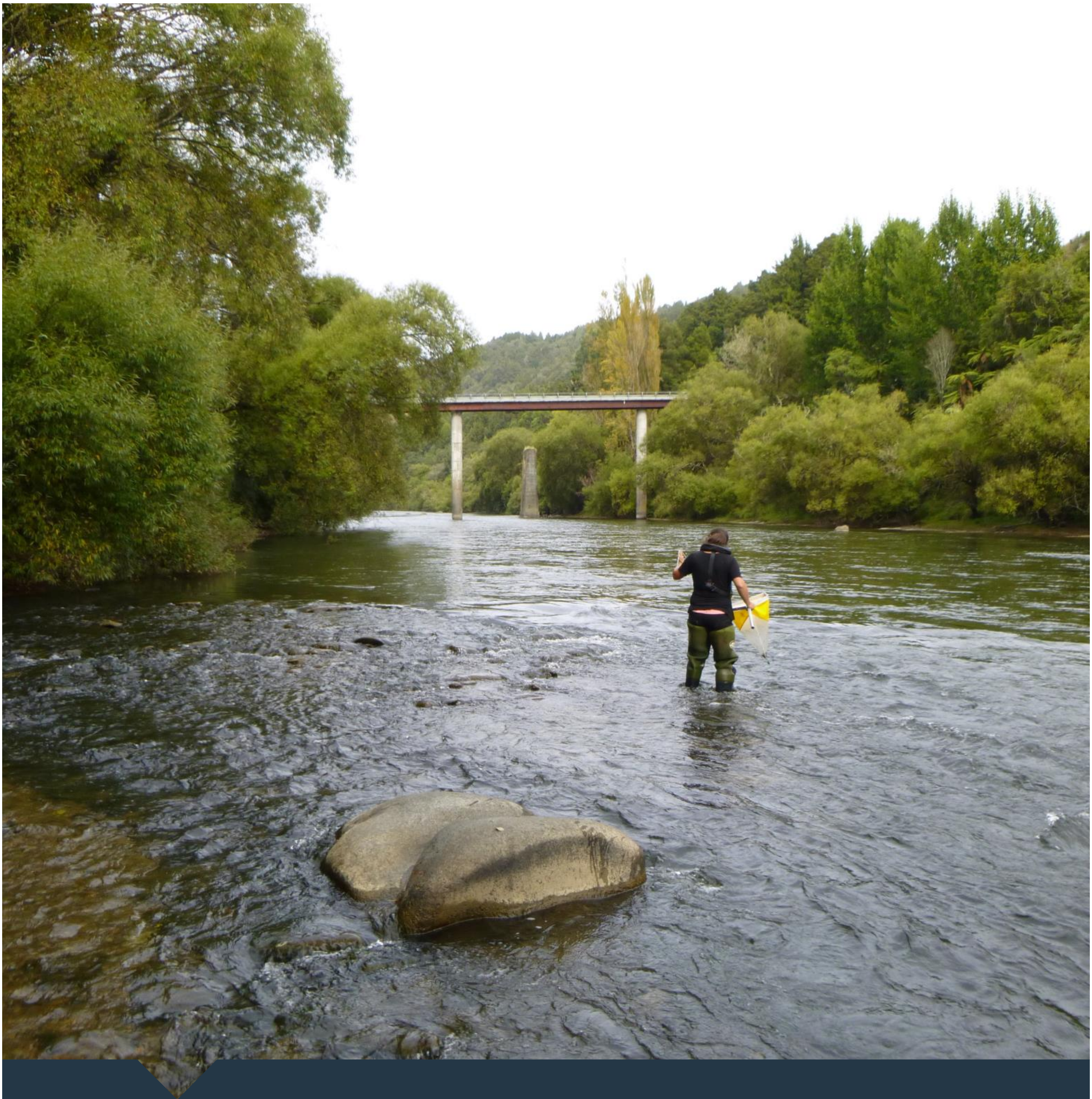

Calibration of the CLUES *E. coli* model for the Taranaki and Manawatū-Whanganui Regions

Stage 1 Technical Report

September 2023

horizons
REGIONAL COUNCIL

Prepared for:

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Acting Science Manager

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Prepared for Horizons and Taranaki Regional Councils

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Climate, Freshwater & Ocean Science

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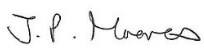	Approved for release by:	Jonathan Moores Regional Manager NIWA Auckland

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Executive summary

Taranaki Regional Council (TRC) and Horizons Regional Council (HRC) have engaged NIWA to undertake a joint calibration of the Catchment Land Use for Environmental Sustainability (CLUES) model for *E. coli* for the two regions (Taranaki and Manawatū-Whanganui). The recalibration is required to improve the model's fit (compared with the existing national model) in the two regions by:

- Increasing the number of monitoring sites in the regions used for calibration;
- Removing the possibility of bias in the calibrated parameters due to the influence of water quality data from other regions;
- Updating the water quality data used for calibration to be compatible with current land use and mitigation activities in the regions.

The calibration is Stage 1 in a three-stage project. The calibrated model will be used to model the effects of various mitigation activities on *E. coli* loads in the regions' rivers and streams in Stages 2 and 3; those stages will be undertaken and reported separately for each council using bespoke scenarios developed with each council respectively.

CLUES is a catchment-scale, steady-state, mass budget model that estimates mean annual loads of TN, TP and *E. coli* for each segment in the River Environments Classification (REC) stream network. CLUES has been set-up nationally and is intended as a screening tool to support policy development and catchment planning. This project uses only the *E. coli* model component of CLUES. For each REC subcatchment, CLUES estimates *E. coli* loads from diffuse sources (represented by land use) as the product of the source area within the subcatchment and a calibrated source yield. These loads are modified by calibrated delivery exponents that represent the effects of soil drainage, rainfall and annual temperature on *E. coli* loads before delivery to the stream network. The modified load for each subcatchment is added, along with any point sources present, to the instream load for the respective REC river segment. The instream load is routed downstream and is subject to both calibrated instream attenuation and losses in lakes and reservoirs.

The calibrated parameters within the CLUES *E. coli* model are: source yields for different land uses; rainfall, air temperature and drainage delivery exponents; and stream and reservoir decay coefficients. We used a least squares optimisation method for calibration, fitting to 'measured' mean annual yields estimated from measured concentrations and flows using a rating curve method. The method returns an optimised parameter set and the uncertainty for each parameter and collinearity (or correlation) between parameters. Calibration is an iterative process whereby the model fit, parameter uncertainty and collinearity determined for a calibration run are used to guide the parameter set-up for the next run. The aim is to progressively optimise the number of parameters while reducing parameter uncertainty and maintaining model fit. Loads with high uncertainty were not used in calibration. We were able to determine mean annual *E. coli* loads for 58 monitoring sites in total.

Calibration was carried out using yields rather than loads to normalise for upstream catchment area. Yields were determined for each site by dividing the site's measured load by the upstream catchment area of the site. The model fit was determined in log-space to counter the wide range of yields between sites and to make the distribution of model errors closer to a normal distribution. We did

not include existing mitigation activities within the calibration, instead it is assumed that the effect of these will be implicit in the calibration.

We carried out 11 calibration runs. The parameter set and uncertainty for the final calibration run is given in Table Ex1 and the calibration performance is summarised in Table Ex2. The model uncertainty reflects the unexplained variability of *E. coli* concentrations both between sites and over time.

Table Ex1 Calibrated parameters and their standard error. tempCoef = air temperature coefficient, rainCoef = rainfall coefficient, yDairy = *E. coli* yield from dairy, ySB= E.coli yield from sheep and beef, yOther = *E. coli* yield from other landuses.

Parameter	Value	Uncertainty (Standard Error)
tempCoef	0.50081	0.10390
rainCoef	1.02764	0.14800
yDairy (peta organisms/km^2/y)	0.00693	0.00249
ySB (peta organisms/km^2/y)	0.00852	0.00138
yOther (peta organisms/km^2/y)	0.00111	0.00059

Table Ex2 Calibration performance for the natural logs of loads and yields.

Performance metric	Load	Yield
Coefficient of determination, R^2	0.927	0.689
Nash-Sutcliffe Efficiency[1], NSE	0.924	0.689
Root Mean Square Error, RMSE	0.587	0.567

The model was able to account moderately well for variations in yield between sites (R^2/model efficiency of 0.689). The model residual error of 0.567 in log space indicates a standard deviation of a factor of 1.76 in estimated yield. The model parameters indicate higher yields for pasture compared with 'other' land uses with the exception of urban land use which was assigned a fixed yield (0.08 peta/km^2/year). There was minimal difference in yields between different pastoral land uses (dairy, sheep and beef, and other stock), but higher yields were associated with more rainfall and warmer air temperatures. Soil drainage class, slope, and stream and reservoir attenuation were not retained in the model because they did not influence model performance and were uncertain.

Overall, these results give confidence that the model provides a suitable foundation for examining freshwater responses to mitigation activities at regional scale in later stages of the broader project.

[1] Nash, J.E. and Sutcliffe, J.V. (1970) River flow forecasting through conceptual models part I — A discussion of principles. *Journal of Hydrology*, 10(3): 282–290.

1 Introduction

Taranaki Regional Council (TRC) and Horizons Regional Council (HRC) have engaged NIWA to estimate the effects of different mitigation activities on the mean annual load and concentration of *Escherichia coli (E. coli)* in rivers and streams in their respective regions. The outputs of the modelling will help the councils to manage their waterways for *E. coli* according to the Human Contact value of the National Objective Framework (NOF) as outlined in the National Policy Statement on Freshwater Management (New Zealand Government 2020).

The modelling was done using the *E. coli* component of the Catchment Land Use for Environmental Sustainability (CLUES; Elliott *et al.* 2016; Semadeni-Davies *et al.* 2019; Semadeni-Davies *et al.* 2020b) model. The CLUES *E. coli* component has been used for three national studies into the effects of stock exclusion and riparian planting in recent years (Semadeni-Davies and Elliott 2017; Semadeni-Davies *et al.* 2018; Semadeni-Davies *et al.* 2020a). The version of the model used for that work had the baseline year 2008 and was calibrated against *E. coli* loads estimated using monitored water quality data collected from 128 sites nationally. The calibration dataset included loads estimated for only 11 water quality monitoring sites located in either Taranaki or Manawatū-Whanganui.

As part of the project scoping for the two regional councils, we found that there were similarities between their modelling needs. It was decided with the councils to split the modelling into three stages. Stage 1, which is documented in this report, is a joint (for the combined regions) re-calibration of the model. Load reduction requirements to meet concentration targets, future state scenario modelling (including summaries of current and future attribute states against NOF criteria for *E. coli*) and cost-effectiveness analysis will be undertaken and reported separately for each council in Stages 2 and 3.

Given the similar environments of the two regions, it was decided that a joint calibration would increase the reliability of the calibration by increasing the amount of water quality data available for calibration and reduce the costs for each council. The model was recalibrated to:

- Increase the number of monitoring sites in the regions used for calibration;
- Remove the possibility of bias in the calibrated parameters due to the influence of water quality data from other regions nationally;
- Update the water quality data used for calibration to be compatible with current land use and mitigation activities in the regions.

1.1 Report contents

This report includes the following sections:

- Section 2 describes the CLUES *E. coli* model and presents the input data used to drive the model and the development of a baseline (2018) scenario to estimate current-state *E. coli* mean annual loads.
- Section 3 describes the calibration process including the method used to calculate loads from monitored flow and water quality data, and description of the calibration method.
- Section 4 presents the outputs of the calibration, with discussion.

- Section 5 gives conclusions on the joint calibration.

There are four Appendices provided with the report that identify the major point sources of *E. coli* (Appendix A), monitoring site locations and metadata (Appendices B and C) and a comparison of the loads and yields determined from monitored data and modelled by CLUES (Appendix D).

2 CLUES *E. coli* model

2.1 Model description

CLUES is a catchment-scale, steady-state mass-budget type of model that estimates mean annual loads of TN, TP and *E. coli* for each segment in the River Environment Classification stream network (Snelder and Biggs 2002; Snelder *et al.* 2010). CLUES has been set-up nationally and is intended as a screening tool to support policy development and catchment planning. The spatial and temporal scales were chosen to allow rapid model setup and scenario creation. The low data requirements and resolution means that CLUES follows an empirical modelling approach. The model description below is summarised from Appendix 1 of Elliott *et al.* (2016).

