Assessment of the CLUES Model for the Implementation of the National Policy Statement on Freshwater Management in the Auckland Region

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Assessment of the CLUES Model for the Implementation of the National Policy Statement on Freshwater Management in the Auckland Region

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NIWA

Executive summary

This report was commissioned by Auckland Council ("the council") to demonstrate how the Catchment Land Use for Environmental Sustainability (CLUES) model can be used as part of the council's implementation programme for the National Policy Statement on Freshwater Management (NPSFM, Ministry for the Environment, MfE, 2011). The NPSFM requires regional councils to, amongst other actions, set water quality limits and, where those limits are exceeded, specify targets for water quality and implement measures to reach those targets. The Ministry for the Environment working document *Freshwater reform 2013 and beyond* (MfE, 2013; henceforth referred to as FRB2013) recommends the use of models in the implementation of the NPSFM to aid communication and understanding of water quality issues among a range of stakeholders, including scientists and other experts, policy makers, regulators and community groups.

CLUES is a steady-state modelling system for assessing the effects of land use change on water quality and socio-economic factors at a minimum scale of sub-catchments. It simulates annual catchment in-stream loads of total nitrogen, total phosphorus, sediments and *E. coli*, nutrient concentrations and generated yields of nutrients and sediment. The model's geographical information system platform (ESRI ArcMap v. 10) means that inputs and outputs can be mapped to allow geo-visualisation of problems, alternative solutions and outcomes. Additionally, CLUES output can be can be exported as CSV files for further analysis in other software packages.

In accordance with the NPSFM and FRB2013 the council would like to assess whether and how CLUES could be used to provide background information to council staff and other stakeholders including community groups and iwi for decision-making. For instance, CLUES water quality simulations could be included in expert reports prepared for council staff or in the council's State of Auckland freshwater report cards to inform the public of water quality issues and possible solutions. CLUES could also be applied interactively at public meetings to facilitate discussion over water management options.

This report:

- Overviews the CLUES model and associated geo-spatial data, including default land cover (based on the Land Cover Data Base for 2002, LCDB2) supplied with the model software. (Section 2.0)
- Develops two land use scenarios relating to the years 1770 ("Pre-European") and 2008. The Pre-European scenario was created to give an insight into historical contaminant loads which are indicative of the background or natural state of water quality in the Auckland region. The 2008 scenario updates the default land use on the basis of land cover mapped in the more recent LCDB3. (Section 2.3)
- Simulates water quality using the default, updated and Pre-European land use scenarios to provide examples of how CLUES results can be extracted and displayed for either further analysis or to aid public understanding of water quality issues. In addition to regional maps, CLUES results are aggregated and displayed in tabular form by catchment for ten river catchments and three lake catchments selected in consultation with the council. (Section 3.0)

- Demonstrates the ability of CLUES to provide current state information on contaminant loads and concentrations in the Auckland region by comparing CLUES results with long-term water quality observations. Sources of model uncertainty and error are discussed and calibration needs with respect to the Auckland region are evaluated. (Section 4.0)
- Overviews proposed changes to freshwater management in New Zealand and where CLUES fits within the context of those changes. The overview presents a number of case studies where CLUES has already been applied to aid planning. Planned user-directed improvements to the model in relation to the proposed changes are also discussed. (Section 5.0)
- Discusses the scope for further work including the need for local calibration. (Section 6.0)

This assessment found that in general, there is a poor fit between CLUES results and estimates of water quality derived from other data sources in the Auckland region and that, consequently, there is a pressing need to calibrate CLUES locally. The data has not been purpose collected for modelling and consists largely of monthly contaminant concentrations taken for state of the environment reporting. These data were collated into 5-year median concentrations for comparison with CLUES. However, at present, there are few water quality monitoring sites in the region which have sufficient sample numbers and hydrometric monitoring nearby to allow the calculation of contaminant loads, needed for calibration, from measured concentrations. There are only a handful of sites suitable for calibration of sediment and nutrient loads and no sites suitable for calibration of *E. coli*. The possibility of instead calibrating using data from Northland and Waikato as well as Auckland is mooted. There is also a need to review the regional spatial data held in the CLUES geospatial database.

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1.0 Background

Auckland Council has commissioned this report to demonstrate the potential use of the Catchment Land Use for Environmental Sustainability (CLUES) model as part of its implementation programme for the National Policy Statement on Freshwater Management (Ministry for the Environment, MfE, 2011, henceforth referred to as NPSFM).

The NPSFM requires regional councils to, amongst other actions, set water quality limits and, where those limits are exceeded, specify targets for water quality and implement measures to reach those targets. In response, the regional council research for the Environment Strategy (2011) states that there is a need for better understanding of the cumulative impacts of human activities on water quality and to identify the ecological limits for those activities. Moreover, the strategy identifies a need for decision support systems and tools which can be used for scenario building, particularly in terms of natural resources, such as freshwater, which are under pressure. This response is echoed in the Ministry for the Environment working document Freshwater Reform 2013 and Beyond (MfE, 2013; henceforth referred to as FRB2013). This document calls for the use of models to aid communication and understanding of water quality issues among a range of stakeholders from scientists and other experts to policy makers and regulators and community groups. The CLUES model is such a tool.

CLUES was developed for the Ministry of Agriculture and Forestry (now Ministry for Primary Industries, MPI) in association with MfE. It is a modelling system for assessing the long-term effects of rural land use change on water quality (as indicated by total nitrogen, TN, total phosphorus, TP, sediment and *E.coli*) and socio-economic factors (e.g., full-time farm equivalents, green-house gas emissions) at a minimum scale of sub-catchments within the NIWA River Environment Classification (REC). CLUES allows users to create both land use change and farm practice (stocking rates, mitigation) scenarios using a range of interactive tools. For each REC river reach, CLUES returns the following key annual water quality indicators: nutrient (total nitrogen and total phosphorus) yields, loads and concentrations, suspended sediment yields and loads and *E.coli* loads. Model results are provided as either shape files or tables which can be exported to other software packages for further analysis.

CLUES is a spatial decision support system which couples a number of existing models within a GIS-platform and is provided free to users as a front-end interface for ArcGIS. The GIS platform means that CLUES-generated results can be displayed with other spatial data such as the location of sensitive ecosystems and cultural and heritage sites. Zoom and pan tools mean that users can see detail or "the whole picture" as required. The inclusion of GIS display tools and the ability to create and simulate multiple scenarios means that CLUES can facilitate a decision making process which is iterative, integrative and participative.

The ability of CLUES to simulate the impacts of land use change and farm practices on freshwater means that CLUES has been used in a number of recent studies commissioned by regional councils including for Environment Canterbury (Lillburne et al., 2011), Environment Southland (Hughes et al, 2013; Semadeni-Davies and Elliott, 2011, Monaghan et al., 2010) and Waikato Regional Council (Semadeni-Davies and Elliott, 2012). In the Auckland region, CLUES was used to provide estimates of current and historical sediment and nutrient loads delivered to the Kaipara

Harbour as part of the Ministry of Business Innovation and Employment funded Clean Water / Productive Land research programme (Semadeni-Davies, 2012). Further work is underway to evaluate the possible impact of riparian and conservation planting on sediment loads delivered to the harbour. CLUES has also recently been applied nationally in a study for the Ministry for the Environment (in preparation) to determine land use capacity related to the impacts of land use intensification on freshwater.

1.1 Study scope

The objective of this project is to demonstrate the potential value of using CLUES as part of the Auckland Council's implementation programme for the NPSFM. It is intended that CLUES be used to provide background information to council staff and other stakeholders including community groups and iwi for decision making. CLUES water quality simulations could be included in, for example, expert reports prepared for the council, council State of Auckland freshwater report cards[1] and on public notice boards. CLUES could also be applied interactively at public meetings to facilitate discussion over water management options.

The following tasks were defined as the scope for the study:

1. Simulation of annual sediment and nutrient annual yields, loads and concentrations from rural land uses across the Auckland region for:
   i. Default land use for the year 2002 (i.e., derived from New Zealand Land Cover Database, LCDB2[2])
   ii. Preliminary land use for the year 2008 derived from LCDB3
   iii. Pre-European land use (1770) based on historic vegetation maps
   iv. Model results presented as maps and in tabular form for ten river catchments and three lake catchments selected in consultation with the council.
2. A summary of the water quality of freshwater bodies across the region with reference to council State of Environment (SOE) reporting. The summary will report any gaps (or confirmation of adequate coverage) with respect to spatial extent across the region and representation of land use types for the purposes of eventual CLUES calibration. It will also make reference to proposed MfE water quality monitoring protocols (Davies-Colley et al., 2011).
3. Comparison of the following model results against equivalent long term observations:
   i. Annual nutrient concentrations simulated for 2002 and 2008 against long-term (5 year) median concentrations recorded at council and NIWA maintained rural freshwater quality monitoring sites.

[1] http://stateofauckland.aucklandcouncil.govt.nz/report-type/freshwater-report-card/

[2] http://www.mfe.govt.nz/issues/land/land-cover-dbase/

The comparison will include an analysis of model fit with respect to different factors which influence water quality such as land use. For sites with poor fit, it will also investigate whether there are any identifiable factors leading to that poor fit.

ii. Annual nutrient loads which are calculated from observed concentrations for water quality monitoring sites with suitable data (i.e., at least 60 observations and nearby flow monitoring). This work will be the first step towards a local calibration of CLUES for the region in the next financial year.

iii. Annual sediment yields against yields calculated from load observations presented in Hicks et al. (2009) and Curran-Cournane et al. (2013).

4. An overview of the CLUES modelling context with respect to data requirements, model uncertainty and applications to date. The overview will also include a discussion of future modelling work that can further aid implementation of the NPSFM, how CLUES fits within FRB2013 and will make reference to the council's submission to MfE in response to the document. Of special interest to the council are the opportunities related to collaborative engagement with stakeholders in real-time (e.g., at public meetings). Also of interest is how CLUES relates to use of other models, tools and programmes.

5. An overview of the aspirations of the CLUES programme including:

   i. Planned updates to the model such as finer spatial resolution, updated land use and linkage to the new REC database.

   ii. Possibilities for tailoring CLUES to the Auckland Region, such as local calibration and the replacement or merging of the REC database with the council's own spatial information.

1.2 Report structure

The report is organised into sections which:

- Overview the CLUES model and associated geo-spatial data supplied with the model software. In addition to the default land use scenario (baseline year 2002), two land use change scenarios are developed relating to the years 1770 ("Pre-European") and 2008. (Section 2.0);
- Simulate water quality using the three land use scenarios to provide examples of how CLUES results can be extracted and displayed for either further analysis or to aid public understanding of water quality issues. (Section 3.0);
- Demonstrate the ability of CLUES to provide current state information on contaminant loads and concentrations in the Auckland region by comparing CLUES results with long term water quality observations. Sources of model uncertainty and error and discussed and calibration needs with respect to the Auckland region are evaluated. (Section 4.0);
- Overview proposed changes to freshwater management in New Zealand and where CLUES fits within the context of those changes. (Section 5.0); and
- Discuss the scope for further work including the need for local calibration. (Section 6.0)

2.0 CLUES

2.1 Model overview

CLUES is a modelling system for assessing the effects of land use change on water quality and socio-economic factors at a minimum scale of sub-catchments (~10km^2 and above). CLUES couples a number of existing models within a GIS-platform and is provided to users as a front-end interface for ArcGIS which queries a geo-spatial database (Figure 1). The CLUES interface has tools which allow users to develop land use change and farm practice scenarios. The latter refer to percentage adjustments to stocking rates and contaminant yields from stock. This study uses CLUES version 10 which was developed specifically for use with ESRI ArcMap 10 GIS software.

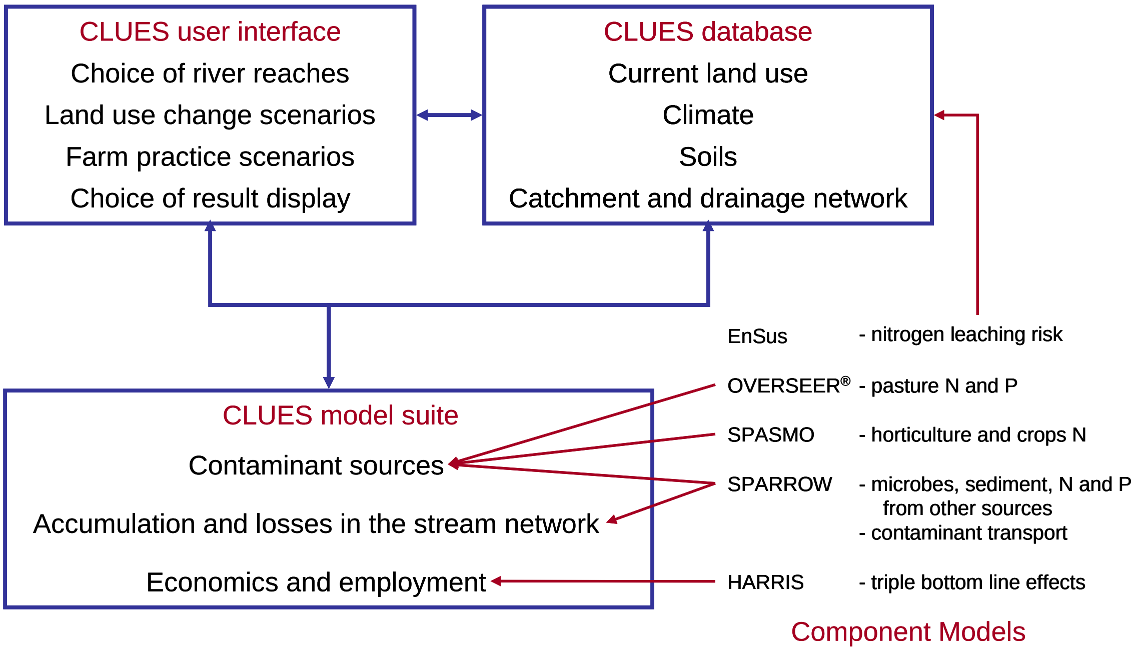


Figure 1: CLUES modelling framework (source: Semadeni-Davies et al., 2011).

The CLUES framework integrates the following models into one tool within a GIS platform:

- **OVERSEER**® (AgResearch, Wheeler et al. 2006) is a farm-scale annual nutrient balance model. A customised, pre-parameterised version of OVERSEER 6 is provided within CLUES which computes nutrient leaching for dairy, sheep and beef and deer farming[3]. The model treats each REC sub-catchment as a single farm and provides annual average estimates of nutrient losses from each land use, given information on rainfall, soil order, topography and fertiliser applications. For other variables, such as fertiliser application rates, typical values are used based on the region and land use.

[3] CLUES has since been updated to use OVERSEER version 6.1

- **SPARROW** (Spatially Referenced Regression on Watershed attributes) - predicts annual average stream loads of total nitrogen, total phosphorus, sediment and *E.coli*. It includes extensive provisions for stream routing and loss processes (storage and attenuation). This modelling procedure was originally developed by the United States Geological Survey (Smith et al. 1997) and has since been applied and modified in the New Zealand context with extensive liaison with the developers. SPARROW has been applied to nitrogen and phosphorus in Waikato (Alexander et al., 2002) and subsequently to the whole New Zealand landscape (Elliott et al. 2005). The SPARROW sediment transport routines were assessed by Elliott et al. (2008) and simulations compared favourably with measured sediment load data.
- **SPASMO** (Soil Plant Atmosphere System Model, HortResearch) - calculates the nitrogen budget for a range of horticultural enterprise scenarios. Detailed simulations for many cases (combinations of crops, climate, fertiliser use) have been run (using a daily time step) to build look-up tables that CLUES queries. It has been validated against data from grazed pasture (Rosen et al. 2004) and pasture treated with herbicide (Close et al. 2003, Sarmah et al. 2004).
- **Harris – triple bottom line** (Harris Consulting, Harris et al., 2009) - estimates economic output from different land use types (pasture, horticulture, forestry and cropping), in terms of Cash Farm Surplus (CFS), Total GDP and Total Employment from that land use, given as a function of output. The calculations are based on the MAF farm monitoring models.
- **EnSus** (Environmental Sustainability, Landcare Research) - provides maps of nitrogen leaching risk, used as an adjunct to interpretation of CLUES results. It is based on studies of nitrogen losses at national and regional scales (Hewitt and Stephens, 2002; Parfitt et al. 2006).

The base areal unit of CLUES is the sub-catchment which comes from the NIWA River Environment Classification (REC) of the national stream and sub-catchment network. Predictions of the CLUES surface water quality and financial indicators can be made for any reach. CLUES does not contain a groundwater model. That is, the water quality effects of groundwater are not simulated - rather, it is assumed that water percolating into the ground will emerge in the same surface river reach sub-catchment.

CLUES is available free of charge for non-commercial use and is provided in geographical packages. Further details on the modelling framework can be found in Woods et al. (2006a) and information on setting up and running CLUES scenarios can be found in Semadeni-Davies et al. (2011 and 2012).

Water quality indicators generated by CLUES that are presented in this report are:

- Nutrient (kg/year), sediment (kilo-tonnes/year) and *E.coli* (10^{15} or one "peta" of organisms/year) loads.
- Nutrient concentrations (mg/m^3)
- Nutrient (kg/ha/year) and sediment (t/ha/year) catchment generated yields – i.e., the yield generated by each REC sub-catchment.

- Nutrient (kg/ha/year) and sediment (t/ha/year) in-stream cumulative yields - calculated as the in-stream load for a river reach divided by contributing area including stream tributaries.

Note that generated and cumulative yields and concentrations for *E.coli* and sediment concentrations for are not available within CLUES.

2.2 Input data

This section describes the geo-spatial data provided with CLUES for each geographical package. This project was undertaken using the North_Auck geographical package which contains spatial information for the Auckland and Northland regions.

2.2.1 Hydrology and catchment properties

The hydrological network within CLUES is derived from the REC. For each river reach in the country, CLUES holds information on:

- the direction of flow and the reach sequence from headwater to river mouth;
- estimated annual mean discharge (refer Woods et al., 2006b);
- stream order; and
- reach type (lake, river or coastal/terminal reach).

Catchment data provided in the CLUES geo-database for each river reach includes:

- land use (see Section 2.2.2);
- annual average rainfall;
- average catchment slope;
- soil order and drainage class (from the NZ Land Resources Inventory, NZLRI, Fundamental Soils Layer – Wilde et al., 2004);
- nutrient leaching and sediment loss (erosion) rates based on soil and slope; and
- known nutrient and *E.coli* point sources such as piggeries, pulp and paper mills, and waste water treatment plants.

The REC reaches simulated in this project were selected from the Northland/Auckland package on the basis of the regional shape file provided by Auckland Council. There are around 9100 REC reaches in the region. Examples of the geo-spatial data held in CLUES across the region are given in Figure 2 for annual rainfall, slope, soil drainage class and soil type. REC sub-catchments which contain a point source have an estimated daily load from the source which is added to the in-stream load. Point sources and their associated daily loads are given in Table 1.

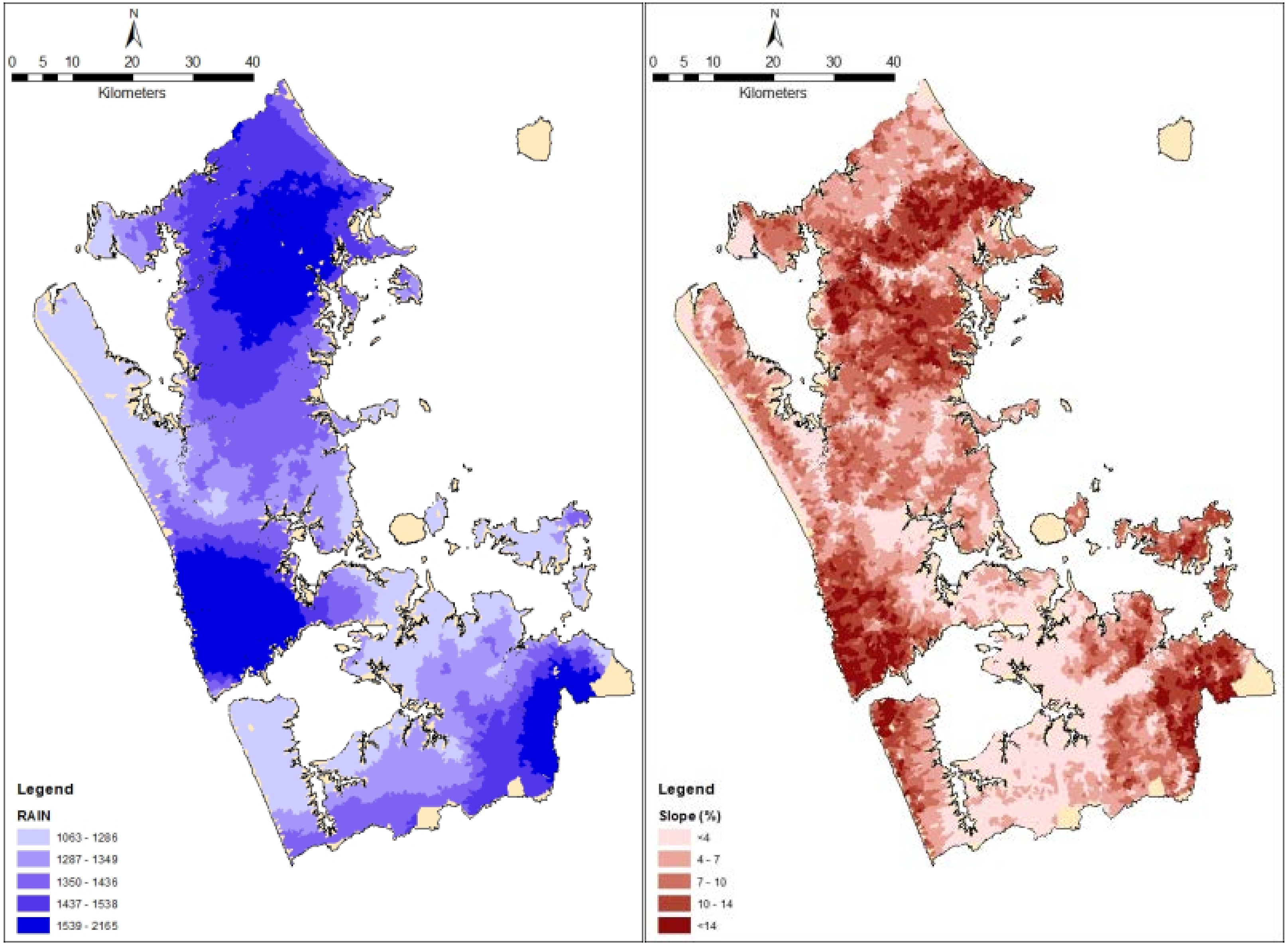


Figure 2 Examples of geo-spatial data held in CLUES which describe the physical characteristics of each REC sub-catchment: this page, left - annual rainfall depth (mm); this page right - slope (%); over leaf, left - soil type; and over leaf, right - drainage class.

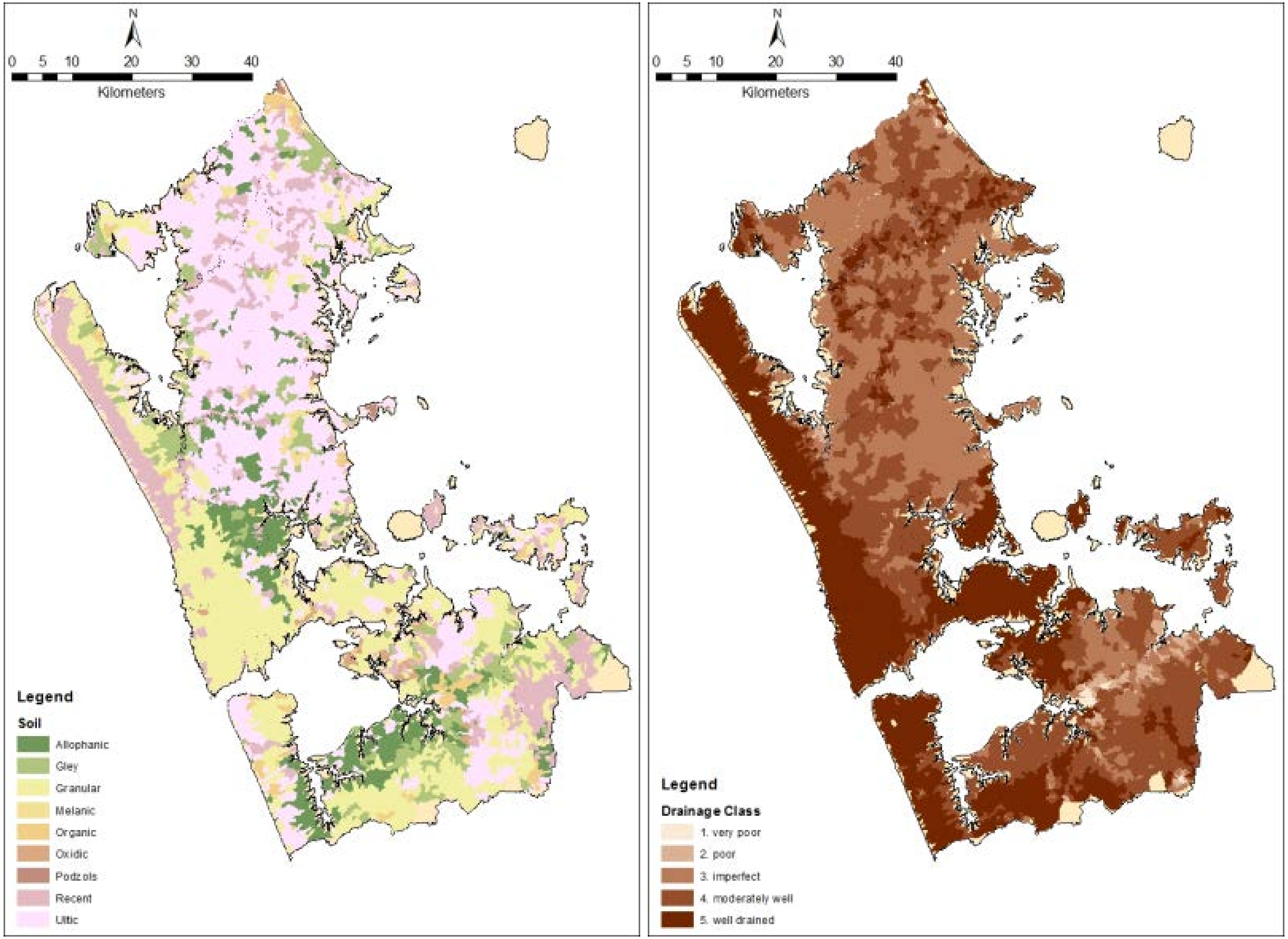


Figure 2 continued, left, soil type, right, drainage class.

Table 1 CLUES point sources in the Auckland region and associated estimated daily contaminant loads

Source	Location	NZ REACH	TN (kg/day)	TP (kg/day)	*E.coli* (organisms/day)
Sewage	Wellsford	2001121	36	9	7.44E+09
Sludge	Beachlands	2006196	15	2	1.67E+11
Sewage	Ardmore	2007489	18	4.5	3.88E+10
Dairy	Paerata	2008970	60	4	1.68E+13
Piggery	Paerata	2009158	200	50	3.11E+11

2.2.2 Land use

CLUES represents land use in each REC sub-catchment by the percentage of the sub-catchment area covered by each of 19 land use classes (listed in Table 2). The default land use layer provided with CLUES was developed with extensive reference to the LCDB2 (Land Cover Database)[4], AgriBase (AsureQuality Ltd)[5], and LENZ (Land Environments of New Zealand)[6] land use geo-databases and refers to land use in 2002. While LCDB2 contains information of the location of broad land use classes (e.g., grassland), AgriBase and LENZ were used to split these classes into sub-classes characterised by different contaminant yields (e.g., lowland intensive, hill country and high country sheep and beef farming). Farming stocking rates and fertiliser application rates to pasture and crops have been derived from national data and represent average annual applications (see Wood et al., 2006a). Considerable effort was expended, with Landcare Research, to ensure that the spatial data coverage was as accurate as possible.

Figure 3 shows the dominant land uses that were used to determine the land cover percentages for each REC sub-catchment in the Auckland region and an example of how this data is represented in CLUES, in this case, the percentage area covered by dairy farms for each REC sub-catchment.

[4] http://www.mfe.govt.nz/issues/land/land-cover-dbase/classes.html (date of last access 25 March 2013)

[5] http://www.asurequality.com/capturing-information-technology-across-the-supply-chain/agribase-database-for-nz-rural-properties.cfm (date of last access 25 March 2013)

[6] http://www.landcareresearch.co.nz/resources/maps-satellites/lenz (date of last access 25 March 2013)

Table 2 CLUES 10 land use classification. (From Semadeni-Davies et al., 2011)

Broad LCDB2 land use type	CLUES land use codes	Class description
Grassland	Dairy	dairy farming
	Sbinten	low land intensive sheep and beef
	Sbhill	hill country sheep and beef
	Sbhigh	high country sheep and beef
	Deer	deer
	Other_ANIM	other types of farm animals
	Tussock	tussock
	Ungr_past	ungrazed pasture
Cropland	Maize	arable crops (based on maize)
	Onions	onions
	Potatoes	potatoes
	Kiwifruit	kiwifruit
	Apples	pip fruit (e.g., apples, pears)
	Grapes	viticulture, vineyards
Forest	Plant_for	planted exotic forest, forestry
	Nat_for	native forest
Scrubland	Scrub	scrubland
Artificial surfaces	Urban	Built up areas, there are no urban sub-classes
Other land use types:	Other	other land covers (e.g., ice, water, bare soil etc.)

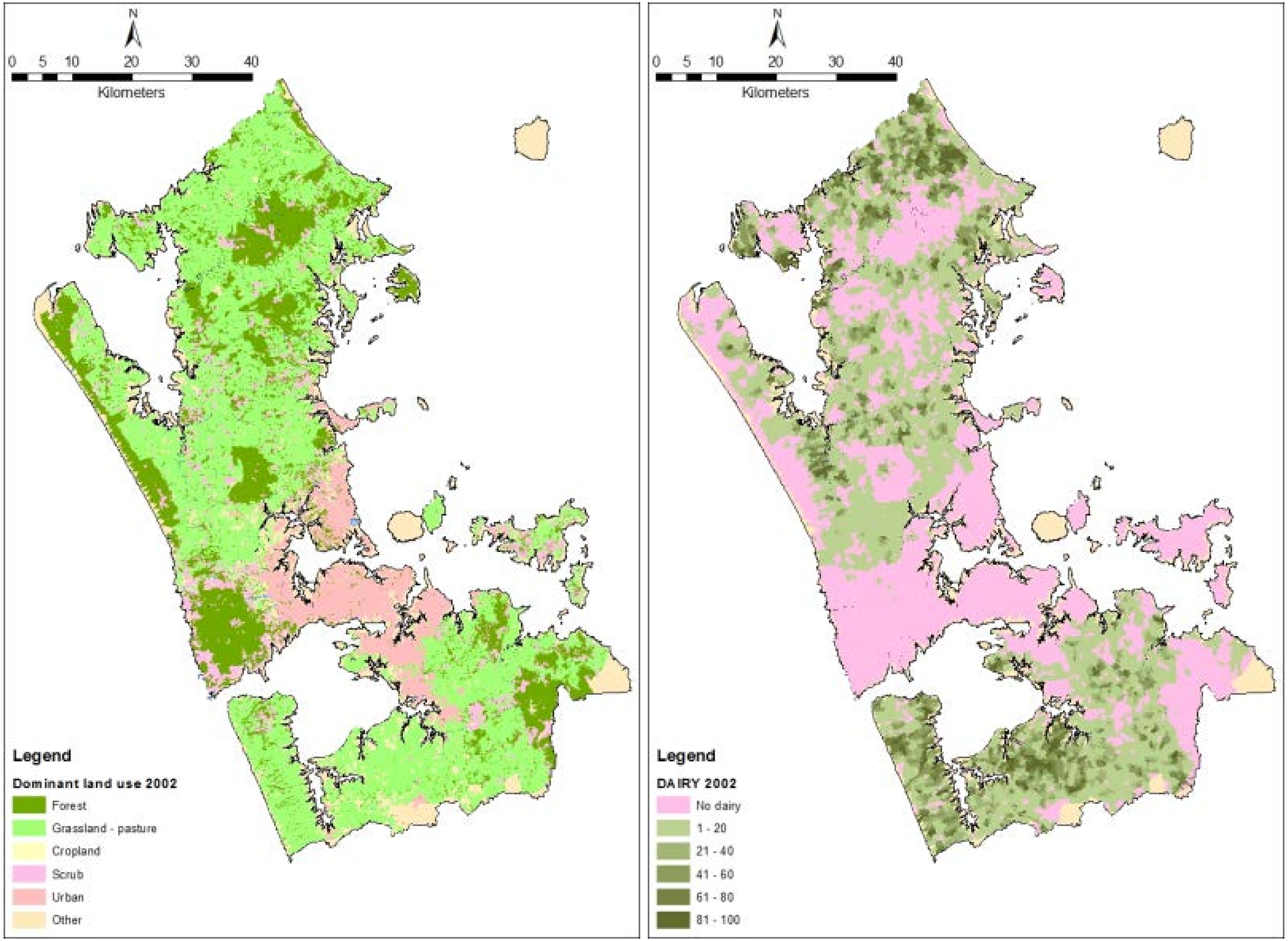


Figure 3 CLUES land use representation: left, dominant land use used to create the default (2002) land use scenario; right, percentage dairy farming by REC sub-catchment from the default scenario.

