

Catchment models for nutrients and microbial indicators
Modelling application to the upper Waikato River catchment

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Contents

Executive summary	6
1 Introduction	9
1.1 Land use scenarios.....	12
2 Nutrients and chlorophyll	14
2.1 Method overview.....	14
2.1.1 Current loads and concentrations.....	15
2.1.2 Point sources and geothermal inputs.....	17
2.2 The models and key results.....	17
2.2.1 Incorporation into the economic model.....	18
2.2.2 TP model.....	18
2.2.3 TN model.....	20
2.2.4 Estimation of chlorophyll from TN and TP.....	21
2.2.5 Sensitivity to the degree of attenuation and a future land use scenario.....	23
3 Microbes	25
3.1 Overview of CLUES modelling.....	25
3.1.1 Observed <i>E. coli</i> concentrations.....	26
3.1.2 CLUES land use scenarios.....	29
3.1.3 Stock exclusion scenarios.....	30
3.1.4 Length of stock exclusion.....	32
3.2 Results with discussion.....	35
3.2.1 Overall patterns and comparison with NOF bottom line.....	35
3.2.2 Effect of fencing with current land use.....	39
3.2.3 Effect of land use change with current fencing.....	39
3.2.4 Combined effect land use change and increased fencing.....	40
4 Conclusions	41
5 Acknowledgements	43
6 References	44
Appendix A Change factors and adjusted median concentrations calculated for the Upper Waikato monitoring stations.	47

Tables

Table 1-1:	Estimated area of future forest conversion to dairy farming in the upper Waikato River catchment by subcatchment.	13
Table 2-1:	Median measured nutrient concentrations.	16
Table 2-2:	Median measured chlorophyll- <i>a</i> concentrations (2007-2012).	16
Table 2-3:	Mean annual load of TN and TP estimated from measurements.	17
Table 2-4:	Point source loadings, excluding dairy sheds, septic tanks, and geothermal sources apart from power stations.	19
Table 2-5:	Estimated geothermal discharges in tributary streams.	19
Table 2-6:	Sensitivity of the nutrient model to assumed attenuation and a land use scenario.	24
Table 3-1:	Five-year median <i>E. coli</i> concentrations (2007-2012) calculated from monthly water quality samples taken from monitoring sites in the study area.	28
Table 3-2:	CLUES land use classes in relation to LCDB2 and MPI land use classes.	29
Table 3-3:	List of scenarios simulated using the CLUES model to obtain estimates of changes in <i>E. coli</i> annual loads.	31
Table 3-4:	Stream lengths (m) eligible for fencing by subcatchment - Current land use.	33
Table 3-5:	Stream lengths (m) eligible for fencing by subcatchment - future land use.	34
Table A-1:	Median <i>E. coli</i> concentrations (CFU/100ml) and CLUES calculated change coefficients (%) from the base-line fencing and current land use scenario (Scenario 2a) with a removal factor of 20%.	48
Table A-2:	Median <i>E. coli</i> concentrations (CFU/100ml) and CLUES calculated change coefficients (%) from the base-line fencing and current land use scenario (Scenario 2b) with a removal factor of 50%.	50

Figures

Figure 1-1:	Monitoring sites and their associated subcatchments.	11
Figure 1-2:	Current land use by subcatchment.	13
Figure 2-1:	Measured and predicted TP loads.	20
Figure 2-2:	Relation between chlorophyll and TP across main stem sites.	22
Figure 2-3:	Down-stream relation between chlorophyll and TN across main stem sites.	22
Figure 3-1:	CLUES model framework. Source: Semadeni-Davies et al. 2011.	26
Figure 3-2:	Five-year median <i>E. coli</i> concentrations (2007-2012) calculated from monthly water quality samples taken from monitoring sites in the study area.	27
Figure 3-3:	Predicted 5-year median <i>E. coli</i> concentrations (CFU/100 ml).	36

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Executive summary

This report describes catchment models for predicting water quality in the upper Waikato River catchment, to support investigations into economic implications of the National Objectives Framework (NOF). This modelling entailed the following two main components:

1. Development of a simplified catchment model for total nitrogen (TN), total phosphorus (TP), and chlorophyll concentrations. The model takes source loadings from pasture, adds other sources, accounts for accumulation and decay between the source and in reservoirs, and predicts mean annual nutrient concentrations. The nutrient concentrations are used to predict phytoplankton chlorophyll levels from observed correlations between nutrients and chlorophyll going down the Waikato River. Periphyton were not addressed in this study, because the study partners considered that phytoplankton was of more concern than periphyton. The model is incorporated into an economic optimisation model (Doole, 2013) which determines land use and mitigation options to meet proposed NOF bottom lines and 'maintain or improve' provisions of the National Policy Statement on Freshwater Management (NPS-FM). Use of the bottom lines does not imply any endorsement of those levels by the partners in the Waikato River study, but is a starting point for economic analysis. Due to time lags in catchment response, the current observed nitrogen concentrations do not necessarily reflect the ultimate 'equilibrium' conditions (Weir et al. 2013) that the catchment model aims to represent. The ultimate conditions could be predicted if the attenuation (losses between the source at the point of generation and the outlet of the subcatchment) were known, but there is uncertainty about the degree of attenuation, so that three different levels were used: a maximum value, to match current concentrations; a low value; and an intermediate value.
2. Prediction of median concentrations of the microbial indicator *E. coli* for current land use and a future land use scenario (conversion of part of the exotic forest to dairying), and for various levels of stock exclusion (none, the current level, a 'Dairy Accord' level corresponding to fencing off second-order streams and larger, and fencing of all streams). The Catchment Land Use for Environmental Sustainability model CLUES (Semadeni-Davies et al. 2011b) was used for this purpose. Stock exclusion was simulated by reducing the *E. coli* yields from stock by 20% and by 50% to approximate low and high mitigation rates. The predicted concentrations were compared with the proposed NOF bottom line for secondary contact recreation and with current concentrations. The length of new fencing was also estimated, to enable the cost of fencing to be estimated (Journeaux 2013).

In both modelling components, the upper Waikato River catchment was subdivided into 24 subcatchments, based on the locations of water quality monitoring stations, and concentration predictions were made where suitable water quality data are available (23 sites for nutrients, 5 main stem sites for chlorophyll, and 20 for *E. coli*). Simulations were made for both current and future land use scenarios.

Nutrients and chlorophyll

The report by Doole (2013) addresses the implications of the water quality model, such as the land-use and mitigation required to maintain or enhance water quality and remain above the NOF bottom line, so the presentation of results related to nutrients and chlorophyll are

left largely to that report. However, to explore the behaviour of the model, we did examine the effect of different attenuation values on TN and chlorophyll with the current land use, and the scenario of converting 25000 ha of forest to dairy. Key findings from these scenarios are:

- The maximum TN attenuation value, which was determined by calibration to current measured loads, ranged from 0 to 74% loss with a median of 45%, while a minimum attenuation value of 20% and an intermediate value of 30% loss was used.
- The model predictions were sensitive to attenuation. In the most extreme case, concentrations in one catchment were predicted to increase by a 147% as a result of delayed responses to past land-use change. At the Narrows (representative of Lake Karapiro) the predicted concentration of TN increased by up to 38% as a result of delayed load, and chlorophyll would consequently increase by 47%. This has important implications for maintaining water quality at the current state. Given the uncertainty in the attenuation values, it is recommended that additional effort be invested in refining estimates of lags and attenuation in the catchment.
- Conversion of 25000 ha of forest to dairy was predicted to increase the TN and TP concentrations. The most pronounced percentage increase was in the Pueto catchment (39% increase in TN, 24% increase in TP). At the Narrows, the TN predicted concentration increased by 5% and the TP concentration by 6%, with an associated increase in chlorophyll of up to 9%. Such increases would need to be offset by mitigation measures or land-use change elsewhere in the catchment to maintain current concentrations, which is the focus of the economic model.

Microbes

The purpose of CLUES *E. coli* modelling was to determine whether:

- conversion of exotic forest to dairy farming will cause water quality at the monitoring sites to exceed the NOF bottom line concentration (median concentration of 1000 CFU/100ml)
- stock exclusion along streams can reduce *E. coli* median concentrations below the NOF bottom line at sites which either currently exceed the bottom line or could exceed the bottom line following dairy conversion, and
- for the future land use, stock exclusion along streams is able to maintain the *E. coli* median concentration at the current value.

The associated cost of stock exclusion is investigated as part of the upper Waikato River catchment Study in Journeaux (2013).

Key model results in relation to *E. coli* are:

- Only one site, Mangawhero, has an observed median concentration which exceeds the proposed NOF bottom line concentration for secondary recreational contact of 1000 CFU/100ml. This is a dairy-dominated catchment with poorly-drained peat soils. All other sites have concentrations less than the

NOF value, and the main stem sites have median concentrations which are two or three orders of magnitude less than the NOF value.

- Fencing according to the Dairy Accord levels (second order and larger streams, including dairy and non-dairy areas) did not reduce the predicted *E.coli* concentration for the Mangawhero below the NOF value using either the upper or lower mitigation factor. Extending fencing to all streams in the Mangawhero subcatchment would reduce the concentration to less than the NOF value if the higher mitigation factor is assumed but not for the lower mitigation value.
- Fencing according to the Dairy Accord levels would reduce concentrations by between 3% and 27% across the upper Waikato River catchment depending on the mitigation factor and the degree of pasture upstream. Extending fencing to all streams reduced *E.coli* concentrations by between 5% and 44 % across the upper Waikato River catchment depending on the mitigation factor and the degree of pasture upstream.
- Conversion of 25000 ha of exotic forest to dairy farming is not predicted to result in any sites, other than Mangawhero, exceeding the proposed NOF bottom line concentration.
- Assuming the current level of fencing, the percentage increase in concentration due to conversions from forest to dairy was estimated to be 0–19 % depending on the extent of upstream conversion (and to a small degree the assumed mitigation factor). The exception is Pueto, which could experience a trebling of *E. coli* concentrations following conversion, because that subcatchment has a small degree of pasture currently and a moderate amount of pasture would be introduced.
- Assuming the low mitigation factor, fencing to Dairy Accord levels was not sufficient to offset the effect of conversion from forest to dairy for four sites. If the upper mitigation factor is assumed, the Dairy Accord level of stock exclusion would offset the effects of land use change for all but one subcatchment (Pueto), and reduce concentrations in many cases.
- Extending fencing to all pasture streams would offset the effect of conversion for all but the Pueto site. The reduction was in the order of 10–5% assuming the low mitigation factor and 20–44% assuming the high mitigation factor.

1 Introduction

As part of the National Objectives Framework (NOF) development (Ministry for the Environment, MfE, 2013a, 2013b). MfE and Ministry for Primary Industries (MPI) are jointly conducting a series of case studies to identify the economic implications of introducing water quality limits to achieve NOF bottom-lines for the compulsory values of ecosystem health and human health for secondary contact health as listed by MfE (2013b). Bottom lines are set nationally and represent the minimum acceptable state required to meet the objectives associated with freshwater values. That is, the bottom line represents the threshold between attribute bands C and D. While it is recognised that regional authorities can choose to set freshwater objectives more stringent than the bottom lines (i.e., NOF attribute bands A, B and C), the decision is dependent on the economic, social, cultural and environmental goals of the community. For this reason, water quality is assessed in the case studies only with regard to the bottom lines which are non-negotiable.

This report is a component of the Upper Waikato case study, which extends from the Lake Taupo outlet to the Waikato at Narrows (which is between Cambridge and Hamilton). In this case study, the compulsory values are indicated by the attributes chlorophyll¹ (calculated as a function of nutrient concentrations) and *E. coli* for ecosystem and human health respectively. Thus, this report focuses on prediction of water quality, and entails the following two main components which are presented separately in the report:

1. Development of a simplified catchment model for total nitrogen (TN), total phosphorus (TP), and chlorophyll concentrations. The model takes source loadings from pasture, adds other sources, and predicts mean annual TN and TP concentrations, which are in turn used to predict chlorophyll levels. The model is incorporated into an economic optimisation model (Doole, 2013) which determines land use and mitigation options to meet proposed NOF bottom lines and 'maintain or improve' provisions of the National Policy Statement on Freshwater Management (NPS-FM, Ministry for the Environment, 2011). A challenge with this work is predicting ultimate future concentrations taking account of time lags from past land-use change.
2. Prediction of median concentrations of the microbial indicator *E. coli* for current land use and a future land use scenario, and for various levels of stock exclusion. The Catchment Land Use for Environmental Sustainability model CLUES (Semadeni-Davies et al. 2011b) was used for this purpose. The predicted concentrations were compared with the proposed NOF bottom line for human health for secondary contact and with current concentrations at 24 monitoring stations. The length of new fencing required for stock exclusion was also estimated, to enable the cost of fencing to be estimated (Journeaux 2013).

Nutrient and *E. coli* concentrations were evaluated at sites where measurements are made, and these sites formed the spatial framework for analysis. With the exception of Waikato at Taupo Gates and Waikato at Reid's Farm, which are located within 10 km of Lake Taupo and represent the inflow water quality to the upper Waikato River catchment, each monitoring site

¹ Chlorophyll concentration is simulated here in preference to periphyton (i.e., slime and algae) which is an attribute for river ecosystem health under the proposed NOF as periphyton was not considered an issue in the catchment area (personal comment Kevin Collier, Waikato Regional Council). See Section 2 for more details.

is associated with its own subcatchment. Each subcatchment represents the contributing area draining to each successive water monitoring site along the drainage network. Of the resulting 24 subcatchments, six are on the main stem of the Waikato River. The monitoring sites and their respective subcatchments are mapped in Figure 1-1.