The CLUES *E. coli* model is based on the United States Geological Survey SPARROW model (SPAtially-Referenced Regression On Watershed attributes; Smith *et al.* 1997; Schwarz *et al.* 2006a; Schwarz *et al.* 2006b). *E. coli* loads from diffuse sources (i.e., land use; see Section 2.2.1) are calculated for each REC subcatchment as the product of the source area and associated source yield. These loads are modified by a delivery exponent that is an exponential function of soil drainage class, the mean annual rainfall and the mean annual temperature. Increased rainfall is expected to increase *E. coli* losses, due to increased percolation and surface runoff of faecal matter. Infiltration of *E. coli* varies with soil properties (McLeod *et al.* 2008), with greater bypass flow in clay soils and greater filtering in well-drained soils. Poor drainage is also expected to lead to greater surface runoff of faecal matter. Temperature may also affect microbial survival and persistence (e.g., Blaustein *et al.* 2013). For each land use within a subcatchment, the *E. coli* load, expressed as the number of organisms (10^{15} or peta organisms) per year, that are delivered to the stream segment is calculated as:

$$S_i = A_i c_i \exp\left(a_R(R - b_R) + a_D(D - b_D) + a_T(T - b_T)\right) \quad (1)$$

where S_i is the source load (peta organisms/y) generated by land use i, A_i is the area of land use i (km^2), c_i is the source coefficient or yield associated with the source, R is the mean annual rainfall (m/y), D is the Fundamental Soil Layer drainage class[2] (dimensionless indicator ranging between 1-5, increasing from poorly drained to well drained), and T is the mean annual air temperature (°C) within the subcatchment. The mean annual rainfall and temperature for each subcatchment have been derived from NIWA Virtual Climate Station Network (VCSN) climate normals. The coefficients b_R, b_D, and b_T are the mean values across all subcatchments modelled of R, D and T respectively. For the two regions, mean values are 1.52 m for rainfall, 11.7°C for temperature and 4.38 for drainage class. The exponent coefficients a_R, a_D, and a_T are calibrated delivery factors for rain, soil drainage, and temperature respectively.

Mean annual loads from point sources (see Section 2.2.2) located within each subcatchment are added to the total generated load from the subcatchment diffuse sources to give the total load delivered to each stream segment. Once delivered to the stream network, the loads are routed

[2] https://lris.scinfo.org.nz/layer/48104-fsl-soil-drainage-class/

downstream. The instream load within a stream segment is calculated as the load from upstream plus the total load delivered to the segment from the segment subcatchment less instream attenuation.

Instream attenuation or decay in streams is modelled as a first-order function of stream length, with the decay coefficient varying as a power function of flow (Elliott *et al.* 2005), so the fraction of load transmitted through a reach, F, is:

$$F = exp\left(-k_{stream} Q^{k_{flow}} L\right) \tag{2}$$

where L is the length of the stream segment (km) and Q is the estimated mean annual stream discharge in (m^3/s) and k_{stream} and k_{flow} are calibrated coefficients.

E. coli loss within lakes (and reservoirs) is determined with an effective settling velocity (Elliott *et al.* 2005), such that the load remaining in discharges from the lake, H, is:

$$H = \frac{Res_{Load}}{Res_{Load} + k_{res}} \tag{3}$$

where Res_{Load} is a function of the estimated inflow and outflow of the lake and k_{res} is a calibrated coefficient representing trapping efficiency within the lake.

2.2 Input data

2.2.1 Diffuse sources / land use

Diffuse sources are represented in CLUES by the proportion of each sub-catchment covered by each of 19 land use classes. The land use data used by CLUES are based on the LCDB5 land cover database[3] and the Agribase dataset for the reference year 2017 under licence from AsureQuality[4] to be compatible with LCDB5. Agribase was used to split grass and cropland land covers from LCDB5 into enterprise types (i.e., stock, crop, and horticulture land uses). The CLUES land use layer was also modified in some locations using other public data sources including elevation, conservation areas (from Department of Conservation), and road centre-lines.

The CLUES land use classes were grouped into seven functional groups that have the same yield parameters for the initial iteration of *E. coli* calibration. The functional groups are listed in Table 2-1 and were made based on our experience with previous *E. coli* modelling.

2.2.2 Point sources

There are two sets of point source data used in the model. The first contains major point sources, such as wastewater treatment plants, discharging to the stream network. The second set consists of estimates of farm dairy effluent (FDE) discharged to waterways in Taranaki by on-farm effluent ponds. Note that FDE is disposed on land in Manawatū-Whanganui and is not included as a source for that region.

[3] https://lris.scinfo.org.nz/layer/104400-lcdb-v50-land-cover-database-version-50-mainland-new-zealand/
[4] https://www.asurequality.com/services/agribase/

Table 2-1: CLUES land use classes grouped into initial functional groups for calibration. The percentage cover for each group is shown for both regions and in total. Land area: Manawatū-Whanganui 22213 km^2, Taranaki 7226 km^2, Total 29440 km^2.

Land use class	Functional group	Percentage of land area (%)		
		Manawatū-Whanganui	Taranaki	Total
Dairy	Dairy	8.0%	30.6%	13.5%
Sheep and Beef (lowland intensive) Sheep and Beef (hill-country) Sheep and Beef (high-country)	Sheep and beef	44.3%	18.3%	37.9%
Deer Other animals	All other stock	2.2%	3.4%	2.5%
Ground crops Surface crops Kiwifruit Other fruit Viticulture	Crops and horticulture	0.8%	0.2%	0.7%
Exotic Forest Native Forest Scrub	Trees	38.0%	44.3%	39.5%
Water (rivers, lakes) Tussock Ungrazed grassland Other	Other	6.0%	2.2%	5.1%
Urban	Urban	0.7%	1%	0.8%

The major point sources and their estimated mean annual loads are listed in Appendix A for both regions. They were determined for Manawatū-Whanganui using data supplied for this project by HRC. The loads determined for Taranaki major point sources come from the existing CLUES model geodatabase, these data were last updated as part of national *E. coli* modelling (Semadeni-Davies *et al.* 2018) and were assessed as suitable by TRC for use in this project.

The mean annual FDE loads from effluent ponds were determined using pond location and farm herd-size data supplied by TRC. Data were supplied for 647 ponds, however, we included estimated loads only for those ponds draining to water. Losses from loads disposed on land were considered to be inherent in the model calibration. The average load of *E. coli* discharged by effluent ponds per head of cattle was estimated as 2.307 x 10^{10} organisms per day, which is based on daily discharges found in Waikato by Donnison *et al.* (2011). The mean annual load estimated for each pond was added to the total load discharged to the stream segment for the REC subcatchment within which the pond is located. Where there are two or more ponds discharging to a stream segment, the loads were summed to give a segment total load for use in the model. In all, pond effluent is added as a point source to 411 Taranaki stream reaches.

2.2.3 Water quality and flow data

Water quality data used to derive load estimates for calibration were supplied to NIWA by Land and Water People (LWP; contact Ton Snelder). These data were drawn from State of the Environment (SOE) monitoring sites as well as NIWA's National River Water Quality Monitoring Network (NRWQN). They are the same data used to derive previous load estimates for both regions by LWP (Snelder 2018; Snelder and Fraser 2022) and for SOE modelling by NIWA (Whitehead *et al.* 2022). The dataset included 12 water quality sites in the Taranaki region 60 sites in the Manawatū-Whanganui region where flows were either concurrently measured or were available from a nearby flow monitoring site. Water quality records for these sites generally include *E. coli* observations on a monthly basis. While the start and end dates of the records and number of observations vary, these sites all met minimum data requirements in that, for the 10-year period 1/1/2011 – 31/12/2020, they had: (1) 60 or more observations; (2) observations for at least 8 of the 10 years; and (3) observations in at least 80 % of the quarters (Snelder and Fraser 2022).

Daily mean flow data for the water quality sites and nearby matched flow sites were supplied by TRC and HRC. We opted to include only water quality sites where observed flow data were available rather than using modelled flow rates due to the sensitivity of load calculations to flow. This decision was made to avoid inclusion of any error in the modelled flows affecting the calibration. This excluded four sites in the Taranaki region where modelled flows were estimated based on extrapolation of monthly gauged sites. In addition, sites where flows were not concurrently measured but were available from a nearby flow site were also excluded when the flows were not considered representative, e.g., due to a major tributary in between the water quality and flow sites. As a result, loads deemed reliable for calibration could be calculated for 58 sites in total – nine in the Taranaki region and 49 in the Manawatū-Whanganui region. Metadata for the sites are given Appendix B and these sites are mapped in Appendix C. The method used for load calculation is described in Section 3.1.

3 Calibration

The calibrated parameters within the CLUES *E. coli* model are the source yields for land use, the rain, temperature, and drainage delivery exponents and the in-stream and reservoir decay coefficients. Calibration is an iterative process whereby the model fit, parameter uncertainty and collinearity determined for a calibration run are used to guide the set-up for the subsequent run. The aim is to progressively reduce the number of parameters and parameter uncertainty while maintaining model fit. For example, if two diffuse sources have similar yields and are collinear, then they may be combined into a single source functional group. Moreover, if the model shows low sensitivity to a parameter with high uncertainty, then that parameter may be removed without unduly affecting model fit.

It is assumed that the current extent of mitigation in the regions is implicit in the model calibration. It was our original intention to undertake the calibration using a baseline scenario that included the current extent of mitigation, particularly stock exclusion because further stock exclusion is included as a Stage 2 scenario by both councils. However, we found inconsistencies in the way mitigations are applied in the two regions and the way information on mitigations, including level of spatial detail, was provided by the two councils. Moreover, adding the effect of existing mitigation would have complicated the model and possibly introduced spurious accuracy. Instead, it was decided to first undertake the calibration with no mitigation in place to see if the calibration could still provide robust parameters with no regional bias. We found this was the case (see Section 4).

3.1 Calculation of 'measured' loads from concentration and flow data

The model coefficients were determined by calibration to measured yields (i.e., load divided by contributing area) determined for water quality sites in both regions where concurrent flow records are also available. The measured loads were based on the lower 95th percentile of the flow record rather than the full record. This was for several reasons:

- The NOF concentration attributes are for the median and 95th- percentile concentrations. Hence, we are interested in conditions that occur most of the time, rather than in relatively rare flood flows. While a large part of the microbial load through a river typically occurs in flood flows (due to the higher concentrations in conjunction with higher flow), such conditions are relatively rare. The NOF swimmabilty target also focusses on normal flows in summer.
- There would be large errors if the full flow range were used, because there are typically few concentration measurements in floods. Load estimates for the lower 95th percentile flow ranger entail less error.
- Load reductions during non-storm conditions are more likely to influence median and 95th percentile concentrations, compared with removing storm loads.
- In some cases, such as the Ōruakeretaki site, concentration can decrease with flow at low flows. This may be due to the influence of ongoing sources that are less diluted at low flow. Even in such cases, neglecting high flows is appropriate because conditions at low flows are captured.

The choice of a 95th percentile rather than some higher percentile is somewhat arbitrary – there is no distinct cutoff defining flood flows. But choice of focussing on flows that occur for 95% of the time aligns with the use of concentrations that occur 95% of the time. The 95th percentile encompasses elevated flows that could arise from small events or during rising and falling limbs of floods, hence capturing the influence of elevated concentrations that typically occur at high flows.

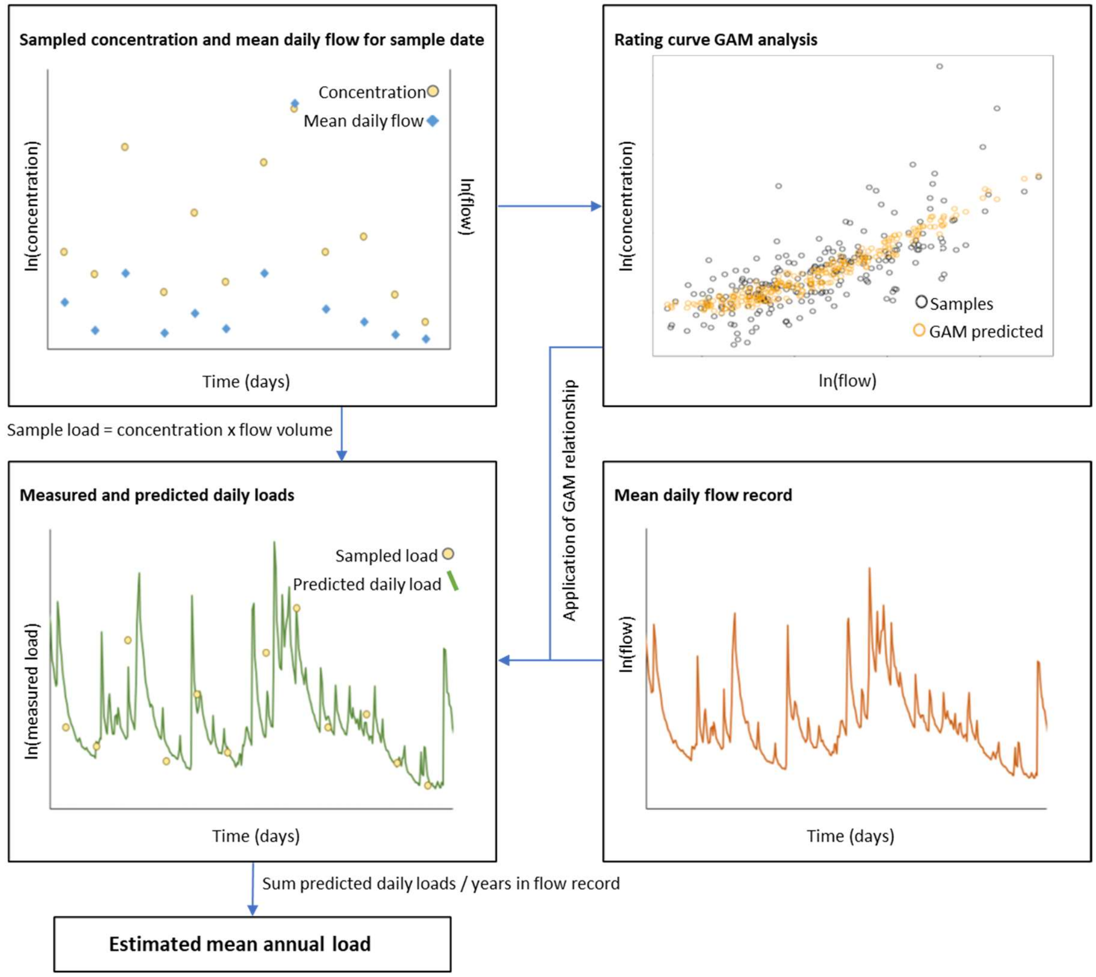

Figure 3-1: Rating curve method of determining monitoring site mean annual loads for calibration.