2.3 Land use scenarios

Two land use scenarios were developed for this project, a Pre-European baseline to give an indication of stream water quality without human activities and a scenario based on land use in 2008 to update the default land use. These scenarios are described further below.

2.3.1 Pre-European

The pre-European CLUES land use scenario is based on a national vegetation layer for the year 1770 supplied by Landcare Research (personal communication: Robbie Price). The layer breaks vegetation in the Auckland region into forest, manuka/kanuka scrub, grass, swamp and fern (Figure 4) and was derived from a variety of sources including historical vegetation maps and pollen analysis. The map shows broad agreement with other sources for this time period (e.g., Beever, 1981; *Te Ara - the Encyclopedia of New Zealand*, 2012). Forest was assigned to the CLUES land cover class Native Forest, and the other vegetation types were grouped into the CLUES Scrub land use class. The pre-European land use scenario was created by overlaying the 1770 vegetation layer onto a CLUES scenario table so that each REC sub-catchment was split into weighted proportions of native forest and scrub.

2.3.2 CLUES updated land use (2008)

Figure 5 shows the provisional dominant land use for each REC sub-catchment and the percentage dairying based on LCDB3 and AgriBase for the year 2008. The 2008 land use scenario was created for a planned update of the CLUES default land use geo-spatial database and is not yet publically available; its use in this project was negotiated by Auckland Council subject to the understanding that since the layer has not been ground-truth tested, it may not give a true representation of regional land use. Note that the land use map shown in Figure 5 does not have the same spatial resolution as that shown in Figure 3: the latter shows land use before spatial aggregation into REC sub-catchments. However, within the model, the two scenarios have the same spatial resolution. Overall, there has been little change in the broad land use classes between LCDB2 and LCDB3.

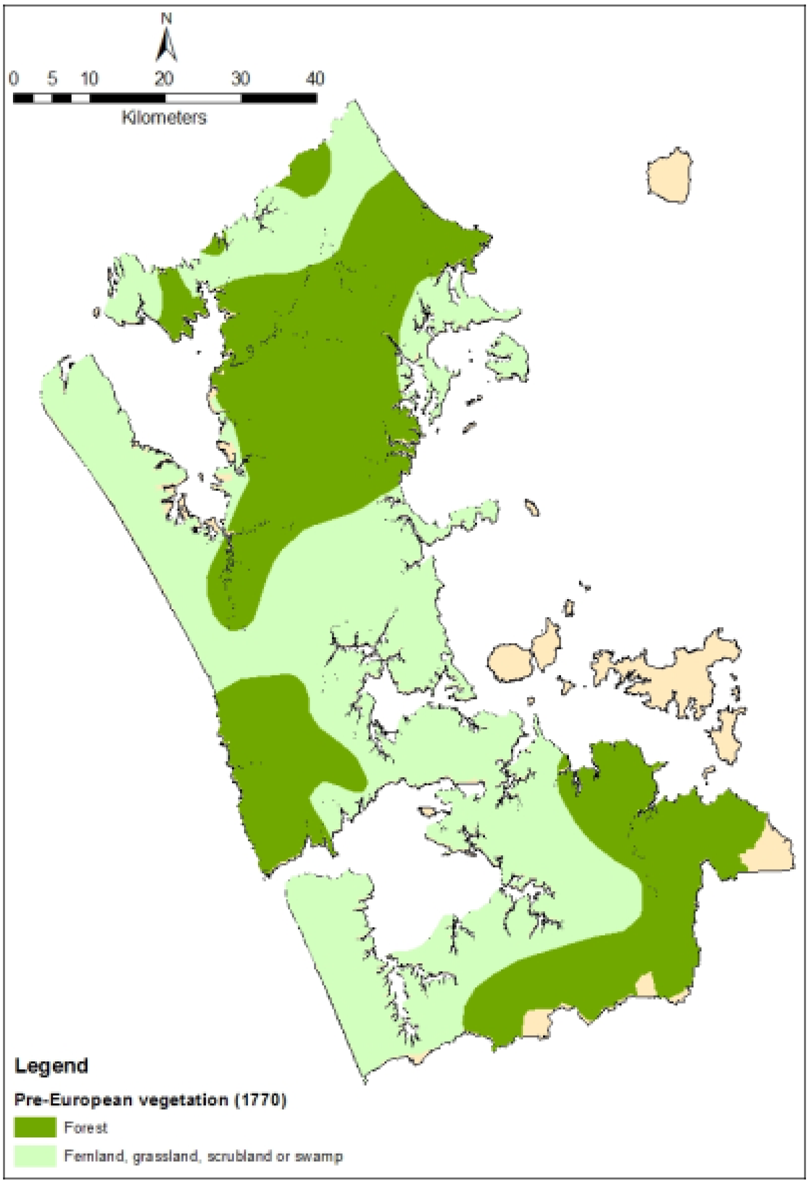


Figure 4 Pre-European vegetation cover. (Source, Landcare Research, off-shore islands not included)

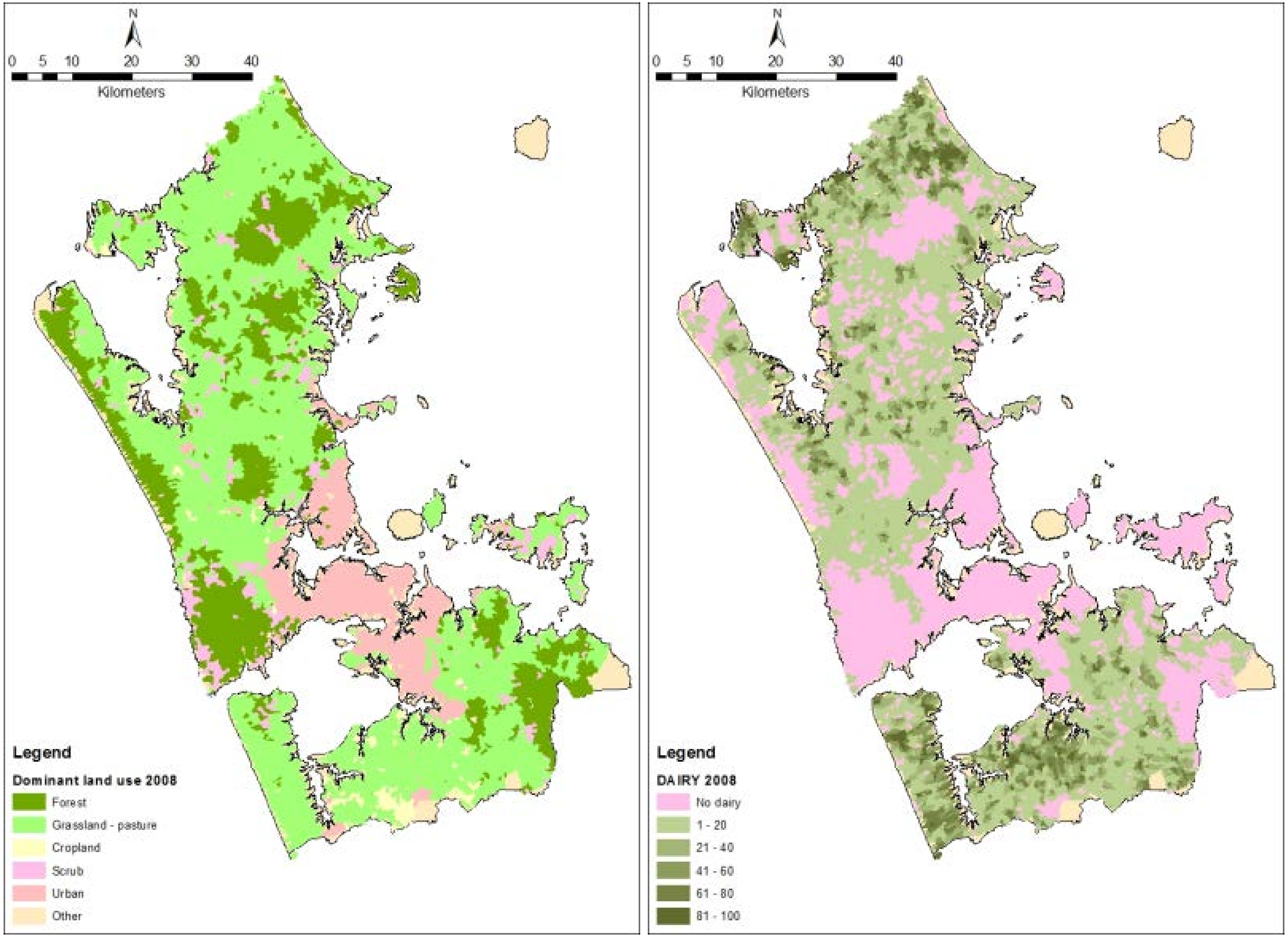


Figure 5 Provisional LCDB3 CLUES land use for 2008 by REC sub-catchment: left, dominant land use; right, percentage dairy farming

3.0 CLUES output

Three sets of CLUES results are presented in this section. They are:

1. Maps of generated nutrient and sediment yields; and
2. Maps of nutrient concentrations, to show the potential value of CLUES for geo-visualisation both to determine likely source areas and water quality hot-spots.
3. Simulated loads reported for ten river catchments draining to coastal receiving waters and three lake catchments in order to demonstrate how data can be extracted from CLUES for further analysis.

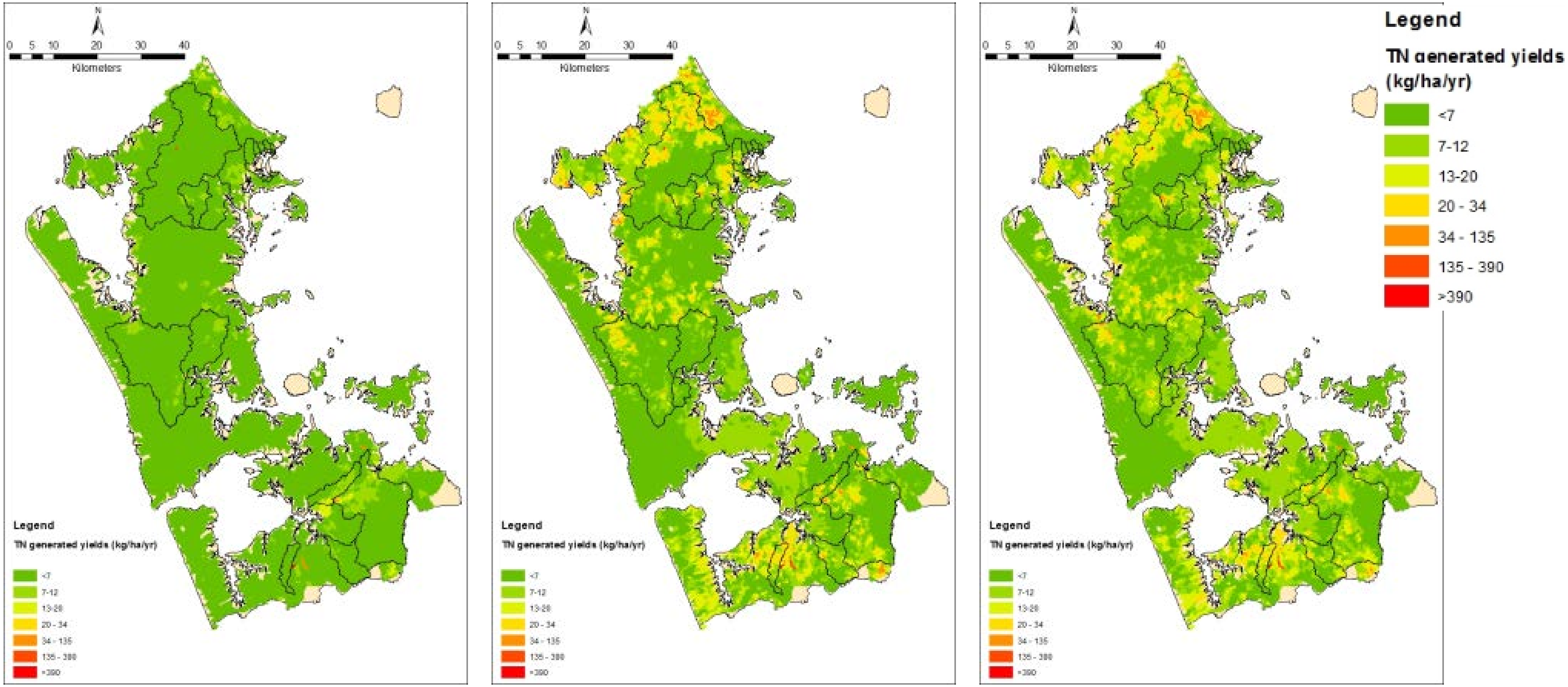
Note that generated and cumulative yields and concentrations for *E.coli* and concentrations for TSS are not available within CLUES. In addition to these outputs, CLUES results are compared to water quality estimates derived from observations at monitoring stations across the region in Section 4.0.

3.1 CLUES generated yields

Generated yields for TN, TP and TSS for the three land use scenarios are mapped in Figure 6 to Figure 8, using the same legend interval for each set of maps, respectively. Generated yields are calculated for each river reach sub-catchment as the load generated by the sub-catchment divided by the sub-catchment area. Accordingly, these maps show the relative importance of each sub-catchment as a contaminant source.

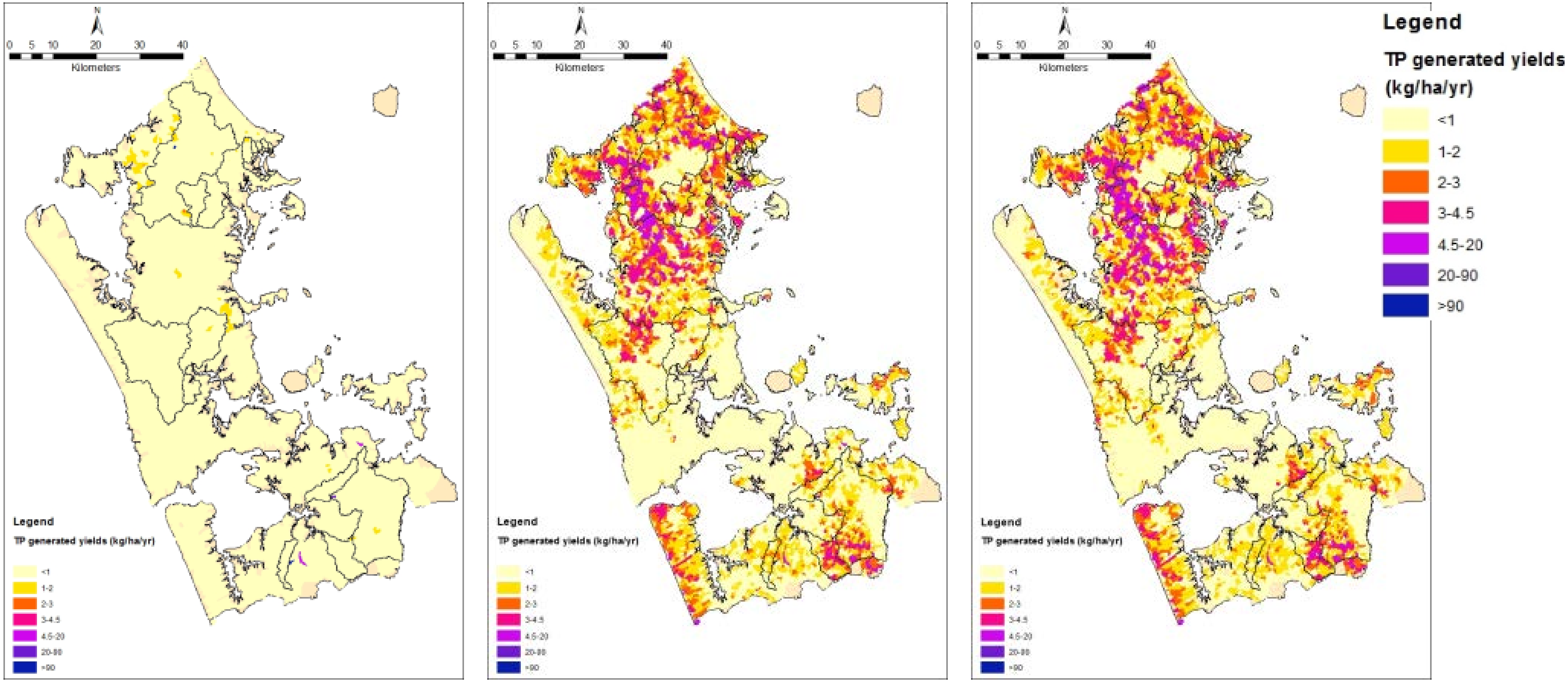
As can be expected, the greatest changes in generated yields were between the 1770 scenario, which had very low yields, and the 2002 default land use. For the most part, yields are fairly similar for the 2002 and 2008 scenarios. For these two scenarios, the highest nutrient yields are associated with dairy and intensive sheep and beef farming, particularly in the north including the upper reaches of the Hoteo River, along with market gardening in the south.

The main drivers in CLUES for sediment generation are vegetation cover, slope and soil type. While there is no clear relationship between land use and sediment generation, there has been a regional increase in estimated sediment yields between 1770 and the present day in areas of deforestation.



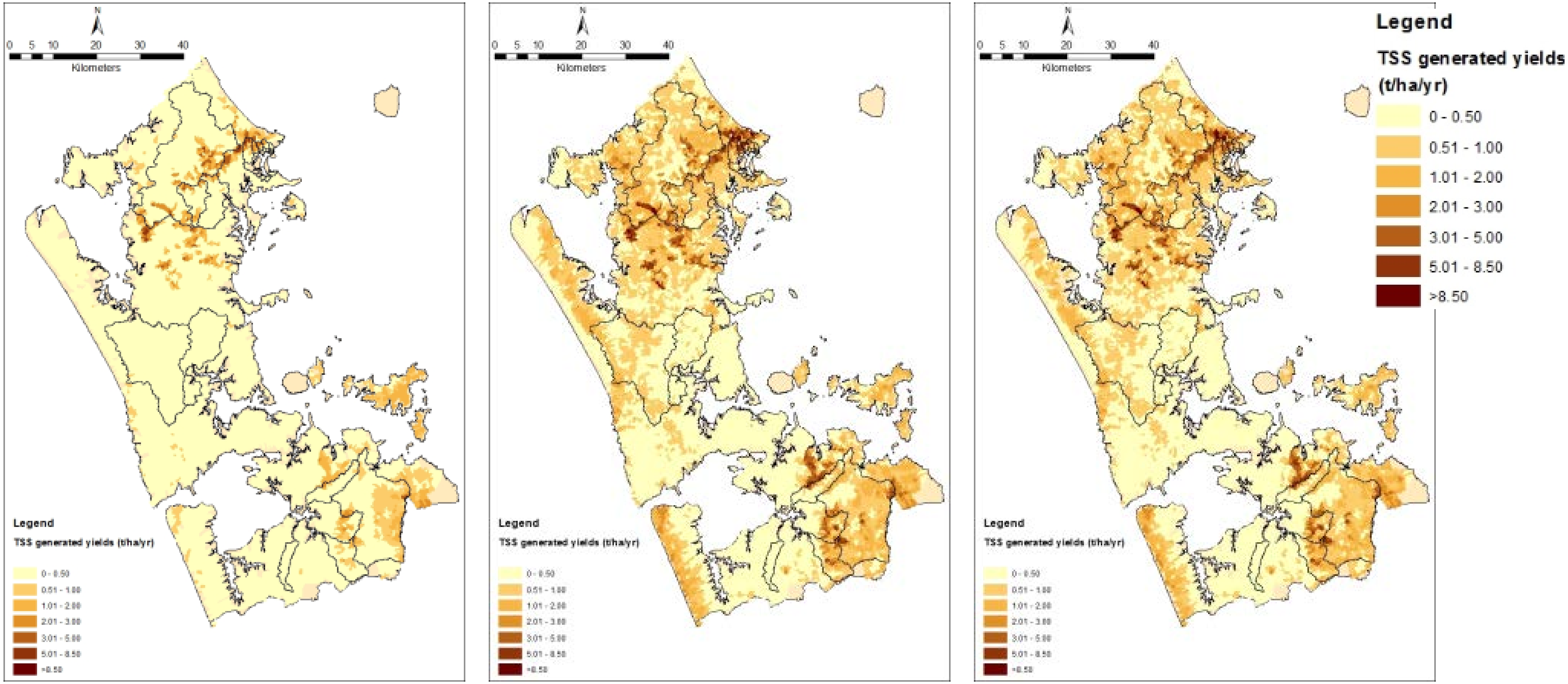
Pre_European (1770) Default (2002) Updated (2008)

Figure 6 Total nitrogen generated yields by REC sub-catchment for the three land use scenarios. Reporting catchment boundaries marked in black.



Pre_European (1770) Default (2002) Updated (2008)

Figure 7 Total phosphorus generated yields by REC sub-catchment for the three land use scenarios. Reporting catchment boundaries marked in black.



Pre_European (1770) Default (2002) Updated (2008)

Figure 8 Total suspended sediment generated yields by REC sub-catchment for the three land use scenarios. Reporting catchment boundaries marked in black.

3.2 CLUES concentrations

CLUES calculates nutrient concentrations for each river reach on the basis of a statistical relationship between the mean annual simulated load and estimated mean average annual river flow (Woods et al., 2006b) as recorded in the CLUES hydrological database. The method also takes into account other factors which influence nutrient concentrations, these are:

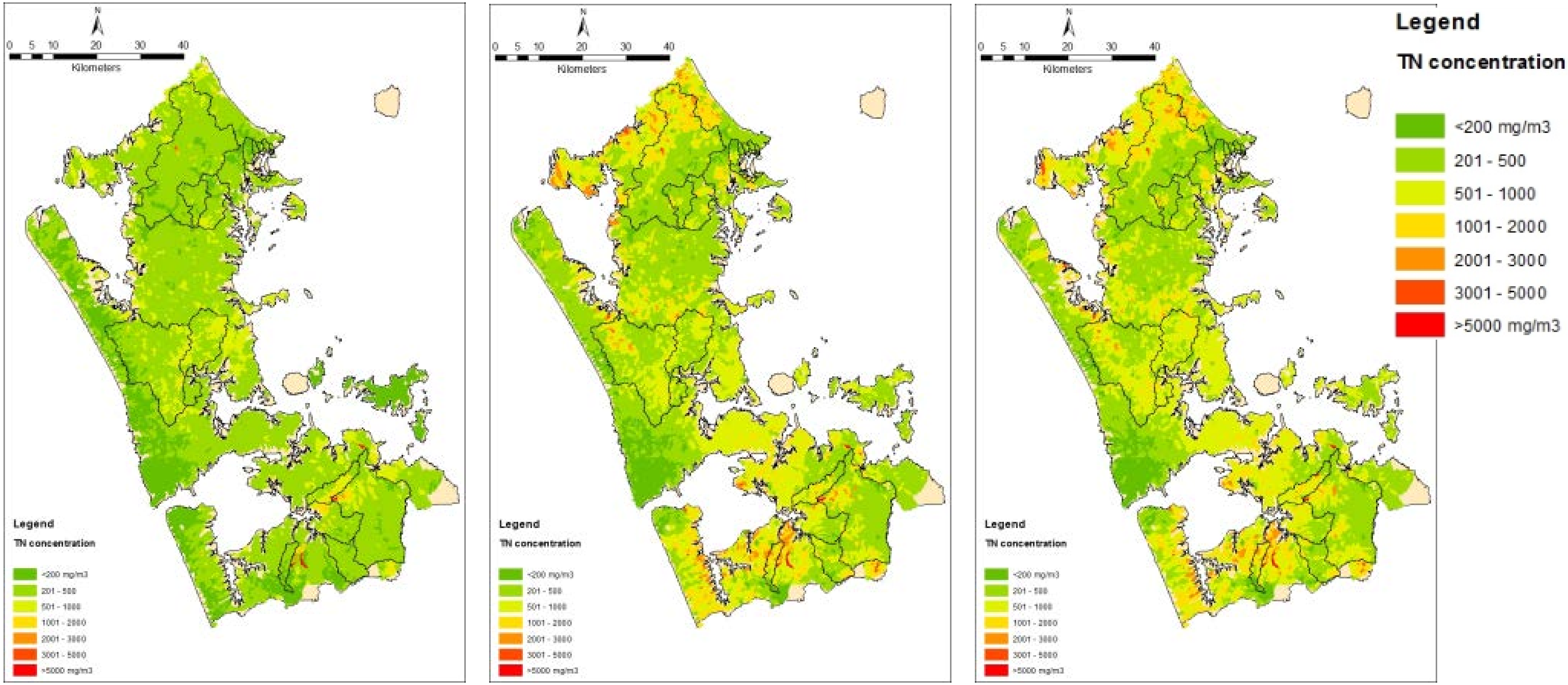
TN: sediment yield, mean annual flow divided by mean annual flood flow, average temperature in the catchment, fraction of hard-rock geology in the upstream catchment.

TP: sediment yield; mean annual flood flow; ratio of sediment load to phosphorus load; mean annual flow; percent of native vegetation in the upstream catchment.

The relationship was derived from national water quality data; the methodology followed is summarised in the CLUES user manual (Semadeni-Davies et al, 2011). Full details can be found in Oehler and Elliott (2011) and Elliott and Oehler (2009).

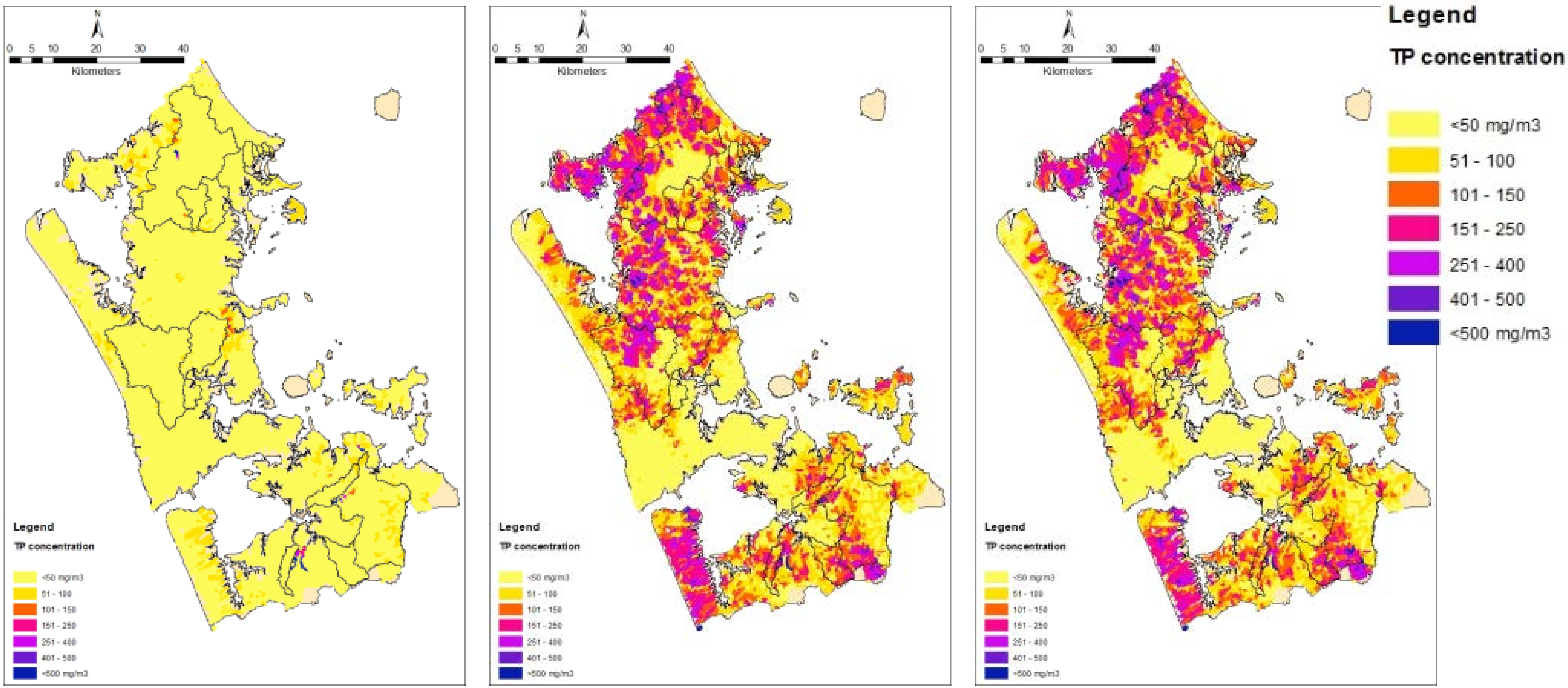
The nutrient concentrations simulated for the three land use scenarios are mapped in Figure 9 for TN and Figure 10 for TP using the same legend interval for each set of maps, respectively. It can be seen that the highest estimated nutrient concentrations are associated with the same areas of pastoral land use in the north and market gardening and agriculture in the south which are associated with the highest generated yields.

Note that CLUES does not calculate concentrations for sediments or *E.coli.*



Pre_European (1770) Default (2002) Updated (2008)

Figure 9 Total nitrogen concentrations (mg/m^3) by REC sub-catchment for the three land use scenarios. Reporting catchment boundaries marked in black.



Pre_European (1770) Default (2002) Updated (2008)

Figure 10 Total phosphorus concentrations (mg/m^3) by REC sub-catchment for the three land use scenarios. Reporting catchment boundaries marked in black.

3.3 Reporting Catchments and Lakes

Loads and yields are presented here for 13 catchments selected in consultation with the Council. There are ten river catchments draining to coastal receiving waters and three lake catchments.

The reporting river catchments draining to coastal receiving water are listed in Table 3, along with their coastal receiving waters, and mapped in Figure 11. The catchments are predominantly rural; and, with the exception of the Whangateau Estuary which consists of 15 small stream catchments draining into the estuary, all are river catchments. Water quality is monitored in seven of the catchments (as indicated in Table 3). The Hoteo catchment and its immediate receiving waters in the Kaipara Harbour are the focus of two research programmes funded by Ministry of Business, Innovation and Employment (MBIE): Cumulative Effects of Contaminants (led by NIWA) and Clean Water / Productive Land (led by AgResearch). CLUES has been applied to the Kaipara Harbour for the latter programme (Semadeni-Davies, 2012).

The three lake catchments are Lake Waimanu near Bethell's Beach which drains into the Te Henga Wetland, Cossey's Resevoir in the Hunua Ranges and Spectacle Lake to the region's north east. The lakes and their catchments are mapped in Figure 11, and their areas are given in Table 4.

Table 3 Reporting catchments listed by receiving environment, catchments with SOE quality monitoring sites are shaded blue.

Catchment	Drainage area (ha)	Coastal receiving environment
Whangateau Estuary	3302.3	Whangateau Estuary
Mahurangi River*	5571.7	Mahurangi Harbour
Hoteo River*	39892.5	South Kaipara Harbour
Kaipara River	26702.4	South Kaipara Harbour
Rangitopuni River	9747.7	Upper Waitemata Harbour
Brigham's Creek	2150.0	Upper Waitemata Harbour
Papakura Stream	4108.2	Manukau Harbour (Pahurehure Inlet)
Wairoa River	25818.8	Hauraki Gulf
Hingaia stream	5404.3	Manukau Harbour (Pahurehure Inlet)
Whangamaire River	2322.2	Manukau Harbour (Pahurehure Inlet)

*Areas have been adjusted for the misconnected section of the Hoteo catchment

Table 4 Lake and drainage area of the lake reporting catchments

Lake	Area (ha)	
	Catchment	Lake
Cossey's Creek Dam	2123.8	113.2
Lake Wainamu	476.9	15.0
Spectacle Lake	622.8	43.8

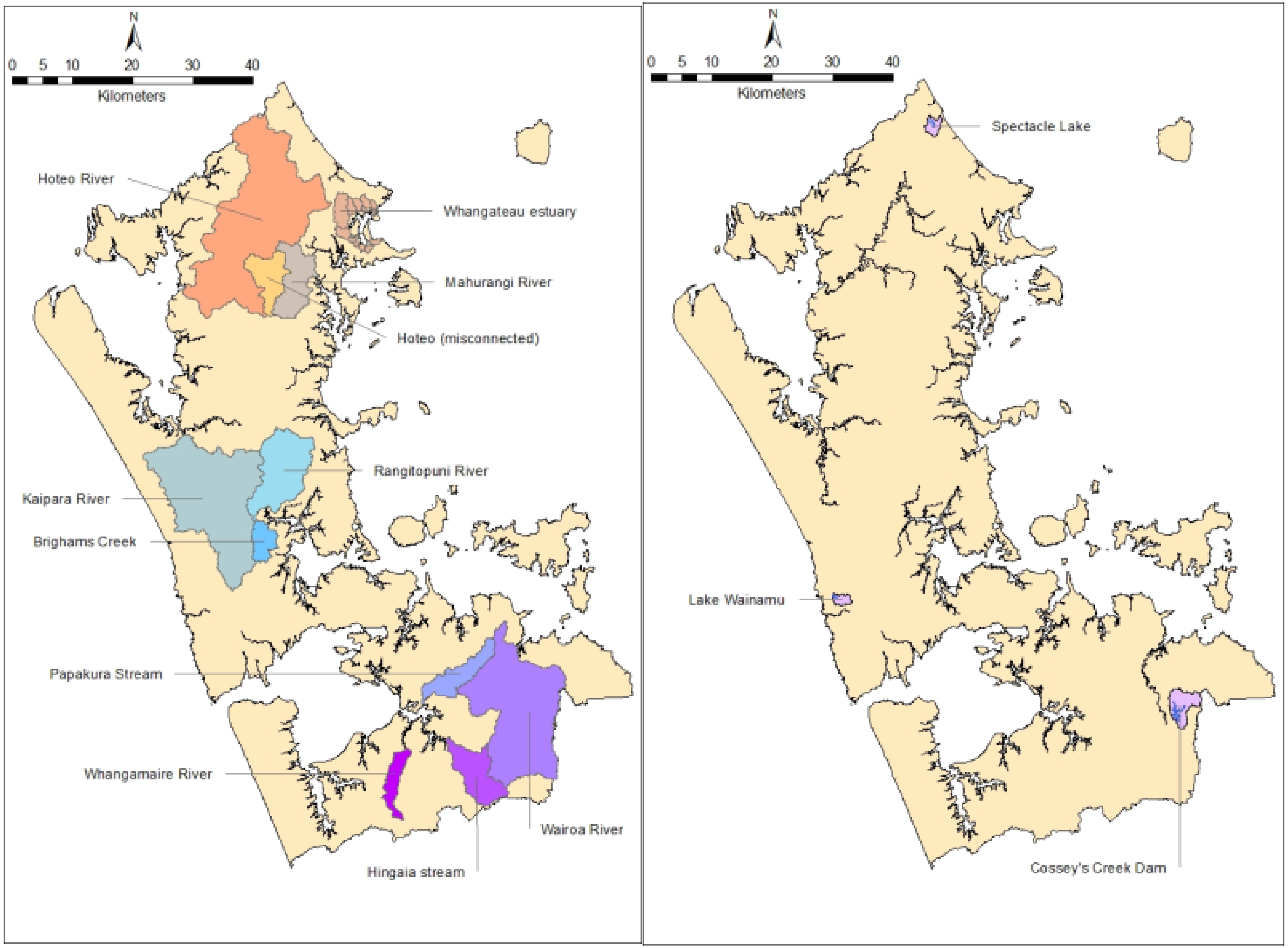


Figure 11 Location of the reporting river (left) and lake (right) catchments including the misconnected section of the Hoteo River.

