ climate model out of a range of climate models was used.

Climate change was predicted to increase the mean annual sediment load to the harbour by 42.8% by 2051 (Figure 15 and Figure 16, and Table 8 and Table 9). Part of this increase can be attributed to the increase in mean annual rainfall. For New Zealand as a whole, measured sediment loads increase with the square of mean annual precipitation (e.g., Elliott 2008), so we would expect the mean annual rainfall increase of 4.4% by 2050 to increase the sediment yield by 9%. This by itself does not explain the 42.8% increase in predicted sediment load. Similarly, Figure 7 suggests that an increase of 4.4% in mean annual rainfall would increase the modelled sediment yield by approximately 14%, so the increase in mean annual rain does not account for the 42.8% increase.

The increase in sediment yield beyond that expected from the increase in mean annual rainfall is a consequence of increased variability in rainfall. With climate change, the percentage increase in the largest rainfalls was more than the percentage increase in mean annual rainfall. For example, the largest daily rainfall in the 50-year simulation period (240.6 mm on 18 May 2005) was predicted to increase in intensity by 9.7% by 2050. Such large events are responsible for a large proportion of the mean annual sediment load (Section 3.3). Moreover, the sediment loss increases sharply with rainfall for large events (Figures 6 and 7). For the largest rainfall event, the sediment load increased by 23%. Other large events had a greater percentage increase in rainfall and sediment load, giving rise to the overall increase of 42.8% in mean annual load.

These predictions are somewhat on the conservative side; that is, they may if anything over-state the effect of climate change. One reason is that the wettest climate model from a range of models was selected for this study. Moreover, a somewhat conservative method was used to predict the increase in extreme rainfall from the increase in annual temperature and annual rainfall, in line with current advice to MFE (MFE 2008; Parshotam et al. 2009, Section 3.4.2). Ideally, a range of climate models would be run to obtain a range of predictions of future sediment yields, to get a better representation of the prediction uncertainty, but that was beyond the scope of the current study.

While the model captures some effects of climate change, such as altered runoff generation and associated erosion, it does not capture others. The model does not include mass erosion events such as landslides, which could increase in response to increased rainfalls in extreme events. Also, the model does not account for increased weathering rates of soils resulting from increased temperatures. Increased temperatures and rainfall may promote increased vegetation growth, which would decrease erosion, but this effect is expected to be minor considering that water is not a major limiter of vegetation growth in the Tauranga area.

The increase in sediment load due to climate change averaged over the period from 2001 to 2051 was 19.8% (Table 9). This was less than the effect in 2051 because the effect of climate change gradually increased over time.

In general, the response to climate change followed the same pattern in all subcatchments and was of the same order of magnitude in all the subcatchments, although there were some differences between subcatchments (Table 8 and Table 9, Appendix 1, and Figure 17). Urban subcatchments such as Bellevue had a smaller effect of climate change because a constant concentration was assumed for runoff from impervious surfaces. Another reason for the variability is that the response to a change in rainfall depends on the soil type (Section 3.1).