The measured mean annual loads are estimated by fitting a rating curve to the natural log of the monthly *E. coli* concentrations against the natural log of the daily flow rate for each respective sampling date, with an additional seasonality and trend term. Log-space is used to even out the weighting of high to low flows and concentrations. The estimation was made in the R programming language (R Core Team 2018) using the Generalised Additive Model regression analysis included in the Mixed GAM Computation Vehicle (mgcv; Wood 2013a; Wood 2013b) library for R. Since the load calculations were carried out in log-space, when the loads are back-transformed the model error term no longer has a mean of zero which can result in retransformation bias (i.e., predictions that systematically underestimate the response); for this reason, the transformed mean loads were adjusted according to Duan (1983). Once fitted, the derived curve relationship for each site was applied to the site's daily flow time-series over the entire period of the flow record to derive a time-series of mean daily concentrations. The concentrations were multiplied by the corresponding daily flow volumes to give the estimated daily loads and were then summed to give the mean annual load.

The suitability of the rating curve derived loads for model calibration was assessed for each site by generating confidence intervals and standard deviations for the natural log-transformed mean annual loads by repeating the rating curve procedure using a bootstrapping approach. This approach takes random samples of the original water quality data and estimates the natural log-transformed mean annual load for each of these. A standard deviation greater than one signals that the mean annual load calculated for the site is uncertain and the site should be removed from the calibration data set. The proportion of the total annual load associated with flows greater than the 95th percentile flow rate was also determined. This was done, along with a visual inspection of the rating curve, to ensure that the sampling covered the range of flows recorded in the flow record (up to 95th percentile flow).

3.2 Calibration method

Calibration was undertaken in Python using the SciPy[5] Least Squares Optimisation tool[6]. SciPy is an open-source library that contains a range of algorithms for scientific analysis. The optimisation tool seeks to find the best fit between predicted and measured values, here the natural log of measured and modelled yields, determined for the monitoring sites by minimising the sum of their differences or residuals. The yields are calculated from loads by dividing the load for each site by its upstream catchment area. This is done to normalise the loads for area, to avoid an artefact that might arise due to large catchment areas generally having higher loads than small catchments. Log-space is used to contract the wide range of estimated yields and make errors more normally distributed.

The SciPy Least Squares Optimisation tool also returns the Jacobian matrix (i.e., matrix of first-order partial derivatives of predicted values with respect to parameters) for the parameter set. This is used to determine the uncertainty for each parameter, expressed as the standard deviation of that parameter, and the collinearity or correlation between pairs of parameters (see, for example, Nikitas and Pappa-Louisi 2000 for the method). This conventional approach to determining parameter uncertainty has been demonstrated to be appropriate for the type of water quality model used in studies such as this one (Alexander *et al.* 2002).

4 Calibration results with discussion

4.1 Measured loads

Calibration was undertaken against the estimated loads determined for 58 water quality monitoring sites, 9 in Taranaki and the rest in Manawatū-Whanganui. These sites are listed with their upstream areas in Appendix B (Table B-3 and Table B-4) along with the percentage area covered by each land use functional group. While the final calibration grouped “Trees” with “Other” land uses – see below – this land use class has been kept separate in Table B-3 and Table B-4 for reference as it is the main land use class in this group. The site locations are mapped in Appendix C.

The total monitored area and percentage land use coverage upstream of calibration sites are summarised in Table 4-1. The area upstream of the calibration sites represent around 70% of the total area in the two regions and the land use breakdown upstream of the calibration sites is fairly similar to the coverage for the total land area. However there are differences in the two regions. While pasture is around half of the land area both regions, in Taranaki, dairy makes up 31% of the land area compared to 22% for other stock, and in Manawatū-Whanganui dairy represents only 6% or the land are compared to other stock (47%). The percentage cover of land uses upstream of the calibration sites is very similar to the breakdown for the total areas with the exception of dairy farming which is has slightly lower representation upstream of the calibration sites which could be due to generally lower representation of lowland areas by monitoring. The representativeness of the

[5] https://scipy.org/ (date of last access 24 February 2023)
[6] https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.least_squares.html (date of last access 24 February 2023)

sites in relation to land use and other upstream characteristics affecting water quality was analysed in more detail by LWP. Their assessment has been documented in reports for Taranaki (Fraser and Snelder 2019; Fraser 2022), but not for Manawatū-Whanganui, however, we were provided a general overview of the analysis by HRC. LWP found that the upstream area of most of the monitoring sites is found in the upland areas of the two regions. Furthermore, areas that have either very high or very low stocking densities or have a high proportion of native forest are under-represented by the monitoring sites. This means that the calibration outputs may not be representative of these conditions.

Table 4-1: Percentage land use coverage upstream of monitoring sites compared to the total area modelled.

Area modelled		Area (km^2)	Percentage cover				
			Dairy	SB and Deer	Trees	Urban	Other
Both regions	All	29440	14%	40%	40%	1%	6%
	Upstream of calibration sites	20643	8%	44%	42%	0%	6%
Manawatū-Whanganui	All	22213	8%	47%	38%	1%	7%
	Upstream of calibration sites	18237	6%	46%	41%	0%	7%
Taranaki	All	7226	31%	22%	44%	1%	2%
	Upstream of calibration sites	2405	24%	28%	47%	0%	2%

4.2 Calibration outputs

We undertook 11 calibration runs. The initial calibration run had 13 parameters, namely the drainage, temperature, and rainfall delivery factors, the two stream and reservoir attenuation parameters and diffuse source yields for each of the seven functional land use groups listed in Table 2-1. The parameter set for the final calibration run is given in Table 4-2 and the calibration performance is summarised in Table 4-3. The performance metrics in Table 4-3 are commonly used to assess the fit of water quality models (Moriasi *et al.* 2015) and were determined for the natural logs of both loads and yields.

The model was able to account moderately well for variations in yield between sites (R^2 of and model efficiency of 0.689). The model residual error of 0.567 in log space indicates a standard deviation of a factor of 1.76 in estimated yield. The model parameters indicate higher yields for pasture compared with 'other' land uses, little difference between pastoral land uses (dairy, sheep and beef, and other stock), and greater losses associated with higher rainfall and warmer temperatures. Soil drainage class and stream and reservoir attenuation were not retained in the model because they did not influence model performance and had high uncertainty.

As noted above, we did not consider the effects of current mitigation activities in the calibration, that is, the effects of existing mitigation are inherent in the calibration. The current level of mitigation activities will be used as baseline conditions for future state modelling in Stages 2 and 3. We note that there was no discernible regional bias in the model residuals.

The seven diffuse source functional groups listed in Table 2-1 were reduced to three in the final calibration: dairy; sheep and beef (other dry stock including deer were aggregated into this functional group); and all other land uses except urban.

Table 4-2: Calibrated parameters showing uncertainty (standard deviation) and parameter collinearity. tempCoef = air temperature coefficient, rainCoef = rainfall coefficient, yDairy = *EE. coli* yield from dairy, ySB= *E. coli* yield from sheep and beef, yOther = *E. coli* yield from other landuses.

Parameter	Value	Uncertainty (standard error)	Correlation matrix				
			tempCoef	rainCoef	yDairy	ySB	yOther
tempCoef a_T	0.50081	0.104	1.000	0.120	-0.336	0.084	0.331
rainCoef, a_R	1.02764	0.148		1.000	-0.449	0.453	-0.520
yDairy (peta orgs/km^2/y)	0.00693	0.002			1.000	-0.416	-0.023
ySB (peta orgs/km^2/y)	0.00852	0.001				1.000	-0.496
yOther (peta orgs/km^2/y)	0.00111	0.001					1.000

Table 4-3: Calibration performance for the natural logs of loads and yields.

Performance metric	Load	Yield
Coefficient of determination, R^2	0.927	0.689
Nash-Sutcliffe Efficiency[7], NSE	0.924	0.689
Root Mean Square Error, RMSE	0.587	0.567

The estimated yields for dairy and sheep and beef are similar and we did several calibration-runs with a single pasture yield without much loss in model fit. However, it was decided to keep these sources separate in the final calibration on the basis of recent research that indicates that the subtle difference is important (Muirhead 2023).

For urban land use, we used a fixed value (0.08 peta organisms/km^2/y) taken from an NIWA internal review of urban *E. coli* sources (Dr Jennifer Gadd, unpublished. 2017) that was carried out as part national *E. coli* modelling (Semadeni-Davies *et al.* 2018). The fixed value was used because, while locally important for *E. coli* loads in or downstream of urban areas, the land use covers less than 1% of the total area in the Taranaki and Manawatū-Whanganui regions, this resulted in unfeasibly high urban yields with extremely high associated uncertainty. Furthermore, the alterative of lumping urban land use within the *other* land use class resulted in loads from urban areas that were too low. This review found that urban yields for *E. coli* are highly variable and are a function of the sources present (*e.g.,* water fowl and other animal excreta, illegal wastewater connections), the type and condition of sanitary sewers (i.e., combined vs. separate sewers) and the degree and effectiveness of stormwater treatment. The value chosen is at the higher end of the range cited. It should be noted that the urban yields cited were determined from stream data and therefore may include the effects of attenuation/die-off.

[7] Nash, J.E. and Sutcliffe, J.V. (1970) River flow forecasting through conceptual models part I — A discussion of principles. *Journal of Hydrology*, 10(3): 282–290.

We found that the stream and reservoir attenuation parameters where both very low and were associated with high uncertainty. The uncertain reservoir attenuation reflects the fact that there are few reservoirs/lakes upstream of monitoring sites in the study area. The low stream attenuation is somewhat surprising since die-off/attenuation of *E. coli* would be expected, however non-zero attenuation was also found in similar *E. coli* modelling (Elliott et al., 2016). This might reflect interaction between stream attenuation and source coefficients (decreasing attenuation can be compensated to some degree by increasing source coefficients. We decided to accept the negligible attenuation of the calibrated model, rather than forcing a specific attenuation coefficient, to retain integrity of the calibrated parameter set. Due to the high uncertainty and low value, the coefficient was set to zero.

The rainfall parameter suggests that for every 1 m increase in rainfall, the *E. coli* load delivered from land increases by a factor of 2.8. The rain delivery factor may result in unrealistically large losses from high rainfall areas outside the range of the calibration data (e.g., extreme rainfalls of 10 m/y) so that an alternative more linear or sigmoid dependence may be more appropriate. Similarly, a 1°C increase in temperature would result in a load increase factor of 1.65. The temperature delivery factor is positive, which is consistent with observations of generally higher *E. coli* concentrations in warmer areas (McDowell *et al.* 2013) but is contrary to the general understanding that greater decay occurs at higher temperatures (e.g., Blaustein *et al.* 2013). The model was not sensitive to drainage class and this term was removed from the model, which is likely due to the majority of soils in the regions having good to excellent drainage. This is somewhat aligned with other studies, such as for the Waikato (Semadeni-Davies and Elliot 2013; Semadeni-Davies and Elliott 2013; Semadeni-Davies and Elliot 2014) where there was a contrast between well-drained and poorly-drained soils and the presence of high intensity agriculture on poorly drained soils.

The measured and modelled loads and yields are given for the calibration sites in Appendix B. Figure 4-1 is a scatter plot of the natural logs of the measured and modelled yields and Figure 4-2 shows the model residuals. The natural logs of the loads and yields, and the model residuals are also mapped for each site in Figure 4-3. Interestingly, the Taranaki sites have higher modelled and measured yields than the Manawatū-Whanganui sites. The loads are lower in Taranaki, however, this is largely due to smaller catchment areas upstream of the sites. The residuals indicate that there is no regional bias in the calibration.

