Tauranga Harbour Sediment Study: Sediment Load Model Implementation and Validation

NIWA Client Report: HAM2009-007
March 2009

NIWA Project: BOP09216

Tauranga Harbour Sediment Study: Sediment Load Model Implementation and Validation

A. Parshotam
S. Wadhwa
B. Mullan

Prepared for

Environment Bay of Plenty

NIWA Client Report: HAM2009-007
March 2009

NIWA Project: BOP09216

National Institute of Water & Atmospheric Research Ltd
Gate 10, Silverdale Road, Hamilton
P O Box 11115, Hamilton, New Zealand
Phone +64-7-856 7026, Fax +64-7-856 0151
www.niwa.co.nz

Contents

Reviewed by:

Sandy Elliott

Approved for release by:

Terry Hume

Formatting checked

A. Bartley

Executive Summary

This report describes the implementation and validation of the GLEAMS model for simulating sediment generation in the rural and urban areas of the catchment surrounding the Tauranga Harbour. The model so developed and implemented is called the “GLEAMS-TAU” model.

The input data requirements of the study are detailed as well as the assumptions for creating climate and land use scenarios established by Parshotam et al. (2008). A validation of the GLEAMS-TAU model is performed using monitoring data.

The predictions of the combined GLEAMS-TAU sediment load model and sediment stream network routing procedure were compared with sediment load estimates derived from monitoring data at Waimapa, Kopurererua and Waimapu Streams. The modelled loads compare well with these data, giving confidence in the application of the sediment load model for providing predictions of long-term average sediment loads for a range of catchment conditions.

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 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).

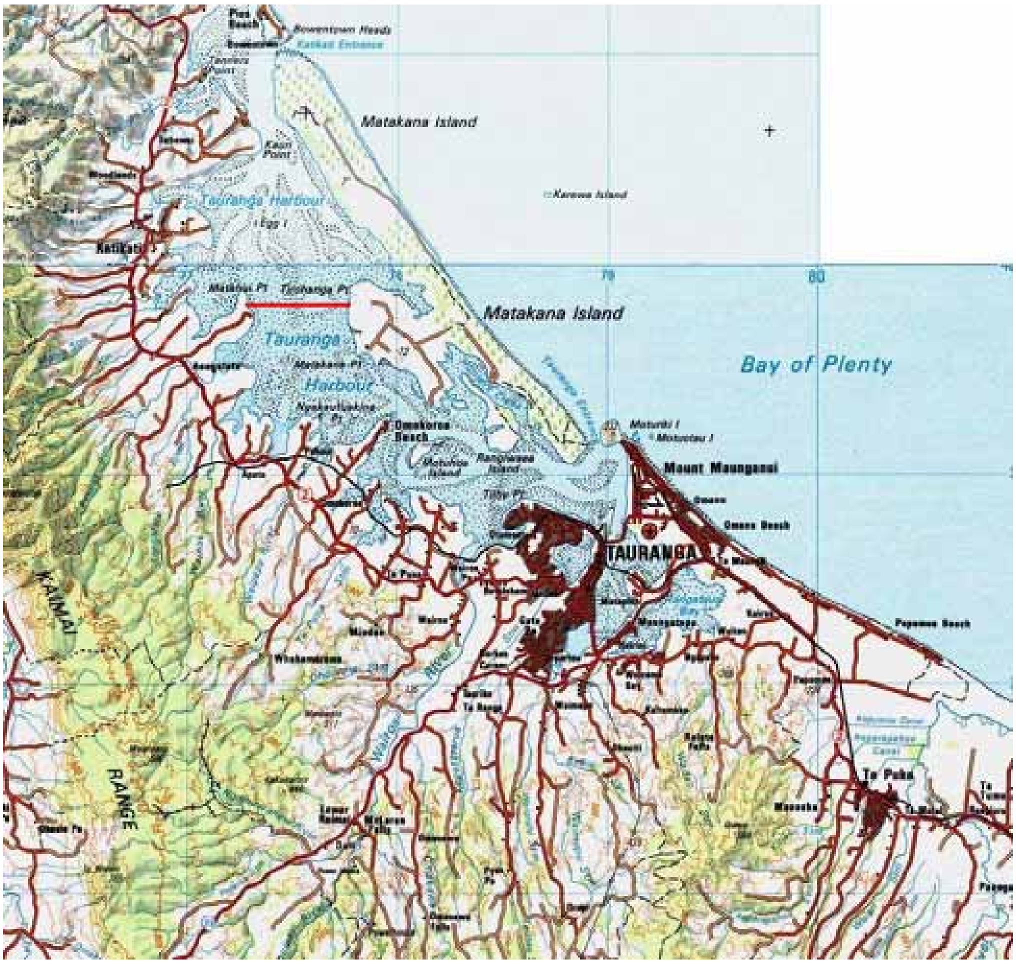


Figure 1: Tauranga Harbour, showing the study area from the South of the red line extending from Matahui Point to the harbour entrance at Mount Maunganui.

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 yields from each subcatchment 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 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 (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 Climate and land use scenarios

In an earlier report, as part of module A: Specifications of Scenarios, the land use and weather associated with 3 scenarios was outlined (Parshotam et al. 2008). This provided a basis for agreement on the assumptions regarding the scenarios. In this report, we present further details of the land use associated with these scenarios. A summary of scenarios is provided in Table 1.

Table 1: Scenarios defined with respect to land use and weather that are required for driving the various models.

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

1.4 This component of the study

This report is part of Module B1 which describes the model implementation and validation predicting sediment runoff from the land catchment surrounding the Tauranga Harbour.

This report describes the model structure, setup and data input requirements of the GLEAMS model for simulating sediment generation in the rural and urban areas of the catchment surrounding the Tauranga Harbour, passing it through sedimentation ponds, if and when necessary and routing sediment through the stream network to the estuary. The model so implemented is called the "GLEAMS-TAU" model. This report also compared GLEAMS-TAU with monitoring data from the catchment.

Sediment load data from GLEAMS-TAU for the whole catchment are provided as inputs to the USC-3 sedimentation model. Calibration of the USC-3 model (addressed in a separate report) is achieved by running the model for the historical period 1943 to 2001, with sediment inputs from the catchment appropriate to that period, which in turn are hind-cast by the GLEAMS-TAU model. The GLEAMS-TAU model is also used to predict sediment runoff for the period 2001 to 2051. The predictions are to be used in the validation of future catchment development scenarios. GLEAMS-TAU is also used for prediction of the combined effects of land development and climate change. Model predictions for the various land-use and climate scenarios are presented in a separate report (Parshotam 2009).

A key benefit of our modelling approach is its predictive ability, allowing 'what if' scenarios to be examined. These predictions can be an important aid in decision making. Models such as these can and have been used to provide guidelines to protect estuaries; evaluate impacts of development and urbanisation; flows and loads in the stream network; identify sediment loading “hotspots”; determine the effectiveness of urban and agricultural detention ponds; evaluate the impacts of changing land-use management; predict sediment accumulation and runoff from impervious surfaces; and evaluate erosion and deposition in streams.

Earlier GLEAMS-based models, such as BNZ (Basin New Zealand) (Stroud and Cooper, 1997), GLEAMSHELL (Rodda et al. 1997) and WAM-O (Watershed Assessment Model – Okura) (Stroud et al. 1999) have been used to address a variety of water quality issues at scales ranging from small watersheds to larger basins. Some example applications of these GLEAMS-based models, primarily in the Auckland region include: studies of sediment loss from vegetable growing fields at Pukekohe (Stroud and Cooper, 1998); identifying sediment sources and potential effects of landuse change in the Mahurangi catchment (Stroud and Cooper, 1997; Oldman et al. 1998; Stroud, 2003); impacts of urban and motorway development on sedimentation in Orewa estuary (Williamson et al. 1998); estimating the effects of urbanisation on sediment loss in the Mangemangeroa catchment (Oldman and Swales, 1999); determining the effects of rural intensification options on sediment loads to the Okura estuary (Stroud, et al. 1999; Stroud and Cooper, 1999); and contaminant accumulation in the Upper Waitemata Harbour (Green et al. 2004) and the Central Waitemata Harbour (Parshotam et al. 2007 a, b, c). There have been no similar studies in the Tauranga area.

2. Model description

2.1 GLEAMS-TAU model description

The procedure for deriving catchment sediment loads involves dividing a catchment into uniform grid cells of user-defined size. Predictions are made of the daily runoff of water and sediment from the grid cells using the field-scale physics-based mathematical model GLEAMS (Knisel and Davis, 2000) as its core model. The primary information requirements are the catchment characteristics, including climate, topography, soils and land use. A GIS interface is used to manage the spatial information required (see Figure 2) as input (e.g., soil patterns, land use and topography). Model simulations are conducted for unique combinations of soil, slope and land cover. The version of the GLEAMS model modified and adapted for our purposes in Tauranga is referred to as the GLEAMS-TAU model. The Basin Unique Cell Shell (BUCSHELL) model within GLEAMS-TAU generates input parameter files for each unique combination and runs GLEAMS for each model (see Figure 3).

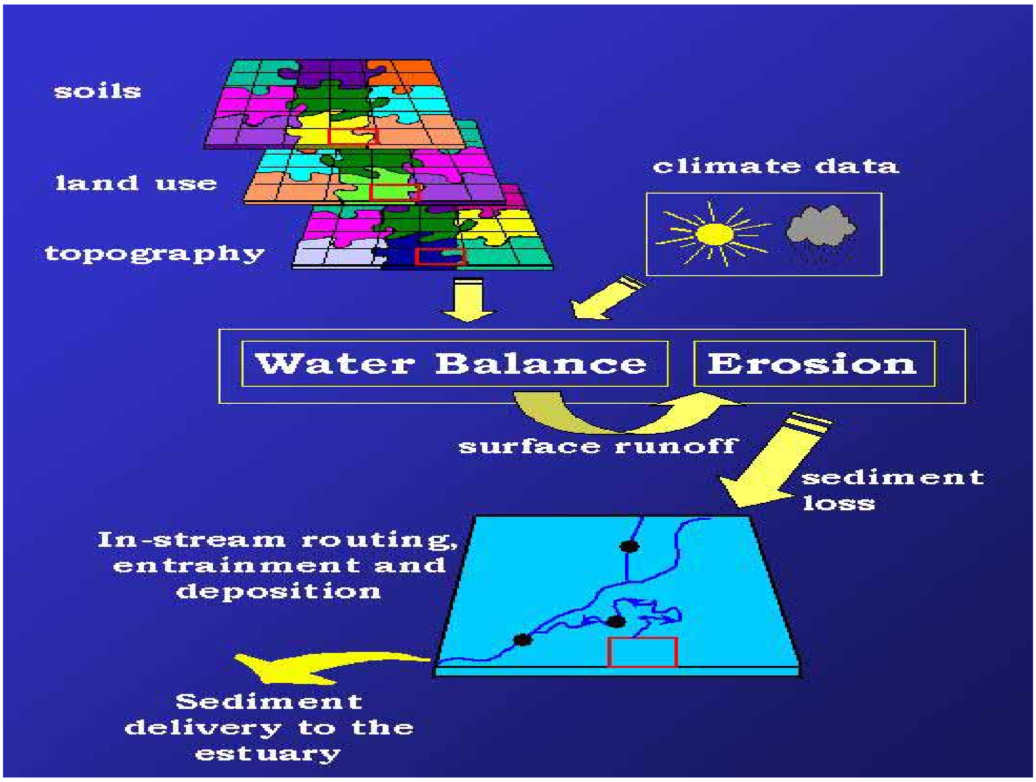


Figure 2: Data sources and procedure for estimating catchment sediment loads.

The GLEAMS-TAU model uses soils and land use data for each cell, together with long-term climate data (rainfall, temperature, and solar radiation) to calculate a daily water balance for each cell. This study uses a 50-year climate data record. A long-term record is used to capture a suitable range of climate conditions. Incoming rainfall is proportioned between surface runoff, storage in the soil profile, evapotranspiration and percolation beneath the root zone. Predictions of surface runoff are coupled with soil, vegetation and slope properties to calculate particle detachment and hill-slope sediment transport and deposition. The load from a grid cell may also be passed through a silt control pond. The predicted surface runoff, subsurface runoff and sediment generated from each grid cell may be aggregated on a catchment scale and/or routed through the stream network, via connected reaches, to the catchment outlet at the estuary. Stream bank erosion and stream bed erosion is not represented in the model.

GLEAMS has been previously validated against monitoring data at other locations in New Zealand. Information from previous catchment modelling studies and the literature was also used to define suitable parameter values for this study. This study however differs from previous studies in its prediction of sediment generation from the urban area, the creation of historical land use scenarios, and the use of future climate change scenarios. Also, the soils in this study are different from previous studies, so new parameters beyond those previously established were used. The parameters were established based on previous experience and on guidelines contained in the GLEAMS manuals. Model validation against measured sediment loss was conducted to confirm that these parameters were appropriate.

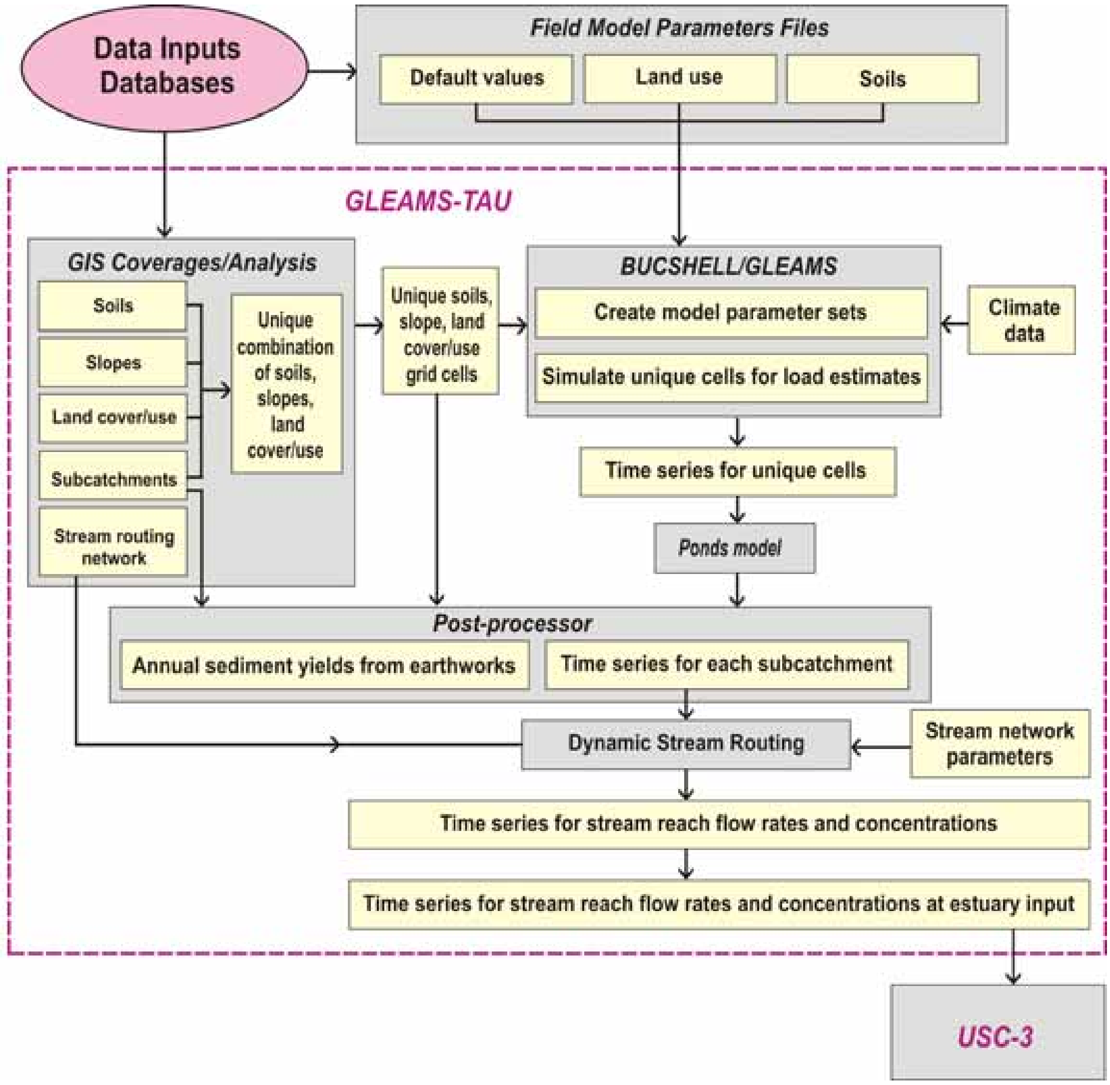


Figure 3: GLEAMS-TAU model structure.

2.2 Setting up GLEAMS-TAU

Digitised soil, topographical and land-use data are pre-processed within a GIS to provide input to GLEAMS-TAU (see Figure 3). Associated subcatchments (known as CSUs or Catchment Sub-units) are also assigned for each raster grid, to enable summarising of the predictions at subcatchment scale, and to enable the passing of sediment and water into the stream network.

GLEAMS-TAU was established using a 30 m x 30 m grid. This resulted in 1,103,461 grid cells for the 994 km^2 catchment but was needed to provide the scale necessary to adequately represent the terrain and soils, any site developments, and rural intensification. The extent of the modelled catchment is shown in Figures 4 to 6. Populating the model required building extensive parameter files.

The following steps were required to estimate sediment generation in the Tauranga Harbour using GLEAMS-TAU:

1. Create files of unique combinations of soils, slope and land cover classes using pre-processing.

2. Set up soils and landuse parameter files.

3. Set up the daily rainfall and monthly temperature and monthly solar radiation files.

4. Run the GLEAMS model for each unique combination of soil, slope and land cover.

5. Run silt pond model where appropriate.

6. Combine results from GLEAMS runs to give daily load for each CSU.

7. Combine loads from CSUs to give a time series of loads from each catchment outlet to the harbour.

8. Pass loads and rainfall runoff from CSUs through the stream network, to obtain stream reach flow rates and concentrations.

9. Pass subcatchment sediment loads at the estuary input in the appropriate form and data format to the USC-3 model.

2.3 The GLEAMS model

Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) (Knisel and Davis, 2000) is the core model used in GLEAMS-TAU. GLEAMS is a mechanistic, continuous-simulation, field-scale model, which was developed as an extension of the Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) model (Knisel, 1980). In the current work, the latest version of GLEAMS, i.e., GLEAMSv3.0 (Knisel and Davis, 2000) was used. GLEAMS consists of four major components: hydrology, erosion/sediment yield, pesticide transport, and nutrients. GLEAMS estimates surface runoff and sediment losses from the 'field', assuming that a field has homogeneous land use, soils, and precipitation. A full description of how the GLEAMS model works is given in Knisel (1993).

One of the factors responsible for variation in sediment losses across a catchment is the variation in rainfall. If rainfall were low during a period of earthworks then measured sediment losses would be less than if major rainfall events occurred. As field studies are typically short-term, the data they generate may not take into account this source of variability (Stroud et al. 1999). This is particularly relevant when predictions are to be made of the consequences of future earthworks activity, where a risk-based approach that includes some representation of rainfall variability must be used. This is where the strength of a simulation modelling approach becomes particularly apparent because it synthesises a record of sediment runoff using long-term rainfall data (50 years in our case) that can be used to examine risks of certain values being exceeded.

GLEAMS is based on a rich set of experimental data, and good guides on parameter values are available, so it requires little or no calibration. Moreover, we have conducted extensive tests of the model's ability to predict sediment loss from earthworks activity, particularly in the Auckland area. Predictions from the model have consequently been compared to monitoring data. Confidence in our modelling approach for other land uses is derived from its success in predicting sediment loss from pasture, pine and mixed land-use catchments of the Mahurangi estuary (Stroud and Cooper, 1997; Stroud et al. 1999), Okura (Stroud and Cooper, 1999) and Whitford (Senior et al. 2003). The study at Okura (Stroud and Cooper, 1999) examined sediment in the Alexandra Stream during the earthworks phase of catchment development. The study at Whitford examined earthworks associated with individual site developments and road construction during rural intensification. The current study in the Tauranga area has required a reassessment of model parameters and in addition includes new methodology and estimates of sediment runoff from the urban area of a catchment. Hence this study includes a validation component, in which the predictions are compared with field measurements made in the Tauranga Harbour catchment.

2.4 Bare earth / earthworks

In GLEAMS, bare earth is considered to be just another land cover. Soils may be modified to reflect topsoils removal associated with earthworks practices. Seasonal restrictions for earthworks practices were assumed (pers. comm., Stephen Park, Environment BOP) and these restrictions held for all soils, limiting earthworks to between 1st October and 30th April inclusive, with earthworks stabilisation in the off-season. Note that exceptions for winter earthworks are allowed in Tauranga according to erosion and sediment control guidelines for some soils textures (Environment BOP 2001, Chapter 1) but these exceptions were not considered.

2.5 Silt control ponds

The pond model was first developed for use in the Auckland area and allowed for the following:

- Up to 10 sediment size classes, which settle independently in the pond (well-mixed settling during storms, and quiescent settling between storms).

- Transient concentrations in the pond as the concentration in the pond adjusts to a new inflow.

- Decanting of the pond water during quiescent settling between storm events, followed by quiescent settling between runoff events.

- Flow varying through a storm event (of 1 day duration). This was achieved by: calculating an effective curve number for the event (based on GLEAMS output runoff); distributing the event rain over time using the design storm hyetograph as in TP108 (ARC, 1999); applying this rainfall and the SCS curve number equation to calculate excess rainfall through the event; translating this to the pond with no lag or attenuation (justified on the basis of the small catchments leading to a silt control pond); distributing the daily sediment load (from GLEAMS) over time using a power sediment rating curve. Note that siltation pond performance is not very sensitive to the details of the timing of inflows, as there is storage/buffering in the pond.

- Summing the pond outlet flux over time (including during the decant phase) to give the outlet sediment load for the event.

- Applying the pond model for each event in the GLEAMS output file, to derive a time-series of event loads after ponds.

The dimensions of the ponds were set to match those in Environment BOP (2001, Chapter 5). The decant rate was set at $4Ls^{-1}ha^{-1}$, the mean pond depth was set at 1.5 m, and the dead storage was 30% of the total pond volume (at the outlet level).

For standard sediment retention ponds, the median settling velocity was adjusted so that the long-term average sediment removal achieved by ‘2%’ ponds was 70%. This removal efficiency is commonly accepted as a representative value for silt control ponds with silty-clay soils in the Auckland area (Bannister, pers comm.). Note that in the Bay of Plenty, soil texture tends to be dominated by sand and silt, rather than clay and more detail on the performance of silt control ponds in Tauranga is desirable. The median settling velocity was 0.4 m/day, corresponding to spherical quartz particles with a diameter of 4 microns, and the $\log_{10}$-s.d. of particle sizes was set at 1.5, consistent with measurements of particle sizes in urban runoff (Hicks, 1994). Note that the removal efficiency is less for larger storms, as in larger storms the main pond discharge operates and the residence time of the water is less.

2.6 Post-processing

The predicted daily sediment loads from each unit cell corresponding to a soil-slope-land use / cover combination are input to an MS-Access database and aggregated to produce daily sediment loads from each CSU, which are subsequently passed through a stream network. The sediment loads, broken down by particle size class are then passed directly to the USC-3 estuary model as a time series of daily sediment loads at each estuary inlet point for the full period of model runs. Exactly how these loads are incorporated into the USC-3 model is explained by Green (2009).

2.7 Stream routing

A sediment routing model has been developed for use within GLEAMS-TAU to more accurately describe the movement of sediment through the stream channel network to the estuary. The model reads in daily water and sediment discharge time series from GLEAMS CSU's, and also reads information describing the river network, and how the CSU's link to the network. The results for all reaches at all time-steps are saved in a model output file which can be used for further analysis or modelling of receiving waters.

The peak flow is determined from the daily runoff volume. It is assumed that flow within the day varies as a triangular hydrograph whose duration is twice the time of concentration (T_c, in minutes). T_c is obtained from empirical equations for the Auckland area (calculated using TP108 (ARC, 1999)). The daily runoff volume is obtained by summing the daily runoff volumes for all upstream areas.

The sediment discharge is obtained by calculating the input of sediment from upstream reaches, and removing daily sediment deposition in each reach. Deposition is calculated using a fall velocity with an assumed steady-state flow at the peak flow rate, with well-mixed conditions in the water column in each reach. The model is able to simulate the routing of multiple particle sizes or classes (e.g., sand, silt and clay).

The method is applicable only for: (1) subcatchments with time of concentration much less than the time-step of the GLEAMS model (one day), and (2) for obtaining approximate estimates of peak flows and sediment discharges, since it makes a quasi-steady state assumption.

The routing model produces a time series for all reaches, on all days, by particle size with the following information: peak flow, sediment (concentration, input, output, storage), both as total sediment, and by particle size class. All loads were added for the terminal reaches within a subcatchment to obtain the total load from the subcatchment.

Reservoirs are simulated in the model by widening the relevant stream.

The issue of erosion and subsequent transport by later larger floods is not addressed in the model and the bed of the stream network is assumed to be purely depositional. It is difficult to fully characterise the stream transport processes, and this remains an area of uncertainty in our modelling.

3. Model input data

3.1 Outlets, subcatchments and catchment management units (CSU's)

An 'outlet' is defined here as a point of input of sediment and water into the estuary. Typically, these points are where a main stream enters the estuary. These same points are termed 'inlets' for the estuary model. A subcatchment is defined in this study as the catchment area associated with an inlet. The number and location of the outlet points were determined based on considerations of estuarine modelling requirements and in conjunction with Environment BOP. "Notional" catchment outlet points from the catchment and into the harbour were defined based on the stream network order from NIWA River Environment Classification (REC), catchment topography and *a priori* knowledge of the estuary. Further details on the outlet locations are given in the report on the implementation of the USC-3 model for the Tauranga Harbour Sediment Study (Green, 2009).

Subcatchments and subcatchment boundaries were generally defined based on topography, supplemented with information on the urban drainage network in some places. Small areas that do not actually drain to an outlet point allocated to the nearest outlet, and the subcatchments were enlarged accordingly. The derivation of the subcatchments and subcatchment boundaries is described below.

Terrains were built from LIDAR and photogrammetry datasets listed in Appendix 1 and presented in Figure 4. These terrains were then converted to rasters of 5 and 10 m cell sizes. For areas where LIDAR and photogrammetric data were absent (Fig. 4), a 15 m DEM from Landcare Research was used. The mosaic tool (with blend option) within ArcGIS was used to obtain a single seamless 10 m DEM for the study area. The coastline was defined by Environment BOP.

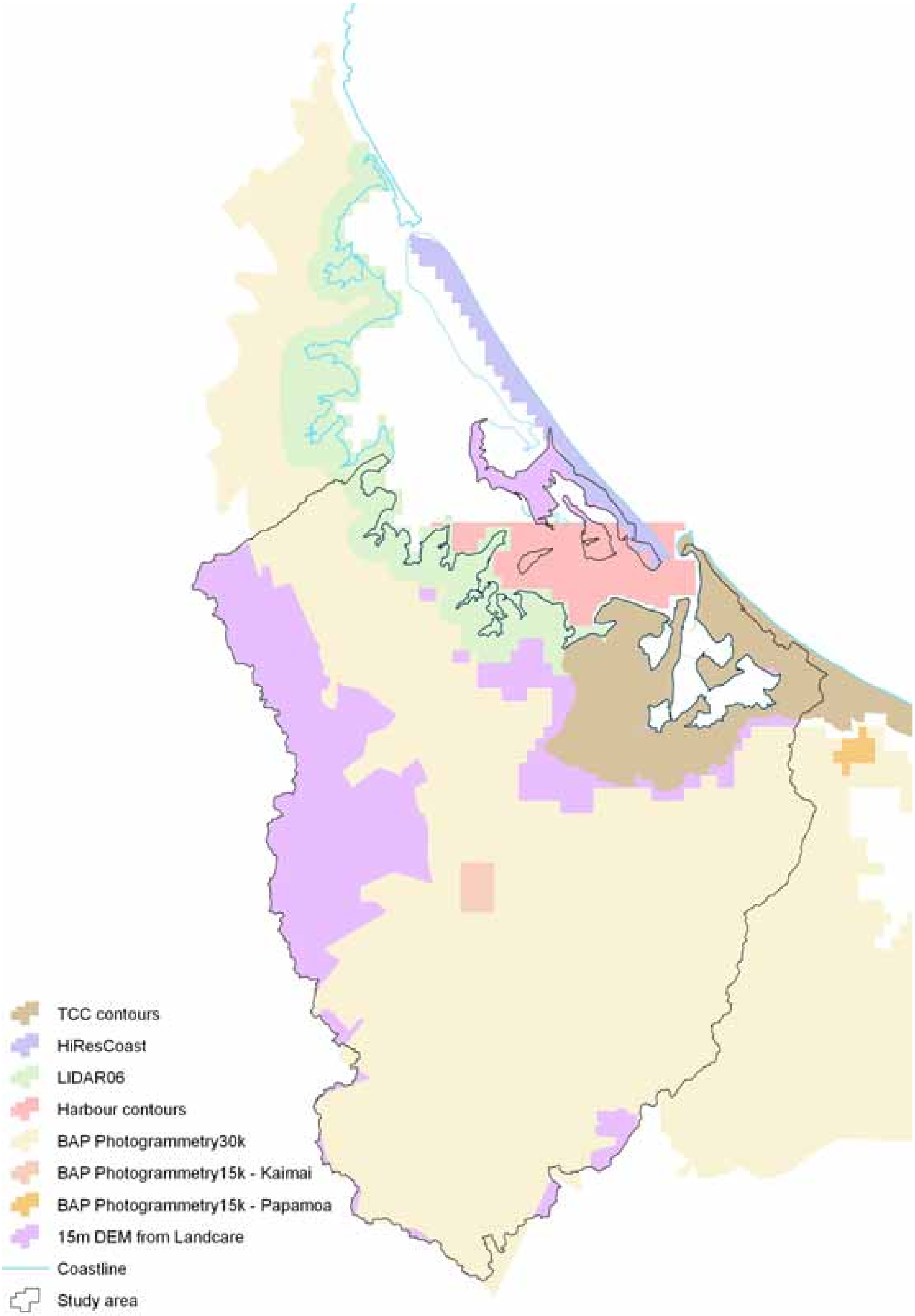


Figure 4: Data sources for deriving catchment terrains. The datasets are given in Appendix 1.

The study area was divided into 219 hydrological CSUs (Catchment Sub-Units) nested within 17 outfall subcatchment areas, given identifiers 1 to 17 (Figure 5).

Drainage basins were delineated from the 10 m DEM using hydrological modelling functions available in ArcGIS Spatial Analyst and applying a threshold value of 20 000 to limit their minimum size. The drainage basins were used as a guide to create all CSUs in the study area of a systematic size. During the DEM analysis, some coastal areas not associated with a stream were omitted. These areas were added back as separate CSU's. The study area boundary was changed at Papamoa after studying the stormwater drainage network from mapped by Tauranga City Council (data were provided by Environment BOP). All other boundaries remained unchanged.

A map of CSUs with unique identifiers used in this study is given in Figure 6 and the subcatchment names, outlet ID's, codes and areas (ha) are given in Table 2.

