# Water quality modelling of the Ruamahanga Catchment

## BASELINE MODEL BUILD AND CALIBRATION REPORT

IZ050100 | April 2018

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|---|---|
| Project no: | IZ501000 |
| Document title: | Baseline Model Build and Calibration Report |
| Revision: | N-001 (Final) |
| Date: | 30 April 2018 |
| Client name: | Greater Wellington Regional Council |
| Project manager: | Michelle Sands |
| Author: | James Blyth, Lydia Cetin, Stu Easton |
| File name: | J:\IE\Projects\02_New Zealand\IZ050100\00 Technical (controlled)\08_Report\IZ050100-NCM-RP-0001_Ruamahanga_Source_model_RevM_FINAL.docx |

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| Revision | Date | Description | Approved | Distribution |
|---|---|---|---|---|
| N-001 | 30/4/2018 | Final Baseline Modelling Report | M Sands | Greater Wellington Regional Council (Natasha Tomic) |

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# Executive Summary

An integrated catchment water quality model of the Ruamāhanga catchment has been developed under a collaborative modelling partnership comprised of GWRC, Jacobs, GNS, NIWA, Waikato University and Aqualinc to help guide the freshwater limit setting process as required under the National Policy Statement for Freshwater Management.

The water quality modelling framework is comprised of an eWater SOURCE model that incorporates inputs from a range of external hydrological models, including TOPNET (upland catchment runoff), Irricalc (quickflow, land surface recharge and irrigation demands on the plains) and MODFLOW-SFR-MT3D (groundwater flux and nitrate load). The water quality modelling framework utilised landuse, soil and climatic conditions from the catchment, and inputs from OVERSEER, literature data and point sources monitoring information (such as wastewater treatment plants). Outputs from the combined water quality and flow model were used as inputs into a hydrodynamic lake model.

The simulated hydrology generally represents the observed data well, however tends to overestimate flows at a number of locations. The nutrient model achieved good calibrations to observed monthly water quality data, however at a few locations (such as Parkvale Weir), calibrations were difficult to achieve due to anomalies in the data and poor flow simulations. Modelling of *E.coli* and Suspended Sediment Concentration's (SSC) carry the most uncertainty, due to a poor relationship of *E.coli* with flow and limited observed SSC data in the catchment. Despite these challenges, the model performance is sufficient to provide for scenario modelling to explore landuse change and catchment management practices that could be adopted in the future, and guide decisions which will inform Greater Wellington Regional Councils Proposed Natural Resources Plan.

Recommendations to enhance the Ruamahanga water quality model include:

- Utilising SOURCE's internal rainfall runoff models to calibrate and simulate flow from the sub-catchments, currently generated by TOPNET and Irricalc. The advantages are better linkages between rainfall-runoff processes for different landuse/soil types (better representation of drainage and pollutant generation), more consistent and balanced subcatchment delineation, model revisions and modifications are more efficient and repeatable. In particular relating runoff process to landuse/soil types is important when modelling landuse change scenarios, as runoff characteristics will vary between landuse (i.e. forest versus pasture) and impact on loads from the catchment. Alternatively, re-calibration of a few key TOPNET tributaries will help improve the flow model.

- A spatial denitrification assessment could be undertaken based on soil, geology, and groundwater quality samples (redox, iron etc) as has recently been applied in Southland (Rissmann et al., 2016) to derive an understanding of denitrification hot spots and help inform the relevance (and locality) of the currently adopted attenuation factors.

- A more accurate (but data and time demanding) approach would be to model *E.coli* in a sub-daily catchment model coupled to a 3D hydrodynamic model of the rivers, which would provide a better estimate of in-stream fate and transport of *E.coli*, and consequently, more accurate swimmability assessments.

- Incorporating a detailed SSC monitoring programme at a number of locations within the catchment, coupled with real time instantaneous turbidity monitoring, will help inform the nature of sediment erosion and deposition processes. Instantaneous observed data and strong SSC/turbidity rating curves will provide a platform for building and calibrating a daily SedNet model, which will simulate SSC better than the current power curve approach.  If SSC calibration data was available a Daily Sednet model could be developed. The Daily Sednet modelling approach uses the same Sednet inputs, except it relies on daily rain to drive erosion to predict daily concentrations and loads.

## Important note about your report

The sole purpose of this report and the associated services performed by Jacobs is to develop a land use and nutrient loss model for the Ruamāhanga Catchment, in accordance with the scope of services set out in the contract between Jacobs and Greater Wellington Regional Council (GWRC). That scope of services, as described in this report, was developed with GWRC.

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# 1. Introduction

In 2014, the Ministry for the Environment (MfE) published the National Policy Statement on Freshwater Management (NPSFM), amended in 2017 to include guidance on microbial water quality objectives (MfE, 2017). This policy statement requires regional councils to set freshwater objectives and limits, and methods for achieving the objectives. Where those objectives are exceeded, the council is required to set targets and implement methods to meet those targets within a defined timeframe. The Ministry for the Environment working document Freshwater reform 2013 and beyond (MfE, 2013) recommends the use of models in the implementation of the NPSFM.

Greater Wellington Regional Council (GWRC) have established the Ruamahanga Whaitua committee, who are a group of local people tasked with recommending ways to maintain and improve the fresh water. The Whaitua committee will develop a Whaitua Implementation Programme (WIP). The Collaborative Modelling Project (CMP) is an important part of the collective knowledge that informed the development of the WIP, with the overarching purpose of the CMP to assist and enable the Whaitua committee, community and stakeholders to make informed discussions on the limit-setting process.

## 1.1 Purpose of this report

GWRC engaged Jacobs, in collaboration with GNS, NIWA, Waikato University and Aqualinc modellers, to develop an integrated catchment water quality and flow modelling framework of the Ruamāhanga catchment to assess water quality and allocation limits under the NPSFM framework.

This report documents the development of the integrated modelling framework, including data used to build the modelling framework, and the model construction and calibration of a baseline ‘scenario’. The model will be used in scenario modelling for the Ruamāhanga Whaitua Committee to explore a range of water quality improvement, rural land management and allocation intervention options.

## 1.1 Integrated Catchment Water Quality Modelling Framework Overview

Given there is a strong physical connection between surface and ground water in the catchment, a modelling framework that can integrate in a computationally realistic manner the exchanges of flow and water quality between the surface and groundwater systems was required. A number of existing models of the Ruamāhanga catchment simulating surface runoff, abstraction demands and groundwater flux were available. The intent of the CMP was to leverage off of these existing models of the catchment and add in surface water contaminant generation and transport. The eWater SOURCE modelling framework was chosen by the modelling team as a suitable software package due to its flexibility in customisation and catchment-scale water quality capability. By these means the variability in flow and water quality from spatially explicit land use and soil combinations were integrated spatially within the SOURCE model and the resulting contaminant concentrations and loads were simulated at a daily time-step over a representative historical period.

The inter-operating surface and groundwater modelling system developed in SOURCE is as follows (illustrated in Figure 1-1):

- TOPNET (Henderson et al, 2011) provided by NIWA produces total stream flow generated from the Hill catchments;
- Irricalc (Aqualinc, 2009) provided by Aqualinc, produces quickflow inputs from the plains catchments and irrigation surface water demands (unrestricted).
- MODFLOW-SFR-MT3D (Bedekar et al, 2016) system, developed in parallel to the SOURCE model by GNS, provided groundwater flux and nitrate loads for input to river links (reaches) (Moore *et al.* 2017);
- Point-source inputs (discharge and effluent concentrations) from five wastewater treatment plants (WWTP) derived from monitoring data and included as inflow nodes within the node-link network
- Surface water abstraction and minimum low flow limits were modelled within SOURCE

- Contaminant diffuse sources are derived from OVERSEER for nutrients, in-stream monitoring data, and literature values where local data was unavailable.

SOURCE integrates these simulated flows into one platform, and models the contaminant generation from different land uses, transport and attenuation through the node-link network representation of the river to the catchment outlet. Contaminants represented in the model include nitrate-nitrogen ($NO_3$-N), ammoniacal nitrogen ($NH_4$-N) and total nitrogen (TN), dissolved reactive phosphorus (DRP), total phosphorus (TP), total suspended solids (TSS) and *Escherichia coli* (*E.coli*). The daily outputs from the models feed into a hydrodynamic water quality model of Lakes Wairarapa and Onoke.

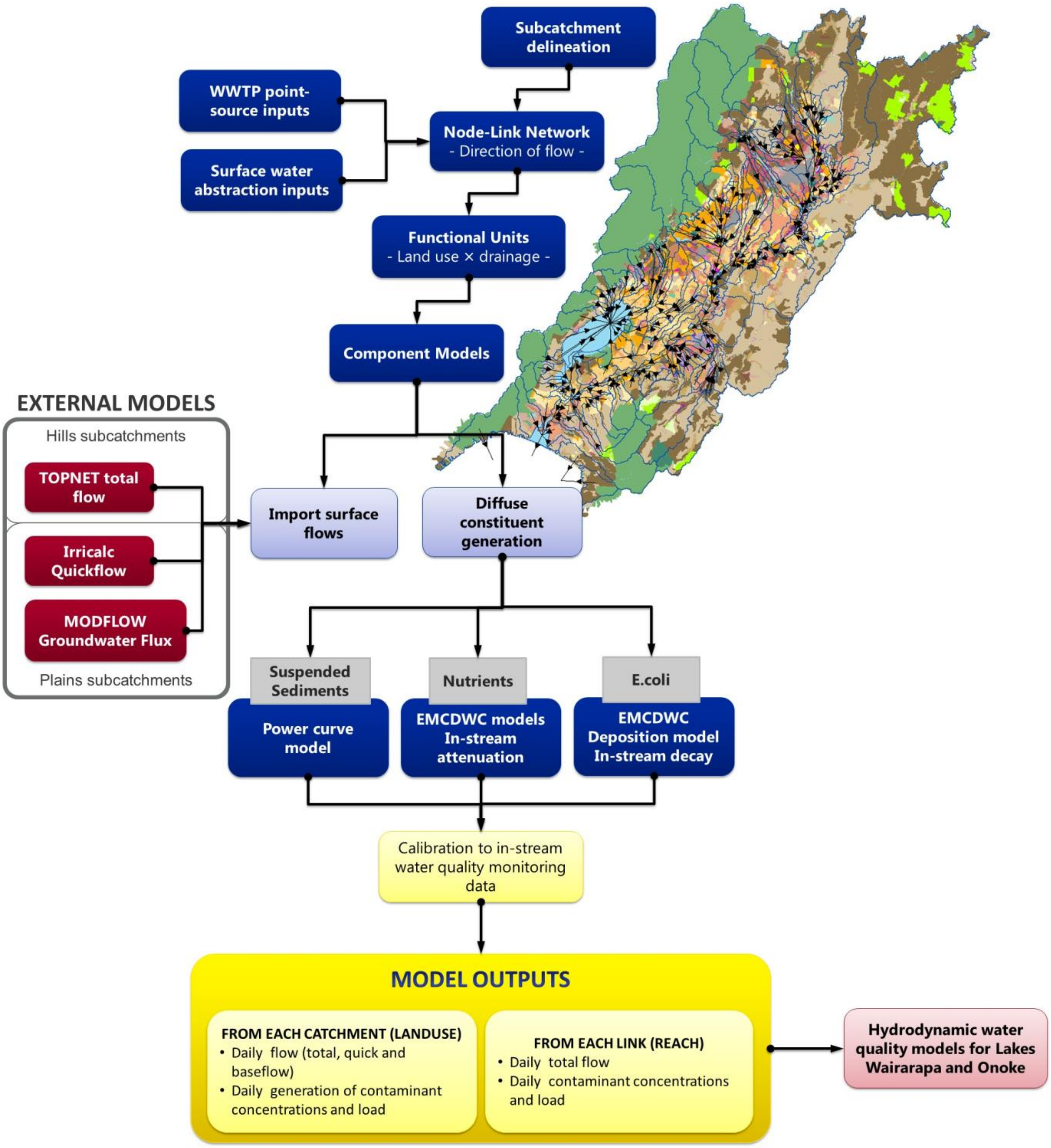

**Figure 1-1. Ruamāhanga catchment conceptual SOURCE modelling framework**

# 2. SOURCE model structure

The eWater SOURCE platform is a semi-distributed catchment modelling framework designed for exploring a range of water management problems (Welsh et al. 2012). It conceptualises a range of catchment processes using subcatchments which are composed of Functional Units (FU) that represent areas of similar hydrology and water quality generation, typically characterised through landuse or soils.

Generally, daily rainfall-runoff modelling using spatially-distributed historical climate data, calibrated to gauged streamflows, enables the representation of spatial and temporal variability in runoff and water quality generation from different land uses across the catchment. For this project daily flows were input as timeseries from TOPNET and Irricalc models, derived externally from SOURCE. It should be noted calibration of surface and groundwater flows and irrigation demand/abstractions were undertaken explicitly in the respective MODFLOW, TOPNET and Irricalc models, rather than in SOURCE. Flows and pollutants are routed through a node-link network representation of the river, where point-sources, water extractions and river operational rules augment the flow in the river network (Figure 2-1).

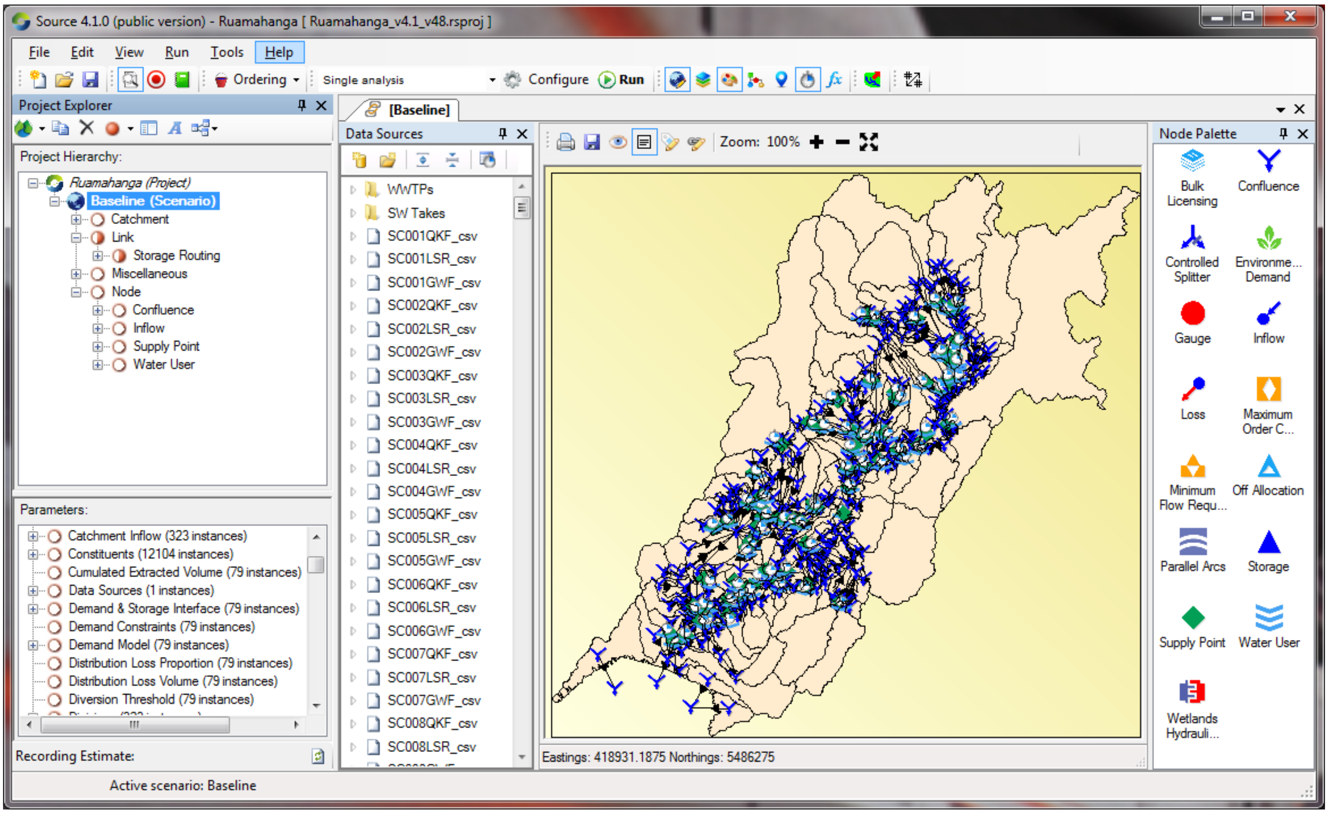

**Figure 2-1: User Interface of SOURCE software. Blue nodes = river confluences; Black arrows denote direction of flow and constituent transport**

## 2.1 Definition of catchments

Subcatchment boundaries and node-link network for the Ruamāhanga catchments (Figure 2-2) were derived from the River Environment Classification (REC) v2.0 database in line with the TOPNET modelled reaches. Upland subcatchments were aggregated to each TOPNET reach inflow point. Subcatchments delineation within the plains area were aggregated based on a combination of REC2 subcatchment boundaries (4th order streams), MODFLOW-SFR reach delineation, flow gauge and water quality monitoring locations.

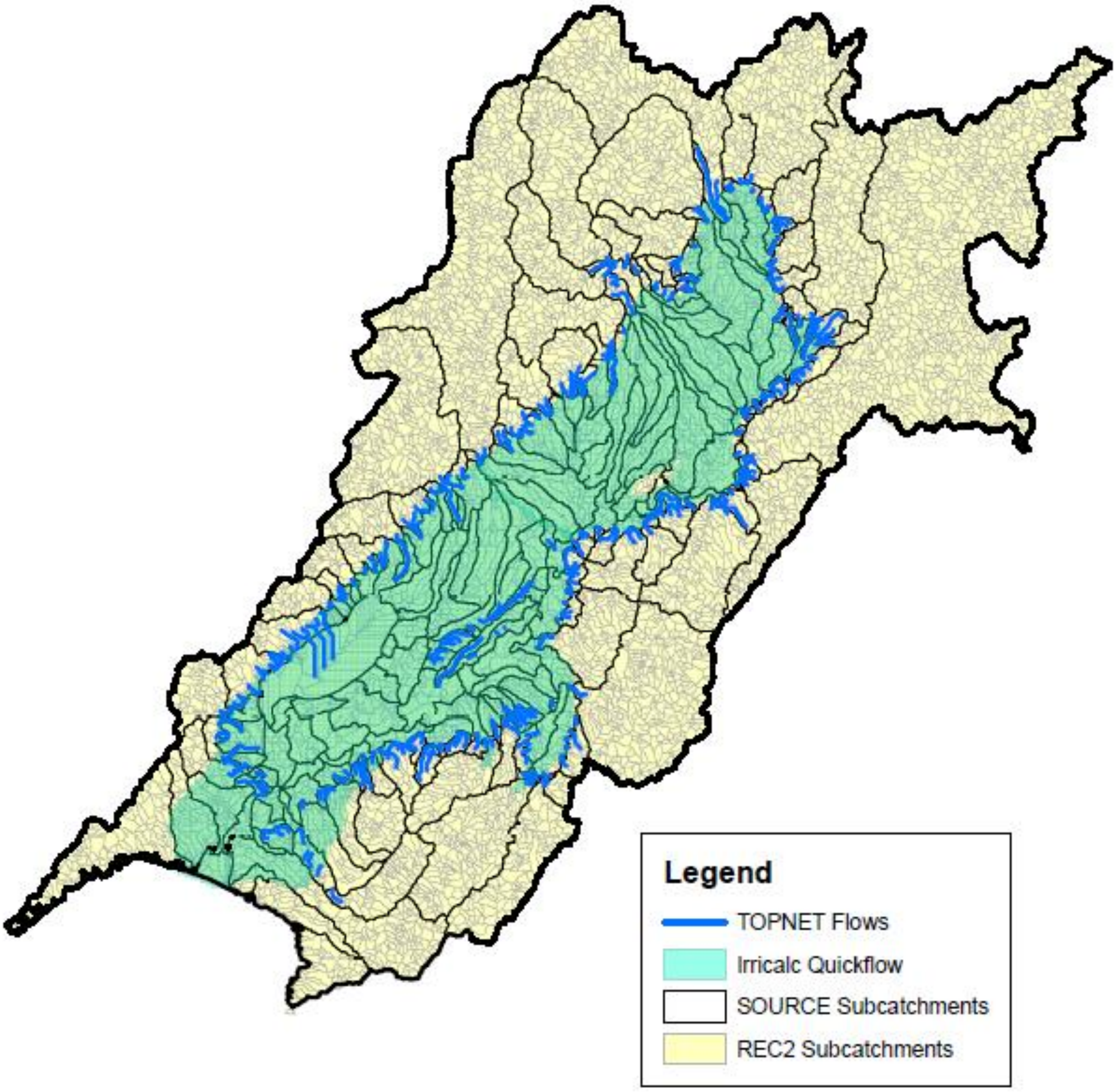

Figure 2-2. SOURCE model subcatchments derived from REC2, aggregated to TOPNET and Irricalc stream inflow reaches

## 2.2 Land use and Soils (functional units)

Land use and soil maps (S-map) were obtained from GWRC, with the landuse map developed from regional knowledge and site visits by staff. Areas of poor, imperfect and well-drained soil types were merged with land use information to derive the functional units in the model. Functional units were categorised to capture the spatial variability in leaching and runoff derived from OVERSEER, producing 45 combinations, illustrated in Figure 2-3. Figure 2-4 illustrates the distribution of land use areas across the catchment, with Sheep and Beef, Native Bush, and Dairy the dominant land use types.

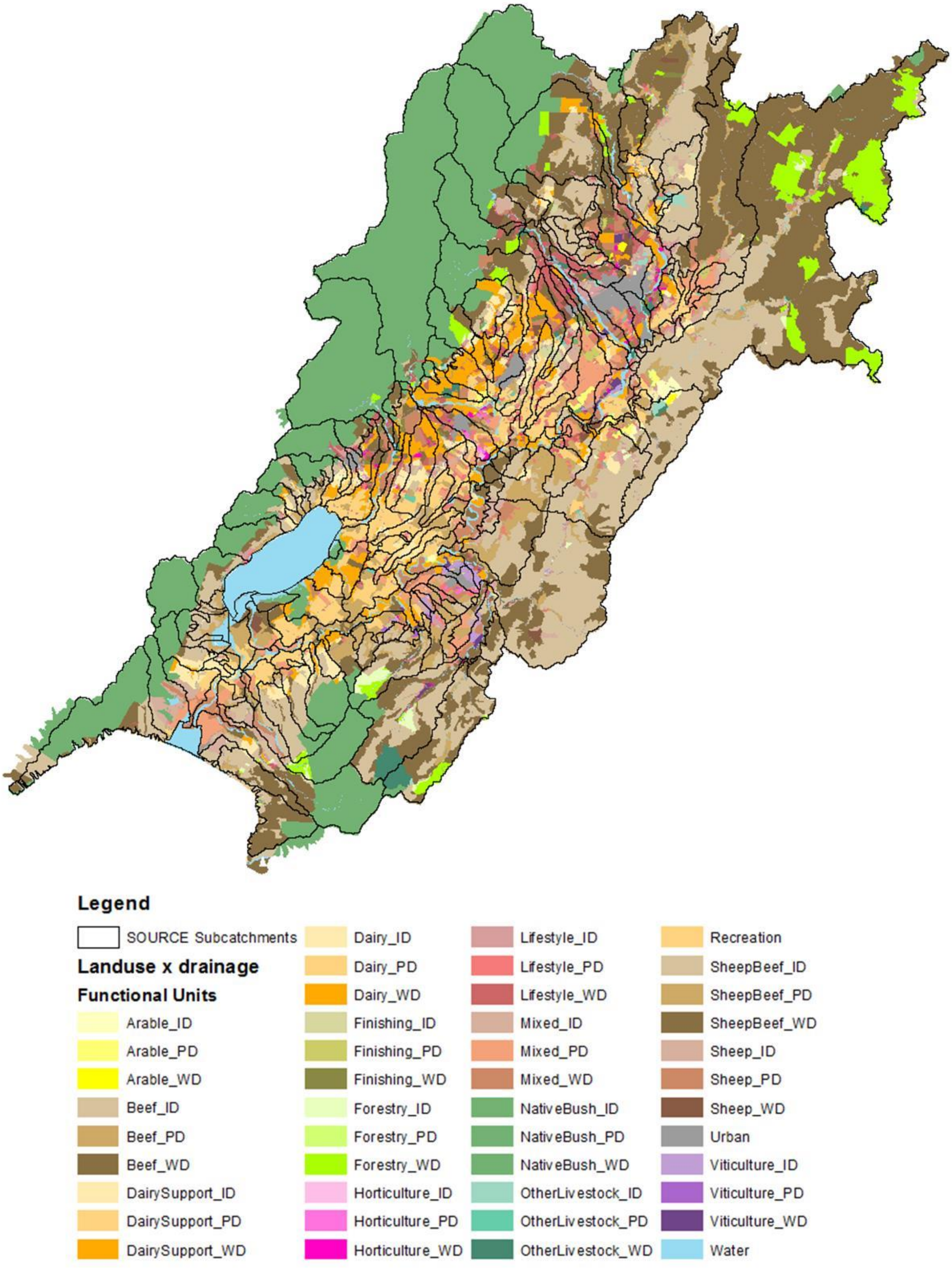

**Figure 2-3. Land use and drainage (based on soil types) categories used to describe functional units in the SOURCE model. IP = Imperfectly drained, PD = Poor drained, WD = Well drained.**

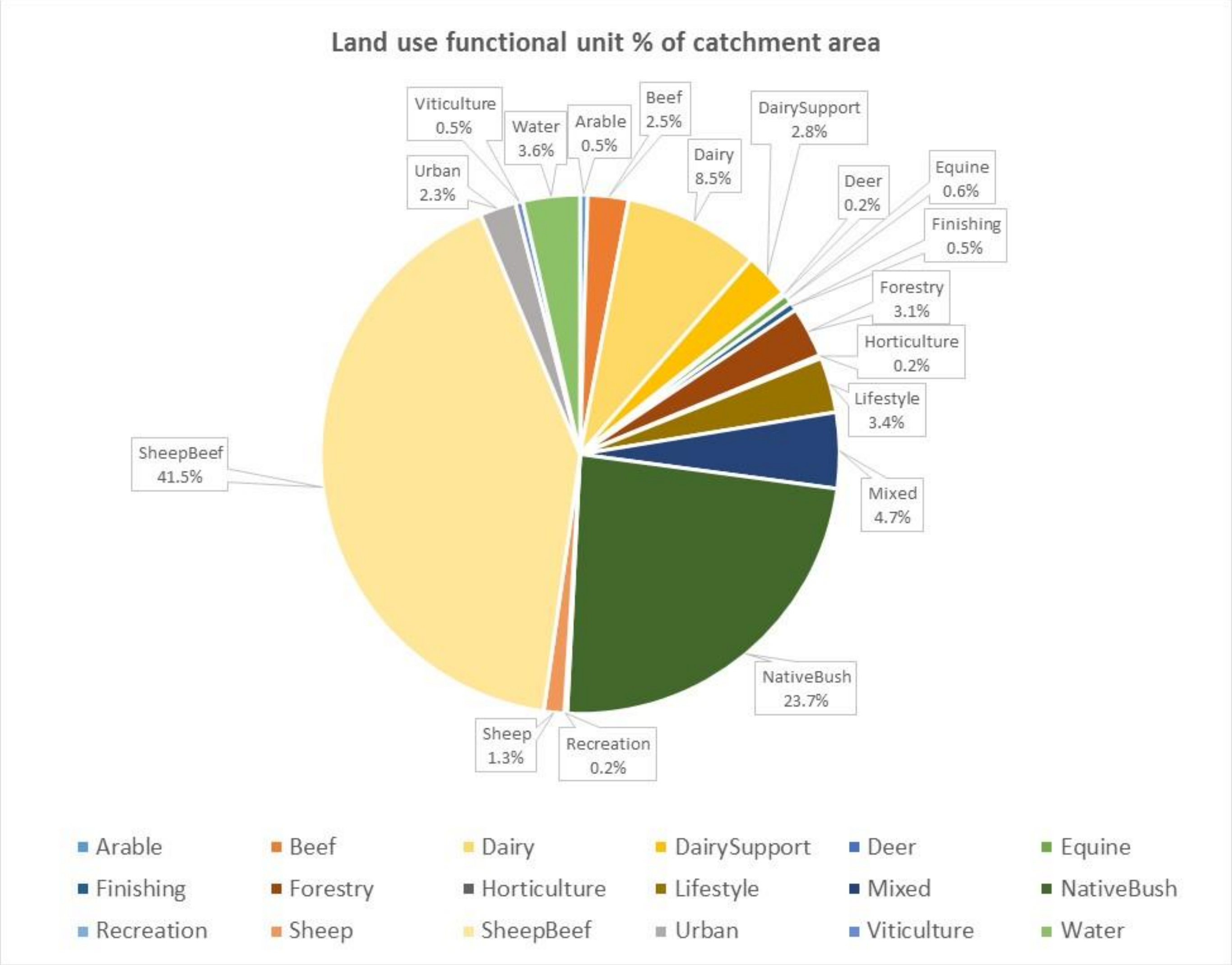

**Figure 2-4: Distribution of Land Use Functional Unit areas as percent of total catchment area.**

## 2.3 Surface water abstraction rules (allocations)

Irricalc modelled 114 consented surface water abstractions, primarily representing irrigation applications for dairy and horticultural land uses, and produced timeseries for each surface water consent, representing the unrestricted irrigated water demand. These demands were used to configure water user nodes in the SOURCE model to represent irrigated water abstractions. Surface water consent rules were configured in the SOURCE supply point nodes, and include low flow restrictions.

