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Northland Sediment Study: *E. coli* modelling

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E. coli modelling

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August 2015

Prepared by:
Christopher Palliser
Sandy Elliott
Sharleen Yalden

For any information regarding this report please contact:

Chris Palliser
Scientist
Catchment Processes
+64-7-856 1748
chris.palliser@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
PO Box 11115
Hamilton 3251

Phone +64 7 856 7026

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Mal Green	Reviewed by:	Malcolm Green
A. Bartley	Formatting checked by:	Alison Bartley
	Approved for release by:	David Roper

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Executive summary

The Northland Sediment Study (NSS) aims to integrate science and economics to assess the potential economic costs of achieving sediment and microbiological water quality objectives in Whangarei Harbour and in the streams and rivers that drain into the Whangarei Harbour.

The NSS comprises two objectives:

1. Development of model frameworks and outputs that will enable the assessment of catchment sediment and *E. coli* loads, and the expression of the environmental outcomes of these loads as attributes.

2. Incorporation of the model frameworks and outputs developed in Objective 1 into a catchment economic model that will be used to identify cost-effective ways to manage sediment and *E. coli* loads in the Whangarei Harbour catchment.

This report documents the development and calibration of a customised version of the CLUES model for *E. coli* for the Northland region, with specific emphasis given to the Whangarei Harbour catchment. The model was calibrated to as many suitable sites in the region as possible, rather than just to those sites within the harbour catchment, in order to improve the model predictions for the harbour catchment. Water quality modelling focussed on 11 "nodes of importance" in the Whangarei Harbour catchment that were identified by the NRC.

This modelling was undertaken to provide input to an economic model (developed by Dr Adam Daigneault of Landcare Research). The economic model addresses the financial implications of adopting various mitigation strategies on pasture land within the harbour catchment that may be required to achieve concentration targets as described in the NPSFM (2014).

Model calibration and predictions

Twenty-five of 73 water quality monitoring sites in Northland satisfied three selection criteria, and were selected for model calibration. Five of these sites fell within the Whangarei Harbour catchment.

A rating curve method was used to calculate stream loads using measured *E. coli* concentrations and measured or estimated stream flows. *E. coli* loads were calculated for catchments defined according to the REC2 subcatchment classification. There were 655 of these subcatchments within the Whangarei Harbour catchment. Areas of land that discharged directly to the harbour were grouped into a single pseudo-catchment and treated as other catchments.

During the model calibration phase, key model parameters were optimised to minimise the RMSE of the overall model load prediction. The RMSE for load prediction[1] was 0.56, with an R^2 value of 0.86. The RMSE, in non-log space, for specific load (or yield) prediction was 0.31, with an R^2 value of 0.62. The calibration process identified that the model was relatively insensitive to land use – it was therefore expedient to group deer, dairy, and sheep and beef land uses in a "pasture" land use group, and several other land uses in a "non-pasture" land use group. The latter included native and exotic forestry.

E. coli loads were estimated for wastewater treatment plants within the Whangarei Harbour catchment, and for farm dairy effluent ponds across Northland. Within the Whangarei Harbour

[1] The natural logarithm of the loads was used.

catchment, the model accounted for three municipal wastewater discharges, and five dairy shed effluent ponds.

Model predictions were counter-intuitive for some land use types. For example, selected forested catchments in Northland exhibited *E. coli* concentrations that were larger than those predicted for catchments where pastoral land use was dominant.

Within the Whangarei Harbour catchment, the model predicted that the overwhelming bulk of the *E. coli* load was derived from streams flowing directly into the harbour, rather than the pseudo-catchment or point source discharges.

Reliability of model predictions

Some key points relevant to management of *E. coli* sources arise from this modelling exercise. It is important to keep these in mind when interpreting the ultimate findings from economic and mitigation modelling:

- Point sources and dairy shed effluent represent a small proportion of the *E. coli* load input to Whangarei harbour. There are also very few dairy sheds in the Whangarei harbour catchment. Although improved management and disposal of dairy shed effluent is likely to be one of the first control measures implemented, the effect of the improved management of these on the concentrations observed at nodes of importance and the loads entering the harbour are likely to be minor.
- At this stage we are unable to reliably differentiate between the contribution from dairy and other pastoral activities to *E. coli* loads (apart from the influence of dairy effluent).
    - The overall loading from pasture is approximately six times larger than that from forested areas.
    - Runoff from some of the forested catchments have unexpectedly high *E. coli* concentrations. This applies especially to sites in the Whangarei Harbour catchment.
    - This information implies that reducing *E. coli* loads by controlling pasture sources alone may not be sufficient to achieve concentration targets.
    - We recommend investigation of some of the forested catchments, to identify the sources of *E. coli*, and identify those measures most likely to minimise *E. coli* concentrations in runoff.
- Overall, there is high uncertainty in model predictions, due to currently unknown factors. This uncertainty should be acknowledged when:
    - determining risks (i.e., which catchments should be prioritised for implementation of mitigation strategies?), and
    - prioritising investment (i.e., which mitigation tools should be implemented, and where should they be implemented in the catchment).

Stream flows and *E. coli* concentrations are not currently measured at all of the sites of interest in the catchment (nodes of importance). The estimated concentrations and loads at some of these sites are high and relatively uncertain. It would be advantageous to monitor *E. coli* at these nodes to improve load estimates.

1 Introduction

1.1 The Northland Sediment Study

Northland Regional Council (NRC) has identified that sediment and *E. coli* are key water quality challenges in the Northland region (e.g., Ballinger et al. 2014).

As a result, the Ministry for Primary Industries (MPI) commissioned the Northland Sediment Study (NSS).

The aim of the NSS is to develop a model that will integrate science and economics to assess the potential economic costs of meeting a range of attribute states[2] for sediment and *E. coli* in the Whangarei Harbour and freshwater environments that drain into the Whangarei Harbour.

The Northland Sediment Study comprises two objectives:

1. Develop model frameworks and outputs that will enable the assessment of catchment sediment and *E. coli* loads and the expression of the environmental outcomes of these loads as attributes. MPI has contracted NIWA to deliver this objective.

2. Incorporate the model frameworks and outputs developed in Objective 1 into a catchment economic model that will be used to identify cost-effective ways to manage sediment and *E. coli* loads in the Whangarei Harbour catchment. MPI is contracting another provider to deliver this objective.

Objective 1 of the NSS comprises six workstreams.

- **Workstream A** – Preparation. The tasks in Workstream A are: identify catchment locations for attribute evaluation; identify harbour habitats for attribute evaluation; digest feedback from November 19 (2014) workshop convened by the Ministry for the Environment on possible sediment attributes; develop thinking on possible *E. coli* attributes for freshwater and the estuary receiving waters, including a methodology for evaluating possible *E. coli* attributes from the products of the catchment and estuary modelling.

- **Workstream B** – Attributes. The tasks in Workstream B are: make final choice of estuary sediment attributes; make final choice of freshwater sediment attributes; make final choice of freshwater and estuary *E. coli* attributes.

- **Workstream C** – Whangarei catchment modelling. The tasks in Workstream C are: SedNetNZ sediment modelling; CLUES *E. coli* modelling.

- **Workstream D** – Mitigation costs and efficiencies. The task in Workstream D is to agree on and specify mitigation (sediment and *E. coli*) costs and efficiencies to be included in the economic model.

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[2] The words "attribute" and "state" herein have the meanings ascribed by the National Policy Statement for Freshwater Management (NPSFM) (2014). An "attribute" is a measurable characteristic of freshwater, including physical, chemical and biological properties that support particular values. An "attribute state" is the level to which an attribute is to be managed to provide for a particular value.

- **Workstream E** – Whangarei Harbour sediment budget. The task in Workstream E is to establish an annual-average sediment budget for Whangarei Harbour.

- **Workstream F** – external review.

The products from each workstream are to be provided to Objective 2 for incorporation in the catchment economic model.

1.2 The National Policy Statement for Freshwater Management

The National Policy Statement for Freshwater Management (NPSFM) (amended in 2014) establishes a legal and policy framework for building a national limits-based scheme for freshwater management. The Policy requires maintaining or improving overall water quality in a region and safeguarding of the life-supporting capacity, ecosystem processes and indigenous species (including their associated ecosystems) of freshwater. It also requires protection of (secondary) contact recreation.

Regional councils are required to have set freshwater objectives by 2030 that reflect national and local values; set flow, allocation and water quality limits to ensure freshwater objectives are achieved; address over-allocation; manage landuse and water in an integrated way; and involve iwi and hapū in freshwater decision-making. Councils and communities can choose the timeframes to meet freshwater objectives and limits.

The management process prescribed by the NPSFM centres on limiting resource use in “freshwater management units” in order to achieve specific, agreed values. The steps involved are:

- Agree on desired values, which are the intrinsic qualities that people appreciate or benefit from, or the uses to which people put freshwater. Examples are mahinga kai (Maori traditional food and other natural resources, including the places they are obtained and the practices around their acquisition) and swimming.

- For each value, identify the aspects to be managed. For example, for the value of ecosystem health, the aspects to be managed might include trophic state, toxicants and light.

- For each aspect to be managed, identify attributes. Attributes are the characteristics or properties of freshwater associated with each aspect to be managed. Examples are *E. coli* contamination, which is reflective of a health risk, or the DIN burden, which has a bearing on aesthetics (e.g., by stimulating periphyton blooms).

- Decide on the state of each attribute that is necessary to provide for the value at the desired level. This might be a particular DIN concentration during low flow.

- Convert attribute states into “SMART” (specific, measurable, achievable, realistic and time-bound) management objectives.

- Formulate limits to resource use that will result in the achievement of the objectives. There are two types of limit: limits to extraction (e.g., the amount of water taken for irrigation) and limits to disposal of contaminants (e.g., dairy-shed effluent).

- Develop a suite of management actions that, when implemented, will limit resource use accordingly.

The relationships between values, attributes and states in a range of freshwater environments are codified in the National Objectives Framework (NOF).

Estuaries and coastal systems are specifically excluded from consideration in the NPSFM, but they must be "given regard to" when setting limits for freshwater.

The Northland Sediment Study is designed to answer the question: what might it cost to manage, under the NPSFM, sediment and *E. coli* across a whole catchment that includes an estuary at the base of the freshwater drainage network?

The question is to be answered by developing a catchment economic model that links together sources and sinks of sediment and *E. coli* and overlays mitigation costs and efficiencies. Put simply, the model will allow different types and levels of mitigation to be applied to the catchment and will show, firstly, how sediment and *E. coli* in the waterways and in the estuary change as a result and, secondly, the costs incurred in applying the mitigation.

1.3 This report

This report, which arises from **Workstream C** – Whangarei catchment modelling, describes the *E. coli* modelling for the Whangarei Harbour catchment.

The model is calibrated to current *E. coli* loads in the river drainage network (see Figure 1-1). Although MPI and NRC are primarily interested in the Whangarei Harbour catchment, it was decided that the model would be calibrated to all suitable sites in the Northland region to prepare for any future region-wide application of the model.

MPI and NRC also required the current *E. coli* loads entering Whangarei Harbour and the current *E. coli* concentrations at 11 sites in the harbour catchment to be estimated. These sites are identified as 'nodes of importance' in this report (see Figure 2-5).