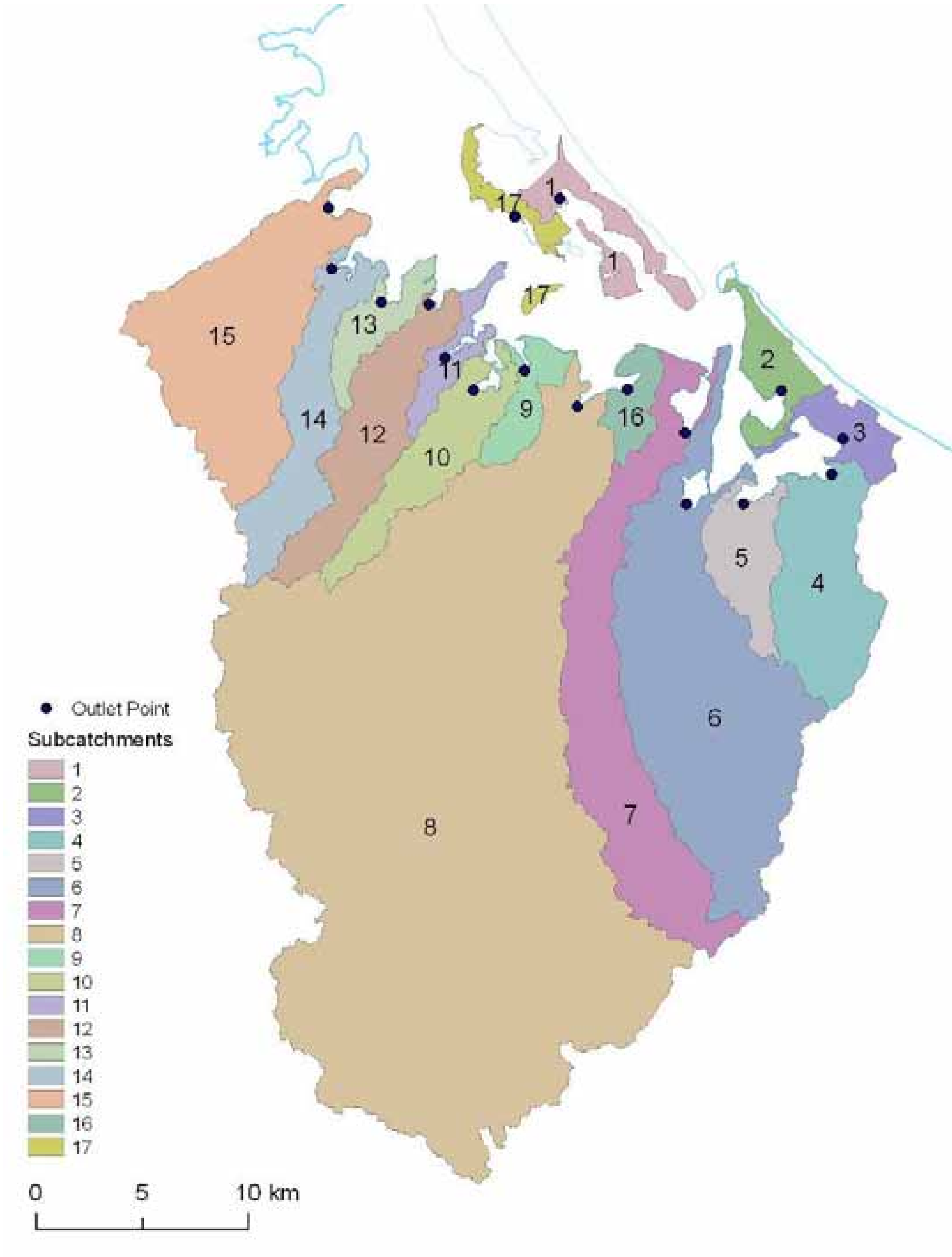


Figure 5: Map of subcatchments and corresponding outlet points. The subcatchment names are given in Table 2.

Table 2: Subcatchment names, outlet ID's, codes and area.

Subcatchment name	Outlet ID	Area (ha)
Matakana 1	1	1409
Mt Maunganui	2	1299
Papamoa	3	1182
Waitao	4	4332
Kaitemako	5	1989
Waimapu	6	11824
Kopurererua	7	7879
Wairoa	8	46534
Oturu	9	1158
Te Puna	10	2799
Mangawhai	11	957
Waipapa	12	3680
Apata	13	1240
Wainui	14	3523
Aongatete Bellevue	15	7854
Bellevue	16	950
Matakana 2	17	755
Total catchment		99366

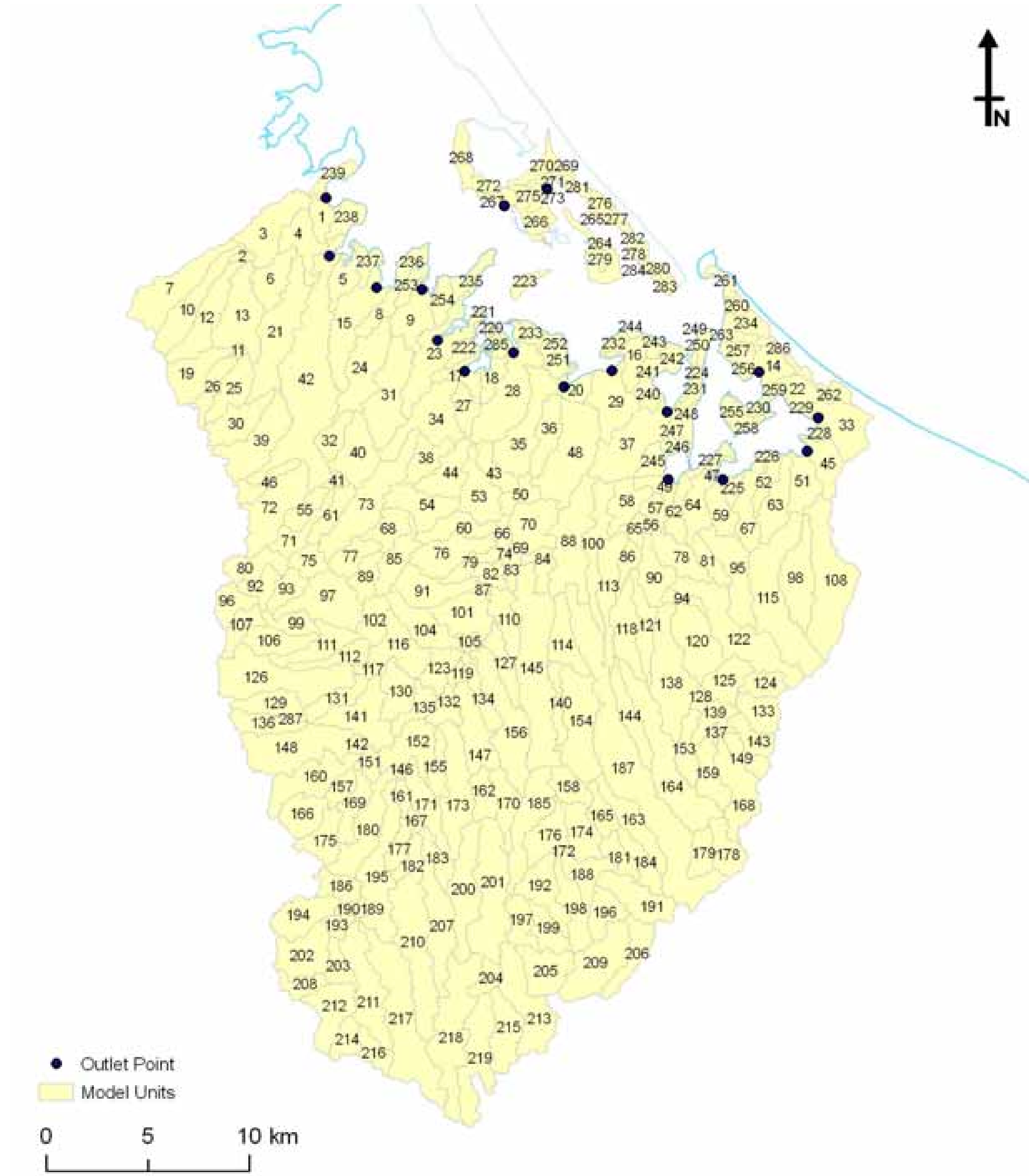


Figure 6: Map of hydrological catchment management units (CSU's), and their unique identifiers.

3.2 Soils

Soil layers and maps (see Figure 7), including names, classes, orders, symbols and descriptions for the study area were obtained from the NZLRI and were provided by Environment BOP. A breakdown of the major soils in the Tauranga region as a percentage of total subcatchment area is given in Tables A1 and A2 of the appendix. Key soil types in the study catchment are:

1. pumice soils in the south eastern part of the catchment. These soils have properties dominated by a pumiceous and glassy material with a low content of clay (which typically contains allophane);

2. acid gley soils around the coast. These soils generally occur on relatively stable land surfaces, and have been subject to a fluctuating ground-water table;

3. podsols on the western hillslopes and generally on the outskirts of the catchment. These soils are acid soils with low base saturation; and

4. allophanic soils in the majority of the catchment. These soils have properties that are strongly influenced by minerals with minerals with short-range order, especially allophone, imogolite and ferrihydrite.

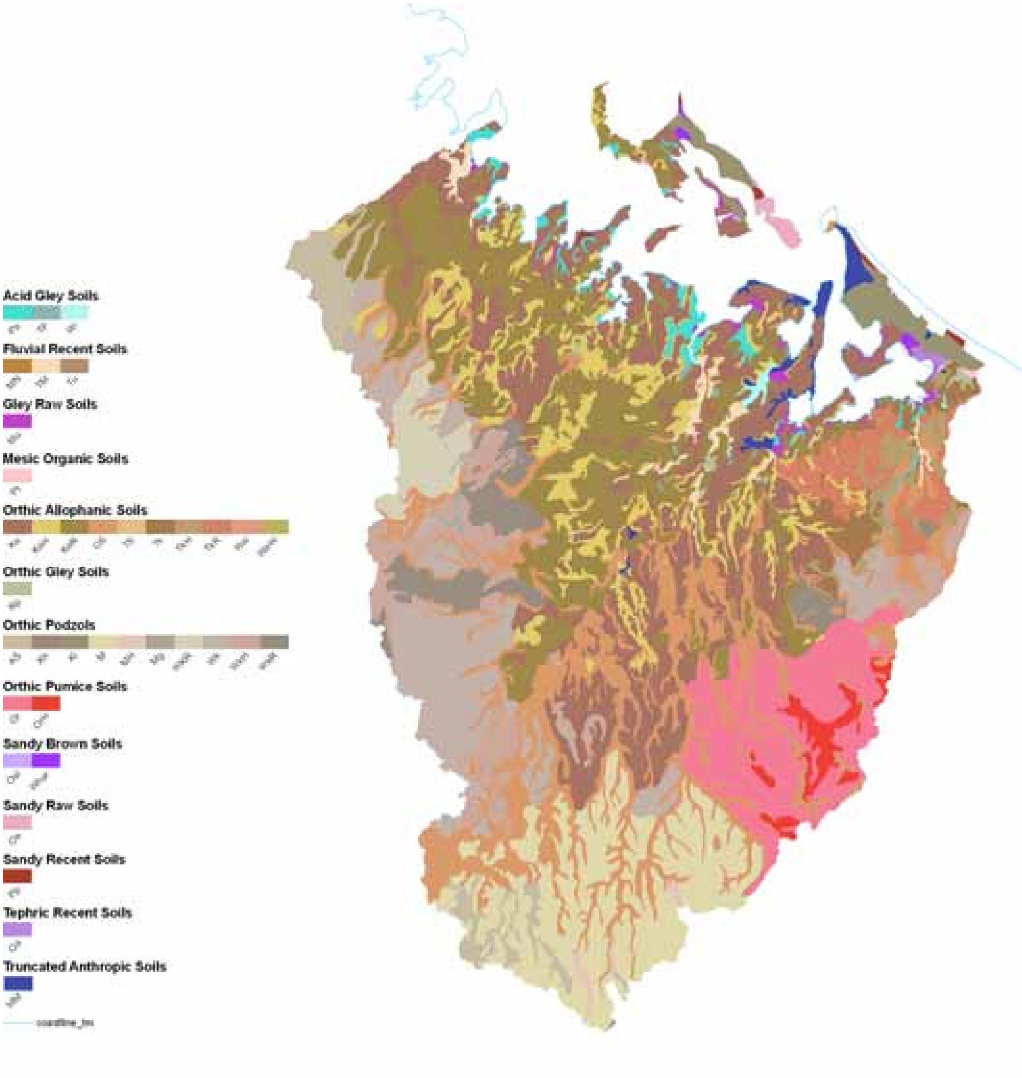


Figure 7: Major soils in the Tauranga Harbour region.

Detailed soil profile information was obtained from Linda Lilburne, Landcare Research using *S-map*, the multi-layer soil database for each soil type in the map above. The *S-map* names of the soils in Figure 7 are given in Table A2 of the appendix. This data included soil symbols, depths, organic carbon (%), soil texture (clay (%), sand (%), silt (%)), wilting point, field capacity, porosity, bulk density, saturated hydraulic conductivity (Ksat), rooting depth, drainage classes, permeability and structure classes. Further information on these soils and soils in the Tauranga region was derived from published data and reports (Rijkse, 2003).

The map of soil types was used as an input GIS overlay to GLEAMS-TAU. Soil input files were set up to include the 36 major soil classes (including landfill), with 36 further bare earth classes being the respective soil classes with their topsoils removed to reflect earthworks practices. During the earthworks phase of site development, topsoil is generally removed, thus exposing clay-dominated subsoils. This practice was simulated in the modelling. Because subsoil clay has little organic matter associated with it, it is more easily detached from the soil surface and entrained within the surface runoff, compared with a soil with more organic matter. Generally less erosion occurs for higher clay content, which counters the effect of reduced organic matter.

There is a high proportion of allophanic soils in the area. Allophanic soils have unusually high specific surface areas and the specific areas for short-range order minerals for the Katikati soils is taken to be 40 m^2 g $soil^{-1}$ (Saggar, et al. 1994). The specific surface area for clay particles for all other soils in the area was assumed to be 20 m^2 g $soil^{-1}$. This factor is used in the calculation of the sediment enrichment ratio (ratio of the specific surface area of the eroded soil particles in relation to the specific surface area of the original soil).

The number of soil horizons was limited to 5. The effective rooting depth was assumed to equal the depth of the bottom horizon. The soil evaporation parameter was taken from textural classes (U.S. Department of Agriculture, Soil Conservation Service, 1984).

SCS Hydrologic soil groups define groups of soils having similar runoff potentials under similar storms and cover conditions (US Department of Agriculture, 2007). These are used in the model for allocating rainfall-runoff parameters, and are related to soil texture and profile Ksat. There are no dual hydrologic soil groups defined, that is, soils belonging to more than one hydrological soil group. SCS soil groups were assigned for each soil type, based on textural, mineralogic, and structural descriptions of the soils.

Details on vegetative cover coefficients and Manning's roughness coefficients are given in reports on previous studies in New Zealand (as referenced in Section 1.4).

The soil erodibility factor (K-factor) is a quantitative description of the inherent erodibility of a particular soil; it is a measure of the susceptibility of soil particles to detachment and transport by rainfall and runoff. Soil erodibility is a sensitive parameter since it is a multiplicative factor in estimating rill and interrill erosion. Soil texture is the principal factor affecting K-factor, but structure, organic matter, and permeability also contribute. Equations in the GLEAMS manual were used to relate K-factor to these parameters. In using this equation, the soil carbon % was restricted to a maximum of 6%, to avoid unrealistically low values of K-factor that would otherwise result. The VSF (%) (the very fine sand fraction) was assumed to be one-half of the sand fraction. Soil structure codes were derived from morphological descriptions. Soil permeability codes were derived from broad classes extracted from the database defined in terms of slow (< 4 mm/hr), moderate (4 to 72 mm/hr) and rapid (> 72 mm/hr), and refined using Ksat values – taking the slowest horizon to represent the profile. The soil erodibility factor for these soils ranged in value from 0.03 to 0.47.

3.3 Topography

The mean slope angle for each cell was determined from the 10 m DEM (described above). The cell slopes were grouped in intervals of 3 degrees to determine slope classes and the spatial distribution of these groups was used as input to GLEAMS-TAU (see Figure 8).

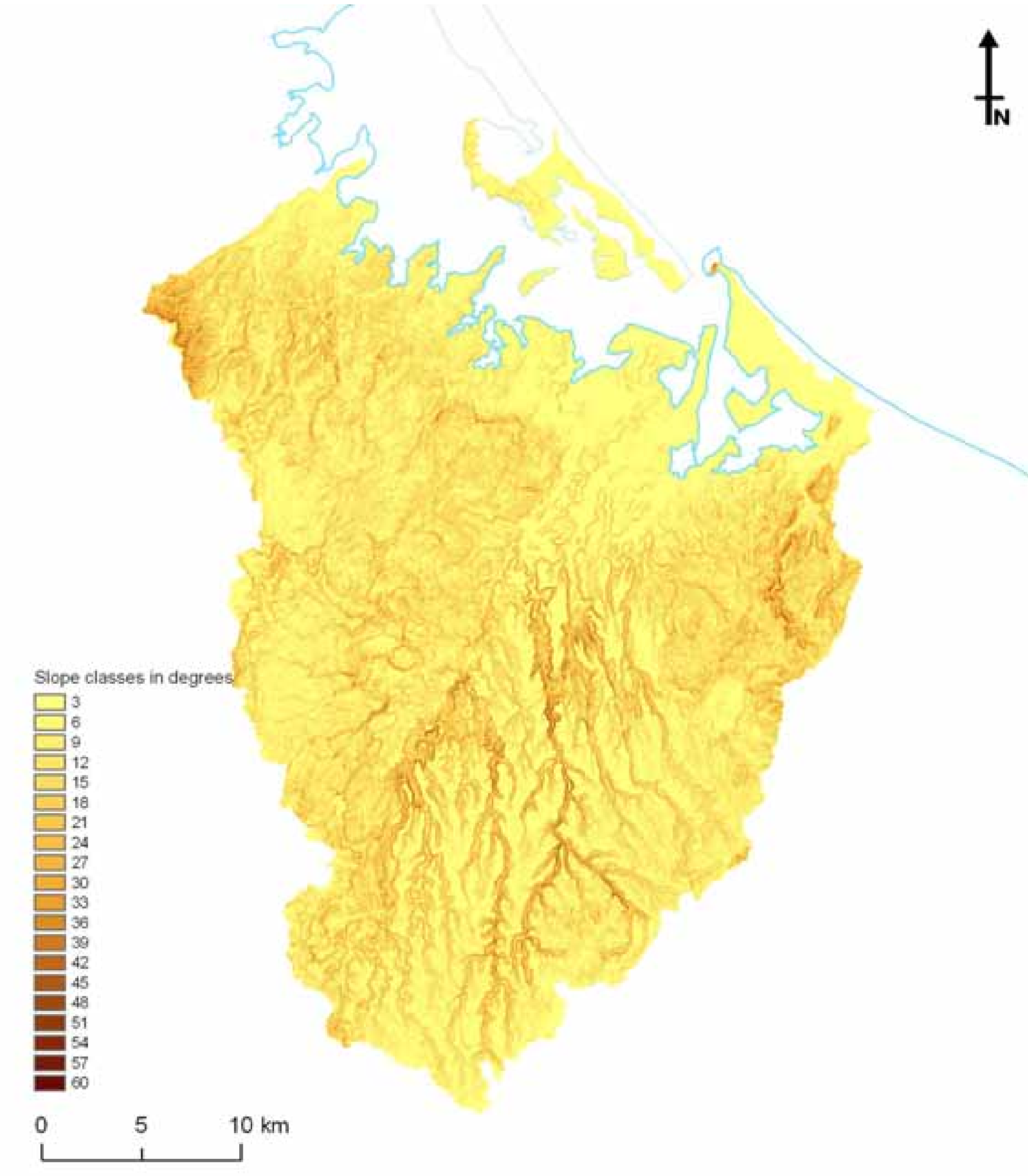


Figure 8: Slope angle classes in the Tauranga Harbour catchment. The first class corresponds to slopes between 0 and 3 degrees.

Slope angle classes ranged from 3 to 60 degrees and these values were used in the model simulations. Table 3 gives the percentage of the land falling within slope angle classes.

Table 3: Percentage of the land falling within slope classes.

Slope angle class	Percentage of land area
0-3	22.4
3-6	20.6
6-9	15.1
9-12	11.6
12-15	8.8
15-18	6.7
18-21	4.9
21-24	3.5
24-27	2.5
27-30	1.7
30-33	1
>33	1.2

The prevalence of steep slopes occurs around gullies, in the eastern hills and ranges, and to the northwest where the land gradually rises to the hills of the Kaimai range.

3.4 Climate

The preparation of climate information for the historical period (1943 and 1959), the current time (2001), and the future period (2010 to 2050) to be used in the GLEAMS-TAU model is discussed in this section in relation to climate scenarios established by Parshotam et al. (2008). The data sources for these scenarios are given in Appendix 2.

3.4.1 Present climate

Present–day climate

To construct present-day weather time series for driving models, long-term composite Tauranga station data (daily rainfall, monthly min/max temperature) from Griffiths et al. (2003) was used, supplemented with records from the Tauranga Airport AWS (Automatic Weather Station) (-37.67242 latitude, 176.19635 longitude) for the period 2002–current. This gives a combined record covering a period of over 50 years. Data gaps at the Tauranga airport site were filled with data from other Tauranga sites. The Tauranga Airport B76621/B76624 stations are recommended temperature and rainfall reference stations within the Bay of Plenty (Griffiths et al. 2003). These reference stations represent high-quality, long-record, open climate stations and have been used to monitor climate variability and change in the Bay of Plenty, and as sites for predictions into the future (Griffiths et al. 2003).

Climate: spatial distribution

The spatial distribution of long-term average annual temperature and rainfall for the catchment were obtained from NIWA's climate grids, which were interpolated from observation stations using ANUSPLINE (Tait et al. 2006) (see Figures 9 and 10).

As can be expected from the topography in the study area, rainfall increases from the coastal lowlands to the Kaimai ranges. The map of median annual rainfall for the catchment (Figure 10) was produced from the gridded interpolated data discussed above. The spatial variation of rainfall and the station location allow the study region to be split into three rainfall regions / zones: Zone 1 (RR1): 1125-1700 mm/yr; Zone 2 (RR2): 1701-2050 mm/yr and Zone 3 (RR3): 2051-2536 mm/yr (Figure 11). The boundaries of the zones were edited in manually within GIS, using the spatial pattern of median annual rainfall as a guide. The GLEAMS model was run with a different weather input for each of these three climate zones to predict sediment runoff.

Temperature data for rainfall zone RR1 were taken from long-term composite data at the Tauranga Airport reference station (see Figure 11). Minimum and maximum temperature data for rainfall zone RR2 and RR3 are created by applying temperature offsets based on Figure 8 of -1 and -2 degrees (°C) respectively, to the minimum and maximum monthly temperature data for rainfall zone, RR1. The mean monthly minimum temperature for rainfall zone, RR1, during the period 1958-2007, is 10.1 °C and the mean monthly maximum temperature for rainfall zone, RR1, during the period 1958-2007, is 18.9 C.

Daily rainfall for rainfall zone RR1 was taken from the representative Tauranga Airport reference station. The daily rainfall data for rainfall zones RR2 and RR3 were created by applying a multiplying factor based on Figure 10 of 1.35 and 1.57 respectively to the daily rainfall data from RR. The *mean* annual rainfall for rainfall zones, RR1, RR2 and RR3 during the period 1958 and 2007, is 125.8 cm, 169.9 cm and 197.5 cm, respectively. Note that 50 years of daily rainfall data during the period 1958 and 2007 was used for our modelling for all scenarios and 50 years of daily rainfall data during the period 1959 and 2008 was used for model validation.

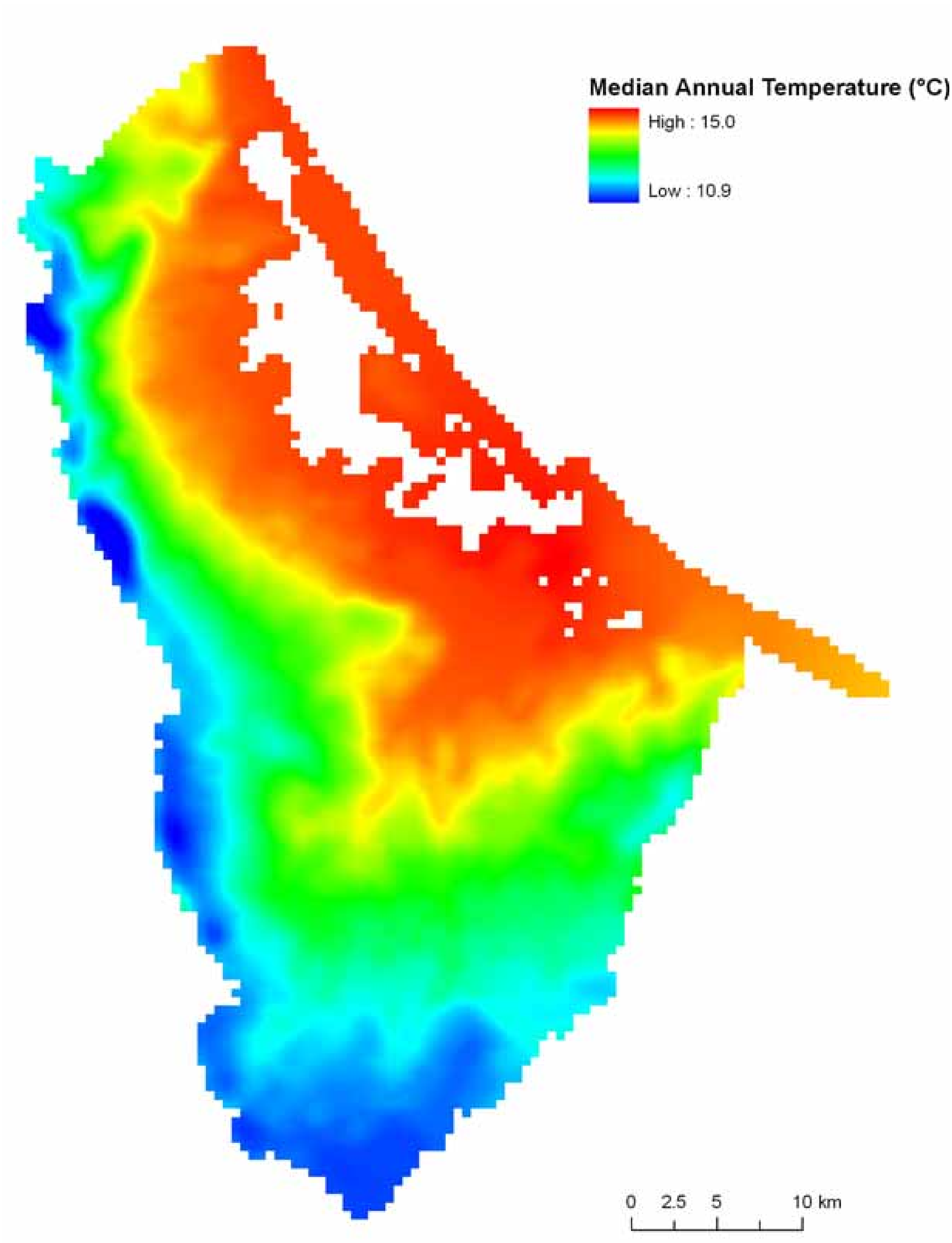


Figure 9: Map of median annual temperature in the vicinity of the Tauranga Harbour, obtained from NIWA's climate grids, which were interpolated from observation stations using ANUSPLINE.

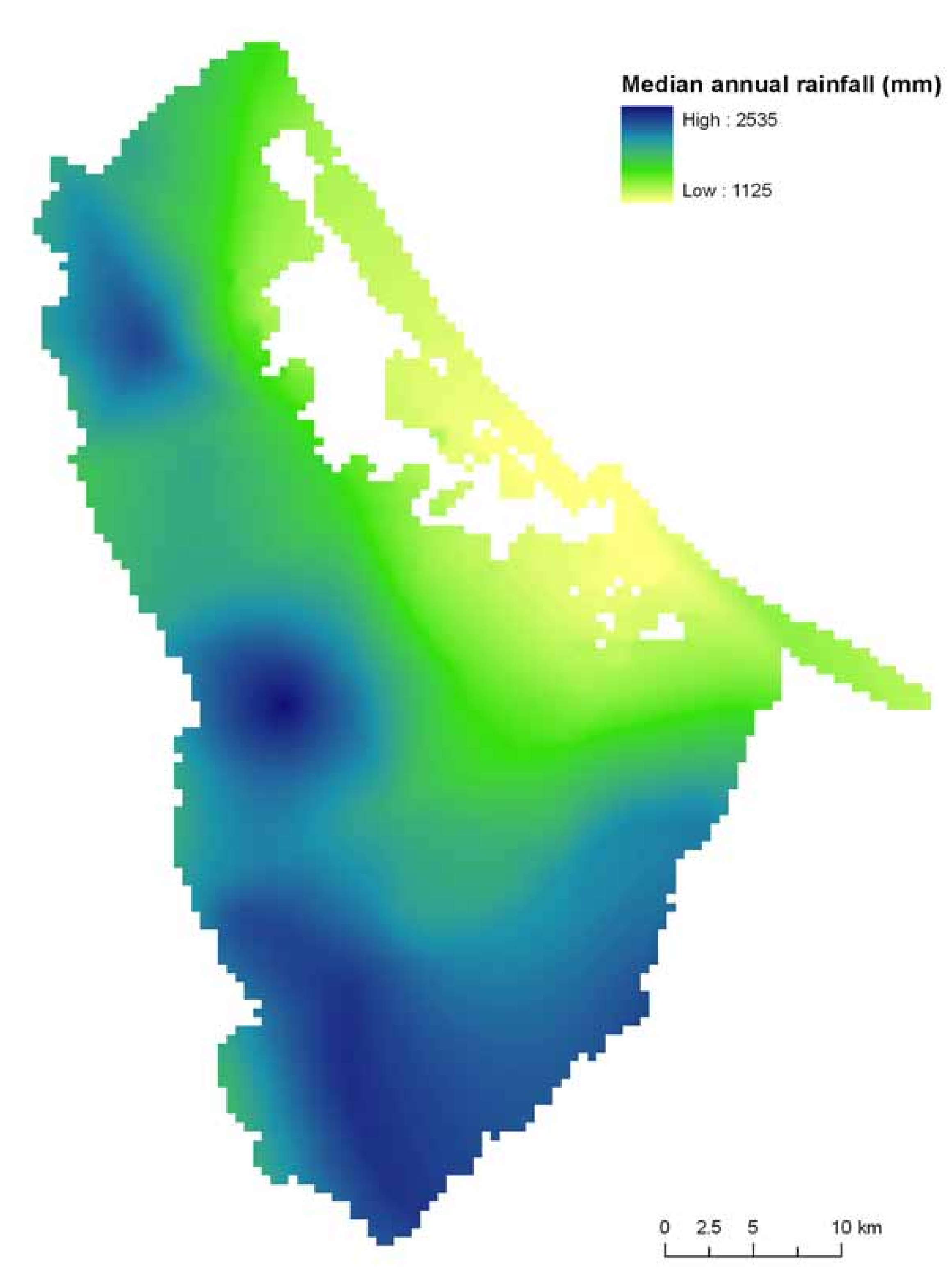


Figure 10: Map of median annual rainfall in the vicinity of the Tauranga Harbour, obtained from NIWA's climate grids, which were interpolated from observation stations using ANUSPLINE.