The actual (non-logged) load residual for most of these sites was quite minor, however, there are notable differences in the modelled load for monitoring sites located on the main-stem of the Manawatū River downstream of Woodville and for two neighbouring sites in the Whanganui River catchment. The two Whanganui sites are HRC-00059 (Whanganui at Te Rewa) and NRWQN-00019_NIWA (Whanganui at Paetawa), which is located about 3.5 km downstream of the former. While the modelled loads are very similar (around 30 peta organisms/y), and are close to the measured load at Te Rewa (34 peta organisms/y), the measured load at Paetawa (53 peta organisms/y) is much higher than would be expected given its close proximity to Te Rewa and the absence of any known point sources. The sites have similar flow records, but the median annual concentration at Paetawa (138 Orgs./100 ml) is higher than at Te Rewa (125 Orgs./100 ml).

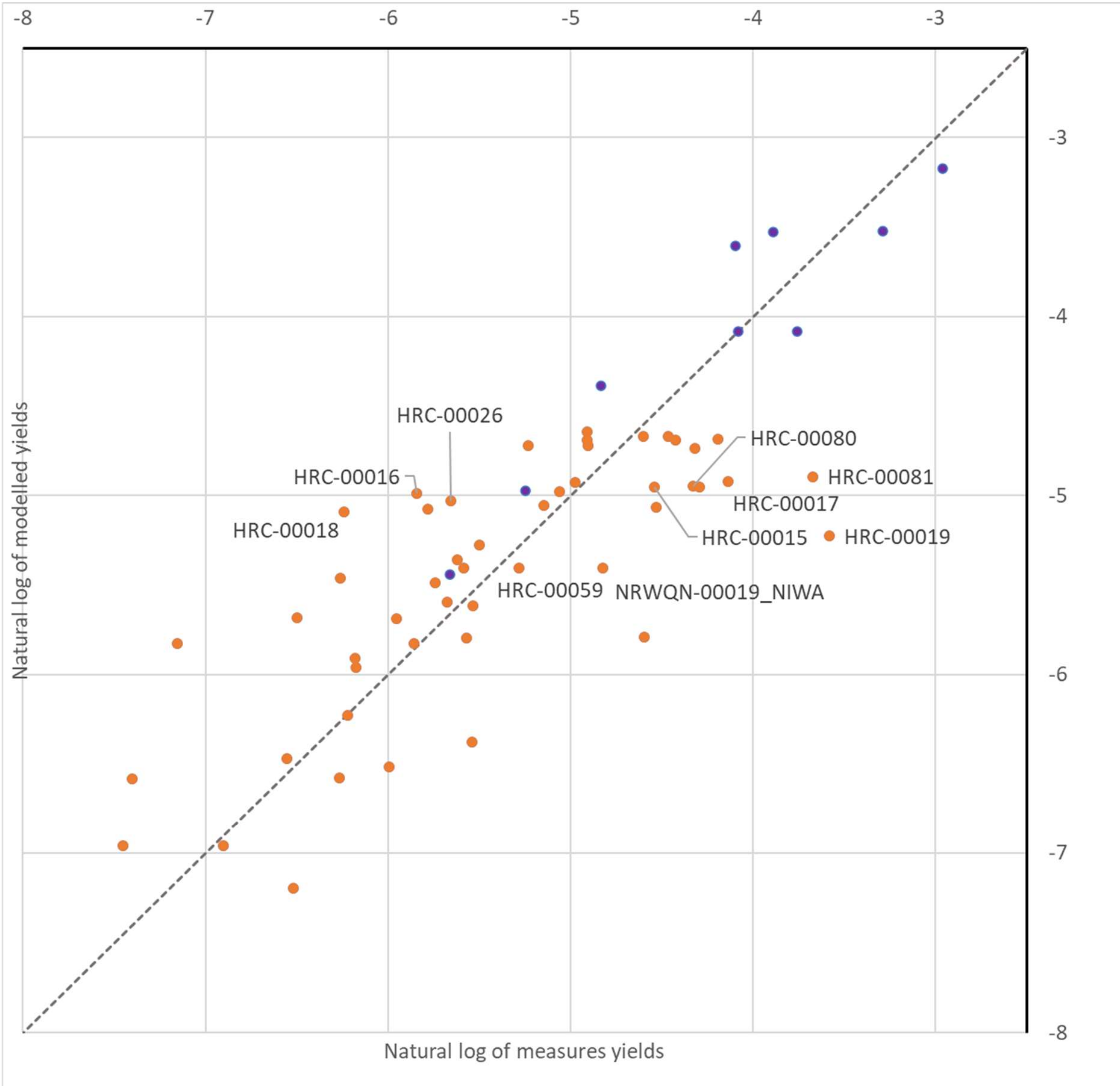

Figure 4-1: Scatter plot for the final calibration. The 1:1 line is shown for reference. Sites discussed are labelled. Sites in Taranaki are shown in blue, sites in Manawatū-Whanganui are shown in orange.

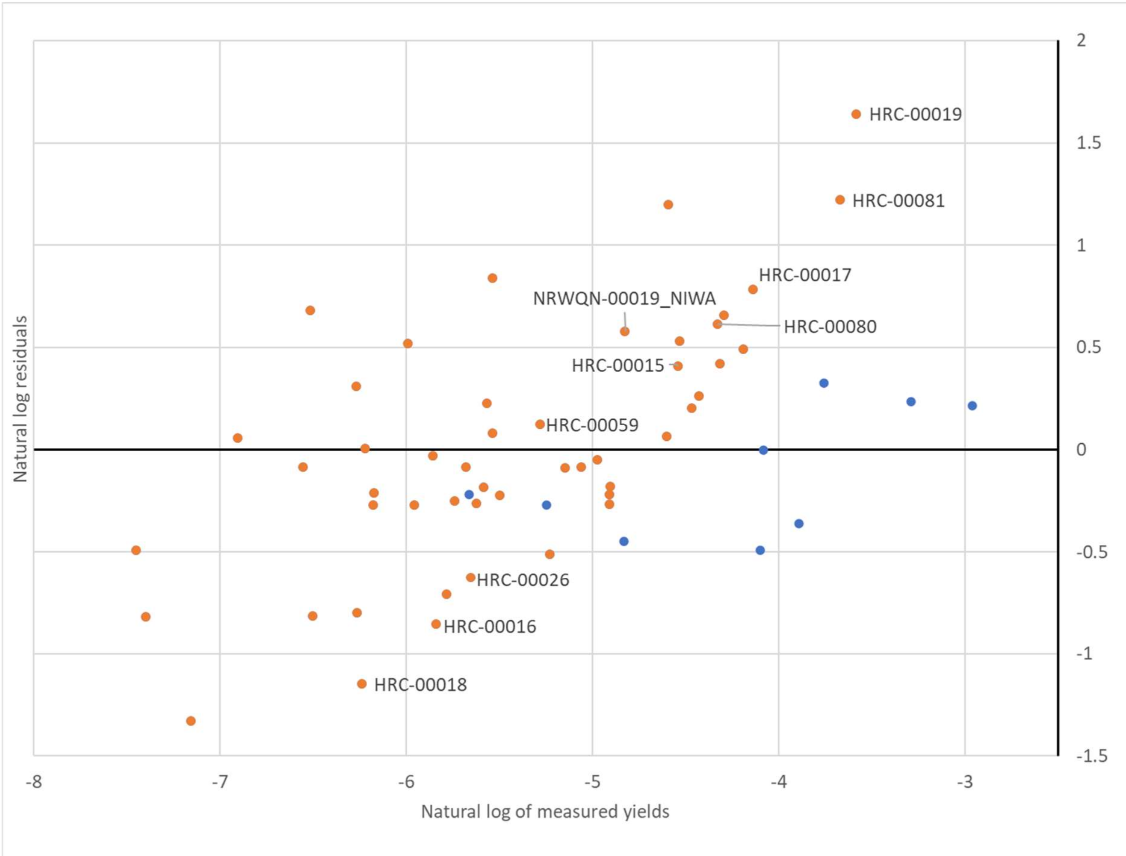

Figure 4-2: Residual plot for the final calibration. Sites in Taranaki are shown in blue, sites in Manawatū-Whanganui are shown in orange. Sites discussed are labelled.

As noted above, there were sites of concern in the Manawatū River catchment downstream of Woodville: HRC-00017 (Manawatū at Upper Gorge), HRC-00015 (Manawatū at Teachers College), HRC-00080 (Manawatū at u/s PNCC STP), LAWA-101931 (Manawatū at d/s PNCC STP) and HRC-00081 (Manawatū at u/s Fonterra Longburn) (see Figure C-4 for mapped locations). The modelled load at the Upper Gorge site (23 peta organisms/y) is around half that of the measured load (51 peta organisms/y). This underestimation is propagated downstream so that the other sites, with the exception of Fonterra Longburn (see discussion below), have a similar discrepancy between the modelled and measured loads. The measured and modelled loads, median concentrations and flow rates for the Upper Gorge and the sites directly upstream are given in Table 4-4. The model fit for the upstream sites is good with the exceptions of HRC-00019 (Manghao at Ballance), where the modelled load is underestimated, and HRC-00016 (Manawatū at Hopelands), where the modelled load is overestimated. Together, the total modelled load from these upstream sites is similar to the total measured load. The increase in measured loads from these upstream sites and at Upper Gorge is around 30 peta organisms/y.

There are other outliers evident in the charts (e.g. Manawatu at Weber Road, HRC-00018, and Mangatoro at Mangahei Rd, HRC-00026), however, the actual load difference are small.

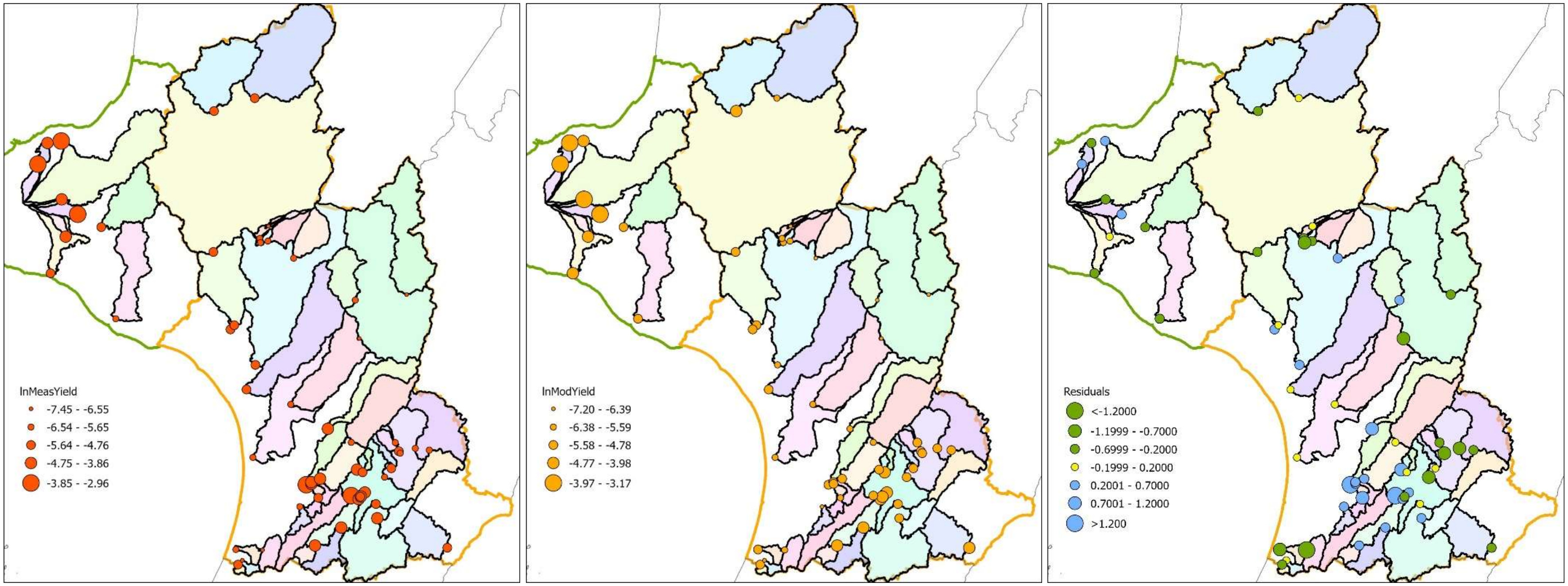

Figure 4-3: Calibration output map showing the natural logs of the measured and modelled *E. coli* yields (left and centre) and model residuals (right) for each monitoring site. Taranaki is outlined in green and Manawatū-Whanganui in yellow. The bold black outlines show the catchment areas for the downstream most sites. The coloured areas show the subcatchments for each of the monitoring sites.

Table 4-4: Estimated measured and modelled loads, measured concentrations and flow rates at Manawatū at Upper Gorge and upstream sites. Upstream sites shaded grey.