The land use proportion in each of the reporting catchments are given in Table 5 for the 1770 scenario and Table 6 for the 2002 and 2008 scenarios. The LCDB3 land use breakdown is very similar to the default land use. The greatest differences for the river catchments are seen in the Whangamaire catchment, which has seen a decrease in dairy farming but an increase in cropping, Brigham's Creek which has had a decrease in dry-stock in favour of cropping (namely vineyards) and the Whangateau catchment area which has also had decrease in dry stock and dairying, and a corresponding increase in forestry and cropping. The Rangitopuni, Brigham's Creek, Wairoa and Papakura catchments have all had an increase in dairy farming, albeit minor. Of the lake catchments, Lake Waimanu catchment has a decrease in dairy to dry stock; the other two catchments have very little change.

3.3.1 Load and yield estimates – river catchments

Loads for the river catchments were collated from CLUES results exported as CSV files into Microsoft Excel by first identifying the NZ Reach number of the terminal (coastal reaches) for each catchment and then extracting the CLUES loads for those reaches using a vertical lookup statement. In catchments with more than one reach draining to the receiving water (e.g., Whangateau Estuary which received discharge from 15 small coastal streams), loads were added to give a total load from the catchment. Yields were calculated as the total load reaching the coastal receiving water divided by the total catchment area.

Note that there is a known error in the REC which links NZ reach 2001769 (Hoteo River) to NZ reach 2001784 (Mahurangi River). The error has resulted in a section (marked in Figure 11) of the Hoteo catchment mistakenly being included as part of the Mahurangi catchment in the REC. Moreover, the sequence of river reaches in this section of the Hoteo is also incorrect with the flow direction running from west to east instead of east to west. Thus, NZ reach 2001702, which should link to the Hoteo River main channel, is shown in the REC as a minor head water tributary of the Mahurangi River.

Within CLUES, the misconnection does not affect the generated yields calculated for each sub-catchment, but does have an impact on downstream loads and concentrations. For the Hoteo catchment, the impact on loads are likely to be relatively minor with respect to total contaminant loads reaching the South Kaipara Harbour due to relative size of the total catchment area. In addition, the water quality monitoring station in the Hoteo catchment (Hoteo@Gubbs) is upstream of the misconnected area and therefore is not affected. However, the misconnected area has a greater impact on the model results for the Mahurangi Harbour due to its relative size with respect to the actual catchment area. To counter the error, separate model runs were made for the Hoteo and Mahurangi catchments. For the Hoteo catchment, the total load generated by the misconnected area (i.e., upstream of reach 2001769) for each scenario was added to the total load at the river terminal reach. This approach could lead to a small overestimation of loads as the effect of in-stream attenuation and storage in the rivers lower reaches is not taken into account. For the Mahurangi catchment a CLUES flow barrier, which breaks the connection between reaches in the REC, was placed at the misconnection to block contaminant transport from the Hoteo catchment prior to simulating the catchment under each of the three scenarios.

Table 5 CLUES Pre-European (1770) percentage area land use cover, approximated by vegetation, aggregated by reporting catchment

Reporting Catchment	Scrub	Forest
Coastal receiving water		
Whangateau Estuary	33	67.0
Mahurangi River	0	100
Hoteo River	22	78
Kaipara River	63	37
Rangitopuni River	100	0
Brigham's Creek	100	0
Papakura Stream	65	35
Wairoa River	17	83
Hingaia stream	11	89
Whangamaire River	53	47
Lake receiving water		
Cossey's Resevoir	0	100
L. Waimanu	0	100
Spectacle Lake	100	0

Table 6 CLUES default (2002) and updated (2008) percentage area land use aggregated by reporting catchment

Catchment	Dairy		Dry stock		Crops*		Forest		Scrub		Urban		Other
	2002	2008	2002	2008	2002	2008	2002	2008	2002	2008	2002	2008	2008
Whangateau Estuary	11	8	46	36	0	4	40	45	2	4	0	0	2
Mahurangi River	9	5	46	45	0	1	38	37	3	7	4	4	1
Hoteo River	15	14	43	43	0	0	36	39	5	3	0	0	1
Kaipara River	9	9	61	56	1	4	20	22	7	6	2	3	1
Rangitopuni River	4	8	62	59	1	2	27	25	6	4	1	1	1
Brigham's Creek	2	3	84	70	5	14	4	3	1	0	5	8	1
Papakura Stream	14	13	54	45	0	1	15	34	4	6	12	1	2
Wairoa River	11	16	44	58	0	7	32	15	13	1	0	2	2
Hingaia stream	18	36	62	43	4	19	13	1	3	0	1	1	0
Whangamaire River	46	17	42	47	11	2	1	16	0	3	1	15	1
Cossey's Resevoir	0	0	2	0	0	0	95	95	3	0	0	0	5
Lake Waimanu	0	0	4	1	0	0	74	73	23	22	0	0	3
Spectacle Lake	42	32	28	35	0	0	29	24	1	1	0	0	9

* Including horticulture and viticulture

The estimated loads and yields for each of the river catchments are reported in Table 7 to Table 10 for TN, TP, TSS and *E.coli* respectively. The results show that land use change from 1770 has increased the estimated loads and yields of all contaminants, as might be expected. The Hoteo River has the greatest estimated loads of nutrients and sediment, this finding is not surprising given that this catchment has the largest area. Wairoa has the highest estimated *E.coli* loads. The catchments with the highest estimated yields are Whangamaire and Hoteo for TN; Whangateau, followed by Hingaia and Hoteo for TP and TSS; and Whangateau, Mahurangi and Papakura for *E.coli*. *E.coli* loads are strongly affected by in-stream attenuation, which could explain why the estimated *E.coli* yields are lower than could be expected in some streams with high proportions of farming.

In relation to land use, the high nutrient yield catchments have a high proportion of pastoral land use, including dairy farming and dry stock, in the 2002 and 2008 land use scenarios. In the Whangamaire catchment up to 20% of the area is used for market gardening. While, Brigham's Creek and Rangitopuni also have high proportions of pastoral land use in the 2002 and 2008 scenarios, these catchments are dominated by dry stock (sheep and beef) farms.

Table 7 TN loads and yields for river catchments Simulated using the three land use scenarios

Catchment	Pre-Euro 1770		Default 2002		Updated 2008	
	Load (t/yr)	Yield (kg/ha/y)	Load (t/yr)	Yield (kg/ha/y)	Load (t/yr)	Yield (kg/ha/y)
Whangateau estuary	12.9	3.9	17.9	5.4	17.6	5.3
Mahurangi River	22.1	4.0	33.1	5.9	29.0	5.2
Hoteo River	160.2	4.0	271.8	6.8	274.4	6.9
Kaipara River	78.6	2.9	118.3	4.4	131.4	4.9
Rangitopuni River	34.7	3.6	36.7	3.8	46.2	4.7
Brigham's Creek	5.1	2.4	7.1	3.3	10.0	4.7
Papakura Stream	16.5	4.0	22.1	5.4	24.2	5.9
Wairoa River	84.7	3.3	124.7	4.8	129.5	5.0
Hingaia stream	18.4	3.4	30.7	5.7	31.8	5.9
Whangamaire River	4.8	2.1	21.6	9.3	20.1	8.7

Table 8 TP loads and yields for river catchments Simulated using the three land use scenarios

Catchment	Pre-Euro 1770		Default 2002		Updated 2008	
	Load (t/yr)	Yield (kg/ha/y)	Load (t/yr)	Yield (kg/ha/y)	Load (t/yr)	Yield (kg/ha/y)
Whangateau estuary	1.4	0.4	5.1	1.5	5.0	1.5
Mahurangi River	1.3	0.2	4.9	0.9	5.0	0.9
Hoteo River	11.7	0.3	50.2	1.3	52.5	1.3
Kaipara River	5.1	0.2	18.0	0.7	19.4	0.7
Rangitopuni River	2.1	0.2	5.2	0.5	6.2	0.6
Brigham's Creek	0.5	0.2	0.4	0.2	0.6	0.3
Papakura Stream	0.5	0.1	1.2	0.3	1.4	0.3
Wairoa River	7.0	0.3	17.2	0.7	18.7	0.7
Hingaia stream	1.2	0.2	4.9	0.9	5.3	1.0
Whangamaire River	0.3	0.1	1.4	0.6	1.3	0.5

Table 9 TSS loads and yields for river catchments Simulated using the three land use scenarios

Catchment	Pre-Euro 1770		Default 2002		Updated 2008	
	Load (kt/yr)	Yield (t/ha/y)	Load (kt/yr)	Yield (t/ha/y)	Load (kt/yr)	Yield (t/ha/y)
Whangateau estuary	3.6	1.1	7.2	2.2	5.9	1.8
Mahurangi River	1.9	0.3	4.4	0.8	4.5	0.8
Hoteo River	21.2	0.5	44.0	1.1	43.4	1.1
Kaipara River	3.6	0.1	12.3	0.5	11.9	0.4
Rangitopuni River	1.1	0.1	3.2	0.3	3.2	0.3
Brigham’s Creek	0.2	0.1	0.7	0.3	0.7	0.3
Papakura Stream	0.9	0.2	2.8	0.7	2.8	0.7
Wairoa River	9.5	0.4	22.2	0.9	22.0	0.9
Hingaia stream	1.9	0.3	6.8	1.2	6.6	1.2
Whangamaire River	0.1	0.1	0.5	0.2	0.5	0.2

Table 10 *E.coli* loads and yields expressed in number of organisms for river catchments Simulated using the three land use scenarios

Catchment	Pre-Euro 1770		Default 2002		Updated 2008	
	Load (10^{15}/yr)	Yield (10^{12}/ha/y)	Load (10^{15}/yr)	Yield (10^{12}/ha/y)	Load (10^{15}/yr)	Yield (10^{12}/ha/y)
Whangateau estuary	0.09	0.0	4.36	1.3	3.36	1.0
Mahurangi River	0.12	0.0	5.63	1.0	5.39	1.0
Hoteo River	0.21	0.0	9.27	0.2	9.08	0.2
Kaipara River	0.12	0.0	5.27	0.2	5.00	0.2
Rangitopuni River	0.07	0.0	2.55	0.3	2.52	0.3
Brigham’s Creek	0.01	0.0	0.60	0.3	0.59	0.3
Papakura Stream	0.07	0.0	4.10	1.0	4.04	1.0
Wairoa River	0.26	0.0	13.94	0.5	13.68	0.5
Hingaia stream	0.04	0.0	2.30	0.4	2.14	0.4
Whangamaire River	0.01	0.0	0.60	0.3	0.60	0.3

3.3.2 Load and yield estimates – lake catchments

Lakes are represented in CLUES as ‘tagged’ river reaches, as shown in Figure 12 for Lake Waimanu, which has three inlet reaches and a single outlet. Inflow loads cannot be calculated simply as the sum of the CLUES loads for the inlet; doing so would not take into account the lake storage and attenuation terms in CLUES. For this reason, the study back calculated lake inflows from outflows using the same method as that used by Verburg et al. (2013) for lakes in the Bay of Plenty.

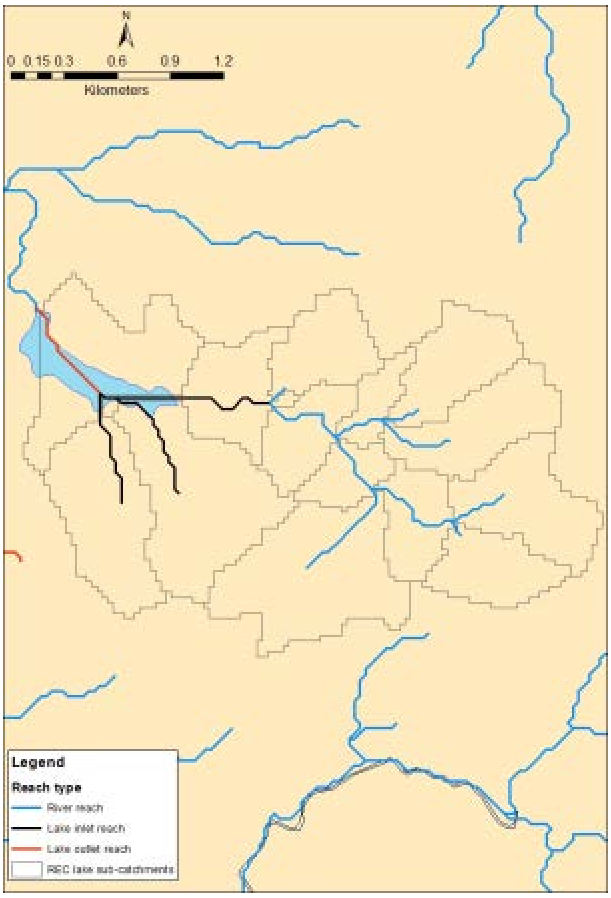


Figure 12 Representation of lakes in CLUES showing the L. Waimanu catchment area.

Under the method, the total inflow load for each contaminant is calculated as:

$$Load_{in} = Load_{out}\left(1 + \frac{KRES}{RESLOAD}\right)$$

where $Load_{out}$ is the total load exiting the lake (if a lake has more than one outlet, the sum of the outflow loads is used), *KRES* is a settling parameter within the CLUES parameter set and *RESLOAD* is the lake hydraulic overflow rate in the CLUES geo-database and is the average annual discharge rate divided by the lake area. Note that atmospheric deposition directly onto the lake surface is included in the calculated load, however, deposition is minor compared to loads generated on land and is not considered here.

Cossey's Dam, which has the greatest catchment area, has the highest simulated loads of all the contaminants under all scenarios (reported in

Table 11 to Table 14). Cossey's Dam also has the highest estimated sediment yields followed by Lake Wainamu. Both these lakes are in forested areas with steep slopes. Spectacle Lake has the highest estimated nutrient and *E.coli* yields which is in keeping with the high proportion of pastoral land use in the catchment area.

Table 11 Simulated TN loads and yields for the three land use scenarios

Catchment	Pre-Euro 1770		Default 2002		Updated 2008	
	Load (t/yr)	Yield (kg/ha/y)	Load (t/yr)	Yield (kg/ha/y)	Load (t/yr)	Yield (kg/ha/y)
Cossey's Dam	6.9	3.2	6.7	3.2	6.6	3.1
Lake Wainamu	0.9	1.9	0.9	1.8	0.9	1.8
Spectacle Lake	2.0	3.2	5.2	8.3	4.5	7.2

Table 12 Simulated TP loads and yields for the three land use scenarios

Catchment	Pre-Euro 1770		Default 2002		Updated 2008	
	Load (t/yr)	Yield (kg/ha/y)	Load (t/yr)	Yield (kg/ha/y)	Load (t/yr)	Yield (kg/ha/y)
Cossey's Dam	1.1	0.5	1.2	0.6	1.1	0.5
Lake Wainamu	0.1	0.3	0.2	0.4	0.2	0.3
Spectacle Lake	0.1	0.2	1.0	1.6	1.0	1.6

Table 13 Simulated TSS loads and yields for the three land use scenarios

Catchment	Pre-Euro 1770		Default 2002		Updated 2008	
	Load (t/yr)	Yield (kg/ha/y)	Load (t/yr)	Yield (kg/ha/y)	Load (t/yr)	Yield (kg/ha/y)
Cossey's Dam	1492.6	702.8	1538.2	724.3	1500.2	706.4
Lake Wainamu	137.2	287.7	147.4	309.1	141.3	296.3
Spectacle Lake	33.5	53.7	133.8	214.9	133.8	214.9

Table 14 Simulated *E.coli* loads and yields expressed as organisms per year for the three land use scenarios

Catchment	Pre-Euro 1770		Default 2002		Updated 2008	
	Load (1012/yr)	Yield (109/ha/y)	Load (1012/yr)	Yield (109/ha/y)	Load (1012/yr)	Yield (109/ha/y)
Cossey's Dam	3.2	1.5	9.3	4.4	4.3	2.0
Lake Wainamu	0.30	0.6	1.3	2.6	0.7	1.5
Spectacle Lake	1.8	3.0	108.8	174.7	107.9	173.2

4.0 Comparison of CLUES results against other estimates of water quality

In this section, the results obtained from the CLUES model for the 2002 and 2008 land use scenarios presented above are compared to other estimates derived from observations (henceforth referred to as observed data) of water quality to give an indication of model performance and local calibration needs in the Auckland region. Comparisons are made between estimates of annual median nutrient concentrations calculated for 31 water quality monitoring stations. Where flow data were available, comparisons are also made against nutrient loads calculated for nine of those sites for TN and eights for TP. Finally, sediments yields estimated for nine sediment monitoring stations were compared against CLUES sediment yields. No comparisons were possible for *E.coli* as CLUES does not have the ability to calculate *E.coli* concentrations and there are no monitoring sites with sufficient or suitable data for calculation of *E.coli* loads from observed concentrations. The choice of monitoring sites for comparison with CLUES results was driven by data availability and is discussed further below. Note that the CLUES results for each sub-catchment containing a monitoring station relate to the outlet point of the reach and not the location of the station. Model performance and sources of error are discussed further in Section 4.4.

4.1 Stream nutrient concentrations

CLUES is an annual contaminant loads model; nutrient concentrations are calculated by CLUES using the method described by Oehler and Elliott (2011) and Elliott and Oehler (2009). The method derives concentrations from a statistical relationship based on mean annual flow rates (as described in Section 3.2). CLUES nutrient concentrations simulated using the Default (2002) and Updated (2008) land use scenarios were compared to long term median concentrations of TP and TN in samples collected at 31 monitoring sites spread across the region. Three sets of median concentrations were derived from the observed data, i.e., median of all data and the median for the time periods 1998-2002 and 2004-2008 to enable direct comparison with the CLUES scenarios. For the concurrent five-year comparisons, sites with fewer than 40 months of monitoring data were excluded from the comparison as it was deemed that the median concentrations calculated may not be representative of average water quality at these sites.

The monitoring stations include council SOE monitoring sites and two NIWA monitoring sites (Hoteo@Gubbs and Rangitopuni@Walkers). The data were obtained from the National River Water Quality database maintained by NIWA. While CLUES was developed primarily for rural land uses, it does contain an urban land use class, for this reason the eight stations in predominantly urban catchments are included in the analysis. However, the urban land use class in CLUES uses the same yields as the “other” land cover class and is not calibrated for urban land use. The stations are mapped in Figure 13 and listed in Table 15. Land use is summarised in Figure 14 land use data supplied by the council which was derived from the LCDB2 (personal communication, Martin Neale, email dated 6/6/13) and Figure 15 and Figure 16 for the two land use scenarios respectively.

While the land uses are fairly similar, there are some discrepancies in some catchments, most noticeably in the largely forested West Hoe catchment. For this site, both CLUES land use scenarios include substantial areas of pastoral land use due to the position of the monitoring station, which is just below the confluence of two head water streams. The REC reach extends downstream of the monitoring point into pastoral land effectively doubling the catchment area simulated in CLUES. It should also be pointed out that there is some doubt around the REC reach and sub-catchment mapping for the Papakura site. The area upstream of this site is very flat and mapping undertaken by the council, which included analysis of LIDAR imagery, showed that the Papakura Stream catchment has different boundaries than represented in the REC. The REC calculated contributing area for this site is around 75% of the actual contributing area.

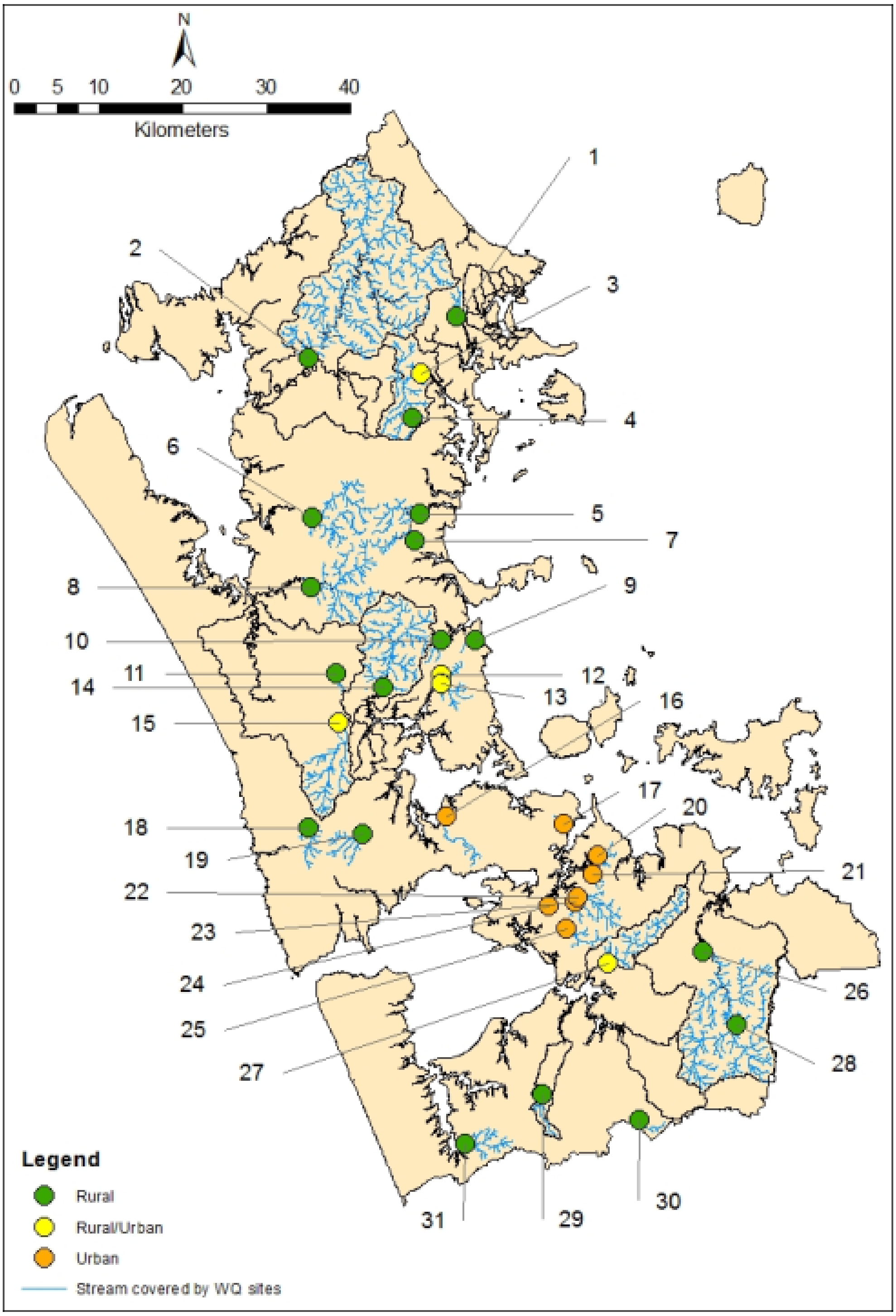


Figure 13 Location of freshwater water quality monitoring sites in the Auckland region in relation to the reporting catchments and the stream network. Sites are number from north to south, site names are listed in Table 15.

Table 15 Freshwater water quality monitoring stations in the Auckland Region. Sites are numbered from north to south. Sites within the reporting catchments are shaded blue. Upstream catchment areas have been calculated within GIS from REC sub-catchments upstream inclusive of the site NZ reach.

Map Key	Site	Stream	Area (ha)	NZ Reach	Start date
1	Matakana@Wenzlicks Farm	Matakana R.	663	2001344	16 Dec. 1986
2	Hoteo@Gubbs*	Hoteo R.	26653	2001653	1 Feb. 1989
3	Mahurangi@Warkworth water treatment plant	Mahurangi R.	4013	2001738	7 July 1993
4	Mahurangi@Forestry HQ	Mahurangi R.	833	2002015	3 Aug. 1993
5	Waiwera@McCathies Falls	Waiwera R.	3133	2002902	24 June 1986
6	Makerau@Railway	Makerau R.	4917	2002945	6 Jan. 2009
7	West Hoe@Halls	West Hoe Stm.	128	2003138	16 Jan. 2002
8	Kaukapakapa@Taylors Rd	Kaukapakapa R.	6288	2003565	6 Jan. 2009
9	Vaughans@Lower Weir	Vaughans Stm.	253	2004122	4 July 2001
10	Okura Creek@Awanohi Rd	Okura Ck.	611	2004093	5 Sept. 2003
11	Riverhead@Ararimu	Ararimu Stm.	366	2004467	6 Jan. 2009
12	Lucas@Gills Rd Bridge	Lucas Ck.	651	2004500	3 Aug. 1993
13	Oteha@Days Bridge	Oteha R.	1195	2004535	24 June 1986
14	Rangitopuni@Walkers*	Rangitopuni R.	8181	2004545	1 Feb. 1989
15	Kumeu River@ No. 1 Bridge	Kumeu R.	4621	2004945	3 Aug. 1993
16	Oakley@Carrington Creek	Oakley Ck.	1288	2005765	8 Aug. 1994
17	Omaru@Maybury st	Omaru Ck.	343	2005837	27 Jan. 2009
18	Cascade Stream@Confluence	Cascade Stm.	1454	2005866	26 June 1986
19	Opanuku@Candia Rd Bridge	Opanuku Stm.	1636	2005960	26 June 1986
20	Pakuranga@Botany Rd	Pakuranga Ck.	737	2006225	9 Nov. 1992
21	Pakuranga@Greenmount Drive	Pakuranga Ck.	356	2006372	9 Nov. 1992
22	Otara@Kennnell Hill	Otara Ck.	1898	2006642	8 Jan. 1992
23	Otara@East Tamaki Rd	Otara Ck.	927	2006681	17 Oct. 1985
24	Otaki@Middlemore Crescent	Otaki	158	2006774	9 Nov. 1992
25	Puhinui@Drop Structure	Puhinui Ck.	1257	2007136	2 Feb. 1994
26	Wairoa@Tourist Rd	Wairoa R.	14556	2007413	25 June 1986
27	Papakura@ Porchester Rd Bridge	Papakura Stm.	3571	2007536	4 Aug. 1993
28	Wairoa Trib@Caitchons Rd	Wairoa R.	249	2008323	7 Jan. 2009
29	Whangamaire@ Woodhouse Rd*	Whangamaire Stm.	805	2009245	7 Jan. 2009
30	Ngakaroa@Mill Rd	Ngakaroa Stm.	445	2009507	4 Aug. 1993
31	Waitangi Stream@Falls Rd	Waitangi Stm.	1809	2009665	7 Jan. 2009

*NIWA monitoring sites

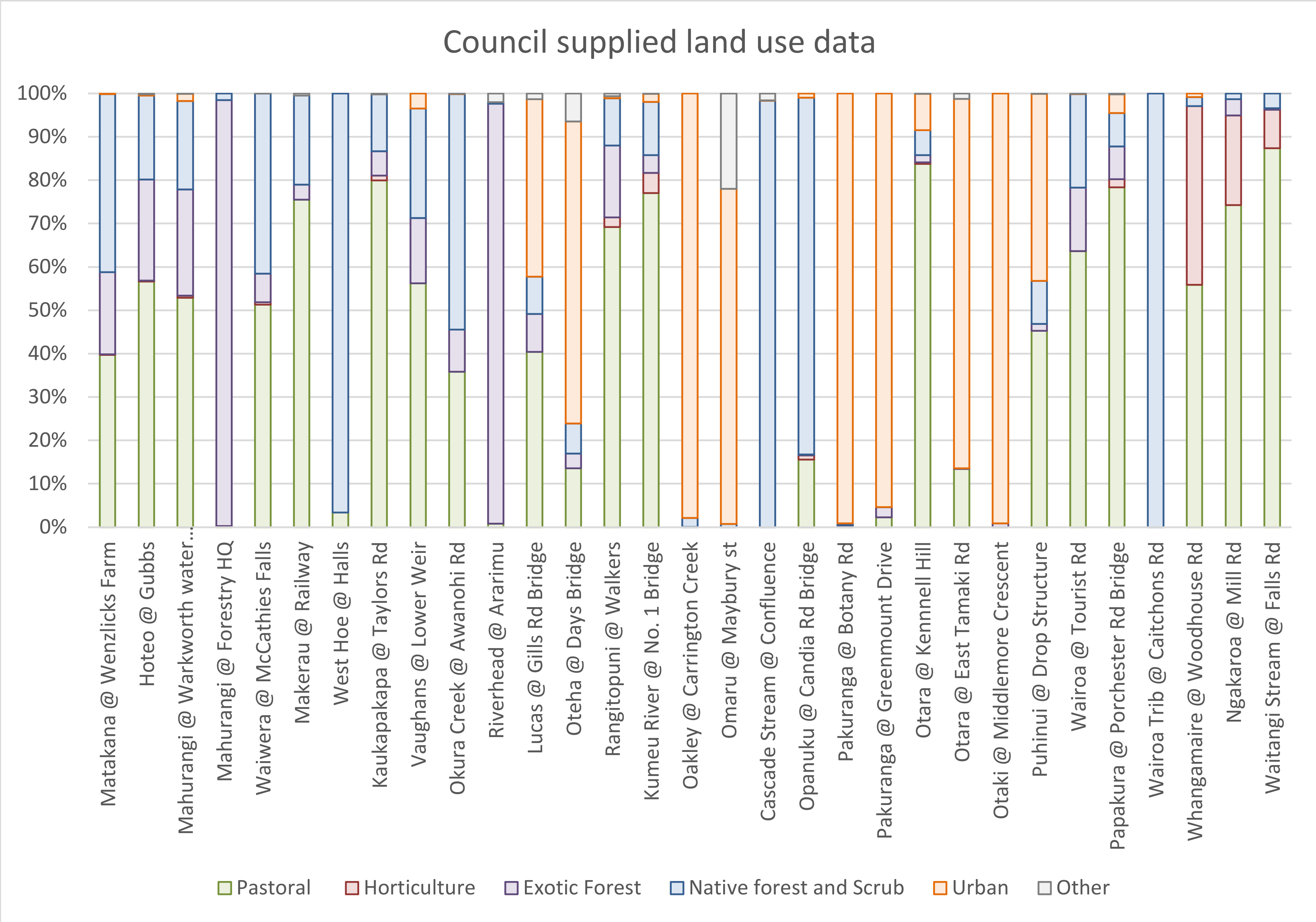


Figure 14 Land use in the upstream contributing areas for each monitoring site: council supplied land use data (based on LCDB2 data)