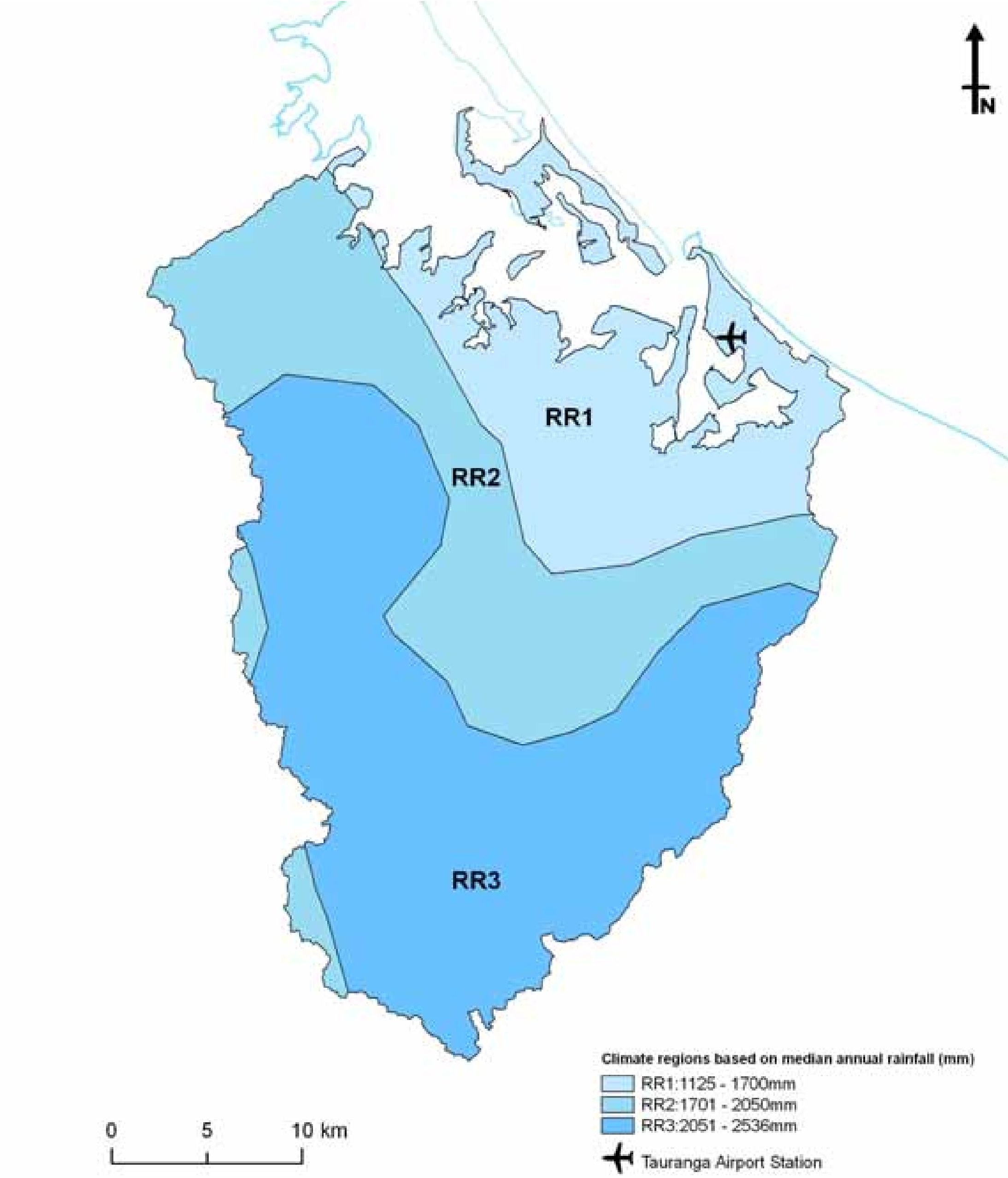


Figure 11: Map of rainfall regions / zones in the study area based on median annual rainfall.

3.4.2 Future climate scenarios

Global and national perspectives on climate change

The Intergovernmental Panel on Climate Change (IPCC) issued updated global climate change assessments during 2007 (IPCC, 2007a, b). The IPCC presented projections for 6 emissions scenarios (called “marker” scenarios) to cover a wide range of possible future economic, political and social developments during the 21st century. Figure 12 shows the IPCC projected range of global temperature increases likely out to 2100 that occur as a consequence of the 6 emission scenarios. These projections are aggregated from the simulations of about 20 global climate models. The model-average temperature changes over time are shown for three of the marker scenarios in the boxed part of Figure 12, and temperature increases at 2100 for all 6 scenarios at the right-hand side.

There is a substantial spread in projected warming. One factor causing the spread in temperature increase is the range of plausible emissions scenarios (the temperature consequence is represented in Figure 12 by a separation between the coloured lines or, at 2100, between the coloured marks near the middle of the grey bars). The second factor is the variation in climate response by the models for the same emissions (represented for warming to 2100 by the height of the grey bars). The multi-model average, or IPCC ‘best estimate’, of the global temperature increase for the mid-range A1B scenario is +2.8°C at 2100, with a range for A1B between 1.7 and 4.4°C. The A1B scenario is characterised by rapid economic growth with a balanced emphasis on all energy sources.

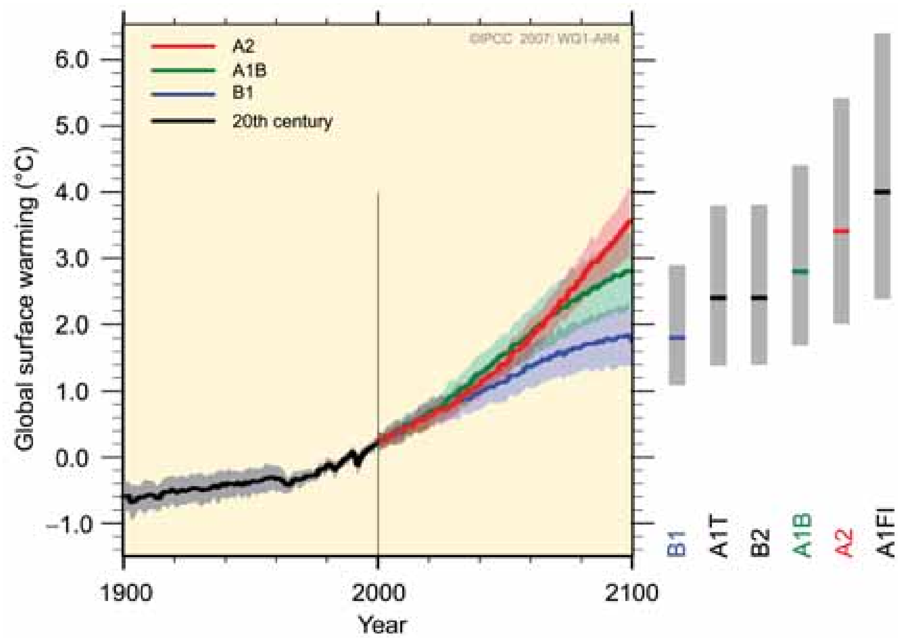


Figure 12: IPCC projections of global temperature increase. Solid coloured lines are multi-model global averages of surface warming (relative to 1980-1999) for emission scenarios B1, A1B and A2, shown as continuations of the 20th century simulations (black line). The coloured shading denotes the ±1 standard deviation range of individual model annual averages. The grey bars at right indicate the best estimate (solid horizontal line within each grey bar) and the 'likely range' across 6 scenarios that span the full range of all IPCC 2007 emission scenarios. (Adapted from Figure SPM-5, IPCC 2007a, b).

This report for Tauranga draws on the new (2007) global scenario information. NIWA has used climate model data from the IPCC Fourth Assessment to update its climate change scenarios for New Zealand. After validating how well the climate models simulate current climate and its variability in the New Zealand and broader Pacific region, 12 global models were selected.

The 12 global models have been downscaled to provide information on spatial variations around New Zealand. To do this, a relatively high resolution regional climate model (RCM) is driven by a low resolution global climate model. The hypothesis behind the use of high-resolution RCMs is that they can provide meaningful small-scale features over a limited region at affordable computational cost compared to high-resolution GCMs. These downscaled models were applied for the SRES A1B emissions scenario, which is a mid-range scenario between 'business as usual' and extreme cuts in emissions. The results are described in a guidance manual prepared for the Ministry for the Environment (MfE, 2008), and supersede the previous New Zealand scenarios developed by NIWA from the IPCC Third Assessment (MfE, 2004). Just as Figure 12 shows a wide range in global warming, so the models have a similarly wide range in projected New Zealand warming.

Figure 13 shows the 12-model average 50-year rainfall trends over New Zealand. The changes are expressed relative to 1980-1999 (1990 for short), which is considered to be indicative of the "current" climate. This convention follows the approach in the MfE guidance manual (MfE, 2008) and in IPCC (2007a).

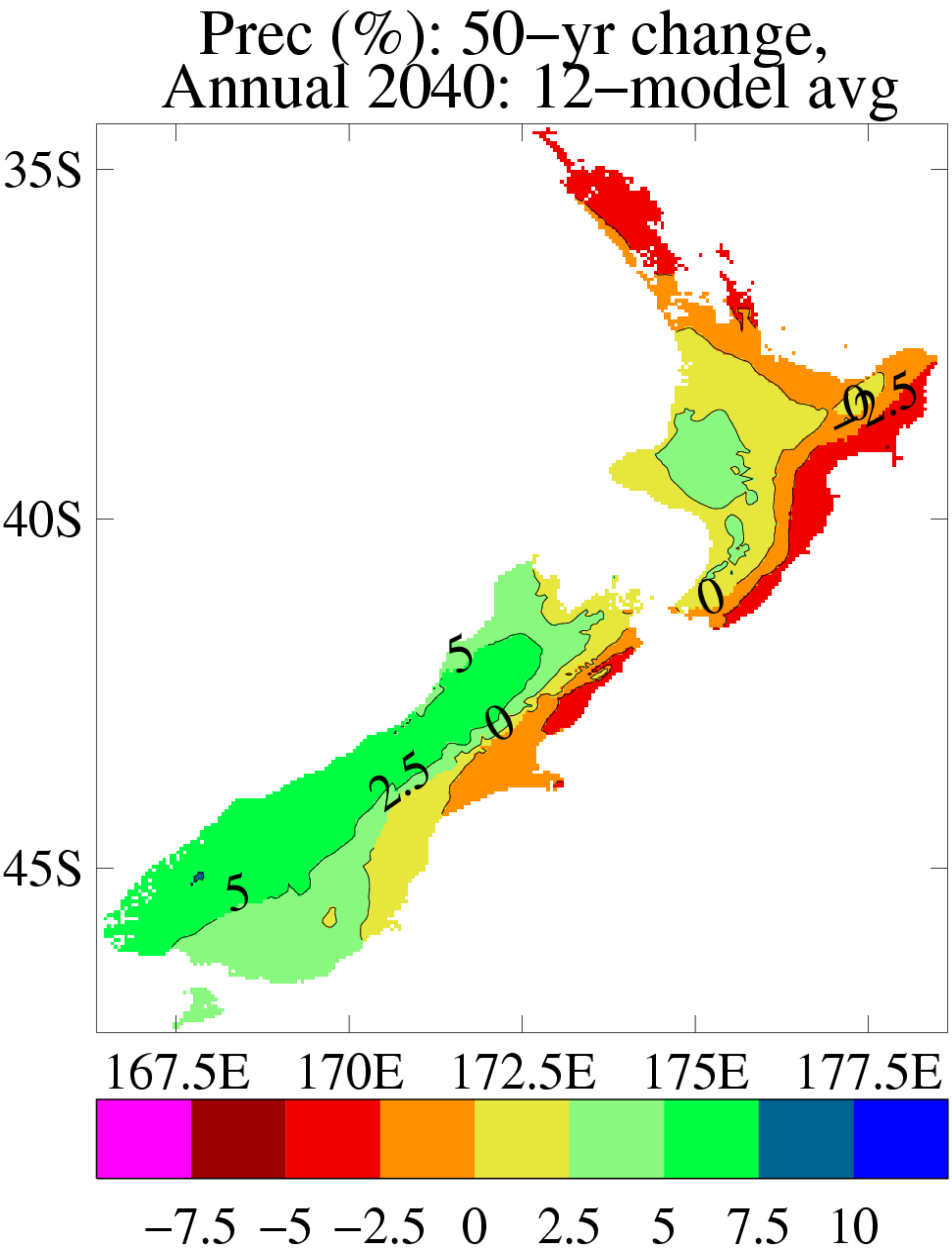


Figure 13: Fifty-year change (in %) in annual precipitation over New Zealand, from 1980-1999 to 2030-2049, as an average over 12 selected climate models.

Future climate change scenarios for Tauranga

There is a reduction of only a few percent in annual rainfall in the Tauranga area (12-model average, Figure 13). However, there are large variations between models, and also between seasons.

A single climate model based on the mid-range A1B emissions scenario was used for this sediment modelling study. Ideally, erosion predictions would be made for a number of climate models to give a range of predictions, but that approach was not taken in this study. Rather, the 'wettest' model was used to represent an extreme in the climate (while still retaining the mid-range emissions scenario). The climate for the wettest model is compared with other models in Figures 14 and 15.

Figure 14 shows the changes in annual means at 2060 for all 12 models. The annual precipitation changes at 2060 are +4.4% for the wettest model (the model called *ncar_ccsm30),* -1.7% for the 12-model average, and +0.6% for the hottest model. The hottest model has an annual temperature increase of +2.50°C (relative to 1990), whereas the annual temperature increase for the 12-model average is +1.42°C, and for the wettest model is +1.45°C.

The seasonal changes in temperature and precipitation at 2040 for the Tauranga grid-point are shown in Figure 15. From Figure 15, it is clear which is the "hottest" model (M=miroc32_hires), since this one has the fastest temperature increase for every season. However, the pattern of rainfall changes is more complex. The 'wettest' model (labelled N in Figure 15) does not have the highest precipitation in all seasons. Nevertheless, we chose it for use in sediment model as it has the largest annually averaged increase in precipitation.

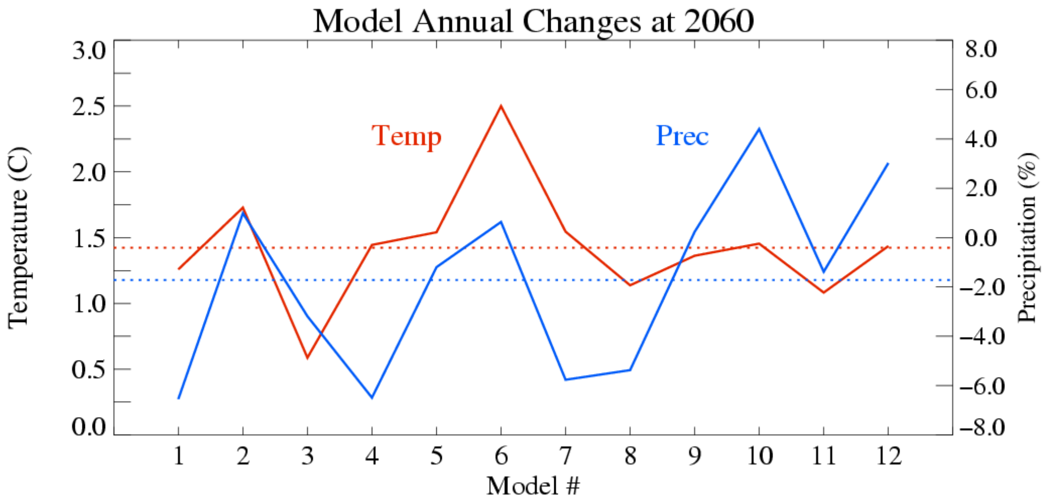


Figure 14: Annual changes at Tauranga grid-point 1990 to 2060 for 12 models: temperature in red (°C, left-hand axis), and precipitation in blue (%, right-hand axis). The horizontal dotted lines mark the 12-model averages. Model number 6 corresponds to *miroc32_hires* (the 'hottest' model), and number 10 to *ncar_ccsm30* (the 'wettest' model'.

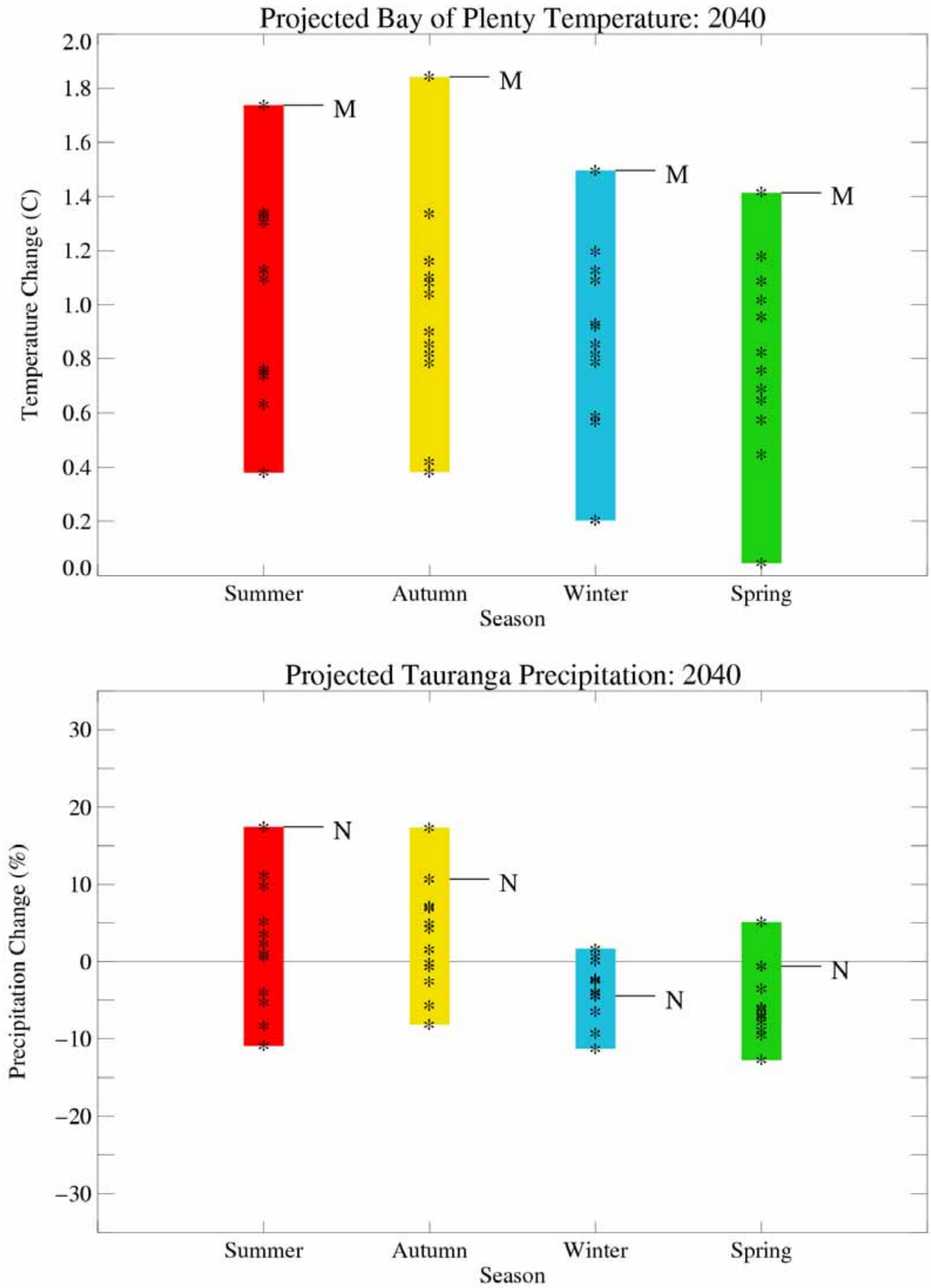


Figure 15: Projections of seasonal changes in temperature (°C, upper panel) and precipitation (%, lower panel) change at 2040, relative to 1990 increase, relative to the 1980-1999 average, downscaled for the Tauranga grid-point. Vertical coloured bars show the range across 12 climate models, with stars marking the individual model changes. The symbol M (upper panel) indicates the warming for model *miroc32_hires*, and symbol N (lower panel) the rainfall changes for model *ncar_ccsm30*.

For the Tauranga Harbour sediment study, scenarios were required at 10-year time increments out to the 50-year planning horizon: that is, at 2020, 2030, 2040 and 2050. Scenarios were developed as “time-slices”, in which a long period of historical data is adjusted to have the desired mean climate at the selected future time.

The approach is to take observed data from Tauranga airport for 1913-2007 (daily rainfalls and monthly minimum and maximum temperatures), and apply the scenarios as offsets to generate new time series at the five future dates. For rainfall, the 1913-2007 observed data is taken unchanged as representing the “current” climate at the nominal year 1990. There are significant trends in minimum temperature (although not maximum) over this period, so the observed monthly temperature data are de-trended and the mean level reset to the 1980-1999 average.

For each future period and for each of the three scenarios, the monthly mean changes in precipitation, and in maximum and minimum temperature, are applied to the Tauranga airport data. For temperature, scenarios are only needed for the new monthly means. For rainfall, daily values are required for input to the sediment calculation. The mean rainfall changes are applied to the daily data so as to leave unchanged the number of rain days and the inter-annual variability of the current climate: i.e., the rainfall offset in mm is added or subtracted, with the change partitioned proportionately across only those days recording rain.

Future changes in extreme rainfall

One of the important consequences expected in a warming climate is an increase in <u>extreme</u> rainfalls. This occurs because of higher potential moisture content in air at higher temperatures, and a shift towards more convective rainfall in the climate models. Observations have shown an increase during the 20th century in extreme rainfalls in many parts of the world (IPCC, 2007a, Figure TS-11a in Technical Summary). However, a recent analysis of New Zealand daily rainfall does *not* show a uniform trend over the country due to the interaction of atmospheric circulation and the country’s complex topography. For the period 1930-2004, western sites show an increase in daily rainfall extremes, but ‘eastern’ sites (of which Tauranga is one) show a decrease (Griffiths, 2005). Nevertheless, NIWA recommends in the guidance manual (MfE, 2008) that increasing future rainfall extremes should be assumed everywhere, until such time as more research can identify any regional differences. The implication for the current study is that extreme rainfalls may be over-estimated.

Daily rainfalls at Tauranga were adjusted according to the monthly mean scenario offsets at each future time period. A further distributional adjustment was then made to increase the daily rainfall extremes in a way that maintained the prescribed monthly mean changes. The distributional adjustment is a purely empirical one, although it is based on analysis of future rainfall changes simulated by NIWA's regional climate model.

The changes to daily rainfalls were as follows:

1) Reduce the number of "rain-days" (i.e., with a daily total at least 0.1mm) by 1.75% per 1°C increase in annual-average temperature. This corresponds typically to about 6 fewer rain-days per year for a 1°C warming.

2) Calculate the rainfall percentiles P from the daily data (all months and years combined, but after the monthly mean adjustment has been applied). The percentile values are changed according to the formula:

   Change in daily rainfall (in % per °C) =6.15$\left(1-\frac{1}{2.3}\ln\left(100-P\right)\right)$

   This formula gives zero change at percentile P=90, +8% change at P=99.5, and about -6% change at P=0. For P>99.5, the change is capped at +8% per degree Celsius of local warming (taken as the change in annual-average temperature). This 8%/°C value is widely recognised as the rate at which the water vapour saturation level increases in the atmosphere (the so-called Clausius-Clapeyron relationship), and is the upper limit recommended in the MfE (2008) guidance manual for adjusting return periods of extreme rainfall.

3) A final iteration is then required, since the redistribution of daily amounts can cause the long-term monthly totals to differ from the mean-change scenario. All rain-day amounts are adjusted by the percentage needed to ensure the new monthly mean changes are consistent with the prescribed scenario changes: for example, if the January rainfall (averaged over all years) had increased by 10.2 mm but the scenario required a 10.0 mm increase, then all rainfall amounts in January would be multiplied by 0.98.

The distributional adjustment has the effect of decreasing the number of days per year when rain falls, and pushing more precipitation into the upper tail of the rainfall distribution.

A summary of all future rainfall and temperature offsets is given in Table A4.

Application to other rainfall zones

Once the predicted future climate predictions were developed for the Tauranga zone (RR1), predictions for other rainfall zones (RR2 and RR3) were obtained by the applying temperature offsets and rainfall factors for the current climate (as discussed in Section 3.4.1).

3.5 Land use/cover

The preparation of land use / cover information for: (1) two dates in the historical period (1943 and 1959), (2) the current time (defined as 2001 for the purposes of this study), (3) the current time (2001) with 2007-2008 bare earth data used for model validation, and (4) the future period (2011 to 2051 in increments of 10 years) for use in the GLEAMS-TAU model are discussed in this section. This preparation includes a land use / cover basemap, areas and location of exposed /bare earth, a detailed breakdown of the urban zone, the location of rural and urban roads, and estimates of the impervious and pervious fractions in the urban area. The data sources for these scenarios are given in Appendix 3.

Land use / cover basemap

A land use / cover basemap for the catchment was based on the New Zealand Landcover Database 2 (LCDB2). The LCDB2 is based on Landsat 7 ETM + satellite imagery with 70 land cover classes, and provides a snap-shot of land cover in 2001/02 (see Figure 16). Data were available from Environment BOP with ground-truthing performed by Environment BOP in 2003-2004. There are 30 LCDB2 land cover classes in the area of study (see Figure 16) and these were further reclassified into 18 *generalised* GLEAMS land cover categories, including zero-sediment producing classes such as open water, lakes and ponds for use in the GLEAMS-TAU catchment model (see Figure 17).

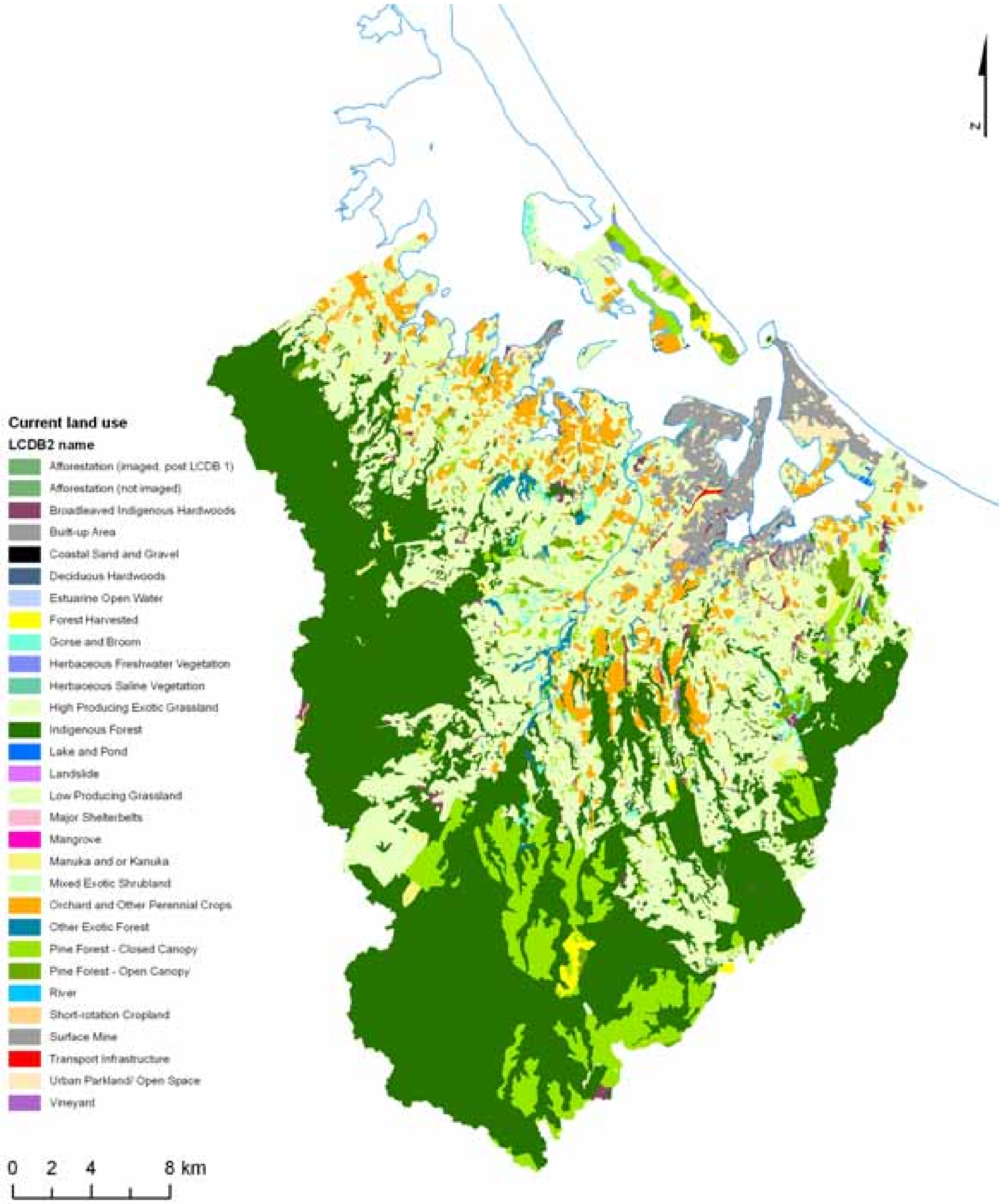


Figure 16: Land cover of the study area prepared from New Zealand's Land Cover Database (LCDB2).

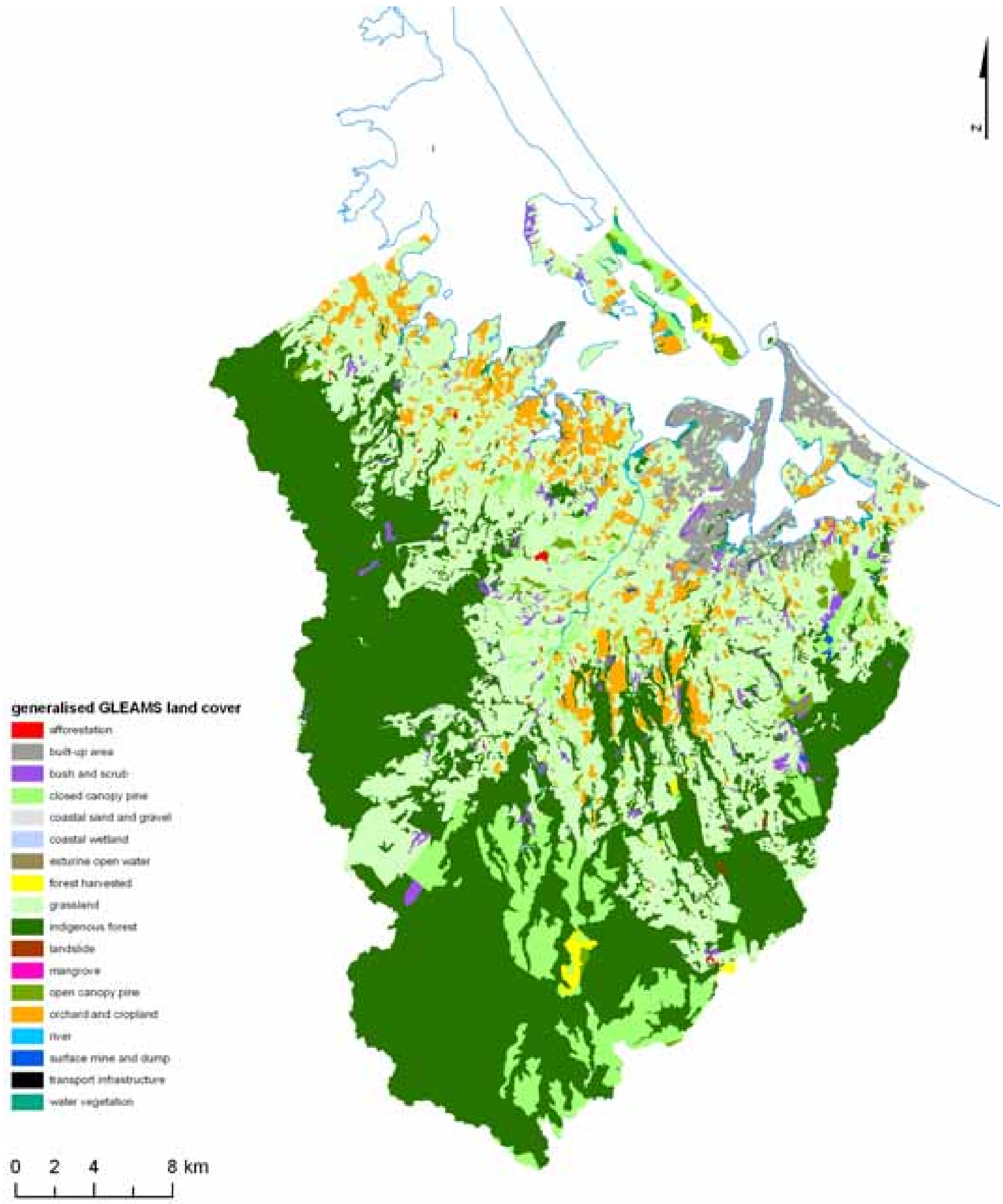


Figure 17: Map of generalised land use / cover used for the GLEAMS-TAU model.