Potable abstractions (a total of 16) were also incorporated into the SOURCE model. GWRC provided revised estimates of the instantaneous abstraction amounts for these takes (versus what is consented) that was applied in the model at relevant locations as a constant daily demand.

The following approach was undertaken on the consented (irrigated) surface water abstractions:

- The 114 consented takes were agglomerated into their relevant subcatchments through GIS. The daily abstraction timeseries for each consent within that subcatchment were added together, after being filtered to ensure the consents were active for the relevant modelling period.
- A total of 61 ‘agglomerated’ abstraction timeseries (within 61 SOURCE subcatchments) were defined.
- For each of these subcatchments, a water user and supply point node was added into the SOURCE modelled river network. The agglomerated daily abstraction timeseries (as csv’s) were imported and

assigned to each respective node to represent the cumulative (modelled) daily abstraction that could be occurring.

- For each node, a number of functions/control rules were coded in. This was driven by the consenting requirements for ramp downs and cease takes based on low flows at certain flow control sites (i.e. Ruamahanga at Waihenga flow gauge). Not all consents had restrictions imposed.
    - Low flow ramp down – assign a rule based on when a reaches flow drops below a threshold, the restriction on the daily modelled abstraction is activated
    - Low flow cease abstraction – as above, however ceases abstraction.

During the set-up of ramp down and cease take abstractions rules for each of the agglomerated water supplies, some issue with simulated versus observed flows were identified. At a number of locations, the modelled hydrological flow inputs simulated flows higher than observed, which meant the consented ramp down or cease take flow would not activate. For example, a cease take on a number of consents was driven by flow at the Waihenga station, where abstraction was to cease when observed flows dropped below 8.5 $m^3$/s. However, simulated flows in SOURCE at this location did not drop below 11 $m^3$/s, resulting in the cease take rule never being active.

To resolve this issue, flow duration curves were created for the observed and simulated data at each of the control sites where cease take and ramp down rules were linked to abstractions. The exceedance percentile for the ramp down or cease take flow in the observed data was then used to determine a ‘scaled’ value. For example, 8.5 $m^3$/s in the observed data for Waihenga is equivalent to a likelihood of exceedance of 0.975. This exceedance value is equivalent to 13.4 $m^3$/s in the simulated flows, and therefore the latter value was then applied in the model functions to cease abstraction.

There is no annual abstraction allocation applied to any surface water consents. Review of a number of existing Irricalc surface water abstractions showed no single consent reached their annual allocation volumes. For this reason, coding annual allocation restrictions in the models was not undertaken.

Groundwater abstractions were modelled in MODFLOW, and assumed accounted for in the groundwater flux inputs.

## 2.4 Oporua flood spillway

The Oporua flood spillway is located in the lower reaches of the Ruamāhanga River, and diverts flood waters into Lake Wairarapa at certain thresholds. Discussions with GWRC and analysis of flood data from the Oporua water level site identified that the spillway operates when flow at the Waihenga station is between 800-900 $m^3$/s, slightly less than the mean annual flood. The spillway itself has a maximum capacity of ~700 $m^3$/s (Personal Communication Mike Gordon 26 September 2016). This was incorporated into the SOURCE model through control rules around spillway operation. The following assumptions were made:

- Spillway operates when Ruamāhanga River at Waihenga is flowing at > 850 $m^3$/s
- The spillway has a maximum capacity of 700 $m^3$/s

Therefore, when flow exceeds 850 $m^3$/s, any additional flow up to 1,550 $m^3$/s is routed down the Oporua Spillway into the lake. Flows exceeding 1,550 $m^3$/s will continue down the Ruamāhanga River (less the 700 $m^3$/s directed through the spillway).

## 2.5 WWTPs

The major point sources of pollutants in the Ruamāhanga catchment are the five wastewater treatment plants (WWTPs) of Masterton, Carterton, Featherston, Greytown and Martinborough. Greater Wellington Regional Council supplied data for each of the WWTPs, summarised in the Table 2.5. The WWTPs have been operating in the Ruamāhanga catchment for approximately the last 40 years, but the majority of monitoring data is from the last 5 or in some cases 10 years.

In order to derive point-source inputs to the model that covers the full simulation period at a daily timestep, discharge and effluent quality monitoring data were infilled. Generally, discharge data was recorded on a daily basis with minimal missing data. To extend the discharge record rainfall recorded at the closest rainfall station (Table 2.5) was used to derive representative discharge based on a rainfall threshold and the 95th percentile discharge in order to capture even discharges. Carterton WWTP discharge data was only available for a short period, with no data collected between July and December; therefore, a monthly pattern could not be derived. The median value of the record was used as a constant discharge as the data demonstrated very little variation in daily discharge.

Effluent quality data was generally recorded monthly or fortnightly, and a monthly pattern derived from the entire monitoring record for each WWTP was used to infill missing data to derive a daily timeseries. Graphs for each of the WWTP inputs to the SOURCE model are given in Appendix A. No Nitrate data was available for Greytown WWTP, therefore, based the ratio of Nitrate to Total Nitrogen calculated for the other WWTP data (between 1-10%), an average of 5.7% was used to derive Nitrate concentrations based on TN data from Greytown WWTP.

**Table 2.5. Summary of Ruamāhanga catchment WWTP point-source monitoring data**

| WWTP | Length of discharge record | Number days missing discharge data | Rainfall gauge for discharge infilling | Length of water quality record | Number of water quality data records |
|---|---|---|---|---|---|
| Masterton | 1/01/2001 – 31/07/2015 | 0 | East Taratahi | 1/01/2001 – 31/07/2015 | <177 |
| Carterton | 1/03/2014 – 30/06/2015 | Data did not cover simulation period | - | 25/11/2011 – 18/05/2015 | 86 |
| Featherston | 1/07/2005 – 30/09/2014 | 6 | Tauherenikau | 22/02/2006 – 7/05/2012 | 55 |
| Greytown | 18/03/2005 – 4/06/2014 | 0 | Woodside | 1/08/2001 – 30/04/2012 | 966 |
| Martinborough | 1/12/2007 – 31/03/2015 | 11 | Martinborough EWS | 10/12/2002 – 18/06/2013 | <257<br>($NO_3$ & DRP = 82) |

**Discharge to land**

Masterton WWTP has in the past decade implemented changes to improve water quality, now discharging to the Ruamāhanga River (rather than the Makoura Stream) and in 2009 beginning to discharge to land. Carterton WWTP in 2006 began discharging to land, particularly in the summer months, to improve the Mangatarere Stream health. Data on specific discharge volumes and quality were not of sufficient length (some data available post 2014, which is outside the simulation time period) or quality to enable inclusion in the SOURCE model, and therefore, all point-source discharge is currently direct to stream for the basecase model.

## 2.6 Hydrological Model linkages

Generally, in SOURCE rainfall-runoff models generate runoff from the catchments based on daily inputs of spatially gridded rainfall and potential evapotranspiration (PET). Given the availability of simulated surface flows from TOPNET and Irricalc that represent these rainfall-runoff processes, the observed catchment runoff model was used to import timeseries for each subcatchment in the following manner:

1) Subcatchments in the SOURCE model were allocated to either a TOPNET or Irricalc flow requirement.

2) TOPNET total flow was converted to a runoff rate (mm/d) based on the corresponding upstream REC2 catchment area and input to the observed catchment runoff model, which partitions the total flow into quick and baseflows using a Boughton baseflow filter (Boughton, 1993).
3) Irricalc quick flow grids were converted to a runoff rate based on grid cell size (5 km × 5 km) and aggregated for each allocated SOURCE subcatchment. The observed catchment surface runoff model was used to import a timeseries of Irrical quickflows. Note that the land surface recharge derived from Irricalc is used as direct recharge inputs to the MODFLOW models.
4) Groundwater flux (i.e. the exchange of flows within a river reach depending on gaining or losing connectivity), representing baseflow in the lower reaches, was determined from the MODFLOW models and input as a timeseries flux for each SOURCE link that fell within the northern and southern groundwater domains (Moore *et al.* 2017).

The node-link network, based on the direction of flow to the catchment outlet, delivers runoff generated from these models for each subcatchments and transports (or routes) the flow through the network to provide the cumulative flows within each river reach (a link in the model). Flow routing is implicit in the simulated flows from the external TOPNET and Irricalc models, therefore, SOURCE did not include flow routing in the links (assumed straight through routing where flows are passed through network at each timestep). The upper catchment flow was represented through TOPNET runoff, while the lower catchments were represented by Irricalc quickflow and MODFLOW GW Flux (baseflow). The MODFLOW model also incorporated TOPNET runoff as an input, so the groundwater fluxes linked back into the SOURCE model will not be double counting the upland runoff.

The flows within the SOURCE model represent calibration to status-quo (Baseline) conditions over the period 1 July 1992 to 30 Aug 2014. This period has been defined by the MODFLOW SFR outputs which were imported into the model to represent baseflow in the lowland reaches. It should be noted calibration of surface and groundwater flows and irrigation demand/abstractions were undertaken explicitly in the respective MODFLOW, TOPNET and Irricalc models.

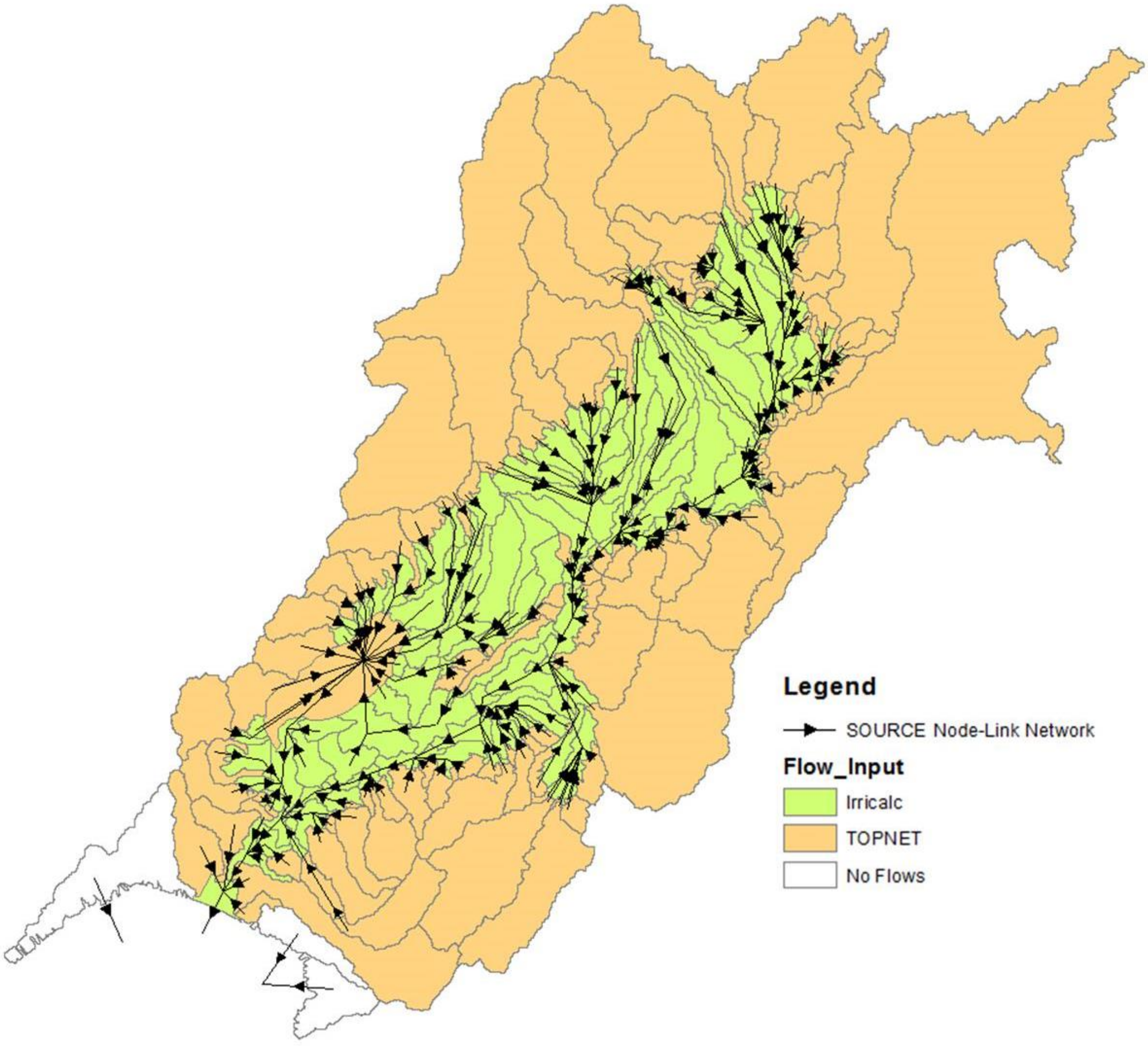

**Figure 2-5. SOURCE model subcatchments and node-link network, with colours indicating TOPNET or Irricalc surface flow assignment.**

### 2.6.1 Comparison of generated and gauged flows

The gauged flow data obtained from GWRC is of good quality, with a continuous flow record (converted from stage) for a long period of record. This data was converted to daily mean flows for comparison to modelled flows once integration of all external hydrological model inputs was completed as a form of ‘model calibration’.

Mean annual flows (MAF) and mean annual low flows (MALF) have been calculated for a number of sites comparing the observed and simulated SOURCE flows. These are presented in Table 2-2. In addition, the simulated and observed data have been compared to determine the Nash Sutcliffe Efficiency (NSE) and Percent Bias (PBIAS).

NSE is a measure of goodness of fit for many hydrological models, being a normalized statistic that determines the relative magnitude of variance between simulated and measured data (Moriasi *et al.* 2007). NSE was calculated as an average weighting (50/50) between the flow duration curve and the 7-day rolling average flows at each site. 7-day flows were used rather than the daily to be consistent with the GNS MODFLOW calibration. PBIAS represents the average tendency of simulated data to be larger or smaller than their observed counterparts. Moriasi *et al.* 2007 model performance indicators are summarised in Table 2.1. Flow duration curves comparing measured and modelled daily flows are presented in Figure 2-6 to Figure 2-15.

Table 2.1 : Moriasi *et al.* 2007 model performance indicators (flow)

| Calibration Performance | NSE | PBIAS |
|---|---|---|
| Very Good | 0.75 to 1.0 | <±10% |
| Good | 0.65 to 0.75 | ±10% to ±15% |
| Satisfactory | 0.50 to 0.65 | ±15% to ±25% |
| Unsatisfactory | <0.50 | >±25% |

Examination of the simulated daily flow data against the observed resulted in NSE values worse than the 7-day averages. The model data will be used in its entirety when assessing flow and water quality scenarios (i.e. the entire flow period and water quality concentrations will be used to derive single statistical values for the 22 year simulation). For this reason, the daily fit of simulated and observed flow data is considered less significant than the overall model performance for the entire period.

Generally, the simulated flows are higher than the observed (exhibited in the positive PBIAS in Table 2-2), moving downstream in the Ruamahanga Catchment. This can be attributed to complexities with the groundwater-surface water exchange processes and some unsatisfactory runoff calibrations from a few locations (for example, Kopuaranga at Stuarts). The resulting higher flows can impact on water quality modelling, with greater loads produced. However, this can be compensated through the water quality calibration approach by incorporating attenuation factors that may be slightly higher than what is occurring in reality.

Table 2-2 : Observed and modelled flow comparison statistics

| Flow gauge site | MAF ($m^3/s$) | | MALF ($m^3/s$) | | NSE (0-1) | PBIAS (%) | Comparison Period |
|---|---|---|---|---|---|---|---|
| | OBS | MODEL | OBS | MODEL | | | |
| Kopuaranga at Stuarts | 3.68 | 4.47 | 0.66 | 0.28 | 0.67 | 34% | 2009-2014 |
| Kopuaranga at Palmers | 2.72 | 3.29 | 0.31 | 0.17 | 0.68 | 26% | 1992-2014 |
| Ruamahanga at Wardells | 23.64 | 26.35 | 2.57 | 3.28 | 0.83 | 9% | 1992-2014 |
| Ruamahanga at Waihenga | 81.04 | 93.17 | 9.48 | 15.9 | 0.57 | 10% | 1992-2014 |
| Mangatarere at Gorge | 1.88 | 2.76 | 0.15 | 0.52 | 0.72 | 1% | 1999-2014 |
| Mangatarere at SH2 | 4.37 | 4.23 | 0.55 | 0.4 | 0.65 | -8% | 2009-2014 |
| Taueru at Te Whiti Bridge | 6.09 | 10.7 | 0.33 | 1.77 | 0.83 | 11% | 2002-2014 |
| Waiohine at Gorge | 23.7 | 23.9 | 3.39 | 4.89 | 0.61 | 12% | 1992-2014 |
| Waingawa-Kaituna | 9.98 | 8.27 | 1.19 | 1.40 | 0.76 | -19% | 1992-2014 |
| Otukura Weir | 0.56 | 0.74 | 0.09 | 0.18 | 0.41 | 35% | 1998-2014 |

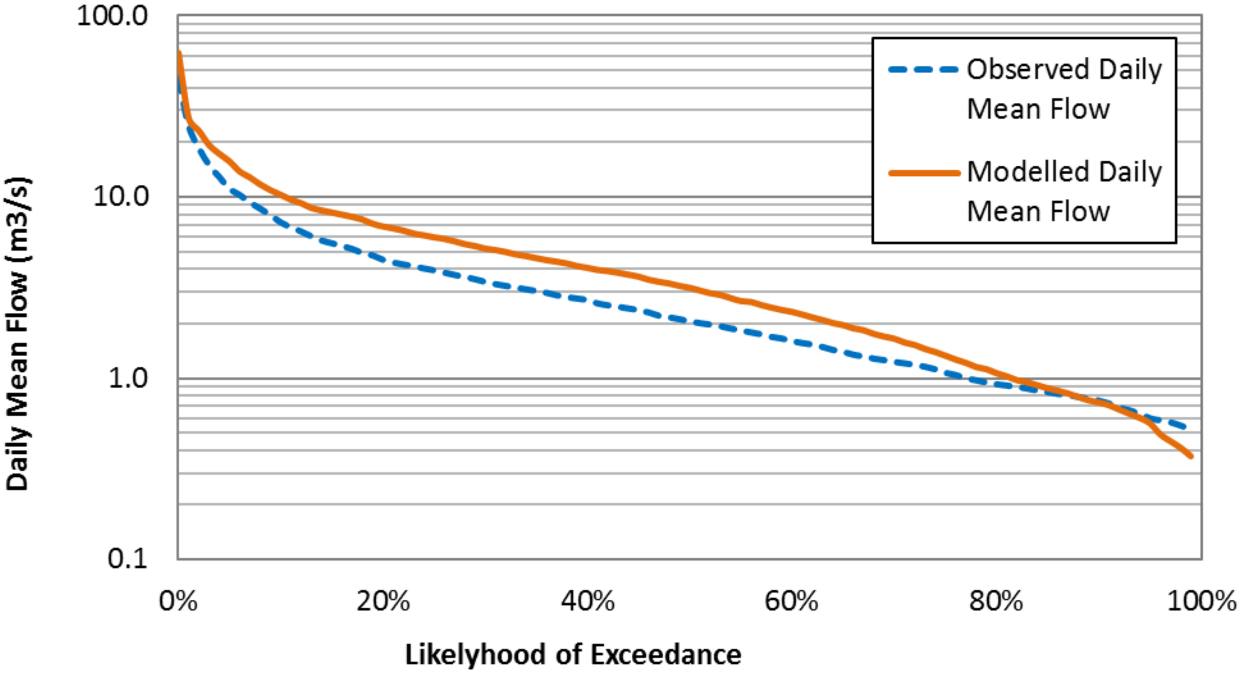

Figure 2-6: Kopuaranga River at Stuarts observed and modelled flow duration curves

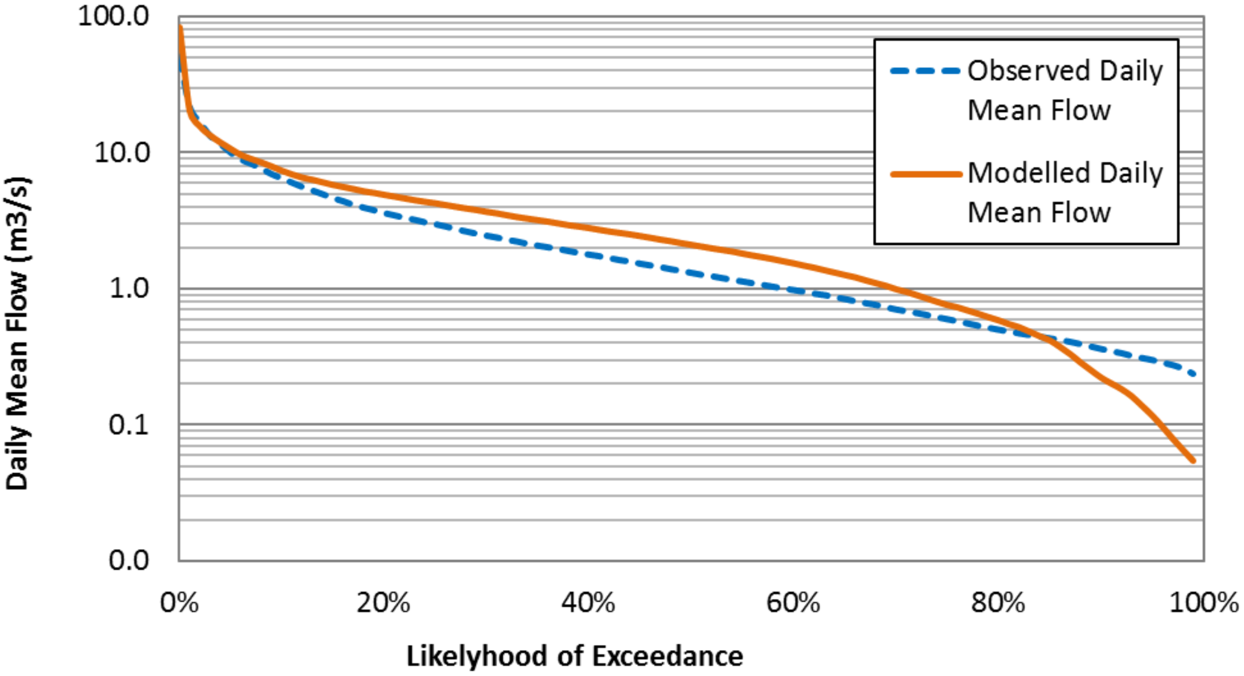

Figure 2-7: Kopuaranga River at Palmers observed and modelled flow duration curves

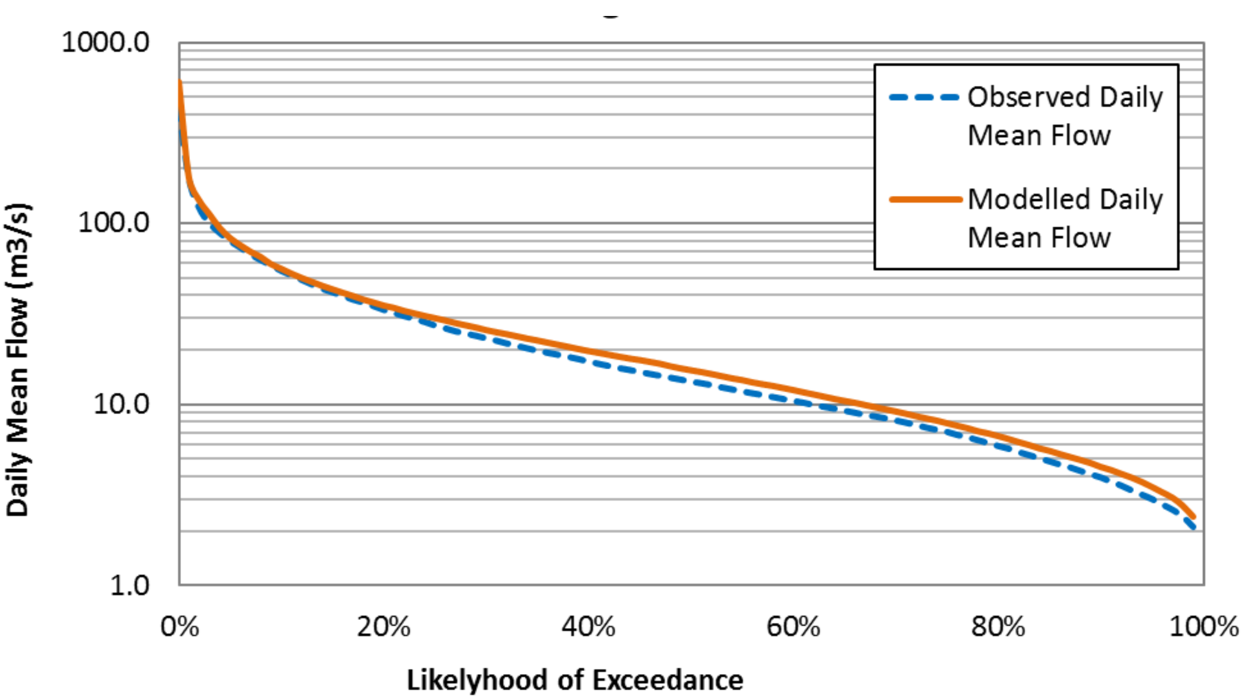

Figure 2-8: Ruamahanga River at Wardells observed and modelled flow duration curves