The Catchment Land Use for Environmental Sustainability model (CLUES; Elliott et al. 2005, Semadeni-Davies et al. 2011) was identified as a suitable model for estimating contaminant loads and concentrations. CLUES has been set up on a regional basis and has been calibrated nationally. However, to update and improve the spatial representation of the catchment, the CLUES model was customised (called 'customised CLUES' in this report) and recalibrated specifically for this application.

Customisations included:

- Introduction of a slope term.
- Adjustment of model parameters where appropriate to improve the fit of model predictions with measured loads.
- Use of a formal method for assessing goodness-of-fit and the variability and inter-dependency of the adjusted model parameters.

This report describes the development and calibration of the customised CLUES model using 2011 land use in the Northland region. The 2011 land use data were provided by Dr John Dymond of Landcare Research. Customised CLUES was calibrated against measured *E. coli* loads, which were determined from *E. coli* concentrations and flow data from a number of sites in the region.

This report describes the customisations and the processes followed to identify sites suitable for calibration, and compares modelled or predicted loads with measured loads. Recent use of CLUES to predict contaminant loads in the Waitaki catchment was described by Palliser et al. (2015).

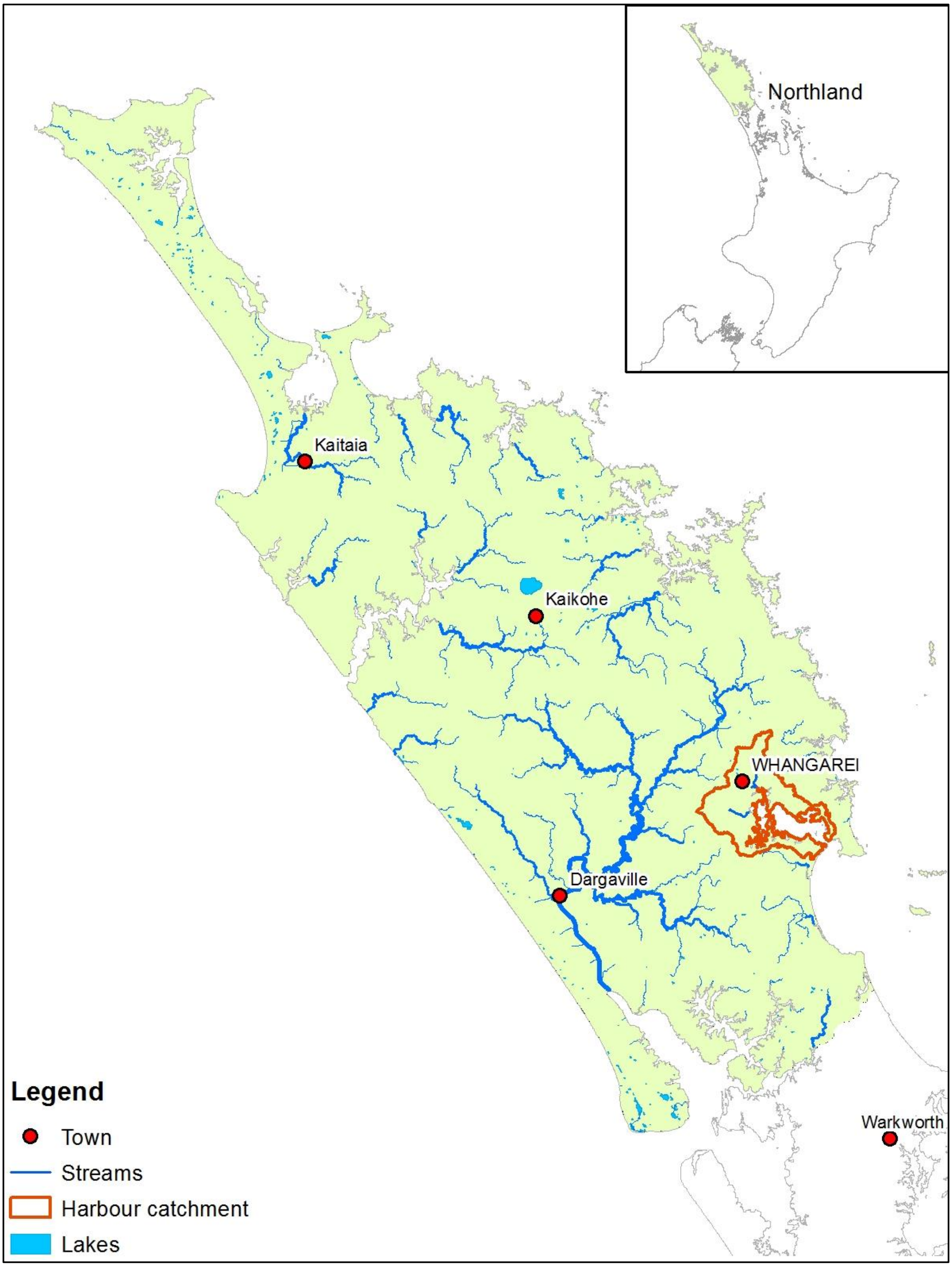


Figure 1-1: Northland region showing streams of order ≥ 3, lakes, major towns and the Whangarei Harbour catchment.

2 Method

2.1 Overview

The CLUES model determines mean annual loads of *E. coli*. The catchment of interest is broken into REC2 subcatchments, and each subcatchment has a number of landuses with associated yields, which are modified according to environmental factors such as rainfall. These sources are accumulated and decayed down the stream network, with addition of point source loading. This gives estimated loads for each stream reach in the catchment.

The various parameters in the model are determined by calibration to measured loads. Rather than using parameters from national calibration exercises, we re-calibrated the model for Northland using data from 25 suitable sites, including five sites in the Whangarei Harbour catchment. The resulting parameters were then applied to the Whangarei catchment.

After calibration, the loads for all the streams became known as the 'current loads', because they were based on the current (2011) land use. The current loads estimated for 655 streams in the harbour catchment represented the baseline load used by the economic model. Thereafter, the economic model applies the relative efficiencies of different mitigation options to estimate the change in load from the current load for each defined land cover (pasture, forest, other) in each of the 655 streams. For example, fencing a stream along a dairy farm is assumed to reduce *E. coli* loads from that farm by approximately 60%.

The predicted *E. coli* loads were converted to *E. coli* concentrations. A linear relationship between load and concentration was assumed, i.e., if a mitigation option reduces loads by X%, then current concentrations were assumed to reduce by X% as well. This linearity assumption has not been validated with experimental data because it would require long-term observations covering a period of substantial change. It is possible to envisage situations where the relationship may break down, such as under large climate shifts, timing of loading, or large land-use changes. Nevertheless, this is a reasonable assumption, and significantly more detailed modelling and measurement would be required to improve upon it.

The economic model focuses on calculated concentrations at the so-called 'nodes of importance' – 11 sites in the harbour catchment identified by NRC as being of particular value. The current concentrations at those locations were determined from measurements where available, or were estimated from the estimated current loads and flow rates (see Section 2.7).

The *E. coli* load to the Whangarei harbour was also determined. While *E. coli* loads into the harbour are not being investigated by the economic model, changes in harbour *E. coli* loads are still considered to be of interest as co-benefits from policies for controlling sediment loading to the harbour and *E. coli* concentrations in stream. For example, fencing undertaken to reduce streambank erosion will also reduce *E.coli* losses from that farm.

2.2 Calibration sites and measured loads

Water quality sites were deemed suitable for model calibration if they had more than 50 *E. coli* observed data points[3] with corresponding flow data.

[3] Otaika at Otaika Valley Road (site number 100431) being the only exception to this, having n = 48.

Censored data are data reported by a laboratory as less than or greater than a numeric value. Censoring was minimal: ≤ 6% for the RWQMN (River Water Quality Monitoring Network) sites and ≤ 8% for sites used to assess recreational water quality (the latter are sampled more frequently, but only in the summer months). The censored values included < 10 cfu/100 ml (cfu stands for colony forming unit) and > values. For this work these censored concentrations were set at the < and > values, e.g., "<10 cfu/100 mL" was used as "10 cfu/100 mL".

Application of the criteria above excluded seven of the 43 RWQMN (River Water Quality Monitoring Network) sites, and 16 of the 30 recreational water quality monitoring sites, giving a total of 50 sites.

Mean annual loads for suitable sites were calculated for all of these sites using rating curve methods. The methods fit a rating curve to the relationship between concentration and flow, and then apply this relationship to continuous flow records over the time period of interest (20 years in this case). Two separate load values were determined: a) using all flows (L_A) and b) using only flows below the 95th percentile of flows (L_{95}). The reasoning is that L_A is of interest for harbour loading, but L_{95} estimates have less error (because they omit the uncertain contributions from storms) and are more relevant to normal flow conditions. In order to establish the variation in L_A and L_{95}, the ratio of the upper 90% confidence interval (CI) to the lower 90% confidence interval was calculated for L_A, (i.e., (90% upper CI L_A) / (90% lower CI L_A)) and for L_{95}, using bootstrap resampling[4] of the concentration data. The results are given in Table 2-1. Because of the wide variation in the ratio for L_A, calibration of the customised CLUES was limited to L_{95}.

Table 2-1: The mean annual load ratio of the upper 90% CI to the lower 90% CI for the RWQMN sites. L_A represents the load calculated for all flow conditions, and L_{95} represents loads calculated for flows less than the 95th percentile.

(90% upper CI L_A) / (90% lower CI L_A)			(90% upper CI L_{95}) / (90% lower CI L_{95})		
Range	Mean	Standard deviation	Range	Mean	Standard deviation
3.4–592.9	51.5	114.3	1.5–10.3	3.4	2.5

The rating curve method requires a flow record, but flow data are not recorded at all water quality monitoring sites. For several water quality sites, there was not a flow recorder at the actual site, but there was a suitable record within a reasonable distance to generate a synthetic flow record. These records were provided by the NRC. A rating curve method based on Generalised Additive Modelling (GAM) was used to calculate measured loads, as used in Palliser et al. (2015). However if:

- no concentration-vs-flow rating curve was available for a site because there was no nearby flow site, or
- there was too much uncertainty in the calculated load, i.e.,
  - the standard deviation of the natural logarithms of bootstrap replicates for $L_{95} > 1$, or
  - (95% lower CI L_{95}) / (L_{95}) < 0.5, or

[4] Random sampling with replacement.

- (95% upper CI L_{95}) / (L_{95}) > 2.0,

then the site was discarded[5]. Twenty-five of the 50 sites were deemed suitable for calibration purposes (23 RWQMN and two recreational sites). Figure 2-1 shows the location of the 25 calibration sites, Figure 2-3 shows the location of the five calibration sites within the Whangarei Harbour catchment, and Table 2-3 summarises measured concentrations and flows.

[5] These criteria could equally apply to specific loads or yields, peta *E. coli*/ha-y.