The GLEAMS parameters for all GLEAMS-TAU generalised land use classes were established based on previous experience and on guidelines contained in the GLEAMS manuals. For example, information on orchards and cropland was taken from earlier studies and included planting and harvesting regimes, leaf area index (LAI) and ground cover distributions over the season, crop yields, dry matter yield ratios, fertiliser application and rates (by month). Runoff curve numbers used in the GLEAMS-TAU model were obtained from standard tables of curve numbers.

Exposed / bare earth

Sediment loss from exposed or bare earth can be significant and these areas need special consideration. Exposed/bare earth was treated as a separate land use in the study and digitised aerials were overlayed onto the land use / cover base map.

Figure 18 gives the aerial photograph coverage from data provided by Environment BOP for the year 2007, used to identify areas of bare / exposed earth. Figure 19 shows a worked digitization with categories of bare/exposed earth areas created for 2007. More recent 2008 aerial photographs available from GoogleEarth^{TM} were also used for clarification to assist with the digitization process.

Generally, agricultural exposed/bare earth and metal roads as obtained from aerial photographs were found to be in classified in LCDB2 as high-producing exotic grassland; earthworks (with or without pond) was classified in LCDB2 as mostly high producing exotic grassland, with some indigenous forest, and some orchard and other perennial crops; quarry with pond was classified as surface mine and closed canopy pine forest in LCDB2. All this also depended on location. Areas of earthworks are generally within or near the Tauranga City and Western Bay of Plenty urban areas and there is very little scattered outside of these areas.

GLEAMS parameters for all GLEAMS-TAU exposed / bare earth classes were taken from earlier studies. Metal roads were modelled with the same parameters as bare earth. Topsoil was removed in the model for urban earthworks areas.

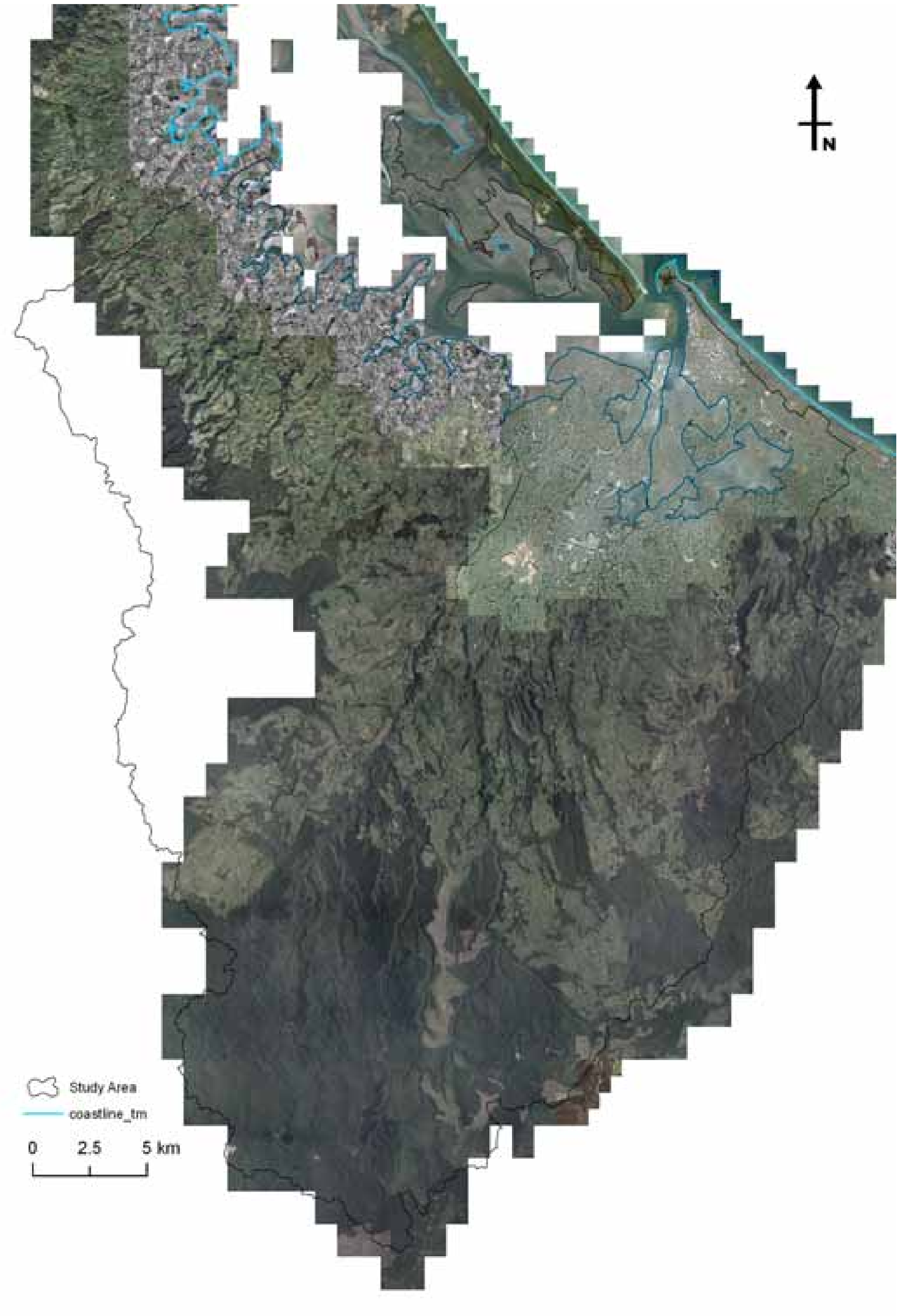


Figure 18: 2007 aerial photograph covering most of the study area.

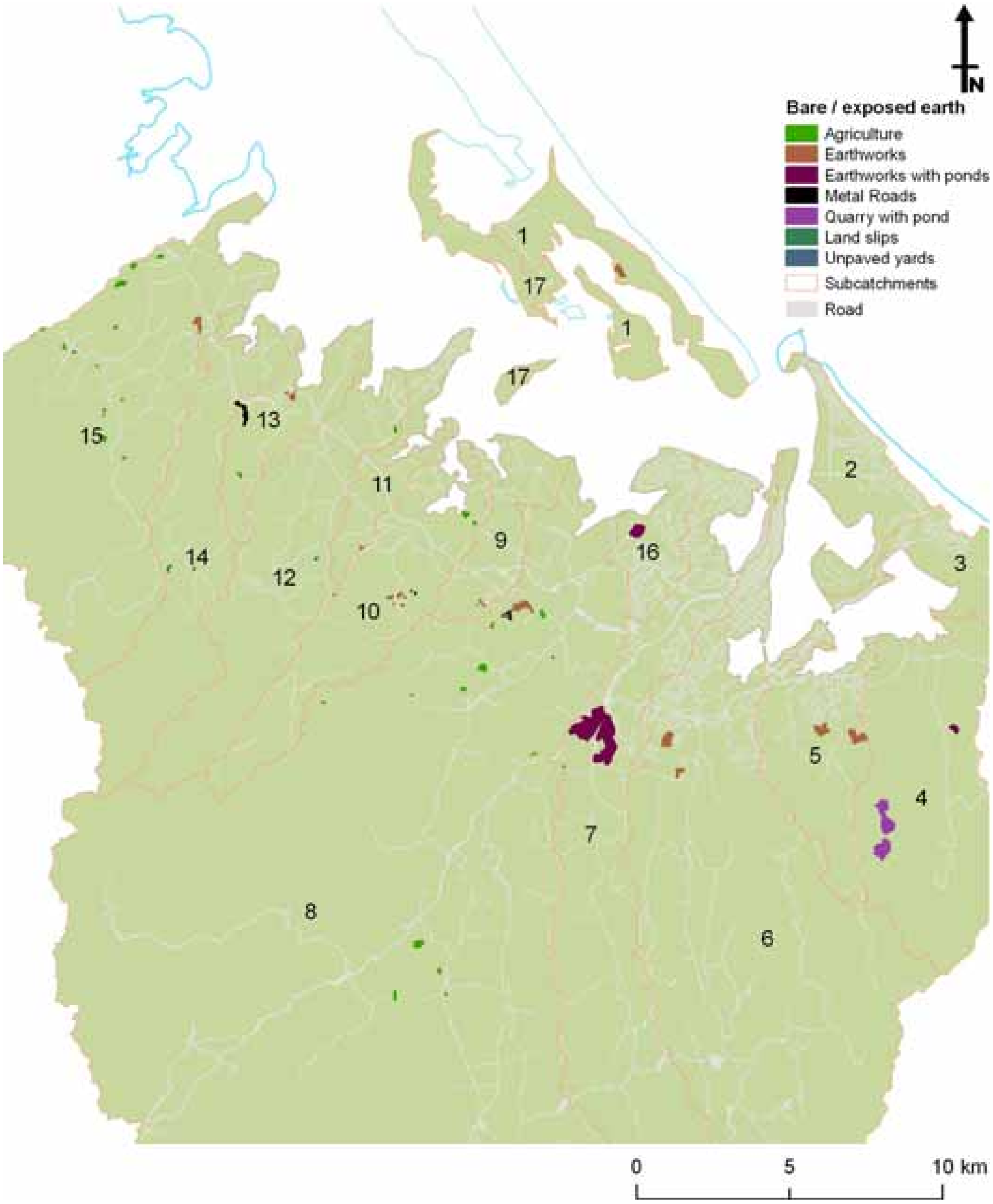


Figure 19: 2007 areas of bare/exposed earth in the study area.

Urban zones

Sediment loss from urban environments was estimated by dividing what is a single 'built-up' area class in LCDB2 into respective zones and estimating sediment from each of these urban zones.

Zoning information from 1) District Plan Zoning – Tauranga District Council and 2) District Plan Zoning – Western Bay of Plenty District Council was used to divide the LDCB2 'built-up' and neighbouring rural area within and near Tauranga city and Western Bay of Plenty, into respective zones (see Figures 20 and 21).

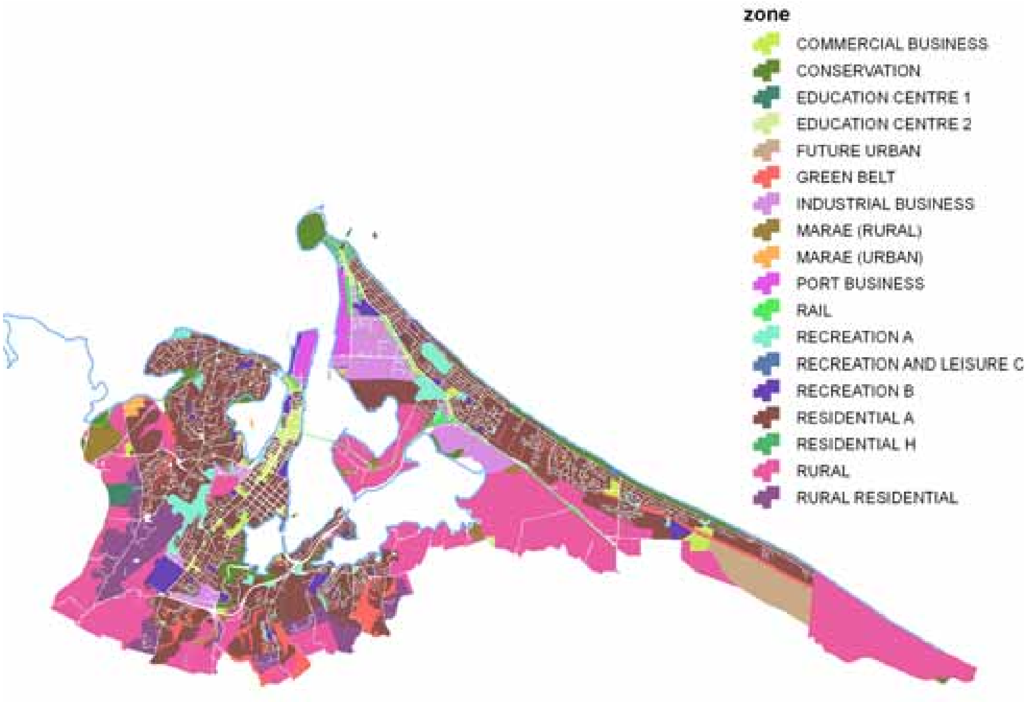


Figure 20: District Plan Zoning – Tauranga District Council.

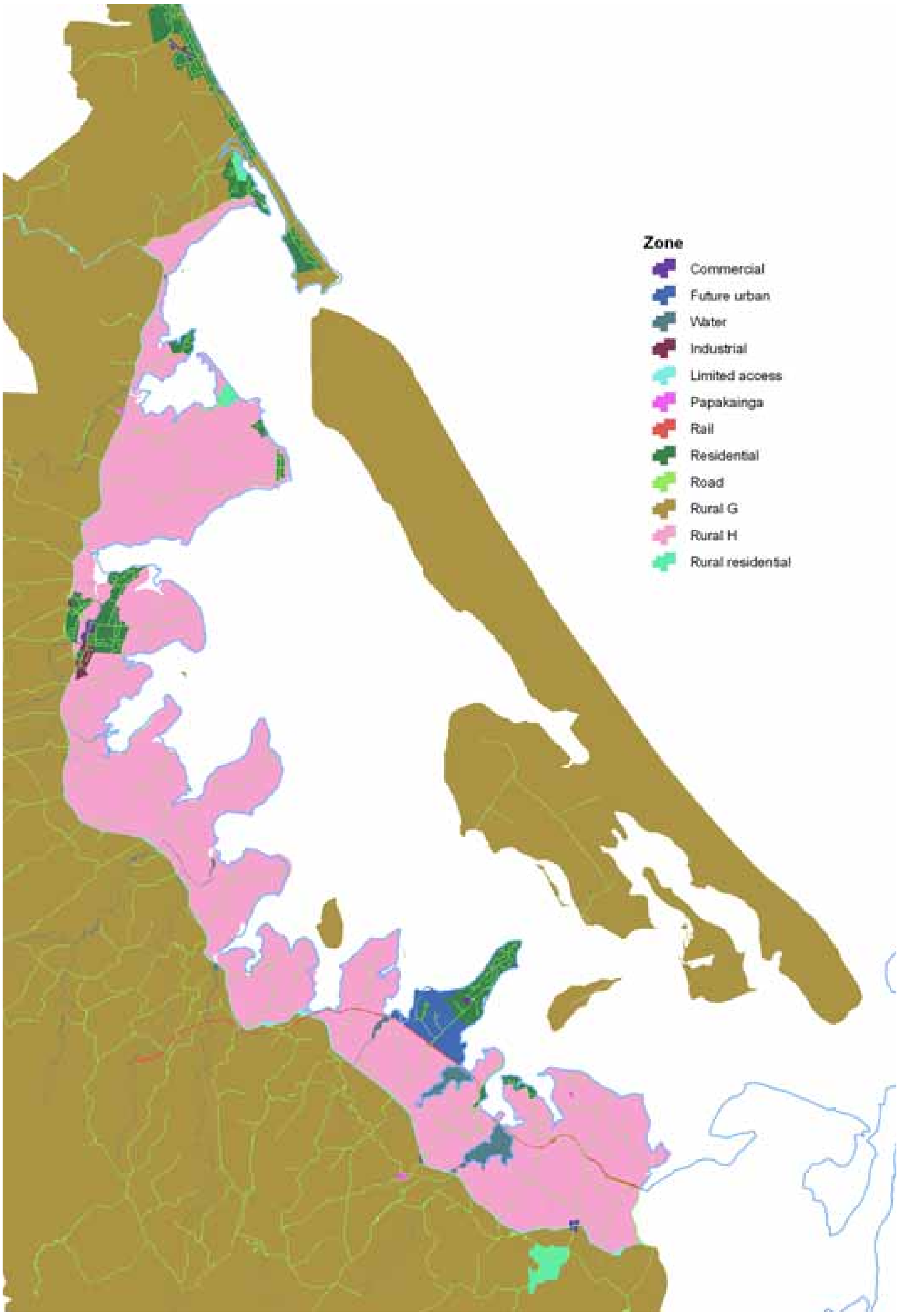


Figure 21: District Plan Zoning – Western Bay of Plenty District Council.

A breakdown of these urban zones is shown in Tables 4 and 5. Western Bay of Plenty zones are mostly rural with commercial and industrial type areas making up only 0.1% of the total area. Tauranga City is typically 40% rural or conservation, with 13 % commercial and 46 % residential areas. Further information on the original urban classes in Tables 4 and 5 is given in SmartGrowth (2007).

Table 4: Zones and areas within the Tauranga District.

Urban zoning	Area (ha)	Area (% of total urban area)
Commercial business	228	1.95
Conservation	573	4.90
Education centre 1	52	0.44
Education centre 2	7	0.06
Future urban	339	2.90
Green belt	357	3.05
Industrial business	594	5.08
Marae (rural)	148	1.26
Marae (urban)	46	0.39
Port Business	163	1.39
Rail	124	1.06
Recreation A	353	3.02
Recreation and leisure C	6	0.05
Recreation B	281	2.40
Residential A	4034	34.52
Residential H	35	0.30
Rural	3597	30.78
Rural residential	728	6.23

Table 5: Zones and areas within Western Bay of Plenty district.

Urban zoning	Area (ha)	% of total urban area
Commercial	44	0.02
Future Urban	197	0.10
hydro	824	0.42
Industrial	159	0.08
Limited access	292	0.15
Papakainga	179	0.09
Rail	191	0.10
Residential	1181	0.60
Roads	3460	1.77
Rural G	181449	92.74
Rural H	7536	3.85
Rural residential	146	0.07

The Tauranga District Council and Western Bay of Plenty District Council zones were then re-classified into a smaller set of classes used for modelling, according to Tables 6 and 7. The urban zones were then overlaid on the LCDB land cover. Examination of aerial photographs was often necessary in the reclassification process, particularly for the Western BOP urban area with less detailed zoning information. Railway land and tracks were reclassified into a separate ‘other’ urban class, a class which also included small LCDB2 ‘built-up’ areas, not included in a particular zone, and rural residential land. Roads for Tauranga City were obtained from the road cadastral map. The GIS road layer for the Western Bay of Plenty urban areas was included in the District Plan Zoning information and was identical to the road cadastral map. A further use of road cadastral information including a breakdown of roads according to vehicle density is presented in a later section.

Table 6: TCC zones and their reclassification.

Zoning	LCDB2 classes or new urban classes
Commercial business	Commercial business
Conservation	LCDB2
Education centre 1	LCDB2
Education centre 2	LCDB2
Future urban	LCDB2
Green belt	LCDB2
Industrial business	Industrial business
Marae (rural)	LCDB2
Marae (urban)	Residential
Port Business	Industrial business
Rail	Other urban
Recreation A	Open spaces/parkland
Recreation and leisure C	Open spaces/parkland
Recreation B	Open spaces/parkland
Residential A	Residential
Residential H	Residential
Rural	LCDB2
Rural residential	LCDB2

Table 7: Western Bay of Plenty zones and their reclassification.

Zoning	LCDB2 classes or new urban classes
Commercial	Commercial business
Future Urban	LDCB2
Industrial	Industrial business
Limited access	LCDB2
Papakainga	LDCB2
Rail	Other urban
Residential	Residential
Roads	Roads
Rural G	LDCB2
Rural H	LDCB2
Rural residential	LDCB2

Rural and urban roads

Sediment loss from roads is estimated by first identifying roads in the catchment, classifying these roads into respective classes based on roading density, and estimating sediment loss based on the respective roading class.

A road GIS layer was created by merging the transport infrastructure layer given in LCDB2 (see Figure 22), which primarily represents motorways and state highways, with the very detailed road cadastral (polygon) maps provided by Tauranga City Council for Tauranga City and Western BOP. Some roads that were classified as 'both' were reclassified into either rural or urban if it was clearly observed to be one or the other from aerial photographs. The roads were reclassified into four road classes: rural roads, urban roads, semi-urban roads and major strategic/arterial roads.

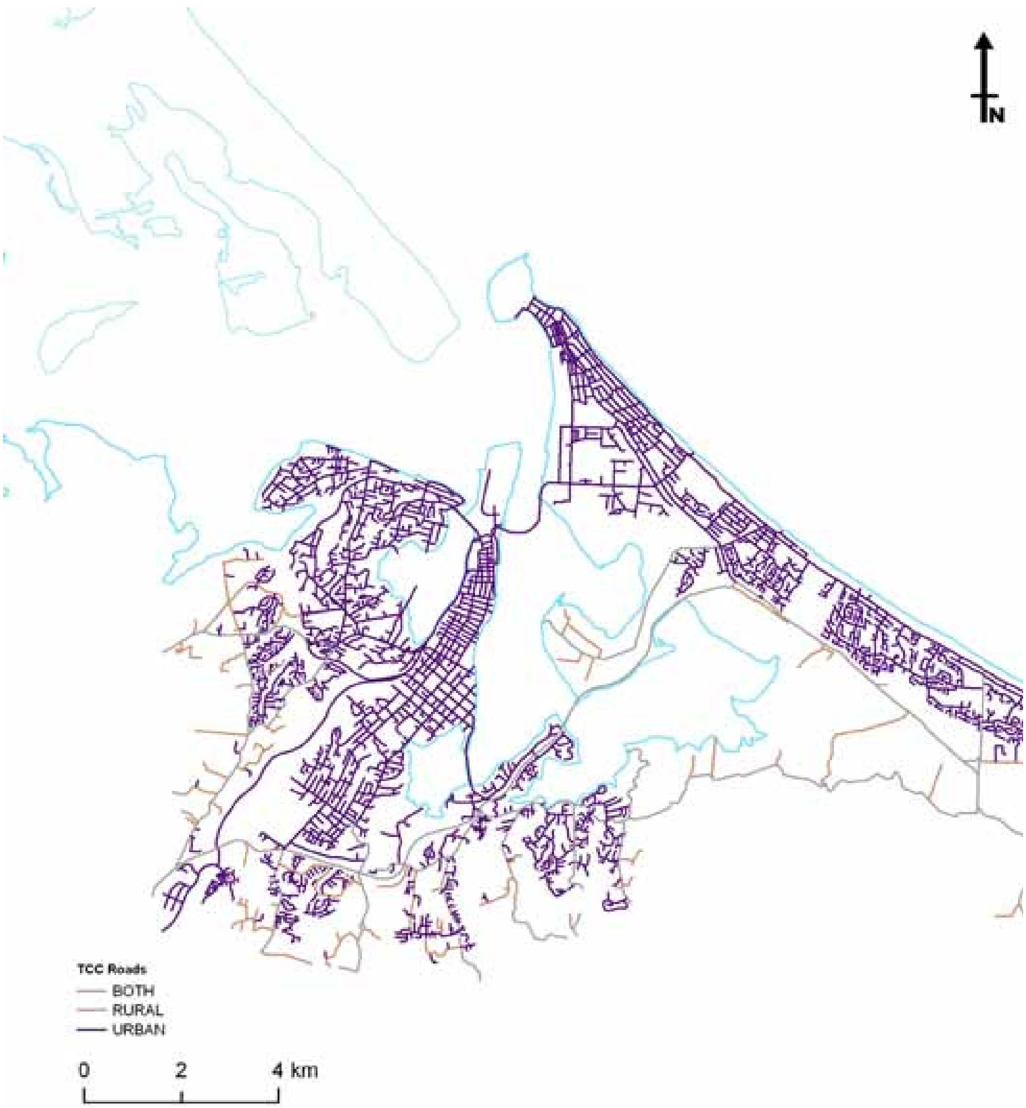


Figure 22: Road cadastral maps for Tauranga City.

Impervious and pervious fractions

Sediment loss from the impervious and pervious fractions of the urban area was estimated by dividing the residential, commercial and industrial areas of the urban area into respective pervious and impervious fractions based on default values and estimating sediment loss from each fraction.

A breakdown of the various urban land use classes into pervious, and impervious fractions, was derived using 2001 defaults used for Auckland City (Timperley and Reed, 2008) and given in Table 8. From examination of aerial photos, the breakdown was seen to be appropriate for Tauranga. The pervious urban fractions include urban open spaces, parks, residential lawns and the like, whereas the impervious fractions generally include roofs, roads and paved surfaces. Note that the percentage of impervious surfaces is practically the same in the commercial and industrial areas, i.e., 89% versus 88%, and hence a common new *business impervious* class was created. Likewise, a new *residential impervious* class was created. Note that buildings generally occupy a smaller fraction of residential areas compared to industrial and commercial areas.

Table 8: Breakdown of surface fractions into pervious and impervious fractions.

	Residential	Commercial	Industrial
Roofs	0.19	0.29	0.29
Roads	0.16	0.27	0.26
Paved	0.11	0.33	0.33
Pervious	0.54	0.11	0.12

The estimate of the surface fraction of roads given in Table 8, assumes that the road is all impervious (Moores, pers comm.) and does not include the pervious strips along the sides of the road. The cadastral maps, however, do include these strips of land.

A fraction of the road width was estimated to determine the impervious area of road, thus reducing the road area (and thus increasing the pervious area). The fractions of road width that were impervious were modified by visual inspection from recent aerial photographs. Areas of roads in residential, commercial and industrial areas, being ‘over-estimated’ in the cadastral maps were thus considered to be only 50%, 100%, and 100% impervious, respectively. Likewise, areas of motorways, rural roads and urban roads were considered to be only 50%, 30% and 80% impervious, respectively.

The road widths were also somewhat related to vehicle density in the respective zones (see Table 9). A breakdown of road area into fractions using Auckland City defaults according to the number of vehicles per day (vpd) (See Table 9) was used for guidance as this information was not readily obtainable from TCC.

Table 9: Breakdown of road fractions (2001 Auckland defaults).

	Residential	Commercial	Industrial
Roads < 1000 vpd	0.21	0.10	0.10
Roads 1000-5000 vpd	0.45	0.30	0.26
Roads 5000-20000 vpd	0.22	0.50	0.50
Roads 20000-50000 vpd	0.12	0.10	0.12

3.5.1 Current land use / land cover scenarios

A current (2007-2008) land use and land cover scenario (Figure 23) was created by overlaying the final road map, the urban land use maps, and then the 2007 bare/exposed earth map (Figure 19) onto the LCDB-based map of generalised GLEAMS-TAU land cover (Figure 17). This current land use and land cover scenario with current earthworks areas was considered representative of the 2007-2008 period and was used for model validation where predictions were compared with measurements.

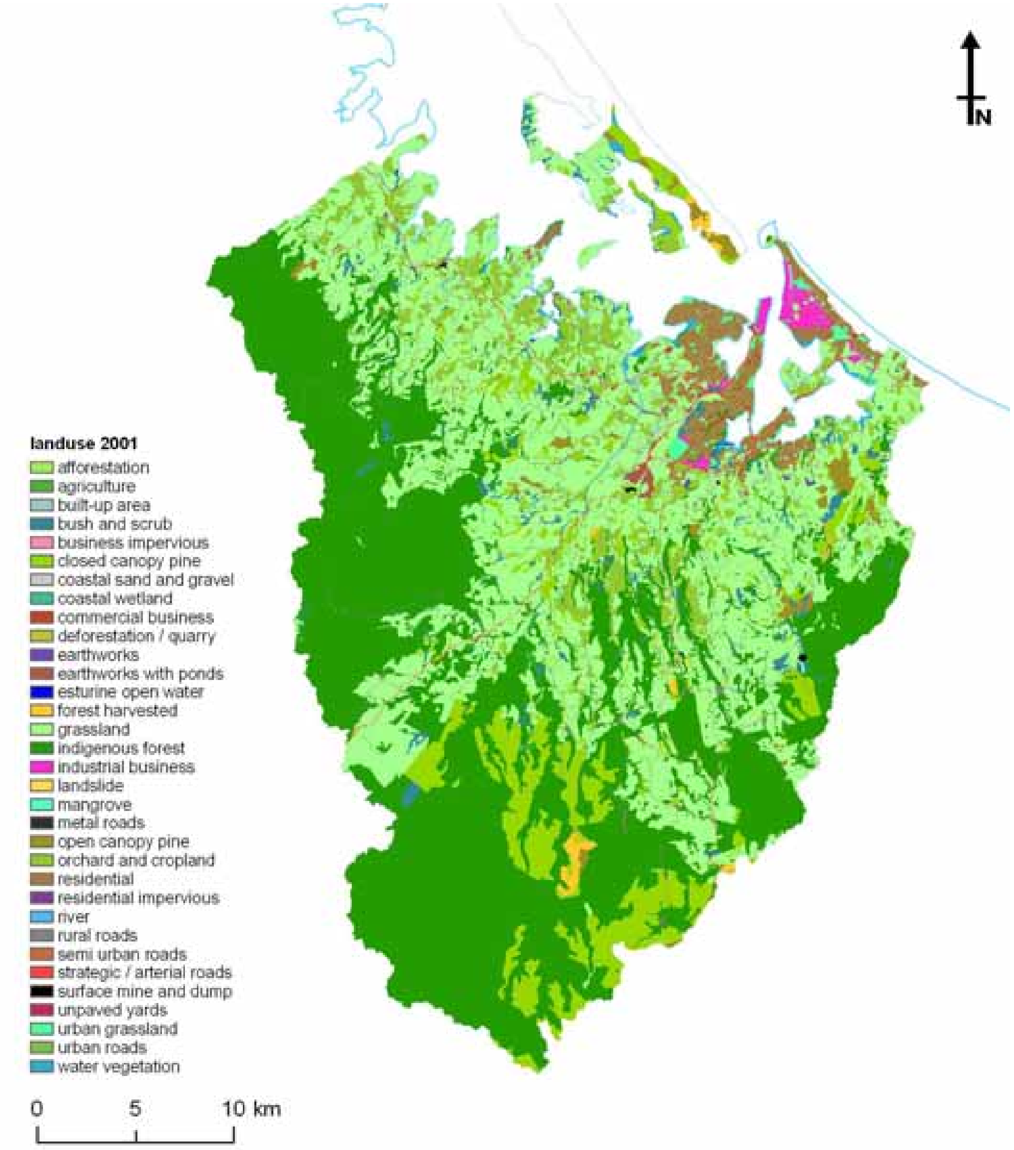


Figure 23: Map of current (2007-2008) land use/cover scenario used for GLEAMS-TAU model validation.