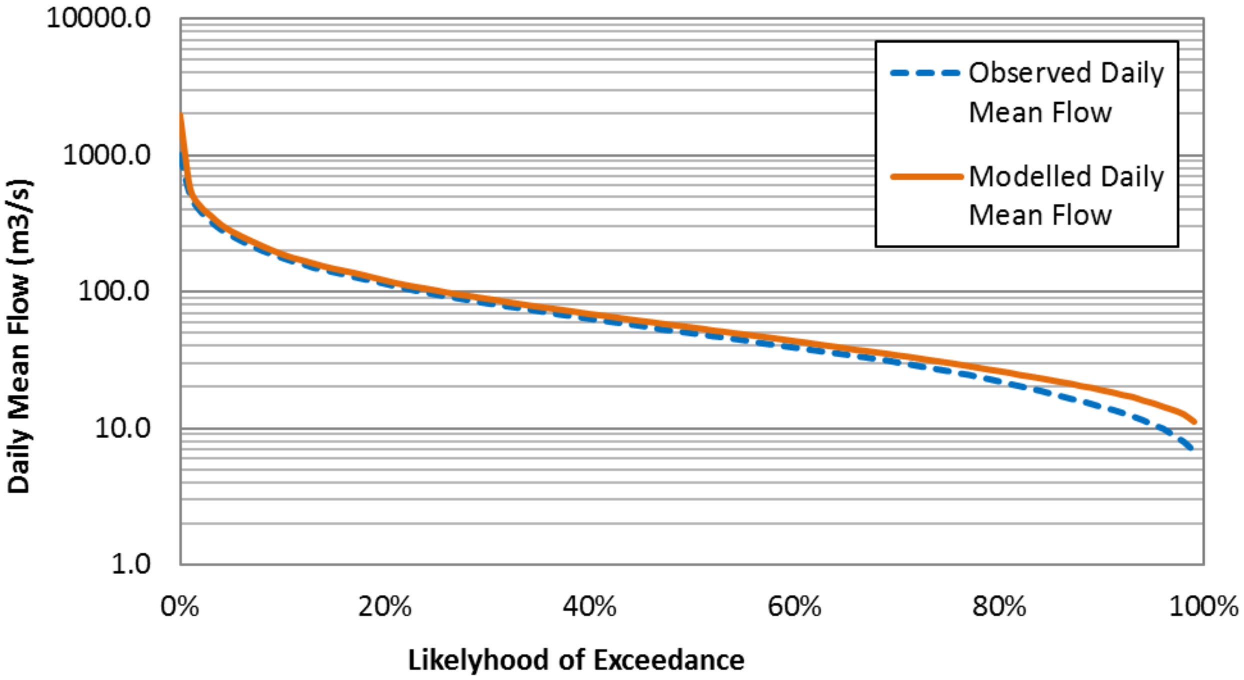

Figure 2-9: Ruamahanga at Waihenga observed and modelled flow duration curves

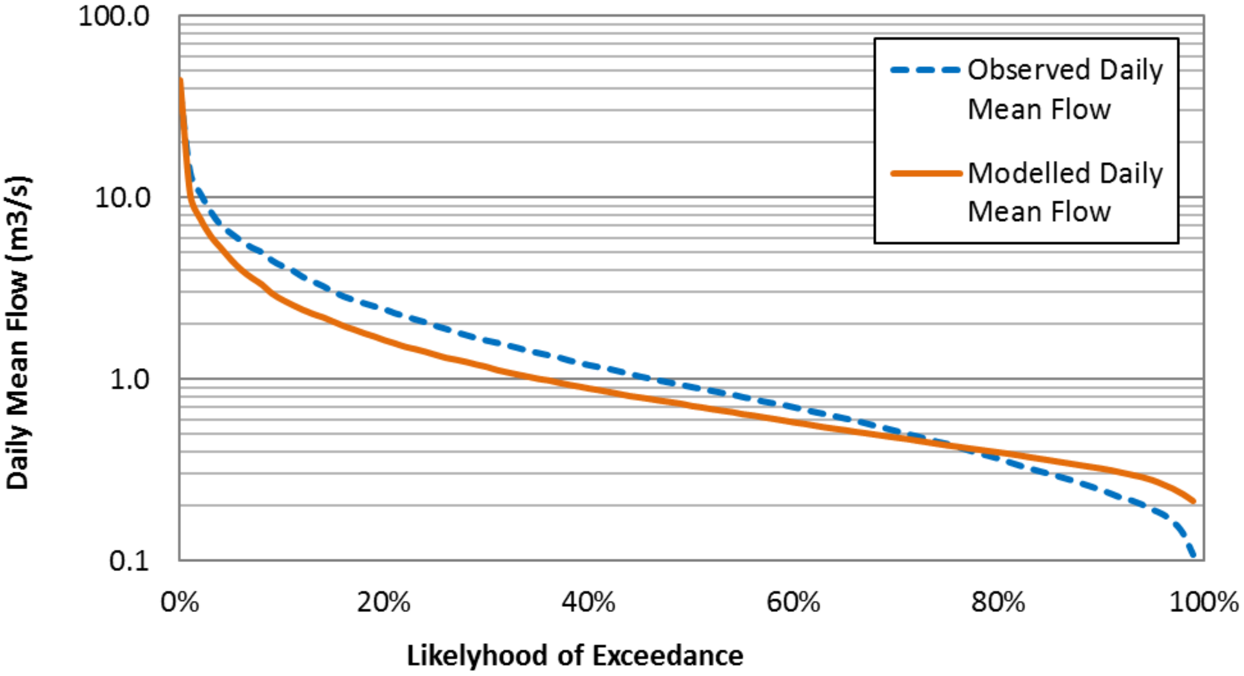

Figure 2-10: Mangatarere River at Gorge observed and modelled flow duration curves

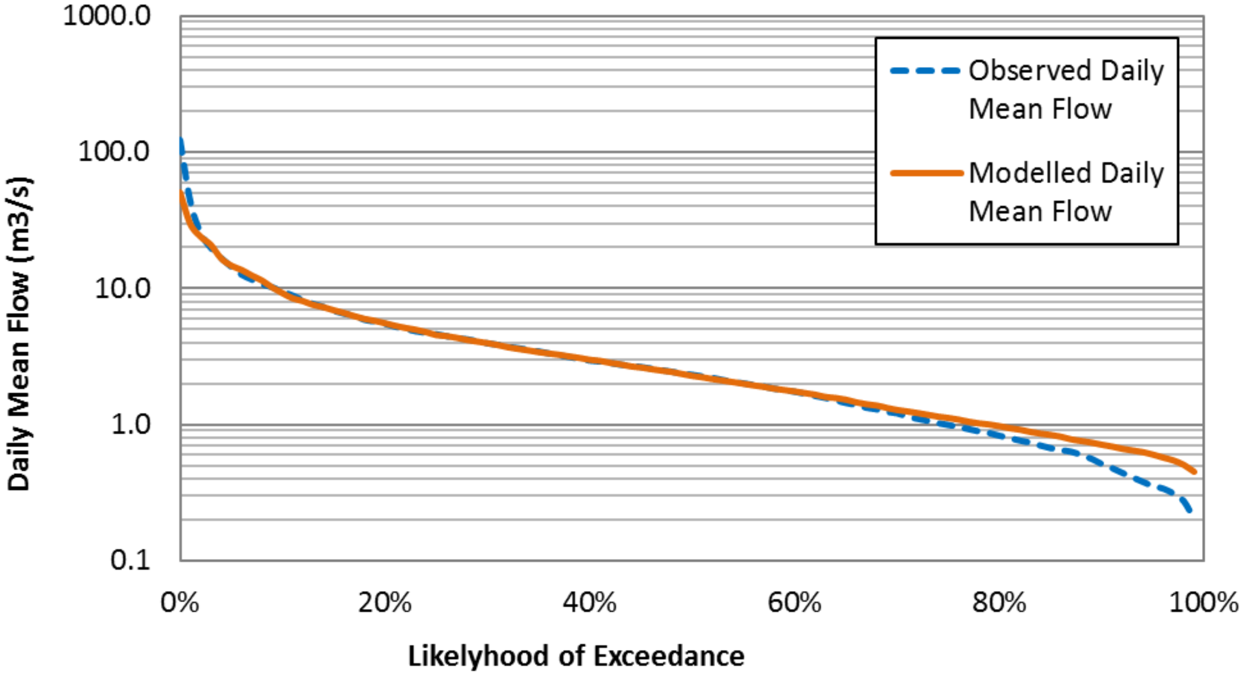

Figure 2-11: Mangatarere River at SH2 observed and modelled flow duration curves

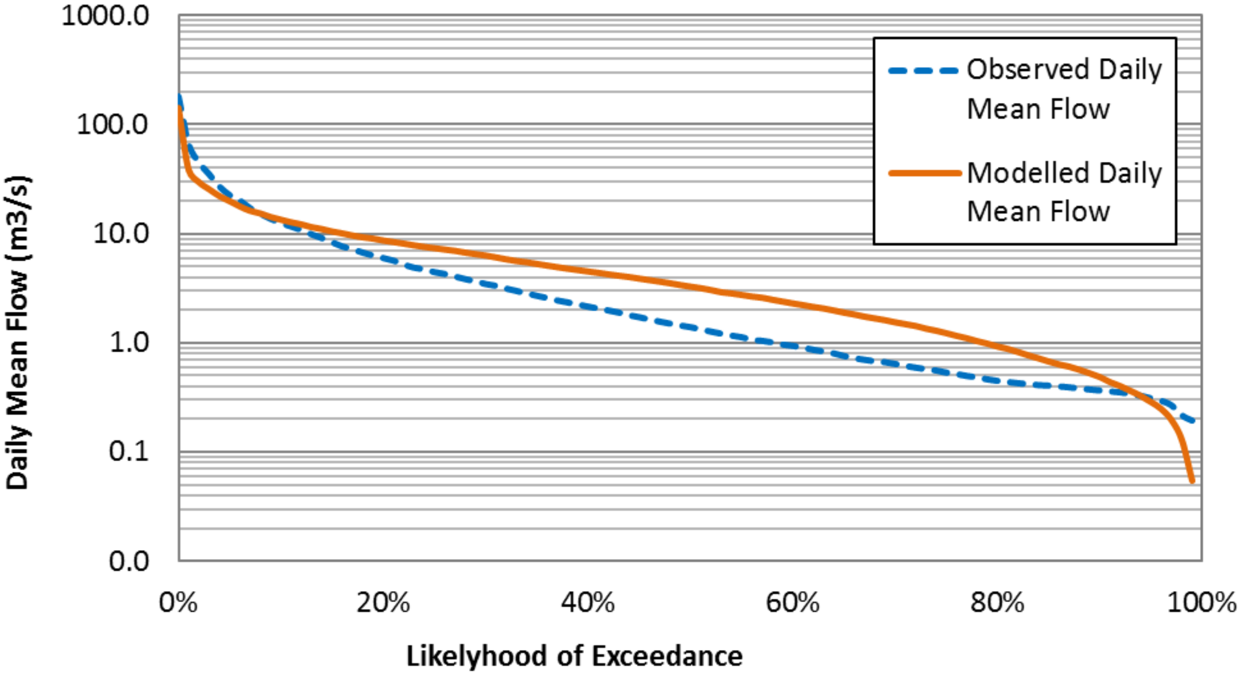

Figure 2-12: Taueru at Te Whiti Bridge observed and modelled flow duration curves

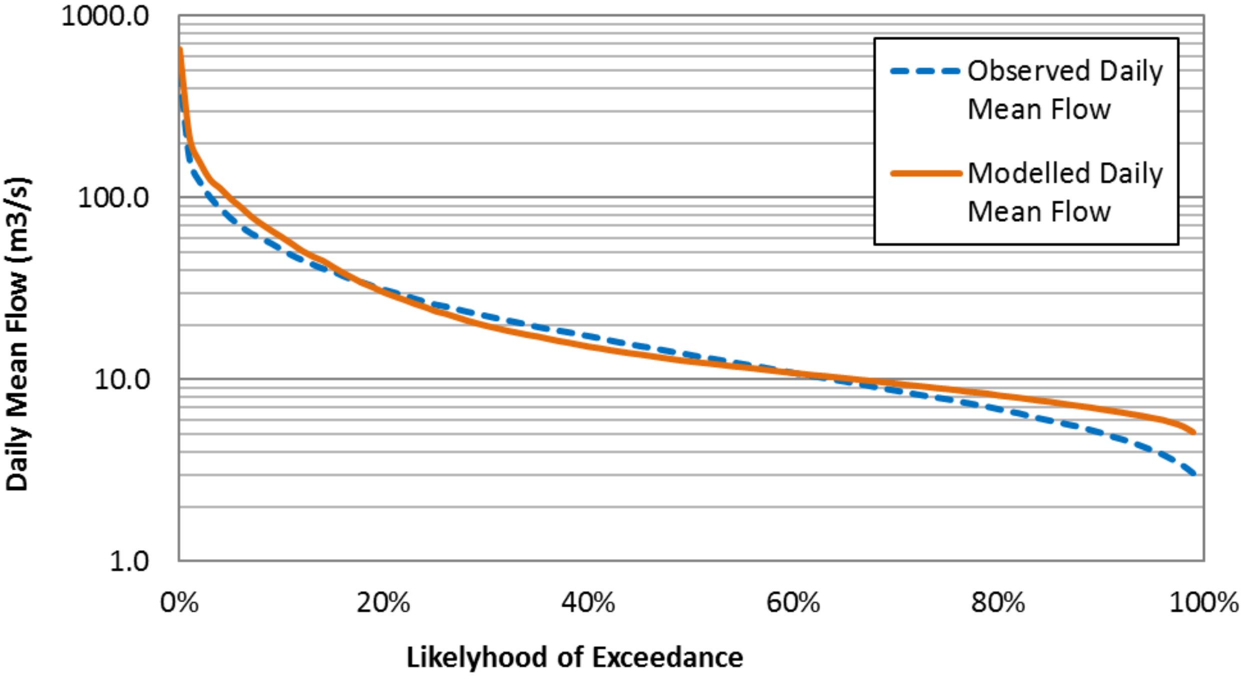

Figure 2-13: Waiohine at Gorge observed and modelled flow duration curves

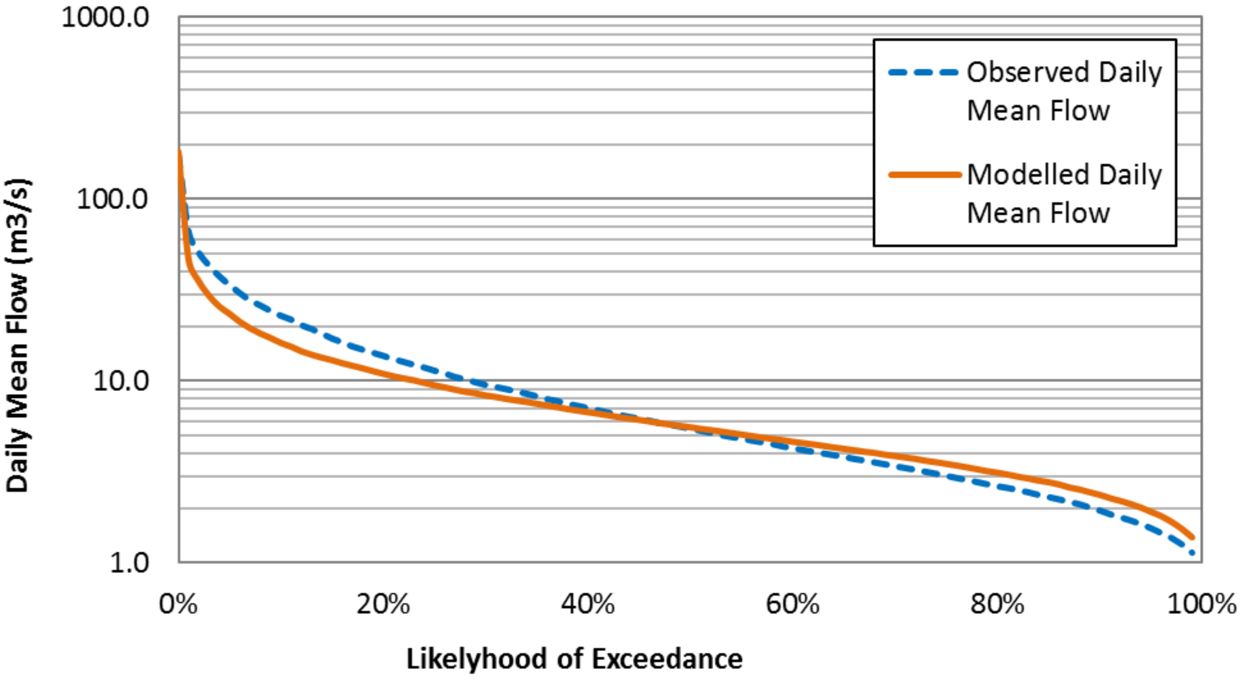

Figure 2-14: Waingawa River at Kaituna observed and modelled flow duration curves

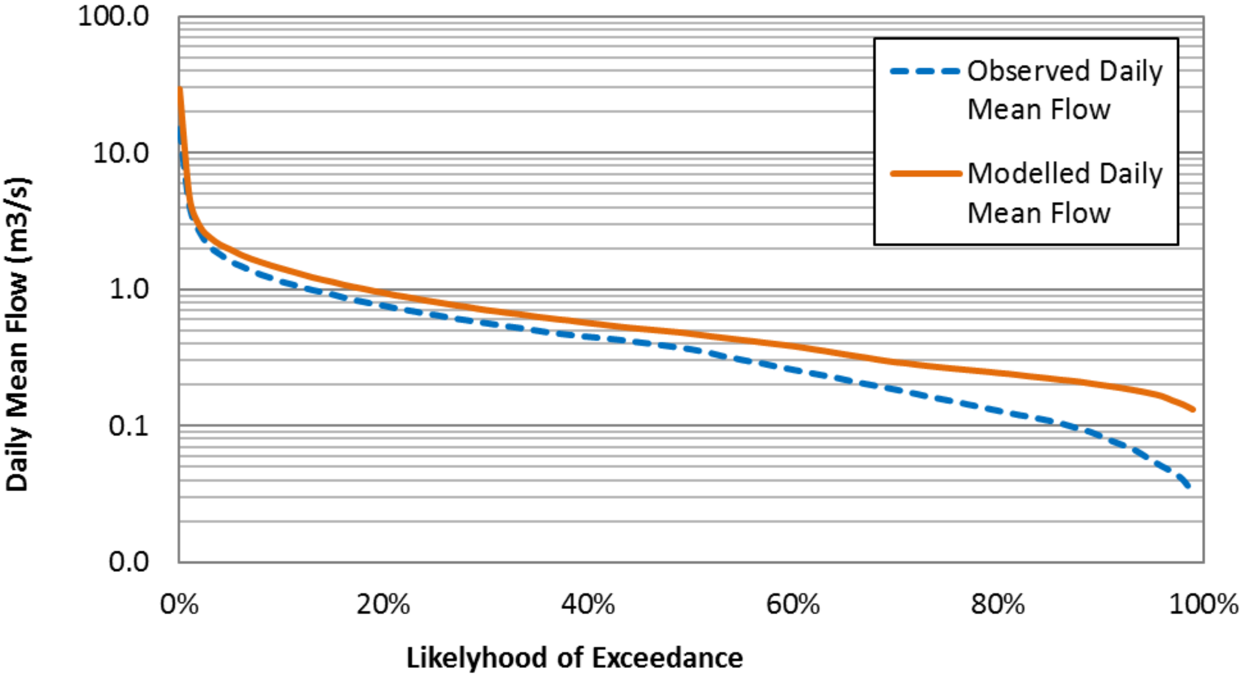

Figure 2-15: Otukura Weir observed and modelled flow duration curves

# 3. Nutrients

Nutrients represented in the model include nitrate-nitrogen ($NO_3$-N), ammoniacal nitrogen ($NH_4$-N), total nitrogen (TN), dissolved reactive phosphorus (DRP), and total phosphorus (TP).

Nutrient generation from different land uses are informed by OVERSEER modelling of representative farms and literature data. These represent the unattenuated concentrations generated from a particular land use and soil drainage category that aligns with the SOURCE model FUs. After generation, nutrient loads are transported via surface water and shallow groundwater pathways.  Nutrient loads from surface water pathways are derived by multiplying the surface runoff generated from each land use type within each subcatchments by an estimated Event Mean Concentration (EMC) for each nutrient constituent. Nutrient transport via shallow groundwater pathways are represented by multiplying the volume of baseflow by an estimated dry weather concentration (DWC) for a particular subcatchment and land use type. The total nutrient load for each subcatchment is then transported to the river on a daily time step.

In addition, nitrate derived from groundwater sources was deemed a significant contributor to overall catchment nitrate loads, and was modelled externally to SOURCE via MODFLOW solute transport module. Timeseries spanning the full simulation period were provided by GNS as nitrate loads and converted to concentrations using the corresponding groundwater flux. The groundwater nitrate concentrations were included in the relevant gaining model links as a daily input timeseries.

## 3.1 OVERSEER modelling

OVERSEER modelling (version 6.2.1) was conducted for fifteen representative farms to generate a spatial nitrate leaching and TP runoff maps for each land use category for the whole catchment. Representative farms were developed by Ministry for Primary Industries (MPI) and the farm descriptions are outlined in Table 3-1.

**Table 3-1 : OVERSEER farm codes and descriptions**

| MPI Farm Code | Representative Farm Description |
|---|---|
| 1b | Low rainfall dairy |
| 1a | Moderate rainfall dairy |
| 3 | High rainfall dairy |
| 2 | Irrigated dairy |
| 4 | Organic dairy (low intensity) |
| 5 | Summer dry sheep and beef finishing |
| 6a | Summer wet sheep and beef breeding |
| 6b | Summer wet sheep and beef finishing |
| 7 | Sheep and beef and bulls |
| 9 | Sheep and beef and grazing |
| 8b | Sheep and beef livestock trading, 20% cropping |
| 8a | Irrigated sheep and beef livestock trading |
| 10 | Finishing beef, 65% cropping |
| 11b | Low rainfall dairy support, 15% cropping |
| 11a | High rainfall dairy support, 48% cropping |

There was a range in climate and soil types across the Ruamahanga catchment. Therefore, the climate and soil types were changed in each representative farm to reflect each combination of climate and soil type within the catchment (a total of 244 scenarios).

- Climate and soil were changed for each block within each farm, for each scenario. Where there was a range in annual average rainfall, the midpoint of the range was chosen. Evaporation was set to default for the block.
- Some representative farms involved a mixture of soil types, however these were all changed to one soil type at a time for the OVERSEER scenario runs.
- Slope was kept the same as the original representative farms.

Soil texture is required to be specified in OVERSEER for recent and brown soils as either light, medium, or heavy. Using OVERSEER Best Practice Guidelines, the recent and brown soils were classified as medium. Raw soils identified in the scenarios were assigned N and P loss values from ‘recent’ soils with medium texture.

The nutrient budget calculated by OVERSEER gives total N and P loss to water. This value is calculated from Leaching – urine patches; Leaching – other; Runoff; Direct (animals, drains); Direct pond discharge; Border dyke outwash; and Septic tank overflow.

In most cases N loss to water was made up of a mixture of ‘Leaching – urine patches’ and ‘Leaching – other’ (e.g. fertiliser). This was grouped as total N leaching and was assumed to be nitrate. Other forms of N loss to water other than leaching, such as direct loss to stream, were disregarded. TP runoff was calculated using the ‘Runoff’ value only, rather than total P loss to water. Other forms of P loss to water other than runoff were also omitted.

The average N leaching and TP runoff for each scenario were then calculated as some scenarios were made up of more than one representative farm. Scenarios identified as lake, river, or town were excluded. The average N leaching and TP runoff were then mapped across the Ruamahanga catchments based on the spatial variability in rainfall and soil types, and to land use Functional Units in the SOURCE model. These maps are shown as Figure 3-1 and Figure 3-2.

OVERSEER has been used to calculate the nutrient budget for different farming scenarios, however the model relies on averaged input data to generate annual average nutrient budgets. The nutrient budget is calculated by balancing the inputs, farm resources and characteristics, and farm production. By changing the soil and climate in each scenario but not the number of stock on the properties, we have assumed that there is no change to production (e.g. still feeding the same number of cows, producing the same amount of grass and feed, producing the same volume of milk solids). Irrigation was also kept the same as the original scenarios regardless of the amount of rainfall. Realistically production and other aspects such as nutrient budgets would slightly change with alterations to the OVERSEER model.