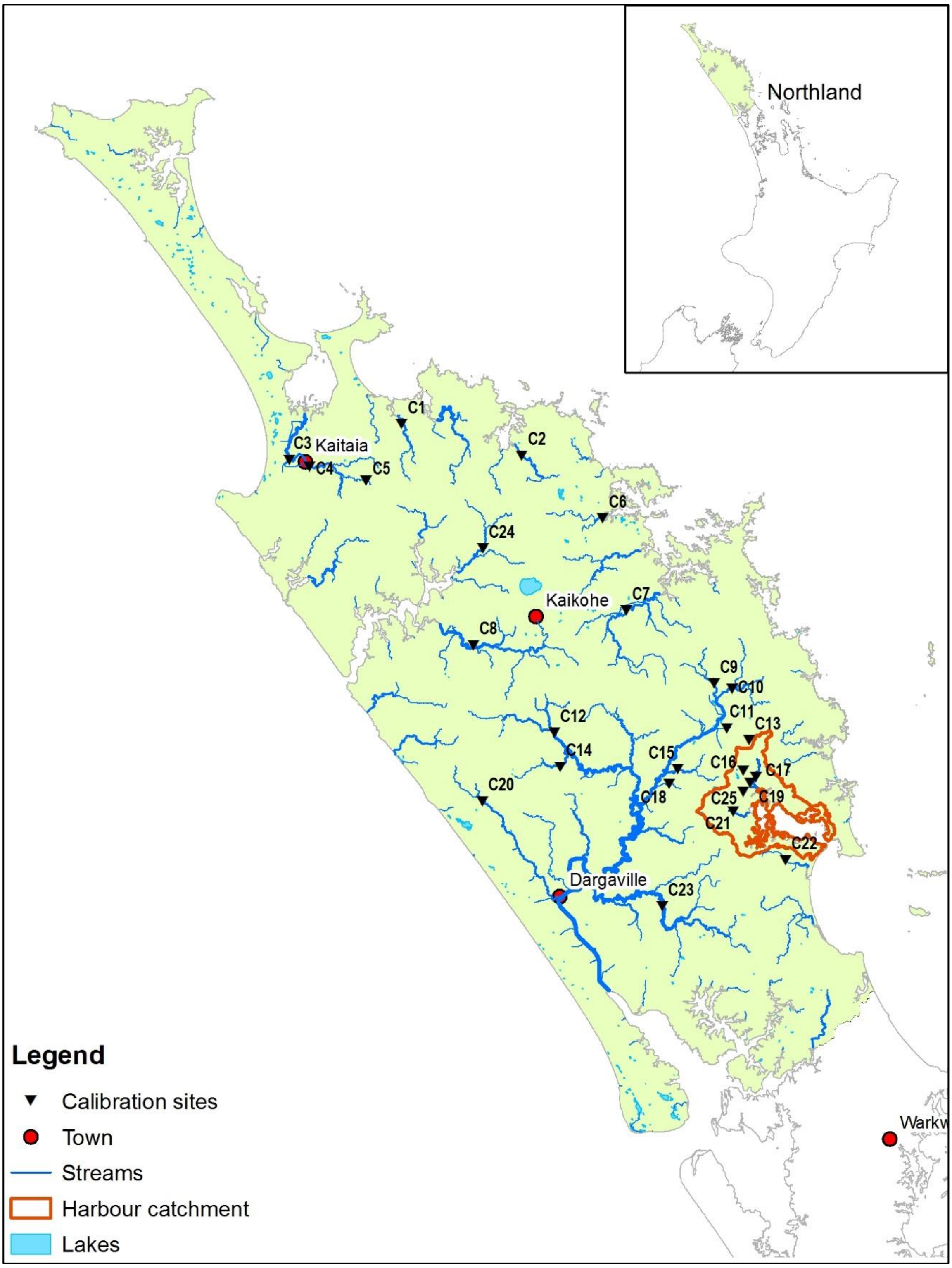


Figure 2-1: Northland region showing streams of order ≥ 3, lakes, major towns, the Whangarei Harbour catchment and the calibration sites. See Table 2-2 for a list of sites (denoted by C).

Table 2-2: Map key for calibration sites. Blue text indicates sites in the Whangarei Harbour catchment.

Label	Name, site ID
C1	Oruru at Oruru Road, 108979
C2	Kaeo at Dip Road Bridge, 102674
C3	Awanui at Waihue Channel, 100370
C4	Awanui at FNDC take, 100363
C5	Victoria at Thompsons Bridge, 105532
C6	Kerikeri at Stone Store, 101530
C7	Waiharakeke at Stringers Road Walking Bridge, 100007
C8	Punakitere at Taheke, 105231
C9	Waiotu at SH1 Bridge, 102248
C10	Whakapara at Cableway, 102249
C11	Mangahahuru at Apotu Road Bridge, 100281
C12	Mangakahia at Twin Bridges, 109096
C13	Mangahahuru at end Of Main Road, 100237
C14	Opouteke at Suspension Bridge, 102258
C15	Mangere at Knight Road Bridge, 101625
C16	Waharohia at Waikahitea Confluence, 107773
C17	Hatea at Mair Park Foot Bridge, 100194
C18	Waipao at Draffin Road Bridge, 108941
C19	Waiarohia at Second Ave, 108359
C20	Kaihu at Gorge, 102256
C21	Otaika at Otaika Valley Road, 110431
C22	Ruakaka at Flyger Road Bridge, 105008
C23	Manganui at Mitaitai Road, 102257
C24	Waipapa River at Puketi Forest, 103248
C25	Raumanga Stream, 103246

2.2.1 Land areas around the harbour fringe

The REC (River Environment Classification) network on which CLUES is based did not extend to the shoreline fringes of the Whangarei Harbour. This area (called 'pseudo-catchments' in this report) is 3814 ha in extent and represents 14% of the total area of the harbour catchment (see Table A-1 in Appendix A for the percentage of land use by area for the pseudo-catchments). There were 61 pseudo-catchments across the harbour catchment and their loads were obtained in a similar way to CLUES, i.e., multiplying the area of each land use in a pseudo-catchment by its yield coefficient (peta *E. coli*/ha/y), and then summing the individual load estimates. The yields were obtained from the model calibration as explained later. Unlike the rest of customised CLUES catchment areas, the loads from these areas were assumed to discharge directly to the harbour unattenuated.

Table 2-3: Calibration site data in Northland. Concentration data over the last 20 and last 5 years. Flow data over the last 20 years. Raumanga Stream (103246) and Waipapa River at Puketi Forest (103248) are Recreational sites, Kerikeri at Stone Store (101530) is both a RWQMN and Recreational site, Waipapa River at Puketi Forest is both a RWQMN (101751) and Recreational site (103248), the rest are RWQMN sites. Blue text indicates sites in the Whangarei Harbour catchment.

Water quality sites								Site from which flow was obtained		
Site name	Site ID	N/period		Measured median concentration (cfu/100 ml) /period		Measured 95th percentile concentration (cfu/100 ml) /period		Site name	Site ID	Measured mean flow (L/s)
		20 yr	5 yr	20 yrs	5 yrs	20 yrs	5 yrs			
Waiharakeke at Stringers Road Walking Bridge	100007	101	59	379	379	3978	6696	Waiharakeke at Willowbank	3819	5232
Hatea at Mair Park Foot Bridge	100194	90	67	302	259	7270	6306	Hatea at Whareora Road	5538	1333
Mangahahuru at end Of Main Road	100237	113	59	228	323	2042	2402	Mangahahuru at County Weir	46674	646
Mangahahuru at Apotu Road Bridge	100281	184	58	494	457	3943	4001	Mangahahuru at County Weir [a]	46674	962
Awanui at FNDC take	100363	153	58	272	269	1970	2036	Awanui at School Cut	1316	8340
Awanui at Waihue Channel	100370	381	73	307	246	4663	4824	Awanui at School Cut [b]	1316	9113
Kerikeri at Stone Store	101530	246	225	245	216	7270	8918	Maungaparerua at Tyrees Ford [c]	3506	5256
Mangere at Knight Road Bridge	101625	242	74	583	512	17264	22460	Mangere at Knights Road	46646	1717
Waiotu at SH1 Bridge	102248	176	59	357	384	4278	5570	Waiotu at SH1 Bridge	46627	4629

Water quality sites								Site from which flow was obtained		
Site name	Site ID	N/period		Measured median concentration (cfu/100 ml) /period		Measured 95th percentile concentration (cfu/100 ml) /period		Site name	Site ID	Measured mean flow (L/s)
		20 yr	5 yr	20 yrs	5 yrs	20 yrs	5 yrs			
Whakapara at Cableway	102249	183	58	187	231	6621	6176	Whakapara at Cableway	46632	7202
Kaihu at Gorge	102256	150	60	148	173	4106	6131	Kaihu at Gorge	4611	3969
Manganui at Mitaitai Road	102257	157	59	122	146	3134	896	Manganui at Permanent Station	46651	7475
Opouteke at Suspension Bridge	102258	178	60	158	157	1680	2102	Opouteke at Suspension Bridge	1046651	3997
Kaeo at Dip Road Bridge	102674	99	59	650	703	5794	6176	Kaeo at Fire Station [d]	2624	4261
Raumanga Stream	103246	143	79	228	211	3255	3076	Raumanga at Bernard Street	5528	345
Waipapa River at Puketi Forest	103248	91	49	63	58	1219	1043	Waipapa at Forest Ranger	47804	5253
Ruakaka at Flyger Road Bridge	105008	101	59	633	747	9177	11248	Ruakaka at Flyger Road	5901	875
Punakitere at Taheke	105231	161	60	399	471	3477	2964	Punakitere at Taheke	47595	6918
Victoria at Thompsons Bridge	105532	179	56	160	158	1333	1144	Victoria at Victoria Valley Road	1351	999

Water quality sites								Site from which flow was obtained		
Site name	Site ID	N/period		Measured median concentration (cfu/100 ml) /period		Measured 95th percentile concentration (cfu/100 ml) /period		Site name	Site ID	Measured mean flow (L/s)
		20 yr	5 yr	20 yrs	5 yrs	20 yrs	5 yrs			
Waharohia at Waikahitea Confluence	107773	100	45	521	525	2948	3485	Waiarohia at Lovers Lane	5527	257
Waiarohia at Second Ave	108359	121	66	399	399	4586	5421	Waiarohia at Lovers Lane	5527	409
Waipao at Draffin Road Bridge	108941	101	60	602	613	6840	8239	Waipao at Draffin Road	46641	825
Oruru at Oruru Road	108979	95	66	275	262	5567	7794	Oruru at Saleyards	1903	2899
Mangakahia at Twin Bridges	109096	77	59	122	128	3666	4113	Mangakahia at Gorge	46618	12365
Otaika at Otaika Valley Road	110431	48	48	484	484	4378	4378	Otaika at Kay	5659	919

[a] Synthetic record created from Mangahahuru at County Weir as advised by NRC. [b] Synthetic record created from Awanui at School Cut as advised by NRC. [c] Although nearest flow site is Kerikeri at Peacock Gardens, it only has 18 months of record and has not been processed to any degree of accuracy. A rough correlation was therefore done from mean to low flow between Kerikeri at Peacock Gardens and the NIWA flow station Maungaparerua at Tyrees Ford as advised by NRC. [d] Flow site not rated above low flows (NRC).

2.3 Land use

Land use was provided by Dr John Dymond of Landcare Research for the Northland region and is the 2011 land use – see Figure 2-2 and Figure 2-3.