3.5.2 Historical land use / land cover scenarios

Aerial photographs for 1943 covering only the 'inhabited' areas (see Figure 24), and 1959 land use layers with broad categories, including areas of bare ground (see Figure 25), were obtained from Environment Bay of Plenty.

The 1943 aerial photographs available, which represent only urban areas, were digitized and classified into residential, commercial, industrial, rural and open spaces/ parks (see Figure 24).

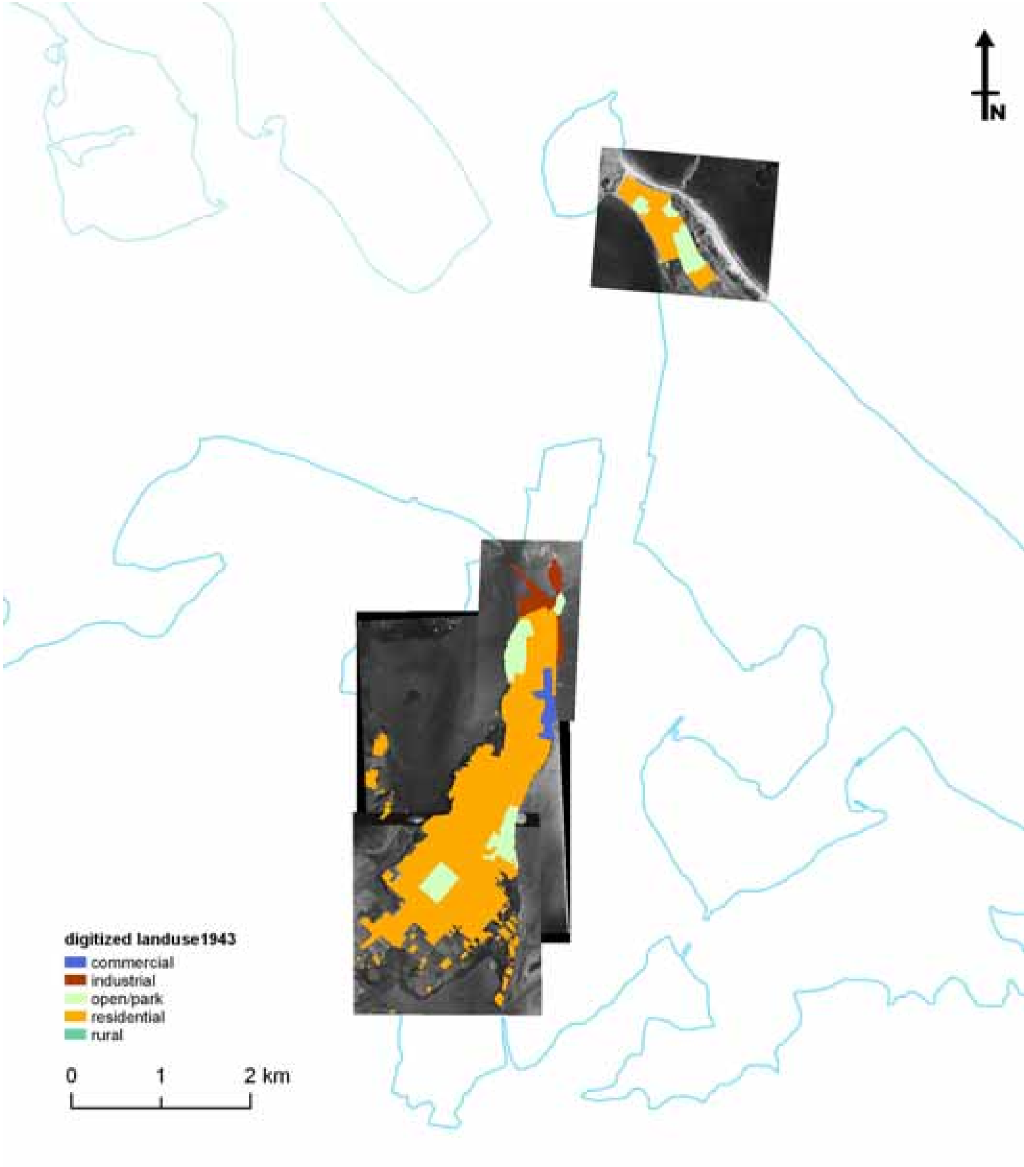


Figure 24: Digitization of the available 1943 aerial photographs.

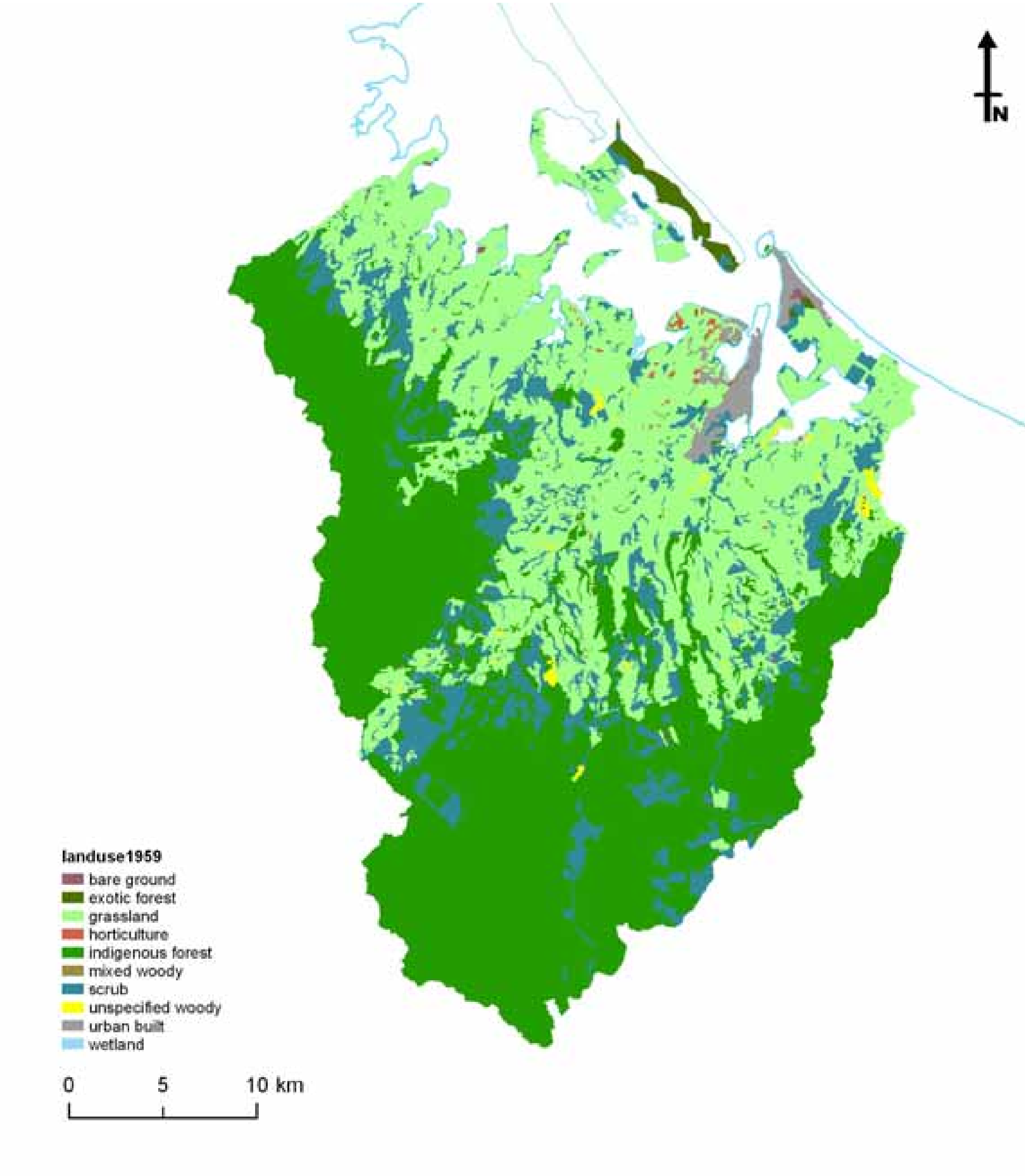


Figure 25: Map of 1959 landuse use / land cover.

The 1959 landuse layer provided by Environment BOP used to create a 1959 scenario was reclassified into generalised GLEAMS-TAU land use classes according to Table 10:

Table 10: Reclassification of 1959 land use classes.

Landuse class	Generalised Gleams land use class
Urban built	Built-up
scrub	Bush and scrub
Unspecified woody	Bush and scrub
Mixed woody	Bush and scrub
Grassland	Grassland
Indigenous forest	Indigenous forest
Exotic forest	Closed canopy pine
Wetland	Water vegetation
Horticulture	Orchard and cropland
Bare ground	Earthworks or agricultural bare ground

Bare ground was classified as earthworks (without treatment pond), or agricultural bare ground according to location. A final map of the final 1959 reclassified land use / cover into generalised GLEAMS classes is shown in Figure 26.

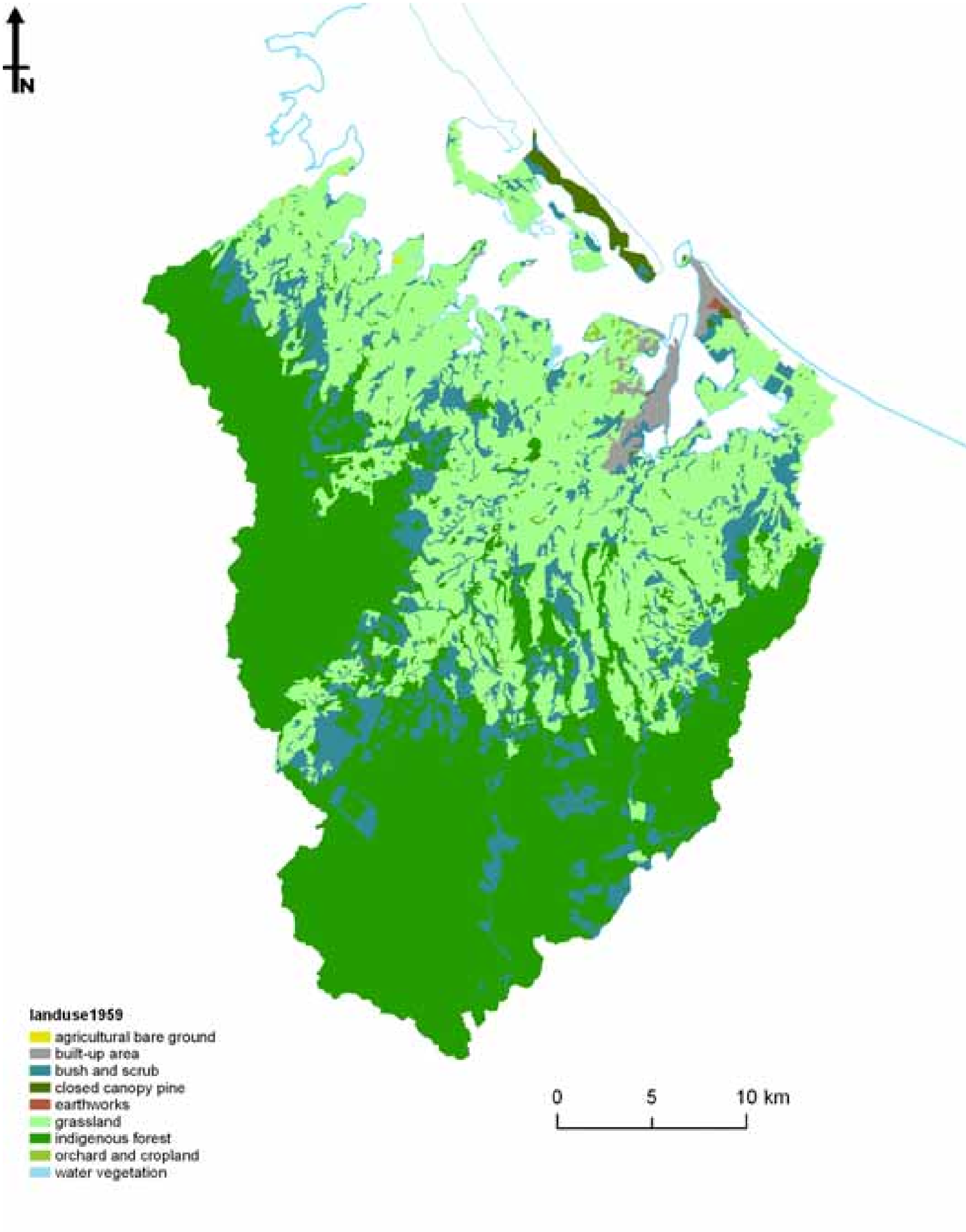


Figure 26: 1959 reclassified land use/cover into generalised GLEAMS classes.

General differences between the 1959 digitisation and LCDB2 land use classes are observed from land use difference maps but these differences could also have to do with digitisation and reclassification error. Generally, indigenous forest areas have diminished between 1959 and 2001, and have been replaced by grassland. Built-up areas have replaced areas of grassland. Grassland and closed canopy pine have replaced scrub. Grassland has replaced some horticulture, and closed canopy pine. Some grassland has been replaced by orchard and cropland. In the original 1959 land use layer with broad categories, unspecified woody areas are classified as indigenous forest and exotic forest areas as closed canopy pine in LCDB2.

The 1943 land use cover scenario was created by superimposing 1943 urban digitised areas onto the 1959 land cover layers. The urban built-up area in 1959 that was not built-up in 1943 was classified in the 1943 land use/cover as grassland (the final figure is not shown). No earthworks was estimated for 1943.

The 1943 aerial photographs were examined to determine pervious to impervious proportions in urban areas. There was a greater proportion of pervious to impervious areas in 1943 than currently, but the photos were not of sufficiently high clarity to determine exact proportions. For expediency, and since small areas are involved, the residential, commercial, industrial and open spaces/parks were combined into a single ‘built-up’ area, and assigned a special-case land use with a weighted-average sediment load value.

3.5.3 Future land use /cover scenarios

Future urban growth

The Western Bay of Plenty sub-region 50-year strategy and implementation plan on future urban growth is presented in Section 7 of SmartGrowth (2007) and provides projected future urban boundaries for the years 2021 and 2051.

For this study, we have used a version of the boundaries as amended on 21 March 2008, as provided by Environment BOP. It was assumed that there will be no rural residential growth outside of the amended *sub-regional* urban limit during the future time period. This assumption also follows from an agreement with Environment BOP that rural residential was not going to be modelled in this exercise. This rural residential growth does not exclude rural residential development within the sub-regional urban limits gradually over time. Future land cover outside of the amended sub-regional urban limits given in SmartGrowth (2007) is assumed to be the same as at 2001.

For the purposes of the GLEAMS modelling and in order to achieve a smooth progression of land cover and change in sediment runoff we mapped the land cover (and defined the weather – previous section) in 10-year intervals using buffer techniques within GIS. This extended the urban area into available land for urbanising excluding reserves, parks, and the like.

Urban boundaries in the year 2011 were derived by interpolation between the current boundary (built-up areas and urban open space from LCDB2) and the SmartGrowth (2007) boundary for 2021. Urban boundaries in the years 2031 and 2041 were derived by interpolation between the SmartGrowth (2007) urban boundaries for 2021 and 2051. This interpolation was done such that the increase in areas between time intervals was consistent with projected additional population in 5-year intervals as tabulated in Figure 7 of SmartGrowth (2007) and summarised in Maps 1 & 2: Western Bay of Plenty Sub-Region Settlement Plan of SmartGrowth (2007). The resulting urban boundaries in decadal intervals are shown in Figure 27. They are consistent with urban boundaries previously agreed to Environment BOP (Parshotam et al. 2008). These boundaries identify the greenfields areas available for urban growth by decade and are confined within the subregional urban limits from the sub-regional settlement pattern, shown in Map 2 of SmartGrowth (2007).

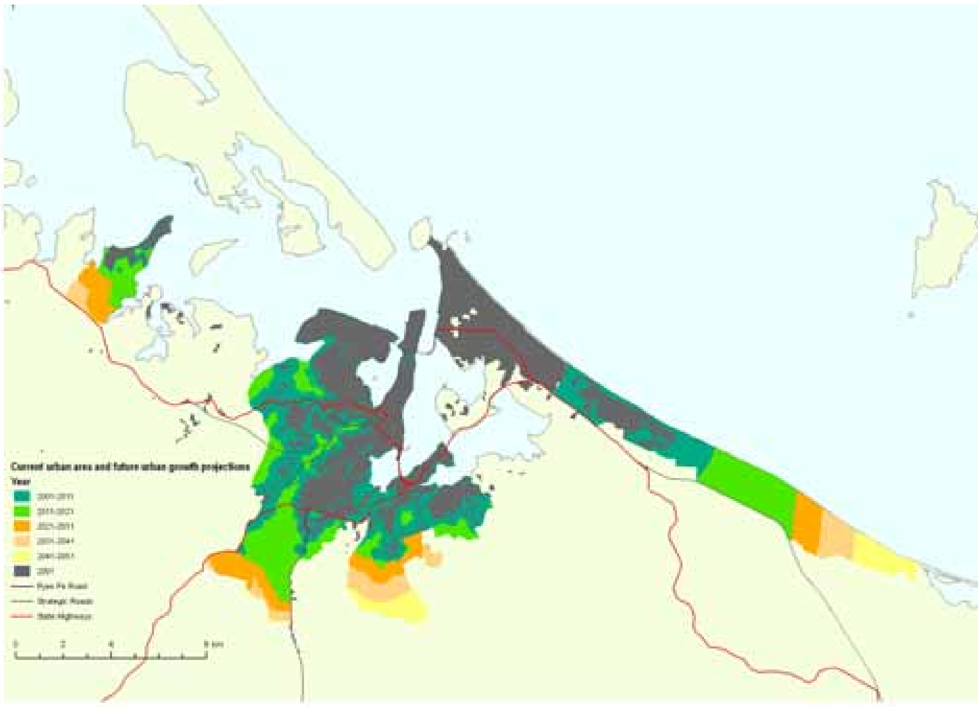


Figure 27: Map of current urban area and future urban growth projections (source: Parshotam et al. 2008).

The urban growth (greenfields) areas have been assigned to the following growth-area suburbs: Papamoa, Tauranga Central, Tauranga South, Tauranga West and Omokoroa. Table 11 summarises these areas from Figure 27: Residential Development Timing Diagram of SmartGrowth (2007) and also given in Maps 1 & 2: Western Bay of Plenty Sub-Region Settlement Plan of SmartGrowth (2007).

Table 11: Pre- and post-2021 urban growth (greenfield) areas

	pre-2021	post-2021
Papamoa	1274	770
Tauranga Central	1203	186
Tauranga South	904	755
Tauranga West	1262	196
Omokoroa	263	307

Changes in areas of urban growth (greenfields) (in ha) are derived in 5-year intervals from proportions of 1) 5-year population changes given in Figure 7: Residential Development Timing Diagram of SmartGrowth (2007) and, 2) total population changes during years 2001 - 2021 and 2021 - 2051 (see Table 12). The area changes are given in Table 13. The population changes for 2001-2006 are derived from 2001 and 2006 census data, also from Figure 7: Residential Development Timing Diagram of SmartGrowth (2007). These changes, from Table 13 are grouped into 10-year intervals (see Table 14). Note that only part of the established Papamoa increase is in the catchment study area. This area is clipped within GIS once the catchment study area was established. This ensured that all estimates of land use areas and their changes, were only from within the study area.

Table 12: Population changes in 5-year intervals (from Figure 7 of Smartgrowth (2007)).

	2001-2006	2006-2010	2010-2016	2016-2021	2021-2026	2026-2031	2031-2036	2036-2041	2041-2046	2046-2051
Papamoa	4500	3595	4794	4798	3817	4032	3905	3907	4320	4581
Tauranga Central	1140	3368	2713	2211	1713	863	974	796	121	0
Tauranga South	1984	848	340	405	1574	2087	2355	2025	1925	1926
Tauranga West	1593	1691	1098	663	390	62	37	0	0	0
Omokoroa	208	592	1000	2250	2350	2000	1600	0	0	0

Table 13: Greenfields area changes (in ha), available for urbanising derived from 5-year population changes in respective regions.

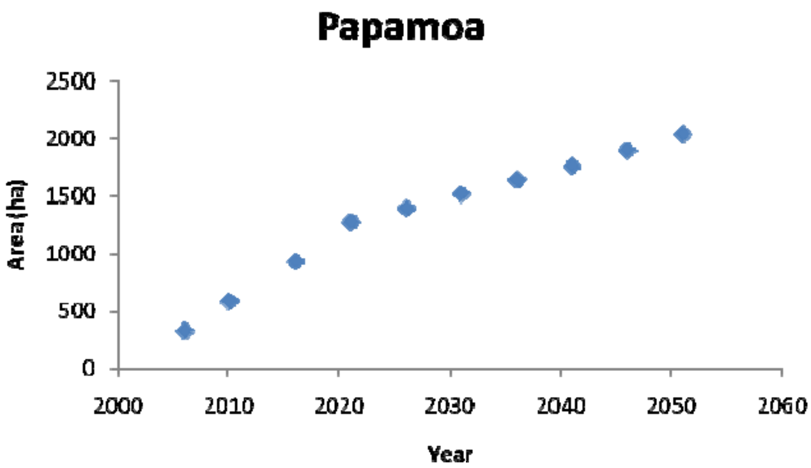
	2001-2006	2006-2010	2010-2016	2016-2021	2021-2026	2026-2031	2031-2036	2036-2041	2041-2046	2046-2051
Papamoa	324	259	345	346	120	126	122	122	135	144
Tauranga Central	145	430	346	282	71	36	40	33	5	0
Tauranga South	502	214	86	102	100	133	150	129	122	122
Tauranga West	398	423	275	166	156	25	15	0	0	0
Omokoroa	14	38	65	146	121	103	83	0	0	0

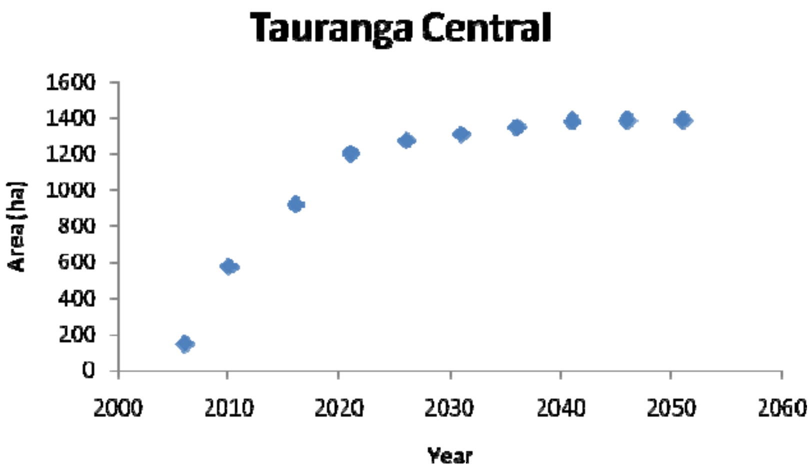
Table 14: Greenfields area changes (in ha) available for urbanising given in 10 year intervals.

	2001-2010	2011-2020	2021-2030	2031-2040	2041-2050
Papamoa	583	691	246	245	279
Tauranga Central	575	628	107	74	5
Tauranga South	716	188	232	278	245
Tauranga West	821	440	181	15	0
Omokoroa	52	211	224	83	0

Cumulative changes in areas urbanised

The cumulative areas of greenfields that have become urbanised were calculated from Table 13 and are given in Figure 28. These also show times of rapid growth and slowing down.





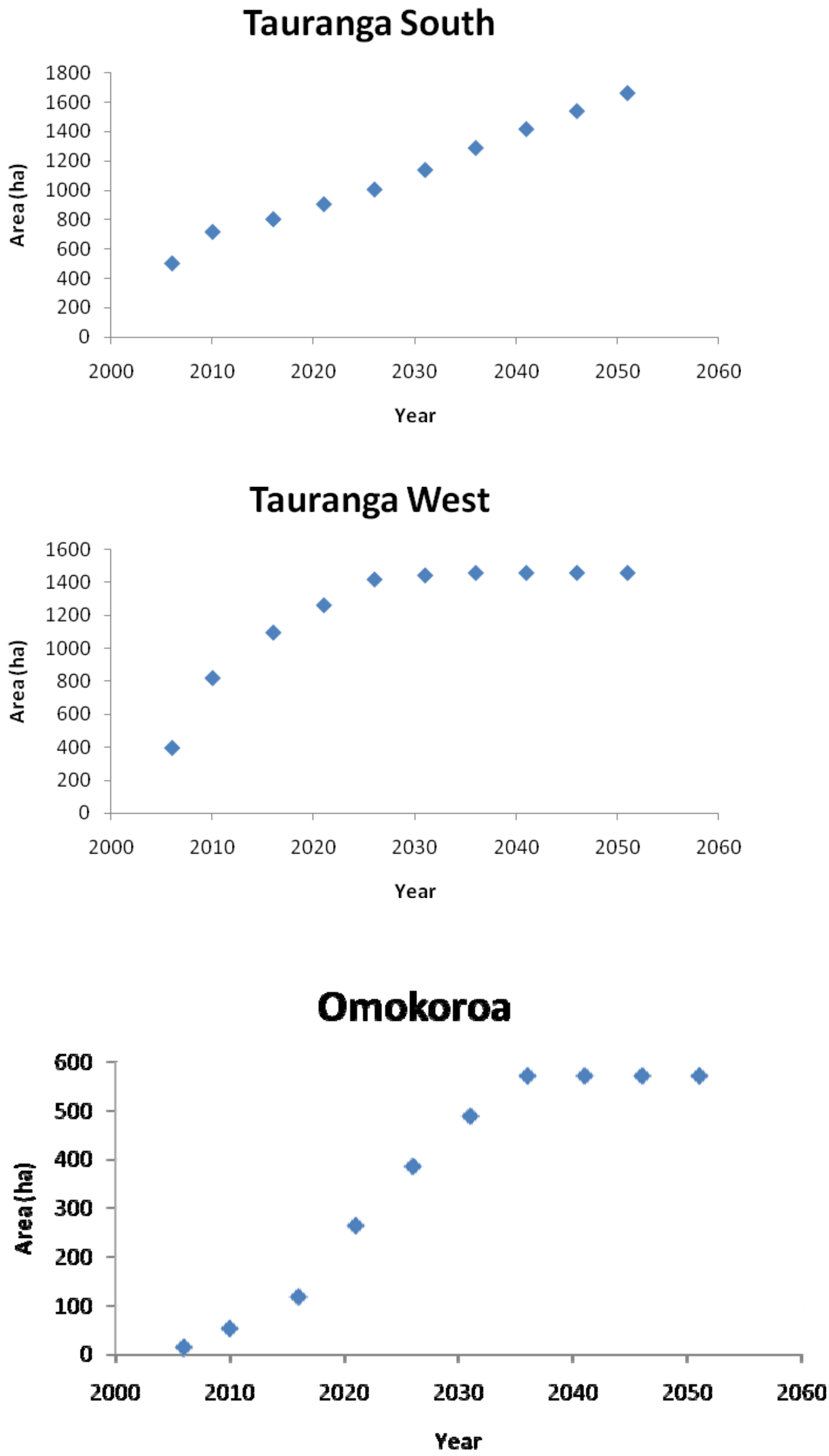


Figure 28: Cumulative changes in greenfields area (in ha) urbanised over time in respective regions.

Business land changes

Business land changes by 2021 and 2051 were taken from the business land staging plan given in Section 7.2.4 of SmartGrowth (2007), and summarised in Table 15 from Section 7.2.4 of SmartGrowth (2007). Note that these are only provided as areas, and not as GIS shape files.

Table 15: Business land staging plan from Section 7.2.4 of SmartGrowth (2007).

	Growth Management Area Location	Land available for development start date	Additional Zoned capacity (ha usable) by 2021	Additional Zoned capacity (ha usable) by 2051
Katikati	Katikati	2005	40 ha	
Omokoroa	Omokoroa (South of railway)	2007	40 ha	
Te Puna	Te Puna Station Rd	2008	30 ha	
Tauranga West	Tauriko	2008	150 ha	
Tauranga Central	Pyes Pa	2006	15 ha	
Papamoa	Papamoa East – Wairakei (Stage 1)	2008	120 ha	
Papamoa	Papamoa East – Te Tumu (Stage 2)	2021		100 ha
Te Puke	Te Puke	2008	50 ha	
Paengaroa	Rangiuru	2007	150 ha	100 ha
	(subject to Eastern arterial timing)			
Subregional	To be determined (refer 7.2.4 Action 4)			

These business areas were distributed over time according to population changes given in Figure 7 of SmartGrowth (2007). The resulting areas of new business, broken down by area and time period, are given in Table 16.

Table 16: Area of new business land (ha) from the business land staging plan.

	2001-2010	2011-2020	2021-2030	2031-2040	2041-2050
Papamoa	55	65	32	32	36
Tauranga Central	7	8	0	0	0
Tauranga South	0	0	0	0	0
Tauranga West	98	52	0	0	0
Omokoroa	8	32	0	0	0

Residential land changes

The new residential area (including open spaces) changes were obtained by removing business area changes from the total urban area. The resulting areas are shown in Table 17.

Table 17: Area of new residential land (ha).

	2001-2010	2011-2020	2021-2030	2031-2040	2041-2050
Papamoa	528	626	214	213	243
Tauranga Central	568	620	107	74	5
Tauranga South	716	188	232	278	245
Tauranga West	724	388	181	15	0
Omokoroa	44	179	224	83	0

Roads, residential and business impervious areas

The future areas of business and residential development described above are mostly on greenfields areas and there are no detailed plans showing the locations of new roads. This poses a problem in estimating the pervious and impervious fractions in new-development areas.

The breakdown of the future urban area into impervious and pervious fractions (where there are no detailed plans showing the locations of new roads) differs from the breakdown of the current area into impervious and pervious fractions (where roading information was available). Roading information when available was taken from the road cadastral layer but two new special land use classes were created for all *future* urban growth projection scenarios based on the current urban impervious and pervious fractions and Table 8: 1) total *residential impervious*, including roads, and 2) total *business impervious*, including roads.

The proportions of total impervious surfaces (roofs, roads, and paved surfaces) and total pervious surfaces for built-up areas (including urban open spaces, parks, residential lawns and the like) (Table 8), were assumed to apply to all built-up areas in the catchment. These proportions were assumed to remain unchanged for all future scenarios. The future residential pervious fraction and the future business pervious fraction is, for example 54% and 11% of the total available urban area, respectively.

The future impervious area is derived by summing the future residential and future business impervious areas. The fraction of future urban area that is 1) residential impervious, including roads and 2) business impervious, including roads, is given in Tables 18 and 19, derived from Tables 8, 9, 16 and 17. In Tauranga Central in years 2031-2040, for example, 46% of the urban area is residential impervious with the remaining 54% being urban open spaces and lawns, excluding reserves, conservation land, and the like.

Table 18: Fraction of future urban area that is *residential impervious*, including roads.

	2001-2010	2011-2020	2021-2030	2031-2040	2041-2050
Papamoa	0.417	0.417	0.400	0.400	0.400
Tauranga Central	0.454	0.454	0.46	0.46	0.46
Tauranga South	0.46	0.46	0.46	0.46	0.46
Tauranga West	0.405	0.405	0.46	0.46	-
Omokoroa	0.390	0.390	0.46	0.46	-

Table 19: Fraction of future urban area that is *business impervious*, (including roads)

	2001-2010	2011-2020	2021-2030	2031-2040	2041-2050
Papamoa	0.084	0.084	0.116	0.116	0.116
Tauranga Central	0.011	0.011	0	0	0
Tauranga South	0	0	0	0	0
Tauranga West	0.106	0.106	0	0	-
Omokoroa	0.135	0.135	0	0	-

The business impervious areas (including roads), the residential impervious areas (including roads), and the pervious areas are distributed randomly for the future according to fractions of the *future* urban area, given in Tables 18 and 19.