Site	Mean annual load (peta organisms/y)		Median concentration (Orgs/100 ml)	Mean annual flow rate (m^3/s)
	Measured	Modelled		
HRC-00017 (Manawatū at Upper Gorge)	50.87	23.26	335	80.1
HRC-00019 (Mangahao at Ballance)	7.77	1.50	300	13.8
HRC-00024 (Mangatainoka at Brewery SH2 Br)	4.75	3.88	130	17.0
HRC-00050 (Tīraumea at Ngāturi)	5.26	5.53	380	15.3
HRC-00016 (Manawatū at Hopelands)	3.67	8.63	130	24.3
HRC-00020 (Mangapapa at Troup Rd)	0.20	0.24	380	0.7
Upstream total	**21.65**	**19.78**	**219***	**71.02**

*Flow weighted total

The cause of the increase in loads between the combined upstream sites and the Gorge site is unclear. The jump in load is associated with an increase in concentration (from a calculated flow weighted median concentration of 219 to 335 Orgs./100 ml) and flow (from a combined upstream mean annual average of 71 to 80 m^3/s measured at Upper Gorge); the jump in load is not likely to be an artefact of the method used to calculate 'measured' load. It is unlikely to be related to the Woodville Sewage Treatment Plant (STP) because concentrations of upstream and downstream sites[8] on the Mangaatua Stream are about the same (around 420 – 430 per 100 ml median concentration according to LAWA) and the estimated point source load is low (0.003 peta organisms/y). Nor is the increase likely to be related to Woodville itself because the load and concentration in the Mangapapa and Mangaatua streams, which drain Woodville, is small compared with the Gorge load and concentration. The subcatchment area (447 km^2) for the Upper Gorge site represents around 14% of the site's total upstream area (3172 km^2), and the implied yield from the intervening catchment (calculated as the difference in the load from upstream and the site load over the subcatchment area) is 0.065 peta organisms/km^2/y. This yield is an order of magnitude higher than the calibrated yields from intensive pasture. We have been unable to identify any high intensity land use that could explain the high yield.

There is also a large difference between the modelled (31 peta organisms/y) and measured (107 peta organisms/y) at the u/s Fonterra Longburn site. The measured load calculation used the same flow record as the Teachers College, and up and downstream PNCC STP sites. These sites are located around 7 km upstream. There is a 15% difference in median concentration between the STP downstream site (440 Orgs./100ml) and the u/s Fonterra Longburn site (510 Orgs./100ml), which is probably due to influxes of urban and rural runoff from the Mangaone Stream that runs through Palmerston North. However, this difference in concentration is not enough to explain the difference

[8] These sites were not used in the calibration.

in the measured load. The concentration at u/s Fonterra is surprisingly high. At the site downstream (LAWA-101932, Manawatū d/s Fonterra Longburn)[9], the concentration is about 410 per 100 ml and at Ōpiki (HRC-00013_NIWA, Manawatū at Ōpiki Bridge) further downstream is 280 per 100 ml. This suggests the possibility, which is being explored by HRC, that the difference is a measurement artefact at the u/s Fonterra site, rather than an actual increase in load, .

We note that the estimated loads calculated by LWP were similar and also showed unexpected jumps in load between Whanganui at Te Rewa and Whanganui at Paetawa as well as at Upper Gorge and between Manawatū at d/s PNCC STP and Manawatū at u/s Fonterra Longburn.

The model uncertainty reflects the variability of *E. coli* concentrations both between sites and over time. We note that measured *E. coli* concentrations are highly variable possibly due to, for example, native populations of *E. coli* in water bodies, in-stream die-off and highly variable discharges of *E. coli* from diffuse and point sources (Wilcock 2006; Muirhead 2015).

5 Conclusions

This report documents the joint calibration of the CLUES *E. coli* model for the Taranaki and Manawatū-Whanganui regions. The calibration was undertaken to improve the model fit for the regions. Model calibration is Stage 1 in a three-stage project. Stages 2 and 3, are being undertaken and reported separately for the two regions and will use the model to assess the impact of various mitigation activities on *E. coli* loads, and, by inference, *E. coli* attributes from the National Objectives Framework (New Zealand Government 2020).

The model was calibrated against *E. coli* yields estimated from monitored water quality and flow records for water quality monitoring sites located within the regions. Overall, the calibration results give confidence that the model provides a suitable foundation for examining responses to mitigation activities at regional scale in later stages of the broader project.

Acknowledgements

We would like to thank Ton Snelder and Caroline Fraser at Land and Water People for providing the water quality and flow data they had collated for TRC and HRC. Modelled current state attributes for all the river segments in both regions was provided by our former NIWA colleague, Amy Whitehead.

[9] Neither of these downstream sites were used in the calibration. The d/s Fonterra Longburn is quite close to the u/s site, but there is a large tributary between the sites that would have a substantial effect of flow.

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Appendix A Major point sources

Table A-1: CLUES mean annual *E. coli* point source loads (peta organisms/year) for Taranaki and Manawatū-Whanganui.

NZSEGMENT	Name	Ecoli_peta organisms/y	Council
6191882	Kaponga	0.000599	Taranaki
6186660	Stratford	0.0666	Taranaki
6214889	Waverley	0.007243	Taranaki
7234946	AFFCO Fielding at Industrial Waste water	0.019916	Horizons
7235055	Dannevirke STP at microfiltered oxpond	0.000442	Horizons
7247235	Eketāhuna STP at Secondary oxpond waste	0.001154	Horizons
7235811	Feilding STP at Secondary oxpond waste	0.015505	Horizons
7242126	Foxton STP at Secondary oxpond waste	0.01287	Horizons
7231319	Halcombe at Secondary oxpond	0.005043	Horizons
7224518	Hunterville STP at Microfiltration Plant	0.000262	Horizons
7229177	Kimbolton STP at oxpond waste	0.000841	Horizons
7230320	Marton STP at Rock filtered oxpond waste	0.046279	Horizons
7174519	National Park STP at Secondary oxpond	0.001188	Horizons
7230015	Norsewood STP at oxpond waste	0.000176	Horizons
7233271	Ohakea STP at Effluent outfall and Riverlands at Industrial wastewater and Bulls STP at Secondary oxpond waste	0.194522	Horizons
7192527	Ōhakune STP at Secondary oxpond waste	0.01284	Horizons
7231038	Ormondville STP at 2nd oxpond waste	0.000135	Horizons
7241128	Pahiatua STP at Tertiary oxpond waste	0.003938	Horizons
7239481	PNCC STP at Tertiary Treated Effluent	0.503744	Horizons
7244835	Pongaroa STP at 2nd oxpond waste	0.000348	Horizons
7236160	PPCS Ōringi STP at oxpond waste	0.000477	Horizons
7194503	Raetihi STP at Secondary oxpond waste	0.001936	Horizons
7193718	Rangataua STP at Secondary oxpond waste	0.000238	Horizons
7236594	Rongotea STP at Secondary oxpond waste	0.002111	Horizons
7234275	Sanson STP at Secondary oxpond waste	0.014824	Horizons
7211096	Taihape STP at oxpond waste	0.079611	Horizons
7150643	Taumarunui STP at Tertiary treated waste	0.004059	Horizons
7241792	Tokomaru at oxpond waste	0.000896	Horizons
7196591	Waiōuru STP at oxpond waste	0.361328	Horizons

NZSEGMENT	Name	Ecoli_peta organisms/y	Council
7196647	Winstone Pulp WWTP at oxpond waste	0.43282	Horizons
7238330	Woodville STP at Secondary oxpond waste	0.003316	Horizons

Appendix B Calibration water quality site metadata

The tables below give site reference data for the water quality monitoring sites used for calibration. Table B-1 (Taranaki) and Table B-2 (Manawatū-Whanganui) give the network location (NZ segment) for each site, the flow monitoring site used for load calculation and the number of samples and length of record with flow available. Table B-3 (Taranaki) and Table B-4 (Manawatū-Whangaui) give the upstream area and the percentage land use coverage upstream of each site. In each table, where there are multiple nested sites in the same catchment, the sites have been grouped by the most downstream site and are ordered from upstream to downstream according to their REC flow sequence number (Hydroseq).

Table B-1: Taranaki monitoring site reference data. Reference data includes network location (NZ segment) and matched flow monitoring site. Number of samples, start and end dates refer to the length of the water quality record for which flows are available during the calibration period (1/1/2011 – 31/12/2020).

Catchment (most downstream site)	Site LAWA ID	Site name	NZ segment	Flow site name	Number of samples	Start date	End date
NRWQN-00036_NIWA	NRWQN-00035_NIWA	WA2 Manganui at SH3	6182471	Manganui at SH3	119	17/1/2011	14/12/2020
	NRWQN-00036_NIWA	WA1 Waitara at Bertrand Rd	6162651	Waitara at Bertrand Rd	118	17/1/2011	14/12/2020
TRC-00001	TRC-00001	Mangaehu at Raupuha Rd Bridge	6190184	Mangaehu at Bridge	118	18/1/2011	9/12/2020
TRC-00003	TRC-00003	Mangaoraka at Corbett Rd	6162452	Mangaoraka at Corbett Rd	119	12/1/2011	9/12/2020
TRC-00005	TRC-00005	Patea at Skinner Rd	6186641	Patea at Skinner Rd	119	12/1/2011	9/12/2020
TRC-00010	TRC-00009	Waingongoro at Eltham Rd Bridge	6192810	Waingongoro at Eltham Rd	119	12/1/2011	9/12/2020
	TRC-00010	Waingongoro at SH45	6202452	Waingongoro at SH45	118	12/1/2011	9/12/2020
TRC-00011	TRC-00011	Waiwhakaiho at SH3	6171148	Waiwhakaiho at Egmont Village	119	12/1/2011	9/12/2020
TRC-00050	TRC-00050	Whenuakura at Nicholson Rd	6213881	Whenuakura at Nicholson Rd	65	9/7/2015	10/12/2020

Table B-2: Manawatū-Whanganui monitoring site reference data. Reference data includes network location (NZ segment) and matched flow monitoring site. Number of samples, start and end dates refer to the length of the water quality record for which flows are available during the calibration period (1/1/2011 – 31/12/2020).

Catchment (most downstream site)	Site LAWA ID	Site name	NZ segment	Flow site name	Number of samples	Start date	End date
HRC-00011	HRC-00011	Manakau at SH1 Bridge	7249277	Manakau at SH1 Bridge	126	20/1/2011	30/11/2020
HRC-00031	HRC-00030	Ōhau at Gladstone Reserve	7247560	Ōhau at Rongomatane	127	19/1/2011	30/11/2020
	HRC-00031	Ōhau at Haines Property	7247544	Ōhau at Haines Ford	66	19/1/2011	30/11/2020
HRC-00035	HRC-00035	Ōroua at Almadale Slackline	7232687	Ōroua at Almadale Slackline	118	12/1/2011	9/12/2020
HRC-00038	HRC-00038	Owahanga at Branscombe Bridge	7247269	Owahanga at Branscombe Bridge	117	10/1/2011	7/12/2020
HRC-00043	HRC-00046	Rangitīkei at Pukeokahu	7208135	Rangitīkei at Pukeokahu	118	24/1/2011	1/12/2020
	HRC-00003	Hautapu at Alabasters	7209566	Hautapu at Alabasters	119	24/1/2011	1/12/2020
	HRC-00045	Rangitīkei at Mangaweka	7218183	Rangitīkei at Mangaweka	119	24/1/2011	2/12/2020
	HRC-00044	Rangitīkei at Onepuhi	7229603	Rangitīkei at Onepuhi	118	26/1/2011	2/12/2020
	HRC-00043	Rangitīkei at McKelvies	7236501	Rangitīkei at McKelvies	118	26/1/2011	3/12/2020
HRC-00054	HRC-00054	Tokomaru at Horseshoe Bend	7242415	Tokomaru at Riverland Farm	120	12/1/2011	10/12/2020
HRC-00055	HRC-00055	Turakina at ONeills Bridge	7227401	Turakina at ONeills Bridge	119	20/1/2011	17/12/2020
HRC-00056	HRC-00056	Waikawa at North Manakau Rd	7248627	Waikawa at North Manakau Road	126	20/1/2011	30/11/2020
HRC-00058	HRC-00009	Makotuku at SH49A	7189858	Makotuku at SH 49A Br	116	17/1/2011	14/12/2020
	HRC-00007	Makotuku at Raetihi	7193268	Makotuku at Raetihi	117	17/1/2011	14/12/2020
	HRC-00066	Makotuku at Above Sewage Plant	7194503	Makotuku at Raetihi	119	17/1/2011	14/12/2020
	LAWA-101929	Makotuku at d/s Raetihi STP	7195002	Makotuku at Raetihi	119	17/1/2011	14/12/2020
	HRC-00028	Mangawhero at Pakihi Rd Bridge	7194090	Mangawhero at Pakihi Rd Bridge	117	17/1/2011	14/12/2020
	HRC-00053	Tokiahuru at Junction	7198731	Tokiahuru at Junction	117	18/1/2011	14/12/2020
	HRC-00058	Whangaehu at Kauangaroa	7223467	Whangaehu at Kauangaroa	117	17/1/2011	16/12/2020
HRC-00081	HRC-00006	Kūmeti at Te Rehunga	7234284	Kūmeti at Te Rehunga	118	9/1/2011	6/12/2020
	HRC-00040	Pohangina at Mais Reach	7234641	Pohangina at Mais Reach	118	12/1/2011	8/12/2020
	HRC-00037	Ōruakeretaki at SH2 Napier	7235868	Ōruakeretaki at SH2 Napier	119	10/1/2011	6/12/2020