Note that within each subcatchment as defined by the monitoring stations, there are a number of smaller River Ecosystem Classification (REC) subcatchments (Snelder et al. 2010). For this report, the larger areas will be referred to as subcatchments, while the REC subcatchments will be referred to as REC units.

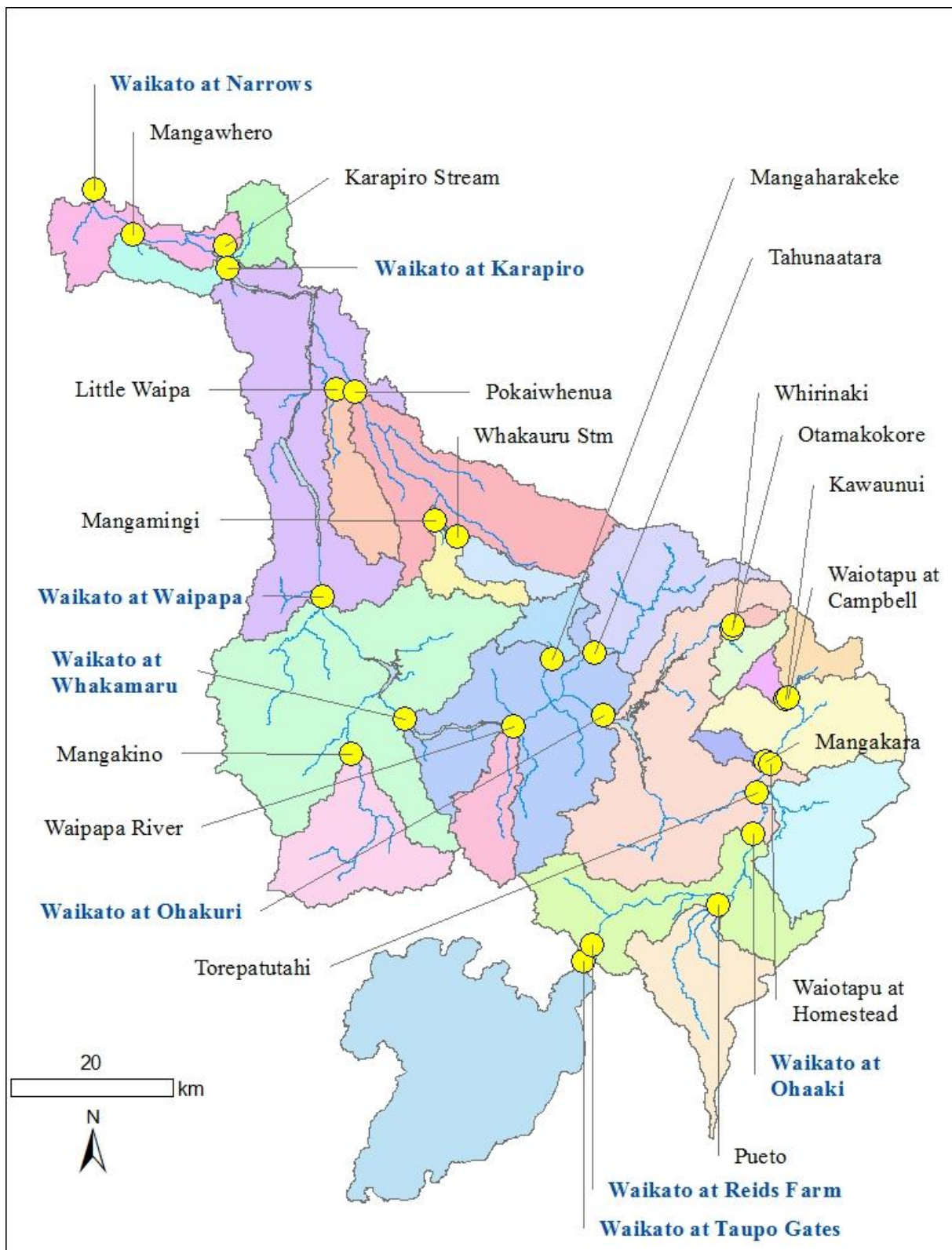


Figure 1-1: Monitoring sites and their associated subcatchments. Main stem sites are labelled in bold blue.

1.1 Land use scenarios

Modelling was carried out for current and future land use using data supplied by the Ministry of Primary Industries (MPI). Current land use data was supplied at the subcatchment scale for nutrient and chlorophyll modelling, and at the REC unit scale for *E. coli* modelling.

In all, seven land uses were modelled, they are:

- Dairy
- Dairy support
- Lowland “easy” sheep and beef
- Hill-country “hard” sheep and beef
- Exotic or plantation forest
- Urban
- Other land uses which includes native forest, scrub, quarries and mines.

The breakdown of land uses by subcatchment derived from the current land use scenario provided by MPI is given in Figure 1-2. The plot also shows the relative area of the subcatchments. It can be seen that the upper catchment is dominated by forestry, dairy farming and sheep and beef farming with some areas of native forest.

The future land use scenario was created using estimates of exotic forest conversion to dairy farming for each subcatchment with an overall decrease in forestry in the upper Waikato River catchment of 25,000 ha (Table 1-1). The land use change estimates provided for this study were derived by WRC, the Ministry for the Environment (MFE), the Waikato River Authority (WRA) and Dairy NZ.

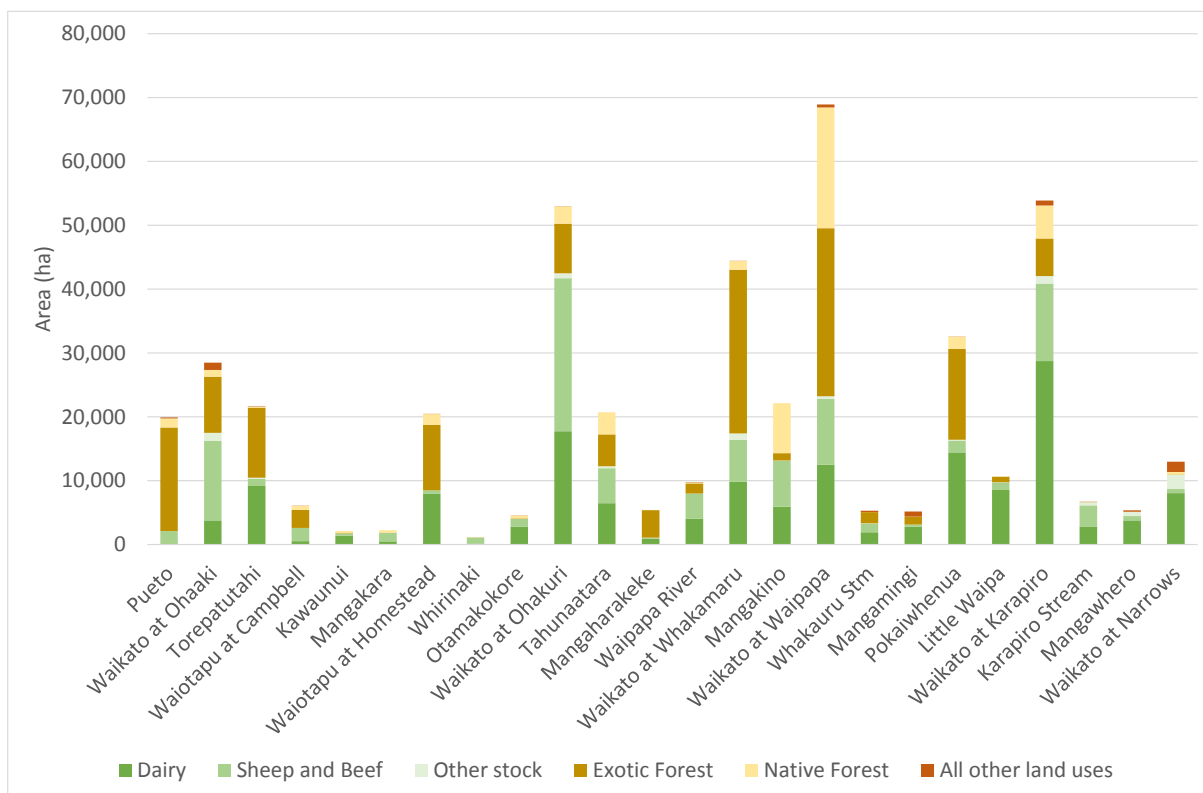


Figure 1-2: Current land use by subcatchment. Source, MPI.

Table 1-1: Estimated area of future forest conversion to dairy farming in the upper Waikato River catchment by subcatchment.

Subcatchment	Area converted (ha)	Reduction in forestry (%)
Pueto	3000	18
Waikato at Ohaaki	3000	37
Torepatutahi	5000	45
Waiotapu at Homestead	2000	20
Tahunaatara	2000	39
Waikato at Whakamaru	2500	10
Waikato at Waipapa	2500	9
Pokaiwhenua	5000	35
TOTAL	25000	17

2 Nutrients and chlorophyll

This section presents the methodology for setting the catchment model for nutrients and estimation of chlorophyll, including estimation of current concentrations and key relationships and parameters. Chlorophyll, which is an attribute for lake ecosystem health, was chosen in preference to periphyton (an attribute for river ecosystem health) in this case study. This was because periphyton was not considered relevant to the whole Waikato catchment (pers. comm. Keven Collier, Waikato Regional Council) as the topography (low gradient) and geology (soft materials e.g. ignimbrite) of the catchment does not lead to stream substrates that support conspicuous periphyton growth. Periphyton requires a stable stony bed with sufficient light penetration for growth, however, the Waikato drainage system is dominated by deep channels with fine substrates. Predictions of the model are embodied in the report on the economic model (Doole, 2013), only key results are presented here.

2.1 Method overview

For each of the subcatchments, the mean annual load of nutrients generated within the catchment was determined based on a) pasture losses (i.e., nutrient yields from pastoral land uses multiplied by the area determined for each of these land uses), as provided by the economic model; b) exotic forest, urban and other diffuse losses (e.g., scrub), determined from land areas multiplied by yield coefficients; c) point sources, derived from discharge records and d) geothermal inputs of nitrogen, derived from analysis of stream water quality.

Attenuation or decay between diffuse sources and the main stem (i.e., within sub-catchment) and attenuation of nutrient loads within the main stem were modelled separately as follows.

The diffuse sources were subject to attenuation before entry into the main stem of the river network. The subcatchment-average attenuation factors for phosphorus were taken from the Catchment Land Use for Environmental Sustainability (CLUES) model² (Woods et al. 2006a; Semadeni-Davies et al. 2011b). These were then modified to improve the match to measured mean annual loads for TP. For TN, a range of attenuation factors was applied to account for uncertainty associated with time lags in groundwater, as explained later.

Attenuation within the main stem (including the hydro reservoirs) was also applied. This attenuation, which was generally a few percent, was also taken from CLUES (which uses an effective settling velocity), with an adjustment in some cases for TN to ensure that the within-catchment attenuation was within reasonable bounds.

The resulting load at a monitoring station was then determined as the sum of the loads from upstream, discounted for within-subcatchment and main stem attenuation.

The mean annual concentrations were then determined from load in the following way. For TP, the proportional change in load under a scenario was applied to the current measured TP concentration to derive the predicted concentration for the scenario. For example, if the loads increased by 10% at a monitoring station, then the concentration increased by 10% from the current mean value. For TN, a similar approach was adopted, except that the proportional increase in load was determined with reference to the current load as estimated from the low-attenuation scenario (which matches current measured loads where available).

² A description of the model, in relation to E. coli modelling, is given in Section 3.1

The TN and TP concentrations were each related to chlorophyll-a concentration at 5 sites along the Waikato River: Ohaaki, Ohakuri, Whakamaru, Waipapa, and the Narrows. The relation between nutrients and chlorophyll was derived from regression relationships going down the stream network and do not take into account whether either of these nutrients is potentially limiting chlorophyll.

2.1.1 Current loads and concentrations

Estimates of current nutrient loads and concentrations were used for model calibration and for a baseline reference point for estimating future conditions.

Water quality data from 26 stations were obtained from the Waikato Regional Council, and measured TN and TP sample concentrations were derived by summing the components or species where necessary. Samples were mainly derived from monthly monitoring over at least 20 years.

Since concentrations are trending gradually over time, methods to estimate the current median concentration were developed. This method involved fitting a smoothed line to the time series from 1993 to 2012, and using deviations of this smoothed line from the smoothed value in mid-2012 to adjust historical values. The medians were taken after this adjustment. Cubic spline smoothing from the R statistical package was used, with a fixed effective degrees of freedom (df parameter) of two to restrict curvature. The resulting median concentrations are shown in the first column of Table 2-1. In general, these concentrations were close to the raw 5-year medians (2008–2012), but in several cases were about 10% above the 5-year median for TN due to time trends over the last 5 years. Concentrations are not shown for the Taupo Gates site because it is close to Waikato at Reids, where the analytical method can detect lower concentrations. Nutrients are not measured at the Waikato at Karapiro site.

For chlorophyll-a concentrations, 5-year median values from monthly samples over the period 2008 to 2012 were used, and results are shown in Table 2-2. The Whakamaru site was removed due to concerns about sampling artefacts (pers. comm. Bill Vant, Waikato Regional Council). For the Taupo Gates site, a value of 0.0009 g/m³ was used based on Lake Taupo data (from Bill Vant, Waikato Regional Council), because of the large number of non-detect values in the samples from the river site.