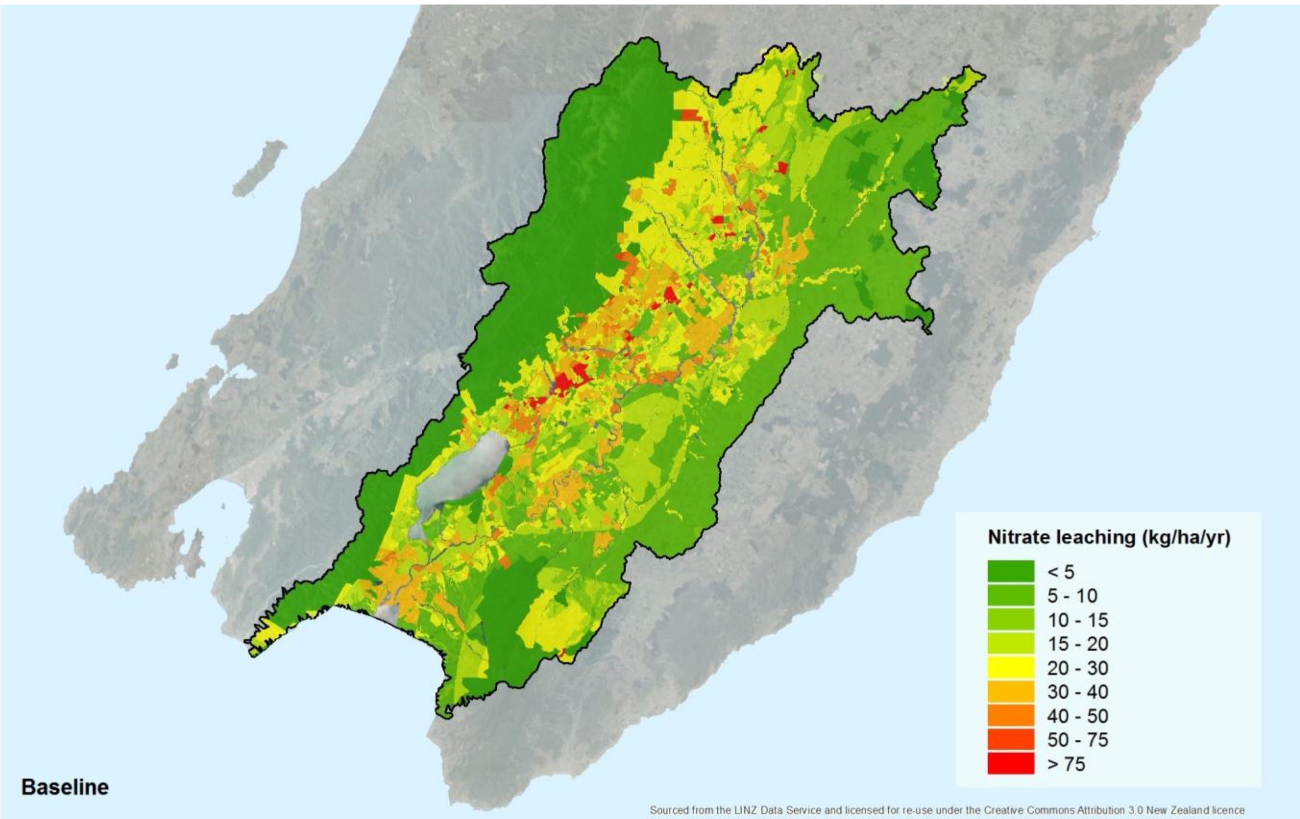

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Figure 3-1 : Mean annual Nitrate-N leaching loads derived from OVERSEER modelling

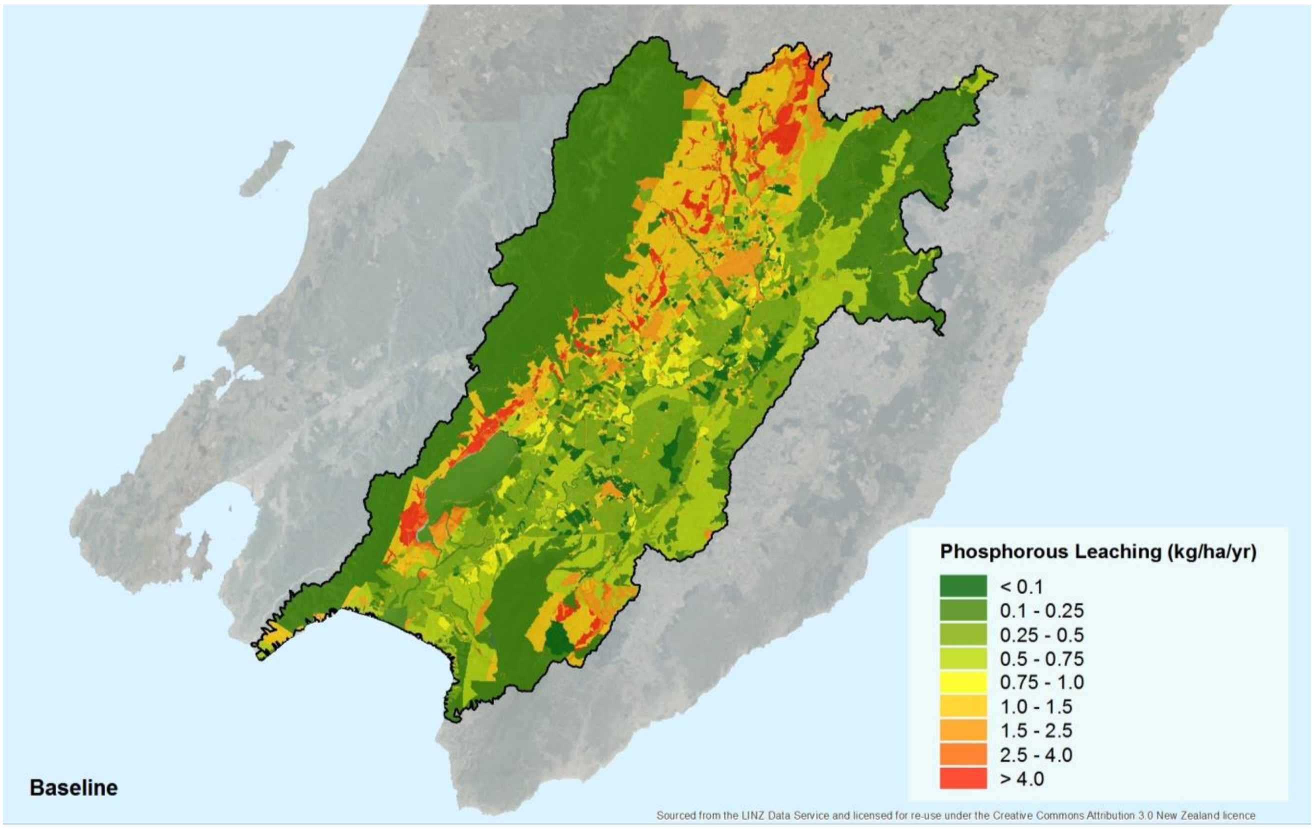

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Figure 3-2 : Mean annual Total Phosphorus runoff loads derived from OVERSEER modelling

## 3.2 Nutrient Generation Inputs

The OVERSEER nutrient maps were used to derive an average Dry Weather Concentration (DWC) for Nitrate-N and Event Mean Concentration for TP for each functional unit within each subcatchment as input to the SOURCE model.

Leaching and runoff rates from OVERSEER were converted to concentrations using the subcatchment baseflow and surface runoff rates from the SOURCE model. This attempts to preserve the spatial variability in rainfall and soil drainage driven nutrient generation from different land use types. As a consequence, some subcatchments resulted in low or high leaching EMC/DWC inputs based on the relative flows apportioned from TOPNET or Irricalc models. The resulting DWC input values are multiplied with daily baseflow to generate a nutrient baseflow load, while EMC's are multiplied with quickflow to produce a quickflow load. The sum of the quick and slow flow loads are calculated at each subcatchment outlet to give the total nutrient load.

Where OVERSEER information or local data was unavailable, EMC and DWC parameters were taken from the literature. Initial Nitrate EMC, and TP DWC parameters were adopted from Barlow et al, (2009), derived from paddock scale measurements of nutrient generation from different agricultural land uses in the Latrobe Valley, Australia. The Latrobe Valley has similar climate and soil drainage as is observed in the Ruamahanga catchment. Initial urban EMC and DWC parameters were adopted from Bartley and Speirs (2010). EMC and DWC parameters were adjusted through calibration within acceptable literature ranges.

Table 3-2 shows the final EMC and DWC values applied to each land use type.

**Table 3-2 : Subcatchment ranges (maximum – minimum) for final calibrated nutrient Event Mean Concentration (EMC) and Dry Weather Concentration (DWC) parameter values. Nitrate and TP concentrations are converted from OVERSEER annual loads for Arable, Beef, Dairy, Dairy Support, Finishing, Sheep and Sheep & Beef**

| Land use | TN | | Nitrate-N | | Ammoniacal N | | TP | | DRP | |
|---|---|---|---|---|---|---|---|---|---|---|
| | EMC | DWC | EMC | DWC | EMC | DWC | EMC | DWC | EMC | DWC |
| Arable | 12 – 2 | 2.5 – 0.1 | 3.5 – 1.2 | 7 – 0.01 | 0.2 – 0.003 | 0.07 – 0.001 | 3.6 – 0.15 | 0.3 – 0.001 | 0.4 – 0.01 | 0.04 – 0.001 |
| Beef | 30 – 2.5 | 8.5 – 0.01 | 8.7 – 3 | 34 – 0.01 | 0.45 – 0.003 | 0.1 – 0.001 | 3.6 – 0.15 | 2.4 – 0.001 | 0.4 – 0.01 | 0.5 – 0.001 |
| Dairy | 45 - 3.7 | 37 – 0.01 | 13 – 4.7 | 28 – 0.03 | 0.6 – 0.005 | 0.5 – 0.001 | 14 – 0.6 | 7 – 0.001 | 1.5 – 0.05 | 0.7 – 0.001 |
| Dairy Support | 30 – 2.5 | 22 – 0.01 | 8.7 - 3 | 85 – 0.05 | 0.45 – 0.003 | 0.3 – 0.001 | 3.6 – 0.15 | 0.7 – 0.002 | 0.4 – 0.01 | 0.2 – 0.001 |
| Deer | 30 – 2.5 | 22 – 0.01 | 8.7 - 3 | 85 – 0.05 | 0.45 – 0.003 | 0.3 – 0.001 | 3.6 – 0.15 | 0.7 – 0.002 | 0.4 – 0.01 | 0.2 – 0.001 |
| Equine | 30 – 2.5 | 22 – 0.01 | 8.7 - 3 | 85 – 0.05 | 0.45 – 0.003 | 0.3 – 0.001 | 3.6 – 0.15 | 0.7 – 0.002 | 0.4 – 0.01 | 0.2 – 0.001 |
| Finishing | 30 – 2.5 | 2 – 0.001 | 8.7 - 3 | 4 – 0.01 | 0.45 – 0.003 | 0.08 – 0.001 | 3.6 – 0.15 | 1.4 – 0.001 | 0.4 – 0.01 | 0.2 – 0.001 |
| Forestry | 3 – 0.2 | 0.05 – 0.001 | 0.9 – 0.3 | 0.1 – 0.001 | 0.04 – 0.001 | 0.001 | 1.1 – 0.045 | 0.001 | 0.1 – 0.003 | 0.001 |
| Horticulture | 10 – 0.8 | 0.5 – 0.01 | 3 - 1 | 0.4 – 0.001 | 0.2 – 0.001 | 0.002 – 0.001 | 1.1 – 0.045 | 0.001 | 0.1 – 0.003 | 0.001 |
| Lifestyle | 30 – 2.5 | 23 – 0.001 | 8.7 – 3.1 | 29 – 0.01 | 0.45 – 0.003 | 0.27 – 0.001 | 3.6 – 0.15 | 0.7 – 0.002 | 0.4 – 0.01 | 0.17 – 0.001 |
| Mixed | 30 – 2.5 | 23 – 0.001 | 8.7 – 3.1 | 29 – 0.01 | 0.45 – 0.003 | 0.27 – 0.001 | 3.6 – 0.15 | 0.7 – 0.002 | 0.4 – 0.01 | 0.17 – 0.001 |
| Native Bush | 1.2 – 0.1 | 0.3 – 0.001 | 0.4 – 0.1 | 1.2 – 0.001 | 0.02 – 0.001 | 0.013 – 0.001 | 0.7 – 0.03 | 0.001 | 0.07 – 0.002 | 0.001 |
| Recreation | 10 – 0.88 | 2.3 – 0.01 | 3 - 1 | 3 – 0.001 | 0.16 – 0.001 | 0.06 – 0.001 | 1.1 – 0.045 | 0.001 | 0.1 – 0.003 | 0.001 |
| Sheep | 30 – 2.5 | 5.7 – 0.001 | 8.7 – 3.1 | 5.6 – 0.01 | 0.45 – 0.003 | 0.1 – 0.001 | 3.6 – 0.15 | 2.6 – 0.002 | 0.4 – 0.01 | 0.2 – 0.001 |
| Sheep & Beef | 36 - 6 | 49 – 0.01 | 11 - 4 | 137 – 0.01 | 0.54 – 0.004 | 2 – 0.001 | 4.8 – 0.2 | 7 – 0.001 | 0.5 – 0.01 | 2 – 0.001 |
| Urban | 36 - 3 | 3 – 0.01 | 10 - 4 | 3.8 – 0.001 | 0.54 – 0.004 | 2 – 0.001 | 3.6 – 0.15 | 0.001 | 0.4 – 0.01 | 0.001 |
| Viticulture | 10 – 0.88 | 3 – 0.01 | 3 - 1 | 6 – 0.001 | 0.16 – 0.001 | 0.02 – 0.001 | 1.1 – 0.045 | 0.001 | 0.1 – 0.003 | 0.001 |

### 3.2.1 Attenuation Factors

Nutrient attenuation factors have been derived from literature ranges, and then calibrated within these ranges to achieve a suitable model fit to the observed water quality data (discussed in Section 3.1). The literature on nutrient attenuation in New Zealand catchments reports a wide range of attenuation factors as shown in Table 3-3. The model includes attenuation factors for $NO_3$-N and TP as concentrations derived from OVERSEER loads were significantly higher than in-stream concentrations. No attenuation factors were applied for TN, $NH_4$-N and DRP, as the EMC/DWC parameters taken from literature are representative of in-stream concentrations that already account for attenuation.

Table 3-3: Nutrient attenuation factors reported for New Zealand catchments

| Literature Source | Nitrogen attenuation factor | TP attenuation factor |
|---|---|---|
| Elliot et al. 2005 | 55% | 56% |
| Elliot et al., 2014 | 0 – 74% | 43 – 76% |
| Alexander et al., 2002 | 42% | - |
| Downs et al., 1997 | 0 – 90% | - |
| Clothier et al., 2007 | 50% | - |

Table 3-4 shows the final attenuation factors applied to the contributing subcatchments upstream of each calibration location.

Table 3-4: Attenuation factor applied to upstream subcatchments of calibration sites

| WQ site | TN (%) | $NO_3$-N (%) | $NH_4$-N (%) | TP (%) | DRP (%) |
|---|---|---|---|---|---|
| Waiohine River at Gorge | 0 | 66 | 0 | 25 | 0 |
| Mangatarere River at State Highway 2 | 0 | 30 | 0 | 60 | 0 |
| Ruamahanga River at Gladstone Bridge | 0 | 75 | 0 | 25 | 0 |
| Taueru River at Gladstone | 0 | 59 | 0 | 25 | 0 |
| Waipoua River at Colombo Rd Bridge | 0 | 62 | 0 | 50 | 0 |
| Kopuaranga River at Stuarts | 0 | 66 | 0 | 40 | 0 |
| Ruamahanga River at Waihenga Bridge | 0 | 62 | 0 | 25 | 0 |
| Tauherenikau River at Websters | 0 | 80 | 0 | 10 | 0 |
| Waiorongomai River at Forest Park | 0 | 65 | 0 | 25 | 0 |
| Waiohine River at Bicknells | 0 | 30 | 0 | 25 | 0 |
| Waingawa River at South Road | 0 | 80 | 0 | 25 | 0 |
| Ruamahanga River at Te Ore Ore | 0 | 73 | 0 | 25 | 0 |
| Ruamahanga River at Pukio | 0 | 62 | 0 | 25 | 0 |
| Huangarua River at Ponatahi Bridge | 0 | 80 | 0 | 25 | 0 |
| Parkvale Stream at Weir | 0 | 65 | 0 | 5 | 0 |
| All other subcatchments | 0 | 75 | 0 | 25 | 0 |

## 3.3 Nutrients Calibration

The nutrient model was calibrated to fifteen water quality monitoring sites (Table 3-5) that had acceptable data quality and either located with a flow gauge or designated as a reporting point (Figure 3-3).

Nitrate DWC and TP EMC values remained unaltered during calibration to retain the OVERSEER modelled inputs, therefore, calibration consisted of adjusting the Nitrate-N EMC, TP DWC and ammoniacal-N, TN, and DRP EMC/DWC parameters by land use within realistic literature ranges, and adjusting the attenuation factor of the contributing subcatchments to each calibration site.

Review of the Nitrate-N loads entering the SOURCE model through groundwater flux identified that instream loads were excessively high, and required correction by a factor of 0.3 (approximately 1/3) to enable acceptable calibrations. The cause for these higher GW flux loads could be due to:

- high OVERSEER leaching rates (applied as a gridded input into the MODFLOW MT3D model)
- under representation of nutrient attenuation factors in MODFLOW MT3D, such as denitrification
- groundwater and nitrate-N inputs higher than what is observed, due to discrepancies in flow calibrations (see Section 2.6.1).
- in the area around the lake, the baseline nitrate OVERSEER leaching map used by GNS was mis-representing Pallic soils in some locations. This was incorrectly applying farm ID 11a rather than 6a and 6b, which applies higher N leaching. In addition, a portion of brown soils to the south east of Ruamahanga River also required their farm ID to be changed to 6a and 6b. Subsequently, higher nitrate-N loads may be present in the MODFLOW-MT3D model and incorporated in the GW flux inputs.
    - It is worth noting that the baseline leaching map was updated prior to model calibration, and EMC/DWC nutrient inputs (for nitrate-N) reflect this, but not the groundwater flux inputs.
    - All scenarios modelled (BAU, Silver and Gold) by GNS use the updated leaching map.

Goodness of fit to the observed in-stream water quality data was assessed using:

- Percent bias (PBIAS; as a measure of the mean difference between observed and modelled data),
- Summary statistics (mean, median and 95th percentile concentrations),
- Box-whisker plots (illustrating the median, 25th and 75th percentiles – the box; 5th and 95th percentiles – the whiskers; dot indicate means)

Moriasi et al. (2007) suggests that monthly water quality model simulations are deemed satisfactory if percent bias is between ±70. Calibration is deemed very good if the percent bias is ± 25%.

### 3.3.1 Sampling data

Fifteen water quality monitoring sites were inspected for spurious data, which was removed from the analysis, and selected as calibration locations (Figure 3-3). Details are given in Table 3-5. The observed data is part of monthly water quality monitoring undertaken by GWRC.

**Table 3-5: Period of record for observed nutrient monitoring data**

| Calibration Site | Constituent | Monitoring period |
|---|---|---|
| Waiohine River at Gorge | TN, $NO_3$-N, $NH_4$-N, TP, DRP | 11/1991-6/2014* (monthly) |
| Mangatarere River at State Highway 2 | $NO_3$-N, $NH_4$-N, DRP | 2/1997-6/2014 (monthly) |
| | TN, TP | 7/2001-6/2014 (monthly) |
| Ruamahanga River at Gladstone Bridge | $NO_3$-N, $NH_4$-N, DRP | 2/1997-6/2014 (monthly) |
| | TN, TP | 7/2001-6/2014 (monthly) |

| Calibration Site | Constituent | Monitoring period |
|---|---|---|
| Taueru River at Gladstone | $NO_3$-N, $NH_4$-N, DRP | 2/1997-6/2014 (monthly) |
| | TN, TP | 7/2001-6/2014 (monthly) |
| Waipoua River at Colombo Rd Bridge | $NO_3$-N, $NH_4$-N, DRP | 2/1997-6/2014 (monthly) |
| | TN, TP | 7/2001-6/2014 (monthly) |
| Kopuaranga River at Stuarts | $NO_3$-N, $NH_4$-N, DRP | 2/1997-6/2014 (monthly) |
| | TN, TP | 7/2001-6/2014 (monthly) |
| Ruamahanga River at Waihenga Bridge | TN, $NO_3$-N, $NH_4$-N, TP, DRP | 9/1996-7/2003* (monthly) |
| Tauherenikau River at Websters | TN, $NO_3$-N, $NH_4$-N, TP, DRP | 11/1991-6/2014* (monthly) |
| Waiorongomai River at Forest Park | TN, $NO_3$-N, $NH_4$-N $^{\#}$, TP, DRP | 10/2003-6/2014 (monthly) |
| Waiohine River at Bicknells | TN, $NO_3$-N, $NH_4$-N, TP, DRP | 11/1991-6/2014* (monthly) |
| Waingawa River at South Road | TN, $NO_3$-N, $NH_4$-N, TP, DRP | 11/1991-6/2014* (monthly) |
| Ruamahanga River at Te Ore Ore | $NO_3$-N, $NH_4$-N $^{\#}$, DRP | 2/1997-6/2014 (monthly) |
| | TN, TP | 7/2001-6/2014 (monthly) |
| Ruamahanga River at Pukio | TN, $NO_3$-N, $NH_4$-N, TP, DRP | 9/2003-6/2014 (monthly) |
| Huangarua River at Ponatahi Bridge | $NO_3$-N, $NH_4$-N, DRP | 2/1997-6/2014 (monthly) |
| | TN, TP | 7/2001-6/2014 (monthly) |
| Parkvale Stream at Weir | TN, $NO_3$-N, $NH_4$-N, TP, DRP | 9/2003-6/2014 (monthly) |

* Gap in total nitrogen and total phosphorus data between 1/1997-7/2001

$^{\#}$ $NH_4$-N was often below detection limit and set to 0.005 mg/L, resulting in a poor dataset for calibration

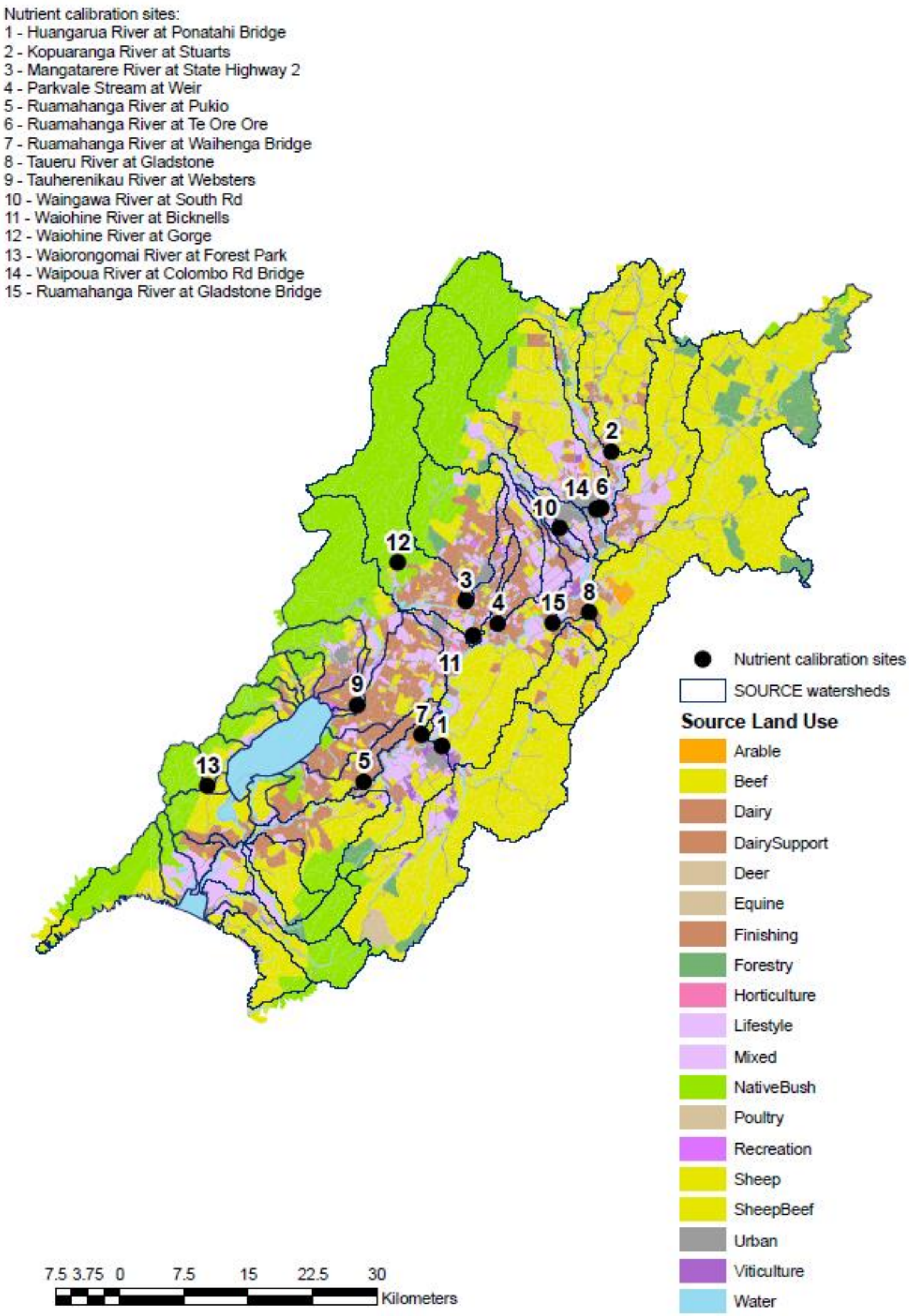


**Figure 3-3: Nutrient calibration sites**

### 3.3.2 Nitrogen Calibration Results

Overall the SOURCE model achieved a good calibration to observed TN concentrations, with PBIAS statistics within the 'Good' and 'Very Good' calibration criteria given by Moriasi et al (2007) (Table 3-6). Good agreement between the overall distribution of observed data and modelled output as illustrated by the box-whisker plots in Figure 3-4.

Similar results were achieved for nitrate-N and ammoniacal-N calibrations, although mean nitrate-N for Tauherenikau River at Websters and mean ammoniacal-N for Mangatarere River at State Highway 2 sites falls into the 'Satisfactory' calibration criteria. Nitrate-N 95th percentile concentrations are underestimated at Parkvale Stream at Weir, and there was difficulty in achieving realistic EMC/DWCs parameters within literature ranges to fit observed data at this site without compromising downstream calibration sites. This could be reflected by uncertainties in modelled flows.

**Table 3-6 Descriptive statistics for observed and modelled Total Nitrogen**

| Calibration Site | Observed TN (mg/L) | | | Modelled TN (mg/L) | | | |
|---|---|---|---|---|---|---|---|
| | Mean | Median | 95th perc. | Mean | Median | 95th perc. | PBIAS |
| Waiohine River at Gorge | 0.08 | 0.06 | 0.20 | 0.06 | 0.05 | 0.13 | -30% |
| Mangatarere River at State Highway 2 | 0.17 | 1.60 | 2.77 | 1.59 | 1.22 | 3.69 | -5% |
| Ruamahanga River at Gladstone Bridge | 0.70 | 0.60 | 1.42 | 0.60 | 0.46 | 1.52 | -15% |
| Taueru River at Gladstone | 1.31 | 1.23 | 2.10 | 1.33 | 1.21 | 2.67 | 1% |
| Waipoua River at Colombo Rd Bridge | 1.22 | 1.10 | 2.36 | 0.91 | 0.56 | 2.16 | -14% |
| Kopuaranga River at Stuarts | 1.34 | 1.28 | 2.10 | 1.13 | 0.95 | 2.66 | -16% |
| Ruamahanga River at Waihenga Bridge | 0.68 | 0.54 | 1.43 | 0.55 | 0.37 | 1.50 | -19% |
| Tauherenikau River at Websters | 0.13 | 0.11 | 0.29 | 0.10 | 0.07 | 0.24 | -25% |
| Waiorongomai River at Forest Park | 0.11 | 0.06 | 0.24 | 0.07 | 0.05 | 0.20 | -6% |
| Waiohine River at Bicknells | 0.51 | 0.46 | 0.95 | 0.41 | 0.21 | 1.31 | -19% |
| Waingawa River at South Road | 0.16 | 0.13 | 0.40 | 0.16 | 0.13 | 0.41 | 1% |
| Ruamahanga River at Te Ore Ore | 0.63 | 0.51 | 1.48 | 0.53 | 0.44 | 1.30 | -16% |
| Ruamahanga River at Pukio | 0.68 | 0.55 | 1.59 | 0.54 | 0.36 | 1.47 | -21% |
| Huangarua River at Ponatahi Bridge | 0.56 | 0.50 | 1.20 | 0.55 | 0.42 | 1.68 | -2% |
| Parkvale Stream at Weir | 2.42 | 2.25 | 5.40 | 2.52 | 1.13 | 9.65 | 4% |

**Table 3-7 Descriptive statistics for observed and modelled Nitrate-Nitrogen ($NO_3$-N)**

| Calibration Site | Observed $NO_3$-N (mg/L) | | | Modelled $NO_3$-N (mg/L) | | | |
|---|---|---|---|---|---|---|---|
| | Mean | Median | 95th perc. | Mean | Median | 95th perc. | PBIAS |
| Waiohine River at Gorge | 0.03 | 0.03 | 0.06 | 0.03 | 0.03 | 0.07 | 5% |
| Mangatarere River at State Highway 2 | 1.41 | 1.39 | 2.43 | 0.94 | 0.75 | 2.20 | -33% |
| Ruamahanga River at Gladstone Bridge | 0.48 | 0.40 | 0.99 | 0.58 | 0.52 | 1.03 | 20% |
| Taueru River at Gladstone | 0.83 | 0.73 | 1.64 | 0.78 | 0.72 | 1.40 | -7% |
| Waipoua River at Colombo Rd Bridge | 1.07 | 0.95 | 2.16 | 0.92 | 1.85 | 0.80 | -14% |
| Kopuaranga River at Stuarts | 0.97 | 0.95 | 1.45 | 1.07 | 0.97 | 2.11 | 11% |
| Ruamahanga River at Waihenga Bridge | 0.49 | 0.42 | 1.00 | 0.50 | 0.44 | 0.95 | 1% |
| Tauherenikau River at Websters | 0.06 | 0.04 | 0.18 | 0.10 | 0.06 | 0.29 | 62% |
| Waiorongomai River at Forest Park | 0.02 | 0.02 | 0.06 | 0.02 | 0.02 | 0.04 | -1% |
| Waiohine River at Bicknells | 0.41 | 0.36 | 0.90 | 0.27 | 0.19 | 0.66 | -35% |
| Waingawa River at South Road | 0.06 | 0.04 | 0.18 | 0.11 | 0.10 | 0.24 | 76% |
| Ruamahanga River at Te Ore Ore | 0.42 | 0.36 | 0.98 | 0.43 | 0.36 | 0.98 | 2% |
| Ruamahanga River at Pukio | 0.43 | 0.35 | 0.96 | 0.51 | 0.46 | 0.95 | 20% |
| Huangarua River at Ponatahi Bridge | 0.26 | 0.22 | 0.68 | 0.37 | 0.30 | 1.05 | 41% |
| Parkvale Stream at Weir | 1.74 | 1.53 | 4.25 | 0.02 | 1.48 | 1.85 | -14% |

