Porirua Whaitua Collaborative Modelling Project

Greater Wellington Regional Council

Baseline Modelling Technical Report

1 | 2

15 March 2019

Client Reference

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Abbreviations

Term	Meaning
CFU	Colony Forming Unit
CLM	Contaminant Load Model
CLUES	Catchment Land Use for Environmental Sustainability
CMP	Collaborative Modelling Programme
Cu	Copper
DRP	Dissolved reactive Phosphorus
DWC	Dry Weather Concentration
E. coli	*Escherichia coli*
EMC	Event Mean Concentration
FU	Functional Unit
FWO	Freshwater Objective
GWRC	Greater Wellington Regional Council
MALF	Mean Annual Low Flow
MLG	Modelling Lead Group
NH_4-N	Ammoniacal – Nitrogen
NRP	Natural Resources Plan
NOF	National Objectives Framework
NPSFM	National Policy Statement for Freshwater Management
NO_3-N	Nitrate – Nitrogen
NSE	Nash-Sutcliffe Efficiency
NZLRI	New Zealand Land Resource Inventory
PBIAS	Percent Bias
PCC	Porirua City Council
PET	Potential evapotranspiration
REC	River Environment Classification
SS	Suspended Sediment
TAoP	Te Awarua-o-Porirua
TAoPWC	Te Awarua-o-Porirua Whaitua Committee
TN	Total Nitrogen
TP	Total Phosphorus
VCSN	Virtual Climate Station Network
VPD	Vehicles Per Day
WCC	Wellington City Council
WIP	Whaitua Implementation Plan
Zn	Zinc

Executive Summary

An integrated catchment model of Te Awarua-o-Porirua whaitua has been developed for Te Awarua-o-Porirua Whaitua Committee to help guide the freshwater limit setting process as required under the National Policy Statement for Freshwater Management. The model was developed by Jacobs within the Greater Wellington Regional Council led Te Awarua-o-Porirua Whaitua Collaborative Modelling Programme.

The purpose of the model is to accurately represent current (i.e. “baseline”) hydrological and water quality conditions in the catchment to inform the Te Awarua-o-Porirua Whaitua Committee where there is an absence of in-stream observed data, and to enable the testing of alternative management scenarios involving land use change, contaminant source control, and implementation of stormwater treatment devices.

The baseline model has been successfully calibrated to local in-stream observations to predict daily flows and associated loads and concentrations for suspended sediment (SS), *E. coli*, total nitrogen (TN), nitrate – nitrogen (NO_3-N), ammoniacal – nitrogen (NH_4-N), total phosphorus (TP), dissolved reactive phosphorous (DRP), dissolved copper (dissolved Cu), and dissolved zinc (dissolved Zn).

Model parameterisation utilised data from literature sources, local in-stream monitoring, and previously developed average annual yield models. Development of this model utilised a range of applications, such as the customised contaminant load model for urban contaminants and daily SedNet for sediment generation processes.

The model generally performed well to represent the temporal and spatial variability of flow and contaminants and provides a robust framework for assessing a range of scenarios in the whaitua that may incorporate land use change and catchment specific water quality mitigation implementation.

Important note about your report

The sole purpose of this report and the associated services performed by Jacobs is to develop an integrated hydrological and contaminant model for the Te Awarua-o-Porirua (TAoP) 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.

In preparing this report, Jacobs has relied upon, and presumed accurate, certain information (or absence thereof) provided by GWRC and other sources. Except as otherwise stated in the report, Jacobs has not attempted to verify the accuracy or completeness of any such information. If the information is subsequently determined to be false, inaccurate or incomplete then it is possible that our observations and conclusions as expressed in this report may change.

Jacobs derived the data in this report from a variety of sources. The sources are identified at the time, or times, outlined in this report. The passage of time, manifestation of latent conditions or impacts of future events may require further examination of the project and subsequent data analysis, re-evaluation of the data, findings, observations and conclusions expressed in this report. Jacobs has prepared this report in accordance with the usual care and thoroughness of the consulting profession, for the sole purpose of the project and by reference to applicable standards, procedures and practices at the date of issue of this report. For the reasons outlined above, however, no other warranty or guarantee, whether expressed or implied, is made as to the data, observations and findings expressed in this report.

This report should be read in full and no excerpts are to be taken as representative of the findings. No responsibility is accepted by Jacobs for use of any part of this report in any other context.