Mean annual loads of TN and TP were estimated at sites where there were sufficient flow data using rating-curve methods. In this method, a rating curve was fit to the measured concentrations using the following equation:

$$\ln(C) = s(t) + s(\ln(Q)) + a \sin(2\pi t) + b \cos(2\pi t) \quad (1)$$

Where C is the concentration of the constituent of interest (TN or TP), s is a cubic spline smoothing function, Q is the flow at the time of the sample, and t is time (in years), and a and b are coefficients. Cubic spline smoothing from the R statistical package was used, with a fixed effective degrees of freedom (df parameter) of 2 to restrict curvature. The flow record was also then trend-adjusted as described above for median concentrations. Equation (1) was then applied to the full trend-adjusted hourly time-series over the 20-year period, but with the year fixed to 2012, to derive a time-series of concentrations, which was then multiplied by flow and summed to give the mean annual load trend-adjusted to 2012. The

load was then adjusted by a smearing bias correction factor to account for log-transformation bias (Duan, 1983). The resulting mean annual loads are given in Table 2-3.

Table 2-1: Median measured nutrient concentrations.

Name	TN g/m3	TP g/m3	WRC Site ID
Waikato at Reids	0.06	0.005	1131-127 ^a
Pueto	0.58	0.098	802-1
Waikato at Ohaaki	0.15	0.015	1131-105
Torepatutahi	0.68	0.095	1057-6
Waio tapu at Campbell	1.94	0.088	1186-2
Kawaunui	2.99	0.102	240-5
Mangakara	1.67	0.080	380-2
Waio tapu at Homestead	1.94	0.116	1186-4
Whirinaki	0.83	0.066	1323-1
Otamakokore	1.08	0.144	0683-4
Waikato at Ohakuri	0.22	0.024	1131-107
Tahunaatara	0.82	0.051	934-1
Mangaharakeke	0.75	0.053	359-1
Waipapa Stream	1.45	0.090	1202-7
Waikato at Whakamaru	0.29	0.026	1131-147
Mangakino	0.78	0.048	388-1
Waikato at Waipapa	0.35	0.032	1131-143
Whakauru Stm	0.48	0.043	1287-7
Mangamingi	3.52	0.340	407-1
Pokaiwhenua	2.15	0.109	786-2
Little Waipa	1.89	0.067	335-1
Karapiro Stream	0.91	0.097	1131-81
Mangawhero	3.16	0.201	230-5
Waikato at Narrows	0.45	0.034	488-1 ^b

Notes: ^a Nutrient data from NRWQN site RO6 used at this location, due to lower detection limit.

^b Narrows Bridge and Narrows Boat Ramp data were combined.

Table 2-2: Median measured chlorophyll-a concentrations (2007-2012).

Site	Chlorophyll-a (mg/L)
Waikato at Ohaaki	0.0009
Waikato at Ohakuri	0.0033
Waikato at Waipapa	0.0059
Waikato at Narrows	0.0040
Waikato at Horotiu	0.0077

Errors were estimated using a boot-strapping approach by repeatedly taking random samples of the original water quality data and estimating the mean annual load for each of these samples. The standard error for TN estimated in this way was less than 8% for all sites except for the Whakamaru site, which had 20% error due to estimating concentrations across the wide range of flows. The standard error for TP was generally larger than for TN.

Table 2-3: Mean annual load of TN and TP estimated from measurements.

Site	TN load (t/year)	TP load (t/year)	Error TN (%)	Error TP (%)
Waikato at Ohaaki	845	85.1	8	7
Waiootapu at Homestead	285	46.0	2	24
Otamakokore	47	11.9	3	25
Waikato at Ohakuri	1373	146.1	7	13
Tahunaatara	142	9.9	3	10
Waikato at Whakamaru	1885	166.9	21	20
Mangakino	199	11.5	3	5
Waikato at Waipapa	2324	232.9	3	5
Pokaiwhenua	336	17.3	2	5
Waikato at Narrows	3844	273.8	3	5
Waikato at Reids	310	24.7	2	4

Measured loads at some further sites were estimated without continuous flow records, for the purpose of calibration. For such sites, the measured median concentration was multiplied by a factor to convert to flow-weighted concentration, and this was then multiplied by the mean annual flow to derive the load estimate. The mean annual flow was taken either from historical records, or from the model of Woods et al. (2006b).

2.1.2 Point sources and geothermal inputs

Estimates of point sources loading are shown in Table 2-4. In the table, WRISS is Waikato River Independent Scoping Study (NIWA, 2010, Appendix 13, Table 6). The Waikato Regional Council (WRC) provided most other data. Geothermal sources of TN were estimated from ammonia-N and flow rates in Gibbs (1987) and are shown in Table 2-5. The Wairakei Stream values are corrected for the Wairakei separated water, which is counted as a point source.

2.2 The models and key results

This section overviews the models used to estimate nutrient and chlorophyll loads and concentrations and presents key results. Simulations were made for both current and future land use as described in Section 1.1. For each of the 24 subcatchments, the area was broken into dairy, dairy support, sheep and beef (separated into easy and hard based on slope to represent lowland intensive and hill country farming), exotic forest, urban, and other (miscellaneous) land uses.

2.2.1 Incorporation into the economic model

The catchment modelling described below was formulated in such a way that it could be easily incorporated into the economic model. This involved passing parameters for yields for non-pasture landuses, point source loadings, attenuation factors to each subcatchment outlet, and the total main stem attenuation between each subcatchment outlet and each monitoring station. Incorporation of the hydrology model into the economic model, and results (such as the optimised land-use and mitigations to ensure that water quality is maintained and does not breach NOF bottom lines) are contained in the economic report (Doole, 2013).

2.2.2 TP model

For each of the pastoral land uses listed above, specific yields (kg/ha/year) of TP at source were supplied by the University of Waikato, to be consistent with the economic model. Specific yields for urban land use (0.6 kg/ha/y) and exotic forestry (0.3 kg/ha/year) were chosen to give typical yields of 0.3 kg/ha/y and 0.15 kg/ha/y respectively after attenuation (Williamson, 1993; Elliott and Stroud, 2001). The yield from urban land-use was on the lower end of literature values, to account for very good soil drainage in many of the urban areas in the catchment. Since the miscellaneous land-use was largely native forest and scrub, typical yields for those land uses were applied (0.3 kg/ha/year before attenuation). For the non-pasture sources, the specific yields are loads into the main stem, not at source, because measurements are available at that scale. The yields were multiplied by the areas to give the mean annual load for each land use.

The non-point sources were subject to attenuation before entry into the main stem of the river network. The main stem was defined by the subcatchment outlet locations, and so largely consisted of the Waikato River main stem. The subcatchment-average attenuation factors for phosphorus were taken from the CLUES catchment model by running CLUES simulations with and without attenuation, with standard parameters. The effective decay per unit stream length was then increased by a uniform factor (1.7) for all subcatchments, to optimise the match to measured loads. The resulting losses ranged from 43 to 76%, with a median of 59% loss.

The attenuated load from pastoral sources was then added to the attenuated load from diffuse sources, to derive the total diffuse source for each subcatchment. Point sources were then added to derive the total load entering the main stem.

The load at the outlet of any subcatchment was then determined by accumulating the loads down the drainage network, accounting for main-stream attenuation in the process. Main stem attenuation (which was dominated by the hydro reservoirs), which was less than 5% loss in each reservoir, was taken from CLUES (which uses an effective settling velocity approach). The load from the Lake Taupo outlet was treated like a fixed point source at the top of the Ohaaki reach.

The resulting comparison of measured and predicted loads is shown in Figure 2-1. Predictions were not made for the Whakauru Stream due to high uncertainty of model predictions at this site (this applies for the TN model as well).

The predicted median concentration of TP for a scenario was determined by calculating the percentage increase in load under a scenario compared with the current scenario, and then applying this percentage to the current measured TP concentration at the site in question. For example, if the loads increased by 10%, then the concentration increased by 10% from the current mean value. This ensures that the predicted concentrations for the current scenario are equal to the measured value. While this assumption of proportionality of loads and concentrations has not been tested, it is reasonable.

Table 2-4: Point source loadings, excluding dairy sheds, septic tanks, and geothermal sources apart from power stations.

Point Source Name	TN (t/y)	TP (t/y)	NZ Reach	Subcatchment	Source of information	Disposal
Wairakei power station	44.2	13.1	3042476	Waikato at Ohaaki	TN from Ray et al. (2001). TP from WRISS.	Stream
Ohaaki Power station	0.6	0.7	3039498	Ohakuri at Tailrace	WRC	Stream
Kinleith pulp and paper	164.0	19.2	3031690	Waikato at Waipapa Tailrace	WRC	Stream
Litchfield Dairy	8.4	0.0	3025739	Pokaiwhenua	WRISS	Land. Allow 20% leakage of N, 0% of P.
Tokoroa sewage	58.4	6.6	3027689	Whakauru Stm	WRISS	Stream
Cambridge sewage	50.5	9.1	3020373	Waikato at Narrows	WRC, Bill Vant estimate post 2001.	Streamside soakage. Assume most of waste enters the main stem of the Waikato River
Hautapu Dairy	44.2	0.6	3020218	Waikato at Narrows	WRC	Stream

Table 2-5: Estimated geothermal discharges in tributary streams.

Stream/spring	TN load (t/y)	Discharge subcatchment
Otumuheki	4	Waikato at Ohaaki
Pararikiki	34	Waikato at Ohaaki
Pueto	2	Pueto
Waiotapu	39	Waiotapu at Campbell
Wairakei	Included in point source estimate	Waikato at Ohaaki

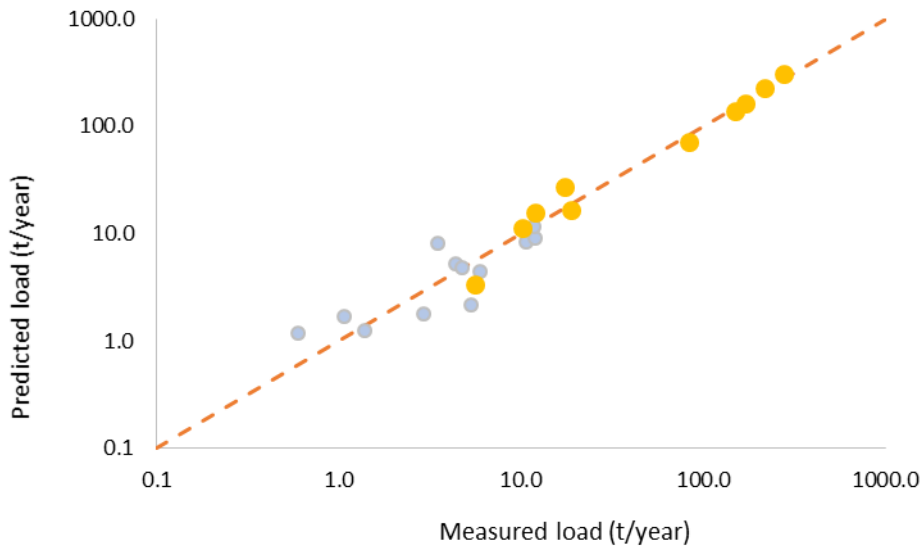


Figure 2-1: Measured and predicted TP loads. The dashed line is the 1:1 curve. Yellow points are where measured loads were estimated from flow records and rating curves, while the grey points are where loads were estimated more coarsely using concentrations and mean flow, as described in Section 2.2.

2.2.3 TN model

For TN, the situation was more complicated, and it was not appropriate to calibrate solely to measured loads, because the current measured TN load may underestimate the equilibrium situation, due to groundwater lags.

An approach was adopted whereby three different levels of attenuation were analysed, bracketing the expected range, and we attempted to predict the loading and concentrations after all lag effects were passed (that is, an equilibrium situation).

The largest attenuation was estimated by calibrating to match current measured mean annual loads exactly; this will over-estimate the attenuation in many cases, because the current load at calibration sites will be lower than the steady-state value. Some judicious lumping of decay coefficients between adjacent subcatchments was required to avoid unreasonable decay coefficients (such as negative attenuation) or where load measurements were not available. The resulting loss percentages ranged from 0 to 74%, with a median of 45%.

In many of the streams in the upper Waikato River catchment, nitrogen concentrations are increasing sharply and there are considerable time lags in groundwater (Weir et al. 2013). Therefore the maximum loss estimates as described are likely to be too high. Thus, two alternatives were developed; a low and intermediate attenuation scenario. The low attenuation scenario applied an estimated lower bound of the attenuation coefficient, generally a loss of 20%, except where the 'maximum' attenuation as described above was already less than this value. This approach will tend to be conservative, in the sense that it will tend to provide higher load estimates. We did not reduce the loss to 0%, as previous research suggests that there is always some level of attenuation, as discussed further below. The intermediate attenuation scenario used a loss of typically 30%, except where the 'maximum' attenuation as described above was already less than this value.