Catchment (most downstream site)	Site LAWA ID	Site name	NZ segment	Flow site name	Number of samples	Start date	End date
HRC-00081	LAWA-101951	Ōruakeretaki at d/s PPCS Ōringi STP	7236160	Ōruakeretaki at SH2 Napier	118	6/2/2011	7/12/2020
	HRC-00047	Raparapawai at Jackson Rd	7237817	Raparapawai at Jackson Rd	119	10/1/2011	7/12/2020
	HRC-00020	Mangapapa at Troup Rd	7238188	Mangapapa at Troup Rd	119	9/1/2011	7/12/2020
	HRC-00026	Mangatoro at Mangahei Road	7235636	Mangatoro at Mangahei Road	119	9/1/2011	6/12/2020
	HRC-00018	Manawatū at Weber Road	7235487	Manawatū at Weber Road	119	10/1/2011	6/12/2020
	HRC-00016	Manawatū at Hopelands	7238779	Manawatū at Hopelands	119	10/1/2011	7/12/2020
	HRC-00005	Kahuterawa at Johnstons Rātā	7241259	Kahuterawa at Johnstons Rātā	118	12/1/2011	8/12/2020
	HRC-00010	Mākuri at Tuscan Hills	7243830	Mākuri at Tuscan Hills	119	10/1/2011	7/12/2020
	HRC-00022	Mangatainoka at Larsons Road	7246861	Mangatainoka at Larsons Road	117	10/1/2011	7/12/2020
	HRC-00019	Mangahao at Ballance	7240715	Mangahao at Ballance	117	11/1/2011	8/12/2020
	HRC-00008	Mākākahi at Hāmua	7244807	Mākākahi at Hāmua	117	11/1/2011	7/12/2020
	HRC-00023	Mangatainoka at Pahiatua Town Br	7241237	Mangatainoka at Pahiatua Town Br	117	11/1/2011	8/12/2020
	HRC-00083	Mangatainoka at u/s Pahiatua STP	7241121	Mangatainoka at Pahiatua Town Br	116	10/1/2011	16/12/2020
	LAWA-101941	Mangatainoka at d/s Pahiatua STP	7241122	Mangatainoka at Pahiatua Town Br	114	10/1/2011	16/12/2020
	HRC-00024	Mangatainoka at Brewery - SH2 Br	7240726	Mangatainoka at Pahiatua Town Br	119	11/1/2011	7/12/2020
	HRC-00050	Tīraumea at Ngāturi	7241723	Tīraumea at Ngāturi	117	10/1/2011	7/12/2020
	HRC-00017	Manawatū at Upper Gorge	7237871	Manawatū at Upper Gorge	118	12/1/2011	8/12/2020
	HRC-00015	Manawatū at Teachers College	7239110	Manawatū at Teachers College	118	12/1/2011	8/12/2020
	HRC-00080	Manawatū at u/s PNCC STP	7239481	Manawatū at Teachers College	118	11/1/2011	8/12/2020
	LAWA-101931	Manawatū at d/s PNCC STP	7239702	Manawatū at Teachers College	107	6/12/2011	8/12/2020
	HRC-00081	Manawatū at u/s Fonterra Longburn	7239663	Manawatū at Teachers College	117	11/1/2011	8/12/2020
NRWQN-00019_NIWA	HRC-00033	Ōngarue at Taringamotu	7147944	Ōngarue at Taringamotu	116	19/1/2011	16/12/2020
	HRC-00032	Ōhura at Tokorima	7152279	Ōhura at Tokorima	117	20/1/2011	16/12/2020
	HRC-00060	Whanganui at Pipiriki	7197112	Whanganui at Pipiriki	117	19/1/2011	16/12/2020
	HRC-00059	Whanganui at Te Rewa	7215327	Whanganui at Te Rewa	117	20/1/2011	16/12/2020
	NRWQN-00019_NIWA	WA4 Whanganui at Paetawa	7215564	Whanganui at Paetawa	115	18/1/2011	15/12/2020

Table B-3: Taranaki catchment and subcatchment areas and land use breakdown upstream of monitoring sites. Catchment area refers to the total area upstream of each site while subcatchment area refers to the area between each site and the next upstream. If there is no upstream site, the catchment and subcatchment areas will be the same.

Catchment (most downstream site)	Site LAWA ID	Site name	Subcatchment						Upstream catchment					
			Area (km^2)	Dairy (%)	Other stock (%)	Trees (%)	Urban (%)	Other (%)	Area (km^2)	Dairy (%)	Other stock (%)	Trees (%)	Urban (%)	Other (%)
NRWQN-00036_NIWA	NRWQN-00035_NIWA	WA2 Manganui at SH3	15	21	1	61	0	16	15	21	1	61	0	16
	NRWQN-00036_NIWA	WA1 Waitara at Bertrand Rd	1099	21	35	43	0	2	1114	21	34	43	0	2
TRC-00001	TRC-00001	Mangaehu at Raupuha Rd Bridge	417	2	39	57	0	2	417	2	39	57	0	2
TRC-00003	TRC-00003	Mangaoraka at Corbett Rd	54	56	33	7	1	4	54	56	33	7	1	4
TRC-00005	TRC-00005	Patea at Skinner Rd	81	63	19	11	7	1	81	63	19	11	7	1
TRC-00010	TRC-00009	Waingongoro at Eltham Rd Bridge	50	72	8	19	1	0	50	72	8	19	1	0
	TRC-00010	Waingongoro at SH45	176	84	10	4	1	1	226	81	9	7	1	1
TRC-00011	TRC-00011	Waiwhakaiho at SH3	60	33	7	57	0	4	60	33	7	57	0	4
TRC-00050	TRC-00050	Whenuakura at Nicholson Rd	444	10	15	74	0	1	444	10	15	74	0	1
Total area upstream of monitoring sites									**2396**	**24**	**28**	**46**	**0**	**2**

Table B-4: Manawatū-Whanganui catchment and subcatchment areas and land use breakdown upstream of monitoring sites. Catchment area refers to the total area upstream of each site while subcatchment area refers to the area between each site and the next upstream. If there is no upstream site, the catchment and subcatchment areas will be the same.

Catchment (most downstream site)	Site LAWA ID	Site name	Subcatchment						Upstream catchment					
			Area (km2)	Dairy (%)	Other stock (%)	Trees (%)	Urban (%)	Other (%)	Area (km2)	Dairy (%)	Other stock (%)	Trees (%)	Urban (%)	Other (%)
HRC-00011	HRC-00011	Manakau at SH1 Bridge	16	0	53	45	0	2	16	0	53	45	0	2
HRC-00031	HRC-00030	Ōhau at Gladstone Reserve	105	2	10	87	0	2	105	2	10	87	0	2
	HRC-00031	Ōhau at Haines Property	50	23	32	31	1	13	155	8	17	69	0	5
HRC-00035	HRC-00035	Ōroua at Almadale Slackline	304	15	42	35	0	7	304	15	42	35	0	7
HRC-00038	HRC-00038	Owahanga at Branscombe Bridge	316	2	68	24	0	5	316	2	68	24	0	5
HRC-00043	HRC-00046	Rangitīkei at Pukeokahu	772	0	32	47	0	21	772	0	32	47	0	21
	HRC-00003	Hautapu at Alabasters	277	0	55	18	1	27	277	0	55	18	1	27
	HRC-00045	Rangitīkei at Mangaweka	1635	0	44	39	0	17	2685	0	41	39	0	19
	HRC-00044	Rangitīkei at Onepuhi	588	7	75	15	0	4	3273	1	47	35	0	16
	HRC-00043	Rangitīkei at McKelvies	603	25	57	8	2	8	3876	5	49	31	0	15
HRC-00054	HRC-00054	Tokomaru at Horseshoe Bend	56	0	12	87	0	1	56	0	12	87	0	1
HRC-00055	HRC-00055	Turakina at ONeills Bridge	842	2	78	19	0	2	842	2	78	19	0	2
HRC-00056	HRC-00056	Waikawa at North Manakau Rd	30	1	5	91	0	4	30	1	5	91	0	4
HRC-00058	HRC-00009	Makotuku at SH49A	25	0	16	64	0	20	25	0	16	64	0	20
	HRC-00007	Makotuku at Raetihi	36	6	72	14	1	7	62	3	49	34	1	12
	HRC-00066	Makotuku at Above Sewage Plant	10	0	83	3	8	6	71	3	54	30	2	12
	LAWA-101929	Makotuku at d/s Raetihi STP	0	0	86	2	0	12	72	3	54	30	2	12
	HRC-00028	Mangawhero at Pakihi Rd Bridge	138	2	40	46	2	10	138	2	40	46	2	10
	HRC-00053	Tokiahuru at Junction	221	0	12	71	0	17	221	0	12	71	0	17
	HRC-00058	Whangaehu at Kauangaroa	1453	1	66	25	0	8	1882	1	57	32	0	9
HRC-00081	HRC-00006	Kūmeti at Te Rehunga	12	26	9	65	0	1	12	26	9	65	0	1

Catchment (most downstream site)	Site LAWA ID	Site name	Subcatchment						Upstream catchment					
			Area (km2)	Dairy (%)	Other stock (%)	Trees (%)	Urban (%)	Other (%)	Area (km2)	Dairy (%)	Other stock (%)	Trees (%)	Urban (%)	Other (%)
HRC-00081	HRC-00040	Pohangina at Mais Reach	487	2	45	50	0	3	487	2	45	50	0	3
	HRC-00037	Ōruakeretaki at SH2 Napier	54	47	19	33	0	1	54	47	19	33	0	1
	LAWA-101951	Ōruakeretaki at d/s PPCS Ōringi STP	2	37	1	2	0	60	57	47	18	32	0	3
	HRC-00047	Raparapawai at Jackson Rd	46	49	28	23	0	1	46	49	28	23	0	1
	HRC-00020	Mangapapa at Troup Rd	27	33	35	27	2	3	27	33	35	27	2	3
	HRC-00026	Mangatoro at Mangahei Road	220	3	85	9	0	3	220	3	85	9	0	3
	HRC-00018	Manawatū at Weber Road	464	13	72	12	0	3	696	10	76	11	0	3
	HRC-00016	Manawatū at Hopelands	435	25	59	12	1	3	1245	18	65	13	0	3
	HRC-00005	Kahuterawa at Johnstons Rātā	38	12	12	71	0	6	38	12	12	71	0	6
	HRC-00010	Mākuri at Tuscan Hills	136	0	78	21	0	1	136	0	78	21	0	1
	HRC-00022	Mangatainoka at Larsons Road	58	2	28	66	0	4	58	2	28	66	0	4
	HRC-00019	Mangahao at Ballance	278	10	22	64	0	3	281	10	22	65	0	3
	HRC-00008	Mākākahi at Hāmua	160	37	40	22	0	1	164	36	41	22	0	1
	HRC-00023	Mangatainoka at Pahiatua Town Br	181	49	37	9	1	5	403	37	37	22	0	3
	HRC-00083	Mangatainoka at u/s Pahiatua STP	3	14	39	13	3	32	406	37	37	22	0	3
	LAWA-101941	Mangatainoka at d/s Pahiatua STP	2	11	28	3	49	9	408	36	37	22	1	3
	HRC-00024	Mangatainoka at Brewery - SH2 Br	7	5	66	6	0	23	415	36	38	22	1	4
	HRC-00050	Tīraumea at Ngāturi	616	3	79	16	0	3	758	2	78	17	0	2
	HRC-00017	Manawatū at Upper Gorge	447	25	55	15	0	5	3172	17	59	20	0	3
	HRC-00015	Manawatū at Teachers College	238	16	52	19	6	7	3897	15	57	24	1	3
	HRC-00080	Manawatū at u/s PNCC STP	51	8	27	47	8	10	3948	15	56	24	1	4
	LAWA-101931	Manawatū at d/s PNCC STP	25	20	48	19	5	8	4011	15	56	25	1	4
	HRC-00081	Manawatū at u/s Fonterra Longburn	184	27	53	3	13	4	4196	16	56	24	1	4
NRWQN-00019_NIWA	HRC-00033	Ōngarue at Taringamotu	1068	1	38	59	0	1	1076	1	38	59	0	2

Catchment (most downstream site)	Site LAWA ID	Site name	Subcatchment						Upstream catchment					
			Area (km2)	Dairy (%)	Other stock (%)	Trees (%)	Urban (%)	Other (%)	Area (km2)	Dairy (%)	Other stock (%)	Trees (%)	Urban (%)	Other (%)
NRWQN-00019_NIWA	HRC-00032	Ōhura at Tokorima	668	1	56	41	0	2	669	1	56	41	0	2
	HRC-00060	Whanganui at Pipiriki	4268	1	28	66	0	5	6023	1	33	62	0	4
	HRC-00059	Whanganui at Te Rewa	589	0	20	78	0	2	6612	1	32	63	0	4
	NRWQN-00019_NIWA	WA4 Whanganui at Paetawa	4	0	31	66	0	3	6616	1	32	63	0	4
Total area upstream of monitoring sites									**18289**	**6**	**46**	**41**	**0**	**7**

Appendix C Calibration water quality site locations

The following maps show the locations of the water quality monitoring sites used in the calibration. In all the maps, Taranaki is outlined in green and Manawatū-Whanganui in yellow. REC streamlines for segments with a stream order of 5 or greater are shown. Black bold outlines delineate the catchment areas for downstream monitoring sites and the coloured polygons show the subcatchment areas between sites for nested sites. Figure C-1 is an overview map that shows the location of all the sites with the downstream sites (red) labelled. All the sites are labelled in the subsequent maps which show smaller areas at a higher resolution. These maps overlap in their extents.