Future land use/cover

A 2001 land cover scenario used as a base map for creating all future land use scenarios was created by overlaying the 2007 bare/exposed earth map (Figure 19) with urban earthworks removed, and the detailed urban breakdown map, onto the map of generalised GLEAMS-TAU land use / covers given in Figure 17. The location of urban earthworks in the 2001-2010 was obtained from changes in the urban area in that period, rather than the actual earthworks in 2007. This was to ensure that the rate of urbanisation and associated earthworks represents a decadal average rather than a rate associated with a particular snapshot in time.

The total impervious and total pervious areas were distributed randomly in the respective residential and business urban areas using within ArcGIS, according to the fractions derived from Tables 18 and 19 (above). All land zoned marae, recreation, green belt, and conservation areas was removed from future urban development, and land available for urban development based on future zoning information was identified. Existing roads were also considered in the final calculation.

Final urban land use maps were created in 10-year increments for the period 2001 to 2051, (Figures 29-34) from the 2001 base map. The 2001 map (Figure 29) covers the period from 2001 to 2010, the 2011 map covers the period from 2011 to 2020, and so on. The earthworks area for given year was taken as 10% of the value for the decadal period, and the locations were distributed randomly over the new area of urbanisation for the decade. For example, the 2031-2040 land use assumes urbanisation to 2031 but earthworks in the 2031-2041 zone with an area equivalent to 10% of the area of the 2031-2041 zone. The 2011 urban area was 'forced' to include current (2008) areas of development. Note that area and location of earthworks in 2051 is not estimated within GIS since there is no information on the land-use between 2051 and 2061.

The land use in the rural area outside of the *sub-regional* urban limit was assumed to be identical for all future years. In the case of forest harvesting, the location of harvesting was assumed to be the same as at present, as we did not have information on future harvesting areas. It is assumed that this harvesting area represents a long-term average harvesting rate.

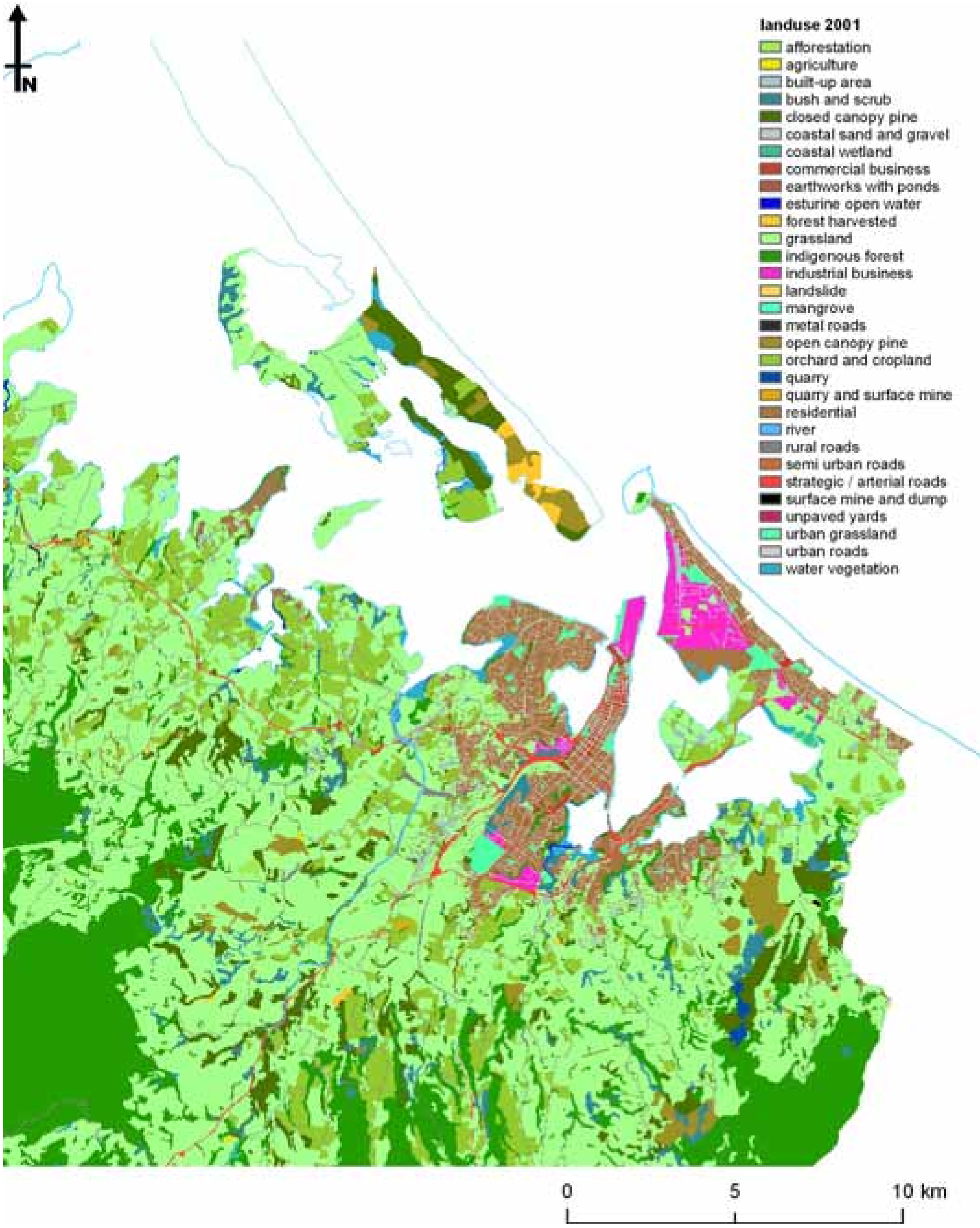


Figure 29: 2001 land use / cover scenario.

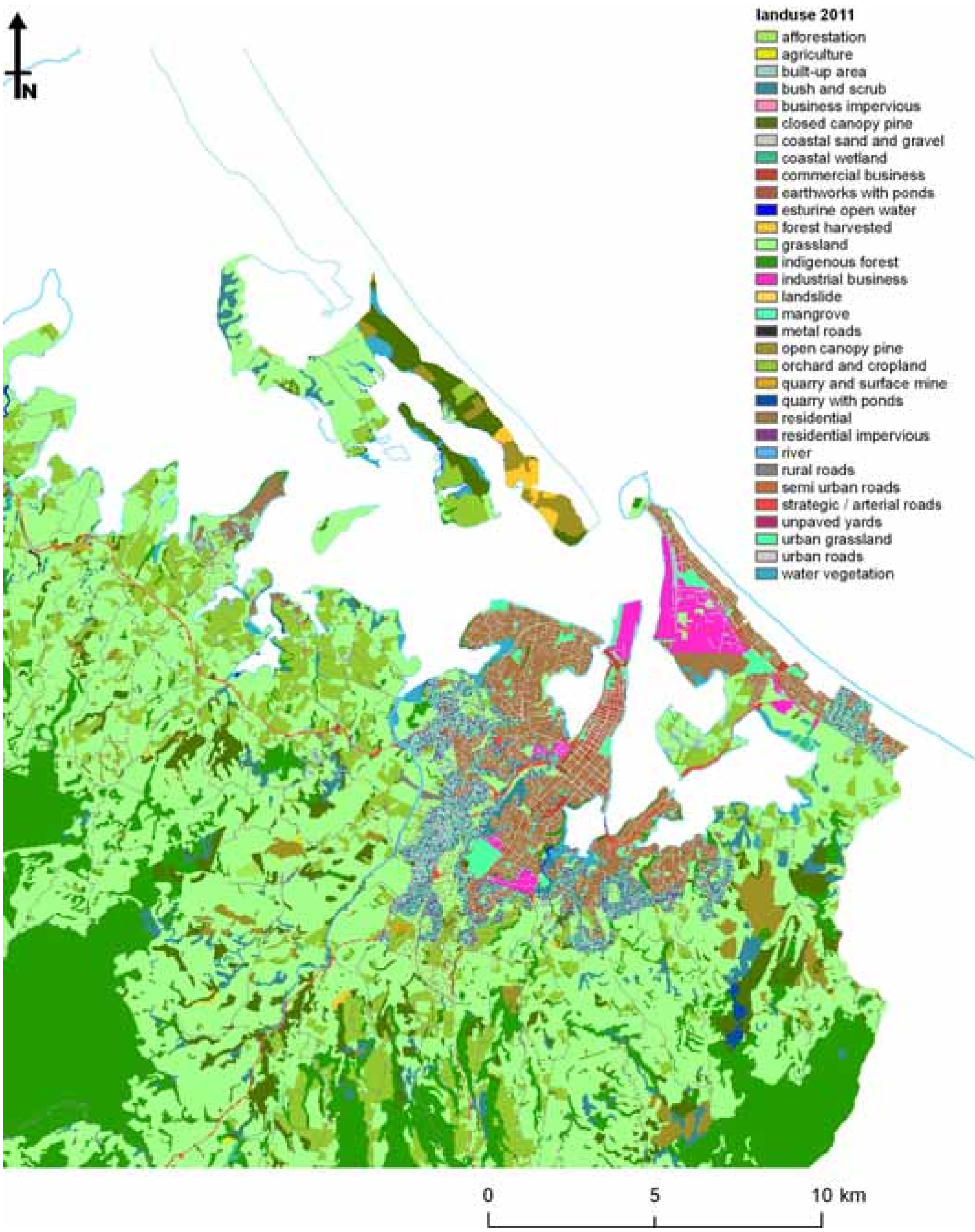


Figure 30: 2011 land use / cover scenario.

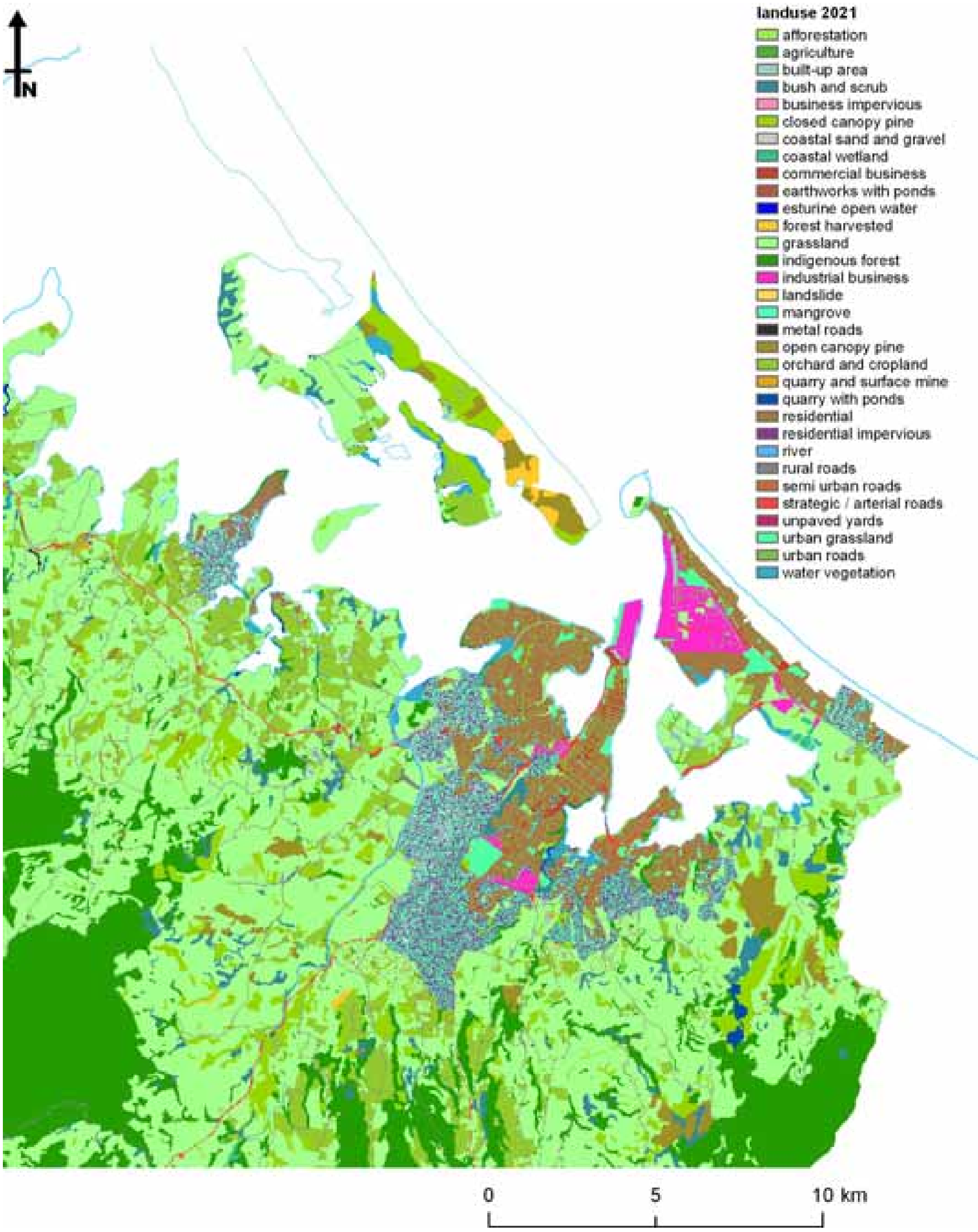


Figure 31: 2021 land use / cover scenario.

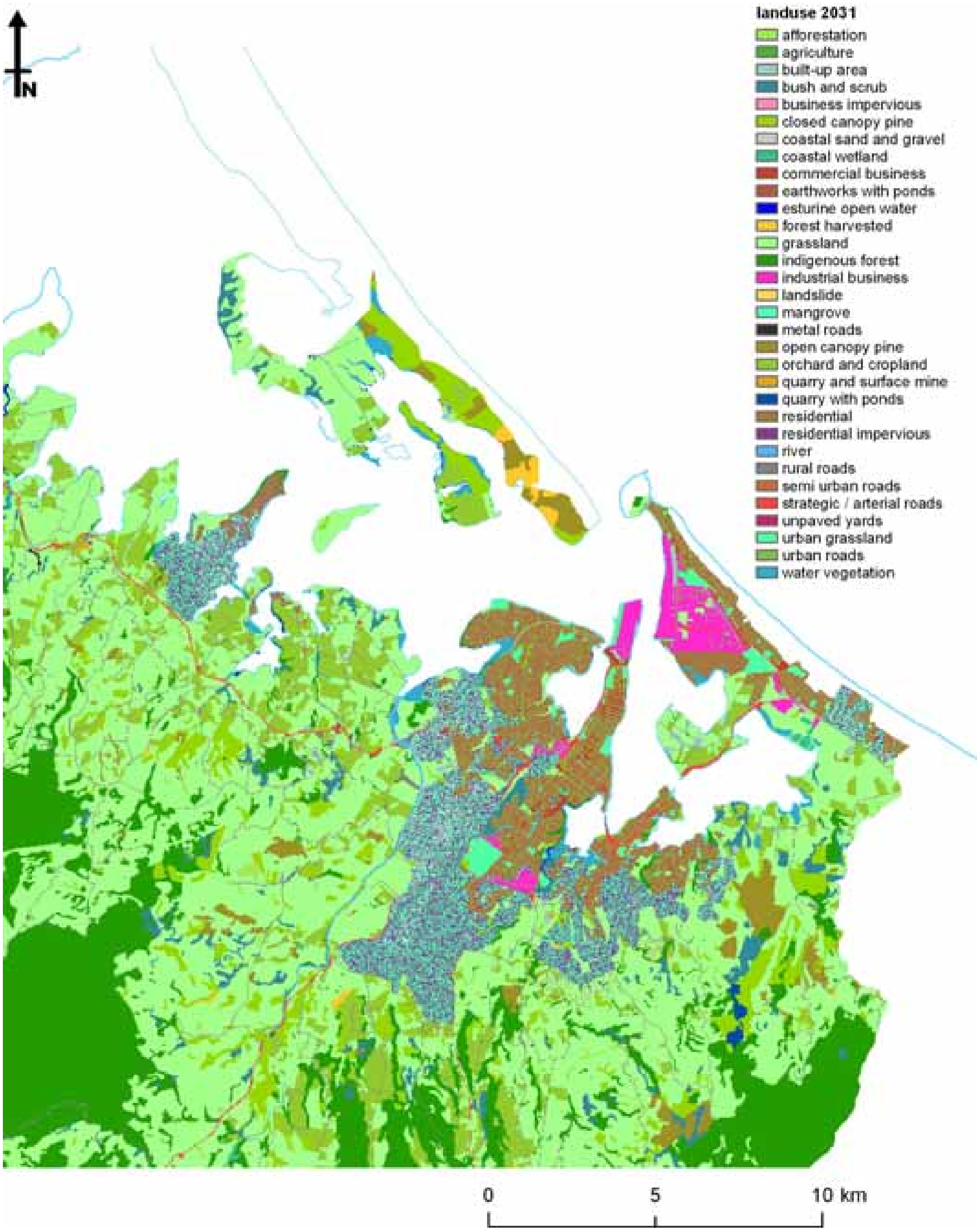


Figure 32: 2031 land use / cover scenario.

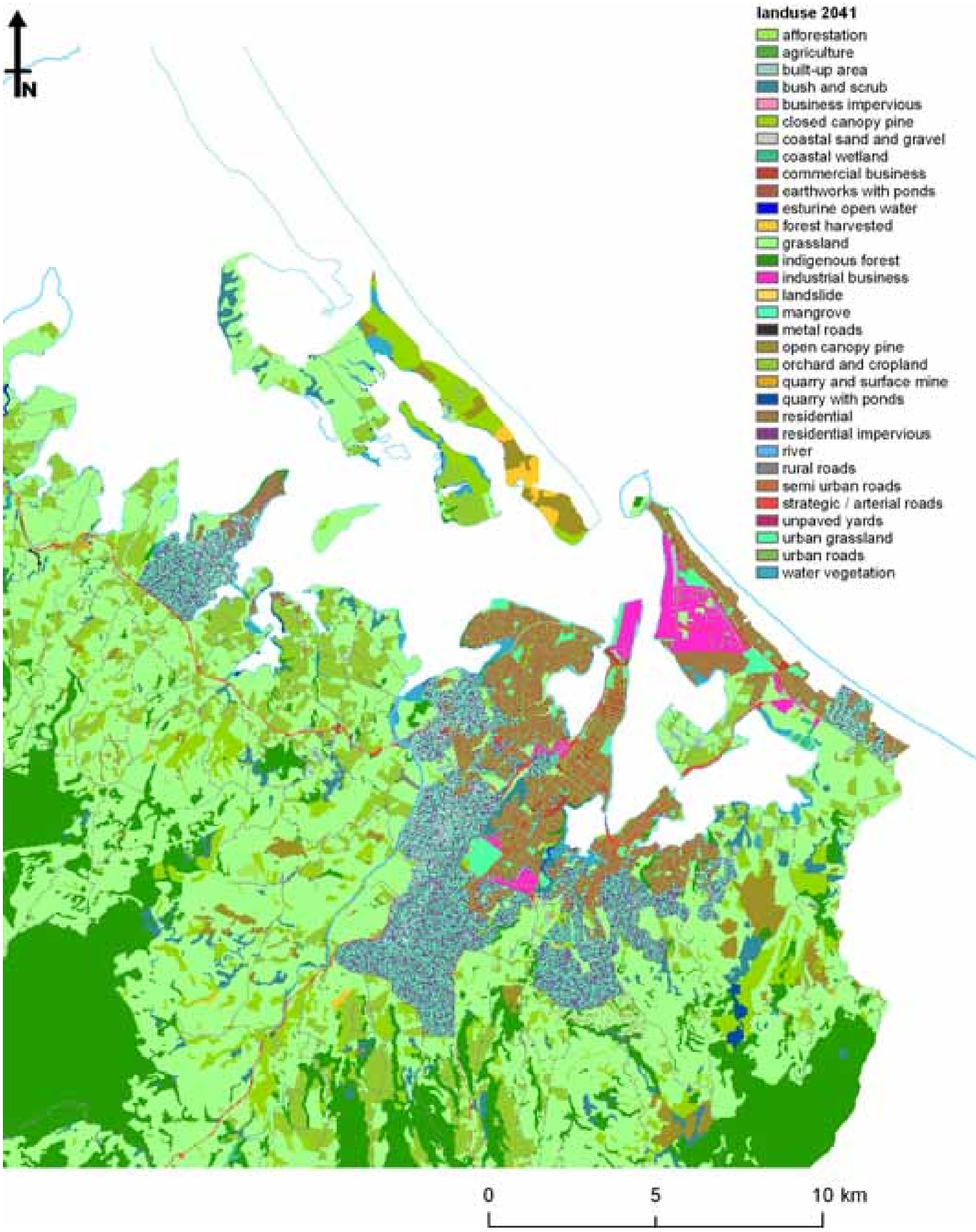


Figure 33: 2041 land use / cover scenario.

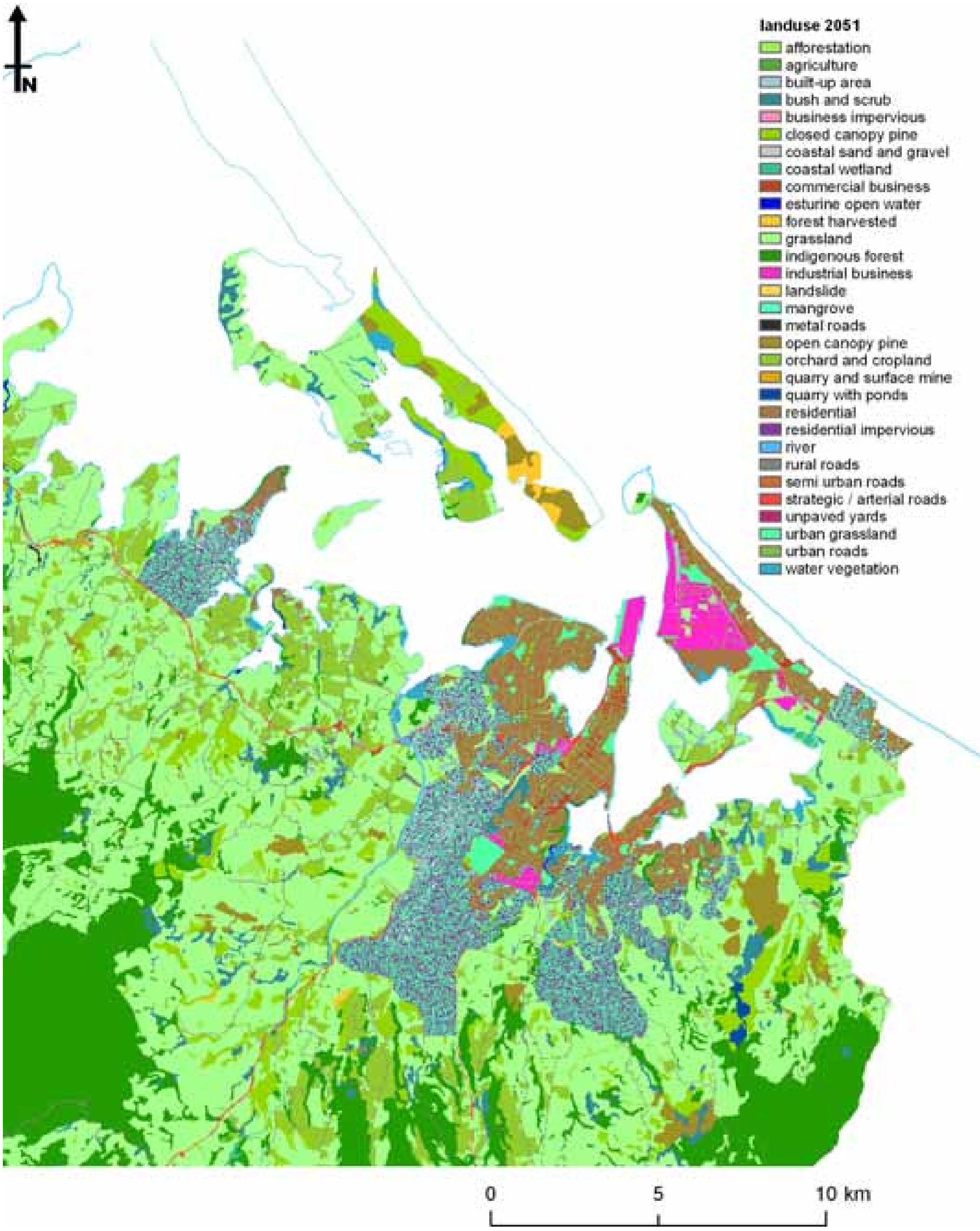


Figure 34: 2051 land use / cover scenario. Note that area and location of earthworks in 2051 is not estimated.

3.5.4 Trends in individual land cover classes from 2001 to 2051

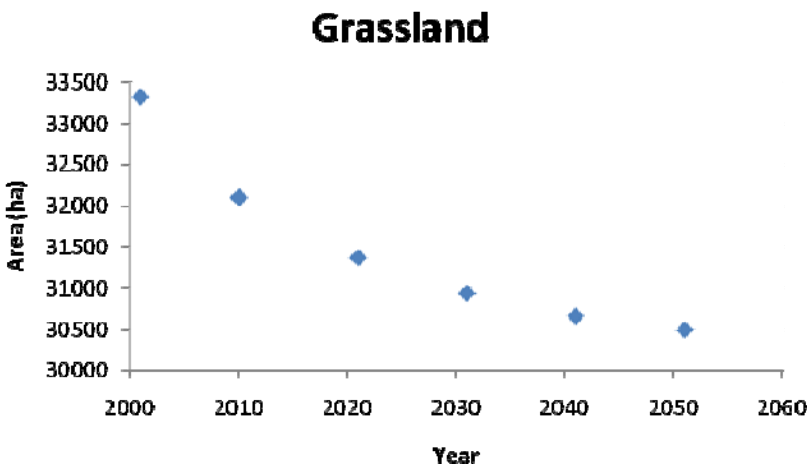
Areas of individual land use/cover classes, from 2001 to 2051, are presented in Table 20. This table also includes the land use/cover areas for 1943 and 1959.

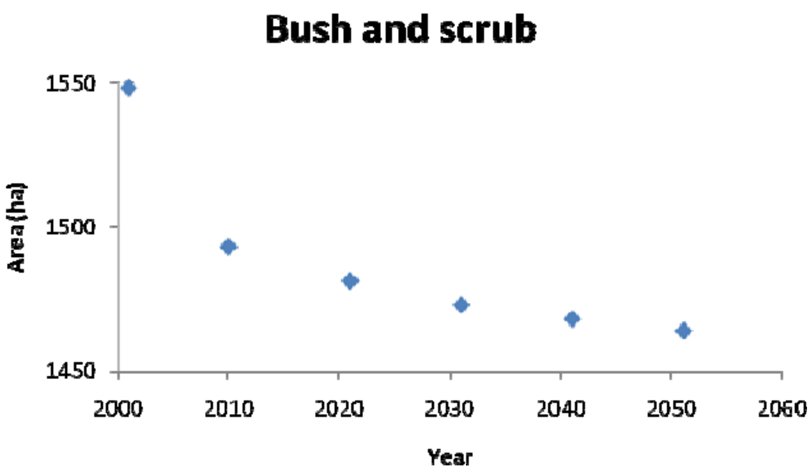
Trends in areas of some land uses/covers of interest are given in Figure 35. Note the general decrease in grassland, bush and scrub, indigenous forest, urban earthwork and increase in urban grassland. Note that area of earthworks in 2051 is not estimated from GIS since there is no information on the land-use between 2051 and 2061 but 19 ha of earthworks were estimated by nonlinear regression by fitting an exponential decay function to 2001-2041 data, and extrapolating to 2051.

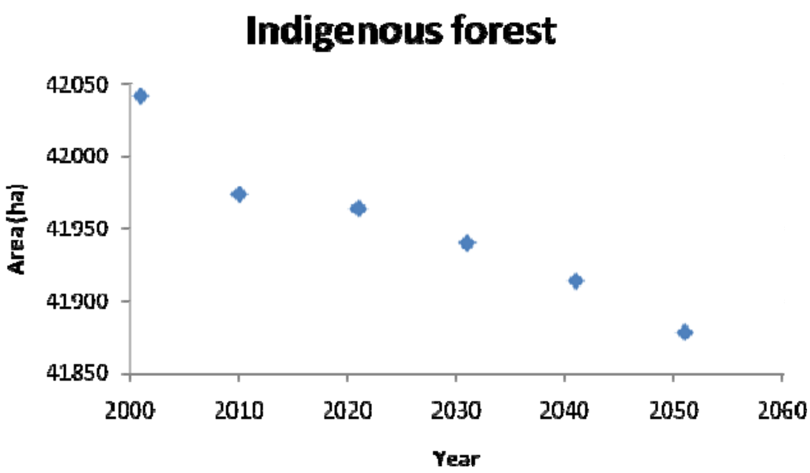
Table 20: Trends in land use/cover areas from 2001 to 2051 (in ha). The 2001*digit* land use/cover refers to 2001 land use/cover including 2007-2008 digitised earthworks and 2001 *rnd* refers to 2001 land use including earthworks obtained by prediction using randomization techniques, is more representative of 2001 and is used to create all future scenarios by iteration.