There is little information on measured attenuation losses. In previous assessments (Anon, 2008), losses were estimated at 50% for the Taupo catchment, although it was acknowledged that this involved considerable uncertainty, and the estimates were based largely on model results, including the SPARROW (Spatially Referenced Regression on Watershed attributes) model which is the foundation for CLUES³. Elliott and Stroud (2001) estimated 59% loss for dairy areas in the Taupo catchment. Alexander et al. (2002) estimated attenuation of 42% in the upper Waikato River catchment, including reservoir attenuation. Downes et al. (1997) established that in-stream nitrate removal efficiency can vary from essentially zero to about 90% for a stream in the Lake Taupo catchment, depending on the state of riparian vegetation, and much of the removed nitrate is remobilised as other forms of nitrogen. In the Manawatu (Clothier et al. 2007), an attenuation factor of 50% has been typically used, although this includes a factor to convert from TN to nitrate and again is based on CLUES catchment modelling. The current CLUES national model (version 10) suggests an average of 35% attenuation. Spring flows with pumice soils in much of the catchment and established riparian vegetation would be expected to reduce opportunities for in-stream attenuation to lower than national average values. It should also be noted that the attenuation estimates are usually tied to estimates of the sources; if the sources are under-estimated, then the losses will tend to be under-estimated as well to achieve the same catchment outlet load. Overall, there is considerable uncertainty about the suitable attenuation factor, and we cannot at this stage provide an assessment of the most likely value.

In most other respects, the calculations proceeded as for TP. An exception was that for non-pasture diffuse losses, coefficients after attenuation were used, rather than before attenuation, to remove any spurious effects of altering the attenuation coefficient. The yields for exotic forest and 'other' land use after attenuation were 2kg/ha/year, and for urban areas the yield was 6kg/ha/year. The reservoir attenuation coefficient was doubled from the Clues values, because otherwise unrealistic attenuation within the subcatchment was required, but the losses were still less than 5%. The attenuation factors were lumped, to avoid unrealistic attenuation values or where there were not suitable load observations for the subcatchment outlet. The Whakauru Stream and Mangamingi subcatchments were lumped, the Waikato at Karapiro, Karapiro Stream, Mangawhero, and Narrows subcatchments were lumped. For calculating concentrations, the loads from the high-attenuation scenario were used as the basis for calculating proportional increases in loading, because that scenario is tuned to current observations.

2.2.4 Estimation of chlorophyll from TN and TP

The concentration of chlorophyll was determined from downstream relationships between nutrients and concentrations, as shown in Figure 2-2 and Figure 2-3. These relationships were used to determine chlorophyll-a as a function of TN and TP at five sites along the Waikato River: Ohaaki, Ohakuri, Whakamaru, Waipapa, and the Narrows. At a particular site, the regression was applied at the current and future TN, and the increase factor was applied to the current measured chlorophyll-a. This ensures that the predicted chlorophyll-a is equal to the measured concentration at the current TN concentration, but that increases follow the trend of the regression. A chlorophyll-a concentration based on TP was derived in a similar fashion. Two separate predictions were provided, and the economic model applied both of

³ SPARROW is used in CLUES to route contaminants through the drainage network and to estimate sediment and E. coli yields.

these as constraints, because the joint distribution of chlorophyll-*a* as a function of both TN and TP is unknown and could not be determined from the available data. However, this implies that neither of these nutrients is specifically limiting chlorophyll-*a* populations in this waterway. Any interpretation of model economic model output must account for this limitation of the approach. A further limitation of the approach is that relationships across sites do not necessarily apply to the responses to nutrient increases at a particular site. More detailed physically-based models and measurements of nutrient-phytoplankton dynamics, including cumulative effects, would be required to derive more robust estimates of phytoplankton chlorophyll-*a* in response to changes in nutrients.

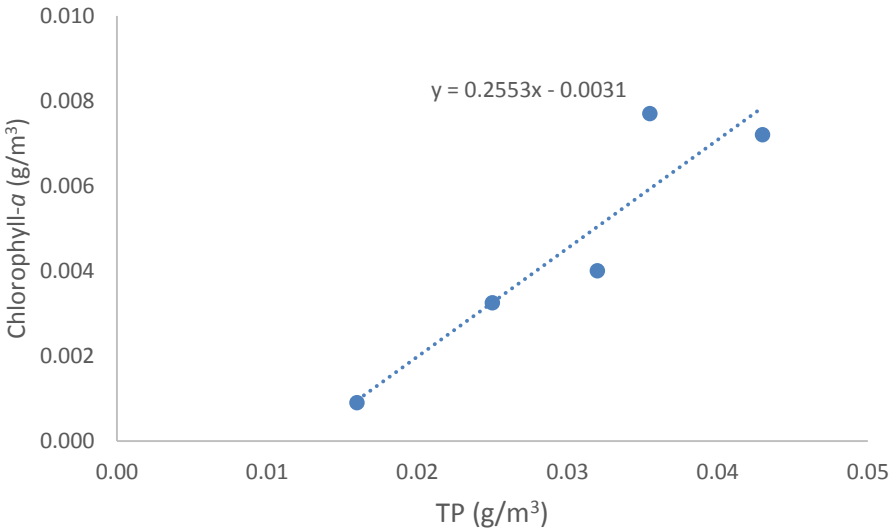


Figure 2-2: Relation between chlorophyll and TP across main stem sites.

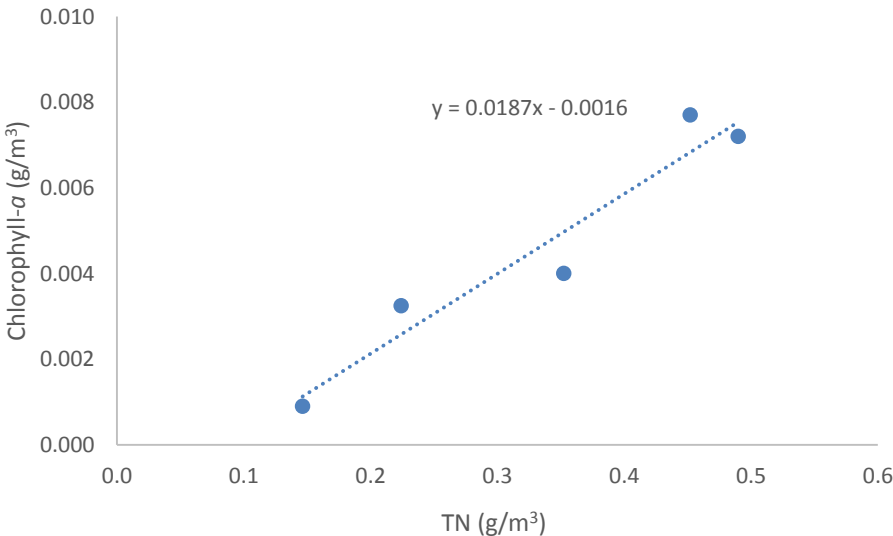


Figure 2-3: Down-stream relation between chlorophyll and TN across main stem sites.

2.2.5 Sensitivity to the degree of attenuation and a future land use scenario

While key implications of the water quality model are presented in Doole (2013), here we present the behaviour of the model in relation to the assumed attenuation and the future land use scenario. In this scenario, the maximum attenuation values were used.

The assumed degree of attenuation has important implications for the ultimate predicted concentration Table 2-6. For example, for the Torepatutahi Stream, the TN concentration is predicted to increase by 147% as a result of delayed responses to past changes in land use, if the attenuation changes from the current value of 74% loss to the assumed minimum value of 20% loss. The implication is that sources of nitrogen will have to decrease substantially to maintain the current concentrations. This is the most extreme case. At the Narrows (representative of Lake Karapiro) the concentration of TN increases by 38% as a result of delayed responses if the attenuation is reduced to the minimum value; the predicted chlorophyll-a concentration at that site would consequently increase by 47%.

Conversion from forest to dairy pasture was predicted to increase the TN and TP concentrations. The most pronounced percentage increase is in the Pueto catchment (39% increase in TN, 24% increase in TP), because this is the subcatchment with the greatest degree of land use change. The conversion also has implications downstream. At the Narrows, the TN concentration was predicted to increase by 5% and the TP concentration by 6%. The increase in chlorophyll is 6% according to the TN / chlorophyll-a regression, and 9% according to the TP / chlorophyll-a regression. From a conservative (worst-case) standpoint, the predicted increase in chlorophyll-a would be 9%. Such increases would need to be offset by mitigation measures or land use change elsewhere in the catchment to maintain current concentrations, which is the focus of the economic model.

Table 2-6: Sensitivity of the nutrient model to assumed attenuation and a land use scenario.

Subcatchment	Baseline (current) concentration (g/m ³)			Increase from maximum to intermediate attenuation (%)		Increase from maximum to low attenuation (%)		Increase from land use change (%)			
	TN	TP	Chlorophyll-a	TN	Chlorophyll-a	TN	Chlorophyll-a	TN	Chlorophyll-a from TN	TP	Chlorophyll-a from TP
Pueto	0.58	0.098		3		9		39		24	
Waikato at Ohaaki	0.15	0.015	0.0009	0	1	1	2	7	17	6	30
Torepatutahi	0.68	0.095		120		147		25		41	
Waiotapu at Campbell	1.94	0.088		0		0		0		0	
Kawaunui	2.99	0.102		0		0		0		0	
Mangakara	1.67	0.080		1		15		0		0	
Waiotapu at Homestead	1.95	0.116		11		18		8		11	
Whirinaki	0.83	0.066		25		43		0		0	
Otamakokore	1.09	0.144		45		65		0		0	
Waikato at Ohakuri	0.22	0.024	0.00325	35	57	44	73	7	11	7	13
Tahunaatara	0.81	0.051		44		63		16		14	
Mangaharakeke	0.75	0.053		0		0		0		0	
Waipapa Stream	1.45	0.090		38		57		0		0	
Waikato at Whakamaru	0.30	0.026	0.00585	36	51	48	67	8	11	7	14
Mangakino	0.80	0.048		21		37		0		0	
Waikato at Waipapa	0.31	0.032	0.004	38	52	50	69	6	9	6	10
Mangamingi	3.52	0.340		46		59		0		0	
Pokaiwhenua	2.06	0.109		46		62		16		16	
Little Waipa	1.89	0.067		84		110		0		0	
Karapiro Stream	0.91	0.097		0		0		0		0	
Mangawhero	3.16	0.201		0		0		0		0	
Waikato at Narrows	0.45	0.034	0.0077	29	36	38	47	5	6	6	9

3 Microbes

This section uses the CLUES model to investigate the extent to which excluding stock from open water ways by either fencing or riparian planting can reduce the concentration *E. coli* in the study area. The associated cost of stock exclusion is investigated as part of the upper Waikato River catchment Study in Journeaux (2013).

Change in *E. coli* concentrations is assessed here against the proposed NOF bottom line for human health for secondary contact of 1000 cfu/100mls. The purpose of CLUES *E. coli* modelling was to determine whether:

- conversion of exotic forest to dairy farming will cause the water quality at the monitoring sites to exceed the bottom line
- stock exclusion along streams can reduce *E. coli* median concentrations below the bottom line at sites which either currently exceed the bottom line or could exceed the bottom line following dairy conversion, and
- for the future land use, stock exclusion along streams is able to maintain the *E. coli* median concentration at the current value.

3.1 Overview of CLUES modelling

CLUES is a modelling system for assessing the effects of land use change and mitigation practices on water quality (TN, TP, sediment and *E. coli*) and socio-economic factors for catchments (~10 km² and above). The basic spatial unit within CLUES is the River Environments Classification (REC) (Snelder et al. 2010) river reach and surrounding subcatchment.

CLUES couples a number of existing models within a GIS-platform (Figure 3-1). Of most importance to this application of CLUES is the SPARROW component which 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). Further details on the CLUES modelling framework can be found in Semadeni-Davies et al. (2011a) and Woods et al. (2006a).

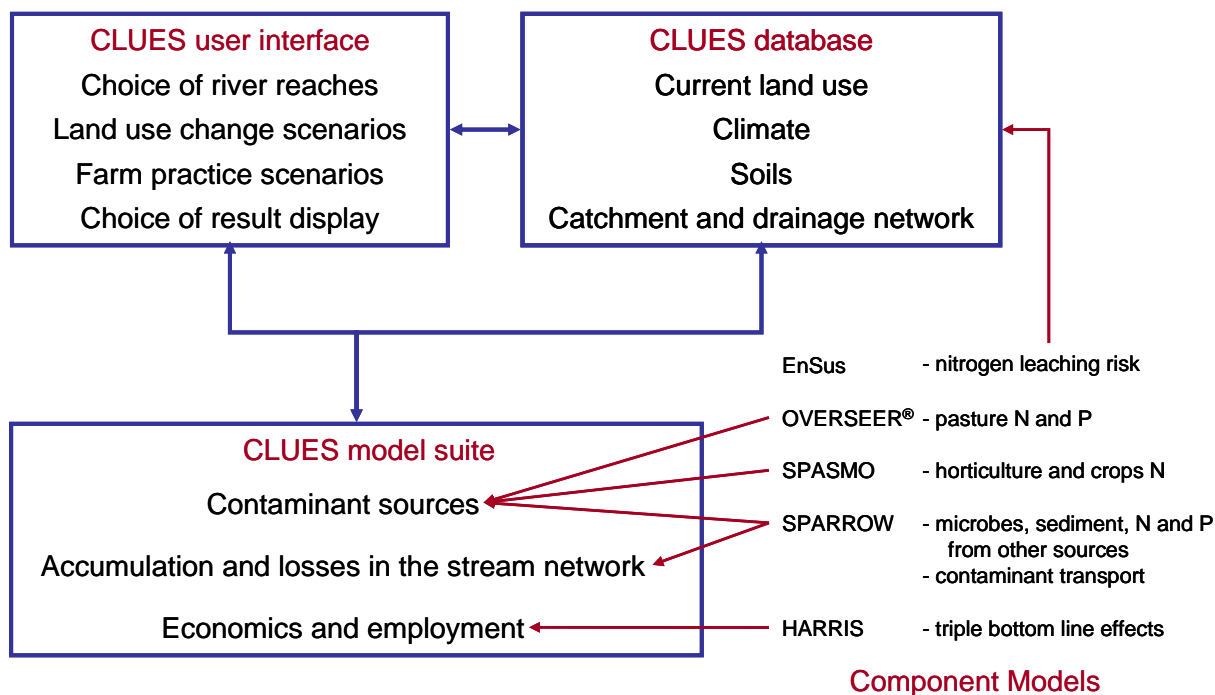


Figure 3-1: CLUES model framework. Source: Semadeni-Davies et al. 2011.