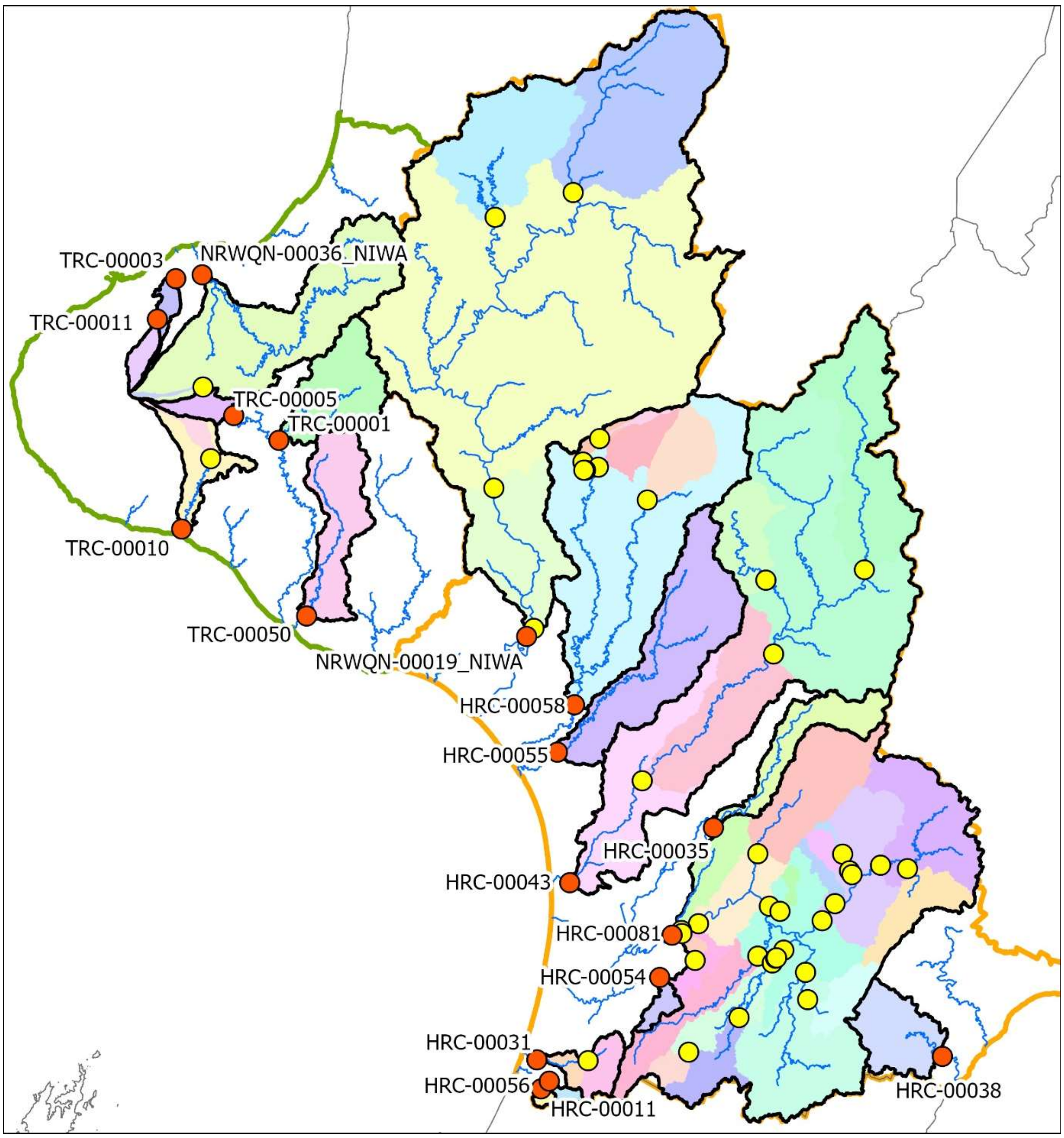

Figure C-1: Overview map showing location of water monitoring sites used for calibration. Downstream sites (red dots) are labelled. Upstream nested sites (yellow dots) are labelled in following maps.

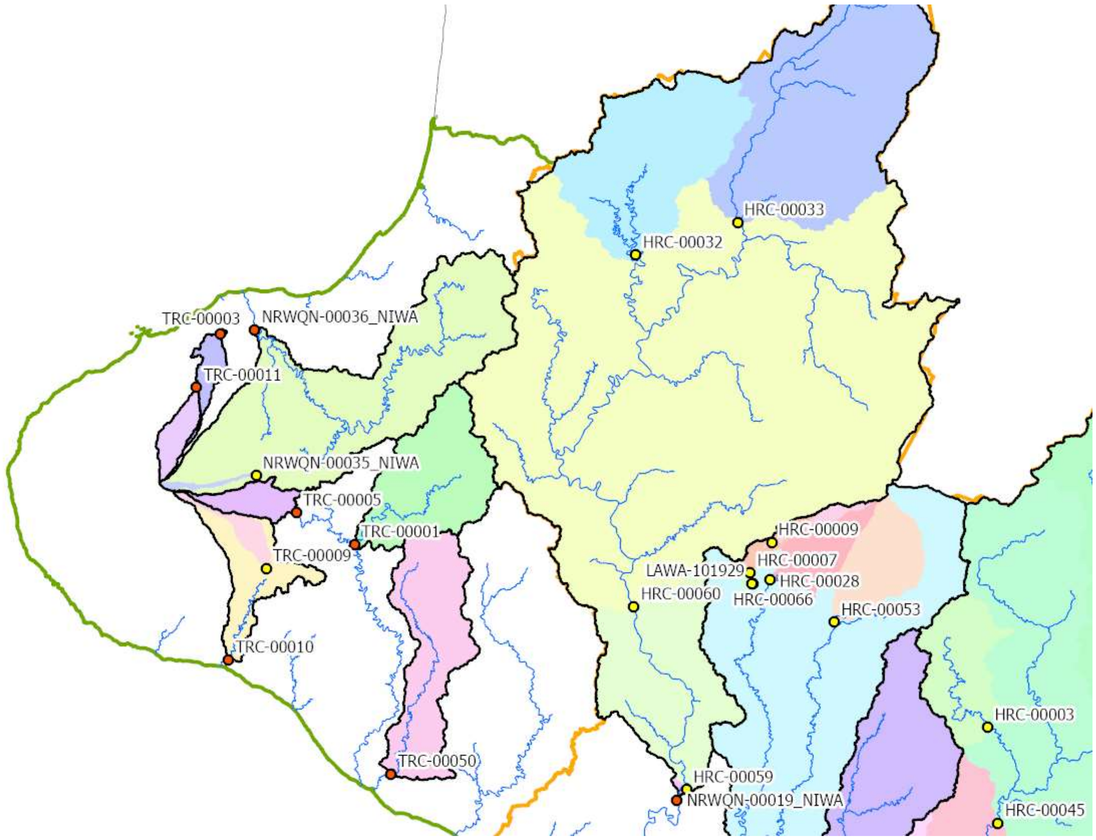

Figure C-2: Taranaki and eastern Manawatū-Whanganui water quality monitoring sites used for calibration.

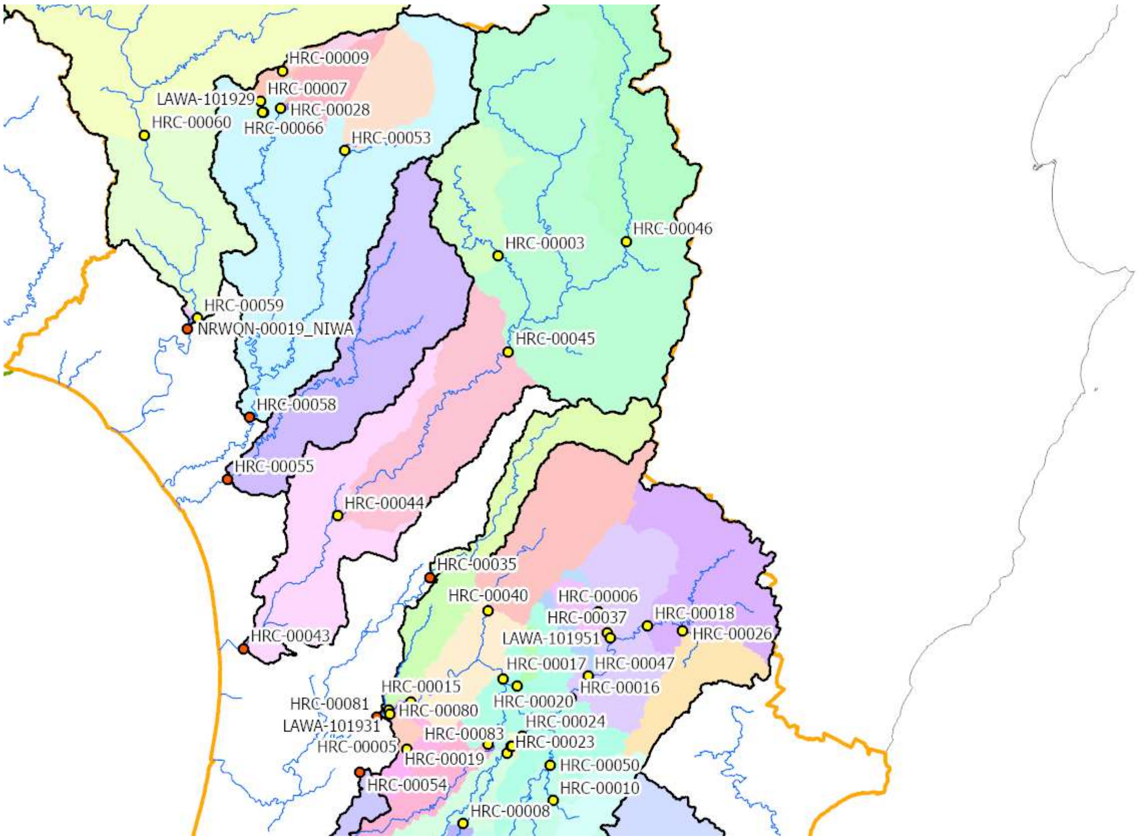

Figure C-3: Central Manawatū-Whanganui water monitoring sites used for calibration.