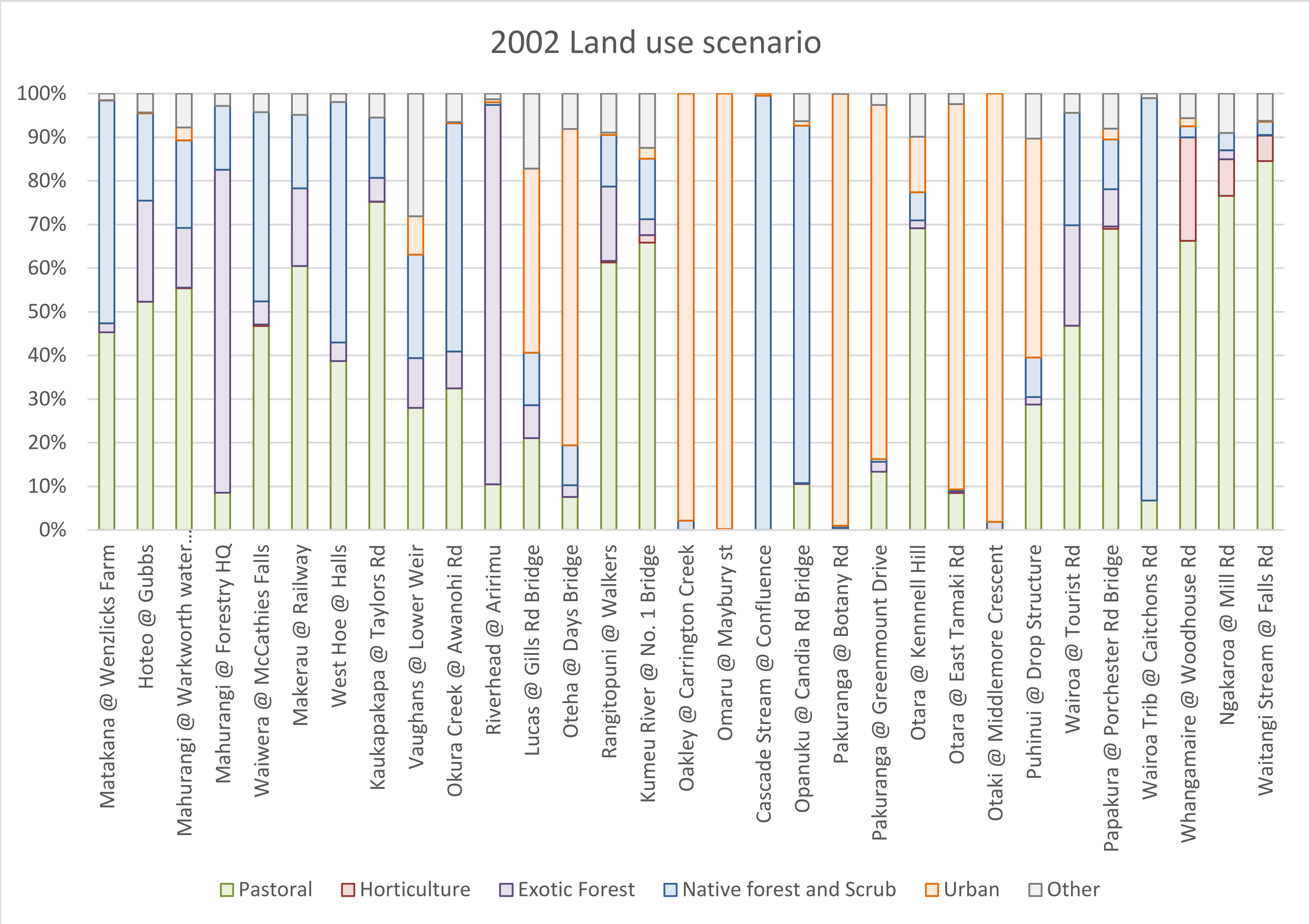


Figure 15 Land use in the upstream contributing areas for each monitoring site: Default 2002 land use scenario

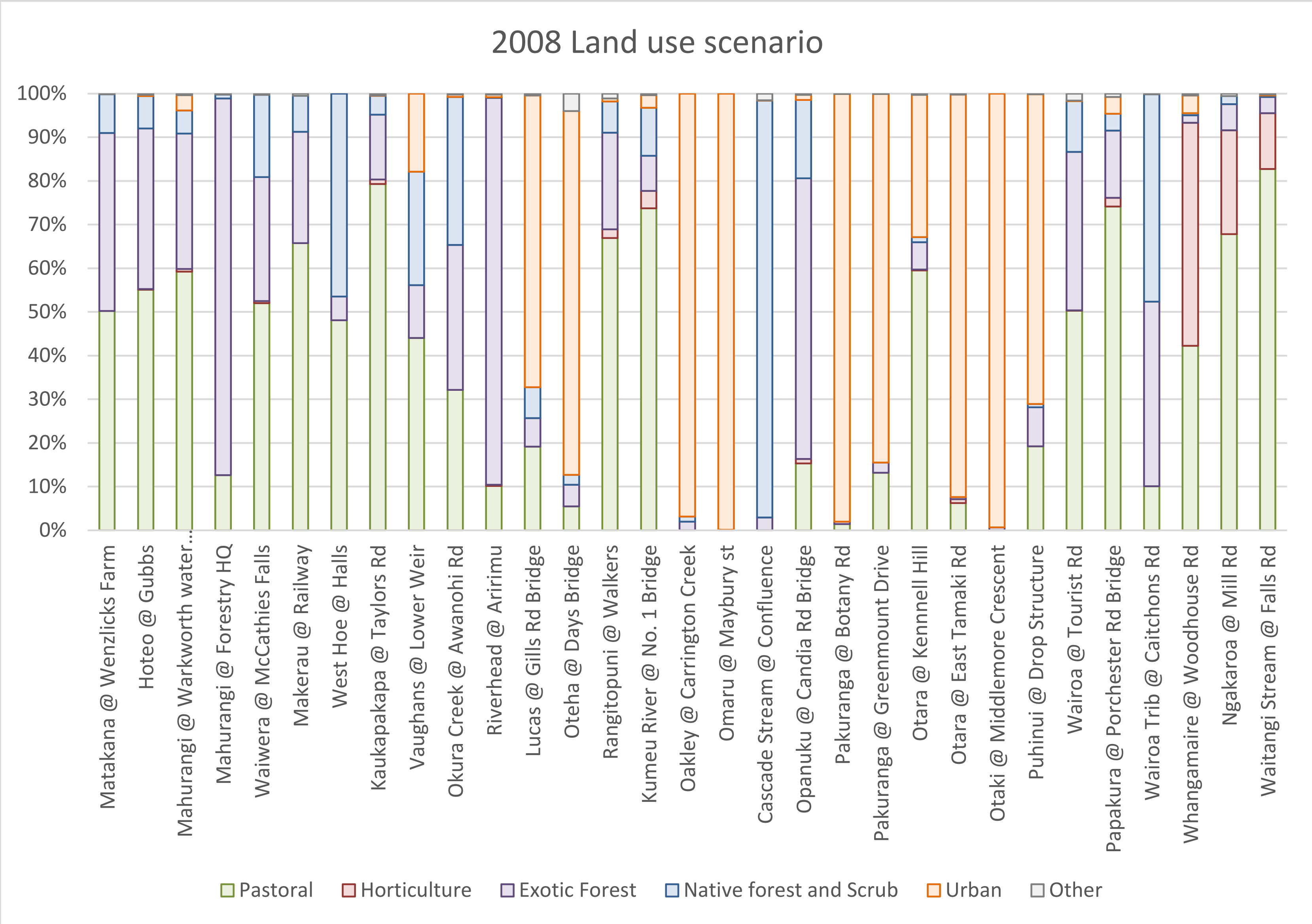


Figure 16 Land use in the upstream contributing areas for each monitoring site: Updated 2008 land use scenario

4.1.1 Observed nutrient concentrations

Median concentrations calculated from observed water quality at each of the sites are summarised in Table 16 for TN and Table 17 for TP, respectively, for all data available to December 2012, and for the five year periods from January 1998 to December 2002 and from January 2004 to December 2008. The number of monthly samples available at each site used to calculate the median value is also shown in the tables. The medians have been ranked from green to red, evenly distributed, to indicate the lowest to highest concentrations for each time period.

While there are variations in rankings for the different time periods, there is a general consistency. The rankings in the tables are broadly consistent with the water quality ratings given in the council SOE reports for 2008 (Neale, 2010a), 2009 (Neale, 2010b), 2010 (Neale, 2012) and 2011 (Lockie and Neale, 2013). However, the council rankings also take other water quality indicators into account such as total and dissolved metals (zinc, copper and lead), dissolved oxygen, pH and conductivity. Rivers with good to excellent water quality as indicated by the SOE reports include Opanuku Stream, West Hoe Stream, Waiwera Stream, Mahurangi River, Wairoa tributary and Cascades Stream. In contrast, Whangamaire Stream, Otaki Creek, Puhinui and Pakuranga Creek were listed as the rivers with the poorest water quality in the SOE reports.

Whangamaire has the highest median TN concentration in Table 16; however, this station was established in 2009 and consequently does not have concurrent data available for the CLUES comparison. This catchment, along with the nearby Ngakaroa and Waitangi catchments, is in an area of market gardening. Nitrogen balances from this area were evaluated on the basis of survey data by Crush et al. (1997). They found that potential N losses from horticultural land use was greater than from dairy farms largely due to regular applications of fertiliser, particularly in winter. They also suggested that high rates of mineralisation of the soil organic matter content in the area could mobilise large amounts of nitrate (NO_3-N) resulting in greater NO_3-N leaching and consequently higher TN loads in groundwater and streams. The observed nutrient concentrations in these catchments are influenced by groundwater from basaltic aquifers which feed the streams. The 2011 SOE report (Lockie and Neale, 2013) states that Whangamaire had the worst water quality of any monitoring site that year noting that TN concentrations exceeded target levels on every sampling occasion during 2011. Oakley Creek, an urban stream, also had high median TN concentrations which could be due to inflows of untreated wastewater following sewer overflows (e.g., Moores et al, 2012). High median TN concentrations were also found for the other urban sites. The Cascades, West Hoe and the Mahurangi River sites had the lowest median TN concentrations.

Pakuranga@Greenmount Drive has the highest median TP concentrations of those listed in Table 17; this is a predominantly urban site. The other urban sites also had high median TP concentrations. Of the rural sites, the highest median TP concentrations occurred in the Kaukapakapa site (established in 2009) and Kumeu River. In contrast to TN, Ngakaroa and Whangamaire have among the lowest low median TP concentrations in Table 17.

While the median TN concentrations are fairly similar between the three calculation periods, there are some notable differences, particularly for Otaki, Otara@East Tamaki and the two Pakuranga sites. There is greater agreement between the three sets of median TP concentrations, however, there was a noticeable increase in median TP concentrations for many sites between 1998-2002 and 2004-2008.

Table 16 Median monthly concentrations of TN and number of months (n) of available data for the Auckland monitoring sites. Concentrations are ranked from lowest (green) to highest (red) with an even distribution.

Monitoring site	All data to Dec 2012		1998 - 2002		2004 - 2008	
	TN (mg/m^3)	n	TN (mg/m^3)	n	TN (mg/m^3)	n
Matakana@Wenzlicks Farm	386	107	497	16	415	55
Hoteo@Gubbs	655	272	716	60	598	60
Mahurangi@Warkworth water treatment plant	262	154	226	53	620	35
Mahurangi@Forestry HQ	390	107	488	16	355	55
Waiwera@McCathies Falls	559	107	545	16	651	55
Makerau@Railway	515	24	-	-	-	-
West Hoe@Halls	216	102	321	10	224	60
Kaukapakapa@Taylors Rd	785	24	-	-	-	-
Vaughans@Lower Weir	590	110	461	16	589	59
Okura Creek@Awanohi Rd	765	92	-	-	719	60
Riverhead@Ririmu	315	24	-	-	-	-
Lucas@Gills Rd Bridge	687	111	649	16	820	55
Oteha@Days Bridge	723	110	745	16	664	54
Rangitopuni@Walkers	661	272	665	60	638	60
Kumeu River@No. 1 Bridge	932	104	1067	16	862	53
Oakley@Carrington Creek	1940	117	2250	17	1885	60
Omaru@Maybury st	960	30	-	-	-	-
Cascade Stream@Confluence	225	104	228	16	242	53
Opanuku@Candia Rd Bridge	450	113	681	17	450	60
Pakuranga@Botany Rd	796	175	727	59	1377	41
Pakuranga@Greenmount Drive	715	176	589	59	1093	41
Otara@Kennnell Hill	908	119	981	17	930	60
Otara@East Tamaki Rd	1100	251	1173	59	1634	41
Otaki@Middlemore Crescent	1127	176	960	59	1635	41
Puhinui@Drop Structure	1187	116	1600	17	1266	59
Wairoa@Tourist Rd	953	178	1096	17	871	60
Papakura@Porchester Rd Bridge	1195	117	1355	17	1127	60
Wairoa Trib@Caitchons Rd	135	28	-	-	-	-
Whangamaire@Woodhouse Rd	15500	28	-	-	-	-
Ngakaroa@Mill Rd	3100	115	3440	17	2960	60
Waitangi Stream@Falls Rd	2030	28	-	-	-	-

Table 17 Median monthly concentrations of TP and number of months (n) of available data for the Auckland monitoring sites. Concentrations are ranked from lowest (green) to highest (red) with an even distribution

Monitoring site	All data to Dec 2012		1998 - 2002		2004 - 2008	
	TP (mg/m^3)	n	TP (mg/m^3)	n	TP (mg/m^3)	n
Matakana@Wenzlicks Farm	48	276	40	57	44	55
Hoteo@Gubbs	54	285	54	60	58	60
Mahurangi@Warkworth	50	190	50	54	43	51
Mahurangi@Forestry HQ	30	197	30	56	30	55
Waiwera@McCathies Falls	50	283	40	57	49	55
Makerau@Railway	45	24	-	-	-	-
West Hoe@Halls	30	102	30	10	30	60
Kaukapakapa@Taylors Rd	94	24	-	-	-	-
Vaughans@Lower Weir	52	111	40	17	54	60
Okura Creek@Awanohi Rd	61	92	-	-	63	60
Riverhead@Ariri mu	26	24	-	-	-	-
Lucas@Gills Rd Bridge	60	201	60	56	60	55
Oteha@Days Bridge	60	286	60	56	55	55
Rangitopuni@Walkers	60	285	53	60	62	60
Kumeu River@No. 1 Bridge	70	191	60	54	70	53
Oakley@Carrington Creek	60	195	60	58	66	60
Omaru@Maybury st	67	30	-	-	-	-
Cascade Stream@Confluence	40	278	30	56	37	52
Opanuku@Candia Rd Bridge	40	289	30	59	40	60
Pakuranga@Botany Rd	88	217	90	58	73	57
Pakuranga@Greenmount Drive	130	217	130	58	94	57
Otara@Kennnell Hill	100	229	100	59	70	60
Otara@East Tamaki Rd	67	292	40	58	60	57
Otaki@Middlemore Crescent	76	218	60	59	89	57
Puhinui@Drop Structure	70	202	60	59	67	59
Wairoa@Tourist Rd	55	293	50	59	56	60
Papakura@Porchester Rd Bridge	80	209	70	59	87	60
Wairoa Trib@Caitchons Rd	41	28	-	-	-	-
Whangamaire@Woodhouse Rd	19	28	-	-	-	-
Ngakaroa@Mill Rd	27	208	20	58	30	60
Waitangi Stream@Falls Rd	19	28	-	-	-	-

4.1.2 CLUES total nitrogen concentrations

CLUES estimates of TN concentrations and departures from median monthly concentrations are given in Table 18 and Table 19 for the Default (2002) and Updated (2008) land use scenarios respectively. In each table, the concentrations are ranked from lowest (green) to highest (red). There are broad similarities in the rankings compared with the rankings for observed median concentrations described above, with some notable exceptions. For the most part, CLUES tended to underestimate TN concentrations, most notably the Whangamaire and Ngakaroa were underestimated by 97% and 90% respectively based on the comparison with the median of all available data. Whangamaire, which has the highest observed median TN concentration, has a mid-range concentration ranking in the CLUES simulations for both land use scenarios (note that data were not available for direct comparisons for either the 1998-2002 or 2004-2008 time periods). In contrast, concentrations simulated for West Hoe and Kaukapakapa are overestimated by 190% and 89 % respectively compared to the median concentrations for all data collected. Again, data were not available for direct comparison for these sites over the 1998-2002 and 2004-2008 time periods. The two land use scenario have very similar results. The sites with the highest CLUES predicted TN concentrations for both scenarios were Otaki, Papakura, Otara@East Tamaki, Omaru and, for the 2002 scenario, Kaukapakapa. The sites with the lowest predicted concentrations were Cascades, Opanuku, Mahurangi@Warkworth and Matakana.

The greatest differences between the simulated TN concentrations for the two land use scenarios are for the Kaukapakapa (decrease), Otaki and Otara@East Tamaki (increases) sites. The 2008 land use scenario for the Kaukapakapa upstream catchment area has a slight increase in dairy (around 2%) and intensive sheep and beef farming (around 8%), but a decrease (around 30%) in hill country sheep and beef farming and a corresponding increase in plantation. Otara@East Tamaki and Otaki are both urbanised catchments located close to each other in South Auckland. The only significant difference in the land use scenarios for these catchments is the loss of forest remnants which are not present in the 2008 land use scenario.

The CLUES simulated TN concentrations at the monitoring sites are plotted a column chart against the observed median concentrations in Figure 17. The sites have been grouped by the dominant land use class in the upstream catchment area. While forest and scrub generally had lower observed and modelled TN concentrations, the extent of other land uses does not seem to influence differences between CLUES estimates and those derived from water quality observations.

Table 18 CLUES TN concentrations simulated for the Default (2002) land use and difference from observed median monthly concentrations. CLUES concentrations are ranked from lowest (green) to highest (red).

Monitoring site	CLUES 2002 (mg/m^3)	Difference from median of all data		Difference from median 1998-2002	
		Absolute (mg/m^3)	%	Absolute (mg/m^3)	%
Matakana@Wenzlicks Farm	238.2	-147.8	-38	-	-
Hoteo@Gubbs	537.4	-117.4	-18	-178.5	-25
Mahurangi@Warkworth water treatment plant	214.4	-47.1	-18	-11.6	-5
Mahurangi@Forestry HQ	429.3	39.3	10	-	-
Waiwera@McCathies Falls	288.2	-270.8	-48	-	-
Makerau@Railway	326.3	-188.7	-37	-	-
West Hoe@Halls	624.7	409.2	190	-	-
Kaukapakapa@Taylors Rd	1482.1	697.1	89	-	-
Vaughans@Lower Weir	399.4	-190.1	-32	-	-
Okura Creek@Awanohi Rd	474.0	-291.0	-38	-	-
Riverhead@Aririmu	488.3	173.3	55	-	-
Lucas@Gills Rd Bridge	468.5	-218.5	-32	-	-
Oteha@Days Bridge	523.0	-200.0	-28	-	-
Rangitopuni@Walkers	390.2	-270.9	-41	-274.5	-41
Kumeu River@No. 1 Bridge	628.2	-303.8	-33	-	-
Oakley@Carrington Creek	709.5	-1230.5	-63	-	-
Omaru@Maybury st	847.8	-112.2	-12	-	-
Cascade Stream@Confluence	188.7	-35.8	-16	-	-
Opanuku@Candia Rd Bridge	193.4	-256.6	-57	-	-
Pakuranga@Botany Rd	774.0	-22.0	-3	47.0	6
Pakuranga@Greenmount Drive	751.9	37.4	5	162.9	28
Otara@Kennell Hill	586.3	-321.7	-35	-	-
Otara@East Tamaki Rd	784.3	-315.7	-29	-388.7	-33
Otaki@Middlemore Crescent	869.2	-257.3	-23	-90.8	-9
Puhinui@Drop Structure	604.5	-582.5	-49	-	-
Wairoa@Tourist Rd	393.9	-558.6	-59	-	-
Papakura@Porchester Rd Bridge	868.1	-326.9	-27	-	-
Wairoa Trib@Caitchons Rd	296.6	161.6	120	-	-
Whangamaire@Woodhouse Rd	412.7	-15087.3	-97	-	-
Ngakaroa@Mill Rd	304.3	-2795.7	-90	-	-
Waitangi Stream@Falls Rd	709.5	-1320.5	-65	-	-

Table 19 CLUES TN concentrations simulated for the Updated (2008) land use and difference from observed median monthly concentrations. CLUES concentrations are ranked from lowest (green) to highest (red).

Monitoring site	CLUES 2008 (mg/m^3)	Difference from median of all data		Difference from median 2004-2008	
		Absolute (mg/m^3)	%	Absolute (mg/m^3)	%
Matakana@Wenzlicks Farm	238.2	-147.8	-38	-176.8	-43
Hoteo@Gubbs	531.9	-123.0	-19	-65.7	-11
Mahurangi@Warkworth water treatment plant	188.6	-72.9	-28	-	-
Mahurangi@Forestry HQ	457.7	67.7	17	102.7	29
Waiwera@McCathies Falls	322.9	-236.1	-42	-328.1	-50
Makerau@Railway	337.8	-177.2	-34	-	-
West Hoe@Halls	752.2	536.7	249	528.2	236
Kaukapakapa@Taylors Rd	767.3	-17.7	-2	-	-
Vaughans@Lower Weir	584.8	-4.7	-1	-4.2	-1
Okura Creek@Awanohi Rd	572.4	-192.6	-25	-146.6	-20
Riverhead@Aririmu	508.4	193.4	61	-	-
Lucas@Gills Rd Bridge	636.3	-50.7	-7	-183.7	-22
Oteha@Days Bridge	603.3	-119.7	-17	-60.7	-9
Rangitopuni@Walkers	493.8	-167.3	-25	-144.1	-23
Kumeu River@No. 1 Bridge	790.8	-141.2	-15	-71.2	-8
Oakley@Carrington Creek	709.6	-1230.4	-63	-1175.4	-62
Omaru@Maybury st	847.9	-112.1	-12	-	-
Cascade Stream@Confluence	188.4	-36.1	-16	-53.6	-22
Opanuku@Candia Rd Bridge	219.4	-230.6	-51	-230.6	-51
Pakuranga@Botany Rd	774.9	-21.1	-3	-602.1	-44
Pakuranga@Greenmount Drive	755.5	41.0	6	-337.5	-31
Otara@Kennell Hill	672.9	-235.1	-26	-257.1	-28
Otara@East Tamaki Rd	826.4	-273.6	-25	-807.6	-49
Otaki@Middlemore Crescent	878.3	-248.2	-22	-756.7	-46
Puhinui@Drop Structure	704.7	-482.3	-41	-561.3	-44
Wairoa@Tourist Rd	427.6	-524.9	-55	-443.4	-51
Papakura@Porchester Rd Bridge	949.3	-245.7	-21	-177.7	-16
Wairoa Trib@Caitchons Rd	316.2	181.2	134	-	-
Whangamaire@Woodhouse Rd	380.4	-15119.6	-98	-	-
Ngakaroa@Mill Rd	339.2	-2760.8	-89	-2620.8	-89
Waitangi Stream@Falls Rd	770.9	-1259.1	-62	-	-

Scatter plots and regression equations are shown in Figure 18 for the median concentrations derived from all observation data against CLUES results simulated for both the 2002 and 2008 land use scenarios. Whangamaire and Ngakaroa are clear outliers for both scenarios. Kaukapakapa is an outlier for the 2002 scenario. When these sites are removed from the analysis, the coefficient of determination (R^2) increases from 0.001 and 0.007 for the 2002 and 2008 scenarios, respectively, to 0.426 and 0.3966. However, the regression line shows a marked departure from the 1:1 line in keeping with the tendency of the model to underestimate TN concentration, particularly as the observed concentrations increase. In the plots, the sites are displayed by land use type; regression by land use type was not possible as there are too few sites in each land use class.

Separate scatter plots were also prepared for the two time periods corresponding to the CLUES land use scenarios, these are shown in Figure 19. While there are regression lines for each of the plots, it should be noted that the 2002 time period had only seven sites with available data and there were no data available for forest and scrub. Like the plots above, it can be seen that the model tends to underestimate TN concentrations. Ngakaroa was again an outlier for the 2008 land use scenario, the overall R^2 rose from 0.09 to 0.4554 when this site was removed. Regression analysis was carried out on data from rural and urban land uses for this scenario, but not for forest and scrub which had only four sites with available data. It can be seen that while the overall fit improves for both scenarios, the relationship between CLUES TN concentrations and the long term median concentrations are fairly poor. The reasons for this are discussed in Section 5.4.

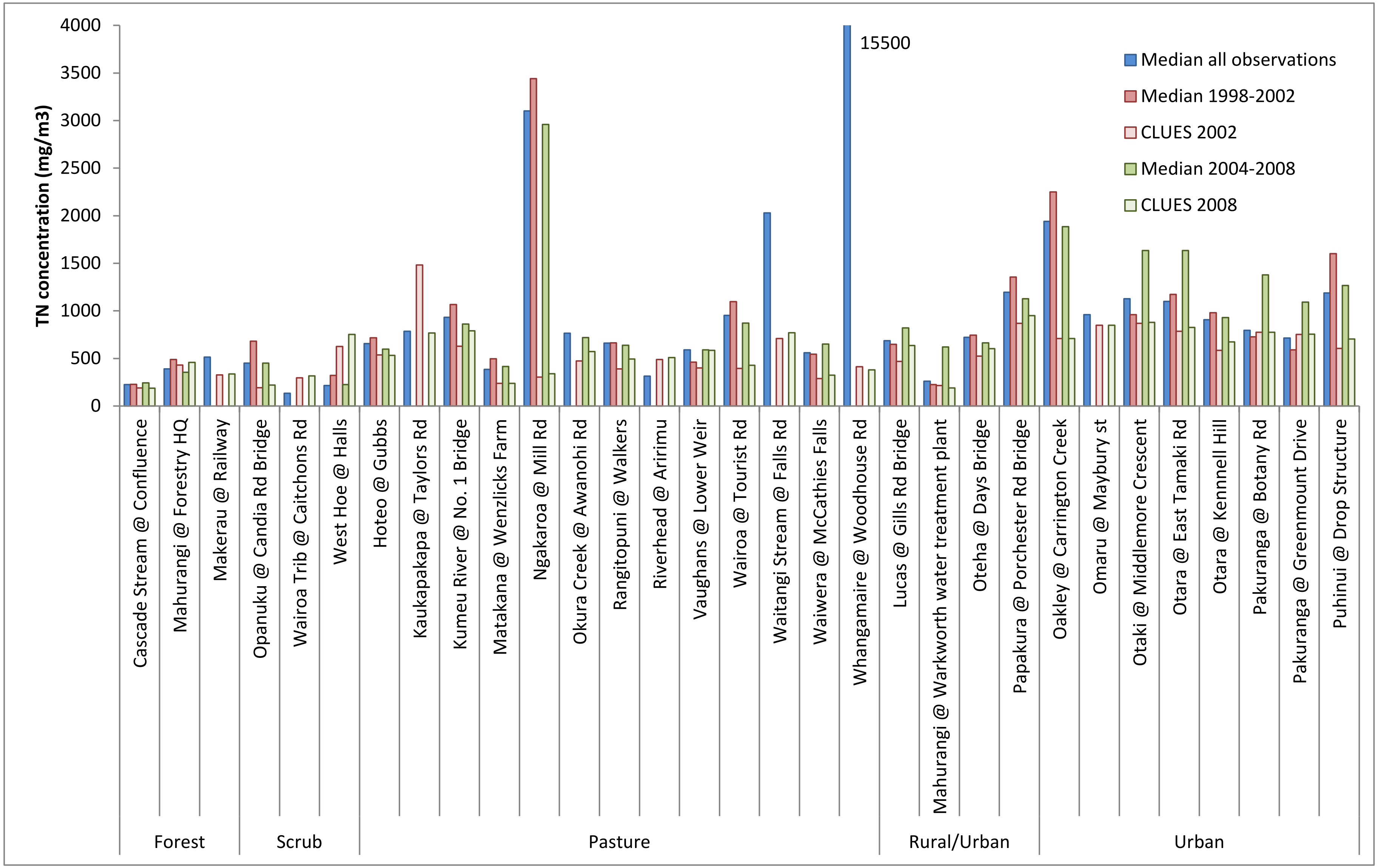


Figure 17 Comparison of observed median monthly TN concentrations against CLUES simulated concentrations. Sites are grouped by the upstream dominant land use type. Note that the observed concentration for Whangamaire all data is off the axis scale.

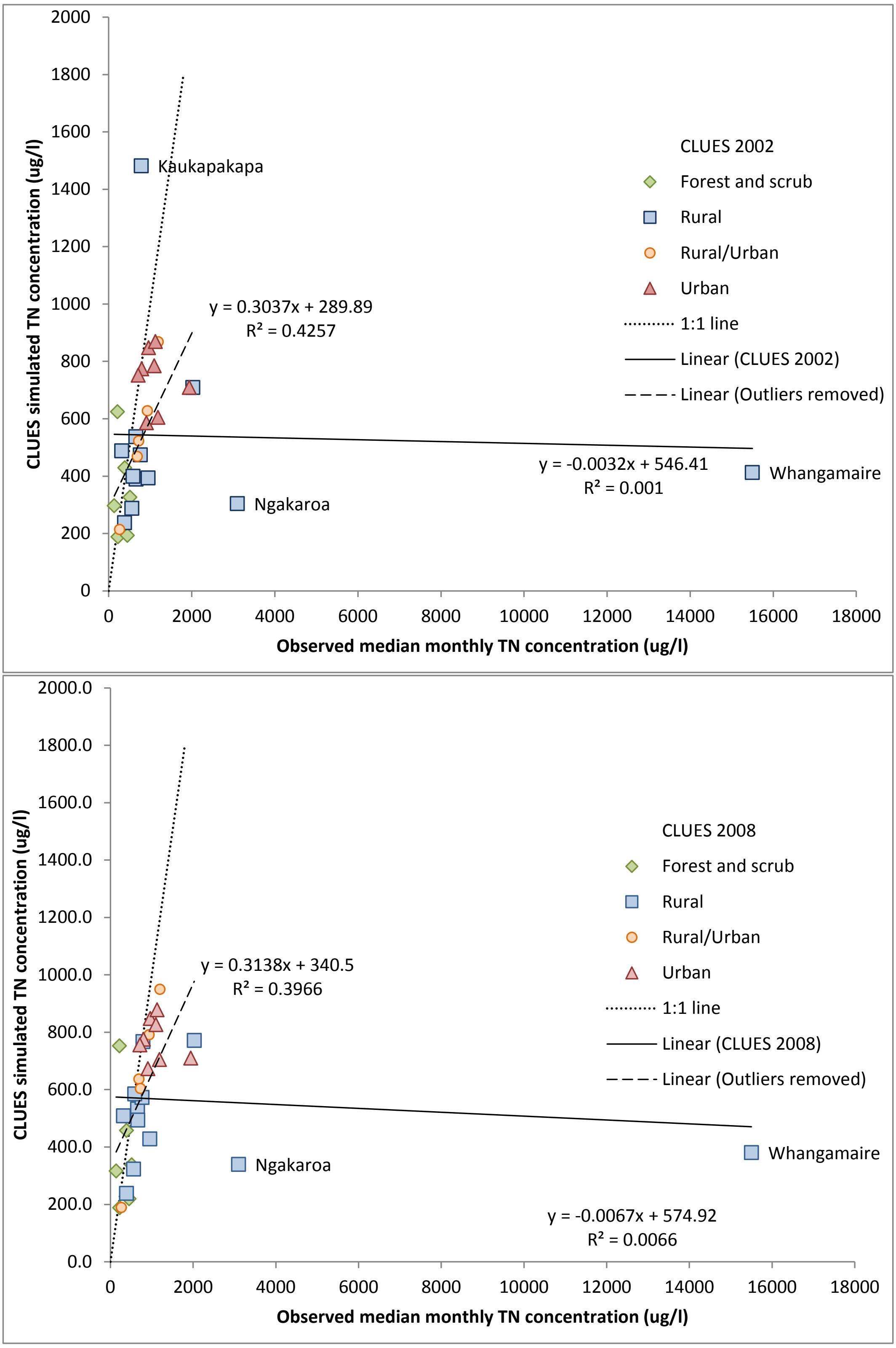


Figure 18 Regression plots of the observed median monthly TN concentrations for all available data against CLUES output for the two land use scenarios, 2002 (top) and 2008 (bottom), with and without outliers removed.