CLUES has been applied in a number of regional and national studies into the effects of land use change and mitigation, including stock exclusion, on water quality including a recent regional application for the WRC (Longhurst, 2012; Semadeni-Davies and Elliott, 2012). Like that study, CLUES is used in this application to adjust observed median *E. coli* concentrations at monitoring sites according to the predicted percentage change in load from current conditions.

3.1.1 Observed *E. coli* concentrations

Five-year (July 2007–June 2012) median *E. coli* concentrations were calculated from monthly water quality data recorded at the water quality monitoring sites in the study area. The data were provided by Waikato Regional Council, and use membrane filtration methods. These sites and their median *E. coli* concentrations are mapped in Figure 3-2 and listed in Table 3-1. Four sites - Torepatutahi, Waiotapu at Homestead, Whirinaki and Mangakino - were excluded from the analysis as there were too few samples (<20) to calculate a reliable median value.

Only the Mangawhero monitoring site, which is located at the outlet of a tributary subcatchment to the main stem, has a median concentration greater than the proposed NOF bottom line for secondary recreational contact of 1000 CFU/100 ml. The Mangawhero subcatchment is dominated by dairy farming and has an area of around 5300 ha, and it also has poorly-drained peaty soils. The main stem sites have lower median concentrations than the tributary sites due to dilution from the Lake Taupo outlet and decay, and are all well below the bottom line concentration.

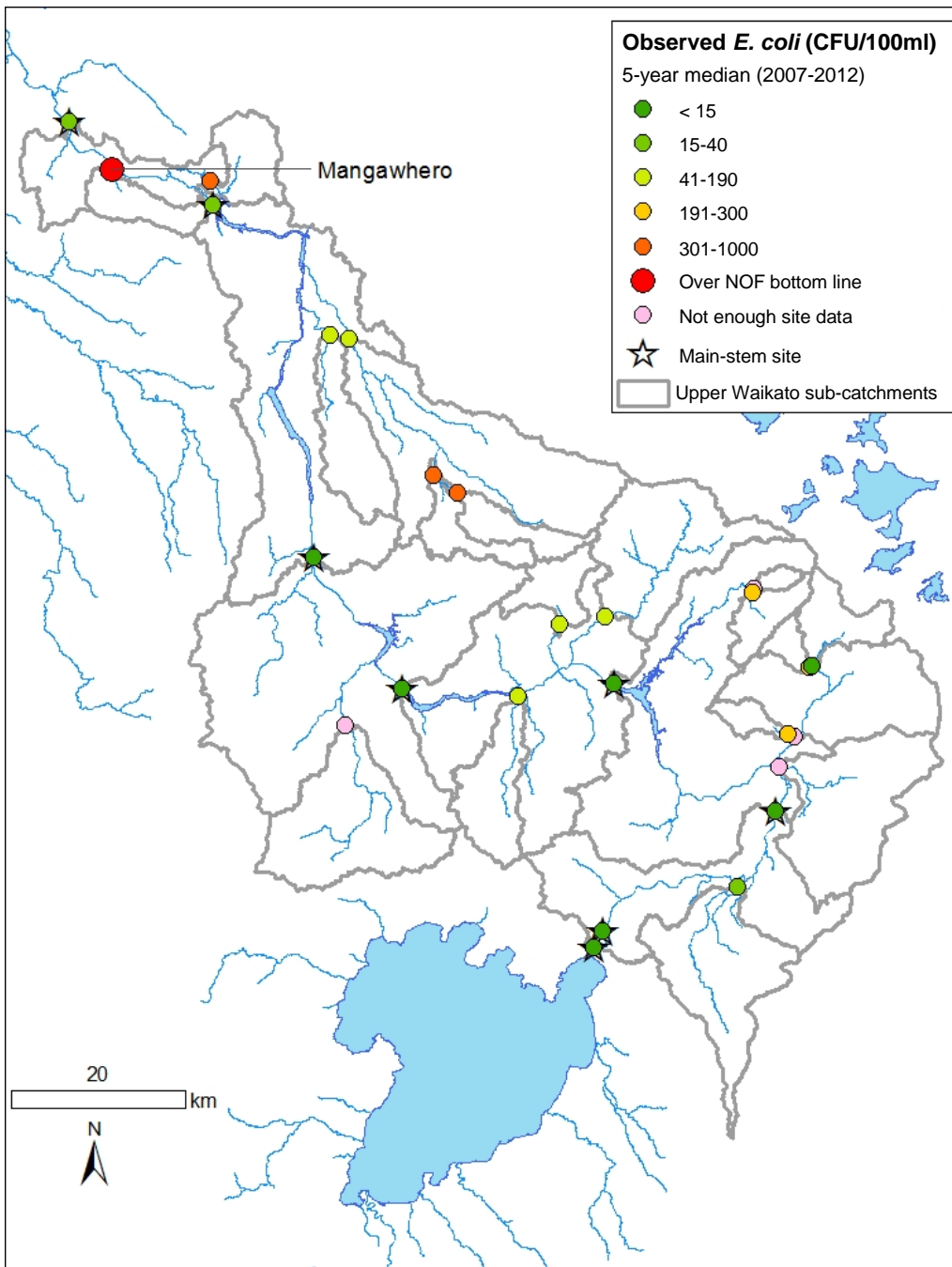


Figure 3-2: Five-year median *E. coli* concentrations (2007-2012) calculated from monthly water quality samples taken from monitoring sites in the study area. The display intervals up to the proposed NOF bottom line have been set automatically according to the Jenks Natural distribution.

Table 3-1: Five-year median *E. coli* concentrations (2007-2012) calculated from monthly water quality samples taken from monitoring sites in the study area. Main stem sites have the prefix Waikato and are shaded.

Monitoring site	Median <i>E. coli</i> concentration (CFU/100 ml)	Number of samples
Waikato at Taupo Gates	2	68
Waikato at Reid's Farm	2	68
Pueto	27	62
Waikato at Ohaaki	13.5	182
Torepatutahi*	50	5
Waiotapu at Campbell	2	64
Kawaunui	300	64
Mangakara	220	64
Waiotapu at Homestead*	140	5
Whirinaki*	32	5
Otamakokore	260	63
Waikato at Ohakuri	3	181
Tahunaatara	150	64
Mangaharakeke	190	63
Waipapa River	120	63
Waikato at Whakamaru	7	178
Mangakino*	40	5
Waikato at Waipapa	9	181
Whakauru Stm	600	63
Mangamingi	700	64
Pokaiwhenua	170	64
Little Waipa	115	62
Waikato at Karapiro	26	103
Karapiro Stream	500	62
Mangawhero	1300	62
Waikato at Narrows	40	180

*excluded sites due to low sample numbers.

3.1.2 CLUES land use scenarios

CLUES represents land use within each REC unit as the percentage of the unit used for a specific land use class. For this study, the default CLUES land use was replaced by updated land use data as described in Section 1.1 for each unit provided as a text file by the MPI. Since the MPI land use classes are not the same as the CLUES classification, the data was reclassified for use in CLUES in consultation with MPI as shown in Table 3-2. The reclassified data were joined to the CLUES geospatial database using the in-built overlay tool to create a new current land use scenario.

Table 3-2: CLUES land use classes in relation to LCDB2 and MPI land use classes.

LCDB2 land use type	CLUES land use classes	CLUES class description	MPI supplied land use classes
Grassland	Dairy	Dairy farming	Dairy
	Sbinten	Low land intensive sheep and beef	Pastoral*
	Sbhill	Hill country sheep and beef	-
	Sbhigh	High country sheep and beef	-
	Deer	Deer	Stock - deer
	Other_ANIM	Other types of farm animals	Stock – Horses Stock – Pigs Stock – Poultry Stock – Other
	Tussock	Tussock	-
	Ungr_past	Ungrazed pasture	Lifestyle blocks
Cropland	Maize	Arable crops (based on maize)	Arable
	Onions	Onions and flowers	Horticulture – Flowers Horticulture – Glasshouse
	Potatoes	Potatoes and market gardens	Horticulture Market gardens
	Kiwifruit	Kiwifruit	Horticulture - Kiwifruit
	Apples	Pip fruit, stone fruit, berries and tropical fruit	Horticulture – Pip fruit Horticulture – Berry
	Grapes	viticulture, vineyards	Horticulture - Vines
Forest	Plant_for	planted exotic forest, forestry	Planted Forest
	Nat_for	native forest	Natural Forest
Scrubland	Scrub	scrubland	-
Artificial surfaces	Urban	Built up areas, there are no urban sub-classes	Urban
Other land use types:	Other	other land covers (e.g., ice, water, bare soil etc.)	-

Note that CLUES has the same input parameters for calculating *E. coli* for the three classes of sheep and beef farming, for this reason, the MPI equivalent, Pastoral land use, was classified as intensive sheep and beef farming.

The future land use scenario is shown in Table 1-1. For CLUES modelling, the percentage reduction in area of exotic forest within a monitoring site subcatchment was applied to all

REC units within the subcatchment. This reduction in forestry was then added to the area used for dairy farming to create a new land use scenario. At this preliminary stage, no attempt was made to simulate dairy conversion in specific locations within a subcatchment according to suitability for dairy farming (e.g., with respect to Land Use Capability).

While not all of the subcatchments are included in the future land use scenario, those up-stream of a subcatchment with dairy conversion will none-the-less be subject to a change in water quality due to the change in the cumulative load of *E. coli* from up-stream. Torepatutahi and Pokaiwhenua have the greatest area of forest conversion to dairy (5000ha each with 45% and 35% of exotic forest to be converted respectively). These subcatchments, along with Pueto, also have the highest proportion of conversion to dairy with respect to their total catchment area (23% for Torepatutahi and 15% each for Pueto and Pokaiwhenua). In contrast, Waikato at Waipapa, which has the largest catchment area and area of exotic forest, is estimated to have only 4% of the catchment area converted to dairying.

3.1.3 Stock exclusion scenarios

Mitigation is simulated in CLUES as a percentage reduction in the yields for each land use within each REC unit. Since CLUES operates at the REC unit, it is not possible to apply mitigation to a specific location within the REC unit. Instead, it is assumed that land uses are evenly distributed spatially across each REC unit. It is also assumed that the reaches which meet the criteria for fencing outlined below have the same level of implementation across the entire study catchment. In reality, some areas within a unit may have higher levels of fencing than others. The pros and cons of applying mitigation factors according to these assumptions have been discussed in detail by Semadeni-Davies and Elliott (2012).

Four levels of stock exclusion were modelled using two different mitigation factors:

- Implementation of stock exclusion
 - No fencing for stock exclusion.
 - Baseline. The stock exclusion mitigation factors below were applied to REC units with a stream order of two or greater but were reduced by 55% to simulate the estimated current level of implementation in the study area which will already be having an impact on water quality. The scenario is in accordance with a survey conducted in 2007 by WRC⁴ which found that around 45% of farms in the upper Waikato River catchment had fencing or planting for stock exclusion on both sides of streams meeting Dairy Accord (Ministry for the Environment, 2003) specifications for exclusion. While dairy farms in the area had a slightly greater implementation of stock exclusion than sheep or beef farms, for the purposes of this study, it was assumed that both stock types had the same level of implementation.
 - Dairy Accord. Stock exclusion of all stock along both banks of non-headwater streams ($\geq 2^{\text{nd}}$ order streams), for both dairy and non-dairy pasture. This scenario applies the mitigation factors below with no

⁴ <http://www.waikatoregion.govt.nz/Environment/Environmental-information/Environmental-indicators/Land-and-soil/Land/Stock-access-to-waterways-data/>

adjustment and is intended to simulate the impact of implementation of the Dairy Accord (Ministry for the Environment, 2003) recommendations for stock exclusion, that is, fencing or riparian planting to exclude stock from streams *deeper than a red-band gumboot, wider than a stride and permanently flowing*.

- Best case – full stock exclusion along both banks of all streams, including headwater streams.
- Mitigation factors – two stock yield mitigation factors were simulated to give conservative and upper end estimates of reductions to *E. coli* median concentrations due to stock exclusion as follows:
 - Low – 20% mitigation of *E. coli* stock yields, this value is the same as that used for CLUES modelling in the Waikato region by Longhurst (2012) and Semadeni-Davies and Elliott (2012) is supported by modelling undertaken by Muirhead et al. (2011).
 - High – 50% mitigation of *E. coli* stock yields, this upper bound was chosen in recognition that stock exclusion can reduce *E. coli* loads by between 30 and 65% (Quinn, 2012) at the farm scale.

These mitigation factors represent the upper and lower bounds in the expected level of *E. coli* removal; the actual removal that can be expected with stock exclusion are likely to lie within these bounds.