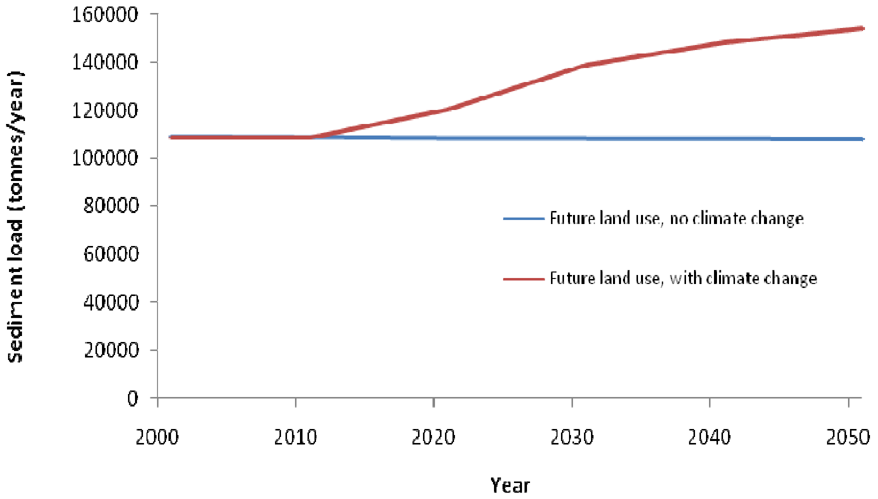

Figure 15: Effect of climate change on the mean annual sediment load entering the southern harbour from the catchment.

Table 8: Effect of land use change and climate change on mean annual sediment load by 2051. The current land use is based on the decadal average urbanisation rates (2001rnd land use scenario).

		Mean annual load (t/y)				**Increase (%)**		
ID	**Name**	**2001**	**2051, Scenario 1 Current land use No climate change**	**2051, Scenario 2 Future land use No climate change**	**2051 Scenario 3 Future land use With climate change**	**Increase from land use change (Scenario 1 to 2)**	**Increase from climate change (Scenario 2 to 3)**	**Combined increase from land use and climate change (Scenario 1 to 3)**
1	Matakana 1	62	62	62	91	0.2%	47.5%	47.8%
2	Mount Maunganui	393	393	393	481	0.0%	22.3%	22.3%
3	Papamoa	318	318	331	459	4.2%	38.6%	44.4%
4	Waitao	8078	8078	8016	11777	-0.8%	46.9%	45.8%
5	Kaitemako	2045	2045	1966	2844	-3.9%	44.7%	39.0%
6	Waimapu	16262	16262	15948	22009	-1.9%	38.0%	35.3%
7	Kopurererua	8113	8113	7851	11226	-3.2%	43.0%	38.4%
8	Wairoa	49641	49641	49664	71491	0.0%	43.9%	44.0%
9	Oturu	453	453	453	656	0.0%	44.8%	44.8%
10	Te Puna	4274	4274	4271	6240	-0.1%	46.1%	46.0%
11	Mangawhai	1251	1251	1171	1623	-6.4%	38.6%	29.7%
12	Waipapa	4722	4722	4738	6673	0.3%	40.9%	41.3%
13	Apata	2955	2955	2954	4116	0.0%	39.3%	39.3%
14	Wainui	4891	4891	4891	6761	0.0%	38.2%	38.2%
15	Aongatete Bellevue	4717	4717	4715	6819	0.0%	44.6%	44.6%
16	Bellevue	267	267	205	398	-23.1%	94.0%	49.1%
17	Matakana 2	316	316	316	457	0.0%	44.6%	44.6%
	Total	108758	108758	107945	154121	-0.7%	42.8%	41.7%

Table 9: Effect of land use change and climate change on mean annual sediment load averaged over the period 2001 to 2051. The current land use is based on the decadal average urbanisation rates (2001rnd land use scenario).