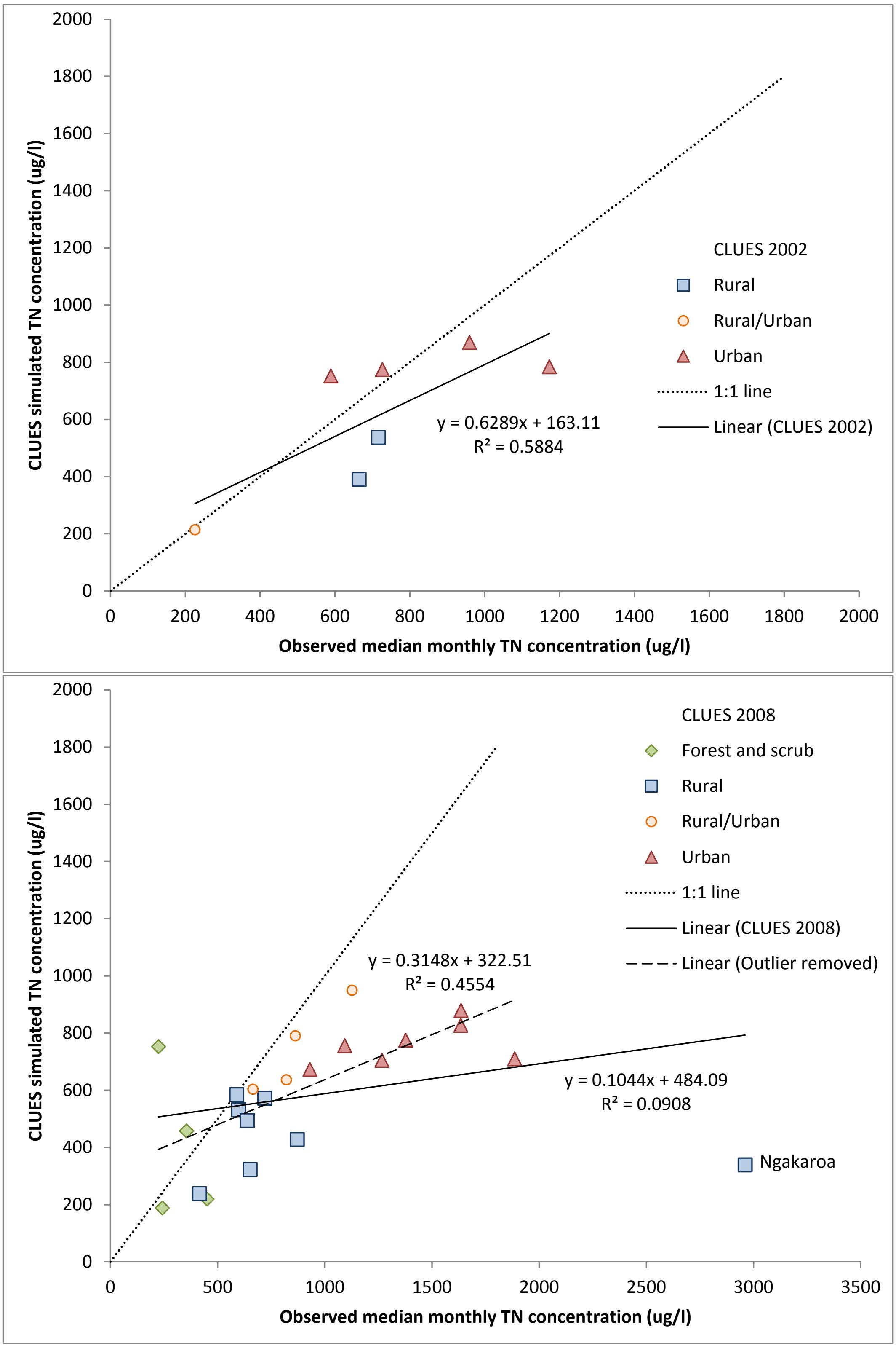


Figure 19 Regression plots of the observed median monthly TN concentrations for each time period (1998-2002, 2004-2008) against the corresponding CLUES output for the two land use scenarios: 2002 (top) and 2008 (bottom), with and without outliers removed.

4.1.3 CLUES total phosphorus concentrations

CLUES estimates of TP concentrations are given in Table 20 and Table 21 for the Default (2002) and Updated (2008) land use scenarios respectively. In each table, the concentrations are ranked from lowest (green) to highest (red). Unlike the TN ranks which were broadly similar to the ranking for the observed median TN concentrations, the CLUES TP rankings are very different to the observed rankings. West Hoe, for example is ranked as having the worst and second worst TP concentration in the CLUES runs but has a mid-range ranking in the observed concentrations. The 2002 CLUES-estimated TP concentration is more than three times greater than the median calculated with all available data (data is not available for the 1998-2002 time period). CLUES TP is overestimated almost five-fold for the 2008 land use scenario. Some of this difference can be explained by the fact that CLUES is calculating loads for a larger area than the contributing area to the monitoring site as discussed above for TN. The CLUES TP concentrations for Waitangi, Whangamaire and Vaughn's are also greatly overestimated.

There are large differences in CLUES TP concentrations simulated for Vaughn's and West Hoe for the two land use scenarios. West Hoe shows a reduction of scrub and forest from 2002 to pastoral land use in 2008 which could explain this difference. Vaughn's is located near the mouth of a minor stream. The 2002 land use scenario has a higher proportion of scrub and forest remnants than the 2008 scenario for this catchment. The sites with the lowest CLUES-simulated concentrations were Oakley, Cascades and Oteha for the 2002 land use scenario and Oakley, Kaukapakapa and Cascades for the 2008 land use scenario. The CLUES estimated TP concentrations for these sites were less than observed median concentrations. Interestingly, Kaukapakapa had one of the worst rankings for the 2002 land use scenario. The difference can be explained by the shift in land use for this catchment described for TN.

The CLUES simulated TN concentrations, grouped by dominant land use, are plotted in a column chart against the observed median concentrations in Table 20. It can be seen that CLUES underestimates TP concentrations simulated for the urban and mixed rural/urban sites but is generally overestimating concentrations for pasture and forested sites.

Regression analysis (Figure 21 and Figure 22) between the CLUES results for both scenarios and the medians calculated for the three observation periods showed poor model fit across the region. While West Hoe, Vaughn's and Pakuranga@Greenmount can be seen as outliers, removing these sites had a minor effect on model fit.

Table 20 CLUES TP concentrations simulated for the Default (2002) land use and difference from observed median monthly concentrations. CLUES concentrations are ranked from lowest (green) to highest (red).

Monitoring site	CLUES 2002 (mg/m^3)	Difference from median of all data		Difference from median 1998-2002	
		Absolute (mg/m^3)	%	Absolute (mg/m^3)	%
Matakana@Wenzlicks Farm	41.1	-6.9	-14	1.1	3
Hoteo@Gubbs	73.4	19.0	35	19.4	36
Mahurangi@Warkworth water treatment plant	66.7	16.7	33	16.7	33
Mahurangi@Forestry HQ	61.8	31.8	106	31.8	106
Waiwera@McCathies Falls	50.4	0.4	1	10.4	26
Makerau@Railway	86.5	42.0	94	-	-
West Hoe@Halls	122.3	92.8	315	-	-
Kaukapakapa@Taylors Rd	93.5	0.0	0	-	-
Vaughans@Lower Weir	98.9	46.9	90	-	-
Okura Creek@Awanohi Rd	86.2	25.7	42	-	-
Riverhead@Aririmu	40.8	15.3	60	-	-
Lucas@Gills Rd Bridge	62.5	2.5	4	2.5	4
Oteha@Days Bridge	31.7	-28.3	-47	-28.3	-47
Rangitopuni@Walkers	64.9	4.9	8	12.1	23
Kumeu River@No. 1 Bridge	35.8	-34.2	-49	-24.2	-40
Oakley@Carrington Creek	19.8	-40.2	-67	-40.2	-67
Omaru@Maybury st	35.3	-31.7	-47	-	-
Cascade Stream@Confluence	31.1	-8.9	-22	1.1	4
Opanuku@Candia Rd Bridge	31.8	-8.2	-20	1.8	6
Pakuranga@Botany Rd	39.7	-48.3	-55	-50.3	-56
Pakuranga@Greenmount Drive	43.8	-86.2	-66	-86.2	-66
Otara@Kennell Hill	56.4	-43.6	-44	-43.6	-44
Otara@East Tamaki Rd	39.4	-27.6	-41	-0.6	-2
Otaki@Middlemore Crescent	43.4	-32.6	-43	-16.6	-28
Puhinui@Drop Structure	41.8	-28.2	-40	-18.2	-30
Wairoa@Tourist Rd	55.2	0.2	0	5.2	10
Papakura@Porchester Rd Bridge	44.8	-35.2	-44	-25.2	-36
Wairoa Trib@Caitchons Rd	40.5	-0.5	-1	-	-
Whangamaire@Woodhouse Rd	61.2	42.2	222	-	-
Ngakaroa@Mill Rd	58.1	31.1	115	38.1	190
Waitangi Stream@Falls Rd	87.4	68.4	360	-	-

Table 21 CLUES TP concentrations simulated for the Updated (2008) land use and difference from observed median monthly concentrations. CLUES concentrations are ranked from lowest (green) to highest (red).

Monitoring site	CLUES 2008 (mg/m^3)	Difference from median of all data		Difference from median 1998-2002	
		Absolute (mg/m^3)	%	Absolute (mg/m^3)	%
Matakana@Wenzlicks Farm	43.8	-4.2	-9	-0.2	-1
Hoteo@Gubbs	74.6	20.2	37	16.4	28
Mahurangi@Warkworth water treatment plant	71.1	21.1	42	28.1	65
Mahurangi@Forestry HQ	78.8	48.8	163	48.8	163
Waiwera@McCathies Falls	57.1	7.1	14	8.1	17
Makerau@Railway	95.9	51.4	115	-	-
West Hoe@Halls	170.0	140.5	476	140.0	467
Kaukapakapa@Taylors Rd	24.4	-69.1	-74	-	-
Vaughans@Lower Weir	171.0	119.0	229	117.5	220
Okura Creek@Awanohi Rd	95.9	35.4	58	33.4	53
Riverhead@Ariirimu	40.2	14.7	58	-	-
Lucas@Gills Rd Bridge	71.3	11.3	19	11.3	19
Oteha@Days Bridge	33.1	-26.9	-45	-21.9	-40
Rangitopuni@Walkers	77.6	17.6	29	15.6	25
Kumeu River@No. 1 Bridge	43.6	-26.4	-38	-26.4	-38
Oakley@Carrington Creek	19.8	-40.2	-67	-45.7	-70
Omaru@Maybury st	35.3	-31.7	-47	-	-
Cascade Stream@Confluence	31.1	-8.9	-22	-5.4	-15
Opanuku@Candia Rd Bridge	38.3	-1.7	-4	-1.7	-4
Pakuranga@Botany Rd	40.4	-47.6	-54	-32.6	-45
Pakuranga@Greenmount Drive	43.4	-86.6	-67	-50.6	-54
Otara@Kennnell Hill	57.4	-42.6	-43	-12.6	-18
Otara@East Tamaki Rd	40.4	-26.6	-40	-19.6	-33
Otaki@Middlemore Crescent	43.4	-32.6	-43	-45.6	-51
Puhinui@Drop Structure	48.8	-21.2	-30	-18.2	-27
Wairoa@Tourist Rd	62.3	7.3	13	6.8	12
Papakura@Porchester Rd Bridge	51.4	-28.6	-36	-35.1	-41
Wairoa Trib@Caitchons Rd	45.7	4.7	11	-	-
Whangamaire@Woodhouse Rd	58.1	39.1	206	-	-
Ngakaroa@Mill Rd	65.2	38.2	142	35.2	117
Waitangi Stream@Falls Rd	94.3	75.3	397	-	-

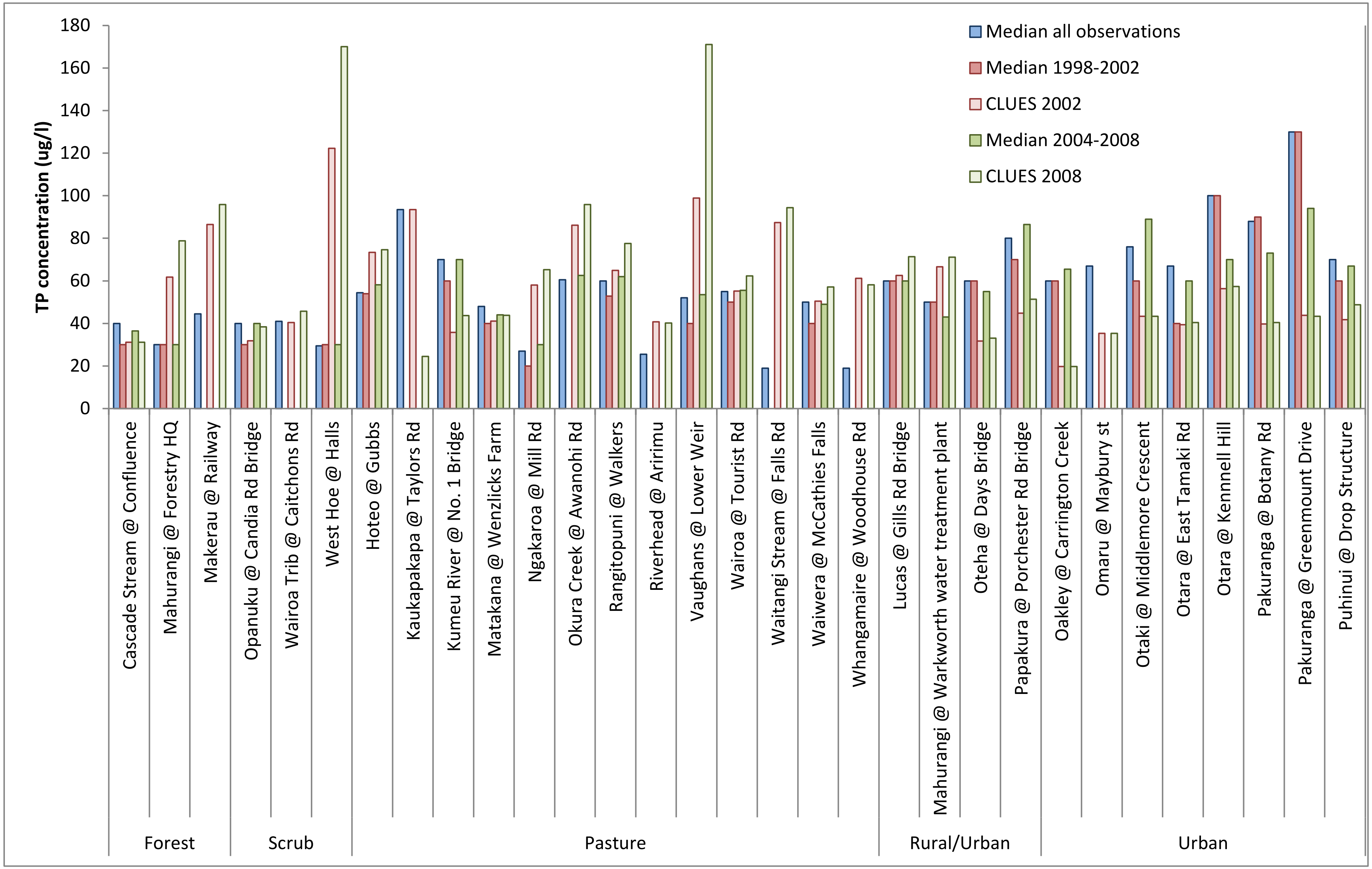


Figure 20 Comparison of observed median monthly TP concentrations against CLUES simulated concentrations. Sites are grouped by the dominant upstream land use type.

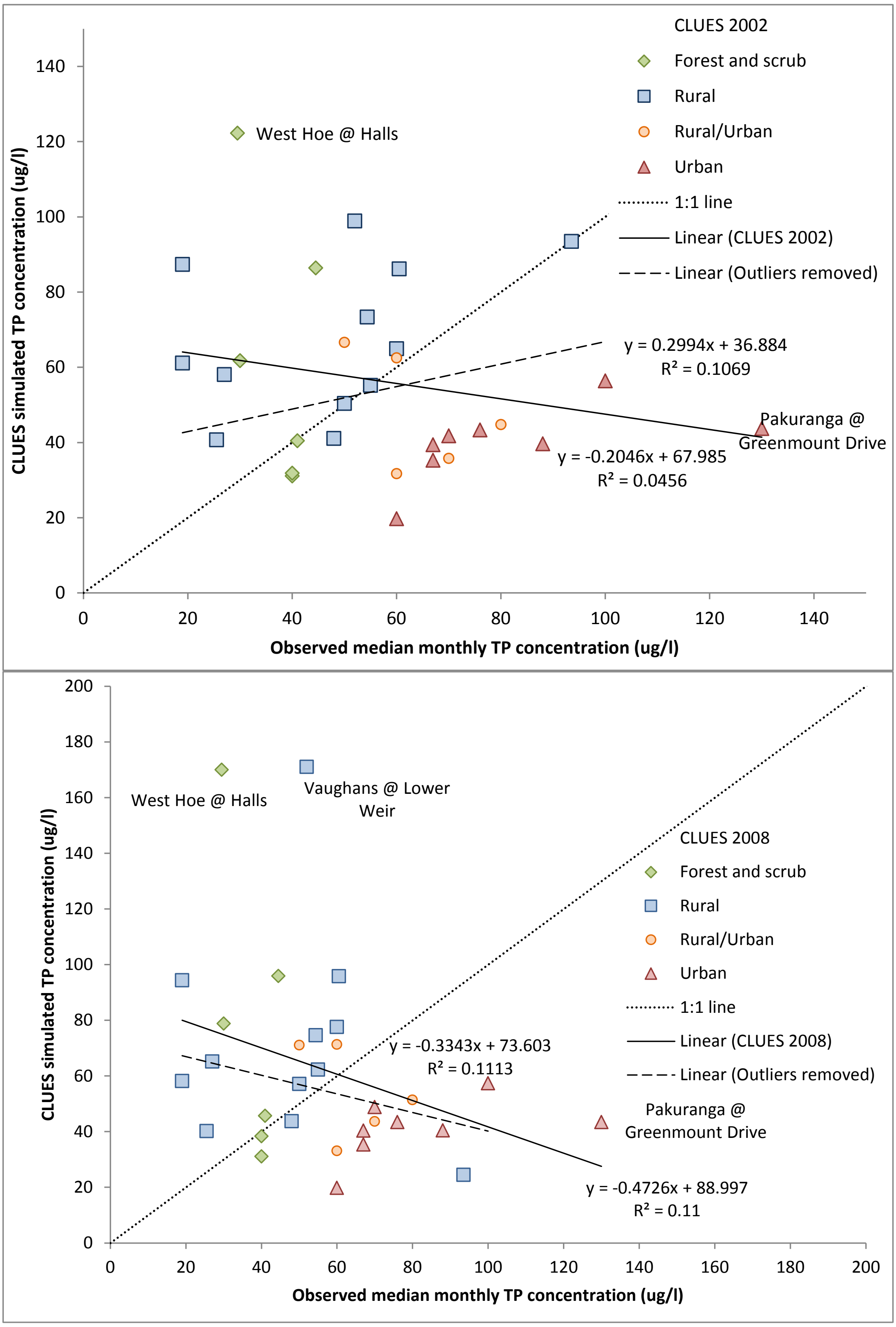


Figure 21 Regression plots of the observed median monthly TP concentrations for all available data against CLUES output for the two land use scenarios, 2002 (top) and 2008 (bottom), with and without outliers removed.

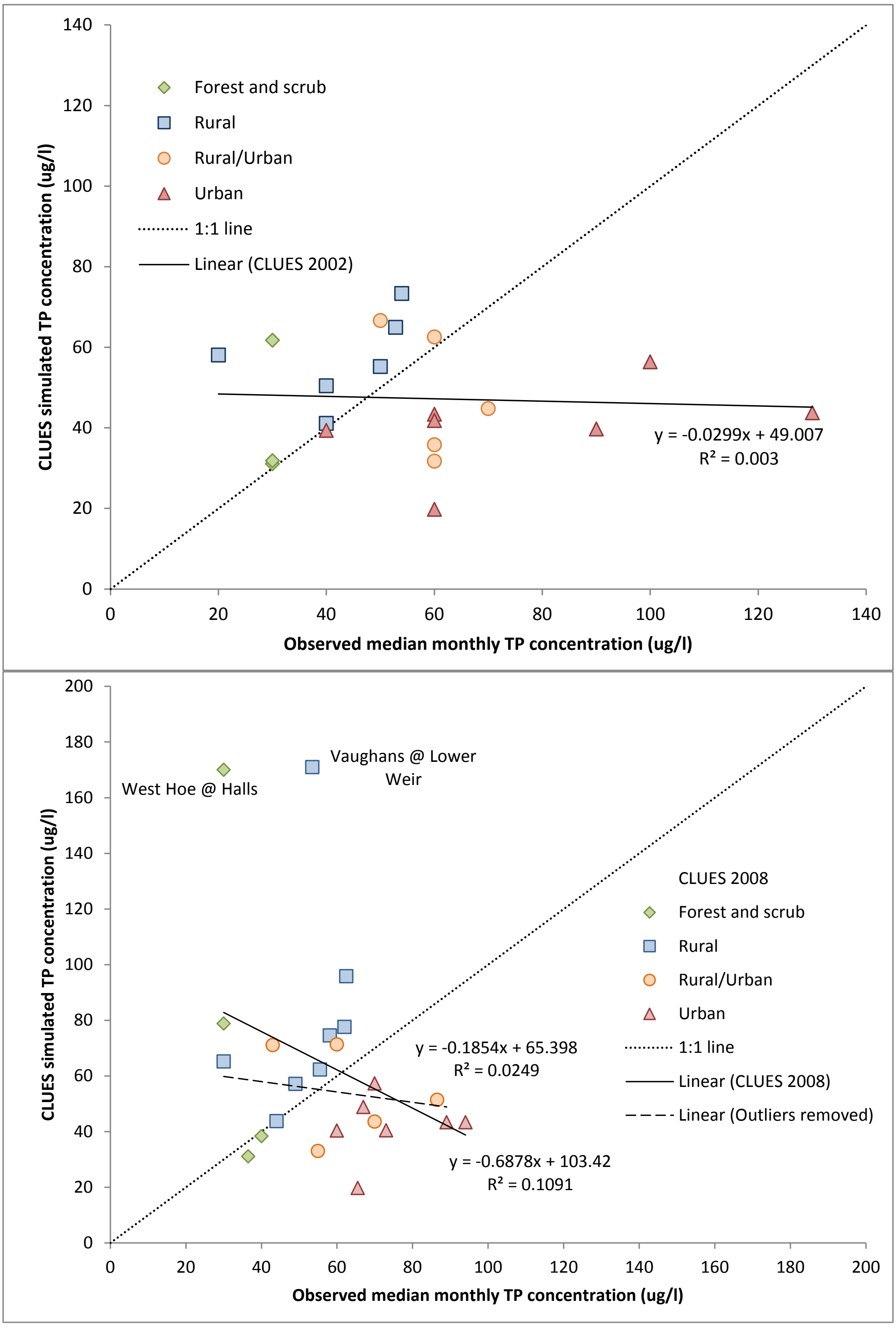


Figure 22 Regression plots of the observed median monthly TN concentrations for each time period (1998-2002, 2004-2008) against the corresponding CLUES output for the two land use scenarios: 2002 (top) and 2008 (bottom) with and without outliers removed.

4.2 Nutrient loads and yields

In the previous section, CLUES nutrient concentrations, which are calculated from load as a function of the estimated mean annual flow rate, were compared to median monthly nutrient concentrations calculated for water quality monitoring sites across the region. In this section, CLUES loads are compared to mean annual loads calculated from the observed monthly SOE concentrations for a sub-set of the monitoring sites. The sites were selected as part of the 'SPARROW for CLUES' calibration process in 2010 according to the proximity of flow monitoring stations and number of monthly observations made over the flow monitoring period (i.e., more than 60 samples concurrent with flow). On the basis of these criteria, comparisons were possible at nine sites for TN and eight for TP as listed in Table 22. Of these sites, five are dominated by pastoral land use, one is urban and the remaining three are mixed rural and urban land uses. None of the sites are dominated by forest.

Table 22 Mean annual loads and yields calculated from measured concentration and flow data for water quality monitoring sites meeting selection criteria. Loads and yields are ranked from high (red) to low (green)

Site	TN			TP		
	Calculated mean load (t/y)	Std dev	Mean yield (kg/ha/y)	Calculated mean load (t/y)	Std dev	Mean yield (kg/ha/y)
Hoteo @ Gubbs	216.46	10.97	8.12	30.63	3.86	1.15
Mahurangi @ Warkworth water treatment plant	17.07	3.29	3.52			
Oteha @ Days Bridge	8.50	5.19	7.11	1.10	0.23	0.92
Rangitopuni @ Walkers	62.74	9.09	7.67	9.41	2.2	1.15
Kumeu River @ No. 1 Bridge	47.00	3.91	10.17	3.52	0.63	0.76
Puhinui @ Drop Structure	11.71	1.87	9.31	0.94	0.1	0.75
Wairoa @ Tourist Rd	168.79	65.99	11.60	16.87	1.97	1.16
Papakura @ Porchester Rd Bridge	59.06	12.13	16.54	5.85	0.59	1.64
Ngakaroa @ Mill Rd	10.88	0.47	24.42	0.24	0.04	0.54

Although the sites were selected in 2010, loads were recalculated for this project to take advantage of new water quality data collected since that time. The nutrient loads for each site were estimated using the rating curve method. The rating curve method extrapolates contaminant concentrations (TN and TP, in this case) over the entire period of interest by developing a relationship between contaminant concentration and stream discharge (Letcher et al. 1999).An example of a rating curve is given in Figure 23. Applying this relationship to the discharge record for each year allows annual loads to be estimated. The regressions were developed in log-transformed space, so a smearing retransformation bias correction was applied (Duan 1983). Because the rating curves were generally curvilinear (as illustrated in Figure 23 for TP monitored at Wairoa@Tourist Rd) the GAM (generalised additive model) routine was used to fit a smoothed relationship. Uncertainties in load estimates were generated by a method called statistical bootstrapping. Bootstrapping, estimates a distribution of possible loads by repeatedly calculating loads from a randomly selected sub-sample of the original data. In this case, uncertainty was calculated by resampling the TN and TP data for each site 200 times.

The calculated mean annual loads and standard deviations for each site are provided in Table 22. Yields, calculated as the load divided by upstream catchment area, are also included to allow comparison between sites. The highest nutrient loads were calculated for the Hoteo and Wairoa monitoring sites, reflecting the fact that these sites have the greatest upstream contributing areas. The site with the highest TN yield was Ngakaroa followed by Papakura and Wairoa. Note that the latter two sites have high variability, as indicated by the standard deviation relative to the mean, of the calculated TN loads. The highest TP yields were for the Papakura and Wairoa sites. The sites with the greatest variability in the calculated loads were Oteha, Wairoa and Papakura for TN and Oteha and Rangitopuni for TP

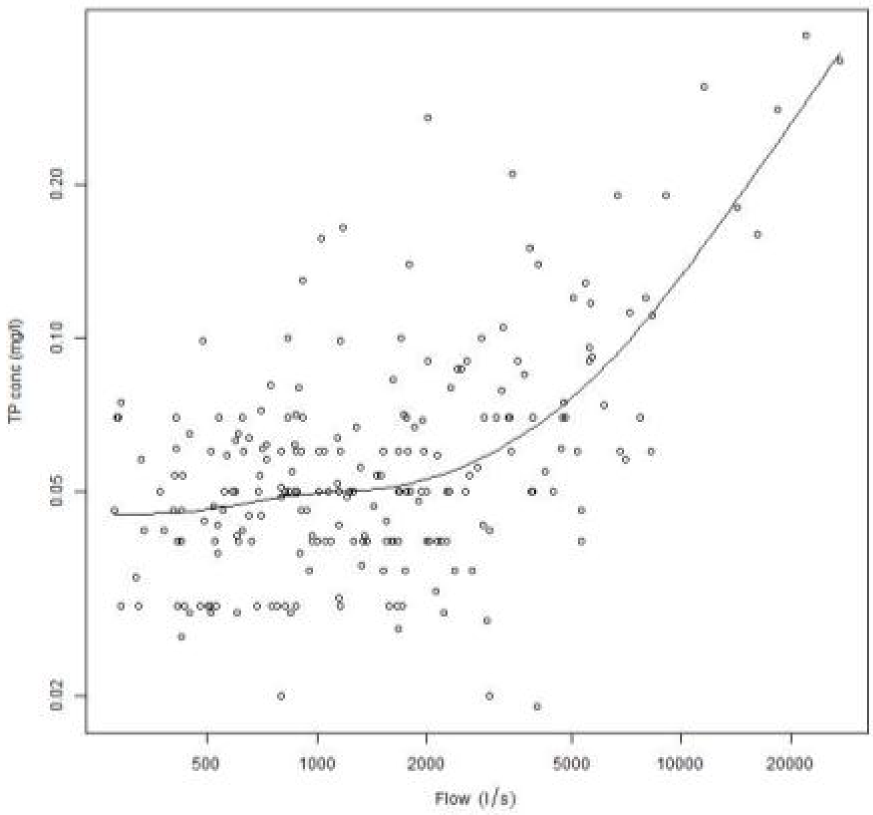


Figure 23	Example of a rating curve showing the relationship between TP concentration and flow at Wairoa@Tourist Road.

4.2.1 CLUES total nitrogen loads and yields

Table 23 shows the TN loads and yields simulated by CLUES for the selected monitoring sites. The loads and yields have been ranked from high (red) to low (green). The percentage differences from the loads and yields calculated above are also given in the table (note that the percentage differences of loads and yields for any given site are the same). With the exception of the Mahurangi site, where loads and yields are overestimated, CLUES is underestimating yields and loads, by as much as 88 % for Ngakaroa. While the rankings are fairly similar for loads, with Hoteo and Wairoa having the highest loads and Oteha and Ngakaroa the least, there are more marked differences in the yield rankings. The sites with the highest simulated TN yields are Hoteo, Papakura and Mahurangi. Papakura was also highly ranked based on the yields calculated from observations (see above), but this was not the case for Mahurangi and Hoteo.

Table 23 CLUES TN loads and yields simulated with the 2002 and 2008 land use scenarios for selected monitoring sites ranked from high (red) to low (green)

Monitoring site	Default (2002)			Updated (2008)		
	Load (t/y)	Yield (kg/ha/y)	Difference from measured (%)	Load (t/y)	Yield (kg/ha/y)	Difference from measured (%)
Hoteo @ Gubbs	209.31	7.85	-3	207.13	7.77	-4
Mahurangi @ Warkworth water treatment plant	28.68	5.92	68	25.23	5.21	48
Oteha @ Days Bridge	4.25	3.56	-50	4.91	4.11	-42
Rangitopuni @ Walkers	31.93	3.90	-49	40.41	4.94	-36
Kumeu River @ No. 1 Bridge	20.87	4.52	-56	26.27	5.68	-44
Puhinui @ Drop Structure	4.71	3.74	-60	5.49	4.36	-53
Wairoa @ Tourist Rd	67.11	4.61	-60	72.85	5.00	-57
Papakura @ Porchester Rd Bridge	20.87	5.84	-65	22.82	6.39	-61
Ngakaroa @ Mill Rd	1.30	2.91	-88	1.45	3.25	-87

Scatter plots of CLUES simulated TN loads and yields for the 2002 and 2008 land use scenarios against those calculated from the observed data (Figure 24 and Figure 25) show a good relationship for loads. However, the strength of this relationship is largely explained by catchment area. When normalised for area, the relationship for yields is poor. Again, model underestimation is evident. As noted above, the contributing area and catchment boundaries for the Papakura site are incorrect in the REC which will have a negative impact on the calculated loads. In addition, the flow is monitored downstream of the water quality sampling site at the Papakura@Great South Road flow monitoring site maintained by Auckland Council. While fairly close, this monitoring station is located in an urban area which means that the flow may be quite different from that experienced at the rural Porchester Road site. That is, the influx of stormwater may be causing flashier responses to rainfall and higher peak flows which may be resulting in distorted load calculations.