Land use/cover	1943	1959	2001 *digit*	2001 *rnd*	2011	2021	2031	2041	2051
bush and scrub	13996	13998	1553	1548	1493	1481	1473	1468	1464
indigenous forest	46668	46669	42044	42042	41974	41964	41940	41914	41878
open canopy pine	0	0	1121	1121	1117	1112	1112	1112	1112
closed canopy pine	775	775	8408	8409	8350	8317	8287	8271	8266
forest harvested	0	0	456	456	455	454	454	454	454
afforestation	0	0	114	114	111	110	110	110	110
orchard and cropland	164	164	4969	4964	4734	4488	4292	4205	4188
earthworks, no pond	0	62	58	0	0	0	0	0	-
strategic / arterial roads	0	0	459	452	381	365	364	364	364
rural built-up area	394	1356	336	338	336	336	336	336	336
grassland	36444	35477	33283	33322	32096	31366	30936	30651	30490
earthworks with ponds	0	0	128	166	114	72	47	26	19†
rural roads	0	0	1548	1544	1504	1452	1437	1432	1430
agricultural bare	109	47	27	27	27	26	26	26	26
urban roads	0	0	639	638	614	613	613	613	613
semi urban roads	0	0	36	36	31	30	30	30	30
metal roads	0	0	7	7	7	7	7	7	7
unpaved yards	0	0	0	0	0	0	0	0	0
deforestation	0	0	50	50	50	50	50	50	50
land slips	0	0	2	2	2	2	2	2	2
quarry	0	0	35	35	34	25	25	25	25
industrial business	0	0	559	559	559	559	559	559	559
urban grassland	0	0	335	335	1290	1891	2285	2524	2661
commercial business	0	0	161	161	161	161	161	161	161
residential	0	0	2366	2366	2366	2366	2366	2366	2366
river	0	0	84	84	84	84	84	84	84
lake and pond	0	0	70	70	70	70	70	70	70
esturine open water	0	0	48	48	45	45	45	45	45
mangrove	0	0	24	24	23	20	20	20	20
residential impervious	0	0	0	0	803	1300	1637	1844	1956
coastal sand and gravel	0	0	5	5	5	5	5	5	5
water vegetation	30	30	385	385	380	373	371	370	370
surface mine and dump	0	0	0	4	0	0	0	0	0
business impervious	0	0	0	0	95	167	167	167	167

† estimated by nonlinear regression


Grassland
33500
33000
32500
32000
31500
31000
30500
30000
Area (ha)
2000
2010
2020
2030
2040
2050
2060
Year


Bush and scrub
1550
1500
1450
Area (ha)
2000
2010
2020
2030
2040
2050
2060
Year


Indigenous forest
42050
42000
41950
41900
41850
Area (ha)
2000
2010
2020
2030
2040
2050
2060
Year

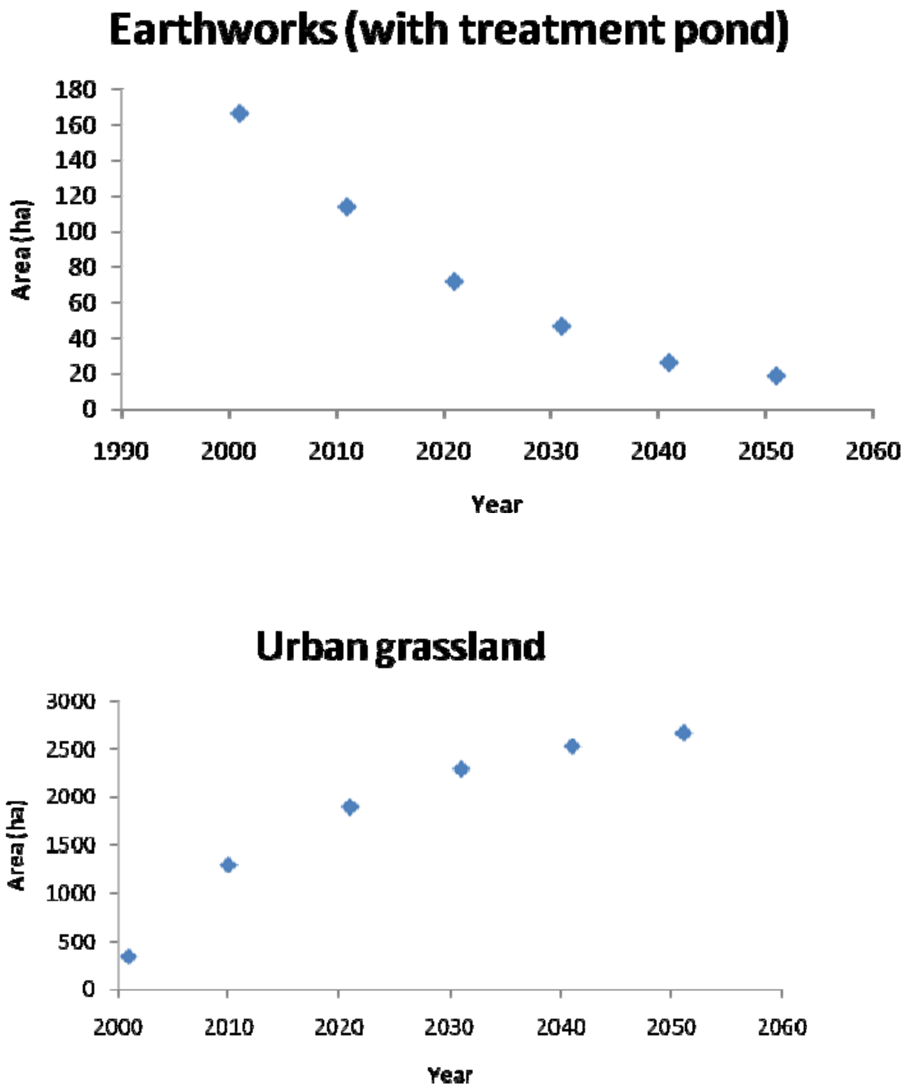


Figure 35: Temporal changes in key land uses over the 2001-2051 period.

3.6 Unique combinations of soil, slope and land use / cover

Standard GIS raster techniques were used to produce unique combinations of soils, land cover, and slope within each rainfall region, RR1, RR2, and RR3 from maps of Tauranga Harbour CSUs, soils, land use / covers and slopes. As an example, the 2001 *digit* scenario had 1576, 1456 and 936 unique combinations in rainfall regions RR1, RR2 and RR3, respectively.

3.7 Sediment runoff loads from special case land use classes

Sediment runoff loads from special case *impervious* land-use classes such as roads, industrial-impervious, commercial-impervious and residential-impervious areas may be incorporated within the GLEAMS-TAU model by means of user-defined concentrations (mg/l). These concentrations were used when vehicle road density data were available. The concentrations were either estimated or calculated from sediment runoff yields (g m^{-2} y^{-1}) for roofs, roads and paved surfaces as given in the CLM v.1.5 model, and summarised in Table 21 (Timperley and Reed, 2008), in conjunction with calculated runoff volumes. The estimates given in Table 21, derived for Auckland are the only estimates available in New Zealand, and they were used in our study. It was assumed that the sediment yields from roads given in Table 21 were only from the impervious area of the road, a reasonable assumption for urban roads (Moores, pers comm.).

Table 21: Sediment runoff yields from impervious areas.

			Yield (g m^{-2} y^{-1})
Roofs	Galvanised steel unpainted		5
	Galvanised steel poorly painted		5
	Galvanised steel well painted		5
	Galvanised steel coated		12
	Zinc/aluminium unpainted		5
	Zinc/aluminium coated		5
	Concrete		10
	Copper		5
	Other materials		10
Roads	*Vehicles per day*	<1000	21
		1000-5000	25
		5000-20000	43
		20000-50000	67
		50000-100000	120
		>100000	170
Paved surfaces other than roads	Residential		50
	Industrial		51
	Commercial		50

Sediment yields from roofs and paved surfaces were averaged at 8 g m^{-2} y^{-1}, and 50 g m^{-2} y^{-1}, respectively, from Table 21. Sediment concentrations from residential, commercial, and industrial impervious areas other than roads were calculated from weighted averages (from Tables 8 and 21) to be 18.6 mg/l, 24.13 mg/l, 27.1 mg/l, respectively, using a 50-year rainfall runoff annual average of 125.8 cm/y. Sediment yields from roads from Table 21 were converted to concentrations of 17 mg/l for rural roads with a vehicle density of <1000 vpd; 20 mg/l for semi-urban roads with a vehicle density of 1000-5000 vpd; 34 mg/l for urban roads with a vehicle density of 5000-20000 vpd; and 53 mg/l for major roads with a vehicle density of 20000-50000 vpd.

Sediment runoff loads from special case land-use classes such as industrial, commercial and residential areas and/or other urban built-up areas were incorporated within the GLEAMS-TAU model through defined concentration (mg/l) which are applied to the runoff generated by the model. Sediment runoff yields from residential, commercial and industrial areas and/or other urban built-up areas were averaged when road information was not available, giving values of 24 g m^{-2} y^{-1}, 27.2 g m^{-2} y^{-1}, 27.1 g m^{-2} y^{-1} and 18.6 g m^{-2} y^{-1} respectively, using a 50-year rainfall runoff annual average of 125.8 cm/y.

There was no account of stream bank erosion associated with urbanisation, and stream channel erosion as described in the NERMN river and stream monitoring programme in the Environment Bay of Plenty (Environment BOP, 2006), due to the uncertainty with erosion and accretion processes, the rural-urban divide in characterising streams, and the difficulty with determining how stream channels should be treated as a special case land use in the model. We note that estimates of sediment yields for urban stream channel erosion do suggest high yields of 6000 g m^{-2} y^{-1} for urban stream channels in Auckland (Timperley and Reed, 2008), but the transferability of this data to Tauranga is not clear. This uncertainty remains a gap in our modelling. Potentially, urban stream bank erosion will increase the yields beyond the values calculated by our model.

Urban runoff curve numbers used in the GLEAMS-TAU model were obtained from standard tables of curve numbers.

3.8 Sediment control with the use of siltation ponds

3.8.1 Urban development

It was assumed that siltation ponds for control of sediment from urban earthworks were only from the year 2001 and later. Pond sizes were sized at 2% of the contributing earthworks area. It was assumed that there was little use of silt control ponds in 1943 and 1959, which is reasonable.

3.8.2 Quarrying

Quarries are potentially a major source of sediment. They are often exposed for long periods of time and the area of bare earth can be considerable. The guidelines of quarrying in Tauranga were followed to match those in Chapter 8 of Environment BOP (2001).

It was assumed that ponds are applied to areas of quarry with pond, with topsoil removed and no seasonal restrictions imposed, from the year 2001.

3.9 Input data for stream routing

A stream network for the study area was delineated from the 10 m digital elevation model (DEM, see Section 3.1) using standard stream delineation techniques in ArcGIS

A map of the stream network in the study area is given in Figure 36, which also includes the site of three monitoring stations used for validation of the model and the band-full stream width (described later).

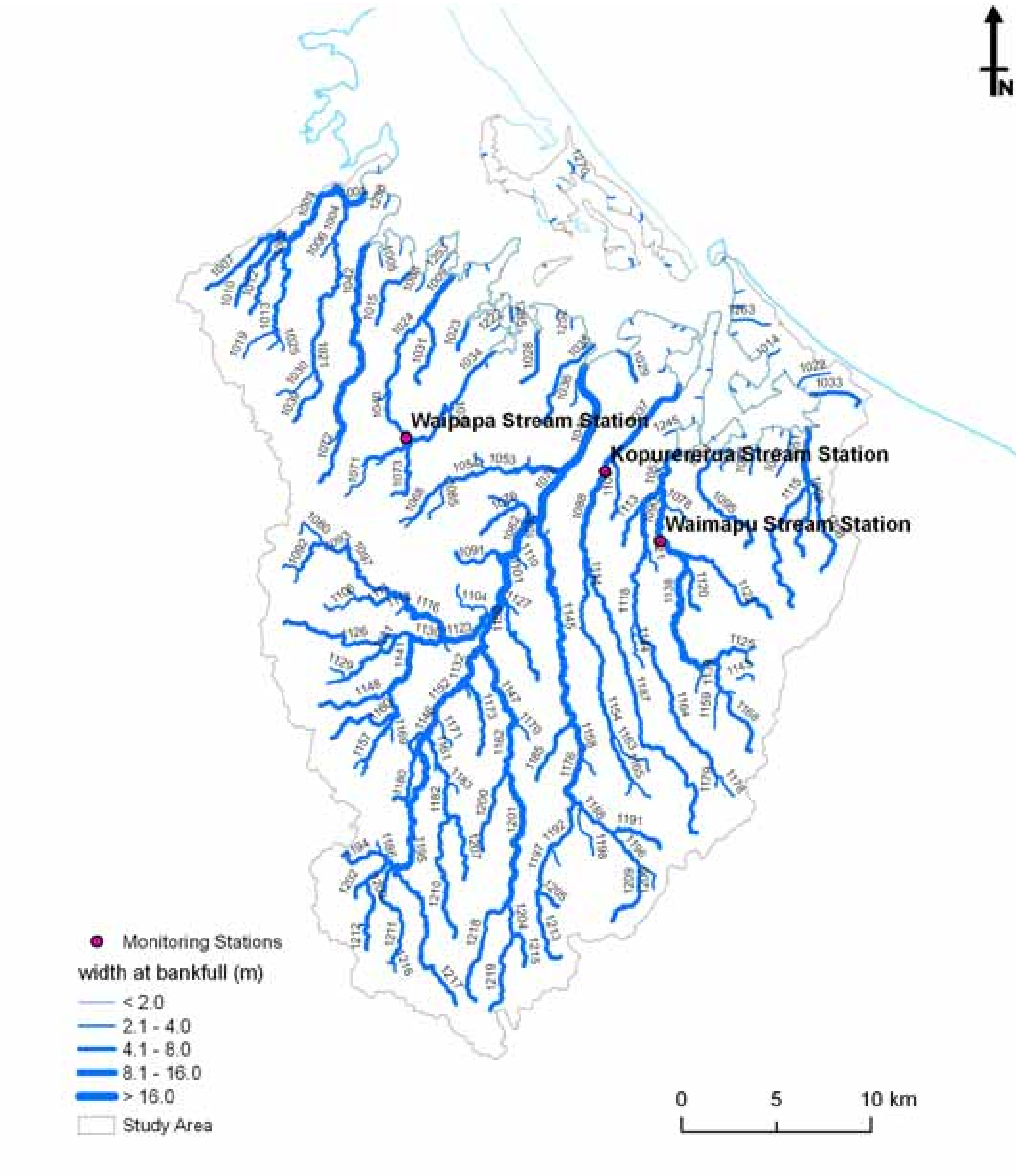


Figure 36: Map of the stream network in the study area with monitoring stations at Waipapa River, Kopurererua Stream and Waimapu Stream.

The average upstream curve number (CN), average upstream slope (by the equal area method), and maximum reach length are required to compute time of concentration using the empirical formula derived from a regression analysis of Auckland catchments given in TP108 (ARC, 1999). The average curve number (CN), average slope, and maximum reach length are derived from the entire area draining to each reach in the river network, i.e., aggregated upstream. A weighted runoff curve number was calculated using the TP108 (ARC, 1999) method from an intersection of model units (CSUs), characteristic land cover descriptions, and a reclassification of soil types into their hydrological soil groups. The zonal statistics tool within ArcGIS was used to calculate average slopes for each MU which was in turn used to calculate average slopes by the equal area method. Reach lengths were calculated using a simple field calculator within ArcGIS. Subcatchments-to-reach linkages were identified by using the spatial join tool within ArcGIS. The channelisation factor, allowing for the effects of urbanisation on runoff velocities was taken as 0.6 for all urban reaches, and 0.7 for reaches in the urban and rural zone. These factors were applied to all current, historical and future urban and rural areas, accordingly. The stream channel width at bankfull, shown in Figure 36, was derived from empirical relationships of stream channel width and catchment area for Waikato, given by Davies-Colley and Quinn (1998). This was considered reasonable as an approximation for Tauranga, based on the similarity of soils and climates in the two regions. The flow at bankfull was derived from empirical relationships of flow at bankfull and catchment area (McKerchar and Pearson, 1989).

A river network data file was created from the above properties containing information on reach IDs, subcatchment IDs, reach-to-reach linkages, subcatchment-to-reach linkages, catchment areas, slopes and lengths, reach slopes and lengths, roughness, channelization factors, width and flow at bankfull, and weighted curve numbers.

A particle data file was created with properties of particles in three sediment classes: clay (< 4 μm diameter), silt (4 to 63 μm) and sand (> 63 μm). A density of 2000kg/m^3, was assumed for clay, silt and sand. The stream routing model is quite sensitive to the assumed particle size distribution. The GLEAMS-TAU model produces fractions of total sediment, and a mix of quantity of aggregates and particles of 5 particle types of eroded sediment in runoff: (1) clay, (2) silt, (3) small aggregates, (4) large aggregates, and (5) sand. Individual mixes of particle and aggregate size fractions were obtained from separate GLEAMS-TAU runs with the dominant soils in the subcatchment. These fractions were grouped into 3 classes of sand, clay and silt, based on particle and aggregate sizes. These fractions, based on GLEAMS-TAU outputs of eroded sediment in runoff were used as inputs to the stream routing model.

Sediment deposition near the Wairoa Powerhouse (Figure 37) is represented in the stream routing model by widening the stream ID 1087 (given in purple) from 19 m to 25 m. The Wairoa Powerhouse is assumed to lie at mid-distance of the stream reach ID 1087.

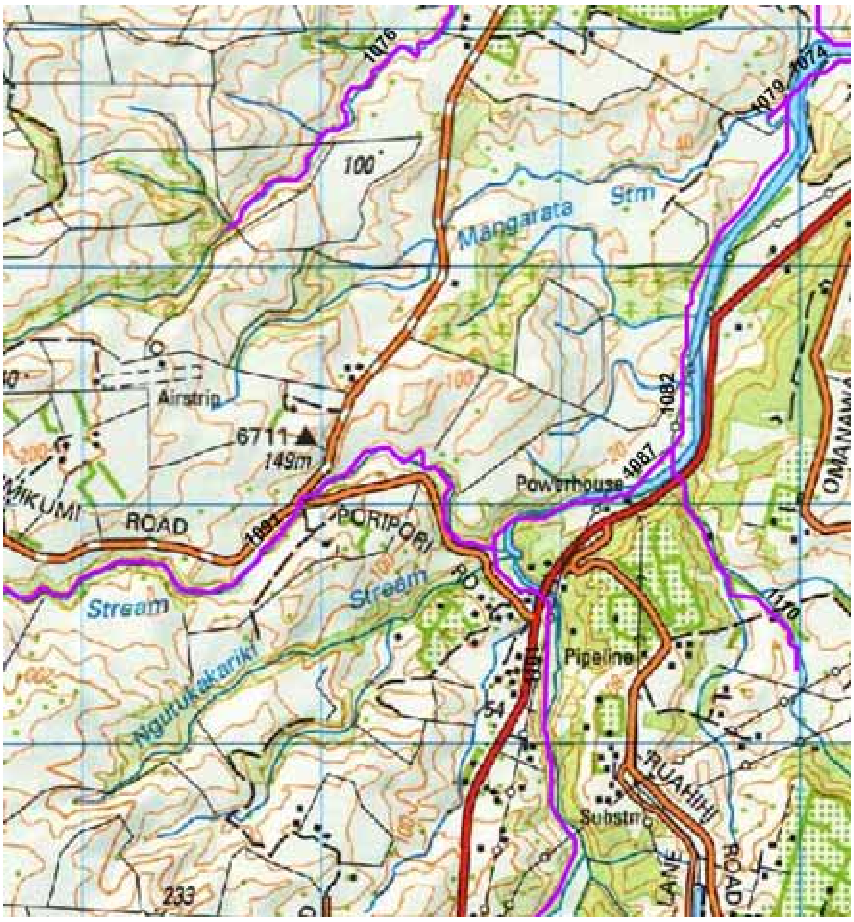


Figure 37: The location of the Wairoa Powerhouse.

4. Model validation

4.1 Data for model validation

To evaluate the routed GLEAMS-TAU model, predicted sediment loads were compared with measured loads at several sites. The measured sediment loads were based on monitoring of flow and sediment concentrations, including recent monitoring conducted specifically for this project. All the data were provided by Environment BOP.

Monitoring data were collated from three existing stream flow monitoring sites: Waipapa Stream at Goodall Road, Waimapu Stream at McCarrol Farm and Kopurererua Stream at SH29 (Figure 36). Tables 22 to 24 give summary information on the sites. The sites were selected to cover a range of land-uses (including recent earthworks in the Kopurererua catchment), and because long-term flow data were available. The streams associated with the monitoring sites are described by Surman et al. (1999).

Table 22: Monitoring sites and location.

	Site number	Map reference number	Easting	Northing
Waipapa stream station at Goodall Rd	13805	U14: 737824	2773700	6382400
Kopurererua stream station at SH 29	14302	U14: 843805	2784200	6380600
Waimapu stream station at McCarrol's farm	14410	U14: 871768	2777900	6387200

Table 23: Monitoring sites, area of catchment area drained and summary of hydrology from long term gauging.

	Catchment area drained (km^2)	Mean flow (L/s)	Mean specific flow ($L/s/km^2$)	7-day low flow (L/s)	Mean annual peak flow (L/s)
Waipapa Stream at Goodall Rd	8.54	488	57	38	23789
Kopurererua Stream at SH 29	59.75	1898	32	1199	12084
Waimapu Stream at McCarrol's farm	56.60	2076	37	679	47007

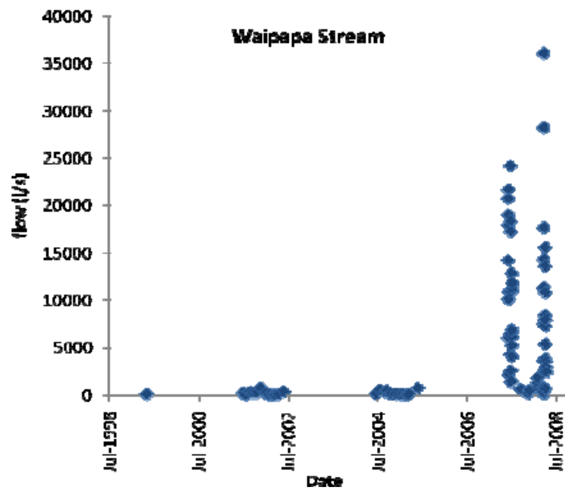
Table 24: Monitoring station sites and land use, soil and slopes of catchments they drain.

	Land use / cover	Soil (from LRI)	Slope (from LRI)
Waipapa Stream at Goodall Rd	Mixed pasture/native, upper sections in bush	Mostly YBL	Moderately steep
Kopurererua Stream at SH 29	Mixed pasture/native, some earthworks	YBP/YBL	Strong rolling to moderately steep
Waimapu Stream at McCarrol's farm	Predominantly pasture. A little bush in gullies	YBL	Rolling to moderately steep

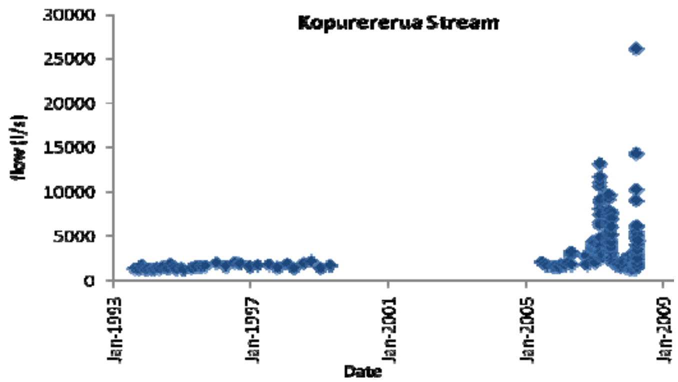
Flow rate at sample dates at the monitoring sites

Figure 38 shows measured flows and sampling times for the monitored sites, including a period of routine monthly sampling prior to 2005 (which was mostly under baseflow conditions) and storm-flow sampling conducted as part of this study.

a)



b)



c)

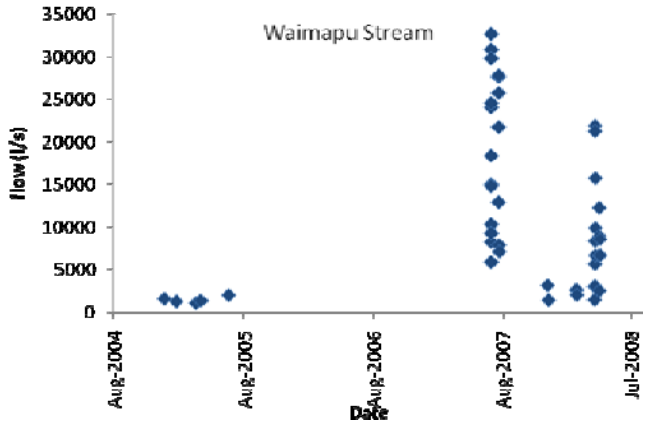


Figure 38: Flow rate at sample times for a) Waipapa Stream at Goodall Rd. b) Kopurererua Stream, at SH 29 and c) Waimapu Stream at McCarrol's farm.

4.2 Suspended sediment concentrations

This section describes the manipulation of results of monitoring and water sampling (at dates given in Figure 38) at the three monitoring stations to obtain sediment loads for comparison with the GLEAMS-TAU sediment load model outputs. Table 25 gives the mean, minimum and maximum flows of the samples collected and the mean and maximum suspended solid concentrations.

Table 25: Summary statistics for flow and suspended sediment (SS) concentrations for samples.

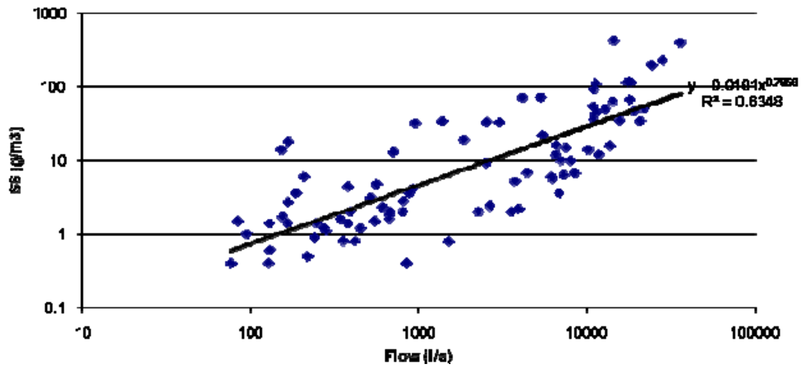
	mean flow (l/sec)	**Minimum flow (l/sec)**	**maximum flow (l/sec)**	**mean SS conc. (g/m^3)**	**Minimum SS conc. (g/m^3)**	**Maximum SS conc. (g/m^3)**
Waipapa Stream at Goodall Rd	5871	76	36096	33.3	0.4	425
Kopurererua Stream at SH 29	3722	1286	26206	157	6.3	4200
Waimapu Stream at McCarrol's farm	11420	1031	32643	111	1.0	675

Figure 39 shows flow as a function of suspended sediment (SS) concentration at Waipapa Stream, Kopurererua Stream, and Waimapu Stream, together with respective regression equations of flow as a function of suspended sediment concentrations. The R^2 values ranged from 0.6 to 0.9 and were considered to be a good and acceptable.

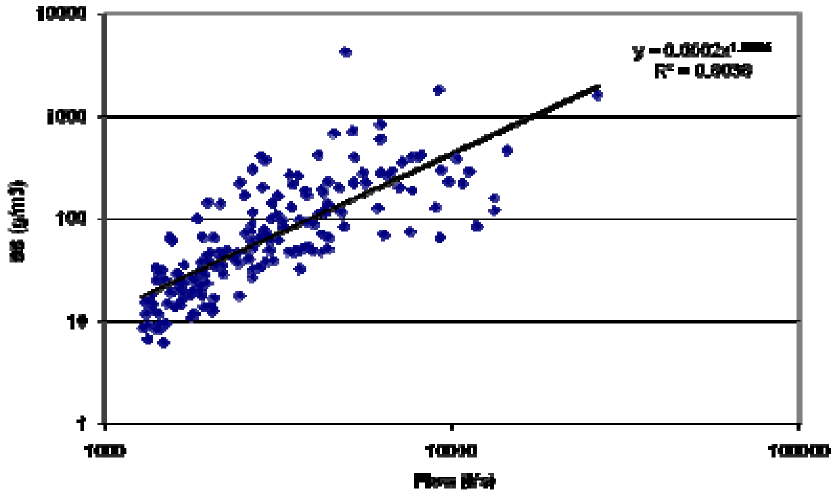
These regression equations were applied to the flow record to obtain a synthetic time-series of concentrations. The measurements are compared with the synthetic series in Figure 40.

The concentrations were multiplied by the measured flow rates to give a time-series of sediment flux, which was then summed over time to give the total sediment load. A smearing bias correction factor was applied to the load account for log-transformation bias (Duan, 1983).

a)



b)



c)

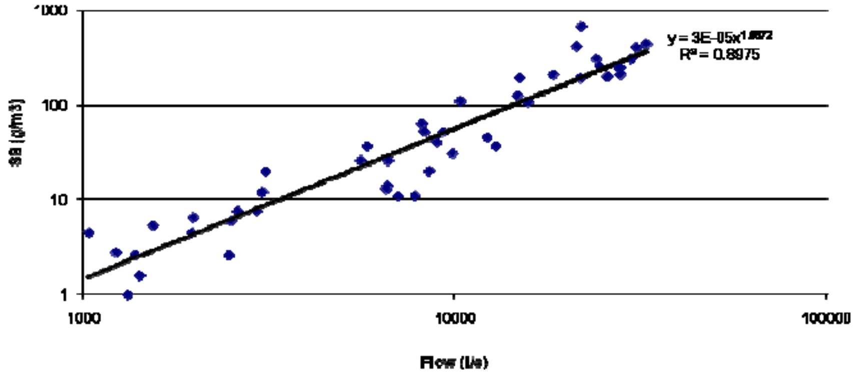
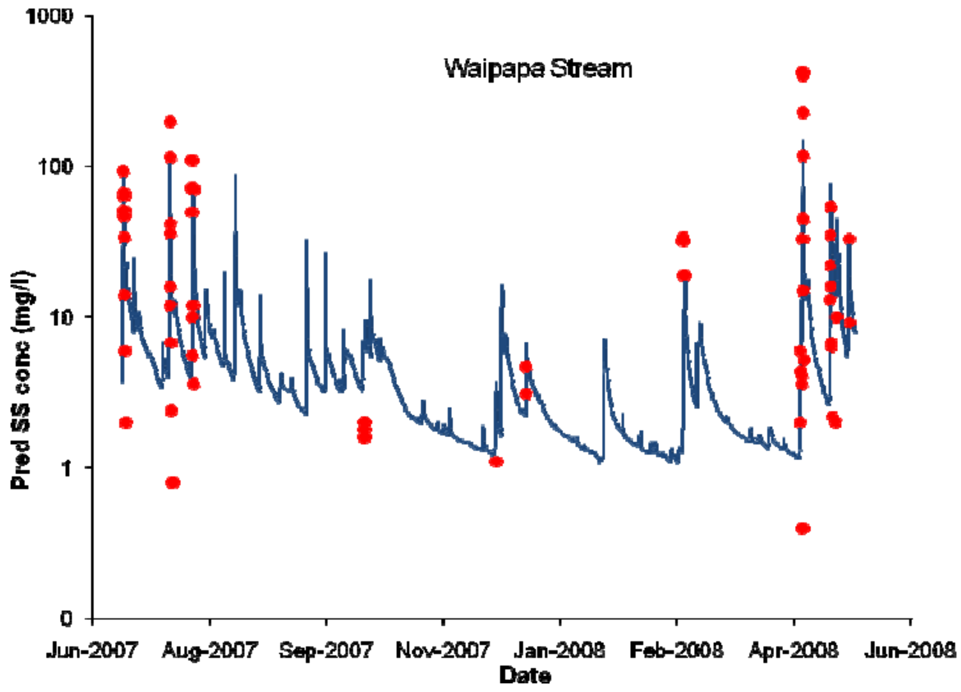
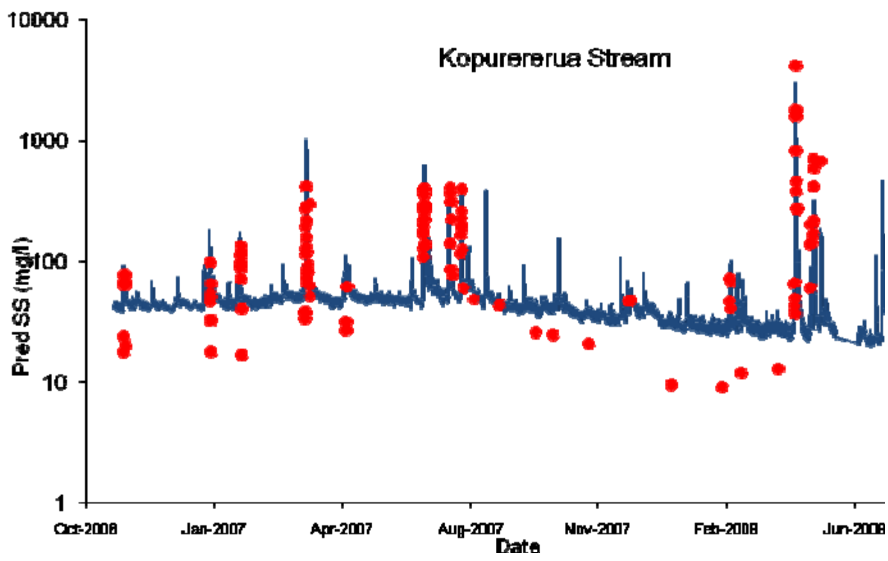


Figure 39: Log plot of flow rate (l/s) as against suspended sediment (SS) concentrations (g/m^3) at a) Waipapa Stream at Goodall Rd, b) Kopurererua Stream at SH 29 and c) Waimapu Stream at McCarrol's farm.

a)


Waipapa Stream
1000
100
10
1
0
Pred SS conc (mg/l)
Jun-2007
Aug-2007
Sep-2007
Nov-2007
Jan-2008
Feb-2008
Apr-2008
Jun-2008
Date

b)


Kopurererua Stream
10000
1000
100
10
1
Pred SS (mg/l)
Oct-2006
Jan-2007
Apr-2007
Aug-2007
Nov-2007
Feb-2008
Jun-2008
Date

c)

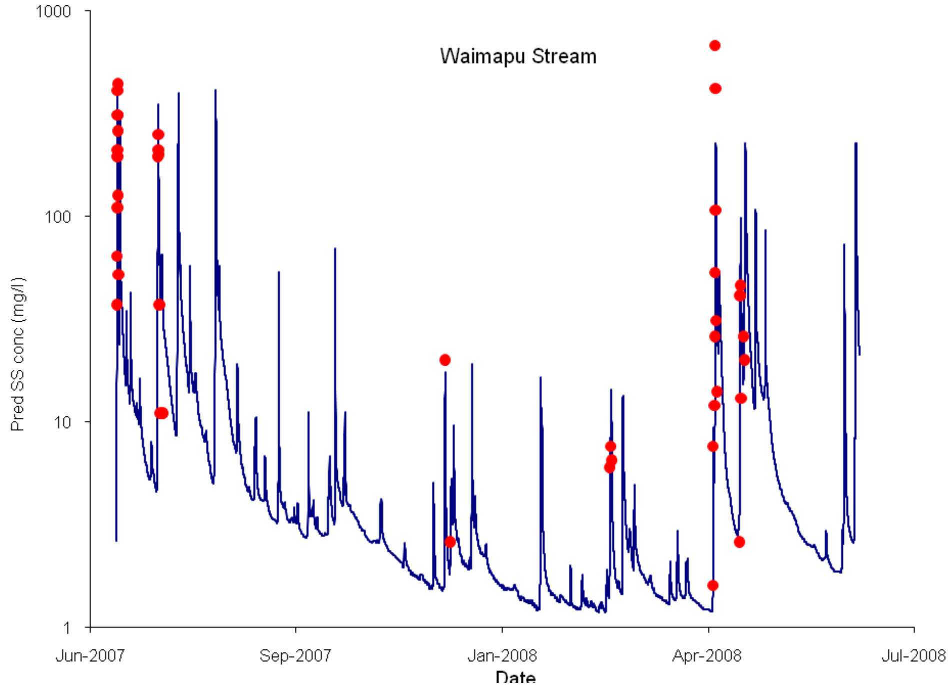


Figure 40: Synthetic suspended sediment (SS) time series (solid line) and measured concentrations (points) during the period of monitoring at a) Waipapa Stream at Goodall Rd. b) Kopurererua Stream, at SH 29 and c) Waimapu Stream at McCarrol's farm.