		Mean annual load (t/y)				Increase (%)		
ID	**Name**	**2001rnd**	**2001-2051, Scenario 1 Current land use No climate change**	**2001-2051, Scenario 2 Future land use No climate change**	**2001-2051, Scenario 3 Future land use With climate change**	**Increase from land use change (Scenario 1 to 2)**	**Increase from climate change (Scenario 2 to 3)**	**Combined increase from land use and climate change (Scenario 1 to 3)**
1	Matakana 1	62	62	63	78	1.3%	24.6%	26.3%
2	Mount Maunganui	393	393	391	438	-0.5%	12.0%	11.5%
3	Papamoa	318	318	329	396	3.3%	20.5%	24.5%
4	Waitao	8078	8078	8029	9839	-0.6%	22.5%	21.8%
5	Kaitemako	2045	2045	1989	2451	-2.7%	23.2%	19.8%
6	Waimapu	16262	16262	16183	19131	-0.5%	18.2%	17.6%
7	Kopurererua	8113	8113	7943	9418	-2.1%	18.6%	16.1%
8	Wairoa	49641	49641	49630	59341	0.0%	19.6%	19.5%
9	Oturu	453	453	455	561	0.3%	23.4%	23.8%
10	Te Puna	4274	4274	4292	5201	0.4%	21.2%	21.7%
11	Mangawhai	1251	1251	1198	1428	-4.2%	19.1%	14.1%
12	Waipapa	4722	4722	4731	5672	0.2%	19.9%	20.1%
13	Apata	2955	2955	2967	3578	0.4%	20.6%	21.1%
14	Wainui	4891	4891	4893	5840	0.0%	19.3%	19.4%
15	Aongatete Bellevue	4717	4717	4750	5835	0.7%	22.9%	23.7%
16	Bellevue	267	267	217	257	-18.6%	18.4%	-3.7%
17	Matakana 2	316	316	316	390	0.0%	23.5%	23.5%
	Total	108758	108758	108376	129856	-0.4%	19.8%	19.4%

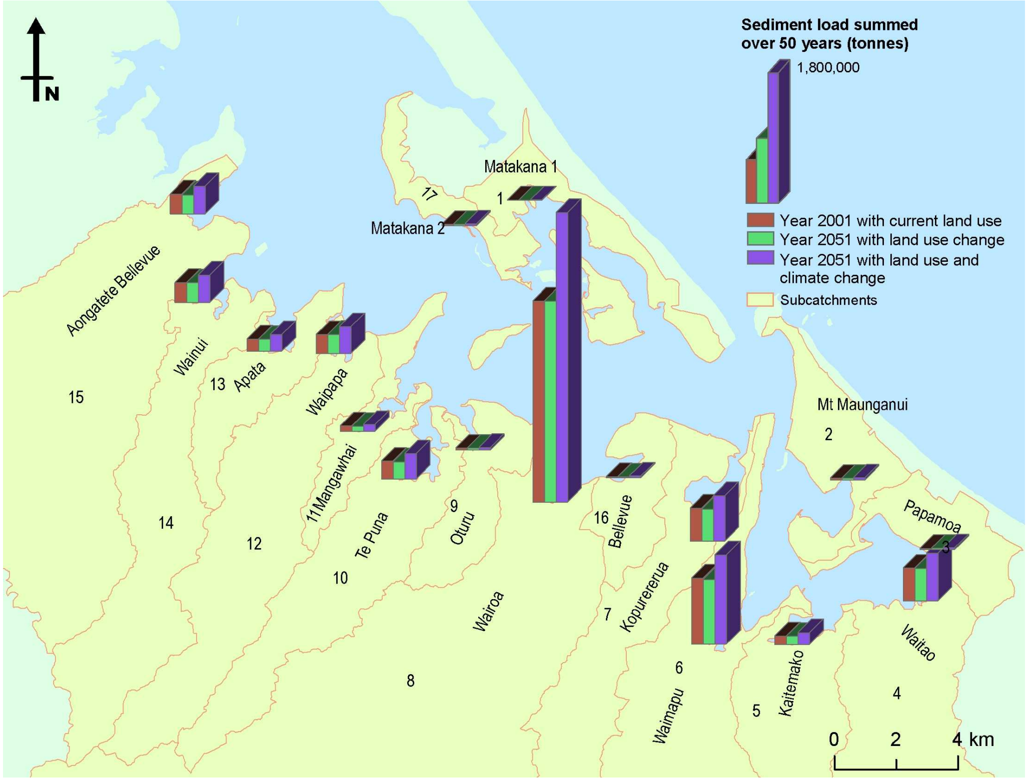

Figure 16: Sediment yield for different subcatchments for the current land use and climate, current climate and 2051 land use, and the 2051 climate and 2051 land use. The current land use is based on the decadal average urbanisation rates (2001rnd land use scenario).