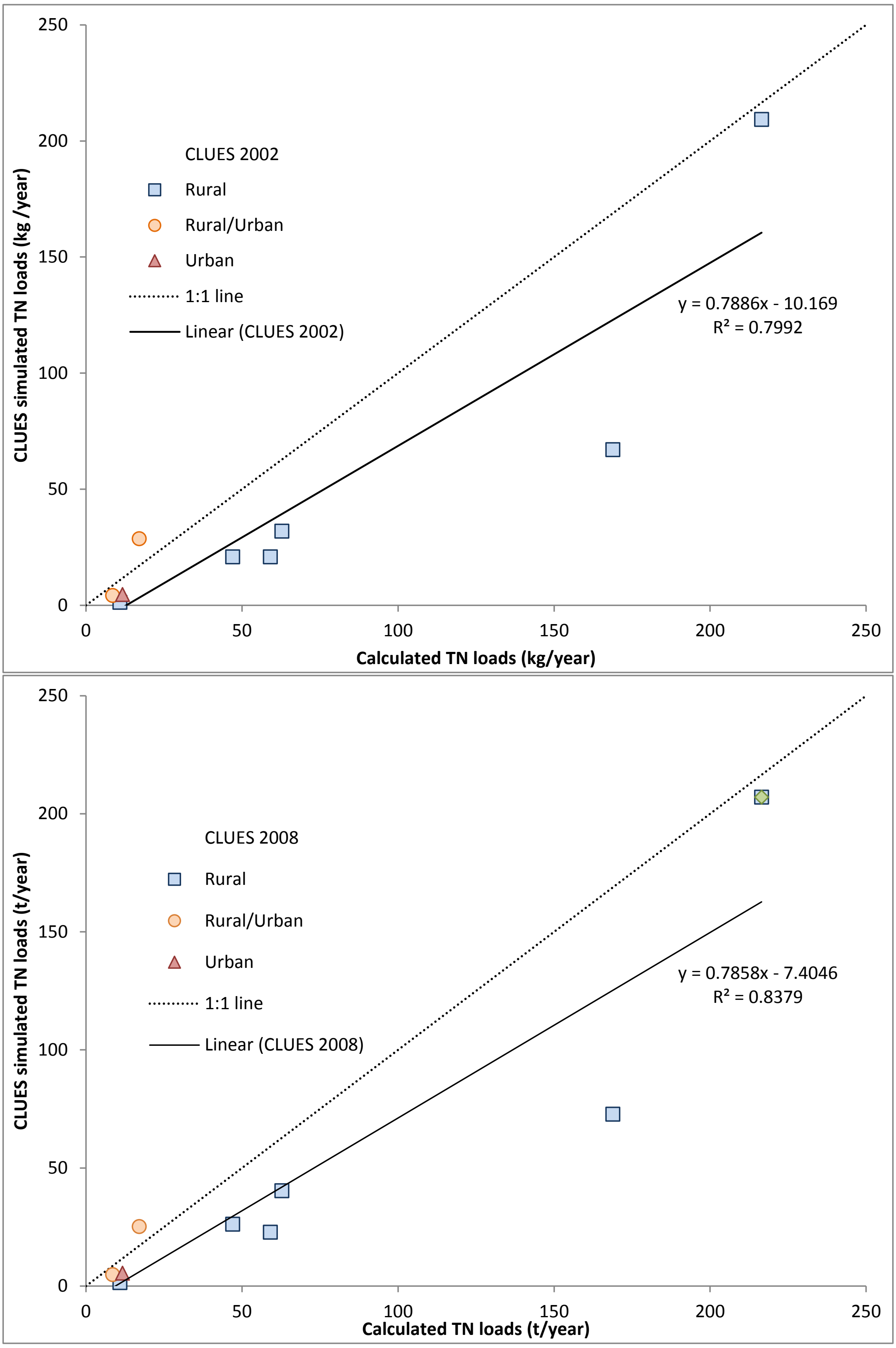


Figure 24 CLUES simulated annual TN loads against loads calculated using monitored concentration and flow data: 2002 (top) and 2008 (bottom)

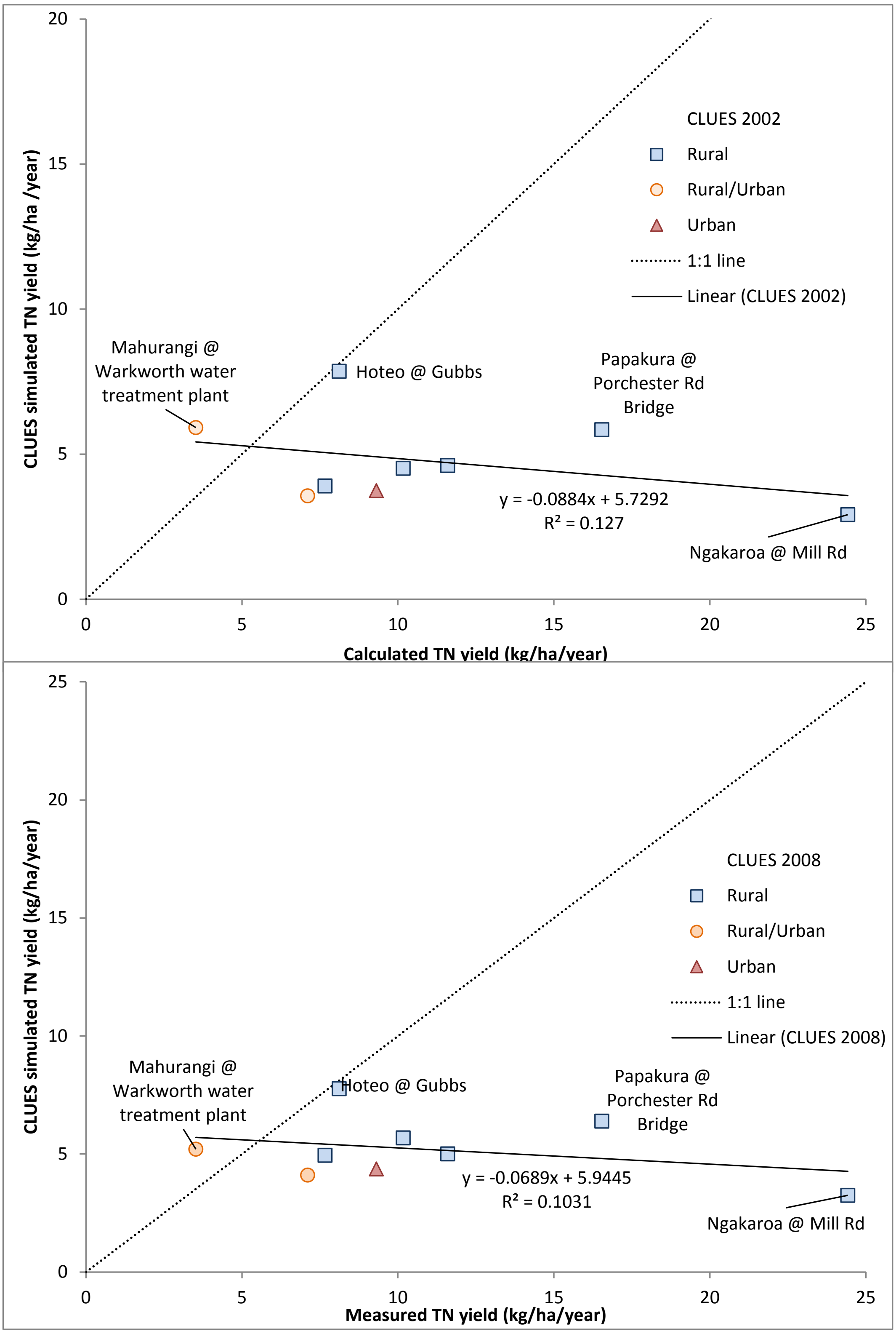


Figure 25 CLUES simulated annual TN yields against yields calculated using monitored concentration and flow data: 2002 (top) and 2008 (bottom)

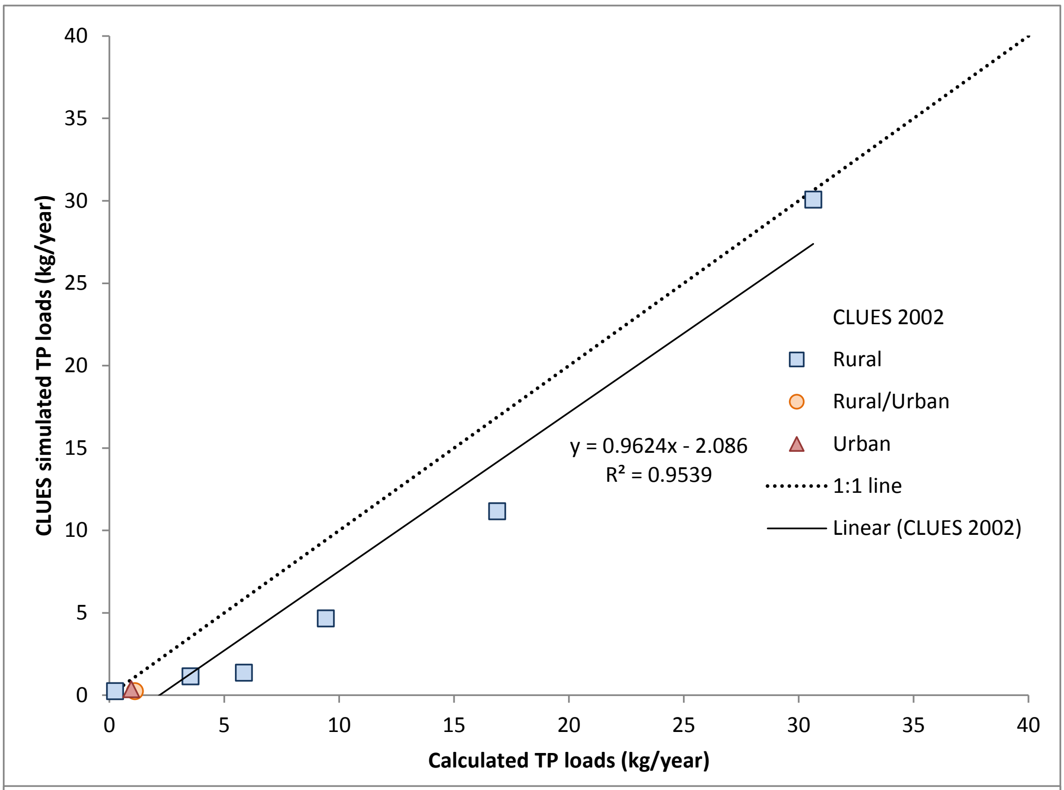
4.2.2 CLUES total phosphorus loads and yields

Table 24 shows the TP loads and yields simulated by CLUES for the selected monitoring sites ranked from high (red) to low (green). The percentage differences from the loads and yields calculated above are also given in Table 24. Like TN, the TP rankings are fairly similar for loads, with Hoteo and Wairoa having the highest loads and Oteha and Ngakaroa the least. However, there are more marked differences in the yield rankings. The sites with the highest simulated TP yields are Hoteo, Wairoa and Rangitopuni. It can be seen that CLUES is substantially underestimating yields and loads at most of the sites with the exceptions of Hoteo and Ngakaroa.

Scatter plots for TP loads and yields for the 2002 and 2008 scenarios are given in Figure 26 and Figure 27, respectively. The plots for the two scenarios are very similar. Like the TN plots, regression analysis shows a good fit for loads but not for yields. Hoteo is the only site with CLUES yields approximating the calculated yields, although Ngakaroa is fairly similar for the 2008 scenario.

Table 24 CLUES TP loads and yields simulated with the 2002 and 2008 land use scenarios for selected monitoring sites ranked from high (red) to low (green)

Monitoring site	Default (2002)			Updated (2008)		
	Load (t/y)	Yield (kg/ha/y)	Difference from measured (%)	Load (t/y)	Yield (kg/ha/y)	Difference from measured (%)
Hoteo @ Gubbs	30.07	1.13	-2	30.57	1.15	0
Oteha @ Days Bridge	0.25	0.21	-77	0.26	0.22	-76
Rangitopuni @ Walkers	4.66	0.57	-50	5.57	0.68	-41
Kumeu River @ No. 1 Bridge	1.15	0.25	-67	1.40	0.30	-60
Puhinui @ Drop Structure	0.37	0.29	-61	0.43	0.34	-54
Wairoa @ Tourist Rd	11.17	0.77	-34	12.60	0.87	-25
Papakura @ Porchester Rd Bridge	1.37	0.38	-77	1.58	0.44	-73
Ngakaroa @ Mill Rd	0.25	0.56	4	0.28	0.63	16



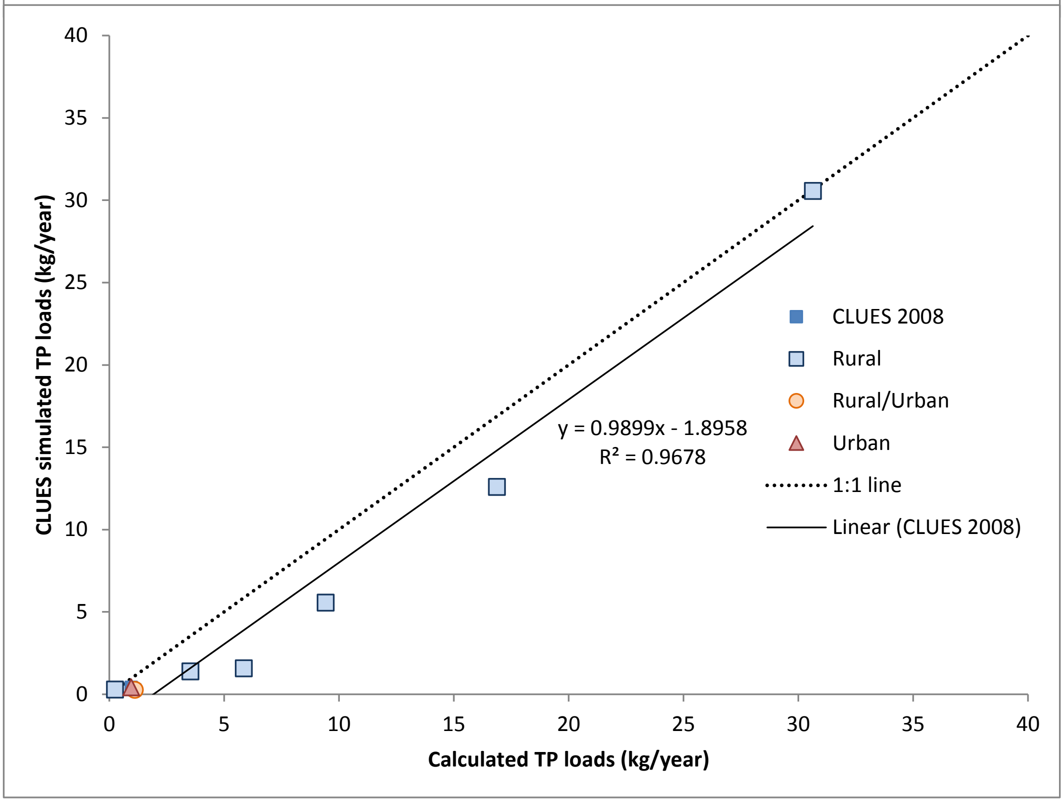


Figure 26 CLUES simulated annual TP loads against loads calculated using monitored concentration and flow data: 2002 (top) and 2008 (bottom)

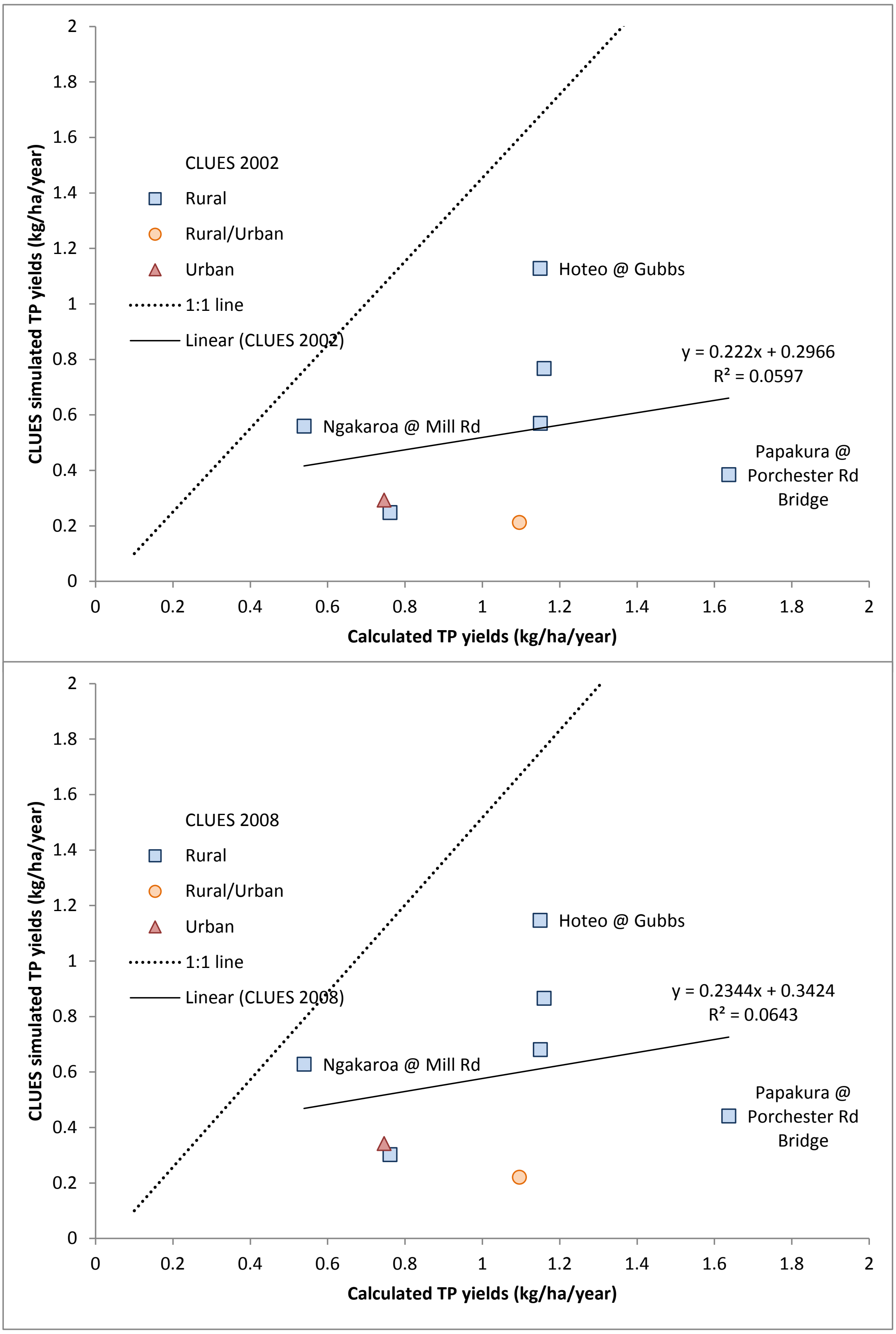


Figure 27 CLUES simulated annual TP yields against yields calculated using monitored concentration and flow data: 2002 (top) and 2008 (bottom)

4.3 Sediment yields

The Auckland Council has calculated mean annual yields of suspended sediments at a total of 15 sites as part of its freshwater sediment monitoring programme. The yields were initially calculated for nine sites in 2009 (Hicks et al., 2009). These sites were revised by the council (Curran-Cournane et al., 2013), and there are currently 10 sediment monitoring sites. Four of the 15 sites appear in both sets of yield calculations. The sites are mapped in Figure 28 and listed in Table 25 along with a description of the upstream catchment characteristics which affect sediment yields. There are no monitoring sites in West Auckland, Auckland City or Manukau/Pukekohe. While most of the sites are rural with mixed pastoral or forest land use, Barwick and Lower Awaruka, are predominantly urban. Both of these catchments are located in the head waters of first order streams. The West Hoe site is also located in a head water stream, near a confluence. Two yields were calculated for the Redwoods site which is dominated by exotic forestry – pre and post-harvest - since CLUES does not take harvesting into account, only the pre-harvest yield is reported here. Note that there are some minor differences in the characteristics recorded in the two sediment monitoring reports. Hicks et al. (2009) for example reports slope as a gradient ratio whereas Curran-Cournane et al. (2013) reports the predominant LRI slope class along with the proportion of the catchment covered with that slope class. Moreover, the former reports runoff as a mean annual rate whereas the latter reports the annual depth of runoff. For this reason, sites that are common to both studies appear twice in Table 25.

The CLUES simulated sediment yields are compared to the two sets of calculated loads in Table 26 and in Figure 29, which groups the sites by dominant land use. The sediment yields simulated for the two land use scenarios are very similar. It is interesting to note that there are large differences in the yields calculated for the sites that are common to both Hicks et al. (2009) and Curran-Cournane et al. (2013). The latter has lower yields for Weiti, Vaughn's and Okura sites but not Mangemangeroa. The sites with the highest calculated yields are Wylie Road, Redwoods (which appear only in Hicks et al. (2009)) and Mangemangeroa, which is unexpected as these sites are largely forested, however, the contributing areas to these sites are on strongly rolling to moderately steep land.

Scatter plots (Figure 30) show that the CLUES yields have better agreement with the yields calculated by Curran-Cournane et al. (2013) than Hicks et al. (2009). Mangemangeroa in an outlier in the CLUES results and has the highest simulated yield. In comparison with Hicks et al. (2009), CLUES yields are underestimated by between 20-80% at all sites but Mangemangeroa and Barwick. There is a more even scatter in the comparison of CLUES estimates with the Curran-Cournane et al. (2013) yields, with CLUES yields at Mangemangeroa, Wairoa, Hoteo, Kaipara and West Hoe being overestimated and the rest of the sites underestimated.

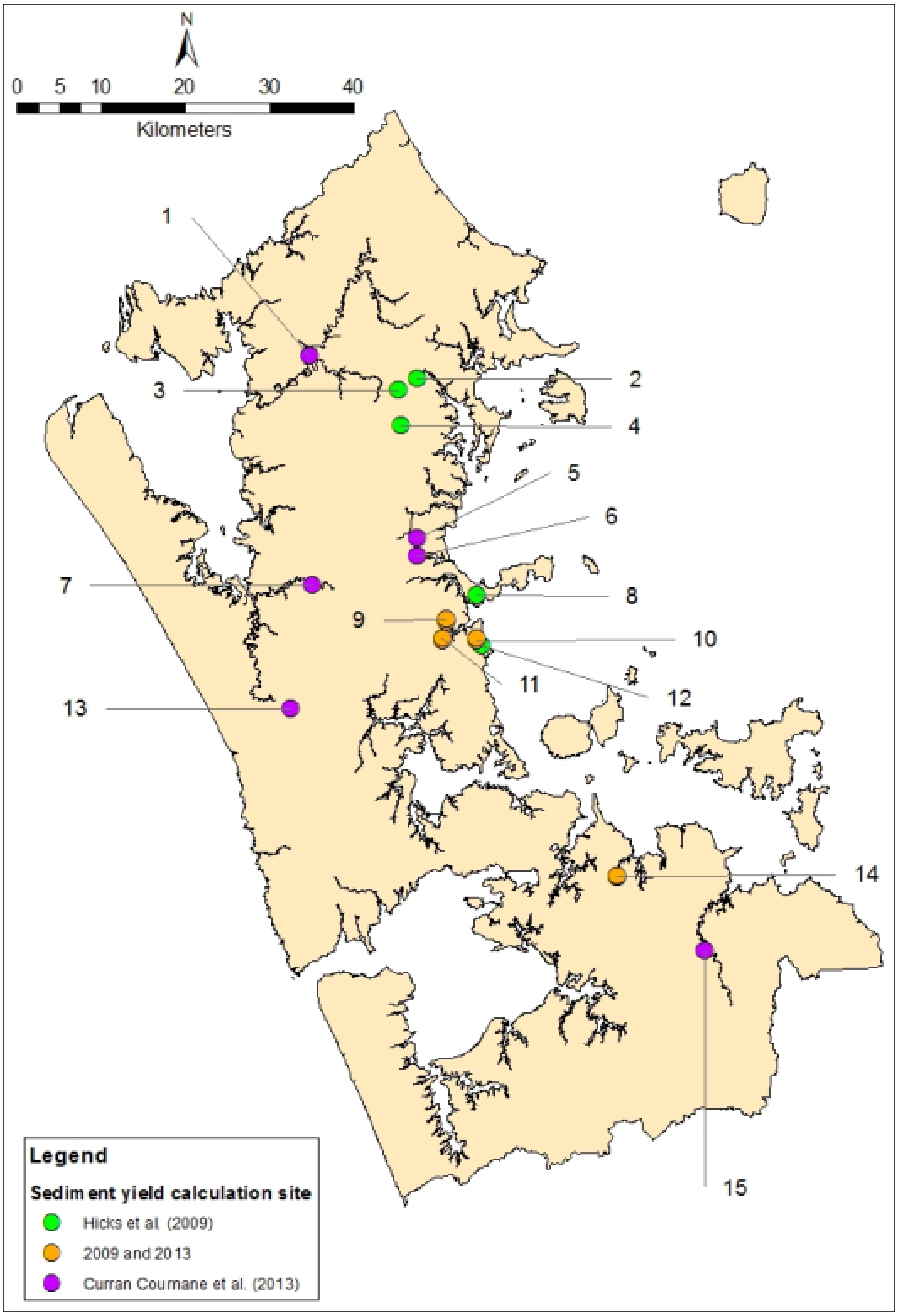


Figure 28 Sediment monitoring sites

Table 25 Sediment monitoring sites and upstream characteristics summarised from Hicks et al. (2009) and Curran-Cournane et al. (2013)

Map Key	Site	REC Reach	Source document	Catchment area (km²)	Lithology (% area)	Land use (% area)	Slope		Rainfall (mm/yr)	Flow	
							(m/m)	Class (% area)		Mean rate (l/s)	Mean annual runoff (mm/y)
1	Hoteo at Gubbs	2001653	Curran-Cournane et al. (2013)	268.0	Waitemata (77%) Mudstone (8%) Alluvium (8%) Limestone (6%) Greywacke (<1%)	Native vegetation (21) Pasture (56) Exotic vegetation (23) Other (<0.5%)		Moderately steep (44%)	1387		659
2	Mahurangi College	2001778	Hicks et al. (2009)	48.8	Sandstone or coarse siltstone (83%) Alluvium (9%)	Pastoral (54%) Native forest (24%)	0.29		1591	1161	
3	Wylie Rd	2001824	Hicks et al. (2009)	1.05	Sandstone or coarse siltstone (100%)	Pastoral (84%) Native forest (12%)	0.32		1570	35.9	
4	Redwoods	2002107	Hicks et al. (2009)	2.68	Sandstone or coarse siltstone (100%)	Exotic forest (99%) Native forest (1%)	0.41		1472	12.88	
5	West Hoe	2003138	Curran-Cournane et al. (2013)	0.5	Waitemata (100%)	Native vegetation (97) Pasture (3)		Moderately steep (74%)	1232		536
6	Orewa at Kowhai Ave	2003268	Curran-Cournane et al. (2013)	9.7	Mudstone (50%) Waitemata (26%) Alluvium (23%) Limestone (1%)	Native vegetation (14) Pasture (83) Exotic vegetation (3) Other (<1%)		Rolling 52%	1232		547

Map Key	Site	REC Reach	Source document	Catchment area (km^2)	Lithology (% area)	Land use (% area)	Slope		Rainfall (mm/yr)	Flow	
							(m/m)	Class (% area)		Mean rate (l/s)	Mean annual runoff (mm/y)
7	Kaukapakapa at Taylors	2003513	Curran-Cournane et al. (2013)	62.00	Mudstone (33%), Waitemata (25%), Alluvium (23%), Conglomerate (16%), Limestone (3%),	Native vegetation (13), Pasture (80), Exotic vegetation (6), Other (1)		Rolling (39%)	1283		651
8	Barwick	2003646	Hicks et al. (2009)	0.25	Sandstone or coarse siltstone (100%)	Urban (93%), Native forest (7%)	0.22		1224	1.733	
9	Weiti Forest	2003911	Hicks et al. (2009)	1.7	Mudstone or fine siltstone - banded (43%), Sandstone or coarse siltstone - banded (21%)	Exotic forest (83%), Pastoral (15%)	0.25		1226	32.68	
	Weiti Forest	2003911	Curran-Cournane et al. (2013)	1.7	Mudstone (51%), Limestone (42%), Waitemata (4%), Greywacke (3%)	Native vegetation (2), Pasture (13), Exotic vegetation (84),		Rolling (51%)	1330		316

Map Key	Site	REC Reach	Source document	Catchment area (km^2)	Lithology (% area)	Land use (% area)	Slope		Rainfall (mm/yr)	Flow	
							(m/m)	Class (% area)		Mean rate (l/s)	Mean annual runoff (mm/y)
10	Lower Vaughan Weir	2004122	Hicks et al. (2009)	2.17	Sandstone or coarse siltstone (89 %), Alluvium (8%)	Pastoral (61%), Native forest (24%)	0.24		1202	43.01	
			Curran-Cournane et al. (2013)	2.3	Waitemata (97%), Limestone (3%)	Native vegetation (27), Pasture (61), Exotic vegetation (6), Other (6)		Strongly rolling (53%)	1067		508
11	Okura at Awanohi Stream	2004093	Hicks et al. (2009)	5.27	Sandstone or coarse siltstone (81%), Sheared mixed lithologies (10%)	Native forest (55%), Pastoral (35%)	0.32		1221	44.5	
			Curran-Cournane et al. (2013)	5.5	Waitemata (75%), Mudstone (22%), Limestone (2%), Alluvium (1%),	Native vegetation (60), Pasture (33), Exotic vegetation (7)		Moderately steep (61%)	1330		436
12	Awaruku	2004196	Hicks et al. (2009)	2.66	Sandstone or coarse siltstone (91%)	Urban (81%), Native forest (9%)	0.19		1199	70.85	

Map Key	Site	REC Reach	Source document	Catchment area (km^2)	Lithology (% area)	Land use (% area)	Slope		Rainfall (mm/yr)	Flow	
							(m/m)	Class (% area)		Mean rate (l/s)	Mean annual runoff (mm/y)
13	Kaipara at Waimauku	2004794	Curran-Cournane et al. (2013)	163	Waitemata (45%), Alluvium (34%), Sand/sand dune 10%, Conglomerate (9%), Mudstone (2%)	Native vegetation (10), Pasture (60), Exotic vegetation (23), Other (7)		Rolling (35%)	1278		567
14	Mangemangeroa	2006429	Hicks et al. (2009)	4.44	Waitemata (100%)	Pastoral (58%), Native forest (38%)	0.29		1177	48.79	
			Curran-Cournane et al. (2013)	4.50	Sandstone or coarse siltstone (100%)	Native vegetation (37), Pasture (56), Exotic vegetation (6), Other (<2%)		Strongly rolling (51%)	1210		344
15	Wairoa at Tourist Road	2007413	Curran-Cournane et al. (2013)	114	Greywacke (58%), Waitemata (33%), Alluvium (6%), Mudstone (2%)	Native vegetation (23), Pasture (63), Exotic vegetation (14)		Moderately steep (29%)	1413		731

Table 26 Annual sediment yields (t/km^2/y) for the Auckland Council sediment monitoring sites

Site	Hicks et al. (2009)	Curran-Cournane et al. (2013)	CLUES 2002	CLUES 2008
Hoteo at Gubbs	-	74	88	85
Mahurangi College	88	-	43	44
Wylie Rd	201	-	77	73
Redwoods (pre-harvest)	172	-	34	35
West Hoe	-	28	32	39
Orewa at Kowhai Ave	-	80	39	38
Kaukapakapa at Taylors	-	76	53	52
Barwick	13		34	32
Weiti Forest	82	50	47	41
Lower Vaughan Weir	98	46	35	33
Okura at Awanohi	74	48	39	37
Awaruku	40	-	33	33
Kaipara at Waimauku	-	32	39	39
Mangemangeroa	89	167	426	423
Wairoa at Tourist Road	-	47	91	93

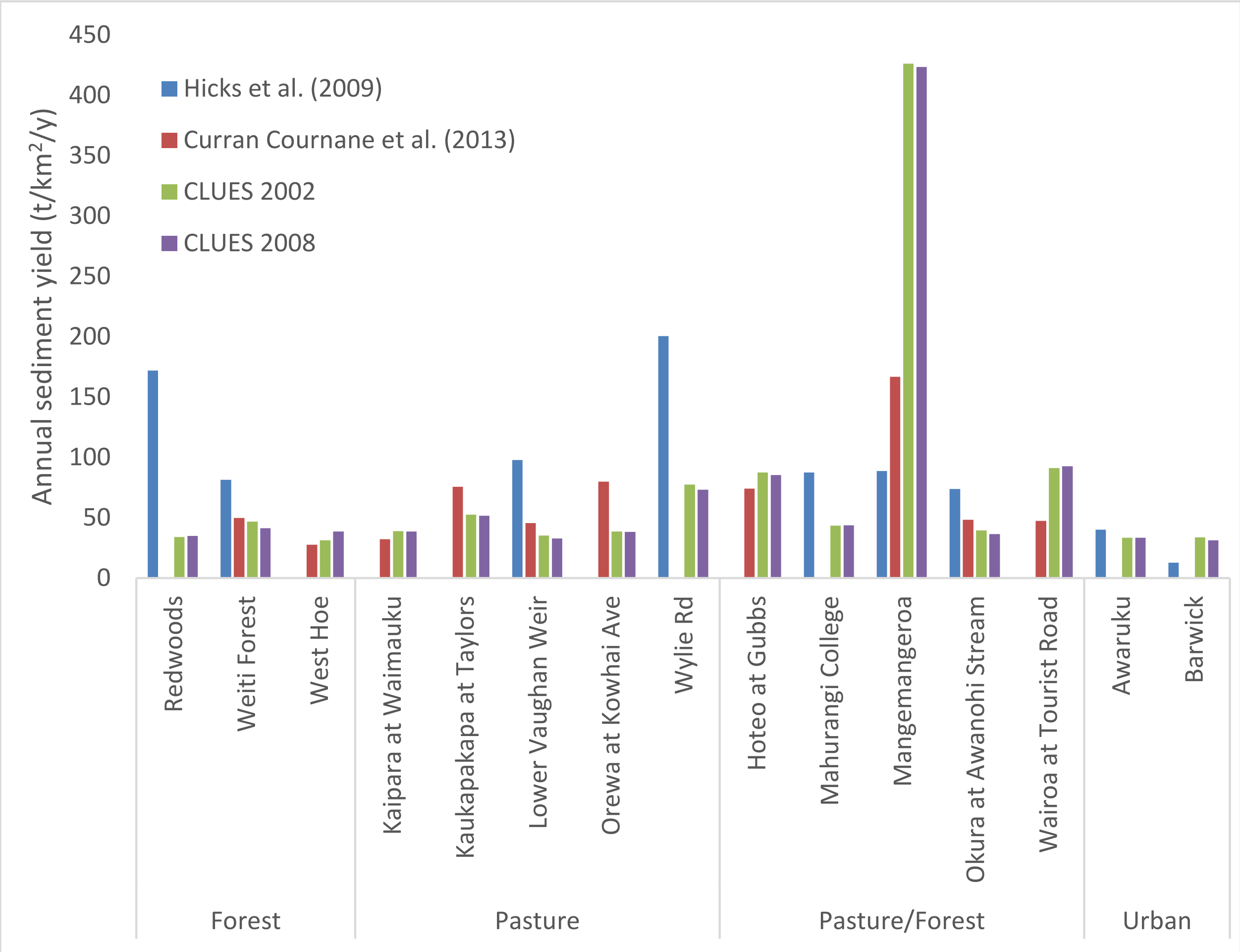


Figure 29 Annual sediment yield by dominant land use

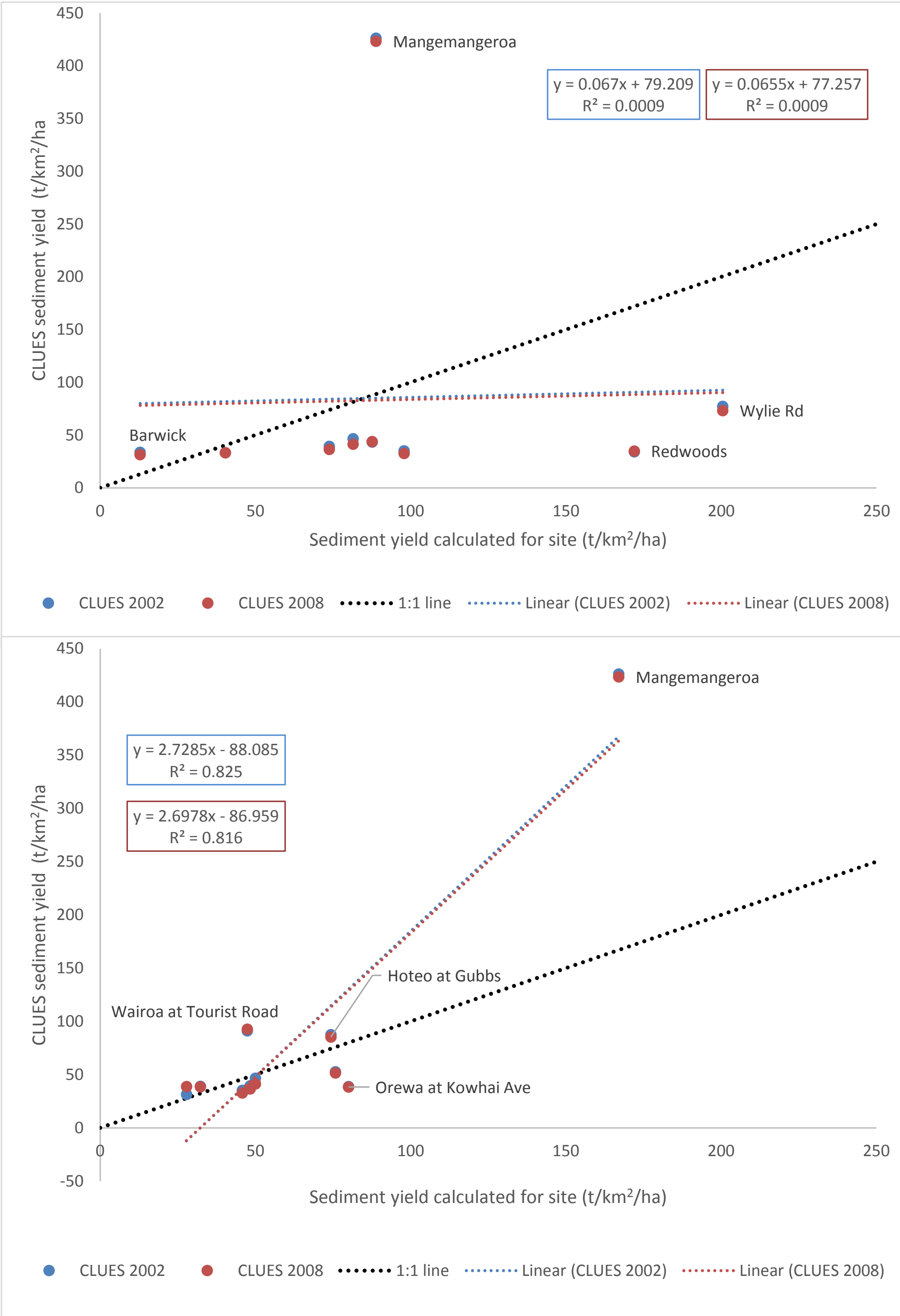


Figure 30 CLUES simulated sediment yield against yields calculated for the Auckland Council sediment monitoring sites: Hicks et al. (2009) – top, Curran-Cournane et al. (2013) - bottom

4.4 Summary and discussion

The comparison of CLUES estimates with observation-based estimates of nutrient loads and concentrations and sediment yields described above shows mixed results. Comparisons were not possible for *E.coli*.