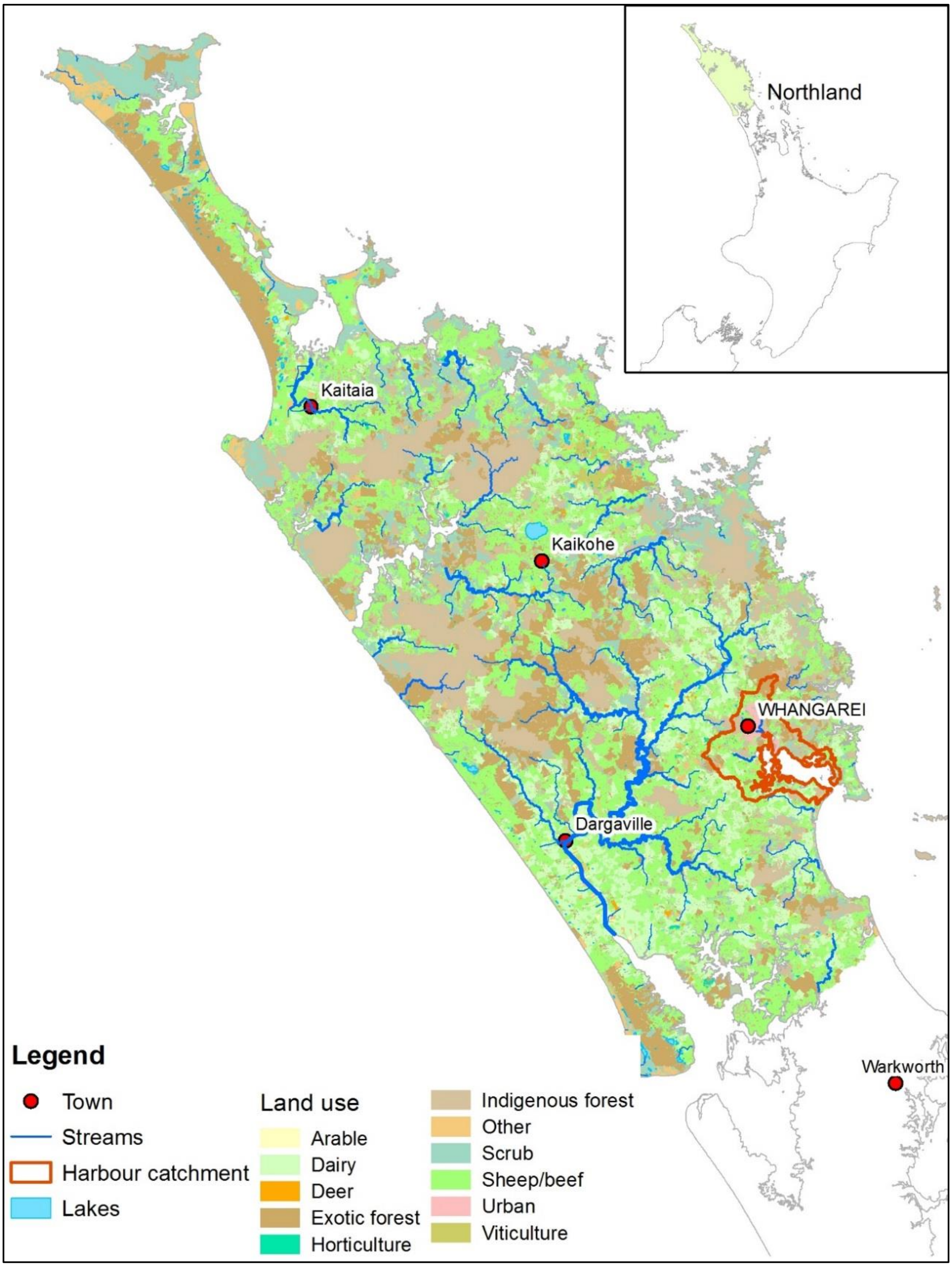


Figure 2-2: Northland region showing streams of order ≥ 3, lakes, major towns, the Whangarei Harbour catchment and the land use. See Table A-1 in Appendix A for the proportion of land use by area for each of the watersheds of the calibration sites.

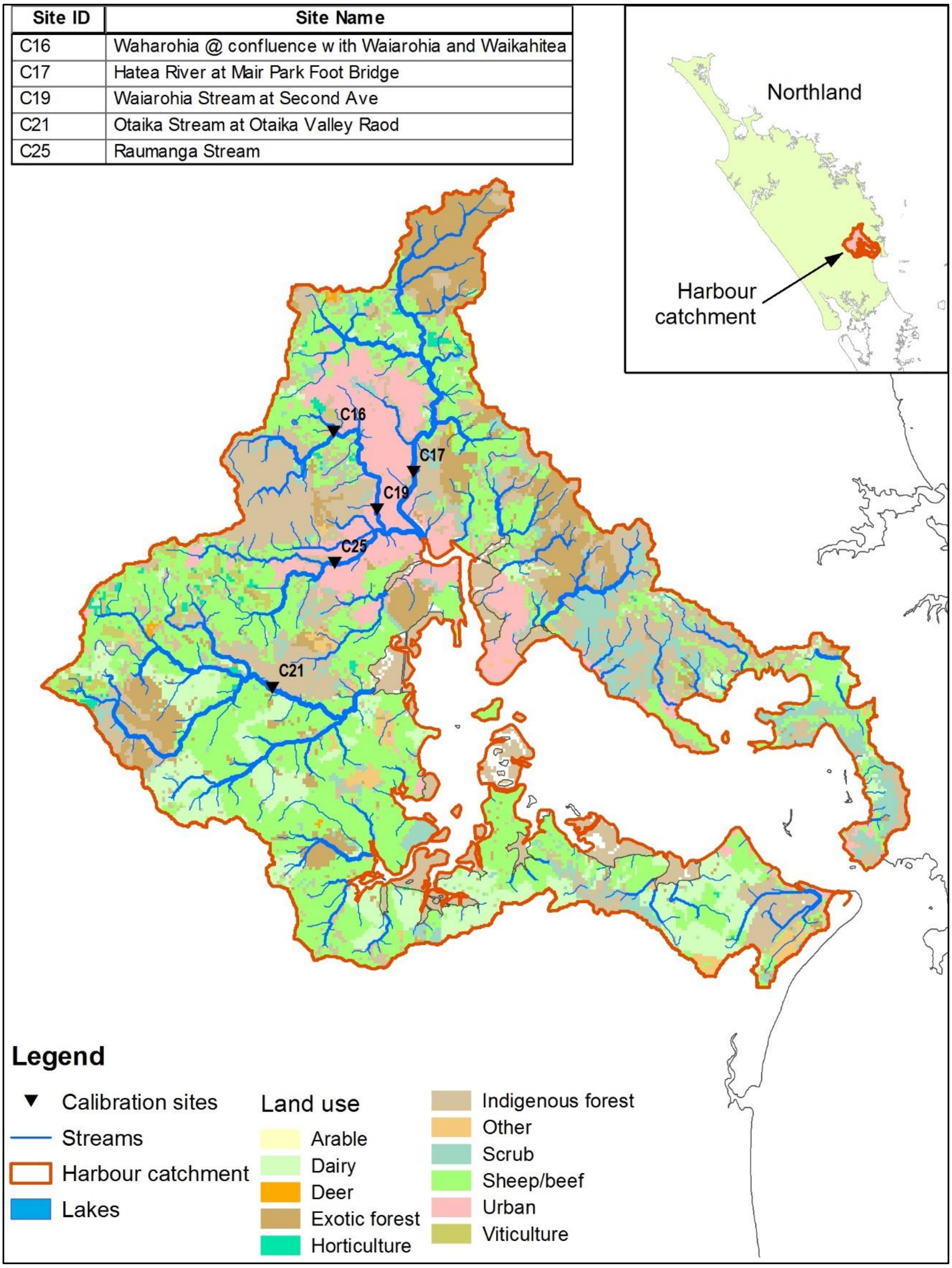


Figure 2-3: Whangarei Harbour catchment showing streams of order ≥ 3, lakes, calibration sites and the land use. See Table A-1 in Appendix A for the proportion of land use by area for each of the watersheds of the calibration sites. See Table 2-2 for a list of sites (denoted by C).

2.4 Point sources

2.4.1 Effluent ponds

Information regarding the location of farm dairy effluent (FDE) ponds and the number of cows on each farm for Northland was provided by NRC. Ponds are classified as follows (Darryl Jones, NRC, *pers. comm.*):

1. 'Permitted activity' – must dispose all diary pond effluent to land.
2. 'Discharge permit' with 'Land App' equal to 'No' – dispose to water.
3. 'Discharge permit' with 'Land App' equal to 'Yes' – dispose to land unless weather and other conditions make this in breach of the consent, in which case they directly discharge from the pond system to surface water.

Of the 974 FDE ponds in Northland (including one that receives poultry effluent), this study included only the ones under 'Discharge permit' with 'Land App' equal to 'No'. There were 276 such ponds, of which five were located in the harbour catchment (see Figure 2-4 and Figure 2-5).

The loading from ponds was determined in the following way. According to work done by Donnison et al. (2011), from 18 September 2007 to 18 January 2008 (122 days) FDE ponds discharged 1.835×10^8 *E. coli* per cow per day, and from 18 January 2008 until 14 March 2008 (57 days) FDE ponds discharged 1.200×10^7 *E. coli* per cow per day. During the January to March period the number of cows being milked declined, with most being dried off mid-March owing to low rainfall. Therefore we estimate that the annual discharge of *E. coli* per cow from FDE = $(1.835 \times 10^8 \times 122) + (1.200 \times 10^7 \times 57) = 2.307 \times 10^{10}$. This is a conservative estimate since most cows have calved before mid-September and are therefore being milked, and are usually dried-off later than mid-March.

2.4.2 Wastewater Treatment Plants (WWTPs)

Only the two WWTPs located within the harbour catchment were included in the calibration (Portland and Whangarei). Portland WWTP discharges directly to the harbour, while Whangarei WWTP discharges into Limeburners Creek (see Figure 2-5). Table 2-4 gives their average *E. coli* loads.

E. coli loads from WWTPs outside the harbour catchment, but inside the Northland region were not included. Loads from septic tanks were also excluded from the model. It was thought that such loads would not make a big difference to the model calibration.

Table 2-4: Average *E. coli* loads from Portland and Whangarei WWTPs over the date ranges shown.