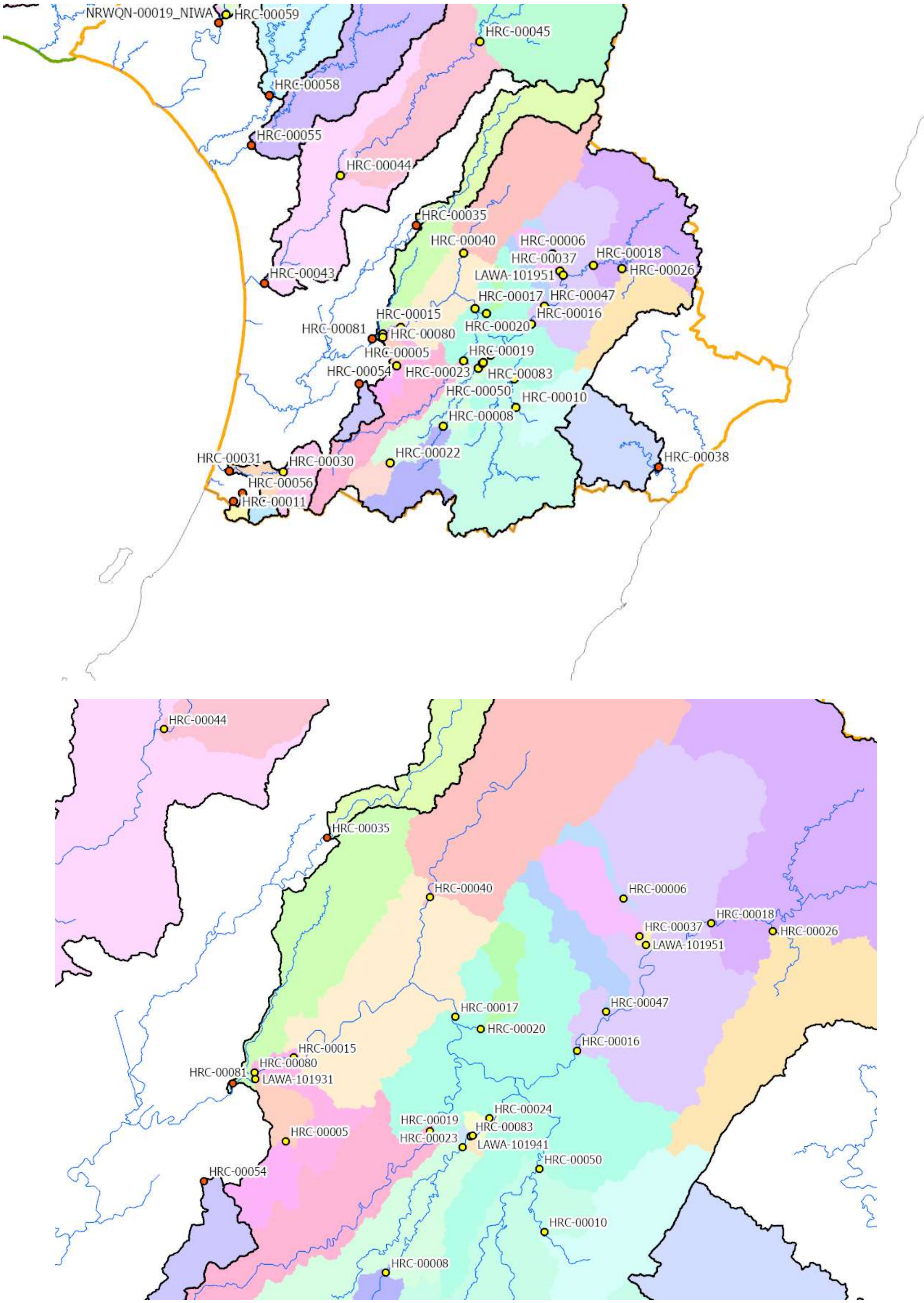

Figure C-4: Central and south Manawatū-Whanganui water monitoring sites used for calibration. Bottom map shows detail for the Manawatū River catchment.

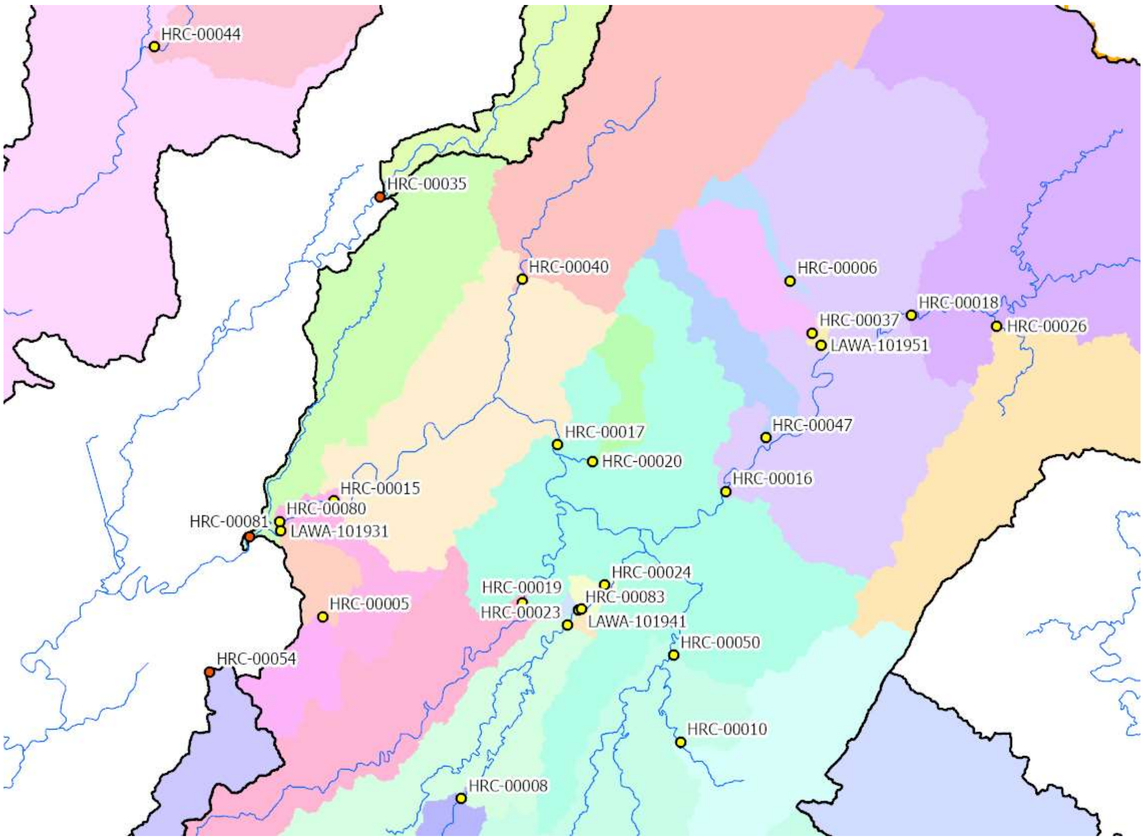

Figure C-5: Manawatū catchment detail map.

Appendix D Measured and modelled loads and yields for sites included in the calibration

Table D-1 (Taranaki) and Table D-2 (Manawatū-Whanganui) give the measured and modelled mean annual loads and yields for the calibration monitoring sites. The top 5 % of flow rates were removed from the flow record for load calculation (see Section 3.1). In each table, where there are multiple nested sites in the same catchment, the sites have been grouped by the most downstream site and are ordered from upstream to downstream according to their REC flow sequence number (Hydroseq).

Table D-1: Taranaki measured and modelled mean annual loads and yields determined for the calibration monitoring sites.

Catchment (most downstream site)	Site LAWA ID	Site name	Load (peta organisms/y)		Yield (peta organisms/km^2/y)	
			Measured	Modelled	Measured	Modelled
NRWQN-00036_NIWA	NRWQN-00035_NIWA	WA2 Manganui at SH3	0.24	0.40	0.0166	0.0272
	NRWQN-00036_NIWA	WA1 Waitara at Bertrand Rd	25.99	18.76	0.0233	0.0168
TRC-00001	TRC-00001	Mangaehu at Raupuha Rd Bridge	2.19	2.87	0.0053	0.0069
TRC-00003	TRC-00003	Mangaoraka at Corbett Rd	1.10	1.58	0.0204	0.0294
TRC-00005	TRC-00005	Patea at Skinner Rd	3.01	2.39	0.0372	0.0295
TRC-00010	TRC-00009	Waingongoro at Eltham Rd Bridge	0.85	0.85	0.0168	0.0169
	TRC-00010	Waingongoro at SH45	1.80	2.82	0.0080	0.0125
TRC-00011	TRC-00011	Waiwhakaiho at SH3	3.12	2.52	0.0518	0.0418

Table D-2: Manawatū-Whanganui measured and modelled mean annual loads and yields determined for the calibration monitoring sites.

Catchment (most downstream site)	Site LAWA ID	Site name	Load (peta organisms/y)		Yield (peta organisms/km²/y)	
			Measured	Modelled	Measured	Modelled
HRC-00011	HRC-00011	Manakau at SH1 Bridge	0.06	0.08	0.0041	0.0051
HRC-00031	HRC-00030	Ōhau at Gladstone Reserve	0.08	0.31	0.0008	0.0029
	HRC-00031	Ōhau at Haines Property	0.29	0.65	0.0019	0.0042
HRC-00035	HRC-00035	Ōroua at Almadale Slackline	3.08	0.93	0.0101	0.0031
HRC-00038	HRC-00038	Owahanga at Branscombe Bridge	1.69	2.82	0.0053	0.0089
HRC-00043	HRC-00046	Rangitīkei at Pukeokahu	0.45	0.73	0.0006	0.0010
	HRC-00003	Hautapu at Alabasters	0.52	0.39	0.0019	0.0014
	HRC-00045	Rangitīkei at Mangaweka	1.64	3.71	0.0006	0.0014
	HRC-00044	Rangitīkei at Onepuhi	6.50	6.45	0.0020	0.0020
	HRC-00043	Rangitīkei at McKelvies	11.09	11.40	0.0029	0.0029
HRC-00054	HRC-00054	Tokomaru at Horseshoe Bend	0.14	0.08	0.0025	0.0015
HRC-00055	HRC-00055	Turakina at ONeills Bridge	3.16	3.79	0.0037	0.0045
HRC-00056	HRC-00056	Waikawa at North Manakau Rd	0.04	0.05	0.0014	0.0015
HRC-00058	HRC-00009	Makotuku at SH49A	0.03	0.02	0.0010	0.0009
	HRC-00007	Makotuku at Raetihi	0.13	0.17	0.0021	0.0027
	HRC-00066	Makotuku at Above Sewage Plant	0.18	0.24	0.0026	0.0034
	LAWA-101929	Makotuku at d/s Raetihi STP	0.11	0.24	0.0015	0.0034
	HRC-00028	Mangawhero at Pakihi Rd Bridge	0.29	0.36	0.0021	0.0026
	HRC-00053	Tokiahuru at Junction	0.33	0.17	0.0015	0.0007
	HRC-00058	Whangaehu at Kauangaroa	7.24	5.76	0.0038	0.0030
HRC-00081	HRC-00006	Kūmeti at Te Rehunga	0.04	0.05	0.0032	0.0041
	HRC-00040	Pohangina at Mais Reach	1.67	1.81	0.0034	0.0037
	HRC-00037	Ōruakeretaki at SH2 Napier	0.32	0.34	0.0058	0.0064
	LAWA-101951	Ōruakeretaki at d/s PPCS Ōringi STP	0.17	0.35	0.0031	0.0062

Catchment (most downstream site)	Site LAWA ID	Site name	Load (peta organisms/y)		Yield (peta organisms/km^2/y)	
			Measured	Modelled	Measured	Modelled
HRC-00081	HRC-00047	Raparapawai at Jackson Rd	0.29	0.31	0.0063	0.0069
	HRC-00020	Mangapapa at Troup Rd	0.20	0.24	0.0074	0.0089
	HRC-00026	Mangatoro at Mangahei Road	0.77	1.44	0.0035	0.0065
	HRC-00018	Manawatū at Weber Road	1.39	4.39	0.0019	0.0061
	HRC-00016	Manawatū at Hopelands	3.67	8.63	0.0029	0.0068
	HRC-00005	Kahuterawa at Johnstons Rātā	0.15	0.06	0.0039	0.0017
	HRC-00010	Mākuri at Tuscan Hills	1.46	0.86	0.0107	0.0063
	HRC-00022	Mangatainoka at Larsons Road	0.88	0.54	0.0151	0.0092
	HRC-00019	Mangahao at Ballance	7.77	1.50	0.0278	0.0054
	HRC-00008	Mākākahi at Hāmua	2.19	1.44	0.0133	0.0088
	HRC-00023	Mangatainoka at Pahiatua Town Br	4.81	3.70	0.0120	0.0092
	HRC-00083	Mangatainoka at u/s Pahiatua STP	2.99	3.73	0.0074	0.0092
	LAWA-101941	Mangatainoka at d/s Pahiatua STP	4.09	3.83	0.0100	0.0094
	HRC-00024	Mangatainoka at Brewery - SH2 Br	4.75	3.88	0.0115	0.0094
	HRC-00050	Tīraumea at Ngāturi	5.26	5.53	0.0069	0.0073
	HRC-00017	Manawatū at Upper Gorge	50.87	23.26	0.0159	0.0073
	HRC-00015	Manawatū at Teachers College	41.73	27.71	0.0107	0.0071
	HRC-00080	Manawatū at u/s PNCC STP	52.23	28.24	0.0132	0.0071
	LAWA-101931	Manawatū at d/s PNCC STP	54.99	28.55	0.0136	0.0071
	HRC-00081	Manawatū at u/s Fonterra Longburn	107.10	31.58	0.0254	0.0075
NRWQN-00019_NIWA	HRC-00033	Ōngarue at Taringamotu	4.26	3.93	0.0039	0.0036
	HRC-00032	Ōhura at Tokorima	4.93	6.45	0.0074	0.0096
	HRC-00060	Whanganui at Pipiriki	21.81	28.35	0.0036	0.0047
	HRC-00059	Whanganui at Te Rewa	33.59	29.71	0.0051	0.0045
	NRWQN-00019_NIWA	WA4 Whanganui at Paetawa	53.12	29.73	0.0080	0.0045

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