**Table 3-8 Descriptive statistics for observed and modelled Ammoniacal-Nitrogen ($NH_4$-N)**

| Calibration Site | Observed $NH_4$-N (mg/L) | | | Modelled $NH_4$-N (mg/L) | | | |
|---|---|---|---|---|---|---|---|
| | Mean | Median | 95th perc. | Mean | Median | 95th perc. | PBIAS |
| Waiohine River at Gorge | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 4% |
| Mangatarere River at State Highway 2 | 0.09 | 0.08 | 0.21 | 0.15 | 0.10 | 0.44 | 64% |
| Ruamahanga River at Gladstone Bridge | 0.02 | 0.02 | 0.07 | 0.01 | 0.01 | 0.03 | -40% |
| Taueru River at Gladstone | 0.02 | 0.01 | 0.07 | 0.01 | 0.01 | 0.03 | -42% |
| Waipoua River at Colombo Rd Bridge | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.03 | 26% |
| Kopuaranga River at Stuarts | 0.02 | 0.01 | 0.05 | 0.01 | 0.01 | 0.04 | -11% |
| Ruamahanga River at Waihenga Bridge | 0.01 | 0.01 | 0.04 | 0.02 | 0.02 | 0.03 | 42% |
| Tauherenikau River at Websters | 0.01 | 0.01 | 0.02 | 0.00 | 0.00 | 0.01 | -34% |
| Waiorongomai River at Forest Park | 0.01 | 0.01 | 0.02 | 0.01 | 0.00 | 0.02 | -6% |
| Waiohine River at Bicknells | 0.01 | 0.01 | 0.03 | 0.02 | 0.02 | 0.05 | 43% |
| Waingawa River at South Road | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | -33% |
| Ruamahanga River at Te Ore Ore | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.03 | 49% |
| Ruamahanga River at Pukio | 0.01 | 0.01 | 0.05 | 0.02 | 0.02 | 0.03 | 20% |
| Huangarua River at Ponatahi Bridge | 0.01 | 0.01 | 0.02 | 0.01 | 0.00 | 0.02 | -33% |
| Parkvale Stream at Weir | 0.03 | 0.02 | 0.11 | 0.03 | 0.02 | 0.13 | 10% |

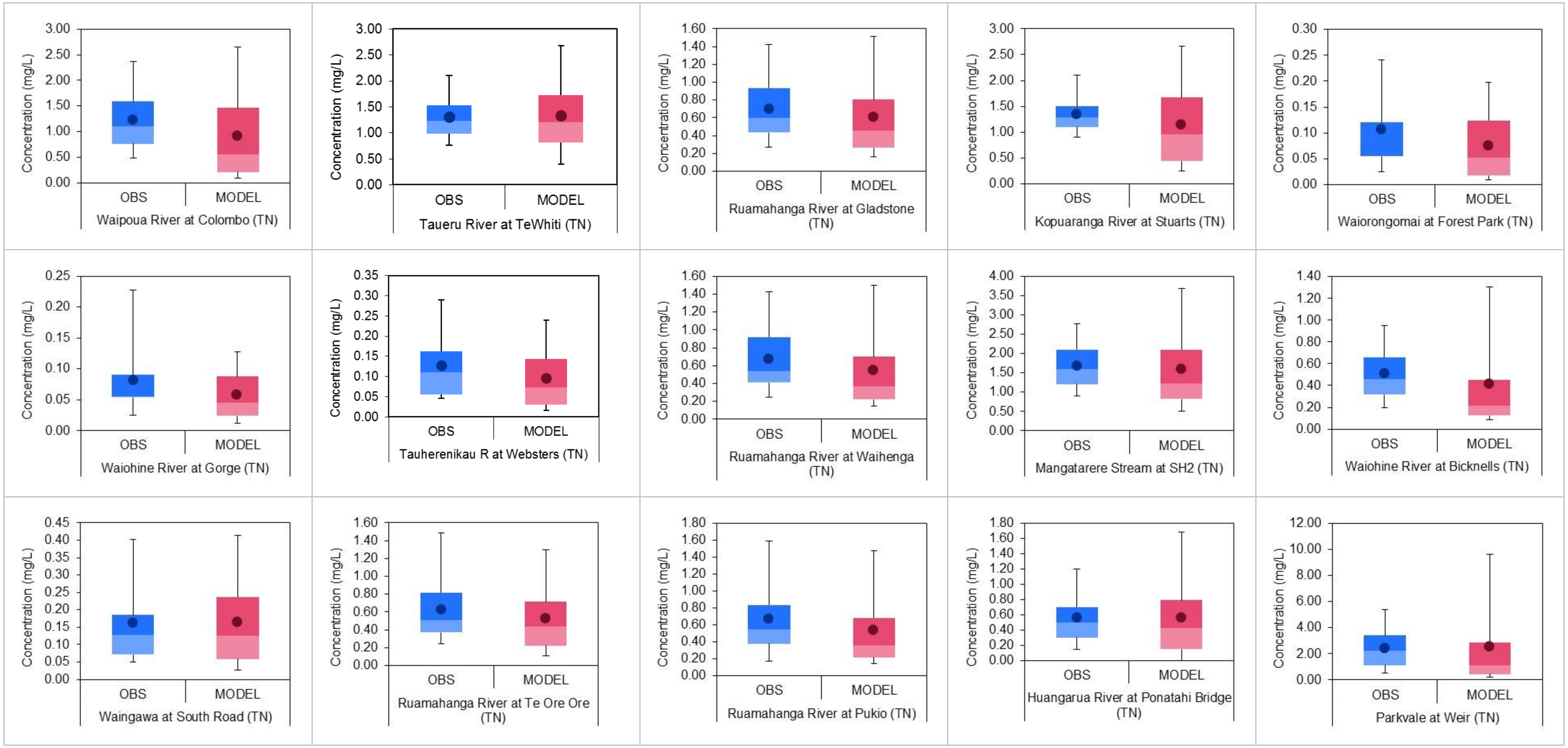


**Figure 3-4: Box plots comparisons between observed and simulated total nitrogen concentration**

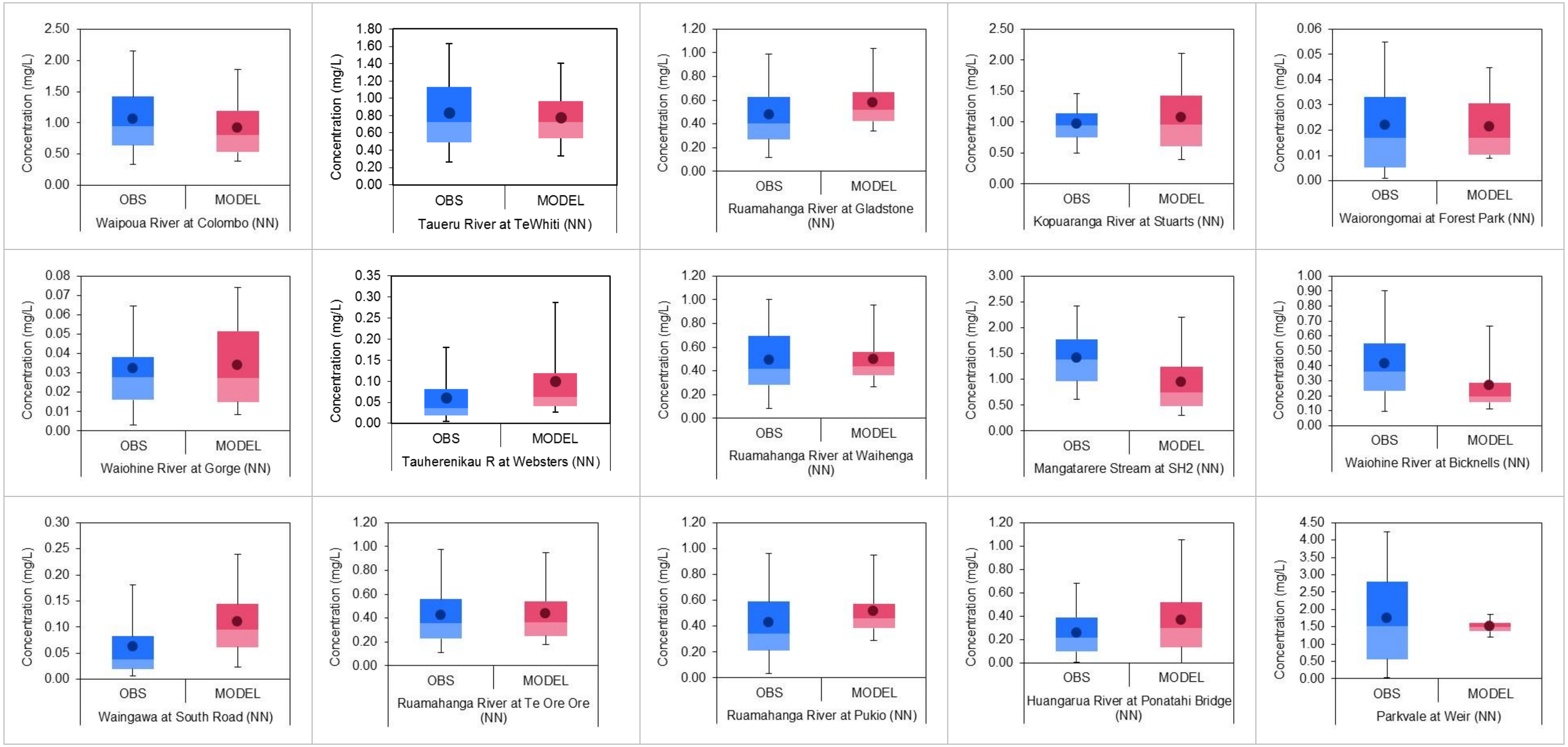


**Figure 3-5: Box plots comparisons between observed and simulated nitrate-N concentration**

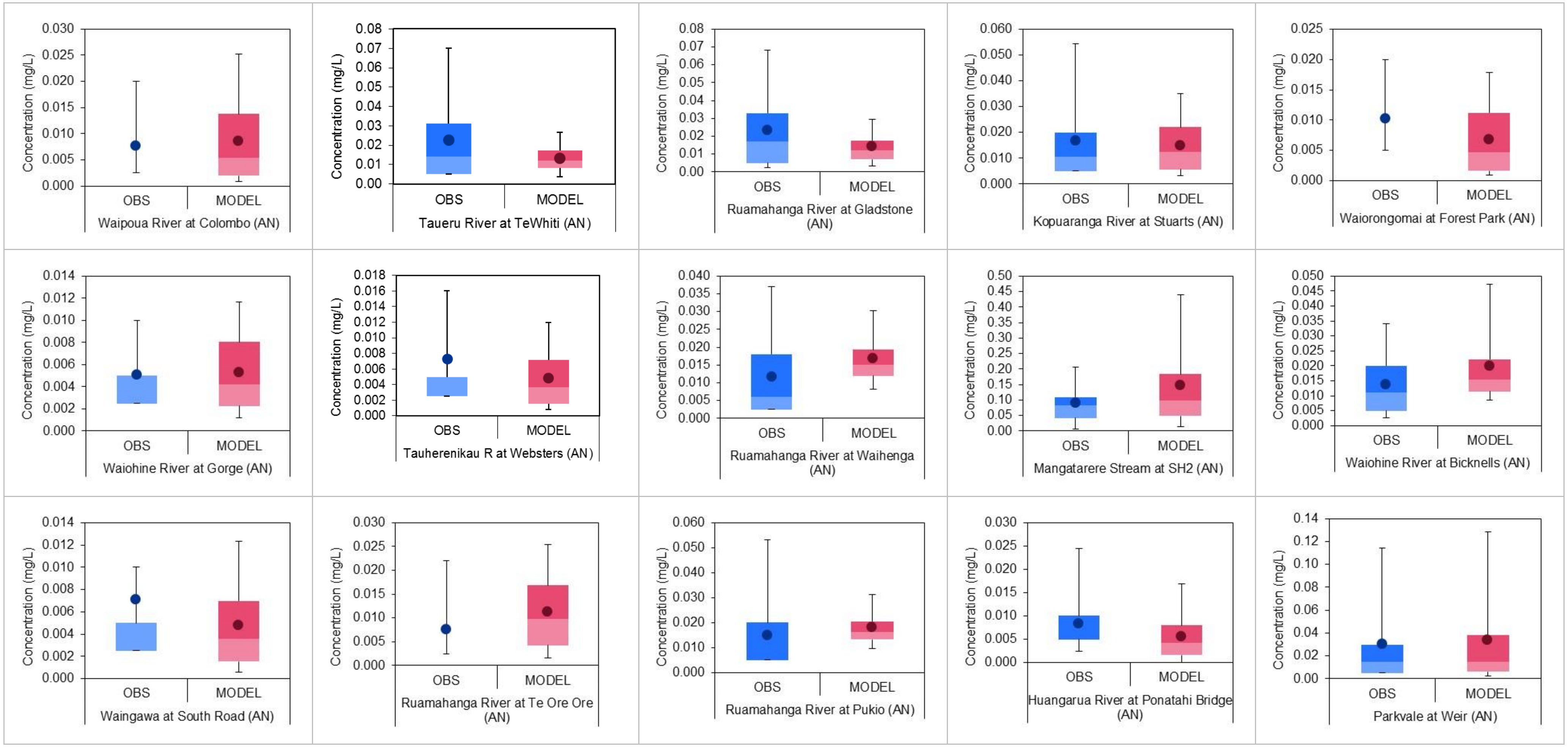


Figure 3-6: Box plots comparisons between observed and simulated ammoniacal-N concentration

### 3.3.3 Phosphorus Calibration Results

Overall the SOURCE model achieved a good calibration to observed TP concentrations, with PBIAS statistics within the ‘Good’ calibration criteria given by Moriasi et al (2007) for the majority of sites (Table 3-9). Good agreement was also achieved between the overall distribution of observed TP data and modelled TP output as illustrated by the box-whisker plots in Figure 3-7, although for some sites the 95th percentiles were underestimated by the model.

Similar results were achieved for DRP calibration in terms of ‘Good’ PBIAS statistic (Table 3-10), including a good estimation of 95th percentiles as illustrated by the box-whisker plots (Figure 3-8).

**Table 3-9 Descriptive statistics for observed and modelled Total Phosphorus**

| Calibration Site | Observed TP (mg/L) | | | Modelled TP (mg/L) | | | |
|---|---|---|---|---|---|---|---|
| | Mean | Median | 95th perc. | Mean | Median | 95th perc. | PBIAS |
| Waiohine River at Gorge | 0.01 | 0.01 | 0.05 | 0.01 | 0.01 | 0.02 | -47% |
| Mangatarere River at State Highway 2 | 0.13 | 0.10 | 0.40 | 0.18 | 0.15 | 0.40 | 31% |
| Ruamahanga River at Gladstone Bridge | 0.06 | 0.04 | 0.17 | 0.03 | 0.03 | 0.06 | -43% |
| Taueru River at Gladstone | 0.07 | 0.05 | 0.19 | 0.05 | 0.04 | 0.08 | -37% |
| Waipoua River at Colombo Rd Bridge | 0.02 | 0.01 | 0.04 | 0.02 | 0.02 | 0.05 | 32% |
| Kopuaranga River at Stuarts | 0.06 | 0.04 | 0.20 | 0.06 | 0.06 | 0.09 | 12% |
| Ruamahanga River at Waihenga Bridge | 0.04 | 0.03 | 0.15 | 0.04 | 0.03 | 0.09 | 1% |
| Tauherenikau River at Websters | 0.02 | 0.01 | 0.06 | 0.01 | 0.01 | 0.04 | -20% |
| Waiorongomai River at Forest Park | 0.01 | 0.01 | 0.02 | 0.01 | 0.00 | 0.02 | -35% |
| Waiohine River at Bicknells | 0.03 | 0.03 | 0.07 | 0.04 | 0.03 | 0.12 | 24% |
| Waingawa River at South Road | 0.02 | 0.01 | 0.04 | 0.01 | 0.01 | 0.03 | -36% |
| Ruamahanga River at Te Ore Ore | 0.04 | 0.02 | 0.15 | 0.03 | 0.03 | 0.06 | -11% |
| Ruamahanga River at Pukio | 0.06 | 0.03 | 0.29 | 0.04 | 0.03 | 0.10 | -27% |
| Huangarua River at Ponatahi Bridge | 0.04 | 0.02 | 0.20 | 0.04 | 0.04 | 0.10 | 2% |
| Parkvale Stream at Weir | 0.09 | 0.07 | 0.25 | 0.09 | 0.05 | 0.30 | -2% |

**Table 3-10 Descriptive statistics for observed and modelled Dissolved Reactive Phosphorus**

| Calibration Site | Observed DRP (mg/L) | | | Modelled DRP (mg/L) | | | |
|---|---|---|---|---|---|---|---|
| | Mean | Median | 95th perc. | Mean | Median | 95th perc. | PBIAS |
| Waiohine River at Gorge | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | -34% |
| Mangatarere River at State Highway 2 | 0.10 | 0.08 | 0.30 | 0.11 | 0.09 | 0.29 | 9% |
| Ruamahanga River at Gladstone Bridge | 0.02 | 0.02 | 0.05 | 0.02 | 0.02 | 0.03 | -34% |
| Taueru River at Gladstone | 0.02 | 0.02 | 0.04 | 0.02 | 0.02 | 0.03 | -2% |
| Waipoua River at Colombo Rd Bridge | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | -9% |
| Kopuaranga River at Stuarts | 0.02 | 0.02 | 0.04 | 0.02 | 0.02 | 0.04 | 21% |
| Ruamahanga River at Waihenga Bridge | 0.02 | 0.02 | 0.03 | 0.02 | 0.02 | 0.03 | -17% |
| Tauherenikau River at Websters | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | -19% |
| Waiorongomai River at Forest Park | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | -13% |
| Waiohine River at Bicknells | 0.02 | 0.02 | 0.03 | 0.02 | 0.02 | 0.04 | 0% |

| Calibration Site | Observed DRP (mg/L) | | | Modelled DRP (mg/L) | | | |
|---|---|---|---|---|---|---|---|
| | Mean | Median | 95th perc. | Mean | Median | 95th perc. | PBIAS |
| Waingawa River at South Road | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 7% |
| Ruamahanga River at Te Ore Ore | 0.01 | 0.01 | 0.03 | 0.01 | 0.01 | 0.02 | 15% |
| Ruamahanga River at Pukio | 0.02 | 0.02 | 0.03 | 0.02 | 0.02 | 0.03 | 9% |
| Huangarua River at Ponatahi Bridge | 0.01 | 0.01 | 0.03 | 0.01 | 0.01 | 0.02 | -11% |
| Parkvale Stream at Weir | 0.04 | 0.04 | 0.10 | 0.04 | 0.02 | 0.15 | -5% |

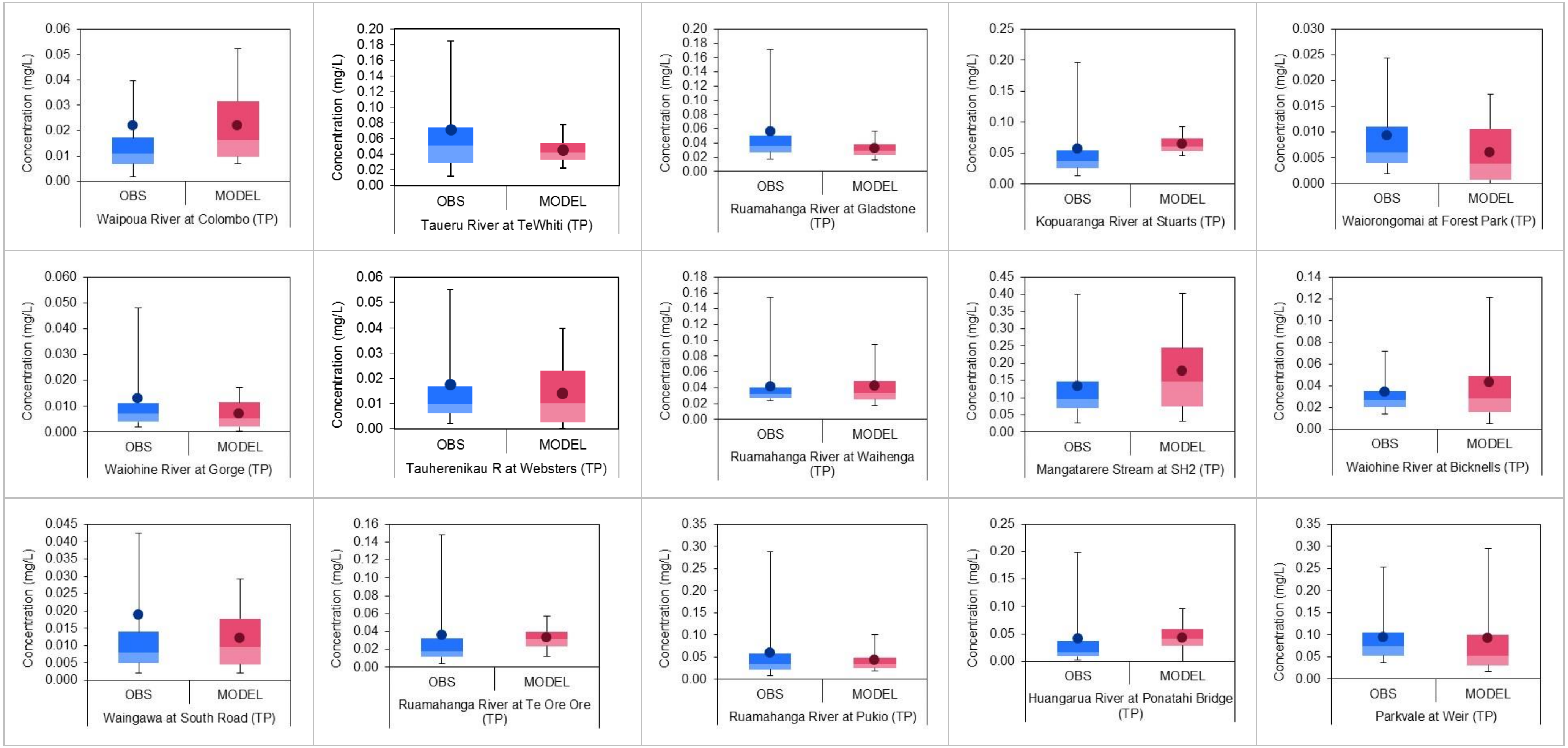


**Figure 3-7: Box plots comparisons between observed and simulated total phosphorus concertation**

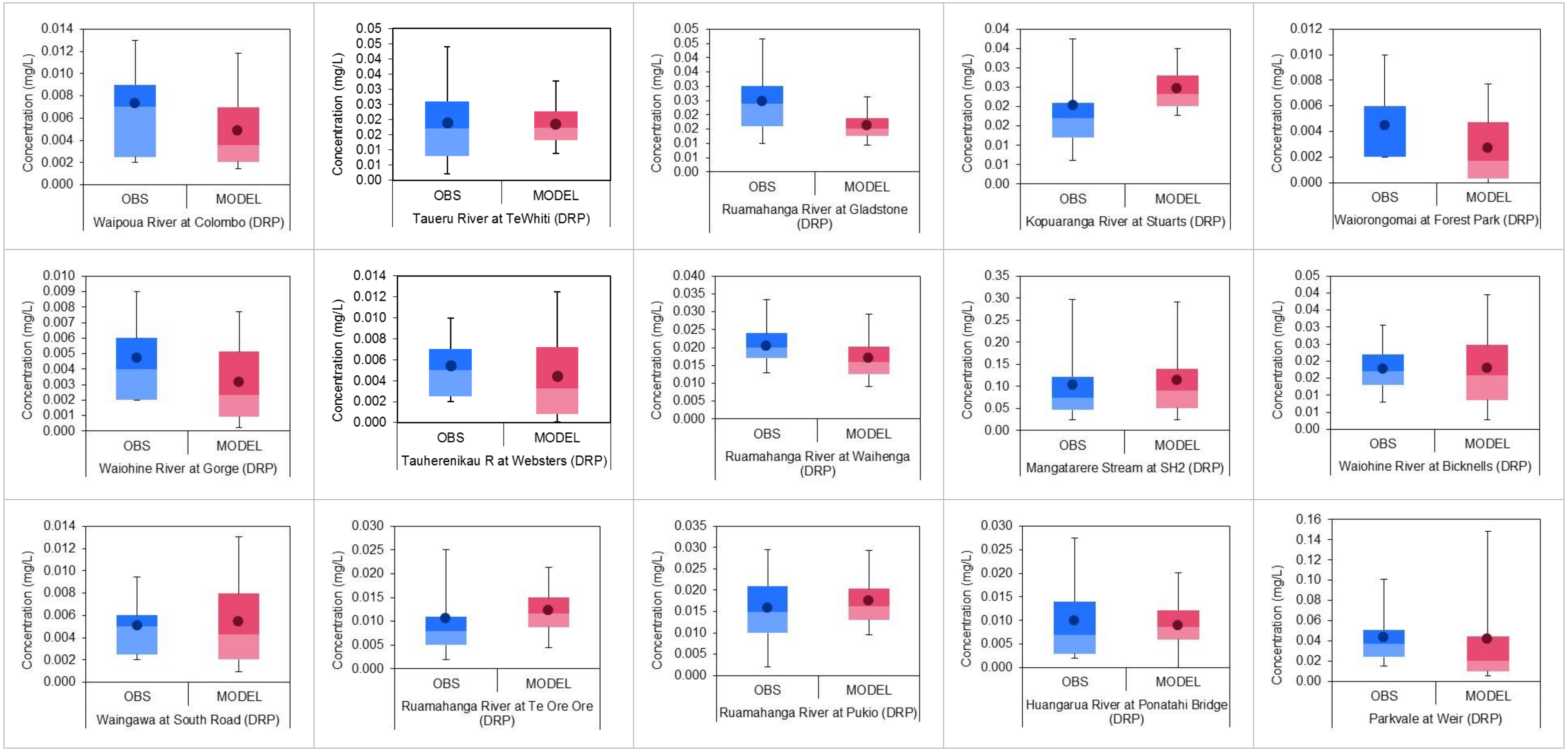


Figure 3-8: Box plots comparisons between observed and simulated dissolved reactive phosphorus concertation

# 4. *E.coli*

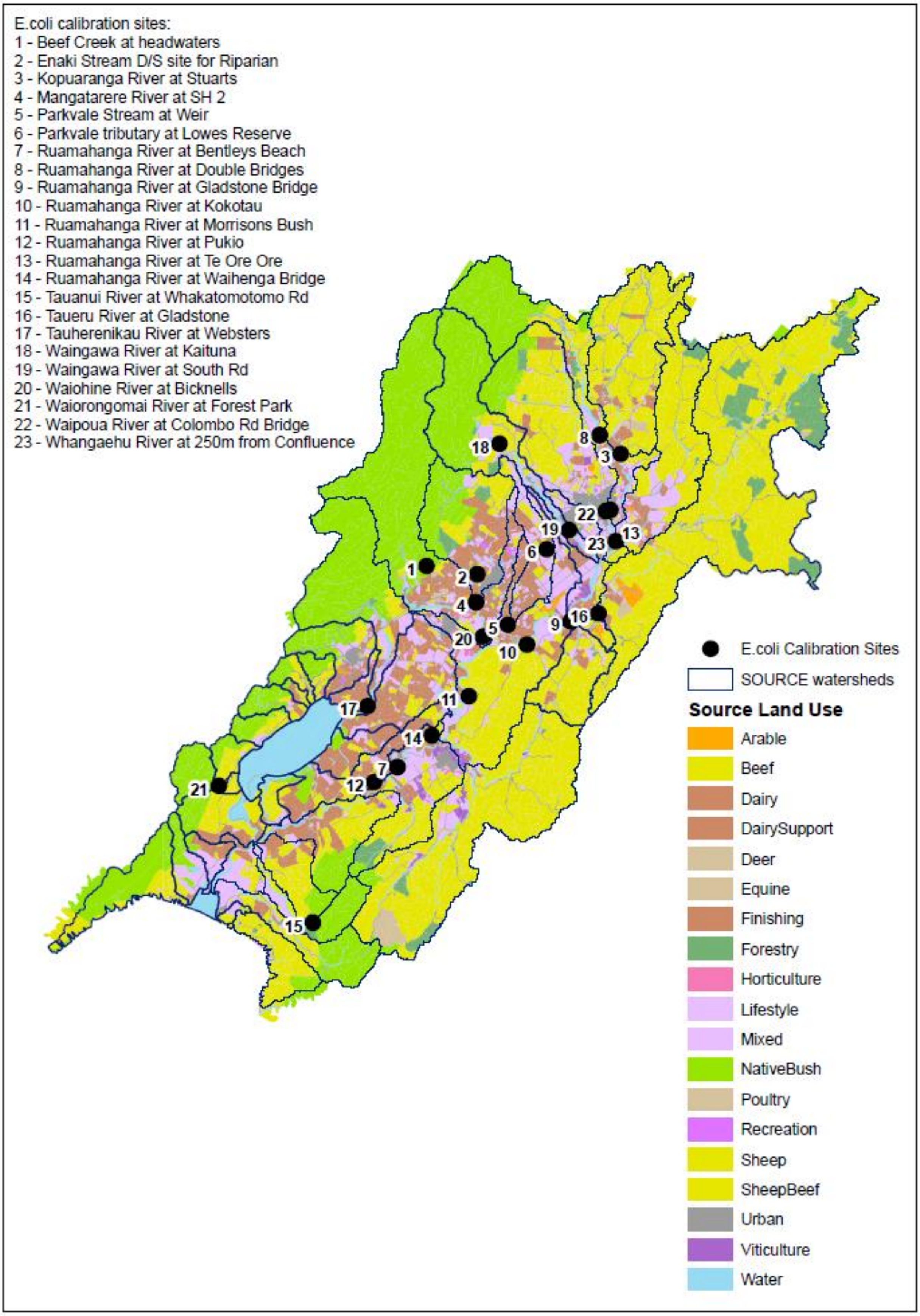
## 4.1 Sampling Data

Monitoring data has been collected at a number of sites in the Ruamāhanga catchment and these have been extracted from GWRC hilltop database. The site with concurrent streamflow data are listed in Table 4-1 below and shown in Figure 4-1. This table lists the start and end dates as well as the number of observations and the median concentration. Note that the data was inspected for spurious data which was removed from the analysis.