WWTP	N	Date range	Load (peta *E. coli*/y)
Portland	17	11/10/2012–3/3/2015	1.2002×10^{-3}
Whangarei – wetland 1	6	28/11/2014–8/1/2015	1.9528×10^{-2}
Whangarei – wetland 2	59	8/2/2007–8/1/2015	5.5178×10^{-2}

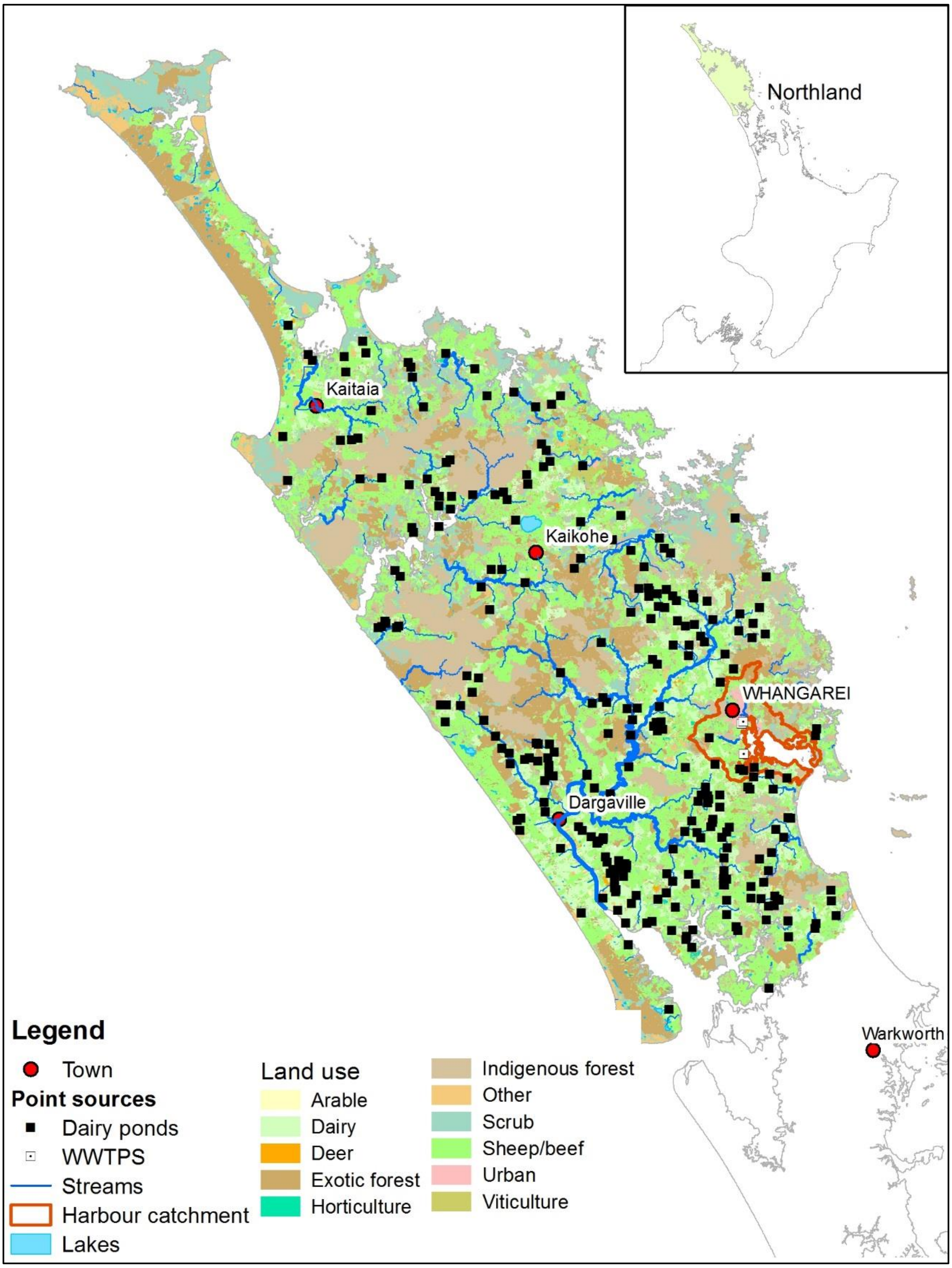


Figure 2-4: Northland region showing streams of order ≥ 3, lakes, major towns, the Whangarei Harbour catchment and point sources within the harbour catchment.

2.5 Model calibration

The model was calibrated by minimising the difference between the measured and predicted loads of 25 calibration sites in the form of the root mean square error (RMSE)[6] in natural log space. The RMSE was calculated using the following equation:

$$\text{RMSE} = \sqrt{\left(\sum (Ln(Predicted\ load) - Ln(Measured\ load))^2 / n\right)} \quad (1)$$

The calibration involved optimising various parameters used in the model to minimise the RMSE. Standard errors were also calculated for the parameters. The parameters that were optimised are described below.

Yield coefficients

The model included the loads from point sources and those from the land use types as given in Table A-1 in Appendix A. The loads from the land uses were calculated by multiplying the area of each land use by its yield coefficient (peta *E. coli*/ha-y, that is, 10^{15} *E. coli*/ha-y). The yield coefficient for "urban" land use was set at 0.99 peta *E. coli*/ha-y, as established for the Waikato and Waipa River catchments (Semadeni-Davies et al. 2015). The other land uses were grouped for yield coefficient purposes as follows:

- "Deer" and "dairy" were assigned the same yield coefficient.
- "Sheep & beef" had its own yield coefficient.
- "Non-pasture" included arable, exotic forest, horticulture, indigenous forest, other, scrub and viticulture land uses, which were assigned a common yield coefficient.

Examination of these three estimated or fitted yield coefficient values after optimisation indicated that it was possible to have similar yield coefficients for deer and dairy as for sheep & beef, and for non-pasture as for sheep & beef. Because the model was unable to provide different yield coefficients for deer and dairy, and sheep & beef land uses, it was deemed expedient therefore, to combine the yield coefficients for deer and dairy and sheep & beef into one called "Pasture", apply a single yield coefficient and re-optimise the coefficients, see Table 2-5 for the results.

Table 2-5: Re-optimisation of the yield coefficients and their standard errors.

Land use	Yield coefficient (peta *E. coli*/ha-y)	Standard error (se)
Pasture = deer, dairy and sheep & beef	0.77	0.17
Non-pasture = arable, exotic forest, horticulture, indigenous forest, other, scrub and viticulture	0.13	0.07

[6] The RMSE is used as a standard statistical metric to measure model performance in many fields, including meteorology, air quality, climate research and agriculture. It assumes the errors (= predicted – measured) are unbiased and follow a normal distribution.

Decay coefficients

There are two of these in the model – one associated with the decay of *E. coli* in the streams and the other with its decay in lakes. Both optimised to approximately zero, so a value of zero was used, i.e., there was no in-stream or in-lake decay.

Land-to-water delivery coefficients

Three land-to-water deliver coefficients – mean annual rainfall, mean LUC soil drainage class, and land slope - were investigated. Each of these modifies the diffuse source coefficient according to an exponential function of the relevant variable (such as rainfall). Addition of drainage and slope terms did not improve the model significantly, so they were removed from the final model. The calibrated exponent for rain was 2.0185 with a se = 0.7953 (where rainfall is in m/y). The statistics for rainfall for each of 25 calibration sites are given in Table B-1 in Appendix B.

The RMSE of the final modelled load (peta *E. coli*/y) equalled 0.56 and a R^2 value of 0.86. In non-log space this means an error factor of exp(0.56) at the one se level. The RMSE, in non-log space, of the final modelled specific load (or yield, i.e., peta *E. coli*/ha-y) was 0.31, with an R^2 value of 0.62. See Table 3-1, Table 3-2, Figure 3-1 and Figure 3-2.

2.6 Loads to Whangarei Harbour

There were four components to calculating the load the Harbour:

- Load from terminal streams, i.e., the loads from the 98 streams that discharge directly into the harbour.
- Load from the pseudo-catchments around the shoreline fringes of the harbour (see Section 2.2.1).
- Load from Portland WWTP (see Section 2.4.2).
- One FDE pond near the shoreline (with 'Discharge permit' with 'Land App' equal to 'No') was not close to a stream, so it was assumed that this pond discharged into the harbour.

In order to obtain the total *E. coli* loads including all flows and not just those from 95th percentile of flows, the ratio L_A/L_{95} (see Section 2.2), was calculated for each of the five calibration sites where suitable measured loads existed (L_A and L_{95}). The mean of these five ratios (26) was then multiplied by the predicted L_{95} for the 98 terminal streams to obtain their contribution to the total *E. coli* load to the harbour.

Similarly, the loads from the 61 pseudo-catchments were multiplied by the mean ratio to obtain their contribution to the total *E. coli* load to the harbour.

2.7 Nodes of importance

There are 11 sites (referred to as 'nodes of importance') within the Whangarei harbour catchment of particular interest to the NRC, in terms of the current median and 95th percentile concentrations (see Figure 2-5). Seven of the nodes of importance are monitored and six of these had sufficient measured data to calculate median and 95th percentile concentrations – only nine concentration data exist for the RWQMN site Raumanga at Bernard Street (304709), so median and 95th percentile concentrations could not be determined with confidence for that site. Insufficient concentration data were available for one node, and no concentration data existed for four other nodes of importance. The median and 95th percentile concentrations ($C_{median,pred}$ and $C_{95,pred}$) for each of these five sites were predicted using the methods described in Section 2.7.1.

2.7.1 Predicted median concentrations for nodes without suitable measurements

The median concentrations were calculated using Equation (2):

$$\boldsymbol{C_{median,pred} = \frac{L_{95} \times R_1}{Q_{mean}}} \tag{2}$$

where $C_{median,pred}$ is the predicted median concentration, L_{95} is the load based on the 95th percentile of flows, Q_{mean} is the mean flow at the closest flow site (adjusted if necessary as described in Section 2.2), and R_1 is a ratio calculated from those six sites where measured median and 95th percentile concentrations exist. R_1 was calculated at those six sites using Equation (3):

$$\boldsymbol{R_1 = \frac{C_{median,meas} \times Q_{mean}}{L_{95}}} \tag{3}$$

where $C_{median,meas}$ is the measured median concentration.

The locations of the five nodes of importance that did not have measured concentrations were examined to see if they were close to any that do. It was found that Raumanga at Bernard Street (304709) was close to Raumanga Stream at swimming pool below falls (103246), and that Otaika weir (Golden Bay surface water take) was close to Otaika at Otaika Valley Road (110431). Therefore $\boldsymbol{R_1}$ for Raumanga Stream at swimming pool below falls (103246) was used for Raumanga at Bernard Street (304709), and $\boldsymbol{R_1}$ for Otaika at Otaika Valley Road (110431) was used for Otaika weir (Golden Bay surface water take) in Equation 1 to calculate $\boldsymbol{C_{median,pred}}$. For the remaining three nodes of importance that did not have measured concentrations and were not close to any that do, $\boldsymbol{R_1}$ was taken to be the average of those that do (1.1766, see Table 2-6), and used in Equation 2 to calculate $\boldsymbol{C_{median,pred}}$.

2.7.2 Predicted 95th percentile concentrations for nodes without suitable measurements

The ratio:

$$\boldsymbol{R_2 = \frac{C_{95,meas}}{C_{median,meas}}} \tag{4}$$

was calculated for the six nodes of importance where measured median and 95th percentile concentrations exist. The mean value of this ratio for those six sites was then applied to the median concentration at the remaining sites to estimate the 95th percentile concentrations for these six sites, $C_{95,pred}$.

$$\boldsymbol{C_{95,pred} = C_{median,pred} \times R_2} \tag{5}$$

Table 2-6: R_1 and R_2 values for six nodes of importance which had measured concentrations.