4.3 Suspended sediment load during the period of recent storm monitoring

The measured load over the duration of monitoring (Table 26) is shown in Table 27 and Figure 41.

Table 26: Period and duration (in days) of recent events at the monitoring sites.

	Start date	End date	Number of days
Waipapa Stream at Goodall Rd	30-Jun-07	18-May-08	323
Kopurererua Stream at SH 29[†]	30-Jun-07	24-Jun-08	360
Waimapu Stream at McCarrol farm	30-Jun-07	24-Jun-08	360

[†]includes earthworks

The Kopurererua stream site at SH 29 site includes earthworks, yet the yield (per unit area) is comparable to other sites.

Supplementary data were collected by Environment BOP both upstream (Keenan Rd) and downstream (SH29) of the Kopurererua earthworks area, for a storm of 84.5 mm on 30 July, 2008. The results indicate little effect of the earthworks (Figure 42), although the sampling frequency at the upstream site was not sufficient to pick up peaks at the upstream site which were evident downstream.

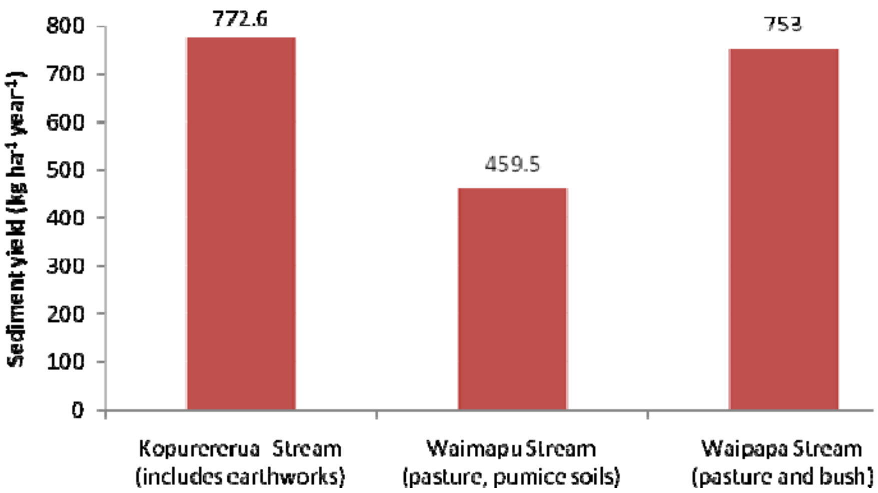


Figure 41: Annual sediment yields (kg ha^{-1} y^{-1}) during the period of monitoring at a) Waipapa Stream at Goodall Rd, b) Kopurererua Stream at SH 29 and c) Waimapu Stream at McCarrol's farm.

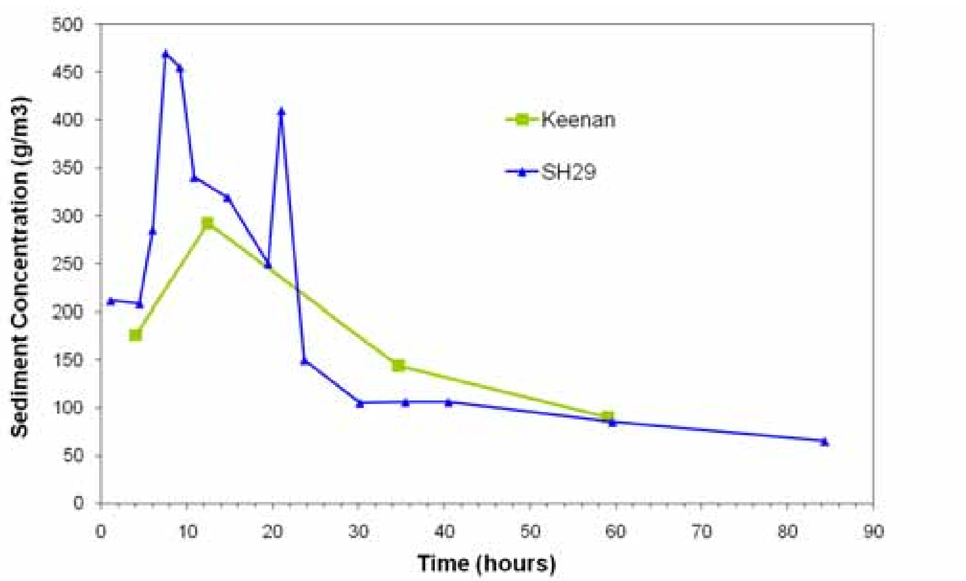


Figure 42: Sediment concentration (g/m^3) at Kopurererua Stream – SH 29, and Kopurererua Stream –Keenan for a single storm event on 30 July, 2008 with 84.5 mm of rain.

4.4 Comparison of measurements with model predictions

This section describes the comparison of measured sediment load estimates with GLEAMS-TAU model results.

The model predictions have not been compared with measurements for individual events. There is a component of natural variability between events that is difficult to model, and sediment models typically have more difficulty making accurate predictions at event scale compared with long-term averages. Hence the ability of the model to accurately predict the probability distribution of event sediment loads remains un-tested.

The monitoring station at Kopurerua is at the end of stream ID 1088, so model predictions were extracted from the end of that reach. The Waipapa Stream station is roughly half way between stream ID 1040 and stream reaches 1041 & 1061, an average of the predictions at the ends of the respective reaches was calculated for comparison with measurements. Similarly, since the Waimapu Stream station is roughly half way between stream ID 1090 and streams 1094 & 1122.

Table 27 presents a comparison of measured and predicted long-term yields, both over the full 50-year period of the simulation. The model predictions are in reasonable agreement with the measurements. This gives us confidence that GLEAMS-TAU provides reasonable predictions of long-term average sediment loads for a range of catchment conditions.

Table 27: Comparison of measurement and modelled data.

	Measurement (kg/day)	Modelled (50 year average) (kg/day)
Waipapa	1761	2240
Kopurererua	13 500	15 691
Waimapu	7106	10724

5. Acknowledgements

We thank Stephen Park and his colleagues for extracting data from Environment BOP records for our use. John McIntosh provided water quality monitoring data. Gareth Evans provided the latest GIS layers when available. Linda Lilburne, Landcare Research provided information on the soils and much useful advice. We thank Sandy Elliott for his review comments on the report.

6. References

Auckland Regional Council (1999). Guidelines for stormwater runoff modelling in the Auckland Region. Auckland Regional Council.

Davies-Colley, R. & Quinn, J. (1998). Stream lighting in five regions of North Island, New Zealand: control by channel size and riparian vegetation. *New Zealand Journal of Marine and Freshwater Research 32*: 591-605.

Duan, N. (1983). Smearing estimate – a non-parametric retransformation method. *Journal of the American Statistical Association 78*: 605–610.

Environment Bay of Plenty (2001). Erosion and Sediment Control Guidelines for Land Disturbing Activities. Guideline Number 2001/03.

Environment Bay of Plenty (2006). NERMN River and Stream Channel Monitoring Programme – 2002/03, 2003/04, 2004/05 and 2005/06. Environmental Publication 2006/15. Available online at http://www.envbop.govt.nz/media/pdf/ER0615.pdf

Green, M.; Timperley, M.; Collins, R.; Senior, A.; Adams, R. & Swales, A. (2004). Prediction of Contaminant accumulation in the Upper Waitemata Harbour – Methods. NIWA Client Report HAM2003-087/1.

Green, M. (2009). Tauranga Harbour Sediment Study: Implementation of the USC-3 Model. NIWA Client HAM 2009-038, March 2009. BOP09216.

Griffiths, G.M. (2005). Changes in New Zealand daily rainfall extremes 1930-2004. *Weather and Climate 26:* 30-46.

Griffiths, G.; Mullan, B.; Thomson, C.; Burgess, S. & Tait, A. (2003). The Climate of the Bay of Plenty: Past and Future. NIWA Client report ALK2003-044, June 27, 2003. Prepared for Environment Bay of Plenty.

Hicks, D.M. (1994). Storm sediment yields from basins with various landuses in Auckland area. Auckland Regional Council Technical Publication No. 54. Auckland Regional Council.

IPCC (2007a). Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S.; Qin, D.; Manning, M.; Chen, Z.; Marquis, M.; Averyt, K.B.; Tignor, M. & Miller, H.L.

(Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Available at http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Pub_SPM-v2.pdf

IPCC (2007b). Summary for Policymakers. In: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Parry, M.L.; Canziani, O.F.; Palutikof, J.P.; van der Linden, P.J. & Hanson, C.E. (Eds.), Cambridge University Press, Cambridge, UK, 7-22. Available at http://www.gtp89.dial.pipex.com/spm.pdf

Knisel, W.G. (ed.) (1980). CREAMS: A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. U.S. Department of Agriculture, Conservation Report No. 26, 640 pp.

Knisel, W.G. (ed.). (1993). GLEAMS Groundwater Loading Effects of Agricultural Management Systems, Version 2.10. Dept. Publication No. 5, Biological & Agricultural Engineering Department, University of Georgia-Coastal Plain Experiment Station, Tifton. 260 pp.

Knisel, W.G. & Davis, F.M. (2000). Groundwater Loading Effects of Agricultural Management Systems. Version 3.0. Publication No. SEWRL-WGK/FMD-050199, revised 081500, Washington.

McKerchar, A.I. & Pearson, C.P. (1989). Flood frequency in New Zealand, Publication No. 20 of the Hydrology Centre, Christchurch, New Zealand.

Ministry for the Environment (2004). Climate Change Effects and Impacts Assessment: A Guidance Manual for Local Government in New Zealand. Prepared by David Wratt, Brett Mullan and Jim Salinger (NIWA), Sylvia Allen and Tania Morgan (MWH New Zealand Ltd), and Gavin Kenny (Earthwise Consulting). Ministry for the Environment Report ME 513, Wellington, 153p.

Ministry for the Environment (2008). *Climate Change Effects and Impacts Assessment. A Guidance Manual for Local Government in New Zealand.* 2nd Edition. Prepared by Mullan, B.; Wratt, D.; Dean, S.; Hollis, M.; (NIWA); Allan, S.; Williams, T. (MWH NZ Ltd) & Kenny, G. (Earthwise Consulting Ltd), in consultation with Ministry for the Environment. NIWA Client Report WLG2007/62, February 2008, 156 p.

Oldman, J.; Stroud, M.J.; Cummings, V.J. & Cooper, A.B. (1998). Mahurangi land use scenario modelling Client Report ARC70216/2, National Institute of Water and Atmosphere, Hamilton.

Oldman, J.W. & Swales, A. (1999). Mangemangeroa estuary numerical modelling and sedimentation. NIWA Client Report ARC70224. National Institute of Water and Atmospheric Research, Hamilton.

Parshotam, A. & Wadhwa, S. (2007a). Central Waitemata Harbour Contaminant Study. GLEAMS model structure, setup and input data requirements. NIWA Client Report HAM2007-162. National Institute of Water and Atmospheric Research, Hamilton.

Parshotam, A. & Wadhwa, S. (2007b). Central Waitemata Harbour Contaminant Study. Landuse scenarios. NIWA Client Report HAM2007-163. National Institute of Water and Atmospheric Research, Hamilton.

Parshotam, A. & Wadhwa, S. (2007c). Central Waitemata Harbour Contaminant Study. Model Results. NIWA Client Report HAM2000-055. National Institute of Water and Atmospheric Research, Hamilton.

Parshotam, A.; Hume, T.; Elliot, S. & Green, M. (2008). Tauranga Harbour sediment study. Specification of Scenarios. NIWA Client report BOP08216 prepared for Environment Bay of Plenty, April, 2008.

Rijkse, W.C. (2003). Soils and land use of Katikati area, Bay of Plenty, New Zealand. Landcare Research Contract Report LC0203/091.

Rodda, H.; Shankar, U. & Thorrold, B. (1997). The Development of Decision Support Tools for Managing Water Quality in Agricultural Landscapes: Year 2. NIWA Consultancy Report MAF7021. National Institute of Water and Atmospheric Research, Hamilton.

Saggar, S.; Tate, K.R.; Feltham, C.W.; Childs, C.W.; Parshotam, A. (1994). Carbon Turnover in a Range of Allophanic Soils Amended with ^{14}C-labelled glucose. *Soil Biol. Biochem. 26(9)*: 1263-1271.

Senior, A.; Oldman, J.; Green, M.O.; Norkko, A.; Hewitt, J.; Collins, R.P.; Stroud, M.J.; Cooper, A.B.; Thrush, S. (2003). Risks to estuarine biota under proposed development in the Whitford catchment. ARC01264; ARC01265; ARC01266.

Hamilton, NIWA Client Report HAM2003-016. National Institute of Water and Atmospheric Research, Hamilton.

SmartGrowth (2007). The Western Bay of Plenty Sub-region 50-year Strategy and Implementation Plan, May 2007.

Stroud, M.J. & Cooper, A.B. (1997). Modelling sediment loads to the Mahurangi Estuary, Unpublished NIWA Client Report ARC60211.

Stroud, M.J. & Cooper, A.B. (1998). Predicting soil loss under outdoor vegetable production at Pukekohe. NIWA Client Report ARC60202. National Institute of Water and Atmospheric Research, Hamilton.

Stroud, M.J. & Cooper, A.B. (1999). Assessment of sediment impacts on Okura estuary associated with catchment developments. Effects of sediment controls. NIWA Client Report ARC00202. National Institute of Water and Atmospheric Research, Hamilton.

Stroud, M.J.; Cooper, A.B.; Botcher, A.B.; Hiscock, J.G. & Pickering, N.B. (1999). Sediment runoff from the catchment of Okura estuary. NIWA Client Report ARC90241/1. National Institute of Water and Atmospheric Research, Hamilton.

Stroud, M.J. (2003). Modelling long-term daily sediment loads to the Mahurangi Estuary. NIWA Client Report HAM2003-144. National Institute of Water and Atmospheric Research, Hamilton.

Surman, M.; Clarke, R. & Carter, M. (1999). Tauranga Harbour Sediment Source Survey. Environment Bay of Plenty Operations report 98/13. January 1999. ISSN 1173-6232.

Tait, A.B.; Henderson, R.D.; Turner, R.W. & Zheng, X. (2006). Thin plate smoothing spline interpolation of daily rainfall for New Zealand using a climatological rainfall surface. *International Journal of Climatology 26*: 2097-2115.

Timperley, M. & Reed, J. (2008). Central Waitemata Harbour Contaminant Study. Development of the Contaminant Load Model. NIWA Client Report HAM2008-045.

U.S. Department of Agriculture, Soil Conservation Service (1984). Engineering Field Manual. U.S. Department of Agriculture, Soil Conservation Service, Washington, DC.

U.S. Department of Agriculture, Natural Resources Conservation Service (2007). National Soil Survey Handbook (NSSH), title 430-VI. [Online] Available: http://soils.usda.gov/technical/handbook/.

Williamson, R.B.; Green, M.O.; Stroud, M.J.; Hume, T.M. & Pridmore, R.D. (1998). Sedimentation in Orewa estuary: impacts of further urban and motorway development. 45p. Report prepared for Auckland Regional Council. Report and project number ARC80234. National Institute of Water and Atmospheric Research, Hamilton.

7. Appendices

Appendix 1: Data sources for model inputs

1) Data sources for delineating subcatchments, the stream network and creating slope maps included LIDAR data, photogrammetric data, DEM data, the coast line and the stormwater drainage network. The maps and data we sourced from EBOP included:

- LIDAR and Photogrammetric data
    - LIDAR06.
    - BAP30k photogrammetric data for 2007, includes.
    - HiResCoast07. High resolution LIDAR data of the coast.
    - Kaimai (TM 16k) photogrammetric.
    - Papamoa (TM 16k) photogrammetric.
- Digital Elevation Model (DEM) data
    - 15m DEM created by Landcare Research.
- The coast line
- Stormwater drainage network
    - GIS layers from TCC for Tauranga city

2) The maps and data we sourced for creating soil maps and deriving soil parameters included:

- Soil layers
    - GIS layers from NZLRI.
    - Data was provided by EBOP
- Soil physical properties and profile information
    - Data from S-map.
    - Data were provided by Landcare Research.

Appendix 2: Data sources for climate scenarios

Climate data was obtained for Tauranga during the period 1958 to 2008, and future climate projections were obtained to 2051 in increments of 10 years. The maps and data we sourced included:

- Climate spatial distributions
    - Data were produced by NIWA
- Historical climate data
    - Long-term composite Tauranga station data (daily rainfall, min/max monthly temperature) from Griffiths et al. (2003)
    - Daily rainfall, min/max monthly temperature) data from CLI-FLO from Tauranga Airport AWS (Automatic Weather Station) data for the period 2002–current
    - Data were produced by NIWA and missing data filled
- Future climate projections for Tauranga between 2001 to 2051 in increments of 10 years.
    - Data were produced by NIWA
- Solar radiation for Tauranga
    - Data were produced by NIWA and missing data filled

Appendix 3: Data sources for land use / cover scenarios

1) The data sources and maps for creating land use /cover scenarios for the period 1943 to 2008 included:

- Land use/cover shapefiles
  - Arc-GIS shape files for 1959
  - Data were provided by the Environment Bay of Plenty (EBOP)
- New Zealand Landcover Database 2 (LCDB2)
  - Based on Landsat 7 ETM + satellite imagery (70 land cover classes)
  - Provides a snap-shot of land cover in 2001/02
  - Ground-truthed in 2003-2004
  - Data were available from EBOP
- Aerial imagery/photography
  - High resolution black and white aerial photographs for 1943
  - High resolution geo-referenced aerial photographs for 2007
  - Data were provided by EBOP.
- Roads
  - Road cadastral maps for TCC and Western BOP
  - Data were provided by EBOP

2) The data sources and maps for creating future land use /cover scenarios for the period 2007 to 2060 from current and future zoning, future population demographics and business land changes information, included:

- Current urban and rural zoning
  - District plan zoning – TCC.
  - District plan zoning – Western BOP.
  - Data were provided by EBOP.

- Future population demographics
  - TCC and Western BOP future demographics.
  - Map 1 of SmartGrowth (2007): Western BOP sub-region settlement plan, p.7.
  - Map 2 of SmartGrowth (2007): Western BOP sub-region main urban areas, p.8.
  - Figure 7 of SmartGrowth (2007): Residential Development Timing Diagram, p. 27.
  - Table of projected additional resident population. p. 238 of SmartGrowth (2007).
- Future business land changes
  - Business Land Staging Plan, Sub-regional settlement plan.
  - Map 3 of SmartGrowth (2007): Business land staging plan, p.9

Table A1: Major soil types (soil symbols) in the Tauranga region from the NZLRI and their areas in a subcatchment as a percentage of the total subcatchment area (SC=subcatchment, TC=total catchment).

SC	AS	Ka	KaH	KaR	Kh	Ki	M	Mg	MH	MM	MN	Mu	Oa	Oe	Or	OrH
1		20.9	0.7	6.8		38.9						4.5		19.1		
2		17.7	0.2			53.2				20.6		2.9		0.4		
3		10.9				34.3				1.4		2.9	9.0	0.6		
4		0.0										0.9	0.3			
5		7.8	8.2	8.0								0.8				
6		20.3	6.5	8.8	0.0					2.4		0.9	0.0		24.6	6.9
7		21.9	4.3	12.0						2.1		1.0			30.0	2.0
8	2.1	12.0	5.2	12.4			19.3	0.0	0.6	0.1	0.2	0.0			2.7	0.3
9		54.8	19.1	19.2								0.7				
10		25.4	20.2	29.1								0.2				
11		35.9	14.0	45.5								0.6				
12		27.7	15.6	29.9								0.5				
13		35.2	13.6	45.1								0.5				
14		13.3	18.6	22.2								0.0				
15	17.2	15.2	3.6	32.9							0.5	0.3				
16		44.9	9.5	22.0						3.9		9.1				
17		24.1	12.8	52.5								1.8		0.7		
TC	2.34	16.05	6.51	15.25	0.0	1.66	9.06	0.01	0.28	0.82	0.11	0.57	0.12	0.29	6.57	1.11

SC	OS	Osl	Pa	Pp	Pt	Rp	Tk	TkH	TkR	TM	TP	Whar	Wi	Wk	WkH	WkR
1		1.2	1.7	2.5								3.7				
2	1.5		0.3	2.4												
3	0.0	1.0		2.5	2.5	5.9	16.1	5.0	0.9	0.7		4.0				
4	19.9		1.2			0.0	10.1	21.2	25.1	1.9	1.8		0.5	1.9	13.5	1.7
5	2.3		0.0				15.9	5.1	50.0	0.7				0.9		
6	10.9		0.4				4.3	0.9	1.9	0.5	0.1			5.0	1.8	3.9
7	20.2		0.0			0.7	0.7			2.9	0.2		1.7			
8	20.8		0.6							0.7	0.2			11.3	6.5	4.9
9	1.7		4.4													
10	3.9		0.7								0.4			0.1	9.3	10.4
11			3.6	0.4												
12	2.5		1.3	0.5							0.4			0.8	6.3	14.5
13			5.4													
14	8.2		1.1							0.6	0.6			7.7	2.1	25.5
15	7.5		1.5							2.4				14.8	0.5	3.5
16			10.6													
17	0.9	1.0	5.0								1.2					
TC	14.73	0.04	0.95	0.12	0.03	0.13	0.13	1.19	2.34	0.91	0.28	0.10	0.16	7.46	4.45	4.85

Table A2: Major soils in the Tauranga region from the NZLRI and their areas.

NZ Soil order group	Area (ha)	% of total area
Acid Gley Soils	1375	1.39
Fluvial Recent Soils	1015	1.02
Gley Raw Soils	568	0.57
Mesic Organic Soils	29	0.03
Orthic Allophanic Soils	57153	57.59
Orthic Gley Soils	129	0.13
Orthic Podzols	29877	30.11
Orthic Pumice Soils	7625	7.68
Sandy Brown Soils	134	0.13
Sandy Raw Soils	287	0.29
Sandy Recent Soils	118	0.12
Tephric Recent Soils	120	0.12
Truncated Anthropic Soils	810	0.82

Table A3: Major soils in the Tauranga region from the NZLRI, their names, symbols and *S-map* names.

Soil name	Symbol	*S-map* name
Arahiwi steepland soils	AS	Aroha_1.1
Katikati sandy loam	Ka	Kati_1.3
Katikati hill slope	KaH	Waite_1.2
Katikati sandy loam, rolling phase	KaR	Kati_1.4
Kaharoa sand	Kh	Mkus_3.1
Kairua loamy sand	Ki	Kairu_1.1
Mangorewa sandy loam	Mg	Mkus_4.1
Mamaku hill soils	MH	MkuH_1.1
Mamaku loamy sand	M	Moka_2.1
Man-made soils	MM	Manm_1.1
Manoeka silt loam	MN	Mano_1.1
Muriwai sand	Mu	Muriw_1.1
Ohineangaanga silt loam	Oa	Ohin_1.1
Ohope sand	Oe	Kyra_9.1
Oropi sand	Or	Oropi_2.1
Oropi hill soils	OrH	Paeng_2.1
Otanewainuku steepland soils	OS	Otan_1.1
Pahoia silt loam	Pa	Paho_1.1
Papamoa loamy sand	Pp	Wiku_3.1
Parton fine sandy loam	Pt	Parto_1.1
Raparapahoe silt loam	Rp	Rapar_1.1
Te Puke sandy loam	Tk	Kati_2.1
Te Puke hill soils	TkH	Tutae_2.1
Te Puke sandy loam	TkR	Kati_2.2
Te Matai silt loam	TM	Tema_1.1
Te Puna silt loam	TP	Tepu_1.1
Waiari silt loam	Wi	Paho_2.1
Whakamarama fine sandy loam	Wk	Ngong_2.1
Whakamarama hill soils	WkH	Ngong_3.1
Whakamarama sandy loam	WkR	Ngong_4.1
Wharere silt loam	Whar	Whar_1.1

Table A4: Tauranga future climate scenario offsets. Hottest, wettest, 12-model average.

Tauranga scenarios: monthly temp (C) & prec (mm) changes for 2020-2060 for
Scenario H: Hottest model (miroc32_hires)
Scenario W: Wettest model (ncar_ccsm30)
Scenario A: 12-model average

Scenario H: Hottest model (miroc32_hires)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature (C)												
2020	1.111	1.069	1.082	1.186	1.032	0.824	0.935	0.964	0.962	0.814	0.804	0.935
2030	1.481	1.426	1.443	1.581	1.376	1.099	1.246	1.285	1.283	1.086	1.072	1.247
2040	1.852	1.782	1.803	1.976	1.72	1.374	1.558	1.606	1.603	1.357	1.341	1.558
2050	2.335	2.315	2.224	2.37	2.122	1.795	1.977	2.001	2.003	1.778	1.794	2.049
2060	2.819	2.847	2.645	2.764	2.524	2.216	2.397	2.395	2.402	2.199	2.248	2.54
Precipitation (mm)												
2020	3.964	-8.937	1.869	1.449	-3.733	-8.1	1.037	-1.348	2.204	11.219	-5.705	-2.779
2030	5.285	-11.916	2.491	1.933	-4.977	-10.799	1.383	-1.798	2.938	14.958	-7.606	-3.706
2040	6.606	-14.896	3.114	2.416	-6.222	-13.499	1.728	-2.247	3.673	18.698	-9.508	-4.632
2050	7.075	-10.52	4.443	3.121	-3.876	-12.633	0.526	-2.356	3.6	16.613	-8.685	-1.064
2060	7.543	-6.145	5.772	3.826	-1.531	-11.767	-0.677	-2.465	3.526	14.528	-7.862	2.505

Scenario W: Wettest model (ncar_ccsm30)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature (C)												
2020	0.867	0.811	0.719	0.772	0.569	0.475	0.475	0.541	0.596	0.66	0.624	0.779
2030	1.156	1.081	0.959	1.029	0.759	0.633	0.633	0.721	0.794	0.88	0.832	1.038
2040	1.445	1.351	1.199	1.286	0.948	0.791	0.792	0.901	0.993	1.099	1.04	1.298
2050	1.655	1.575	1.387	1.445	1.156	0.945	0.969	1.043	1.166	1.258	1.219	1.483
2060	1.864	1.799	1.576	1.603	1.363	1.098	1.146	1.185	1.339	1.417	1.398	1.669
Precipitation (mm)												
2020	11.661	11.56	8.974	9.892	-0.568	5.999	-11.373	-4.5	-3.69	6.414	-3.812	4.586
2030	15.548	15.414	11.965	13.19	-0.758	7.999	-15.164	-5.999	-4.921	8.553	-5.082	6.115
2040	19.435	19.267	14.956	16.487	-0.947	9.998	-18.955	-7.499	-6.151	10.691	-6.353	7.643
2050	18.6	19	13.825	15.358	-0.421	6.254	-17.443	-7.174	-6.31	8.434	-3.63	7.952
2060	17.765	18.733	12.693	14.23	0.106	2.51	-15.931	-6.848	-6.469	6.178	-0.906	8.261

Scenario A: 12-model average

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature (C)												
2020	0.653	0.693	0.604	0.623	0.583	0.527	0.571	0.536	0.535	0.487	0.495	0.551
2030	0.87	0.924	0.805	0.83	0.777	0.703	0.762	0.715	0.713	0.65	0.66	0.734
2040	1.088	1.154	1.006	1.038	0.971	0.878	0.952	0.894	0.891	0.812	0.825	0.918
2050	1.329	1.407	1.267	1.281	1.206	1.116	1.187	1.125	1.099	1.027	1.05	1.159
2060	1.57	1.66	1.528	1.524	1.44	1.355	1.421	1.355	1.306	1.243	1.274	1.4
Precipitation (mm)												
2020	1.529	1.836	2.741	2.007	0.295	-1.507	-3.286	-3.418	-4.669	-2.058	-2.23	-0.326
2030	2.038	2.448	3.654	2.676	0.393	-2.01	-4.382	-4.557	-6.225	-2.744	-2.973	-0.434
2040	2.548	3.061	4.568	3.345	0.492	-2.512	-5.477	-5.696	-7.782	-3.43	-3.716	-0.543
2050	1.653	3.522	4.891	2.816	0.252	-2.286	-5.397	-5.491	-8.493	-4.506	-4.028	-0.334
2060	0.759	3.983	5.215	2.288	0.013	-2.06	-5.317	-5.286	-9.205	-5.581	-4.339	-0.125