These samples are biased towards fine weather and low flows. While these biases could be problematic for many water quality constituents this is less so for *E.coli*. The main risk from *E.coli* occur from recreational activities such as swimming, boating and fishing as these are naturally biased towards fine weather and low flows. For these reasons this is not considered a limitation to the study.

**Table 4-1 : Sites with *E.coli* data**

| Site | Start Date | End Date | No. observations | Median Concentration cfu/100mL |
|---|---|---|---|---|
| Beef Creek at headwaters | 22/09/2003 | 26/06/2014 | 128 | 6 |
| Enaki Stream D/S site for Riparian | 31/01/2002 | 22/10/2014 | 148 | 160 |
| Kopuaranga River at Stuarts | 4/02/1997 | 25/06/2014 | 209 | 240 |
| Mangatarere River at State Highway 2 | 5/02/1997 | 26/06/2014 | 210 | 145 |
| Parkvale Stream at Weir | 22/09/2003 | 26/06/2014 | 130 | 500 |
| Parkvale tributary at Lowes Reserve | 22/09/2003 | 29/05/2014 | 111 | 22 |
| Ruamahanga River at Bentleys Beach | 16/12/2002 | 29/03/2011 | 186 | 48 |
| Ruamahanga River at Double Bridges | 28/11/1991 | 25/08/2003 | 141 | 55 |
| Ruamahanga River at Gladstone Bridge | 4/02/1997 | 25/06/2014 | 210 | 29 |
| Ruamahanga River at Kokotau | 7/11/2001 | 26/01/2015 | 291 | 35 |
| Ruamahanga River at Morrisons Bush | 7/11/2001 | 26/01/2015 | 291 | 24 |
| Ruamahanga River at Pukio | 18/09/2003 | 25/06/2014 | 130 | 98 |
| Ruamahanga River at Te Ore Ore | 4/02/1997 | 25/06/2014 | 211 | 94 |
| Ruamahanga River at Waihenga Bridge | 3/09/1996 | 26/08/2003 | 85 | 33 |
| Tauanui River at Whakatomotomo Rd | 2/10/2003 | 27/06/2014 | 128 | 4 |
| Taueru River at Gladstone | 4/02/1997 | 18/06/2014 | 210 | 110 |
| Tauherenikau River at Websters | 27/11/1991 | 19/06/2014 | 271 | 19 |
| Waingawa River at Kaituna | 7/11/2001 | 26/01/2015 | 282 | 7 |
| Waingawa River at South Rd | 28/11/1991 | 19/06/2014 | 271 | 22 |
| Waiohine River at Bicknells | 27/11/1991 | 26/06/2014 | 270 | 44 |
| Waiorongomai River at Forest Park | 2/10/2003 | 19/06/2014 | 131 | 7 |
| Waipoua River at Colombo Rd Bridge | 4/02/1997 | 19/06/2014 | 210 | 69 |
| Whangaehu River at 250m from Confluence | 4/02/1997 | 25/06/2014 | 210 | 265 |


E.coli calibration sites:
1 - Beef Creek at headwaters
2 - Enaki Stream D/S site for Riparian
3 - Kopuaranga River at Stuarts
4 - Mangatarere River at SH 2
5 - Parkvale Stream at Weir
6 - Parkvale tributary at Lowes Reserve
7 - Ruamahanga River at Bentleys Beach
8 - Ruamahanga River at Double Bridges
9 - Ruamahanga River at Gladstone Bridge
10 - Ruamahanga River at Kokotau
11 - Ruamahanga River at Morrisons Bush
12 - Ruamahanga River at Pukio
13 - Ruamahanga River at Te Ore Ore
14 - Ruamahanga River at Waihenga Bridge
15 - Tauanui River at Whakatomotomo Rd
16 - Taueru River at Gladstone
17 - Tauherenikau River at Websters
18 - Waingawa River at Kaituna
19 - Waingawa River at South Rd
20 - Waiohine River at Bicknells
21 - Waiorongomai River at Forest Park
22 - Waipoua River at Colombo Rd Bridge
23 - Whangaehu River at 250m from Confluence
18
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20
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11
17
14
7
12
21
15
● E.coli Calibration Sites
SOURCE watersheds
Source Land Use
Arable
Beef
Dairy
DairySupport
Deer
Equine
Finishing
Forestry
Horticulture
Lifestyle
Mixed
NativeBush
Poultry
Recreation
Sheep
SheepBeef
Urban
Viticulture
Water

**Figure 4-1: Location of *E. coli* sample sites in the Ruamāhanga used for model calibration**

Plots of observed *E.coli* concentrations and instantaneous discharge are presented in Figure 4-3 for sites with paired gauging stations. Inspection of these figures indicates there is only a weak relationship between discharge and *E.coli* (CFU per 100 ml) at most sites. Therefore, this was not considered feasible to develop a rating type approach for the Ruamāhanga catchment.

The hypothesis that *E.coli* concentration varies by month was investigated by preparing log-transformed box-plots at each of the sites. The sites were pooled by normalising by the median *E.coli* concentration. The resulting plot is shown in Figure 4-2. Figure 4-2 does not present any significant monthly pattern of *E.coli* concentrations throughout the Ruamāhanga catchment. It is of note that some individual sites present evidence of monthly patterns, but overall there is no consistent pattern throughout the catchment.

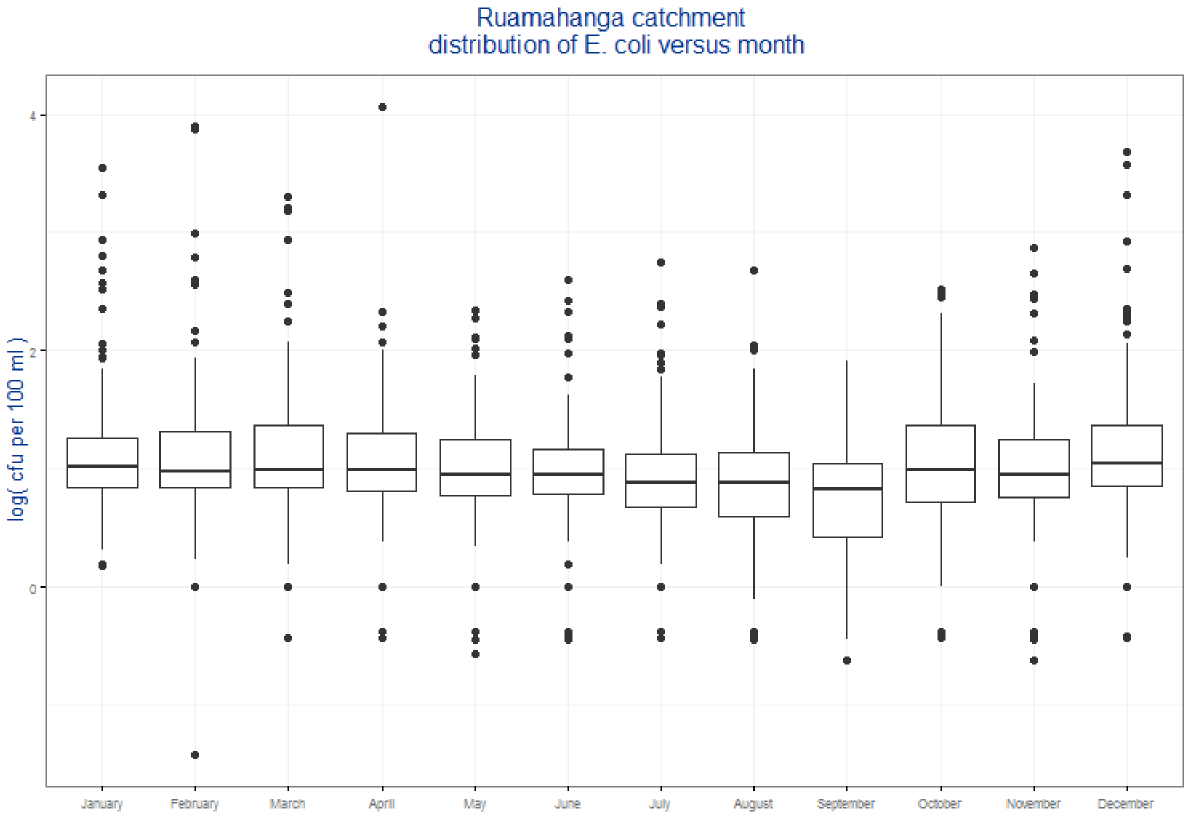


**Figure 4-2 : Distribution of *E. coli* concentration by month for the Ruamāhanga catchment**

Therefore, the data analysis findings were:

- There is no strong evidence that there is a relationship between *E.coli* concentrations and discharge, that is, *E.coli* concentrations do not necessarily increase with discharge.
- There is no strong evidence that *E.coli* concentrations are temporarily based throughout the catchment, although there is some evidence of temporal dependence at individual sites.

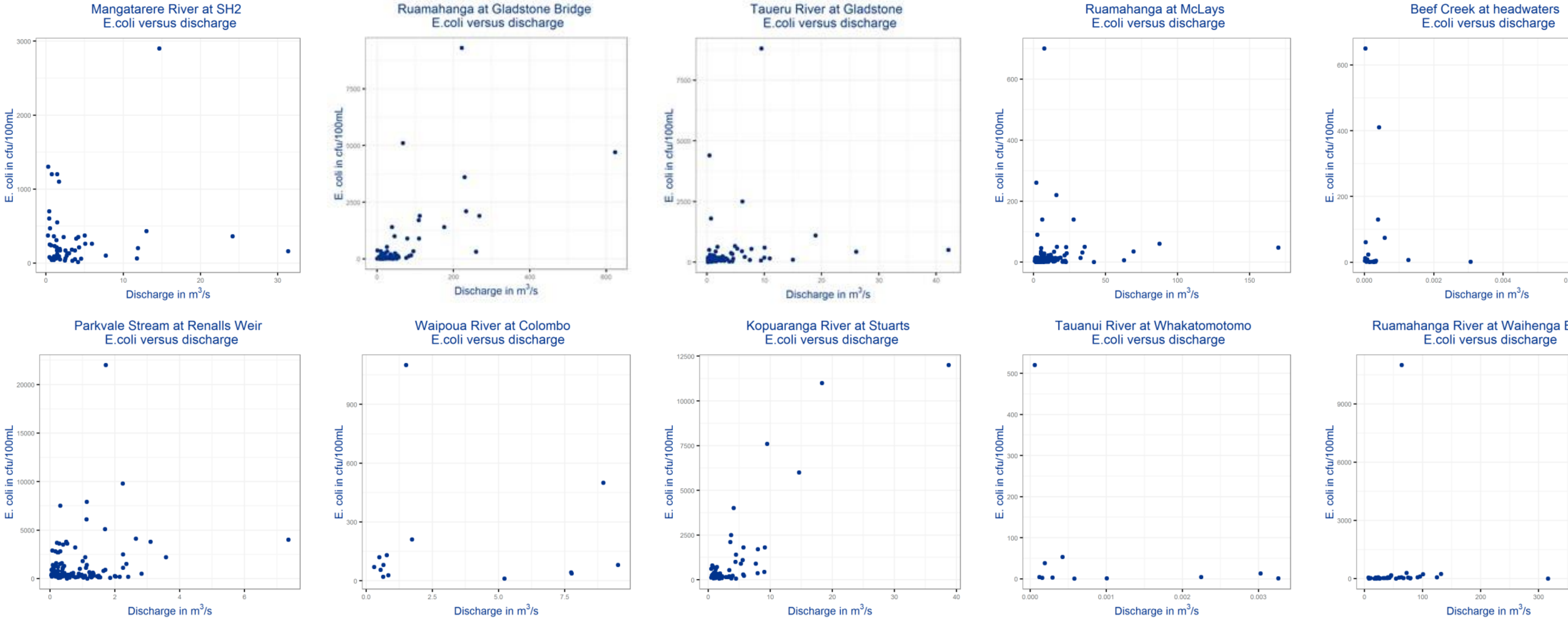


Figure 4-3: Plots of *E.coli* concentration verses discharge at each site

## 4.2 Generation rates

Microbial contamination of water sources is influenced by surrounding land use, and both point and nonpoint (diffuse) sources are of importance (Cho et al, 2016). *E. coli* can be generated from a large variety of sources within a mixed-use catchment. The main sources chosen for the modelling, decided through stakeholder engagement, included:

- Direct access of animals (livestock and waterfowl) to waterways;
- Overland flow through grazed paddocks entraining *E.coli*;
- Pet waste (cats and dogs) in residential and parkland areas,
- Runoff from commercial, industrial and road impervious surfaces; and
- Waste water discharge to streams.

Representation of the relative source load of *E.coli* from these different sources was a focus in the selection and calibration of Event Mean Concentration (EMC) and Dry Weather Concentration (DWC) models. Numerous literature sources informed the initial set of EMC/DWC parameters as deposition concentrations and guided calibration to in-stream monitoring data, including loads used in CLUES for pasture, other rural sources. Further details on the CLUES modelling framework can be found in Semadeni-Davies et al. (2011) and Woods et al. (2006a).

Attenuation of *E.coli* was undertaken through the combination of adjusting EMC/DWC deposition parameters by several orders of magnitude to account for die-off processes, followed by reductions from in-stream removal. This two-step approach was used to calibrate the model to in-stream monitoring data. Die-off reductions were applied uniformly across the catchment, therefore, this resulted in lower EMC/DWCs for some land uses than reported literature values. Despite this limitation, these land use types represent a small proportional area of the catchment and are not significant drivers of *E.coli* loads, which are dominated by rural diffuse sources and wastewater treatment plant discharge.

## 4.3 *E.coli* Calibration

Simulated *E.coli* concentrations for each calibration site was assessed against observed monitoring data using:

- Percent bias (% difference between modelled and observed mean monthly concentrations)
- Comparisons between mean, median and 95th percentile statistics
- Box-whisker plots (illustrating the median, 25th and 75th percentiles – the box; 5th and 95th percentiles – the whiskers)

Simulation of microbial concentrations with a semi-distributed daily catchment model is challenging, and the expectation was to achieve mean concentrations within a reasonable order of magnitude to the observed data, and similar trends in timing of peak concentrations. Efforts were made to achieving a good fit to 95th percentile concentrations, given this statistic is used as an indicator of swimmability under the NPSFM guidelines.

Generally, the model was able to achieve a good fit between observed and modelled means for all sites, reflected in the low PBIAS statistic (Table 4-2), with the exception of the Parkvale Stream at Weir site. There was difficulty in achieving realistic EMCDWCs parameters within literature ranges to fit observed data at this site without compromising downstream calibration sites. This could be reflected by uncertainties in modelled flows.

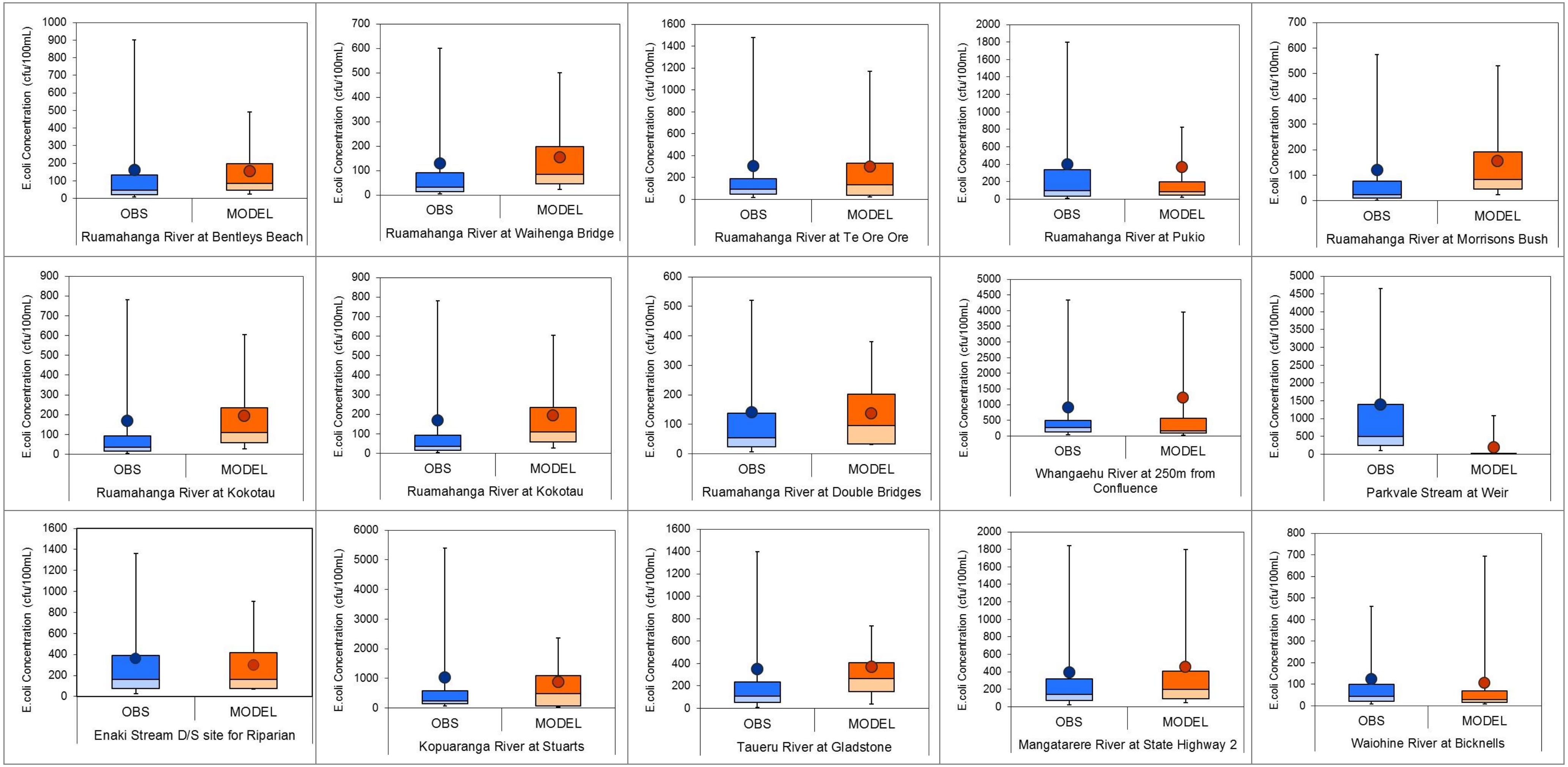
The overall distribution of modelled *E.coli* compared well with the distribution of observed data for the majority of sites (with the exception of Parkvale Stream at Weir site) as shown in the box-whisker plots in Table 4-3. Overall the model performed reasonably well at estimating the 95th percentile, although the model underpredicted the 95th percentile at six sites, which may result in a different swimmability categorisation than observed data.

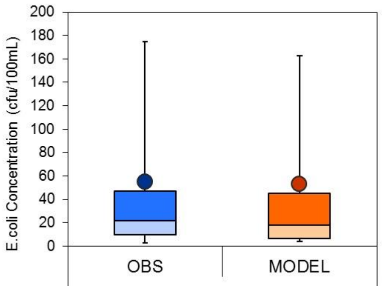
However, the *E.coli* baseline simulations are suitable as a planning tool to assess the relative change of scenarios focused at mitigating poor water quality within the catchment.

**Table 4-2: Comparison between observed in-stream data and modelled outputs for median, mean and 95th percentile concentrations and the percent bias between mean concentrations for the full simulation period**

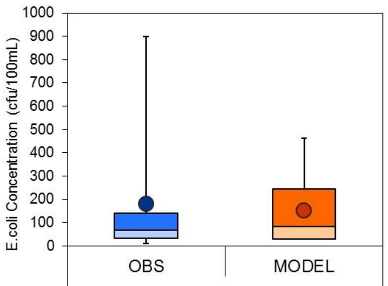
| | Median Concentration (CFU/100mL) | | Mean Concentration (CFU/100mL) | | 95th percentile Concentration (CFU/100mL) | | % Bias between means | % Bias between 95th percentiles |
|---|---|---|---|---|---|---|---|---|
| **SAMPLING SITES** | **OBS** | **MODEL** | **OBS** | **MODEL** | **OBS** | **MODEL** | | |
| Beef Creek at headwaters | 6 | 22 | 26 | 27 | 150 | 47 | -4% | -69% |
| Enaki Stream D/S site for Riparian | 160 | 164 | 301 | 363 | 1576 | 907 | -17% | -42% |
| Kopuaranga River at Stuarts | 240 | 481 | 879 | 1040 | 6078 | 2377 | -15% | -61% |
| Mangatarere River at State Highway 2 | 145 | 212 | 455 | 398 | 2325 | 2174 | 14% | -6% |
| Parkvale Stream at Weir | 500 | 7 | 191 | 1405 | 5550 | 1311 | -86% | -76% |
| Parkvale tributary at Lowes Reserve | 22 | 14 | 27 | 58 | 223 | 89 | -53% | -60% |
| Ruamahanga River at Bentleys Beach | 48 | 84 | 155 | 162 | 1025 | 490 | -4% | -52% |
| Ruamahanga River at Double Bridges | 55 | 96 | 137 | 141 | 521 | 381 | -3% | -27% |
| Ruamahanga River at Gladstone Bridge | 29 | 98 | 199 | 154 | 900 | 657 | 29% | -27% |
| Ruamahanga River at Kokotau | 35 | 109 | 193 | 168 | 878 | 605 | 15% | -31% |
| Ruamahanga River at Morrisons Bush | 24 | 82 | 156 | 121 | 619 | 531 | 29% | -14% |
| Ruamahanga River at Pukio | 98 | 72 | 370 | 401 | 1935 | 851 | -8% | -56% |
| Ruamahanga River at Te Ore Ore | 94 | 133 | 301 | 306 | 1516 | 1218 | -2% | -20% |
| Ruamahanga River at Waihenga Bridge | 33 | 73 | 154 | 131 | 613 | 494 | 18% | -17% |
| Tauanui River at Whakatomotomo Rd | 4 | 4 | 6 | 9 | 39 | 22 | -33% | -44% |
| Taueru River at Gladstone | 110 | 265 | 370 | 350 | 1580 | 763 | 6% | -52% |
| Tauherenikau River at Websters | 19 | 2 | 39 | 48 | 173 | 120 | -19% | -31% |
| Waingawa River at Kaituna | 7 | 15 | 25 | 30 | 130 | 75 | -18% | -42% |
| Waingawa River at South Rd | 22 | 18 | 53 | 55 | 180 | 172 | -4% | -4% |
| Waiohine River at Bicknells | 44 | 24 | 107 | 124 | 510 | 677 | -14% | 33% |
| Waiorongomai River at Forest Park | 7 | 3 | 11 | 11 | 34 | 42 | -2% | 24% |
| Waipoua River at Colombo Rd Bridge | 69 | 62 | 151 | 181 | 909 | 573 | -17% | -37% |
| Whangaehu River at 250m from Confluence | 265 | 164 | 1216 | 911 | 4518 | 4137 | 33% | -8% |

Table 4-3: Comparison of observed and modelled *E.coli* box-whisker plots. The box represents the 25th percentile, median and 75th percentiles, the whiskers represent the 5th and 95th percentile concentrations. Mean concentration is given as a single point.

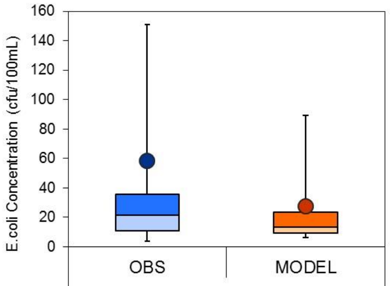




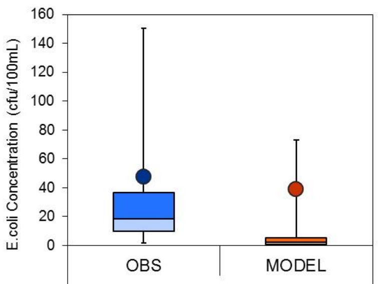
Waingawa River at South Rd



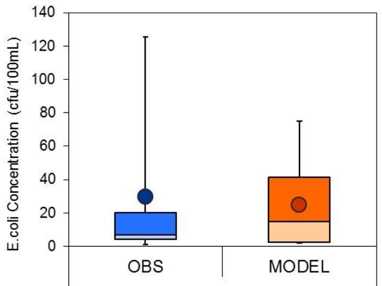
Waipoua River at Colombo Rd Bridge



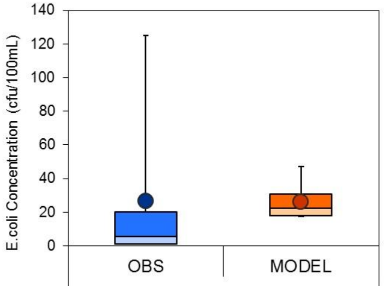
Parkvale tributary at Lowes Reserve



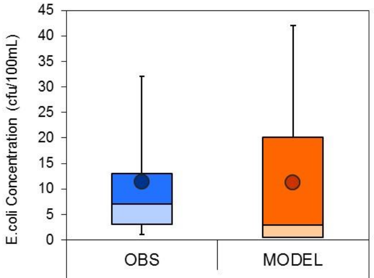
Tauherenikau River at Websters



Waingawa River at Kaituna



Beef Creek at headwaters



Waiorongomai River at Forest Park

# 5. Sediment

Fine sediment generation and transport can be strongly correlated to flows generated within the catchments. Therefore, a power curve that relates Suspended Sediment Concentration (SSC) to the modelled flow was chosen to simulate the daily SSC for each subcatchment in the SOURCE model. This is a well-established technique for determining suspended sediment concentrations. Power curve models were developed through an iterative process; firstly, derived from relationships between observed SSC and gauged flow data for three calibration sites, and secondly, adjusted to return the mean annual sediment yields as modelled by the SedNetNZ model to obtain a broader spatial representation of SSC loads across the catchment.