Site names of nodes of importance	Site ID	R_1 value from Equation 3	R_2 value from Equation 4
Whangarei Falls	105972	0.8825	4.5636
Waharohia at confluence with Waiarohia and Waikahitea	107773	1.6176	6.6373
Hatea at Mair Park Foot Bridge	100194	0.5756	24.3479
Waiarohia at Second Ave	108359	1.4450	13.5857
Raumanga Stream at swimming pool below falls	103246	1.0516	14.5782
Otaika at Otaika Valley Road	110431	1.1931	9.0452
Average		**1.1766**	**13.6389**

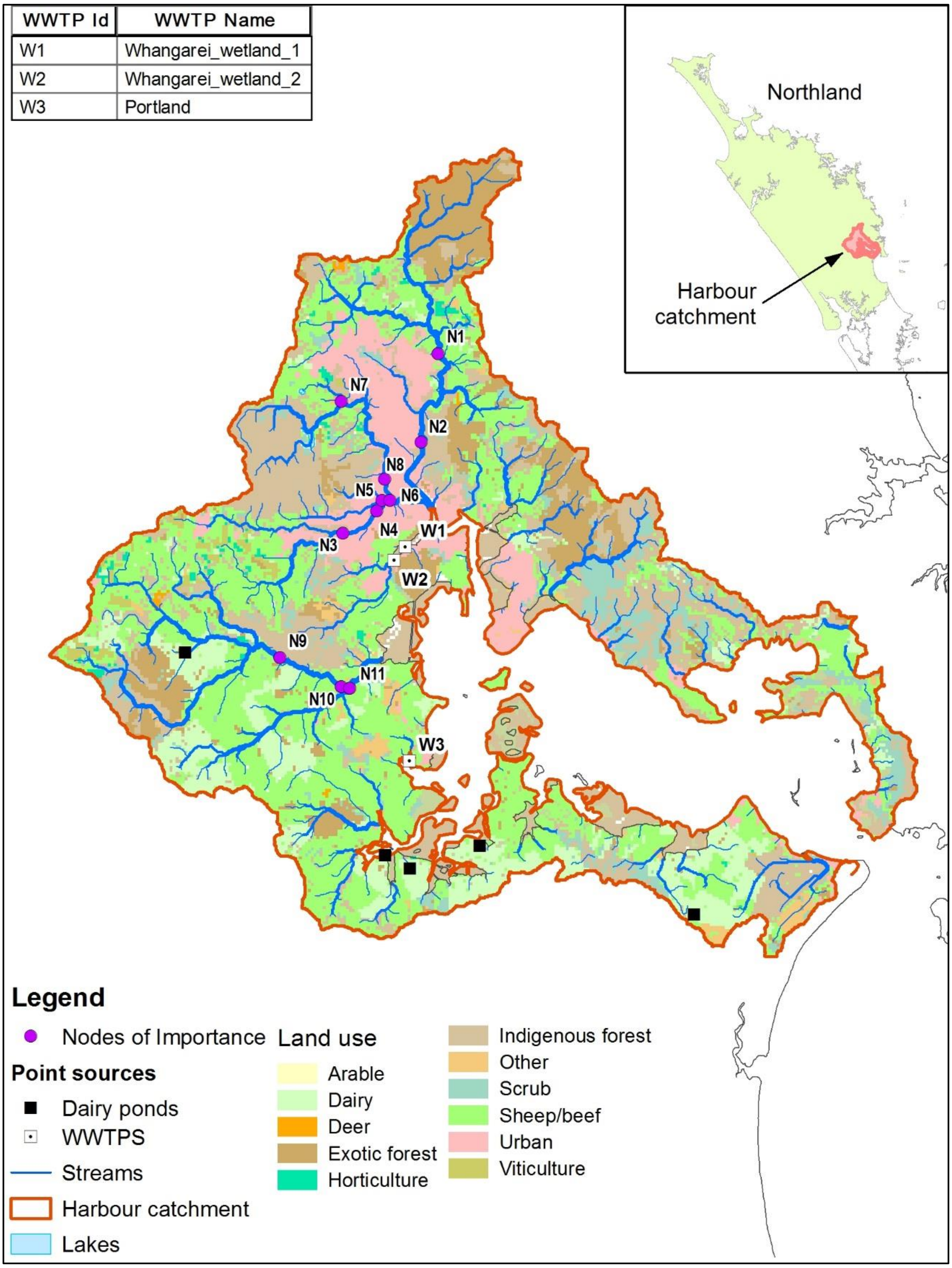


Figure 2-5: Whangarei Harbour catchment showing streams of order ≥ 3, lakes, land use, point sources and nodes of importance. See Table 2-7 for a list of sites (denoted by N).

Table 2-7: Nodes of importance.

Node of importance name	Site ID	Label
Whangarei Falls	105972	N1
Hatea at Mair Park Foot Bridge	100194	N2
Raumanga Stream at swimming pool below falls	103246	N3
Raumanga at Bernard Street	304709	N4
Kirikiri immediately upstream the Raumanga	–	N5
Raumanga immediately upstream the Waiarohia	–	N6
Waharohia at confluence with Waiarohia and Waikahitea	107773	N7
Waiarohia at Second Ave	108359	N8
Otaika at Otaika Valley Road	110431	N9
Otaika weir (Golden Bay surface water take)	–	N10
Puwera immediately upstream Otaika	–	N11

3 Results and discussion

3.1 Calibration

The calibration results are summarised in Table 3-1 and Figure 3-1.

Table 3-1: Measured and predicted (or modelled) *E. coli* loads at the 25 calibration sites. Blue text indicates sites in the Whangarei Harbour catchment.

Calibration site name, site ID	Mean load (peta/y)		Percentage load error[1]
	Measured	Predicted	
Waiharakeke at Stringers Road Walking Bridge, 100007	1.1693	1.0515	-10
Hatea at Mair Park Foot Bridge, 100194	0.1893	0.2322	23
Mangahahuru at end Of Main Road, 100237	0.0868	0.0365	-58
Mangahahuru at Apotu Road Bridge, 100281	0.1935	0.1734	-10
Awanui at FNDC take, 100363	1.4614	1.3080	-10
Awanui at Waihue Channel, 100370	2.2019	1.4465	-34
Kerikeri at Stone Store, 101530	2.1026	1.4942	-29
Mangere at Knight Road Bridge, 101625	1.0449	0.4398	-58
Waiotu at SH1 Bridge, 102248	1.4866	1.2806	-14
Whakapara at Cableway, 102249	2.1856	1.2235	-44
Kaihu at Gorge, 102256	0.8370	0.8256	-1
Manganui at Mitaitai Road, 102257	1.5579	2.0552	32
Opouteke at Suspension Bridge, 102258	0.3814	0.2687	-30
Kaeo at Dip Road Bridge, 102674	0.5593	0.6516	17
Raumanga Stream, 103246	0.0218	0.0780	257
Waipapa River at Puketi Forest, 103248	0.1454	0.3394	133
Ruakaka at Flyger Road Bridge, 105008	0.3473	0.2817	-19
Punakitere at Taheke, 105231	1.1851	2.6746	126
Victoria at Thompsons Bridge, 105532	0.0389	0.0732	88
Waharohia at Waikahitea Confluence, 107773	0.0263	0.0176	-33
Waiarohia at Second Ave, 108359	0.0357	0.0827	132
Waipao at Draffin Road Bridge, 108941	0.2127	0.1958	-8
Oruru at Oruru Road, 108979	0.2339	0.4496	92
Mangakahia at Twin Bridges, 109096	2.5322	1.2821	-49
Otaika at Otaika Valley Road, 110431	0.1176	0.1645	40

[1] Equals (Predicted – Measured)/Measured.

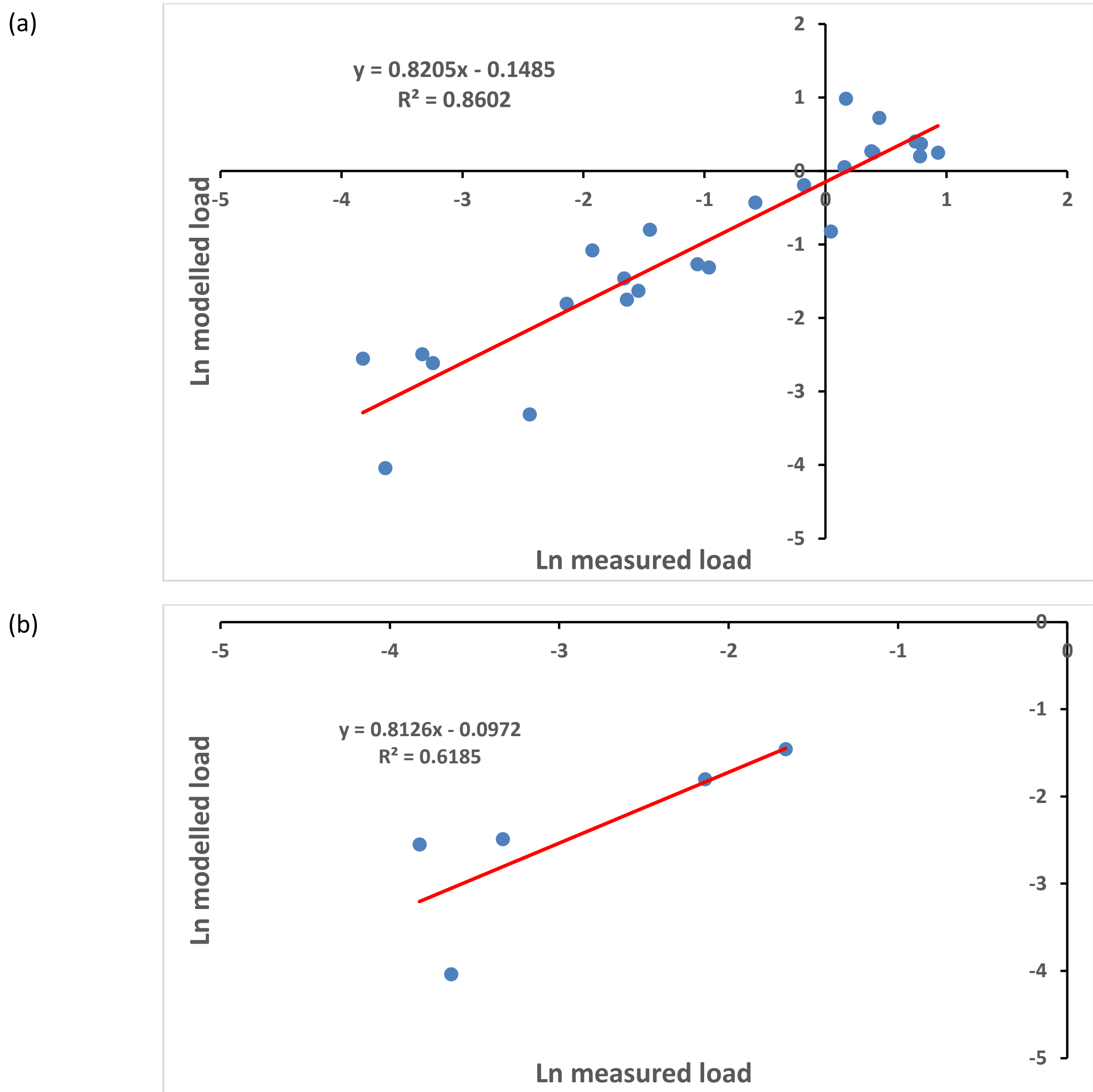
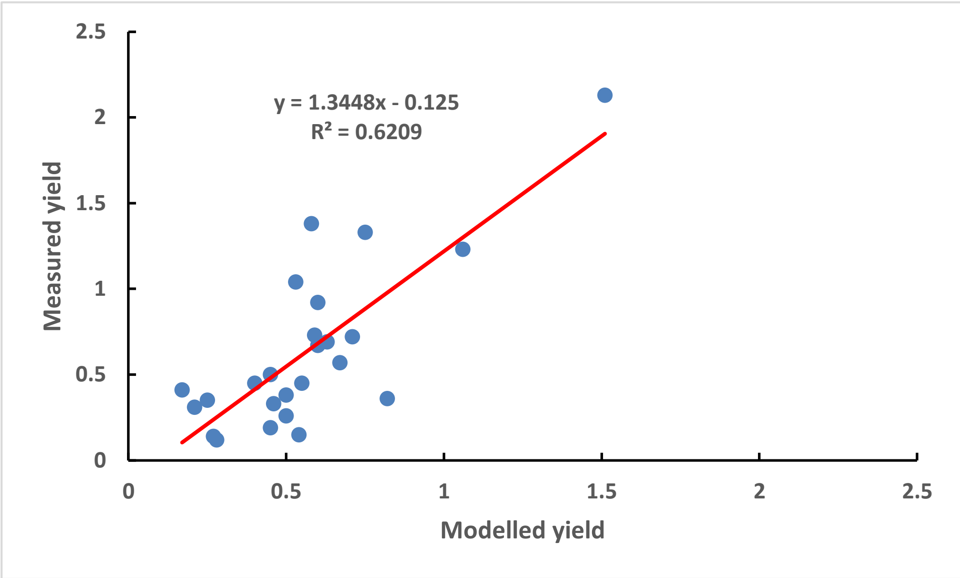