In all, 14 model runs were made, and these are listed in Table 3-3. The baseline scenarios (Scenarios 2a and 2b) which represent the current situation are shaded. Note that the mitigation scenarios were also applied to reaches upstream of Waikato at Taupo Gates. This was done because the WRC survey cited above found that farms in the Lake Taupo area had similar levels of stock exclusion as the upper Waikato River catchment. Hence, it is reasonable to assume that the Lake Taupo reaches will have similar levels of exclusion as the upper catchment in the future. Given the very low *E. coli* median concentrations calculated at Waikato at Taupo Gates (2 CFU/100 ml), the effect of applying the mitigations to the catchment area upstream of the study area is likely to be negligible.

The simulated loads were used to determine concentrations for each of the monitoring site locations. For each baseline scenario (i.e., 2a and 2b), the concentration was set to the observed median concentration. For the other scenarios, the concentration was determined from multiplying the observed concentration by a change coefficient. The change coefficient is the percentage increase in loads compared with the load for the baseline scenario (Scenario 2a or 2b, depending on the assumed mitigation factor).

Table 3-3: List of scenarios simulated using the CLUES model to obtain estimates of changes in *E. coli* annual loads.

Scenario number	Stock Exclusion	Land use	Mitigation factor (%)
1	No fencing	Current	none

2a	Baseline (45% non-headwater streams fenced)	Current	20
2b	Baseline (45% non-headwater streams fenced)	Current	50
3a	Dairy Accord (non-headwater streams fenced)	Current	20
3b	Dairy Accord (non-headwater streams fenced)	Current	50
4a	Best case (all streams fenced)	Current	20
4b	Best case (all streams fenced)	Current	50
5	No fencing	25 kha dairy conversion	none
6a	Baseline (45% non-headwater streams fenced)	25 kha dairy conversion	20
6b	Baseline (45% non-headwater streams fenced)	25 kha dairy conversion	50
7a	Dairy Accord (non-headwater streams fenced)	25 kha dairy conversion	20
7b	Dairy Accord (non-headwater streams fenced)	25 kha dairy conversion	50
8a	Best case (all streams fenced)	25 kha dairy conversion	20
8b	Best case (all streams fenced)	25 kha dairy conversion	50

3.1.4 Length of stock exclusion

The length of stock exclusion along river reaches eligible for fencing for each of the scenarios was determined in order to supply data to AgFirst to allow calculation of the costs associated with fencing as documented in Journeaux (2013). The lengths are repeated here (Table 3-4 and Table 3-5) but are not required by CLUES. The method used to determine lengths is as follows:

1. Use GIS inbuilt tools to calculate the length for each REC river reach. Export this data along with a breakdown of current land use for each REC unit to Excel.
2. In Excel, determine the percentage land area for each REC unit used for dairy and sheep and beef farming.
3. Apply the percentages calculated in Step 2 to the REC reach stream length to give an estimate of the stream length for that reach passing through pastoral land, which is therefore eligible for fencing.
4. Use Excel pivot tables to aggregate the stream lengths eligible for fencing by subcatchment and then for the entire upper Waikato River catchment area. Four pivot tables were created relating to the different fencing and land use scenario.

Table 3-4: Stream lengths (m) eligible for fencing by subcatchment - Current land use. Note that the length refers to the river reach and should be doubled to obtain the length of fencing required to exclude stock on both sides of the stream bank.

Subcatchment	Stream length (m)		Length of streams running through pasture to be fenced (m)					
			Current level of fencing		Dairy Accord		All streams to be fenced	
	Total	Order 2-7	Dairy	Sheep / Beef	Dairy	Sheep / Beef	Dairy	Sheep / Beef
Pueto	344436	155066	371	7775	825	17278	1622	50834
Waikato at Ohaaki	526590	241446	16791	46284	37313	102853	77108	213443
Torepatutahi	402889	203015	40788	4694	90641	10431	170487	22101
Waiotapu at Campbell	125730	53660	3420	8512	7600	18915	14002	44207
Kawaunui	58341	23906	8029	1356	17843	3014	34819	10340
Mangakara	72045	29503	5430	5873	12067	13051	22504	38356
Waiotapu at Homestead	362803	182362	39234	2518	87188	5595	147452	16505
Whirinaki	40150	6597	692	2251	1537	5002	6640	31893
Otamakokore	101339	39005	12037	4692	26749	10427	55297	29619
Waikato at Ohakuri	991019	445305	77954	80968	173231	179929	355481	414958
Tahunaatara	402041	174367	29317	24021	65149	53381	130633	109319
Mangaharakeke	127549	53014	2558	1646	5684	3657	19578	9221
Waipapa Stream	196837	85735	14861	12530	33025	27843	87561	69759
Waikato at Whakamaru	860228	360458	42500	23373	94445	51939	209662	139964
Mangakino	377257	163797	22659	25032	50354	55627	110315	124432
Waikato at Waipapa	1190158	551795	43655	31793	97011	70652	208067	183201
Whakauru Stm	138303	62277	9645	6900	21434	15334	48311	33449
Mangamingi	121407	48885	12728	1194	28285	2654	70755	6682
Pokaiwhenua	608047	307142	57697	11153	128215	24784	258253	44419
Little Waipa	227074	103728	40383	2584	89739	5743	180907	25343
Waikato at Karapiro	964536	453858	113350	36410	251889	80910	509627	209974
Karapiro Stream	130105	57882	10570	10537	23490	23416	51662	61411
Mangawhero	100399	48395	14665	1032	32589	2293	65178	13990
Waikato at Narrows	205208	114553	30557	3147	67905	6993	122714	18412
Total	8674493	3965751	649893	356274	1444207	791721	2958638	1921834

Table 3-5: Stream lengths (m) eligible for fencing by subcatchment - future land use. Note that the length refers to the river reach and should be doubled to obtain the length of fencing required to exclude stock on both sides of the stream bank.

Subcatchment	Stream length (m)		Stream lengths running through pasture to be fenced (m)					
			Current level of fencing		Dairy Accord		All streams to be fenced	
	Total	Order 2-7	Dairy	Sheep / Beef	Dairy	Sheep / Beef	Dairy	Sheep / Beef
Pueto	344436	155066	11668	7775	25928	17278	54684	50834
Waikato at Ohaaki	526590	241446	28419	46284	63153	102853	131436	213443
Torepatutahi	402889	203015	60065	4694	133479	10431	261035	22101
Waiootapu at Campbell	125730	53660	3420	8512	7600	18915	14002	44207
Kawaunui	58341	23906	8085	1356	17968	3014	35026	10340
Mangakara	72045	29503	5530	5873	12289	13051	22842	38356
Waiootapu at Homestead	362803	182362	47216	2518	104925	5595	180740	16505
Whirinaki	40150	6597	692	2251	1537	5002	6640	31893
Otamakokore	101339	39005	12037	4692	26749	10427	55305	29619
Waikato at Ohakuri	991019	445305	77954	80968	173231	179929	355484	414958
Tahunaatara	402041	174367	34995	24021	77766	53381	166306	109319
Mangaharakeke	127549	53014	2601	1646	5779	3657	22691	9221
Waipapa Stream	196837	85735	15354	12530	34120	27843	89521	69759
Waikato at Whakamaru	860228	360458	50410	23373	112023	51939	254993	139964
Mangakino	377257	163797	22659	25032	50354	55627	110371	124432
Waikato at Waipapa	1190158	551795	51323	31793	114051	70652	247720	183201
Whakauru Stm	138303	62277	11229	6900	24954	15334	53973	33449
Mangamingi	121407	48885	12957	1194	28794	2654	72939	6682
Pokaiwhenua	608047	307142	78607	11153	174682	24784	348233	44419
Little Waipa	227074	103728	40453	2584	89896	5743	182039	25343
Waikato at Karapiro	964536	453858	113350	36410	251889	80910	509627	209974
Karapiro Stream	130105	57882	10570	10537	23490	23416	51662	61411
Mangawhero	100399	48395	14665	1032	32589	2293	65178	13990
Waikato at Narrows	205208	114553	30557	3147	67905	6993	122714	18412
Total	8674493	3965751	744818	356274	1655152	791721	3415161	1921834

3.2 Results with discussion

Figure 3-3 shows the predicted concentrations for the monitoring sites using both the low and high mitigation factors. Separate plots are provided for: (a) all the monitoring sites; (b) tributaries; and (c) main stem sites. The change coefficients and the adjusted concentrations for both the mitigation factors are given in Appendix A. Note that although the Torepatutahi, Waitapu at Homestead Whirinaki and Mangakino subcatchments are included in the simulation, the results for their respective monitoring sites are not reported as these sites had too few samples collected to calculate median *E. coli* concentrations.

3.2.1 Overall patterns and comparison with NOF bottom line

What is immediately apparent from the plots is that, like the observed median concentrations presented in Section 3.1.1, the highest median *E. coli* concentrations for all the scenarios are found in the tributary catchments. The median concentrations simulated for the main stem monitoring sites are all much less than the NOF bottom line, for all scenarios. The main stem sites with the lowest calculated median concentrations and the least degree of change are Waikato at Taupo Gates and Waikato at Reid's Farm. These sites represent the inflow water quality to the upper Waikato River catchment and have very low observed *E. coli* concentrations due to attenuation and dilution of pasture inputs into Lake Taupo. The reason for the low median *E. coli* concentrations calculated for the other main stem sites is decay and dilution of *E. coli* in the lakes and main channel. It is also worth pointing out that livestock are more likely to enter and spend time in smaller headwater streams which means that there are fewer direct sources of *E. coli* in the main stem compared to the tributary subcatchments.

The plots also show that the only site which has a median concentration greater than the NOF bottom line in any of the scenarios is Mangawhero. We speculate that site probably has high concentrations due to the large proportion of dairying, the poorly-drained peat soils, and turbidity. Previous regression modelling in the Waikato (Collins, 2003) showed that these factors were important drivers of *E. coli* concentrations. That is, high turbidity reduces the penetration of sunlight reaching the riverbed and lower parts of the water column resulting in lowered sunlight-induced die-off of faecal bacteria. Mangawhero subcatchment is not affected by the future land use scenario as it has no simulated dairy conversion and no upstream tributaries. Hence, the results generated for Scenarios 1-4 are the same as those generated for Scenarios 5-8 respectively. The potential impact of additional stock exclusion for this site is discussed in later sections.

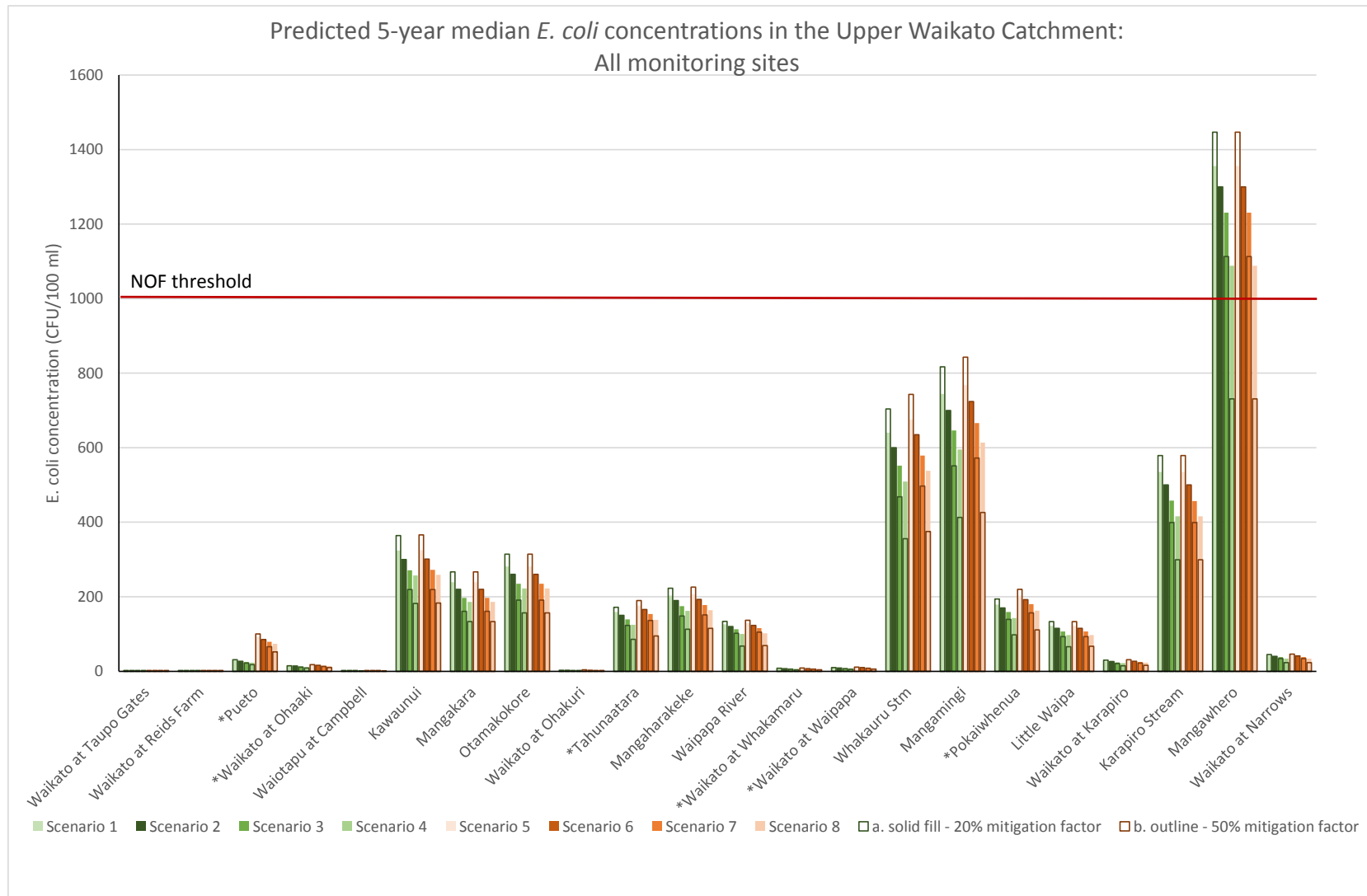


Figure 3-3: Predicted 5-year median *E. coli* concentrations (CFU/100 ml). a. all monitoring stations; b. tributary subcatchment monitoring sites; c. main stem subcatchment monitoring sites. The current land use scenarios are shown in green and future land use scenarios in orange. * refers to subcatchments with dairy conversion from forestry.