While CLUES is able to simulate the relative magnitude of observed SOE median TN concentrations, as shown by the ranking of sites, the model tends to underestimate absolute concentrations and underlying loads and yields. TN concentrations for the three sites in the Pukekohe market gardening area (Whangamaire, Ngakaroa and Waitangi) were greatly underestimated. The contributing areas for these sites have high rates of fertiliser application and are largely spring fed. There was little discernible difference in the relationship between CLUES estimates and observation-based estimates by land use. While the relationship between CLUES- and observation-based TN loads is fairly good, much of the apparent fit is explained by catchment area. The relationships between yield estimates is much poorer.

CLUES did not reproduce the relative magnitude of observed SOE median TP concentrations very well and showed poor model fit with respect to both observation-based absolute TP concentrations and yields. Like TN, much of the relationship between CLUES and observation-based loads is explained by catchment area. Again, CLUES tends to underestimate TP yields and therefore concentrations.

CLUES estimates of annual sediment yields were compared to yields calculated for 15 sites reported in two Auckland Council reports (Hicks et al., 2009; Curran-Cournane et al., 2013). These yields were determined from measured sediment concentrations and flows. There are differences in the yields estimated for the sites the two data sources have in common. Of the two, CLUES yields had greater agreement against the yields estimated by Curran-Cournane et al., (2013), although in general the relationship between CLUES and observation-based sediment yield estimates was poor.

This lack of agreement with observation-based estimates suggests that there is a need for local calibration of the CLUES model for Auckland. The following sections overview the sources of uncertainty in the model and discuss data needs for calibration and validation.

4.4.1 Sources of error and uncertainty

In the modelling context, uncertainty refers to the limitations of the model; sources of uncertainty can be broken down into:

- Model choice and application – is the model fit-for-purpose? How has the model been applied to meet that purpose? How transferable is the model across time and space?
- Choice and representation of model inputs and outputs – which inputs are required to run the model and what are the model outputs? What is the level of knowledge about these inputs and outputs? Is there a match between the scale of the model input and

outputs and the modelling resolution? If not, how is the data aggregated or disaggregated?

- Model structure and simplification – which processes are modelled? How are they represented and to what level of complexity (i.e., empirical, conceptual or physically-based)?
- Model parameters – what are the model parameters and how have they been parameterised? How is the model calibrated? How have catchment parameters been scaled-up or down from point or areal data? Are parameters compensating for each other?

Model error is separate from uncertainty and can refer to

- Input error– What is the accuracy and precision of input data? How has input data been captured, processed and stored? How representative is the input data spatially and temporally? Has the data been purpose collected? Are there any mistakes in the data?
- Errors in calibration and validation data – similar to input data, how reliable is the data used to calibrate and validate the model? Is there sufficient data for calibration and validation (ideally these tasks should be carried out using different data sets)? Is it possible to evaluate sub-routines in the model independently?
- Model error – has the model been correctly coded? Is there an error in the understanding of the processes modelled which has led to a misconception within the model?

Errors and uncertainties within the model propagate at each step in the modelling process such that a small input or calibration error can be translated into a significant error in model output. A more complete discussion of model uncertainty and sources of error in the context of decision support can be found in Walker et al. (2003).

CLUES consists of a framework, described in Woods et al., (2006a), which links several underlying models, each of which has its own inherent assumptions and sources of uncertainty. For instance CLUES takes output from the OVERSEER model as a model input for the calculation of TN and TP yields from pastoral land for each REC sub-catchment. OVERSEER is a whole-farm nutrient budget model that simulates the impact of nutrient use and flows within a farm (product, fertiliser, effluent, supplements or transfer by animals) on nutrient use efficiency and possible environmental losses. At present, CLUES 10 is linked to OVERSEER Nutrient Budgets 6 under a licencing agreement with AgResearch that is updated regularly. OVERSEER has been calibrated by AgResearch; the model's accuracy and sources or uncertainty were discussed most recently by Shepherd et al. (2013). It is noted that OVERSEER uncertainty "*will be greatest for conditions where there are no, or few, data for calibration and validation"* and "*that precision in the context of OVERSEER is about precision of input information"*. Since OVERSEER operates at the farm-scale, the output must be scaled upwards to the CLUES REC sub-catchment scale with associated loss in model accuracy. Within CLUES, the OVERSEER component treats each stock type as a single farm and variables, such as stocking rates and fertiliser application rates are given typical regional values. It should be noted that actual rates may differ in practice resulting in model error.

OVERSEER is used in CLUES to provide input parameters and nutrient yields from pastoral land use to the SPARROW model. Similarly, SPASMO provides N yields from horticulture and crops to SPARROW. SPARROW calculates *E.coli* and sediment yields for each REC sub-catchment from all land uses and nutrients yields from all other land uses. SPARROW is also used within CLUES to simulate contaminant transport, storage and attenuation along the drainage network to calculate in-stream loads. CLUES does not explicitly account for vadose zone or subsurface attenuation, that is, all losses are considered to be stream losses. Future work will place more emphasis on representing subsurface attenuation, although this is a challenging science area.

At present, SPARROW has been calibrated nationally for use in CLUES, using the SAS statistical package, against loads calculated from measured water quality and flow rates from sites across the country. The use of national data assumes that the calibration is valid nationwide which may not be the case regionally. The calibration data comes from both the National River Water Quality Network (NRWQN) operated by NIWA and suitable data from SOE monitoring sites selected on a similar basis to those selected in Section 4.2 of this report. As discussed earlier, there are errors in the load calculation methodology which could explain some of the difference between CLUES loads and those calculated for sites around Auckland.

Contaminant loads calculated for each river reach are the primary outputs of the CLUES model. Concentrations are calculated using the method described in Oehler and Elliott (2011) from loads on the basis of a statistical relationship between observed concentrations and the annual average rate of discharge estimated for the reach (Woods et al., 2006b). This means that the concentration comparison described in Section 4.1 required the primary CLUES output to undergo a further calculation step based on estimated flow data, which is itself subject to error and uncertainty.

Potential sources of error and uncertainty that could be behind the poor level of agreement between CLUES estimates and observation-based estimates in the Auckland region are listed below:

- Comparison with non-purpose collected water quality data. SOE data are collected monthly and may not capture full range of concentrations at a site, particularly for peak flows. Most of the sites do not have concurrent measurement of flow which limits the number of sites for which loads can be calculated. There were no suitable Auckland data for comparing *E.coli* loads with observations. There is an underlying assumption that the CLUES loads and concentrations are equivalent to the median long-term (in this case 5-year) SOE loads and concentrations. Additionally, several sites (e.g., Whangamaire) were established after 2008 which meant that there were no contemporaneous data for model comparison.

- Translation of uncertainty and errors in the underlying models (e.g., OVERSEER and SPARROW, SPASMO) and geospatial database (e.g., estimated mean annual discharge, LRI soil and slope data).
- Use of national water quality data sets for calibration of parameters needed for the calculation of loads and concentrations as discussed above. The tendency of CLUES to underestimate nutrient loads suggests that the model nutrient yields need to be parameterised upwards in the Auckland region.
- Comparison of site observations at a specific location along a reach against CLUES simulations for the river reach at the reach outflow point may not be valid for small streams or head water reaches (e.g., West Hoe).
- Incorrect representation of land use. Comparisons of water quality observations were made against the Default (2002) and Updated (2008) land use scenarios. There may be some differences in the model representation and actuality.
- The calculation methods and parameters vary for different land use types. For instance, nutrient loads from stock are calculated using OVERSEER whereas SPASMO is used to calculate nutrient loads from crops and SPARROW is used for all other land uses. Urban is included as a land use class in CLUES, however, the model is primarily set up for rural land uses and is not intended to model urban contaminant loads.
- Incorrect representation of farm practices. The land use scenarios used default values for stocking rates and fertiliser application rates which have been determined from national data. In addition, mitigations, such as stock exclusion from water ways were not simulated. This means that the yields derived from farming may not be valid for the Auckland regions.
- Incorrect representation of point sources, stock rates and fertiliser application rates, the latter is most notable in the Pukekohe market gardening area (e.g., Whangamaire Stream) (Francis et al. 2003)
- Model simplification of physical processes. For instance, CLUES does not take ground water into account. Large parts of the south Auckland region overlays a complex basaltic aquifer system. Many of the streams in this area are spring fed which could be influencing stream water quality, for instance contributing to elevated nitrogen concentrations. Similarly, CLUES does not simulate mineralisation of organics or bank or bed erosion which are potential sources of nitrogen and sediments, respectively.
- Annual time-step with evens out seasonal differences in climate (e.g., rainfall, evapotranspiration, temperature), stock rotation and fertilizer application rates.

- Inaccurate representation of the REC drainage network. There are known errors in the REC such as a misconnection between headwater reaches of the Hoteo and the Mahurangi Rivers, which was taken into account in this study, and incorrect catchment boundaries and flow paths in the upper Papakura catchment. There may be other less obvious inaccuracies that have not been taken into account here.
- Spatial resolution. CLUES operates at the catchment scale; the lowest spatial unit is the REC river reach and associated catchment. This means that the spatial data described in Section 2.2 must be aggregated, either on the basis of the dominant value or class or as an average. Quasi-spatial distribution of land use is achieved by assigning percentage covers for each land use type within each sub-catchment which makes the assumption that each land use is evenly spread across the sub-catchment. Another source of the potential for scale-related errors is the coupling of CLUES with OVERSEER, which requires the outputs of the farm-scale model to be scaled up for use in CLUES.
- Temporal resolution. CLUES calculates water quality with an annual time-step and does not take seasonal differences in flow or farm practices into account.

There are plans to address some of the concerns relating to model uncertainty and error above as part of on-going CLUES maintenance and development. For instance, while the REC has recently been updated, the update has not yet been implemented in CLUES. This update is planned, pending funding. A potential interim or alternative approach in Auckland would be to use Auckland Council's own drainage network database, provided that it contains the data fields required to run CLUES. Further initiatives to improve CLUES over the next three years are discussed in Section 5.4.

4.4.2 Calibration and validation data needs

The comparison of CLUES and observation-based estimates has demonstrated a need for local model calibration in the Auckland region. To this end, water quality observations are required for both model calibration and validation. While the SOE monitoring gives good geographic coverage and representation of different land use types across the region, the data are not purpose collected for model development. This problem is not unique to the Auckland region and has been noted in a recent evaluation of water quality monitoring nationally made by NIWA (Davies-Colley et al., 2011). The evaluation was undertaken for MfE to establish the needs for a national freshwater monitoring protocol. It was noted that while the NRWQN which is maintained by NIWA has a limited number of monitoring sites, the database has been augmented where possible by SOE water quality data collected by regional councils. However, there are inconsistencies in the sampling, analytical methods, data handling and storage, and reporting between councils. This means that considerable effort is required to integrate SOE data into the NRWQN.

The rationale for establishing a national protocol is to move beyond reporting the environmental state and trends in water quality into providing information that can be used to strengthen the scientific understanding of our waters and the environmental stressors which affect them. This understanding provides a conceptual underpinning for model development, which in turn allows the impacts of catchment-scale (e.g., land use change) and global-scale stressors to be explored and modelled as required to achieve freshwater management objectives (see Section 5.0).

Davies-Colley et al., (2011) recommends that flow data from hydrometric stations be available for each occasion of water sampling at SOE sites. Flow data is crucial for interpreting water quality (particularly for flow-adjustment in trend analysis) and for the calculation of material fluxes (i.e., loads). Concurrent monitoring is a requirement for the NRWQN and is carried out at the two NIWA operated monitoring sites (Hoteo@Gubbs and Rangitopuni@Walkers) in the Auckland region. However, only a handful of the council operated SOE water quality monitoring sites have nearby flow monitoring. In this report, loads were calculated for nine sites for TN and eight for TP. Site selection was made in 2010 to provide data for SPARROW calibration, however, we have identified five more sites (Vaughn's Stream@Lower Weir, West Hoe@Halls, Opanuku@Candia Road Bridge, Okura Creek@Awanohi Rd and Otara@Hills Road Bridge) which may now have sufficient data for load calculation. This possibility needs to be assessed – to this end, NIWA has requested flow data from Auckland Council. None of the sites for which loads were calculated were located in areas of native forest. This is considered a significant gap as native forest is the baseline land use in CLUES for the calculation of background loads.

With regards to sediment yield, there are 15 sites for which yield data are available, of these Auckland Council plans to maintain the 10 sites sampled in Curran-Cournane et al., (2013). There are no sediment monitoring sites in West Auckland, Auckland City or Manukau/Pukehohe.

The need for calibration data is most pressing for *E.coli*, since at present there are no sites in the region with sufficient sample numbers or flow data suitable for calculation of *E.coli* loads required for local calibration.

There are several options available to provide load data for calibration including:

- Establishment of new hydrometric sites or relocation of water quality monitoring sites nearer to existing hydrometric sites. This option will require several years for enough data to be collected in order to calculate loads.
- Use of flow models such as the NIWA TopNet model to simulate river flows to enable load calculation. This option will add another layer of model error and uncertainty to the calibration, particularly in catchments which are currently ungauged.
- Joint calibration using water quality data from sites in lower Northland and the upper Waikato, which have similar environments to the Auckland region, to augment the number of load estimates available.

5.0 CLUES and freshwater management

The main aim of this study was to demonstrate to Auckland Council how CLUES can be used to provide water quality information for consulting with communities, iwi and water users as part the implementation of the NPSFM. This section overviews the NPSFM and supporting documents with respect to CLUES and discusses the use of models such as CLUES in community partnership planning. Examples of the use of CLUES for planning purposes are also given, along with a list of proposed user-directed model improvements.

5.1 Freshwater management framework

Agricultural runoff is a major source of contaminants for New Zealand's freshwater resources. Recent trends (Ballantine and Davies-Colley, 2010) show while water quality is deteriorating in catchments dominated by pastoral agriculture, particularly those with an expansion or intensification of pastoral land use, there have been some improvements where mitigation is practiced. This finding suggests that water quality around the country can be improved with changes to land and freshwater management. The Land and Water Forum (LWF), which consists of a diverse group of organisations including primary industry representatives, NGOs and iwi, was asked by the government in 2009 to conduct a stakeholder-led collaborative process to consider reform of New Zealand's freshwater management system. In September 2010 the LWF reported back to Ministers identifying shared outcomes and goals, and options to achieve them (LWF, 2010). The National Policy Statement on Freshwater Management (NPSFM, MfE, 2011) was released by the government in response to this report and provides central government direction to regional council. The Auckland Council Regional Development and Operations Committee recommended that the council adopt a programme for the implementation of the NPSFM (Auckland Council, 2012). It is this commitment to implementation which is behind the current CLUES project.

The NPSFM is arranged in five sections, each with its own set of objectives:

A. Water quality;

B. Water quantity;

C. Integrated management ;

D. Tangata whenua roles and interests; and

E. Progressive implementation programme.

Parts A and B requires regional councils and unitary authorities to set enforceable water quality and water quantity limits and, where those limits are exceeded, specify targets for improvement and implement measures to reach those targets. Measures can include opportunity analysis, restrictions to expansion and intensification of specified land uses, allocation restrictions, incentives for efficient water use, and mitigation requirements. Part C requires integrated catchment management of activities in recognition of the interactions between land and water environments. Part D requires provision for iwi and hapu involvement to ensure that freshwater management reflects the interests of tangata whenua. Part E prescribes the timeframes for implementation, but does not give advice on how implementation should be carried out.

In response to the NPSFM, the *Regional Council Research for the Environment Strategy* (2011) states that there is a need for better understanding of the cumulative impacts of human activities on water quality and to identify the ecological limits for those activities beyond which water quality becomes unacceptable. Moreover, there is an identified need for decision support systems and tools which can be used or scenario building, particularly in terms of natural resources facing pressures such as freshwater.

The *Second Report of the Land and Water Forum* (2012) stresses the need for catchment-scale water management and the requirements for water quality objectives and limits to be set to achieve those objectives for catchments in keeping with the NPSFM. Leading on from these needs, the *Third Report of the Land and Water Forum* (2012) provides several recommendations of direct relevance to the use of and further development of the CLUES model:

- Recommendation 8 (Managing Water Quality) states that regional councils and catchment communities need to identify the sources and volumes (loads) of all contaminants of concern, assess which tools and methods are best to manage them to achieve freshwater objectives, and monitor and review implementation and outcomes.
- Recommendation 10 (Managing Water Quality) states that the tools adopted should be appropriate for, amongst other factors:
    - the contaminants to be managed
    - the physical characteristics of the catchment
    - the range of land uses in the catchment
- Recommendation 63 (Enabling Change) expressly calls for 'continued investment in the development of models and measurement-based monitoring systems for *practical application to water quality management*.
- Paragraph 84 (Models) of the report stresses the need for continued investment in models that:
    - are based on a strategic approach
    - concentrate on a limited number of interoperable models for application at different scales (catchment and enterprise level) and contaminants
    - concentrate on a limited number of models that can serve multiple land uses

- o are be undertaken in partnership (central and local government, science providers and sector organisations)
- o include guidance and protocols for the use of the modelling tools where they are applied to water quality management in a regulatory framework.

Acting on the advice of the *Land and Water Forum*, MfE released the Freshwater Reform 2013 and Beyond (FRB2013; MfE, 2013) working paper. This document acknowledges the central role of freshwater resources in our cultural identity, economic activities and environmental well-being and proposes a fundamental shift from current effect-based freshwater management to limits-based management *in which targets are set, and limits to achieve those targets are* determined. A number challenges to freshwater management in New Zealand are recognised:

- Water quality is declining in some catchments
- Water is over-allocated in some places
- Decision-making processes are litigious, resource consuming and create uncertainty
- There is a lack of robust information on impacts and outcomes of management decisions. There are particular concerns that some regions set freshwater objectives, rules and timelines for freshwater management without drawing on sufficiently robust information about their impact (particularly economic analysis), without being transparent about why and how decisions are made, and/or proper stakeholder engagement.
- Water is not always used efficiently or for its highest value use.
- Iwi/Māori interests and values are not always fully considered in planning and resource management decision-making.
- Our freshwater management system is insufficiently adaptive and dynamic

To ensure the sustainability of freshwater resources and to meet these challenges, action is proposed in three key areas:

- **Planning as a community** – starting by introducing a collaborative planning option as an alternative to the current system under the Resource Management Act 1991. Planning as a community also requires formalising a role for iwi in providing advice and recommendations that councils must consider before making decisions relating to freshwater management. MfE proposes to provide national guidance and supporting material on the implementation of collaborative planning.
- **A National Objectives Framework** (NOF) that requires setting national minimum environmental states in rivers and lakes for ecosystem health and human activities. Freshwater objectives are the intended environmental outcomes for a water body that will provide for the water values the community considers important. Values include a range of water uses and activities such as irrigation, stock watering, and fishing, boating and ecosystem protection. Under the NOF, it is proposed that for each value

there will be a number of water quality attributes (e.g., turbidity, temperature, pH, contaminant concentrations) and associated indicator bands specific to that value. The bands will represent the range of environmental states A to D (e.g., excellent to unacceptable) with respect to each attribute and will vary depending on the value.

- **Managing within water quality and quantity limits** – this area requires councils to better account for how all water in a region is used and involves limits to be set at the catchment scale on water allocation and contaminant discharged. According to FRB2013:
  'Limits' to use are derived from the specified freshwater objectives for each catchment and refer to the total amount of water that can be taken out of a freshwater body, or of contaminants that can be discharged into it without jeopardising the desired outcomes. Limits are a necessary instrument to achieve freshwater objectives, as part of a wider toolbox that also includes mitigation actions, such as riparian planting. Where limits could have an impact on existing uses, adequate adjustment timeframes must be introduced.

These key areas are illustrated in relation to each other in Figure 31 which has been adapted from FRB2013.

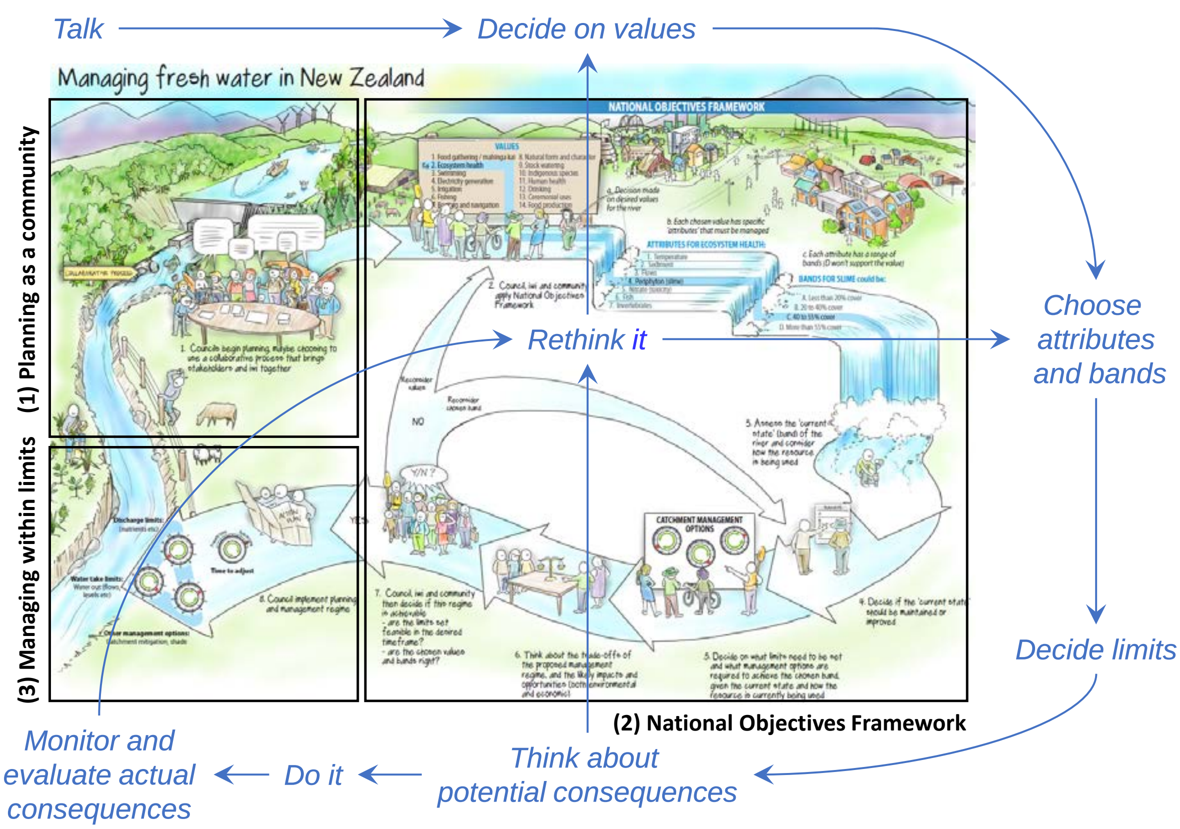


Figure 31 Community planning process under the FRB2013 (adapted by Malcolm Green, NIWA, from MfE, 2013)

CLUES can play a role in Steps 3, 5 6 of Figure 31 as follows:

- **Step 3. Assess the 'current state' (band) of the river and consider how the resource is being used**

  CLUES can be applied to simulate the current state of water quality (as indicated by annual contaminant loads of TN, TP, sediments and *E.coli*) at the REC sub-catchment scale. As demonstrated in this report, simulations can be for the region as a whole or for specific catchments.

- **Step 4 Decide if the current state should be maintained or improved.**

  CLUES output for the 'current state' can be displayed as maps for geo-visualisation and tables for further analysis. This information can be used to determine whether a catchment is meeting the water quality objectives for each attribute and value. The results can be left as contaminant loads, yields or concentrations (as in this report) or translated into different bands to enable stakeholders better understand the output with respect to specific values and attributes. Other information, such as areas of cultural, social or ecological importance, could also be mapped to indicate where action is most needed. This aspect of CLUES use was discussed in Semadeni-Davies et al. (2009 – see summary in Section 0)

- **Step 5 Decide on what limits need to be set and what management options are required to achieve the chosen band.**

  Setting limits requires an understanding of contaminant dynamics and the response of ecosystems to contaminants. Moreover, it should be recognised that the impacts are cumulative such that management decisions made upstream will have a downstream effect. CLUES can be used applied iteratively with multiple land use and farm practice scenarios to help determine the capacity for change possible with respect to the current state. Limits to contaminant loads can be set accordingly. Possible methods of assessing catchment capacity and setting contaminant load limits have been discussed in Elliott and Snelder (2011).

- **Step 6. Think about the trade-offs of the proposed management regime, and the likely impacts and opportunities.**

  CLUES output from multiple scenarios, including the current state, can be displayed as maps and tables in order to aid communication between stakeholders when assessing the likely impacts and opportunities of the proposed management regime. Although not discussed in this report, CLUES also has sub-routines to simulate a range of socio-ecomomic indicators (see Harris et al., 2009) can be used to weigh up the cost implications of land use change and mitigation.

Regionally, questions that can be elucidated with CLUES include: what is the capacity for land use change or intensification of stock rates in a particular catchment? What are the limits associated with that capacity? And is it possible to mitigate in catchments which are not meeting water quality objectives?

To give a topical example, the draft Unitary Plan (2013) proposes requirements to exclude stock on intensively grazed production land from the catchments of all lakes, natural wetlands and rivers and streams (with the exception of intermittent streams). This information can be used to develop a set of expected yield reductions specific to different stock classes in CLUES similar to those applied in Waikato (Semadeni-Davies and Elliott, 2012) and Southland (Hughes et al., 2013; Semadeni-Davies and Elliott, 2011 and Monaghan et al., 2010) which are overviewed along with other examples of CLUES applications in Section 5.3. The yield reductions could be based on *a priori* expert knowledge or on the basis of tiered modelling using tools such as OVERSEER which operates at the farm scale and can be run for representative farm types in order to inform CLUES. The yield reductions would be used to develop a CLUES mitigation scenario to give an indication of where and how this requirement could improve water quality across the region or in priority catchments and whether the improvements will lead to the required water quality objectives being met.

The ways in which CLUES can be used within the freshwater management framework are discussed further in Sections 5.2 and 5.3. Planned changes to CLUES to better meet user requirements for planning applications are discussed in Section 5.4.

CLUES can be freely downloaded and run for non-commercial use, which means that the model is publically available to stakeholders.

NIWA has prepared a submission in response to MfE which is generally supportive of the Freshwater Reform document. With reference to CLUES, the submission notes that:

- NIWA supports the concept of a tiered system of regulation for limit setting, modelling (e.g., OVERSEER at farm scale and CLUES at catchment scale) to understand where and how limits can/should be met, and, advocacy for sector-based initiatives to put in place Good Management Practises to meet the limits.
- NIWA supports the Planning as a Community concept in the Reform.

The submission prepared by Auckland Council to MfE is similarly supportive of the proposed reforms.

5.2 Planning as a community

Participative planning which involves the community in freshwater management is a cornerstone of the FRB2013. To this end, the council has an interest in the opportunities of using models, such as CLUES, to facilitate collaborative engagement with stakeholders (e.g., interactively, at public meetings). While CLUES applications to date have concentrated on expert “behind the scenes” modelling to provide national and local authorities with water quality simulations for planning purposes, the GIS platform and in-built scenario sketch tools mean that CLUES could equally be used in a public setting. These opportunities are discussed further below.

Participative planning provides a forum for sharing disparate knowledge bases and values from stakeholders to enable informed decision making (e.g., Geertman and Stillwell, 2003). The process democratises decision-making by making background information and outcomes transparent and by allowing stakeholders to have their say. Stakeholder participation leads to more informed, holistic and equitable decision making, promotes consensus and improves the acceptance by stakeholders of unpopular decisions (i.e., the greater good). Participation requires political and community support as well as an institutional climate that allows inter-organisational co-operation and encourages innovation. The levels of participation can differ depending on the nature of the decision to be made and the stakeholders involved. The level ranges from informing stakeholders of decisions (e.g., display boards and fact sheets), to consultation to gather information to be used for decision making (e.g., surveys) and to collaboration whereby stakeholders work in partnership with the organising authority to share decision making. Moreover, there can be different levels of participation at different stages in the planning process.

One of the first steps in participatory planning is to perform a stakeholder analysis to establish who key stakeholders are, what knowledge (including expert and tacit knowledge) and values they have and what their relative role will be in the decision making process. Stakeholders can refer to any individuals or organisations that are affected in some way by the decision to be made. They can include diverse groups such as land owners and residents, developers, municipal service providers and utilities, NGOs, industry experts and consultants, emergency services, cultural organisations, politicians and insurers. In the context of this project, the stakeholders identified by the council include local community groups and iwi as well as council planning and policy staff.

Implementation of the NPSFM calls for the use of models to simulate the impacts of land use and farm practices on water quality and quantity and to communicate those impacts to various stakeholders involved in freshwater management. CLUES is such a model and is intended primarily to demonstrate the broad-brush, long-term impacts of land use change and farm practices on catchment scale water quality as indicated by nutrient, sediment and *E.coli* loads. The rest of this section discusses how models can be used with stakeholders and the requirements for successful modelling including gaining public acceptance of modelled data.