Figure 3-1: (a): Measured vs predicted *E. coli* loads (peta *E. coli*/y) for the 25 calibration sites in the Northland region (includes harbour catchment). (b) Measured vs predicted *E. coli* loads for the 5 calibration sites in the Whangarei Harbour catchment.

(a)



(b)

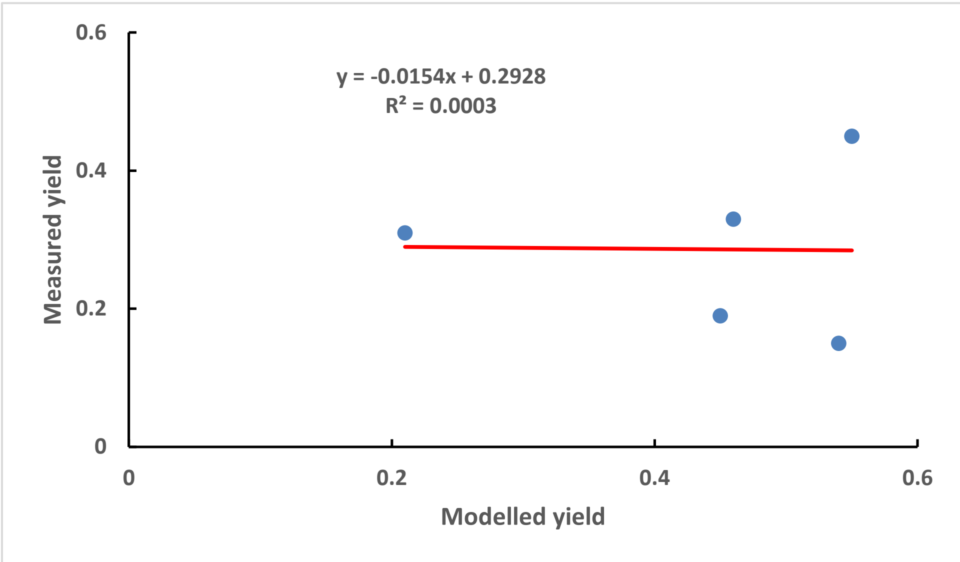


Figure 3-2: (a): Measured vs predicted E. coli yields (peta E. coli/ha-y) for the 25 calibration sites in the Northland region (includes harbour catchment). (b) Measured vs predicted *E. coli* yields for the 5 calibration sites in the Whangarei Harbour catchment.

In order to better understand *E. coli* dynamics, concentrations, yields and land uses at the calibration sites were examined in detail. It was expected that catchments with higher proportions of pasture would have higher *E. coli* concentrations, whereas catchments which were predominantly forested would have lower *E. coli* concentrations. However, as evident in Table 3-2, this was not always the case. For example:

- Awanui at FNDC take (100363), Awanui at Waihue Channel (100370), Kerikeri at Stone Store (101530), Manganui at Mitaitai Road (102257). For these sites, the majority of their watersheds were in pasture, but the *E. coli* concentrations were not higher than the average for all 25 calibration sites.

- Mangahahuru at end Of Main Road (100237), Mangahahuru at Apotu Road Bridge (100281), Kaeo at Dip Road Bridge (102674), Waharohia at Waikahitea Confluence (107773), Waiarohia at Second Ave (108359). For these sites, the majority of their watersheds were forested, but the *E. coli* concentrations were not lower than the average for all 25 calibration sites.

These apparent anomalies cannot be explained at present, but could be related to decay factors and possibly inputs from feral animals in forested areas.

Ruamanga Stream's (103246) load is well over-predicted at 257% (see Table 3-1), yet its concentration is relatively low (211 cfu/100 ml) despite it being 50% sheep & beef (see Table 3-2). It also is 11% urban. The only other site with a relatively high urban land use is Hatea at Mair Park Foot Bridge (100194) at 15% urban. Yet its over-prediction is only 23%, so the yield coefficient for urban is not to blame for the Ruamanga Stream's load over-prediction. The implications of the Ruamanga Stream's load over-prediction means that in the model all downstream reaches will be receiving larger loads. These downstream reaches have three nodes of importance sites: Raumanga at Bernard Street, Kirikiri immediately upstream the Raumanga, and Raumanga immediately upstream the Waiarohia (see Figure 2-5).

Sources of uncertainty in the model include:

- Water quality monitoring sites where there is no coincident flow site, so that flow data is used from a nearby site if there is one.
- Lack of knowledge around *E. coli* land and stream dynamics.
- Groundwater not included in the model, although it is unlikely this is a significant factor for *E. coli*.
- The measured loads, which are used for calibration, have considerable uncertainties. For example, bootstrapping of the load estimate showed considerable imprecision of the load estimate, such 90-percentile L_{95} value was 3.4 times the 10-percentile L_{95} value, on average. There may also be biases in the load estimates (a tendency to under-estimate or over-estimate the measured load in relation to the actual true load) that the bootstrapping method does not evaluate. These sources of measurement limit the accuracy and precision of the model. For example, it would not be reasonable to expect the model residual error to be less than the uncertainty in the measurements.

Table 3-2: Concentrations, yields and land uses for the 25 calibration sites. See Table 2-3 for concentrations and Table A-1 in Appendix A for land uses. Yields = measured loads (L_{95})/area. Forest includes both exotic and indigenous. S & B = sheep & beef. Blue text indicates sites within the Whangarei Harbour catchment.

Calibration site name, site ID	Measured median concentration over last 5 yrs (cfu/100 mL)	Mean yield (peta/ha-y)		Predominant land uses (percent)
		Measured	Predicted	
Waiharakeke at Stringers Road Walking Bridge, 100007	379	0.50	0.45	Forest 46, S & B 29, Dairy 13, Scrub 10
Hatea at Mair Park Foot Bridge, 100194	259	0.45	0.55	Forest 43, S & B 34, Urban 15
Mangahahuru at end Of Main Road, 100237	323	0.41	0.17	Forest 95
Mangahahuru at Apotu Road Bridge, 100281	457	0.45	0.40	Forest 65, S & B 15, Dairy 13
Awanui at FNDC take, 100363	269	0.67	0.60	S & B 46, Forest 36
Awanui at Waihue Channel, 100370	246	0.92	0.60	S & B 48, Forest 35
Kerikeri at Stone Store, 101530	216	2.13	1.51	S & B 35, Dairy 27, Forest 15, Viticulture 14
Mangere at Knight Road Bridge, 101625	512	1.38	0.58	Dairy 41, S & B 34, Forest 19
Waiotu at SH1 Bridge, 102248	384	1.23	1.06	Dairy 35, Forest 34, S & B 29
Whakapara at Cableway, 102249	231	1.33	0.75	Forest 42, Dairy 31, S & B 20
Kaihu at Gorge, 102256	173	0.72	0.71	Forest 44, S & B 29, Dairy 22
Manganui at Mitaitai Road, 102257	146	0.38	0.50	S & B 46, Dairy 28, Forest 21
Opouteke at Suspension Bridge, 102258	157	0.35	0.25	Forest 91

Calibration site name, site ID	Measured median concentration over last 5 yrs (cfu/100 mL)	Mean yield (peta/ha-y)		Predominant land uses (percent)
		Measured	Predicted	
Kaeo at Dip Road Bridge, 102674	703	0.57	0.67	Forest 46, Scrub 26, S & B 22
Raumanga Stream, 103246	211	0.15	0.54	S & B 50, Forest 26, Urban 11
Waipapa River at Puketi Forest, 103248	58	0.12	0.28	Forest 95
Ruakaka at Flyger Road Bridge, 105008	747	0.73	0.59	Dairy 38, S & B 33, Forest 25
Punakitere at Taheke, 105231	471	0.36	0.82	S & B 43, Forest 37, Dairy 10
Victoria at Thompsons Bridge, 105532	158	0.14	0.27	Forest 74, Scrub 14, S & B 11
Waharohia at Waikahitea Confluence, 107773	525	0.31	0.21	Forest 82, S & B 12
Waiarohia at Second Ave, 108359	399	0.19	0.45	Forest 55, Urban 22, S & B 17
Waipao at Draffin Road Bridge, 108941	613	0.69	0.63	S & B 42, Dairy 27, Viticulture 13, Forest 10
Oruru at Oruru Road, 108979	262	0.26	0.50	Forest 43, S & B 32, Scrub 19
Mangakahia at Twin Bridges, 109096	128	1.04	0.53	Forest 63, S & B 32
Otaika at Otaika Valley Road, 110431	484	0.33	0.46	S & B 44, Forest 31, Dairy 14

3.2 Loads to Whangarei Harbour

As noted in Section 2.6, the loads in Table 3-3 are predicted for all flows, not just those from 95th percentile of flows, so are called the 'total loads'. As can be seen, most of the load is coming from the terminal streams.

Total load from point sources

= (load from five FDE ponds) + (load from WWTPs)

= load from four FDE ponds that discharge into streams + load from one FDE pond that discharges directly into the harbour + load from Portland WWTP + load from Whangarei WWTP (wetland 1) + load from Whangarei WWTP (wetland 2)

= 0.0238 + 0.0058 + 0.0012 + 0.0.0195 + 0.0552

= 0.1055 peta/y.

Total load from diffuse sources = 294.3650 peta/y.

Table 3-3: Total predicted *E. coli* loads to Whangarei Harbour.

Source	Predicted total load (peta/y)
Terminal streams [1]	290.0398
Pseudo-catchments	4.4237
Portland WWTP	0.0012
One FDE pond that discharges directly to the harbour	0.0058
TOTAL	**294.4705**

[1] Includes 0.0747 peta/y from the Whangarei WWTP, and 0.0238 peta/y from the four FDE ponds that discharge into streams.

3.3 Nodes of importance

Concentrations predicted at nodes of importance are summarised in Table 3-4.