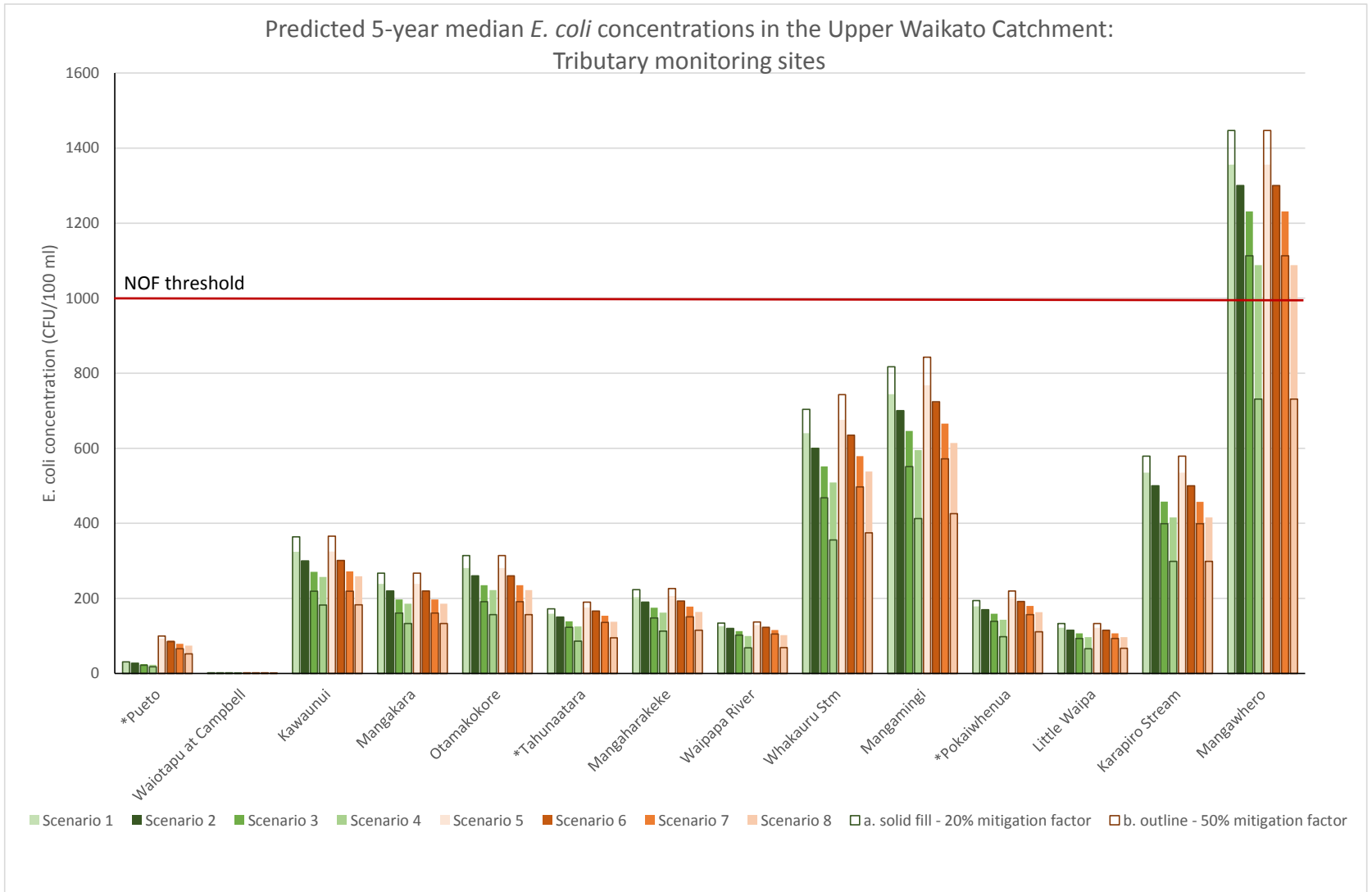
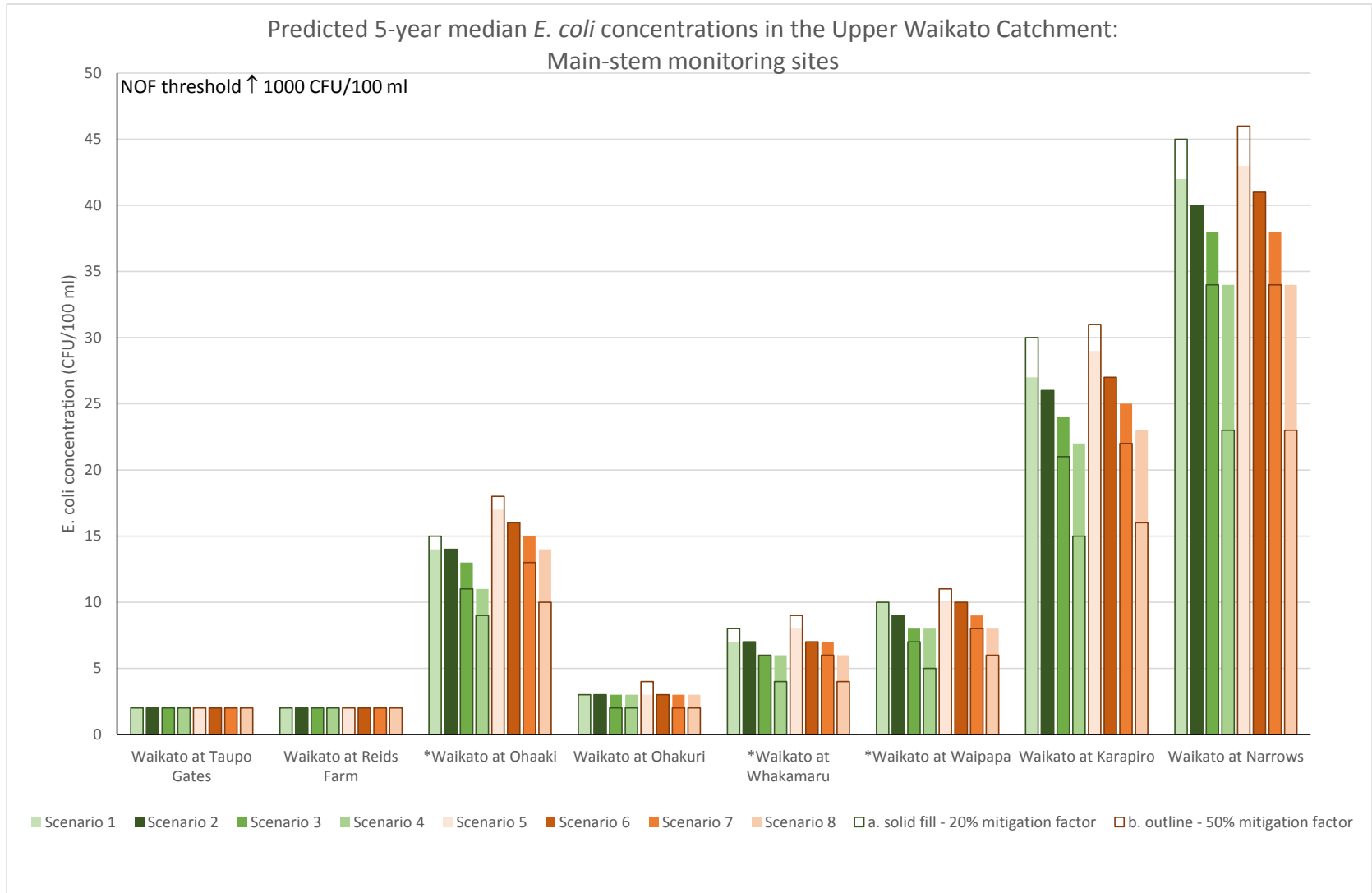


Figure 3-3 continued



C.

Figure 3-3 continued.

3.2.2 Effect of fencing with current land use

From the plots above, it can be seen that the current level of fencing with current land use is likely to be already having an impact on water quality compared to the concentration simulated with no mitigation (Scenario 1). With no fencing, the concentrations are 3–21% greater than current concentrations, depending on the subcatchment and the assumed mitigation factor.

With the extension of fencing to meet the Dairy Accord ($\geq 2^{\text{nd}}$ order streams fenced, for all pasture) and no land use change, the current median *E. coli* concentration could be reduced from current levels by between 3% and 10% assuming the low mitigation factor (Scenario 3a), or between 7% and 27% assuming the high mitigation factor (Scenario 3b). The sites with the greatest potential for reducing median *E. coli* concentrations by implementing Dairy Accord fencing are Kawaunui, Mangakara and Otamakokore. The reduction at Mangawhero is 5% assuming the low mitigation factor and 14% assuming the high mitigation factor. This reduction is not enough to reduce the median *E. coli* concentration below the NOF value.

With full fencing along all streams and no land use change, the adjusted median *E. coli* concentrations are reduced by up to 20% compared with current levels for the low mitigation factor (Scenario 4a) and by up to 45% with the high mitigation factor (Scenario 4b). For the Mangawhero site, full fencing reduces the concentration to below the NOF level for high mitigation factor (44% reduction, to 788 CFU/100 ml), but not for the low mitigation factor (to 1088 CFU/100 ml).

3.2.3 Effect of land use change with current fencing

For the 16 subcatchments with no forest conversion in the local subcatchment, there was nil or minimal increase from the land use change scenarios (Scenarios 5–8 compared with 1–4). Any increase is due to the effect of increased *E. coli* loads from the upstream subcatchments that are subject to conversion. Waikato at Ohakuri, for instance, has four tributary subcatchments with forestry conversion upstream. This subcatchment has an estimated increase in median concentrations of around 3% between Scenarios 1–4 and Scenarios 5–8. At the most downstream site, Waikato at Narrows, the adjusted median *E. coli* concentrations estimated for Scenarios 5–8, are around 1% greater than those estimated for Scenarios 1–4.

For the subcatchments with conversion in the local subcatchment, the effect of conversion varies depending on the degree of conversion, the level of stock exclusion and the mitigation factor. With a continuation of the current level of fencing (Scenario 6a and 6b), the increase in the concentrations is up to 19% for both mitigation factors, apart from the Pueto catchment.

The Pueto site is a special case because it shows a strong effect of conversion. For future land use with baseline proportions of fencing, the simulated concentration is approximately three times the current concentration. The reason for the increase in concentrations is that the Pueto subcatchment is currently dominated by forestry with some native forest and a small proportion of sheep and beef farming. Less than one per cent of the subcatchment is currently used for dairy farming. The land use change scenario is for 18% of the forest area (3000 ha) to be converted to dairying. This increase in dairying amounts to a new source of *E. coli* which results in a large percentage increase in the estimated *E. coli* concentration.

Despite the simulated increase at this site, the *E. coli* median concentrations calculated for the Pueto site are still fairly low compared to other tributary sites in the upper Waikato River catchment.

While the Waikato at Ohaaki subcatchment has a simulated decrease in forestry of 37% (i.e., 3000 ha), and this site is downstream of Pueto, the effect of conversion is less dramatic because the outflow from Waikato dilutes the inputs and the base level of pasture is higher.

3.2.4 Combined effect land use change and increased fencing

Extending stock exclusion to meet Dairy Accord levels was not able to offset the effect of dairy conversion for four sites assuming the low mitigation factor. With the high mitigation factor (Scenario 7b), the Dairy Accord level of fencing is estimated to offset the impacts of land use change except for the Pueto site. Apart from this site, the net reduction in concentration for the high mitigation factor ranges between 2 and 27%. Note that it is assumed that additional fencing is done for all pasture areas, not just in the areas of actual conversion.

Fencing all streams can offset the effect of dairy conversion for all streams even with the low mitigation factor, except for Pueto and Waikato at Ohaaki (Scenario 8a). The Ohaaki site has only a slight concentration increase (1%) at the low mitigation value. Assuming the high mitigation factor (Scenario 8b), fencing all streams reduces the estimated median *E. coli* concentration at all sites, except Pueto. The average reduction is around 40%. At the Pueto site, there is a net increase of 173% for the low mitigation and 93% for high mitigation. Hence, at that site, further mitigation measures would be required to maintain or improve water quality in the face of land use conversion.