Following the criteria set out by Densham (1991), CLUES can be described as a Spatial Decision Support System (SDSS). An SDSS is an interactive, spatially distributed model which can facilitate a decision making process which is iterative, integrative and participative. An SDSS is iterative as it can allow multiple alternatives or scenarios to be simulated, the outcomes of which can be used to derive further alternatives. An SDSS is integrative as it can incorporate a wide variety of data to develop a range of solution alternatives and evaluation criteria. An SDSS is participative as it can be used to encourage stakeholders with different knowledge sets and values to communicate and to explore alternatives and outcomes. An SDSS also provides a tool for communication by allowing geo-visualisation of the problem, decision alternatives and likely outcomes (Dykes et al., 2005; MacEachren and Kraak, 2001):

Densham (1991), among others, has stated that to be considered an SDSS, an application should have the following components:

- A database management system to input, store and analyse large quantities of spatial data,
- The ability to represent complex spatial relationships and structures common to spatial data.
- A library of analytical sub-routines (i.e., modelling capability) that can be used to query the spatial data to forecast the possible outcome of decisions,
- Display and report capability using a variety of forms (e.g., cartographic displays, tables and plots of spatial data and forecasts), and
- An interface to aid users to interact with the system and assist in the analysis of outcomes. The interface should be reliable, efficient, easy to use and easy to understand.

How these components relate to each other and those involved in decision making as part of participative planning has been addressed, among others by Armstrong et al. (1986). The SDSS and its components are illustrated in Figure 32 in relation to the decision making process. This figure has similarities with Figure 31 which illustrates role of community planning within the National Objectives Framework. The decision maker can include individuals or agencies working alone or with other stakeholders. The SDSS user may variously be the decision maker, an expert running the tool on behalf of the decision maker, or another stakeholder participating in the decision making process. Decision making is supported by data which may include observations or *a priori* knowledge from experts, practitioners or other stakeholders. The process may be iterative with the results of the decision informing both the decision maker and the SDSS. The SDSS may be upgraded or recalibrated as a result. There can also be feed-back between the outcome evaluation and the decision maker, that is, unsatisfactory outcomes may lead to decision maker re-defining the problem to arrive at a new set of decision alternatives.

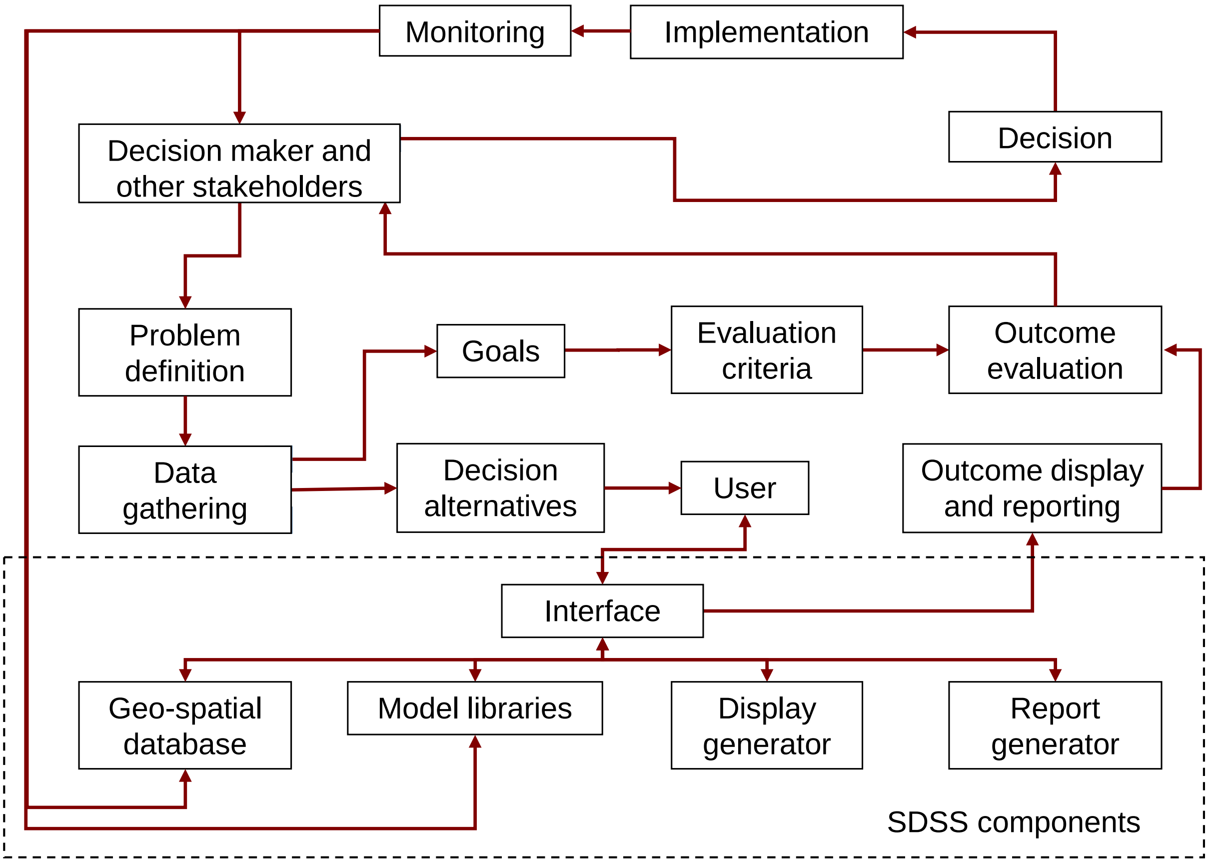


Figure 32 The SDSS within the decision making process

By promoting understanding and facilitating communication between stakeholders, an SDSS such as CLUES can be seen as an example of a Computer Supported Co-operative Work (CSCW) technology. CSCW describes how people work together when interacting with computer and communication technology to assist an organisational activity such as decision making. CSCW technologies enable people to communicate and collaborate through shared workspaces. CSCW technologies can be conceptualised within a matrix (Figure 33) where interaction between participants and technology spans time and distance (e.g., Johansen et al., 1988; Helander et al, 2000; Baeker, 1995).

Thus stakeholders may work with the technology at the same time in a single room, at the same time in different locations, alone at a single location, or alone at different times in remote locations. A SDSS can be used as an aid to participation in each quadrant of the matrix – or rather, at different stages of the decision making process, each of which have different communication needs. The purpose and requirements for the SDSS may differ significantly depending on its position in the matrix, the stakeholders involved and their level of participation. Consider the case of an SDSS to be used at a public planning meeting, which is an example of a co-located, synchronous or face-to-face usage. The SDSS may be used as an aid to collaboration whereby participants can fine-tune scenarios for real-time simulation and evaluation. Alternatively, it may be used to inform stakeholders of pre-defined alternative outcomes simulated by an expert group which have led to a decision. In the former case, the SDSS would need to be simple to use with relatively quick set-up and run-times. In the latter case, the SDSS could be more sophisticated requiring more data for scenario creation and longer set-up and run times. CLUES can be used for both of these examples using different options for scenario building (i.e., sketch or import tools) and can be seen as a compliment for other, more sophisticated models, such as OVERSEER which operates at the farm-scale, in a tiered process.

Space / Time	**Same site (co-located)**	**Different / multiple sites (remote)**
Same time (synchronous communication)	Face to face interaction: • Public meetings • Single display groupware • Shared tables	Remote interaction: • Shared view desktop systems • Video conferencing • Multi-user editors • Media spaces
Different times (asynchronous communication)	On-going tasks: • Team rooms • Public display • Shift work groupware	Communication and co-ordination: • Email • Bulletin boards • Blogs • Workflow management • Version control • Calendars • Organisational memory • Wikis

Figure 33 Computer Supported Co-operative Work matrix showing time and spaced-based views of CSCW technologies. (after Johansen et al., 1988)

The successful use of tools such as CLUES within the community planning process very much depends on the way it is applied and presented to stakeholders. Walker et al. (2003) described the role of models for decision support in the context of policy making and stated that modellers need to present model uncertainties to other stakeholders, particularly where decision making is politicised. They advocate the development of an uncertainty matrix which can be used by stakeholders to evaluate model outcomes. Voinov and Brown Gaddis (2008) documented their experiences in using catchment modelling tools as part of participatory catchment planning which are directly relevant to CLUES. They state that decision alternatives based on purely analytical models can be rejected by decision makers, particularly if they are unpopular or are likely to result in conflict, as they do not take into account the values, knowledge or priorities of the human systems that affects and is affected by the system being modelled. They use case studies to illustrate 12 rules for successful use of models, these rules are summarised below:

1. **Identify a clear problem and lead stakeholders** so that they can understand the issues and see the importance of those issues to them.

2. **Engage stakeholders as early and often as possible** to help set goals and identify issues to be investigated.
3. **Create an appropriately representative working group of stakeholders** that can provide the range of values and knowledge needed for informed decision making acceptable to the public.
4. **Gain trust and establish neutrality as a scientist,** while stakeholders can inform the model, the structure of the model must be scientifically sound and defensible to maintain credibility among decision makers, scientists and stakeholders.
5. **Be aware of stakeholder backgrounds and acknowledge conflict.** The role of the model is to provide a neutral platform for testing decision alternatives. If there is a potential for conflict between stakeholders, ground rules for participation should be agreed at the outset.
6. **Select appropriate modelling tools to answer questions that are clearly identified**. In this case, CLUES is a catchment scale planning tool that can simulate the impacts of land use and farm practices on long-term (annual) contaminant loads.
7. **Incorporate all forms of stakeholder knowledge**. Stakeholders can hold information that is not publicly available or known to model developers. Information can include tacit knowledge which may help identify hydrological, ecological or social processes that should be included in the model set-up.
8. **Gain acceptance of modelling methodology before presenting model results**. Be aware that stakeholders may have no prior experience of modelling and may not understand the value of the model in decision making. Giving stakeholders the opportunity to contribute to model development or challenge model assumptions at an early stage can give them a sense of model ownership making them more likely to accept results. Model transparency and clear documentation is essential.
9. **Develop scenarios that are both politically feasible and most effective.** The decision alternative which has the best environmental outcome may not be viable politically, socially or economically. Stakeholders can provide solutions that are innovative and fulfil community needs.
10. **Engage stakeholders in discussions regarding uncertainty** so that they understand that model results are indicative rather than predictive.
11. **Interpret results in conjunction with stakeholders**. Participatory planning is iterative and stakeholders can develop further decision alternatives on the basis of model results. Stakeholders can also be a communication bridge between the community and the organisations involved in decision making.
12. **Treat the model as a process.** The model is only part of the decision making process. Use the experiences gained in decision making to further develop the model for future use.

5.3 CLUES applications for freshwater management

CLUES has been used in a number of applications for policy making and planning purposes over the last few years. Key studies are listed in Table 27. The examples summarised in this section have been chosen to demonstrate how CLUES can be used by regional councils in relation to implementation of the NPSFM.

Table 27 Key applications of CLUES for land use planning and freshwater management

Location	Client/Partner	Purpose	References
Southland and Otago regions	Ag Research (Pastoral 21)	Investigation of potential for constructed wetlands to improve water quality in Southland and south Otago.	Hughes et al. (2013) – in prep
Kaipara Harbour	AgResearch (MSI Clean Water) and local iwi	Estimation of current and pre-European sediment and nutrient loads to the Kaipara Harbour	Semadeni-Davies (2012)
Upper Whangarei Harbour	Northland Regional Council	Estimation of sediment and contaminant loads from rural and urban land uses	Moores et al. (2012)
Southland - Oreti and Mataura catchments	Environment Southland	Investigation on the impacts of recent and planned land use change on water quality and effectiveness of mitigation options	Semadeni-Davies and Elliott (2011) Monaghan et al. (2010)
Hurunui catchment	Environment Canterbury	Identifying loadings	Lilburne et al. (2011)
Waikato – whole region	Waikato Regional Council	Regional impacts of mitigation to inform planning policy	Semadeni-Davies and Elliott (2012)
Waikato – whole region	Independent Scoping Study	Effects of land use change and interventions on *E.coli*	NIWA / WRSS (2010)
Bay of Plenty – Lake Rotorua	Environment BOP / University of Waikato	Predicting the effects of nutrient loads, management regimes and climate change on water quality of Lake Rotorua	Hamilton et al., 2012
Waikato – whole region	AgResearch (Pastoral21)	Demonstration of ability of CLUES to identify both areas at risk of poor water quality and catchments responsible for downstream water quality deterioration.	Semadeni-Davies et al. (2009)
National	PCE/Motu	Effect of land use intensification nationally	Parshotam et al. (2012)
National	Ministry for the Environment	National land use capacity study.	In prep.
NZ estuaries	NIWA	Linking catchment model to estuary model	Zeldis et al., 2012

5.3.1 Geo-visualisation

CLUES has a GIS platform (ESRI ArcMap) which means that users can use the in-built GIS geo-visualisation tools to identify catchments and river reaches sensitive to changes in land use or farm practices. This ability was demonstrated by Semadeni-Davies et al. (2009; summarised in Semadeni-Davies et al., 2010) who used CLUES to identify water bodies with either existing poor water quality or which are at risk of future water quality degradation. With respect to CLUES output, a critical reach could refer to one with high loadings (i.e., sinks) or generated yields (i.e., sources).

The study showed that by using standard GIS tools, CLUES outputs can be displayed either as concentrations, loads or yields similar to those shown in Section 3.0 if this report, or transformed according to a rating or ranking system similar to the bands proposed in the NOF. In this case, TN and TP concentrations in the Waikato River catchment were mapped in accordance with the Waikato region council water quality classification system which designates three bands for each water quality attribute; namely unsatisfactory, satisfactory and excellent. CLUES was run for two land use scenarios as well as the Default land use. An example is given in Figure 34 for TN concentrations simulated using the Default scenario. Maps were also produced to show REC sub-catchments where a change in land use led to a change in classification. Finally, maps were produced which ranked sub-catchments into decile groupings to identify sub-catchments with the best and worst water quality. The ability to transform maps in this way can aid stakeholders with limited knowledge of water quality issues to interpret CLUES results.

5.3.2 Limit setting

CLUES has been applied nationally as part of an on-going national capacity study commissioned by MfE to determine the change in contaminant loads required to meet proposed minimum states of water quality, at national scale and at a theoretical and hypothetical level. The purpose of this study is to inform policy processes around the NOF, particularly in regard to setting water quality limits and determining the capacity of catchments for land development. At the time of writing (June 2013), the study was not publically available; the expected publication date is September 2013. The approach taken was one of several discussed in Elliott and Snelder (2011).

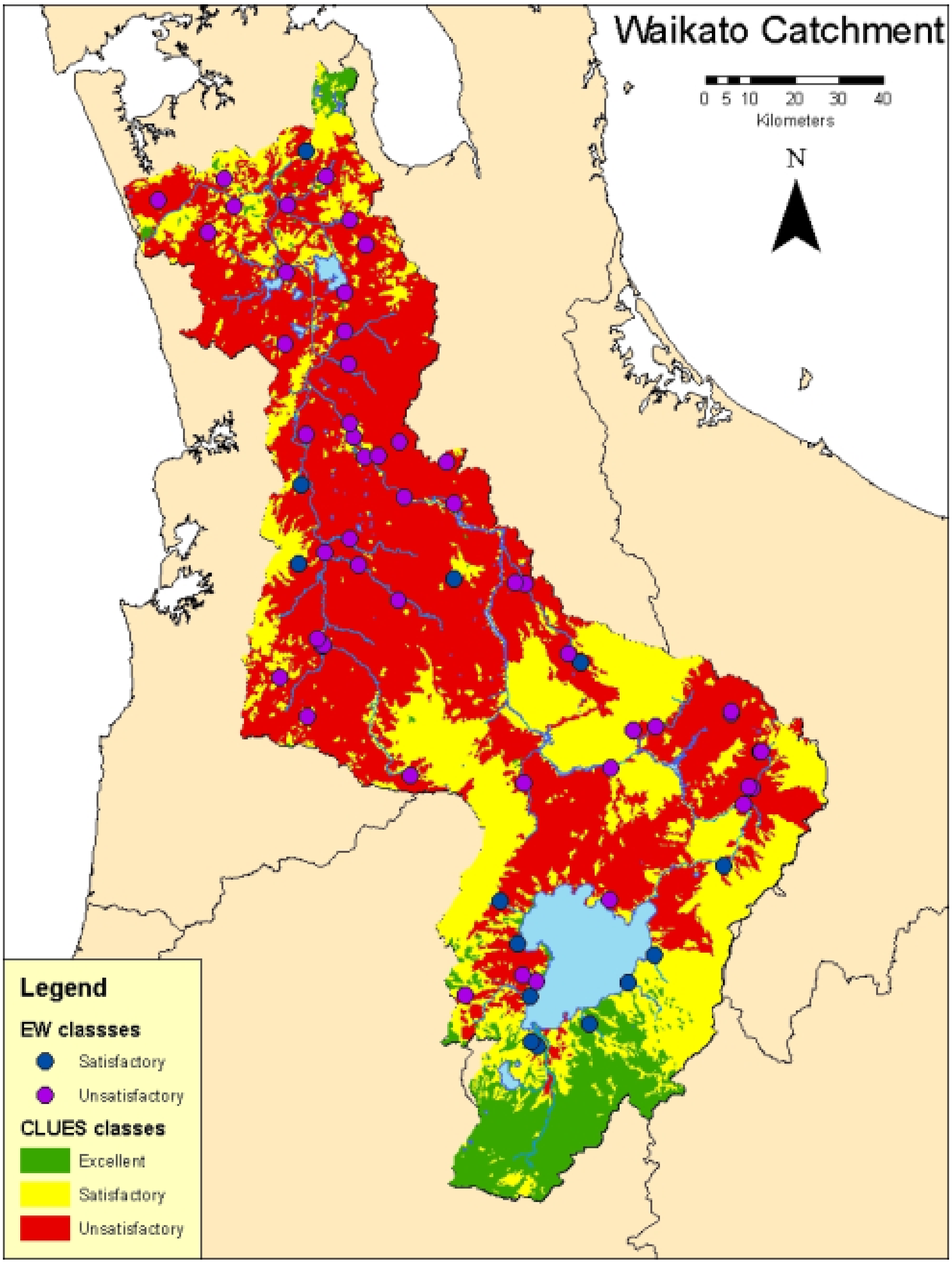


Figure 34: Example of CLUES map transformation for geo-visualisation: TN concentrations classified according to the Waikato Regional Council water quality bands compared to 5-year median concentrations (2003-2007) from SOE monitoring sites (Semadeni-Davies et al., 2009)

5.3.3 Impacts of land use change and mitigation

To date most of the CLUES applications for regional councils have been made to ascertain the impacts of actual or planned land use change, notably dairy conversion, on water quality in specific catchments. Several of these studies, such as the Mataura (Semadeni-Davies and Elliott, 2011) and Oreti (Monaghan et al., 2010) Rivers in Southland, have also simulated the effects of farm management practices for mitigation. Additionally, regional investigations of land use change and mitigation have been made for Waikato (Semadeni-Davies and Elliott, 2012) and Southland / South Otago (Hughes et al., 2013).

The development of land use change scenarios has been discussed elsewhere in this report (see Section 2.3). Investigation of mitigation requires the following steps:

1. Deciding on the choice of farm practices to be simulated - practices investigated to date include stock exclusion and riparian planting, herd housing, stand-off pads, Olsen P management, deferred or low rate farm dairy effluent irrigation, use of nitrification inhibitors and constructed wetlands.
2. Develop rules which determine where the chosen farm practices can be applied with respect to land use and catchment characteristics such as Land Use Capability (LUC; Lynn et al., 2009), soil drainage class, and the removal efficiency of each farm practice for each contaminant. To date, this step has usually been made in collaboration with researchers from AgResearch. The rules have been based on expert knowledge, literature and output from models such as OVERSEER.
3. Determine the extent to which the farm practices can be implemented in each REC sub-catchment using geo-spatial analysis on the basis of catchment characteristics.
4. Weight the removal efficiency for each REC sub-catchment on the basis of the proportional area in the sub-catchment which is suitable for mitigation in order to create a CLUES mitigation scenario that can be used in conjunction with land use scenarios.
5. Run CLUES for each scenario.

While the Southland studies presented CLUES results directly, the Waikato study used the difference between CLUES runs with and without mitigation to determine a difference factor for TN, TP, *E.coli* and sediment loads. Long-term (5-year median) water quality observations of nutrient and *E.coli* concentration and turbidity from 109 monitoring stations were then scaled up or down by the difference factor. The example in Table 28 shows the CLUES calculated percentage change in contaminant loads and subsequent adjustment of long term water quality observations associated with stock exclusion for 11 priority monitoring sites identified by the Waikato Regional Council. Summary statistics for all the monitoring sites are also given.

Table 28 CLUES as an indicative model. Percentage differences calculated using CLUES results for the default and mitigated (stock exclusion) scenarios are used to adjust median values of water quality observations at 11 priority sites. Summary statistics for all sites are also provided. (Semadeni-Davies and Elliott, 2012)

Site by Stream		Total Nitrogen (mg/l)			Total Phosphorus (mg/l)			Turbidity (NTU)			*E.coli* (CFU/100ml)		
		%	Observed	Adjusted	%	Observed	Adjusted	%	Observed	Adjusted	%	Observed	Adjusted
Little Waipa Stream													
335-1	Arapuni - Putaruru Rd (btwn Hildreth and Burnett Rds)	11.3	1.75	1.55	23.2	0.067	0.051	39.3	1.45	0.88	*12.7*	120	105
Piako River													
749-15	Paeroa-Tahuna Rd Br	10.8	2.31	2.06	23.0	0.255	0.196	41.9	11.15	6.48	*12.5*	460	402
Waihou River													
1122-18	Okauia	10.2	1.40	1.25	20.0	0.092	0.074	27.1	4.80	3.50	*12.6*	325	284
Waikato River													
1131-107	Ohakuri Tailrace Br	9.0	0.22	0.20	14.7	0.024	0.020	29.1	1.10	0.78	*12.5*	3	3
1131-133	Tuakau Br	9.7	0.70	0.63	13.7	0.068	0.058	36.2	8.80	5.62	*13.0*	100	87
1131-143	Waipapa Tailrace	8.7	0.33	0.30	14.5	0.032	0.027	25.8	1.34	0.99	*12.3*	8.5	7
1131-328	Narrows Boat Ramp	9.2	0.41	0.37	15.4	0.034	0.029	31.8	2.15	1.47	*12.9*	40	35
Waipa River													
1191-10	Pirongia-Ngutunui Rd Br	11.1	0.98	0.87	19.4	0.054	0.044	36.7	11.90	7.54	*12.7*	290	253
1191-12	SH3 Otorohanga	10.7	0.71	0.63	17.7	0.025	0.021	30.2	3.95	2.76	*12.6*	280	245
Waipapa Stream (Mokai)													
1202-7	Tirohanga Rd Br	11.0	1.40	1.25				34.3	5.60	3.68	*11.8*	150	132
Waitoa River													
1249-18	Mellon Rd Recorder	11.0	2.62	2.33	24.8	0.120	0.090	41.4	10.00	5.86	*12.3*	800	702
Reduction (%) summary for all sites													
Mean average reduction				9.1			15.0			28.1			12.4
Standard deviation				3.3			6.5			13.1			2.7
Maximum reduction				13.4			25.0			44.9			14.6

5.3.4 Linkages between freshwater and coastal environments

An estuary tool has been developed for CLUES and has been applied to estuaries in Marlborough, Northland and Waikato. The tool was also applied nationally to provide nitrogen concentrations for the evaluation of estuary eutrophication as part of the National Capacity Study (Elliott et al., 2013) discussed above, however since the tool has not been tested thoroughly in New Zealand, the simulations made were treated as indicative only. The tool is not currently provided as standard with CLUES pending further assessment. Details can be found in Zeldis et al., (2012) an overview is available at the NIWA website:

http://www.niwa.co.nz/our-science/coasts/research-projects/estuarine-water-quality-the-clues-estuary-tool

The estuary tool couples CLUES simulated nutrient loads to the ACExR (Acadia Centre for Estuarine Research, Gillibrand et al., 2012) estuarine hydraulics modelling system to predict concentrations of salt and nutrients in estuaries. The tool also takes estuary physiographic data from the NIWA Coastal Explorer database (http://wrenz.niwa.co.nz/webmodel/coastal; Hume et al., 2007) and oceanic values of nitrate and salt concentrations from the CSIRO Australian Regional Seas (CARS) climatology (http://www.marine.csiro.au/~dunn/cars2009/). The ocean inputs and inputs from land are flushed and diluted within the estuary, using hydrodynamics determined by the physiography of the estuaries and the volumes and salinities of water entering from land and sea end-members.

The CLUES Estuary Tool addresses the New Zealand Coastal Policy Statement (Department of Conservation, 2010) goals: Enhancement of water quality (Policy 21: identify deteriorating habitats), and Monitoring and reviewing effectiveness of NZCPS (Policy 28: Nationally consistent monitoring, reporting, perspectives).

In addition to the estuary tool, CLUES output has been used to provide sediment loads as input to the USC-3 harbour circulation model in the Kaipara Harbour (Semadeni-Davies, 2012) to simulate sediment distribution around the harbour. The harbour model is currently being calibrated and simulation using the CLUES simulated loads is planned for later this year (personal communication, Mal Green, NIWA, 20 June 2013). The USC-3 model has a daily time-step which requires CLUES sediment loads to be disaggregated from annual to daily loads, this was done on the basis of daily average flow data.

5.3.5 Linkages between urban and rural contaminant loads

CLUES is primarily a rural contaminant loads model. While CLUES does have an urban land use class, the model does not distinguish between different urban land uses and does not provide simulations of contaminants associated with urbanisation. In a recent evaluation of water quality data for catchments draining to the upper Whangarei Harbour undertaken for Northland Regional Council (Moores et al., 2012), CLUES was applied in tandem with Catchment Contaminant Annual Loads Model (C-CALM, Semadeni-Davies et al., 2010) to estimate nutrient, sediment, zinc and copper loads to the harbour. C-CALM is based on the Auckland Council Catchment Loads Model

(Timperley et al., 2010) and was developed for the Landcare Research Low Impact Urban Design and Development research programme.

In this study, the catchments were split into rural and urban zones on the basis of LCDB2 land use classes, each zone was simulated separately using the relevant model. Land use in the urban area was determined from Whangarei District Council land use zones and analysis of aerial imagery while the CLUES default was used to simulate rural land use. Neither farm mitigation nor stormwater treatment were simulated. The results were then combined to give catchment wide estimates of contaminant loads. The same Landcare 1770 vegetation layer as used in this project, was also used to create a pre-European land use scenario to establish background nutrient and sediment yields to the upper harbour.

5.4 User-directed model improvements

A stakeholder workshop consisting of CLUES end users from regional councils and other agencies (e.g., researchers, government departments) was hosted by the Ministry for Primary Industries (MPI) in March 2012 in order to determine how CLUES is currently being used for policy and planning applications and to suggest ways in which the model can be improved. The user-identified model benefits and requirements are listed in Table 29.

As a result of the workshop, funding is being sought from MPI for the next three years for the following:

- Maintenance and Updating
    - Maintain and update land use data interface. A national roll out of LCDB3 land use data transformed for use in CLUES is planned for the coming year. Additionally, it is expected that there will be a formalised link between CLUES and the MPI FarmsOnLine web-tool to enable regular updates of core land use data.
    - Maintenance of code and documentation
    - User support, web page maintenance and training
    - Incorporation of any updates to the OVERSEER model into CLUES, including updating of default stocking rates
    - Update socio-economic model parameters.
    - Update model calibration parameters to incorporate new data
    - Incorporate the new version of the REC

Model Improvements

- Addition of new tools to allow easier creation of land use and farm practice scenarios and to determine land use capacity limits with respect to water quality.
- Initiate the improved simulation of groundwater and irrigation. CLUES currently does not take either into account which has led to problems with the model’s use in areas with complex links between surface water and ground water.

Table 29 Stakeholder identified benefits and suggested improvements to CLUES with respect to policy and planning applications.

Benefits
Looks at whole catchment and attenuation processes in it
Broad scale application
Predicts Mean Annual Loads of total nitrogen, total phosphorus, sediment and E.coli
Has good support across the country and have some good case studies of use
Has current application for policy work – i.e. focus on limit setting
Uses real data that can be calibrated up
Scientists can make an educated judgement when working with council managers
OVERSEER (farm scale) feeds into CLUES (at catchment scale), so has usefulness in terms of scale and building on existing data and information
All councils have ArcGIS so uses current software
Visual presentation of data is powerful and a useful communication tool
Can be aggregated up to national scale
Can act as a tool to assist in limit-setting at regional and national scale
Is a scenario analysis tool
Is operational now, well known and widely used
Comparability/consistency is a strength and important for evidenced based reporting
When end users are engaged it is a very useful as a management tool.
Requirements
Need to build the numbers of ‘expert’ users, on-going regional training is required
Need to better inform in-stream attenuation of nutrients
Better representation of hydrology, particularly ground water and irrigation
Sub-classifications of land use are needed, e.g., irrigated vs. non-irrigated dairy
Need more options for urban land use i.e. light industrial, greenfields, residential
Socio-economic elements not being used – need to get social scientists involved
Adapting for policy use – need summary statistics; not used as much as expected
Need to simplify the outputs an connections with values
OVERSEER feeds into CLUES – assumptions made (i.e. simplified version)
Need to consider increasing temporal scale resolution (e.g. seasonal) and improving spatial resolution
Open source data vs. proprietary
Need to reduce current quite high error factors (-+2 for TN and -+3 for TP)
Need flexibility to cover leaching in shallow soils (OVERSEER link)
Need flexibility around land uses and loss rates / land use variations
Need flexibility and better inputs for localised data
Need support on-going funding re land use database and REC
Need for closer integration with policy development

- Increase the temporal resolution from annual to seasonal in recognition that there are seasonal differences in land use practices (e.g., irrigation, application of fertiliser) and climate and therefore hydrological response;
- Improve spatial resolution. CLUES operates at the sub-catchment scale and spatial information within each sub-catchment is spatially lumped that can lead to problems with the representation of land use and mitigation when setting up scenarios. Modifications will be required within CLUES to capture the benefit of improved spatial resolution of the SPARROW sub-model currently underway.
- Evaluation of other tools and data sets for integration with CLUES (e.g. hydrological models, improved erosion models).

6.0 Summary and scope for further work

This report has been prepared for the Auckland Council to provide background information on the CLUES model in order to assess whether and how the model can be used in the region to aid the implementation of the NPSFM. To this end, the report:

- Demonstrates the ability of CLUES to provide current state information on contaminant loads in the Auckland region and to give an insight into historical (pre-European) contaminant loads which are indicative of the background or natural state of water quality in the region.
- Provides examples of how CLUES results can be extracted and displayed for either further analysis or to aid public understanding of water quality issues in order to facilitate community engagement in collaborative planning.
- Evaluates sources of model uncertainty and error and discusses calibration needs with respect to the Auckland region.
- Overviews proposed changes to freshwater management in New Zealand and where CLUES fits in the context of those changes. Planned improvements to the model in relation to the proposed changes are also discussed.

It was shown that there is a pressing need to calibrate CLUES locally. However, at present, there are few water quality monitoring sites in the Auckland region which have hydrometric monitoring nearby. Without concurrent flow data, contaminant loads required for calibration cannot be calculated. Nine SOE monitoring sites were identified as suitable for TN load calculation and eight for TP, though there may be up to five other sites which could provide data – this possibility needs to be explored. Sediment has been monitored at 15 sites for calculation of sediment yields – on-going monitoring is planned at 10 of these sites. There are currently no sites with data suitable for *E.coli* calibration. Three alternatives were suggested to increase data availability:

- Establishment of new hydrometric sites or relocation of water quality monitoring sites nearer to existing hydrometric sites.
- Use of flow models to simulate river flows to enable load calculation.
- Joint calibration using water quality data from sites in lower Northland and the upper Waikato region.

These alternatives need to be evaluated by the council with respect to their water quality monitoring programme. In the interim, CLUES could be applied to the Auckland region as an indicator model, rather than a predictive model similar to Semadeni-Davies and Elliott (2012) for the Waikato region (see overview in Section 5.3.3).

There is also a need to review the regional spatial data held in the CLUES geospatial database. For instance, the 2008 land use scenario applied in the present study has not yet been quality checked as the data were used before public release. Note that scenario may already be out of date for some areas undergoing land use change. Stock numbers, fertiliser application rates and point sources should also be revised. Furthermore, there are known errors in the REC in the

Hoteo/Mahurangi and Papakura catchments that need to be corrected. A new version of REC has been developed, but has not yet been incorporated into CLUES. Alternatively, the Auckland Council has developed and maintains its own drainage network data base that could be incorporated into CLUES, provided that the database contains data required by CLUES.

Within the context of the NPSFM implementation programme, CLUES could be used to:

- Simulate planned changes to land use in order ascertain their impacts on catchment water quality. This could be done to help determine the capacity for land use change with respect to different values and attribute in order to set water quality limits. This could be done for priority catchments or the region as a whole.
- Simulate whether farm practices such as the planned requirements for region wide stock exclusion and retirement of steep pastoral land can mitigate for current land use in areas with poor water quality or future land use in areas at risk of water quality degradation.
- Provide maps and tables to stakeholders as an aid to public understanding of water quality issues in the region or in priority catchments. For example CLUES maps could be added to the State of Auckland freshwater report cards currently produced by the council. These packs are held by public libraries in the region and are also available online (http://stateofauckland.aucklandcouncil.govt.nz/report-type/freshwater-report-card/).
- Provide for interactive simulation of sketch land use and farm practice scenarios in a public setting as part of community collaborative planning.

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