SedNetNZ was incorporated in the SOURCE sediment modelling process because SedNetNZ has the ability to spatially represent the sediment yield from different erosion processes, and therefore enables modelling of mitigations that target specific erosion sources (for example, stream bank erosion) and allows for mitigations to be applied spatially to target specific areas (for example, to target the top 5% of sediment yielding land). The change in annual yields as a result of mitigation scenarios (e.g. riparian land management) was determined in SedNetNZ, and the resulting percent reductions in sediment yields then applied to the SOURCE model for each of the different Whaitua scenarios.

## 5.1 General approach

The approach presented here disaggregates the annual average sediment load from SedNetNZ, developed by Landcare Research (Dymond et al. 2016), for each subcatchment in the SOURCE model. The disaggregation is based on a power curve relationship of the form:

$$SSC = bQ^a \qquad \textbf{Equation 1}$$

where SSC is the suspended sediment concentration in milligrams per litre, Q is peak flow in litres per second, *a* and *b* are constants and exponents, respectively. Equation 1 is also called a sediment rating curve.

The data to determine the power law relationship was provided by NIWA (pers. comm. Murray Hicks) as instantaneous suspended sediment concentration and flow rates. The fitted *a* parameter was adopted through iterations to achieve a modelled SSC vs flow graphical slope that was similar to the observed data. The *b* constant was scaled at each subcatchment to match the SedNetNZ annual loads.

Alternative approaches were also investigated including a Dry Weather Concentration and Event Mean Concentration, as well as a piecewise relationship for both dry weather and events. In the piecewise relationship dry weather concentration was represented by constant determined from the monthly water quality data and the event concentrations determined from a power curve relationship. However, these were found to be unsatisfactory at reliably describing the suspended sediment concentration across the entire flow range.

### 5.1.1 Sampling data

The analysis utilised the following data, summarised in Table 5-1:

- SSC concentrations and gaugings from NIWA (pers. comm. Murray Hicks), used to fit the power curve (Equation 1),
- SedNetNZ data, used to determine the annual loads of sediment from each subcatchment.
- Flow data for Ruamāhanga catchment gauges from GWRC,
- Ministry of Works (MoW) historical suspended sediment concentration samples for the Ruamāhanga River,

**Table 5-1 Observed suspended sediment data**

| Calibration Site | Data | Data record | Further information | Project use |
|---|---|---|---|---|
| Ruamahanga River at Waihenga Bridge | Continuous flow data | Dec 1956 – Dec 2014 | Stage converted to flow based on gauging | Converted to daily flow |
| | Monthly turbidity data | Sep 1996 – Jul 2003 | Laboratory and in-situ data | Converted to SSC with 1:1.4 ratio |
| | Monthly SSC & flow data | May 1968 – Mar 1987 | Ministry of Works SSC with synchronous flow data (13 records) | Used to calibrate model |
| Kopuaranga River at Stuarts | Continuous flow data | Aug 2009 – Oct 2014 | Stage converted to flow based on gauging | Converted to daily flow |
| | Monthly turbidity data | Feb 1997 – Jun 2014 | Laboratory and in-situ data | Converted to SSC with 1:1.4 ratio |
| | Monthly SSC data | Jan 2008 – Jun 2014 | Laboratory data | Used to calculate TSS:turbidity ratio |
| Waiohine River at Gorge | Continuous flow data | Dec 1954 – Oct 2014 | Stage converted to flow based on gauging | Converted to daily flow |
| | Monthly turbidity data | Nov 1991 – Jun 2014 | Laboratory and in-situ data | Converted to SSC with 1:1.4 ratio |
| | Monthly SSC data | Jan 2008 – Jun 2014 | Laboratory data | Not used as poor quality |

Where necessary, turbidity data was converted to SSC using a 1:1.4 ratio determined from paired monitoring data. SSC data within Ruamahanga was limited, with the record of samples spanning up to 50 years at only three sites.

## 5.2 Sediment Power Curves

The analysis was carried out against three sites in the Ruamāhanga catchment (Figure 5-1) with good quality observed suspended sediment data:

- Ruamāhanga River at Waihenga
- Kopuaranga at Stuarts
- Waiohine at Gorge

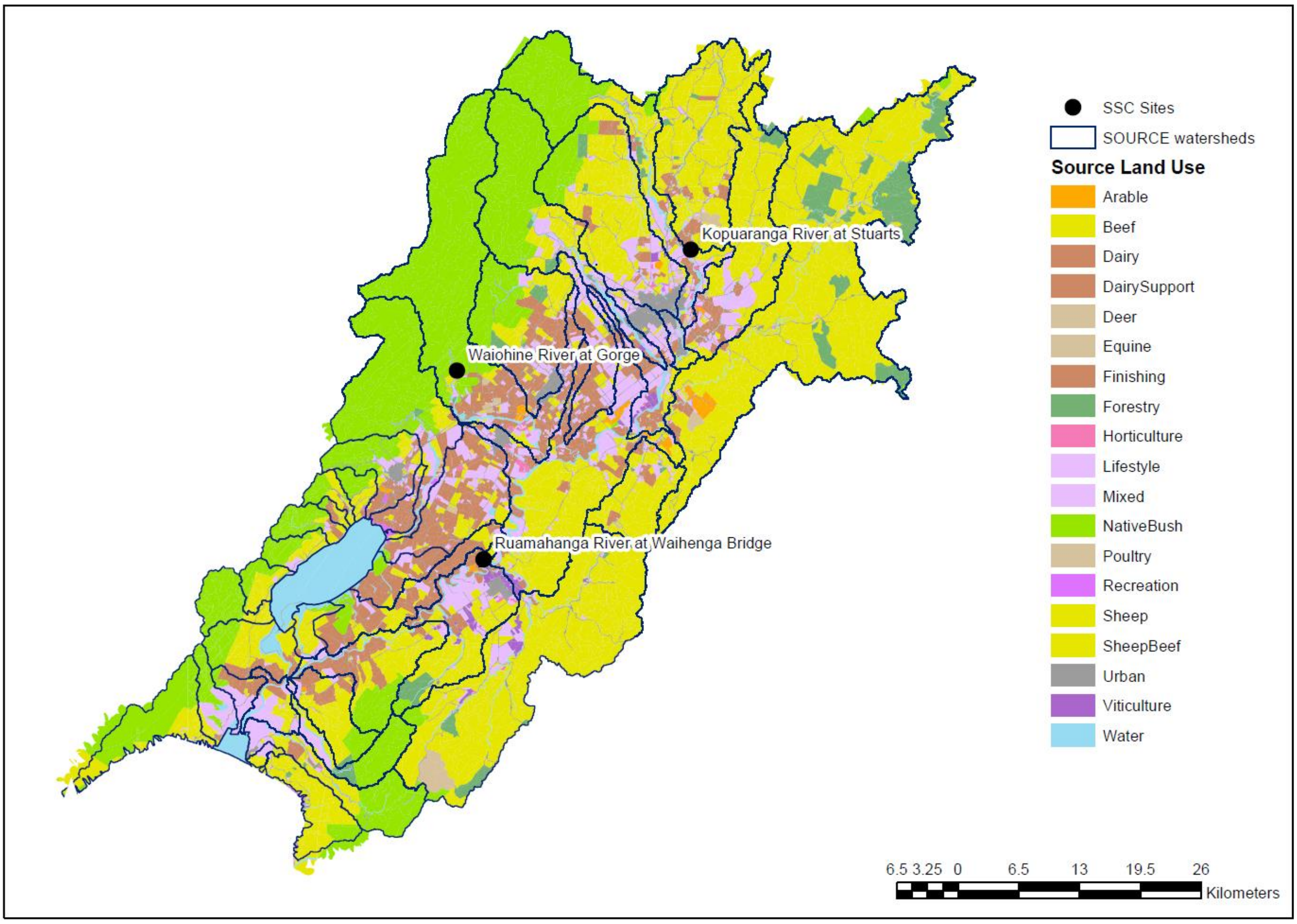


**Figure 5-1: Location of suspended sediment sites in the Ruamāhanga used for creating of power curve models.**

From this data the following individual suspended sediment concentration power curves have been fitted as shown in Figure 5-2. In addition, data has been pooled between all sites as well as Ruamāhanga and Waiohine sites (Figure 5-3) in order to test a normalised power curve applicable for all sites, as well as providing a broader data for the statistical analysis. Sites were pooled by taking the ratio of the mean daily flow. The suspended sediment concentration power curve constant (*b*) and exponent (*a*) for these three sites are presented in Table 5-2.

These results demonstrate the following:

- The power curve at both Ruamahanga River at Waihenga Bridge and Kopuaranga River at Stuarts sites reasonably predicts suspended sediment concentrations.
- The power curve relationships for Waiohine River at Gorge and all sites pooled does not predict suspended sediment concentrations well
- The power curve relationship for the pooled Ruamahanga and Waiohine site satisfactorily predicts suspended sediment concentrations

Given these results an exponent of 1.5 was initially adopted for the analysis. Subsequently, in adjusting the power curve to return SedNetNZ annual loads, it was found that an exponent of 1.8 resulted in a better estimate of the annual sediment loads as well as maintaining a good fit to observed concentration data (i.e. a better slope was exhibited in the power curve plots of simulated and observed SSC).

**Table 5-2: Power curve analysis from observed TSS and gauged flow data**

| Site | b (constant) | a (exponent) | $R^2$ (fit) |
|---|---|---|---|
| Ruamahanga River at Waihenga Bridge | 0.02 | 1.56 | 0.81 |
| Kopuaranga River at Stuarts | 2.12 | 1.67 | 0.79 |
| Waiohine River at Gorge | 0.12 | 0.97 | 0.39 |
| Ruamahanga River at Waihenga and Waiohine River at Gorge | 0.06 | 1.21 | 0.64 |
| All | 0.41 | 0.71 | 0.32 |

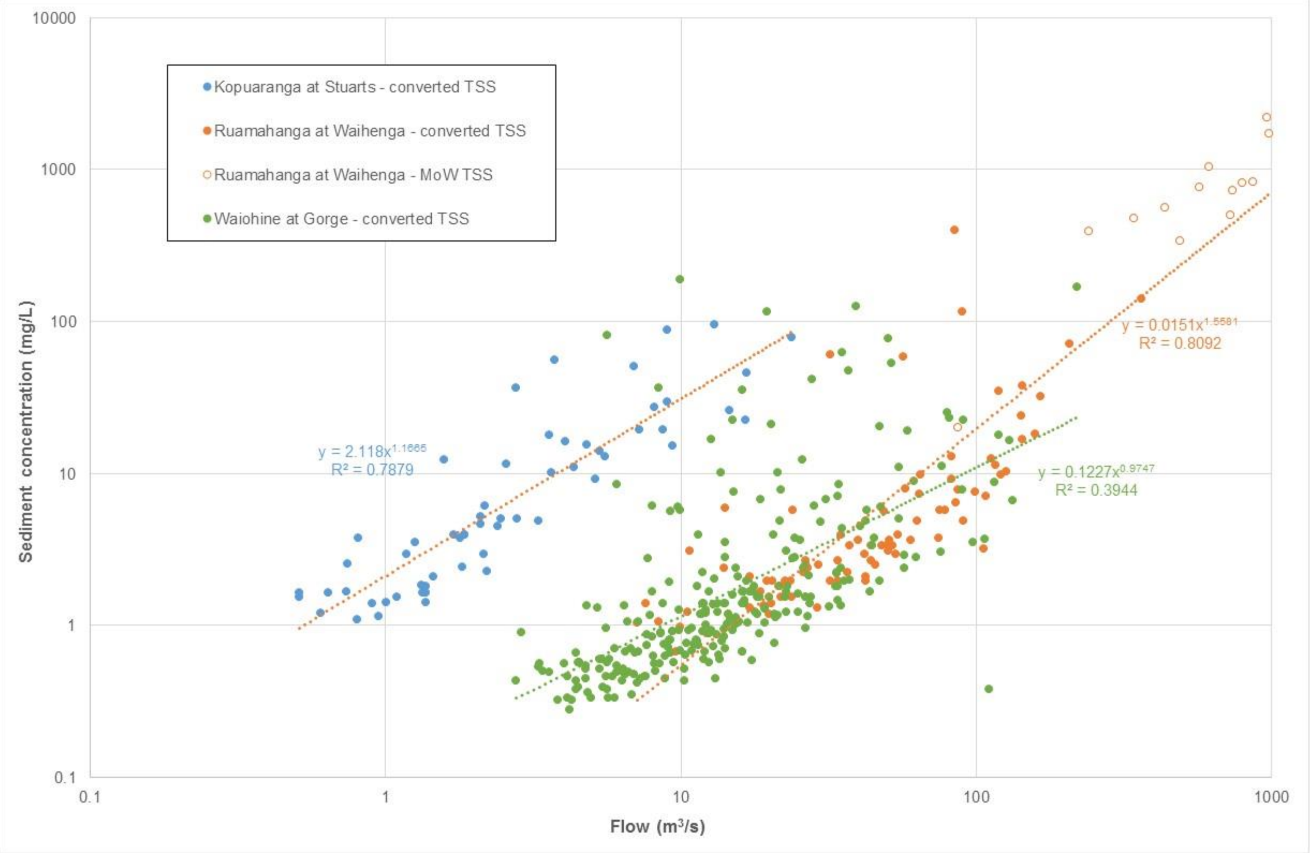


**Figure 5-2: Observed suspended sediment power curves for individual calibration sites**

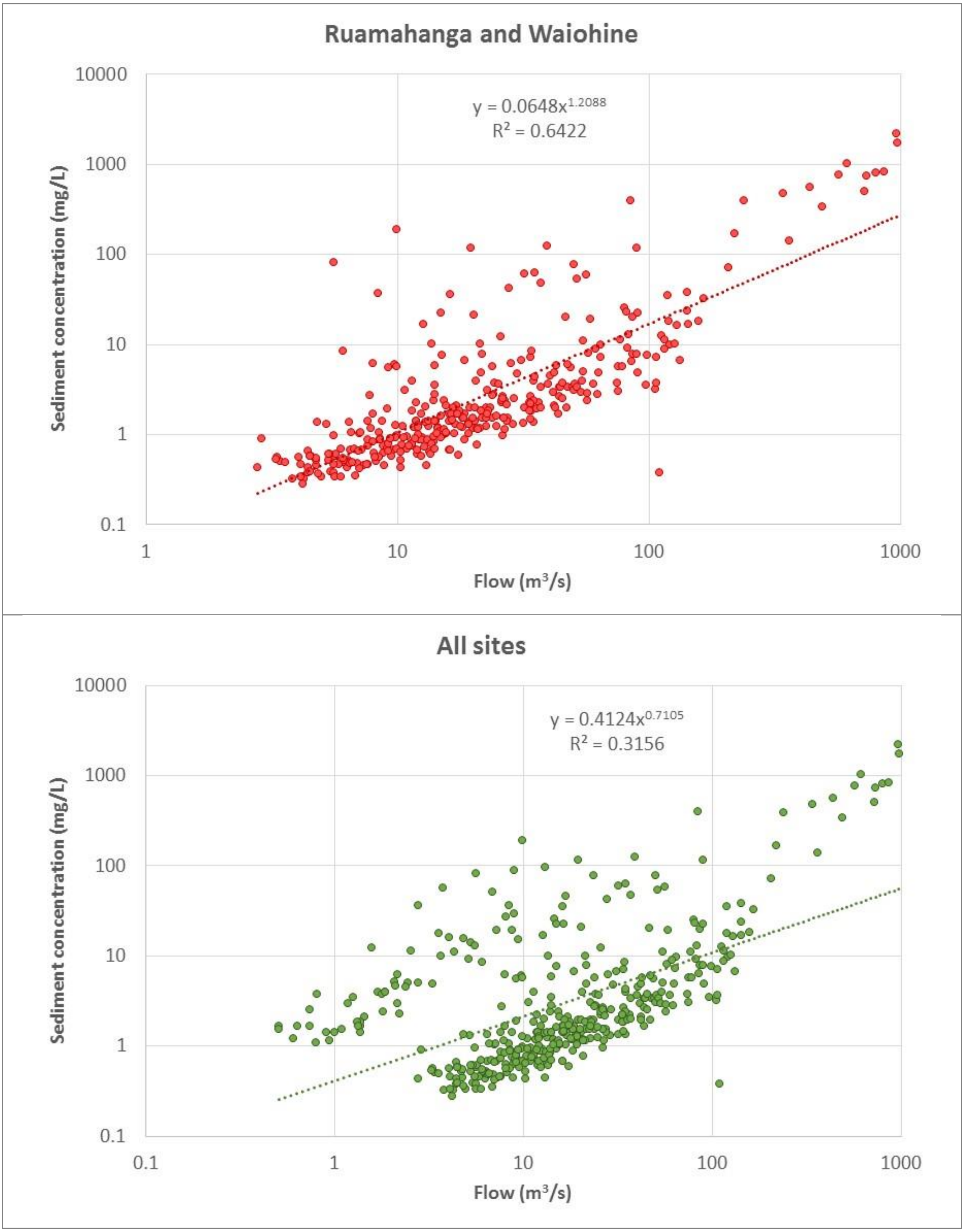


**Figure 5-3: Observed suspended sediment power curves for a) pooled Ruamāhanga and Waiohine sites, and b) all sites.**

## 5.3 SedNetNZ

The SedNetNZ model simulates average annual sediment yields from hillslope (surficial), gully, streambank, earthflow and landslide erosion sources to give an overall sediment budget for each REC subcatchment for the Ruamāhanga catchment extent. The SedNetNZ mean annual sediment yields were extracted for all SOURCE subcatchments, and used to tune the modelled SSC power curves to return the same mean annual sediment loads as SedNetNZ. There were 237 subcatchments of which annual average loads ranged from 2.0 to 216,938 tonnes/year (noting this large variation in loads is heavily influence by catchment area, cover and rainfall). Table 5-3 provides a summary of catchment area and mean annual load as estimated by SedNetNZ, noting Ruamahanga at Waihenga includes the sediment load from Kopuaranga at Stuarts and Waiohine River.

**Table 5-3: SedNetNZ mean annual sediment load**

| Catchment | Area ($km^2$) | Average annual sediment load (t/yr) |
|---|---|---|
| Ruamāhanga River at Waihenga | 2,362 | 1,033,749 |
| Kopuaranga River at Stuarts | 167 | 64,426 |
| Waiohine River at Gorge | 190 | 131,153 |

In order to maintain the average annual loads between SedNetNZ and the power curve relationship, the *b* parameter of the power curve relationship (Equation 1) was adjusted, based on the modelled flow timeseries from each subcatchment.

Figure 5.4 shows the SedNetNZ mean annual load distribution for the Ruamahanga Catchment.

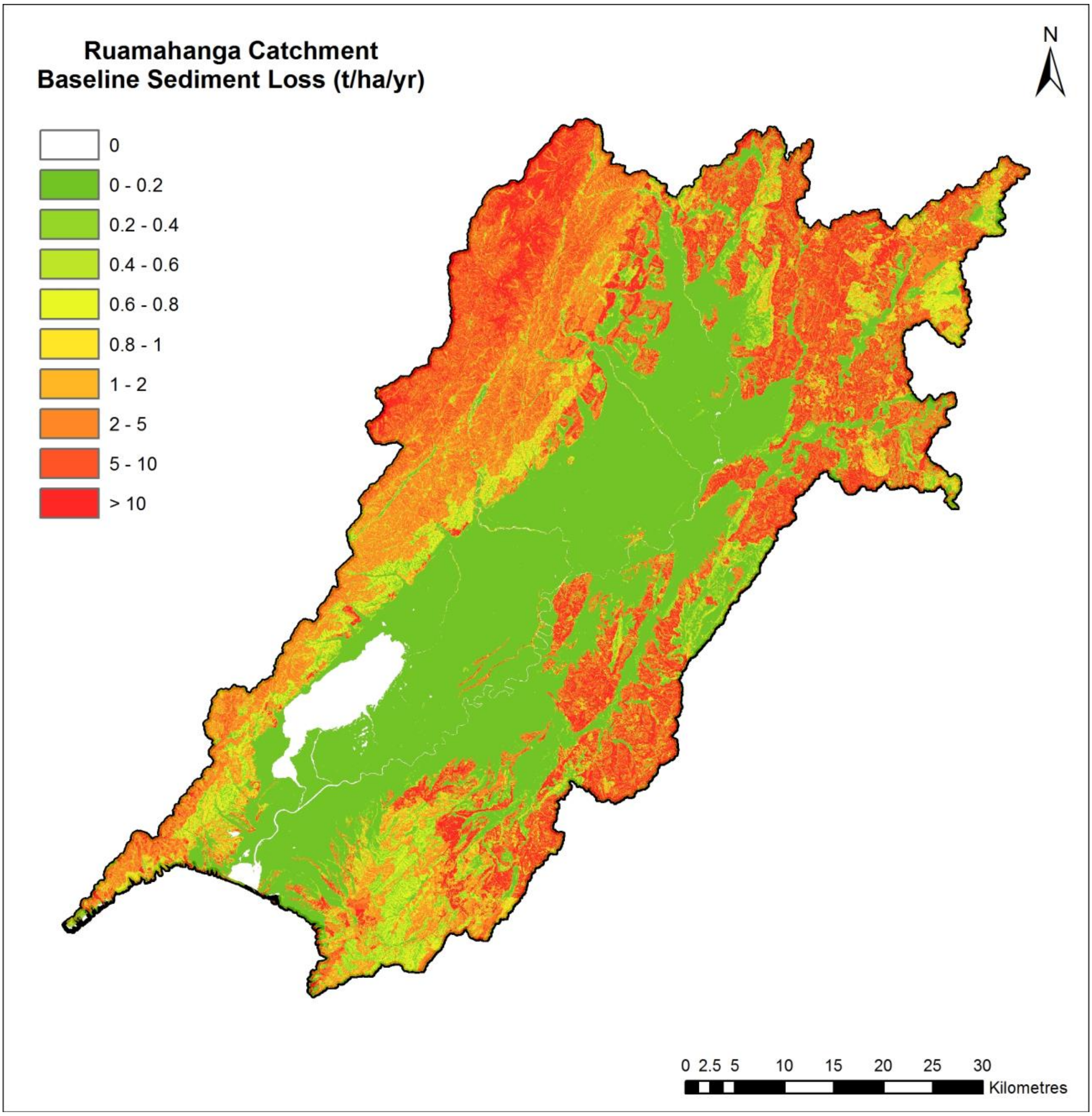


**Figure 5.4 : Baseline model sediment loss from SedNetNZ**

## 5.4 Sediment modelling in Source

The power curve relationship determined above (shown below in Equation 2) was incorporated into the SOURCE model for each of the 237 subcatchments. The suspended sediment concentration was determined by the modelled runoff from each subcatchment, that is, either the Irrical and Groundwater Flux flows or the TOPNET flows.

$$SSC = b_{scaled} Q^{1.8}$$ **Equation 2**

where SSC is the suspended sediment concentration, $b_{scaled}$ is the *b* parameter from Equation 1 selected to maintain the average annual sediment load, *Q* is the subcatchments daily discharge and 1.8 is the exponent that best fits the observed concentration data as well as returns the mean annual sediment load estimated by SedNetNZ.

By using the same rating curve (scaled by different b parameter) across the whole Ruamahanga catchment the cumulative load from individual upstream subcatchments will be close to the average annual load calculated from SedNetNZ for the Ruamahanga where it discharges to the sea.

The results of the sediment modelling using the ‘scaled’ power curve approach is given in Figure 5-5, Figure 5-6 and Figure 5-7, for Ruamāhanga River at Waihenga, Kopuaranga River at Stuarts and Waiohine River at Gorge sites, respectively. The ‘scaled’ power curve relationship for Ruamāhanga River at Waihenga and Kopuaranga River at Stuarts reasonably predicts suspended sediment concentrations. However, at the Waiohine River at Gorge site the model satisfactorily predicts suspended sediment concentrations, with overpredictions of sediment concentrations at high flows.

The ‘scaled’ power curve approach ensures that the average annual load calculated by SedNetNZ for each sub-catchment is returned within the SOURCE water quality model, however concentrations are more uncertain, reflecting the lack of (particularly high flow) suspended sediment concentration monitoring across the Ruamahanga catchment.

The data supplied by NIWA suggests the three sites within the Ruamahanga catchment have three different rating curves. Applying the same rating curve, with an exponent of 1.8 (though with scaled b parameter) across the whole of the Ruamahanga may compound uncertainty in the concentration of sediment for each sub-catchment. With the absence of available monitoring data, this approach is considered acceptable for modelling SSC at this stage.