4 Conclusions

This report describes catchment models for predicting water quality in the upper Waikato River catchment, to support investigations into economic implications of the National Objectives Framework (NOF). This modelling entailed the following two main components:

1. Development of a simplified catchment model for total nitrogen (TN), total phosphorus (TP), and chlorophyll concentrations. The model takes source loadings from pasture, adds other sources, accounts for accumulation and decay between the source and in reservoirs, and predicts mean annual nutrient concentrations. The nutrient concentrations are used to predict chlorophyll levels from observed correlations between nutrients and chlorophyll going down the Waikato River.
2. Prediction of median concentrations of the microbial indicator *E. coli* for current land use and a future land use scenario (conversion of part of the exotic forest to dairying), and for various levels of stock exclusion (none, the current level, a 'Dairy Accord' level corresponding to fencing off second-order streams and larger, and fencing of all streams). The catchment model CLUES (Semadeni-Davies et al. 2011b) was used for this purpose. Stock exclusion was simulated by reducing the *E. coli* yields from stock by 20% and by 50% to approximate low and high mitigation rates.

The upper Waikato River catchment was subdivided into 24 subcatchments, based on the locations of water quality monitoring stations, and model results are given in relation to these subcatchments. Simulations were run for both current and future land use scenarios. Economic considerations of water quality in the upper Waikato River catchment are discussed in Doole (2013) with respect to nutrients and chlorophyll and Journeaux (2013) with respect to stock exclusion to reduce *E. coli* concentrations.

Key findings with respect to nutrients and chlorophyll are:

- The maximum TN attenuation value, which was determined by calibration to current measured loads, ranged from 0 to 74% loss with a median of 45%, while a minimum attenuation value of 20% and an intermediate value of 30% loss was used.
- The model predictions were sensitive to attenuation. In the most extreme case, concentrations in one catchment are predicted to increase by 147% as a result of delayed responses to past land-use change. At the Narrows (representative of Lake Karapiro) the concentration of TN increases by up to 38% leading to a consequent increase in chlorophyll of 47%. This has important implications for maintaining water quality at the current state. Given the uncertainty in the attenuation values, it is recommended that additional effort be invested in refining estimates of lags and attenuation in the catchment.
- Conversion from 25000 ha of forest to dairy was predicted to increase the TN and TP concentrations. The most pronounced percentage increase was in the Pueto catchment (39% increase in TN, 24% increase in TP). At the Narrows, the TN concentration increases by 5% and the TP concentration by 6%, with an associated increase in chlorophyll of up to 9%. Such increases would need to be offset by mitigation measures or land-use change elsewhere in the

catchment to maintain current concentrations, which is the focus of the economic model.

Key findings with respect to *E. coli*:

- Only one site, Mangawhero, has an observed median concentration which exceeds the proposed NOF bottom line concentration for secondary recreational contact of 1000 CFU/100ml. This is a dairy-dominated catchment with poorly-drained peat soils. All other sites have concentrations less than the NOF value, and the main stem sites have median concentrations which are two or three orders of magnitude less than the NOF value.
- Fencing according to the Dairy Accord levels ($\geq 2^{\text{nd}}$ order streams, including dairy and non-dairy areas) does not reduce the predicted concentration for the Mangawhero below the NOF value using either the upper or lower mitigation factor. Extending fencing to all streams in the Mangawhero subcatchment reduces the concentration to less than the NOF value if the higher mitigation factor is assumed but not for the lower mitigation value.
- Fencing according to the Dairy Accord levels reduces concentrations by between 3% and 27% across the upper Waikato River catchment depending on the mitigation factor and the degree of pasture upstream. Extending fencing to all streams reduces concentrations by between 5% and 44% across the upper Waikato River catchment depending on the mitigation factor and the degree of pasture upstream.
- Conversion of 25,000ha of exotic forest to dairy farming is not predicted to result in any sites, other than Mangawhero, exceeding the proposed NOF bottom line concentration.
- Assuming the current level of fencing, the percentage increase in concentration due to conversions from forest to dairy is estimated to be 0–19 % depending on the extent of upstream conversion (and to a small degree the assumed mitigation factor). The exception is Pueto, which could experience a trebling of *E. coli* concentrations following conversion, because that subcatchment has a small degree of pasture currently and a moderate amount of pasture would be introduced.
- Concentrations can increase at sites which do not have conversion in the local subcatchment, due to increases in loads arising from conversions from upstream subcatchments. The increases in such cases are relatively minor due to the effects of dilution and attenuation.
- Assuming the low mitigation factor, fencing to Dairy Accord levels was not sufficient to offset the effect of conversion from forest to dairy for four sites. If the upper mitigation factor is assumed, the Dairy Accord level of stock exclusion offsets the effects of land use change for all but one subcatchment (Pueto), and reduces concentrations in many cases.

- Extending fencing to all pasture streams offsets the effect of conversion for all but the Pueto site. The reduction is in the order of 10–15% assuming the low mitigation factor and 20–44% assuming the high mitigation factor.
- For the Pueto subcatchment, fencing will need to be complemented by other forms of mitigation to maintain or improve water quality with respect to *E. coli* following conversion of forest to pasture.

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Appendix A Change factors and adjusted median concentrations calculated for the Upper Waikato monitoring stations.

Table A-1: Median *E. coli* concentrations (CFU/100ml) and CLUES calculated change coefficients (%) from the base-line fencing and current land use scenario (Scenario 2a) with a removal factor of 20%. Subcatchments with land use change simulated are shaded.

Monitoring site	Scenario 1 No conversion No mitigation	Scenario 2a No conversion Baseline fencing	Scenario 3a No conversion Dairy Accord	Scenario 4a No conversion All streams fenced	Scenario 5 25 kha conversion No mitigation	Scenario 6a 25 kha conversion Baseline fencing	Scenario 7a 25 kha conversion Dairy Accord	Scenario 8a 25 kha conversion All streams fenced
Waikato at Taupo Gates	2 (3)	2 (0)	2 (-3)	2 (-5)	2 (3)	2 (0)	2 (-3)	2 (-5)
Waikato at Reids Farm	2 (3)	2 (0)	2 (-3)	2 (-6)	2 (3)	2 (1)	2 (-3)	2 (-6)
Pueto	29 (7)	27 (0)	25 (-9)	23 (-14)	93 (244)	87 (221)	79 (194)	74 (174)
Waikato at Ohaaki	14 (6)	14 (0)	13 (-7)	11 (-15)	17 (26)	16 (19)	15 (10)	14 (1)
Waiotapu at Campbell	2 (6)	2 (0)	2 (-8)	2 (-17)	2 (6)	2 (0)	2 (-8)	2 (-17)
Kawaunui	324 (8)	300 (0)	271 (-10)	257 (-14)	325 (8)	301 (0)	272 (-9)	259 (-14)
Mangakara	239 (9)	220 (0)	197 (-10)	186 (-15)	239 (9)	220 (0)	197 (-10)	186 (-15)
Otamakokore	281 (8)	260 (0)	235 (-10)	222 (-15)	281 (8)	260 (0)	235 (-10)	222 (-15)
Waikato at Ohakuri	3 (6)	3 (0)	3 (-8)	3 (-16)	3 (9)	3 (3)	3 (-5)	3 (-13)
Tahunaatara	159 (6)	150 (0)	139 (-7)	125 (-17)	176 (17)	166 (11)	154 (3)	138 (-8)
Mangaharakeke	203 (7)	190 (0)	175 (-8)	162 (-15)	203 (7)	190 (0)	175 (-8)	162 (-15)
Waipapa River	126 (5)	120 (0)	113 (-6)	100 (-17)	129 (7)	123 (3)	116 (-3)	102 (-15)
Waikato at Whakamaru	7	7	6	6	8	7	7	6

Monitoring site	Scenario 1 No conversion No mitigation	Scenario 2a No conversion Baseline fencing	Scenario 3a No conversion Dairy Accord	Scenario 4a No conversion All streams fenced	Scenario 5 25 kha conversion No mitigation	Scenario 6a 25 kha conversion Baseline fencing	Scenario 7a 25 kha conversion Dairy Accord	Scenario 8a 25 kha conversion All streams fenced
	(6)	(0)	(-7)	(-16)	(13)	(6)	(-2)	(-10)
Waikato at Waipapa	10 (6)	9 (0)	8 (-7)	8 (-16)	10 (13)	10 (7)	9 (-1)	8 (-11)
Whakauru Stm	640 (7)	600 (0)	552 (-8)	509 (-15)	640 (7)	600 (0)	552 (-8)	509 (-15)
Mangamingi	744 (6)	700 (0)	646 (-8)	595 (-15)	744 (6)	700 (0)	646 (-8)	595 (-15)
Pokaiwhenua	179 (5)	170 (0)	159 (-7)	143 (-16)	203 (20)	193 (13)	180 (6)	163 (-4)
Little Waipa	122 (6)	115 (0)	107 (-7)	97 (-16)	122 (6)	115 (0)	107 (-7)	97 (-16)
Waikato at Karapiro	27 (6)	26 (0)	24 (-7)	22 (-16)	29 (10)	27 (4)	25 (-3)	23 (-13)
Karapiro Stream	535 (7)	500 (0)	458 (-8)	416 (-17)	535 (7)	500 (0)	457 (-9)	416 (-17)
Mangawhero	1356 (4)	1300 (0)	1231 (-5)	1088 (-16)	1356 (4)	1300 (0)	1231 (-5)	1088 (-16)
Waikato at Narrows	42 (5)	40 (0)	38 (-6)	34 (-16)	43 (7)	41 (2)	38 (-5)	34 (-15)

Table A-2: Median *E. coli* concentrations (CFU/100ml) and CLUES calculated change coefficients (%) from the base-line fencing and current land use scenario (Scenario 2b) with a removal factor of 50%. Subcatchments with land use change simulated are shaded.

Monitoring site	Scenario 1 No conversion No mitigation	Scenario 2b No conversion Baseline fencing	Scenario 3b No conversion Dairy Accord	Scenario 4b No conversion All streams fenced	Scenario 5 25 kha conversion No mitigation	Scenario 6b 25 kha conversion Baseline fencing	Scenario 7b 25 kha conversion Dairy Accord	Scenario 8b 25 kha conversion All streams fenced
Waikato at Taupo Gates	2 (6)	2 (0)	2 (-7)	2 (-11)	2 (6)	2 (0)	2 (-7)	2 (-11)
Waikato at Reids Farm	2 (5)	2 (0)	2 (-7)	2 (-14)	2 (6)	2 (1)	2 (-7)	2 (-14)
Pueto	31 (16)	27 (0)	22 (-20)	18 (-33)	100 (271)	85 (214)	66 (143)	52 (93)
Waikato at Ohaaki	15 (13)	14 (0)	11 (-17)	9 (-36)	18 (35)	16 (19)	13 (-2)	10 (-25)
Waiotapu at Campbell	2 (15)	2 (0)	2 (-20)	1 (-41)	2 (15)	2 (0)	2 (-20)	1 (-41)
Kawaunui	364 (21)	300 (0)	219 (-27)	182 (-39)	366 (22)	301 (0)	219 (-27)	183 (-39)
Mangakara	267 (21)	220 (0)	161 (-27)	133 (-39)	267 (21)	220 (0)	161 (-27)	133 (-39)
Otamakokore	314 (21)	260 (0)	191 (-27)	157 (-39)	314 (21)	260 (0)	191 (-27)	157 (-39)
Waikato at Ohakuri	3 (16)	3 (0)	2 (-21)	2 (-41)	4 (19)	3 (3)	2 (-18)	2 (-40)
Tahunaatara	172 (14)	150 (0)	123 (-18)	86 (-42)	190 (26)	166 (11)	136 (-9)	95 (-37)
Mangaharakeke	223 (17)	190 (0)	148 (-22)	113 (-40)	223 (17)	190 (0)	148 (-22)	113 (-40)
Waipapa River	134 (12)	120 (0)	102 (-15)	68 (-44)	137 (14)	123 (3)	105 (-13)	69 (-42)
Waikato at Whakamaru	8 (16)	7 (0)	6 (-20)	4 (-41)	9 (23)	7 (6)	6 (-15)	4 (-38)

Monitoring site	Scenario 1 No conversion No mitigation	Scenario 2b No conversion Baseline fencing	Scenario 3b No conversion Dairy Accord	Scenario 4ab No conversion All streams fenced	Scenario 5 25 kha conversion No mitigation	Scenario 6b 25 kha conversion Baseline fencing	Scenario 7b 25 kha conversion Dairy Accord	Scenario 8b 25 kha conversion All streams fenced
Waikato at Waipapa	10 (15)	9 (0)	7 (-18)	5 (-42)	11 (22)	10 (7)	8 (-13)	6 (-38)
Whakauru Stm	704 (17)	600 (0)	468 (-22)	356 (-41)	704 (17)	600 (0)	468 (-22)	356 (-41)
Mangamingi	817 (17)	700 (0)	551 (-21)	413 (-41)	817 (17)	700 (0)	551 (-21)	413 (-41)
Pokaiwhenua	194 (14)	170 (0)	139 (-18)	98 (-42)	220 (30)	192 (13)	157 (-8)	111 (-35)
Little Waipa	133 (15)	115 (0)	93 (-19)	66 (-42)	133 (15)	115 (0)	93 (-19)	67 (-42)
Waikato at Karapiro	30 (14)	26 (0)	21 (-18)	15 (-42)	31 (19)	27 (4)	22 (-15)	16 (-39)
Karapiro Stream	579 (16)	500 (0)	399 (-20)	299 (-40)	579 (16)	500 (0)	399 (-20)	299 (-40)
Mangawhero	1447 (11)	1300 (0)	1113 (-14)	731 (-44)	1447 (11)	1300 (0)	1113 (-14)	731 (-44)
Waikato at Narrows	45 (13)	40 (0)	34 (-16)	23 (-42)	46 (15)	41 (2)	34 (-15)	23 (-41)