The particularly high concentrations predicted at Puwera immediately upstream of the confluence with the Otaika may be due to the watershed of the former being almost entirely dairy and sheep & beef land uses (see Figure 2-5). But similar to other sites where the concentrations were predicted, there is uncertainty with the method for getting concentrations from loads (see Equations 2 and 5), uncertainty around the relative contributions from pasture and forest, and even poor model performance for some of the streams in the Whangarei catchment (e.g., Ruamanga Stream, 103246).

Considering that the 11 nodes of importance sites are of such particular value to the NRC, we recommend that measurement of *E. coli* concentrations at these sites be included in the regional monitoring programme (see Table 3-4).

Table 3-4: Concentrations at nodes of importance. Brown text indicates measured concentrations, black text indicates concentrations as predicted in Section 2.7.

Node of importance name	Site ID	Label	Median concentration (cfu/100 ml)	95th percentile concentration (cfu/100 ml)
Hatea at Mair Park Foot Bridge	100194	N2	259	6306
Raumanga Stream at swimming pool below falls	103246	N3	211	3076
Whangarei Falls	105972	N1	439	2003

Node of importance name	Site ID	Label	Median concentration (cfu/100 ml)	95th percentile concentration (cfu/100 ml)
Waharohia at confluence with Waiarohia and Waikahitea	107773	N7	525	3485
Waiarohia at Second Ave	108359	N8	399	5421
Otaika at Otaika Valley Road	110431	N9	484	4378
Raumanga at Bernard Street	304709	N4	903 [a]	13164
Kirikiri immediately upstream the Raumanga	–	N5	722	9852
Raumanga immediately upstream the Waiarohia	–	N6	942	12844
Otaika weir (Golden Bay surface water take)	–	N10	871	7883
Puwera immediately upstream Otaika	–	N11	1354	18470

[a] The nine concentration data points have a median concentration of 315 cfu/100 ml.

4 Summary and conclusions

This report has documented the development and calibration of a customised version of the CLUES model for *E. coli* for the Northland region, with specific emphasis given to the Whangarei Harbour catchment. The model was calibrated to as many suitable sites in the region as possible, rather than just to those sites within the harbour catchment, in order to improve the model predictions for the harbour catchment. Water quality modelling focussed on 11 “nodes of importance” in the Whangarei Harbour catchment that were identified by the NRC.

This modelling was undertaken to provide input to an economic model (developed by Dr Adam Daigneault of Landcare Research). The economic model addresses the financial implications of adopting various mitigation strategies on pasture land within the harbour catchment that may be required to achieve concentration targets as described in the NPSFM (2014).

Model calibration and predictions

Twenty-five of 73 water quality monitoring sites in Northland satisfied three selection criteria, and were selected for model calibration. Five of these sites fell within the Whangarei Harbour catchment.

A rating curve method was used to calculate stream loads using measured *E. coli* concentrations and measured or estimated stream flows. *E. coli* loads were calculated for catchments defined according to the REC2 subcatchment classification. There were 655 of these subcatchments within the Whangarei Harbour catchment. Areas of land that discharged directly to the harbour were grouped into a single pseudo-catchment and treated as other catchments.

During the model calibration phase, key model parameters where optimised to minimise the RMSE of the overall model prediction of loads. The RMSE for load prediction[7] was 0.56, with an R^2 value of 0.86. The RMSE, in non-log space, for specific load (or yield) prediction was 0.31, with an R^2 value of 0.62. The calibration process identified that the model was relatively insensitive to land use – it was therefore expedient to group deer, dairy, and sheep and beef land uses in a “pasture” land use group, and several other land uses in a “non-pasture” land use group. The latter included native and exotic forestry.

E. coli loads were estimated for wastewater treatment plants within Whangarei Harbour catchment, and for farm dairy effluent ponds across Northland. Within the Whangarei Harbour catchment, the model accounted for three municipal wastewater discharges, and five dairy shed effluent ponds.

Model predictions were counter-intuitive for some land use types. For example, selected forested catchments in Northland exhibited *E. coli* concentrations that were larger than those predicted for catchments where pastoral land use was dominant.

Within the Whangarei Harbour catchment, the model predicted that the overwhelming bulk of the *E. coli* load was derived from streams flowing directly into the harbour, rather than the pseudo-catchment or point source discharges.

[7] The natural logarithm of the loads was used.

Reliability of model predictions

Some key points relevant to management of *E. coli* sources arise from this modelling exercise. It is important to keep these in mind when interpreting the ultimate findings from economic and mitigation modelling:

- Point sources and dairy shed effluent represent a small proportion of the *E. coli* load input to Whangarei harbour. There are also very few dairy sheds in the Whangarei harbour catchment. Although improved management and disposal of dairy shed effluent is likely to be one of the first control measures implemented, the effect of the improved management of these on the concentrations observed at nodes of importance and the loads entering the harbour are likely to be minor.
- At this stage we are unable to reliably differentiate between the contribution from dairy and other pastoral activities to *E. coli* loads (apart from the influence of dairy effluent).
    - The overall loading from pasture is approximately six times larger than that from forested areas.
    - Runoff from some of the forested catchments have unexpectedly high *E. coli* concentrations. This applies especially to sites in the Whangarei Harbour catchment.
    - This information implies that reducing *E. coli* loads by controlling pasture sources alone may not be sufficient to achieve concentration targets.
    - We recommend investigation of some of the forested catchments, to identify the sources of *E. coli*, and identify those measures most likely to minimise *E. coli* concentrations in runoff.
- Overall, there is high uncertainty in model predictions, due to currently unknown factors. This uncertainty should be acknowledged when:
    - determining risks (i.e., which catchments should be prioritised for implementation of mitigation strategies?), and
    - prioritising investment (i.e., which mitigation tools should be implemented, and where should they be implemented in the catchment?).
- Stream flows and *E. coli* concentrations are not currently measured at all of the sites of interest in the catchment (nodes of importance). The estimated concentrations and loads at some of these sites are high and relatively uncertain. It would be advantageous to monitor *E. coli* at these nodes to improve load estimates.

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Appendix A Percentage of land use by area for the watersheds of the calibration sites and the pseudo-catchments

Table A-1: Proportion of watershed by land use for the calibration sites and the pseudo-catchments. Blue text indicates sites in the Whangarei Harbour catchment.

Calibration site name, site ID	Proportion of land use (%)										
	Arable	Dairy	Deer	Exotic forest	Horticulture	Indigenous forest	Other	Scrub	Sheep & beef	Urban	Viticulture
Waiharakeke at Stringers Road Walking Bridge, 100007	0	13	0	25	0	21	2	10	29	0	0
Hatea at Mair Park Foot Bridge, 100194	0	2	1	27	1	16	1	3	34	15	0
Mangahahuru at end Of Main Road, 100237	0	1	0	83	0	12	0	2	2	0	0
Mangahahuru at Apotu Road Bridge, 100281	0	13	0	53	0	12	0	3	15	2	1
Awanui at FNDC take, 100363	0	8	0	6	1	30	1	7	46	0	0
Awanui at Waihue Channel, 100370	0	9	0	6	1	29	1	7	48	1	0
Kerikeri at Stone Store, 101530	0	27	0	5	1	10	2	5	35	1	14
Mangere at Knight Road Bridge, 101625	0	41	0	1	0	18	1	4	34	0	0
Waiotu at SH1 Bridge, 102248	0	35	0	5	0	29	0	3	29	0	0
Whakapara at Cableway, 102249	0	31	0	11	0	31	2	6	20	0	0
Kaihu at Gorge, 102256	0	22	0	17	0	27	1	3	29	0	0
Manganui at Mitaitai Road, 102257	0	28	0	7	0	14	1	3	46	0	0
Opouteke at Suspension Bridge, 102258	0	2	0	59	0	33	0	3	3	0	0

Calibration site name, site ID	Proportion of land use (%)										
	Arable	Dairy	Deer	Exotic forest	Horticulture	Indigenous forest	Other	Scrub	Sheep & beef	Urban	Viticulture
Kaeo at Dip Road Bridge, 102674	0	5	0	16	0	30	1	26	22	0	0
Raumanga Stream, 103246	0	1	0	2	2	24	0	4	50	11	7
Waipapa River at Puketi Forest, 103248	0	0	0	10	0	85	0	2	3	0	0
Ruakaka at Flyger Road Bridge, 105008	0	38	0	2	0	23	0	4	33	0	0
Punakitere at Taheke, 105231	0	10	0	17	0	20	2	7	43	1	0
Victoria at Thompsons Bridge, 105532	0	2	0	6	0	68	1	14	11	0	0
Waharohia at Waikahitea Confluence, 107773	0	0	0	1	1	81	0	4	12	0	0
Waiarohia at Second Ave, 108359	0	0	0	2	2	53	0	3	17	22	0
Waipao at Draffin Road Bridge, 108941	0	27	0	2	4	8	4	0	42	0	13
Oruru at Oruru Road, 108979	0	4	0	12	0	31	1	19	32	0	0
Mangakahia at Twin Bridges, 109096	0	3	0	30	0	33	0	2	32	0	0
Otaika at Otaika Valley Road, 110431	0	14	1	12	2	19	2	3	44	0	4
Pseudo-catchments	0	7	0	1	0	33	9	19	25	6	0

Appendix B Rain for the watersheds of the calibration sites

Table B-1: Rain (mm/y) statistics for the watersheds of the calibration sites. Blue text indicates sites in the Whangarei Harbour catchment.

Calibration site name, site ID	Rainfall statistic (mm/y)		
	Mean	Min–max	Standard deviation
Waiharakeke at Stringers Road Walking Bridge, 100007	1583	1471–1717	61
Hatea at Mair Park Foot Bridge, 100194	1613	1563–1639	21
Mangahahuru at end Of Main Road, 100237	1637	1634–1641	2
Mangahahuru at Apotu Road Bridge, 100281	1631	1586–1691	14
Awanui at FNDC take, 100363	1660	1441–1709	48
Awanui at Waihue Channel, 100370	1648	1403–1709	65
Kerikeri at Stone Store, 101530	2009	1668–2236	181
Mangere at Knight Road Bridge, 101625	1533	1488–1563	20
Waiotu at SH1 Bridge, 102248	1892	1631–2086	99
Whakapara at Cableway, 102249	1801	1635–2086	139
Kaihu at Gorge, 102256	1746	1491–1992	203
Manganui at Mitaitai Road, 102257	1420	1321–1528	43
Opouteke at Suspension Bridge, 102258	1762	1457–1992	159
Kaeo at Dip Road Bridge, 102674	1946	1755–2236	118
Raumanga Stream, 103246	1549	1500-1556	13
Waipapa River at Puketi Forest, 103248	1867	1626-2236	165
Ruakaka at Flyger Road Bridge, 105008	1532	1491–1546	9
Punakitere at Taheke, 105231	1793	1621–1973	93
Victoria at Thompsons Bridge, 105532	1693	1688–1705	4
Waharohia at Waikahitea Confluence, 107773	1563	1562–1563	0
Waiarohia at Second Ave, 108359	1569	1562–1593	10
Waipao at Draffin Road Bridge, 108941	1515	1430–1555	26
Oruru at Oruru Road, 108979	1708	1680–1717	7
Mangakahia at Twin Bridges, 109096	1737	1533–1992	147
Otaika at Otaika Valley Road, 110431	1480	1418–1556	25