7. Potential improvements to the model

The catchment model, like any model, incorporates assumptions and uncertainties. Potential areas for improvement include:

- Investigation of uncertainty associated with the future climate change. The predicted change in sediment load with climate change was substantial. However, this was based on a single somewhat conservative climate scenario. Running the model with a range of climate scenarios would provide a range of predictions, to give an idea of the uncertainty associated with the effect of climate change. Also, there is scope for improving the methods for generating time series of future climate, considering that these methods are in their infancy and are being actively developed.

- The ability of the model to predict the probability distribution of event sediment loads has not been tested. Longer-term monitoring of sediment yields would build up a picture of the distribution of sediment yields, which could be used to refine the model parameters. Such monitoring would also help to better define the rainfall-sediment relation, which would be useful for confirming the predicted sensitivity of sediment load to rainfall.

- Addition of a stream erosion component (bank and bed), both for rural and urban streams. This is not trivial, as knowledge of erosion rates from streams in the North Island of New Zealand is very limited, and the complex processes of stream erosion are difficult to model.

- Validation of the predicted stream deposition in relation to measured deposition.

- At present, slips are excluded from the analysis on the basis of general observations that the catchment is generally stable (apart from geotechnical failures associated with gullies or road construction). However, a more complete assessment of the role of slips may be warranted, starting with analysis of aerial photographs and an examination of the geomorphology. If slips are included, the analysis would probably have to be supplementary to the GLEAMS-TAU modelling, rather than being incorporated within the model.

- Knowledge of the spatial distribution of rainfall in the catchment is based on sparse data. Additional measurements in the Kaimai Range could refine this aspect of the model.

- The curvature and slope length of the catchment is taken into account in the model. However, the variability of curvature and slope length is not taken into account.

- Measurements of siltation pond performance would improve this aspect of the predictions. However, considering that controlled earthworks make only a small contribution to the overall load, this work probably has low priority.

- The characteristics of soils in quarry and mine areas, and the types of sediment controls employed, are uncertain. However, these land uses were predicted to contribute less than 2.7% of the sediment load to the harbour with fairly conservative assumptions, so this work probably has low priority.

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9. Appendix 1: Breakdown of mean annual load by subcatchment and future time period

Table A1: Table of breakdown of mean annual load (t/y) by subcatchment and time period, with and without climate change.

Subcatchment	2001 digit	2001 rnd	2011	2021	2021CC and urbanisation	2031	2031CC and urbanisation	2041	2041CC and urbanisation	2051	2051CC and urbanisation
Matakana 1	66	62	62	62	77	62	83	62	89	62	91
Mount Maunganui	395	393	386	386	433	393	457	393	476	393	481
Papamoa	321	318	329	329	395	331	423	331	450	331	459
Waitao	8087	8078	8028	8016	9607	8016	10420	8016	11129	8016	11777
Kaitemako	2044	2045	1997	1979	2445	1984	2621	1966	2775	1966	2844
Waimapu	16279	16262	1625	16264	17778	1623	20670	1610	21785	15948	22009
Kopurererua	8115	8113	8086	7892	8673	7862	9998	7851	10605	7851	11226
Wairoa	49649	49641	4963	49615	53161	4955	63861	4966	68268	49664	71491
Oturu	462	453	453	453	558	453	597	453	641	453	656
Te Puna	4396	4274	4271	4271	4845	4271	5540	4271	5917	4271	6240
Mangawhai	1275	1251	1232	1171	1414	1170	1494	1171	1589	1171	1623
Waipapa	4722	4722	4722	4722	5267	4743	6127	4738	6523	4738	6673
Apata	3031	2955	2954	2954	3557	2954	3782	2954	4028	2954	4116
Wainui	4903	4891	4891	4891	5636	4891	6225	4891	6621	4891	6761
Aongatete Bellevue	4924	4717	4715	4715	5720	4715	6194	4715	6641	4715	6819
Bellevue	265	267	217	205	219	205	224	205	230	205	398
Matakana 2	316	316	316	316	389	316	417	316	447	316	457