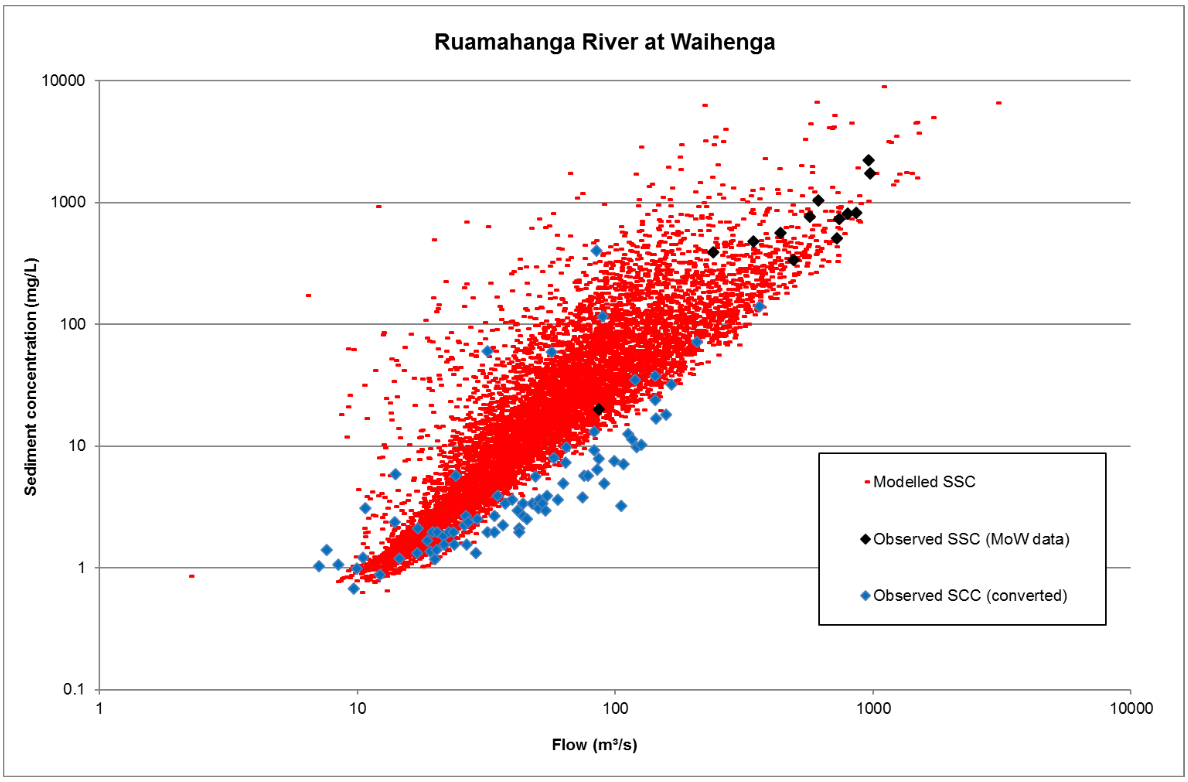


**Figure 5-5: Ruamahanga River at Waihenga modelled and observed sediment concentration rating curves**

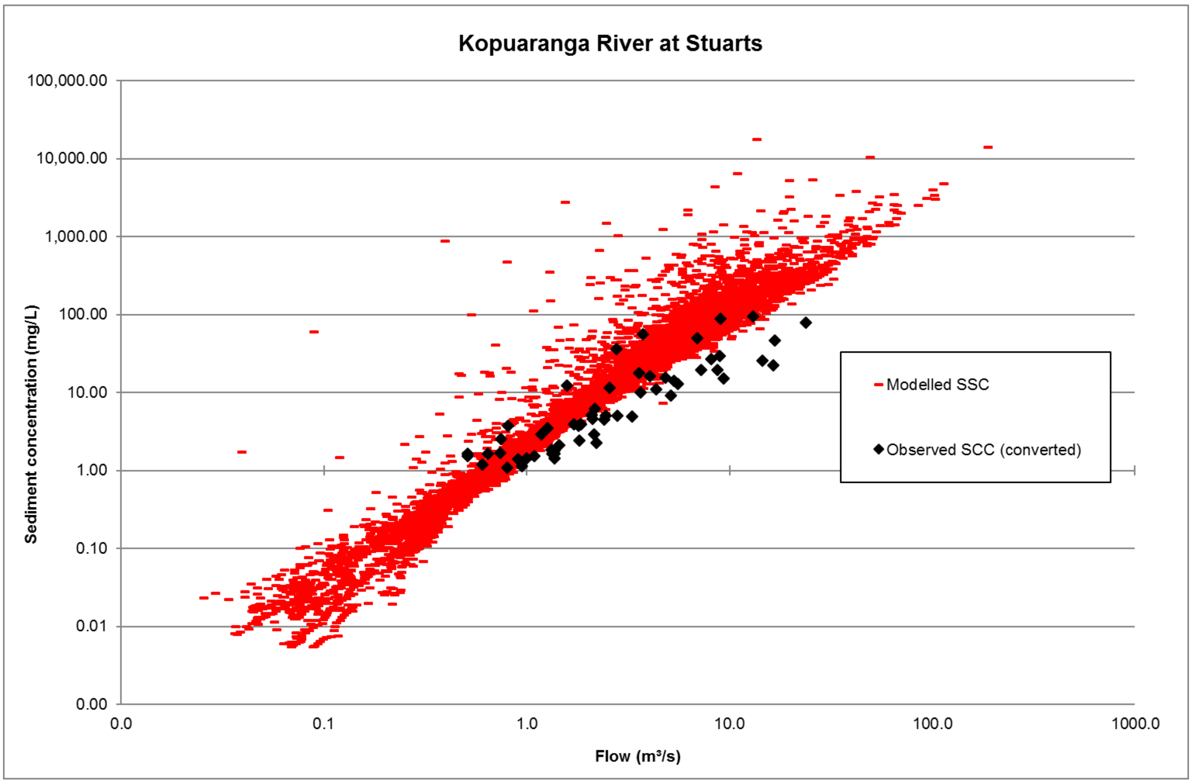


Figure 5-6: Kopuaranga River at Stuarts modelled and observed sediment concentration rating curves

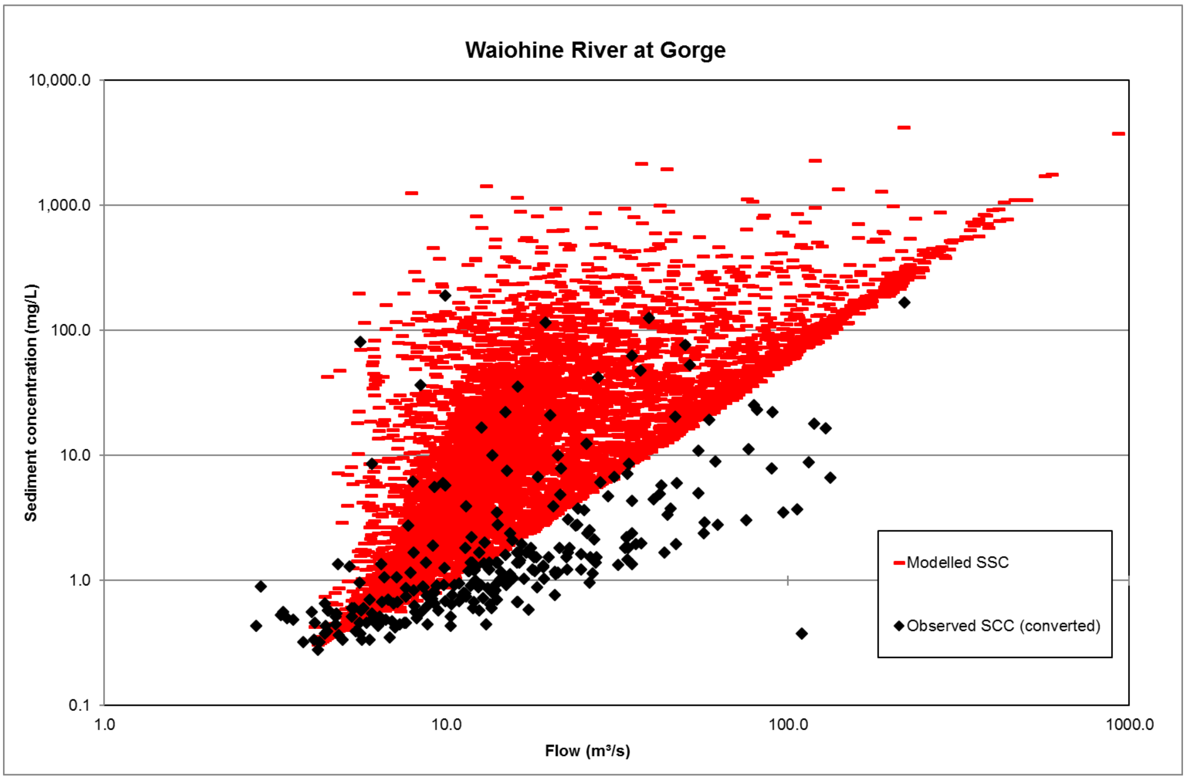
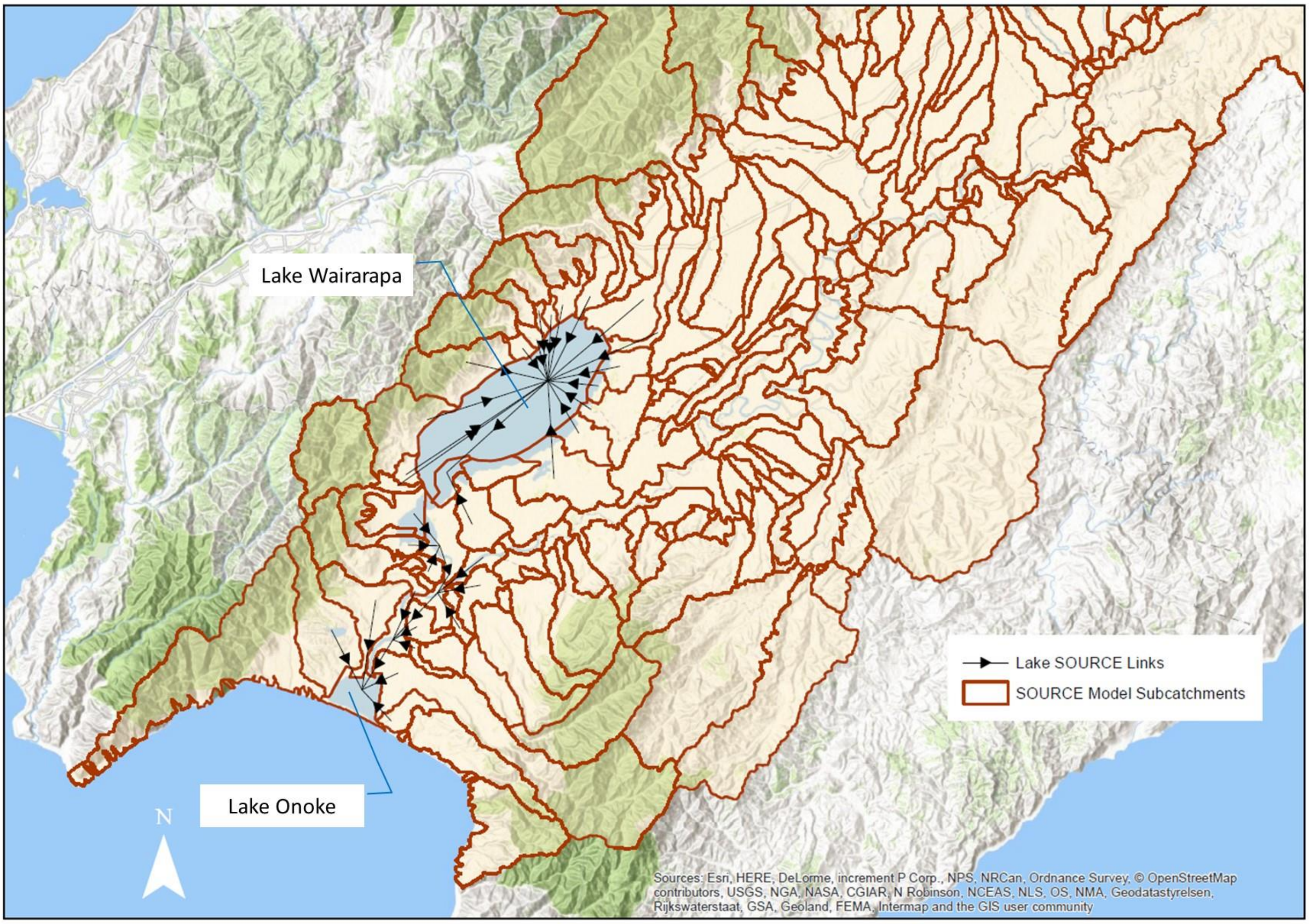


Figure 5-7: Waiohine River at Gorge modelled and observed sediment concentration rating curves

# 6. Inputs to Lake Modelling

Lakes Wairarapa and Onoke are key waterbodies in the catchment that were modelled outside of SOURCE by the University of Waikato, using a lake hydrodynamic and biophysical modelling approach.

The SOURCE model provided flow and water quality (nutrients, suspended sediment and *E.coli*) concentrations at key node locations upstream of Lake Wairarapa and on catchments feeding into Onoke to the University of Waikato models at a daily timestep (Figure 6-1).



Sources: Esri, HERE, DeLorme, increment P Corp., NPS, NRCan, Ordnance Survey, © OpenStreetMap contributors, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community

**Figure 6-1: SOURCE model links provide inputs to Lakes Wairarapa and Onoke hydrodynamic-biophysical models.**

# 7. SOURCE Model Assumptions and Limitations

There are a number of assumptions and limitations throughout the modelling which were implemented for various reasons, including time constraints, modelling efficiencies and practicalities. Some of the key assumptions/limitations are described below.

## 7.1 Catchment areas

Catchment delineation was dictated by accommodating several sources of flow inputs and therefore resulted in aggregation of REC catchments that resulted in the exclusion of some reporting locations on small tributary sites or inclusion of reporting sites that did not align exactly with flow input locations. An example of this is Waingawa River at South Road, where the water quality and flow monitoring site is located ~5 km upstream from where the catchment delineation ended (at the tributary with the Ruamahanga River).

To improve on this would require updates of the hydrological models (TOPNET runoff, MODFLOW GWFlux and Irricalc quickflow) which was not possible in the project timeframes.

Overall, the effects of this are considered minor given the proportionate catchment size and that downstream points would have been calibrated to include this additional load (i.e. a higher attenuation rate would have been applied in the model to calibrate sites to observed data).

## 7.2 Model linkages

At a number of locations there are gaps in the groundwater modelling domain. Some of these locations are present due to the occurrence of natural geological features. The consequence of these ‘holes’ means that no groundwater modelling or Irricalc quickflow modelling has occurred at these locations. TOPNET was used to generate flows from the upland catchments and could have been applied in these holes to generate runoff, however this was not undertaken.  These holes; however, represent a very small area of the total catchment.

SOURCE integrated flow inputs from a range of models. GNS developed a groundwater model domain and incorporated TOPNET flows from the upland catchment as inflows along the edge of this domain. This helped calibrate the groundwater model, and subsequently groundwater fluxes that were linked back into SOURCE.

TOPNET runoff modelling was based off REC catchments. The development of the groundwater model domain in some cases dissected these catchments, rather than being ‘clipped’ to the catchment boundaries. This results in the possible overrepresentation of flows in SOURCE on catchments bordering the fringe of the groundwater domain, as SOURCE utilised TOPNET flows and groundwater fluxes (of which these catchments may have both as inputs). An assessment of each catchment along the fringe of the domain was undertaken, and where ~>70% of the catchment was outside of the groundwater model domain, it was assumed flows were generated from TOPNET runoff only (i.e. no groundwater fluxes were applied). However, this approach was subjective, and subsequently a number of catchments may have both TOPNET flows and groundwater fluxes as inputs into the model.

## 7.3 Annual allocation

There are no annual abstraction allocation amounts applied to any surface water consents. Review of a number of existing Irricalc surface water abstractions showed no single consent reached their annual allocation volumes. For this reason, coding annual allocation restrictions in the models was not undertaken.

## 7.4 Flow calibration

Loads in the water quality model are driven by the flow generation. The Source model used flows from a range of inputs. The flow development framework includes:

- TOPNET (NIWA) provides total stream flow generated from the Hill catchments;

- Irricalc (Aqualinc) provides quickflow inputs from the plains catchments and irrigation surface water demands (unrestricted).
- MODFLOW-SFR-MT3D (GNS) system, developed in parallel to the Source model, provided groundwater flux and nitrate loads for input to river links (reaches);
- Point-source inputs (discharge and effluent concentrations) from five wastewater treatment plants (WWTP) derived from monitoring data and included as inflow nodes within the node-link network
- Surface water abstraction minimum low flow limits were modelled within Source and applied total daily abstraction (agglomerated per subcatchment) along the river links.

The subsequent calibration of these flows series was undertaken by each of the respective parties above, with Jacobs compiling the flow series in SOURCE for the water quality modelling. At a number of sites, calibrations to observed data have led to an over simulation of flow. An accurate flow model is important to ensure generated loads are correctly attenuated. Subsequently, good calibrations of water quality data to observed information are increasingly difficult to achieve if the flows are inaccurate. This can impact on the baseline model and incorporate attenuation factors in catchments that may be higher or lower than in reality, which can then propagate through into scenarios.

## 7.5 Water quality

The observed water quality data was based on monthly water quality monitoring. Generally, this data is obtained during flow conditions representative of the typical river conditions, with less frequent sampling of high and low flow events. As a result, concentrations during peak flows (which are often short duration but can carry large loads) are usually not well represented, and therefore there is the potential that there are concentrations higher than observed, which could mean the model may underestimate some of these upper concentration ranges (i.e. 95th percentiles).

## 7.6 Lakes model inputs/outputs

The constituent and flow outputs from SOURCE modelling were provided to the University of Waikato, whom developed hydrodynamic and biophysical models for Lakes Wairarapa and Onoke.

Given time constraints and additional steps involved in incorporating the lake outputs back into the SOURCE model to transfer flow and nutrients from Lake Wairarapa to Onoke, the University undertook this by incorporating the flows/loads from the Lake Wairarapa with the river/stream flows/loads provided through SOURCE, to determine the inflows that feed into Lake Onoke.

# 8. Conclusion

An integrated catchment water quality model of the Ruamāhanga catchment has been developed under a collaborative modelling partnership comprised of GWRC, Jacobs, GNS, NIWA, Waikato University and Aqualinc. The baseline Ruamāhanga model incorporates hydrological and surface water-groundwater exchange modelling from various sources and adds in water quality functionality to simulate the daily generation and transport of nutrient, sediment and *E.coli* concentrations (and loads) from a variety of rural and urban landuses within the catchment. In addition to diffuse water quality sources, the model incorporates point-source inputs from wastewater treatment plants. The daily outputs from the models feed into a hydrodynamic water quality model of Lakes Wairarapa and Onoke. The model performance is sufficient for scenario modelling for the Ruamāhanga Whaitua to explore a range of water quality improvement and rural land management intervention options.

A number of challenges were experienced during the development of the modelling framework that provide useful lessons for streamlining or enhancing future modelling for other Whaitua Processes (further discussed in Section 9).

The baseline model architecture relies on a number of external flow models which restricts the subcatchment delineation resolution and hydrological representation within the catchment. During the project, changes in data, recalibration of flows and errors in external model inputs required updating across the SOURCE model simultaneously. Considerable time and effort was spent iteratively reviewing and updating data from each external model. Consequently, this process was prohibitive during the scenario modelling phase as the time constraints to re-run external flow models with a range of landuse changes were too long. This resulted in the scenario models utilising the baseline flows only, with the flows only modified by scenario updates to groundwater fluxes and minimum flow control rules. This essentially de-couples the change in loads in scenarios due to landuse changes, which may impact on catchment hydrology (e.g. retirement or pole planting).

The SOURCE model satisfactory simulates flows across the catchment, albeit with a general trend to overpredict low to medium flows (see Section 2.6.1). Re-calibration of a few key tributaries (such as TOPNET flows in the Taueru and Kopuaranga Rivers) could help improve the overall hydrological model but would subsequently require recalibration of the water quality model.

The water quality model has a good fit to the observed in-stream concentration data across many of the calibration sites. Nutrient input concentrations were derived from OVERSEER modelling. Attenuation factors that represent complex natural processes such as nutrient storage and residence time, denitrification, riparian margin uptake and instream cycling and burial were incorporated to fine-tune calibration. Where simulated flows are higher than observed, this can lead to greater generation of nutrient loads. Balancing of this additional load through the calibration process involved incorporating attenuation factors on nitrate-N and total phosphorus that may be higher than what is occurring on the ground.

Suspended sediment concentrations (SSC) were simulated through the use of power curves, driven by calibrating to SedNetNZ annual average loads and limited observed data across three sites. SedNetNZ was incorporated into the baseline modelling approach, as it has useful applications during scenarios, where landuse, land cover and stream bank erosion processes can be modified dependent on the mitigation being implemented (i.e. land retirement, pole planting or streambank fencing). Limited data in Ruamahanga catchment spanning over a 50 year period means confidence in the SSC calibration is only average, but suitable enough given the circumstances to help inform decisions on managing sediment and water quality limit setting. A detailed SSC monitoring programme could be implemented within the Ruamahanga Catchment at a number of sites, and coupled with instantaneous turbidity monitoring could provide enough data (after 1-2 years) to develop an accurate daily SedNet model, better suited for assessing changes in sediment load.

*E.coli* modelling is complex, with flow and *E.coli* concentrations (CFU/100 mL) poorly correlated. The baseline model was satisfactory in representing variations of load from different landuses, however generally resulted in an overestimation of the median and underestimation of the 95th concentrations. The NPSFM swimmability guidelines incorporate four assessment criteria to determine the attribute state of a swimming location. While the baseline model calibration did not focus on these new guidelines, the model will provide a useful platform to simulate on farm mitigations and can be compared to observed data where required, to ensure the relative changes between scenarios are appropriate and their limitations understood.

# 9. Recommendations

Recommendations to enhance the Ruamahanga water quality model include:

- Utilising SOURCE's internal rainfall runoff models to calibrate and simulate flow from the sub-catchments, currently generated by TOPNET and Irricalc. The advantages are better linkages between rainfall-runoff processes for different landuse/soil types (better representation of drainage), more consistent and balanced subcatchment delineation, model revisions and modifications are more efficient and repeatable. In particular relating runoff process to landuse/soil types is important when modelling landuse change scenarios, as runoff characteristics will vary between landuse (i.e. forest versus pasture) and impact on loads from the catchment.

- Should the above recommendation not be undertaken, then re-calibration of a few key TOPNET tributaries will help improve the flow model. In addition, re-running of TOPNET to incorporate landuse change (pole planting, retirement) that is modelled in the scenarios will provide greater understanding of nutrient changes where mitigations may lead to a reduction in flow in some catchments.

- A spatial denitrification assessment could be undertaken based on soil, geology, and groundwater quality samples (redox, iron etc) as has recently been applied in Southland (Rissmann et al., 2016) to derive an understanding of denitrification hot spots and help inform the relevance (and locality) of the currently adopted attenuation factors.

- A more accurate (but data and time hungry) approach would be to model *E.coli* in a sub-daily catchment model coupled to a 3D hydrodynamic model of the River, which would provide a better estimate of in-stream fate and transport of *E.coli*, and consequently, more accurate swimmability assessments.

- Incorporating a detailed SSC monitoring programme at a number of locations within the catchment, coupled with real time instantaneous turbidity monitoring, will help inform the nature of sediment erosion and deposition processes. Instantaneous observed data and strong SSC/turbidity rating curves will provide a platform for building and calibrating a daily SedNet model, which will simulate SSC better than the current power curve approach. If SSC calibration data was available a DailySedNet model could be developed. The DailySedNet modelling approach uses the same SedNet inputs, except it relies on daily rain to drive erosion to predict daily concentrations and loads.

# 10. References

Alexander, R.B., Elliott, A.H., Shankar, U. and McBride, G.B, 2002. Estimating the sources and sinks of nutrients in the Waikato Basin. *Water Resources Research*, 38(12): 1268-1280

Aqualinc, 2009. Estimation of seasonal irrigation water use. Prepared for Irrigation New Zealand

Balfour, M (GWRC), 2014. Estimating consented loads for the five main Wairarapa wastewater treatment plants (Draft).

Barlow, K. B., Christy, B. and Weeks, A, 2009. Nutrient generation and transport at the catchment scale, 18th World IMACS/MODSIM Congress, Cairnes, Australia 13-17 July.

Bartley, R. and Speirs, W, 2010. Review and summary of constituent concentration data from Australia for use in catchment water quality models. eWater Cooperative Research Centre Technical Report. http://www.ewater.com.au/science/papers-and-reports/downloadabledocuments/?format=plain.

Bedekar, V., Morway, E.D., Langevin, C.D., and Tonkin, M., 2016. MT3D-USGS version 1: A U.S. Geological Survey release of MT3DMS updated with new and expanded transport capabilities for use with MODFLOW: U.S. Geological Survey Techniques and Methods 6-A53, 69 p., http://dx.doi.org/10.3133/tm6A53

Boughton, W. C, 1993. A hydrograph-based model for estimating the water yield of ungauged catchments. Hydrology and Water Resources Symposium: Towards the 21st Century: Newcastle: June 30 - July 2 1993: Preprints of Papers. pp 317-324.

Cho, K.H., Pachepsky, Y.A., Oliver, D.M., Muirhead, R.W., Park, Y., Quilliam, R.S., and Shelton, D.R., 2016. Modelling fate and transport of fecally-derived microorganisms at the watershed scale: State of the science and future opportunities, Water Research, 100: 38-56

Clothier, B., Mackay, A., Carran, A., Gray, R., Parfitt, R., Francis, G., Manning, M., Duerer, M. and Green, S., 2007. Farm strategies for contaminant management: a reportby SLURI, the Sustainable Land Use Initiative, for Horizons Regional Council.

Downes, M.T., Howard-Williams, C., Schipper, L.A, 1997. Long and short roads to riparian restoration: Nitrate removal efficiency. In: N.E. Haycock, T.P. Burt, K.W.T. Goulding & G. Pinay (Eds). Buffer zones: their processes and potential for water protection. Quest Environmental, Harpenden.

Dymond, J.R., Herzig, A., Basher, L, Betts, H.D., Marden, M., Phillips, C.J., Ausseil, A.G.E., Palmer, D.J., Clark, M., and Roygard, J, 2016. Development of a New Zealand SedNet model for assessment of catchment-wide soil-conservation works, Geomorphology 257: 85-93.

Elliot, A.H., Alexander, R.B., Schwarz, G.E., Shankar, U., Sukias, J.P.S., McBride, G.B, 2005. Estimation of nutrient sources and transport for New Zealand using the hybrid mechanistic-statistical model SPARROW. Journal of Hydrology (NZ) 44 (1): 1-27.

Elliot, S., Semadeni-Davies, A., Harper, S. & Depree, C, 2014. Catchment models for nutrients and microbial indicators: Modelling application to the upper Waikato River catchment. NIWA, Prepared for Ministry of the Environment. HAM2013-103.

Henderson, R., S. Singh, R. Woods, C. Zammit, 2011. Surface water components of New Zealand's National Water Accounts, 1995-2010, NIWA Client Report

Ministry for the Environment (MfE), 2013. Freshwater reform 2013 and beyond. Wellington: Ministry for the Environment.

Ministry for the Environment (MfE), 2017. National Policy Statement for Freshwater Management (Amended). Wellington: Ministry for the Environment.

Moore, C., Toews, M., Gyopari, M. & Mzila, D, 2017. Ruamahanga Catchment Groundwater Modelling. GNS Science Report 2016/162. October 2017. Baseline Model.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D. and Veith, T.L, 2017. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. American Society of Agricultural and Biological Engineers. Vol. 50 (3): 885-900

Ministry for the Environment, 2017. Swimming categories for E. coli in the Clean Water package: A summary of the categories and their relationship to human health risk from swimming. Wellington: Ministry for the Environment. New Zealand.

Rissmann, C., Rodway, E., Beyer, M., Hodgetts, J., R., Snelder, Ta., Pearson, L., Killick, M., Marapara, T. R., Akbaripasand, A., Hodson, R., Dare, J., Millar, R., Ellis, T., Lawton, M., Ward, N., Hughes Ba., Wilson Kb., McMecking, J., Horton, Tc., May, D., Kees, L, 2016. Physiographics of Southland Part 1: Delineation of key drivers of regional hydrochemistry and water quality. June 2016. Technical Report. Publication No 2016/3. aLWP Ltd; bLandpro Ltd; cGeological Sciences, University of Canterbury

Semadeni-Davies, A., Elliott, S., Shankar, U, 2011a. The CLUES Project: Tutorial manual for CLUES 3.0. Prepared for Ministry of Agriculture and Forestry. NIWA Client Report: HAM2011-003.

Welsh WD, Vaze J, Dutta D, Rassam D, Rahman JM, Jolly ID, Wallbrink P, Podger GM, Bethune M, Hardy M, Teng J, Lerat J, 2012. An integrated modelling framework for regulated river systems. Environmental Modelling and Software, 39, 81-102.

Woods, R., Elliott, S., Shankar, U., Bidwell, V., Harris, S., Wheeler, D., Clothier, B., Green, S., Hewitt, A., Gibb, R. and Parfitt, R, 2006. The CLUES Project: Predicting the Effects of Land-use on Water Quality – Stage II. NIWA Client Report HAM2006-096.

# Appendix A. WWTP SOURCE model input timeseries

**Masterton WWTP**