This report has been prepared on behalf of, and for the exclusive use of, GWRC and the TAoP whaitua committee, and is subject to, and issued in connection with, the provisions of the agreement between Jacobs and GWRC. Jacobs accepts no liability or responsibility whatsoever for, or in respect of, any use of, or reliance upon, this report by any third party.

1. Introduction

In 2014, the Ministry for the Environment (MfE) published the National Policy Statement for Freshwater Management (NPSFM), amended in 2017 (MfE, 2017). This policy statement requires regional councils to set freshwater objectives (FWOs), targets, and limits for water quality constituents. Where limits are exceeded, the council is required to set targets and implement methods to meet those targets within a defined timeframe. The MfE 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) established the Te Awarua-o-Porirua Whaitua Committee (TAoPWC), a community group tasked with making recommendations for land and water management in the Te Awarua-o-Porirua Whaitua (catchment). The Whaitua committee will develop a Whaitua Implementation Programme (WIP), which will inform the proposed GWRC Natural Resources Plan (NRP).

Jacobs have been engaged by GWRC as part of TAoPW Collaborative Modelling Project (CMP), 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.

Jacobs have developed an integrated catchment flow and water quality modelling framework of the Porirua whaitua to assess in-stream water quality conditions. This model will be used for scenario modelling to explore likely water quality changes in response to land use changes and contaminant mitigation tools in the urban and rural environments. Model outputs are used directly by the Whaitua Committee and provide inputs into a coastal harbour model and economic models developed by other modelling partners within the CMP.

1.1 Purpose of this Report

This report documents the development of the integrated modelling framework for current conditions (baseline scenario), including:

- Data used to build the modelling framework;
- Model framework development and calibration for flow, suspended sediment, nutrients, metals, and *E. coli*; and
- Analysis of freshwater attribute states consistent with the NPSFM framework for nutrients and *E. coli*.

2. Catchment Model Configuration

2.1 Overview of Source model

As water quality is strongly dependent on the hydrological characteristics of a catchment, an integrated flow and water quality model was required. The available data inputs to the model were varied, including observed flow and water quality information on different spatial and temporal resolutions (i.e. 15 minute to daily), whilst contaminant models were represented as an annual average load. The eWater Source modelling framework was chosen to develop a robust integrated catchment water quality model.

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 sub-catchments which are composed of Functional Units (FU) that represent areas of similar hydrology and constituent generation, typically characterised through land use or rainfall-runoff response. Daily rainfall-runoff modelling calibrated using spatially-distributed historical climate data enables the representation of spatial and temporal variability in runoff and water quality generation from different land uses across the catchment. Flows and pollutants are routed through a node-link representation of the stream network (Figure 2.2). Contaminants generated at known point sources are also integrated.

The developed model predicts daily flows and associated loads and concentrations for Suspended Sediment (SS), *E. coli*, Total Nitrogen (TN), Nitrate – Nitrogen (NO_3-N), Ammoniacal – Nitrogen (NH_4-N), Total Phosphorus (TP), Dissolved Reactive Phosphorous (DRP), Total Copper (Total Cu), Dissolved Copper (Dissolved Cu), Total Zinc (Total Zn), and Dissolved Zinc (Dissolved Zn).

2.2 Model Configuration and Data Sources

Catchment model development involves several steps (Figure 2.1) that integrate the topographical and climatic data and existing land uses, to represent the spatial and temporal heterogeneity of the Porirua catchment characteristics. These steps include:

- Defining sub-catchment boundaries and the node-link network
- Assigning functional units
- Importing climate data
- Input of wastewater overflows
- Rainfall-runoff and constituent model configuration
- Model parameterisation

The necessary data collated from different sources are presented in Table 2.1.

Table 2.1: Data requirements for the Catchment model

Data utilised for Source catchment model	Data Source
River Environment Classification (REC) v2.3 GIS	NIWA
Catchment Land Use for Environmental Sustainability (CLUES) rural land use and contaminant yields	NIWA
Customised Contaminant Load Model (CLM) yields	Moores et al. 2017 (developed within the CMP)
GWRC GIS land use data	GWRC
Building footprints	Wellington City Council and Porirua City Council
Regional aerial imagery (2012 & 2013)	LINZ
Virtual Climate Station Network (VCSN) gridded daily rainfall and potential evapotranspiration (PET) data (5 km resolution)	NIWA
Rainfall and Evaporation gauged data	NIWA and GWRC
Wastewater overflow time-series and locations	Wellington Water
In-stream observed time-series data for flow, suspended sediment, nutrients, metals, and *E. coli*	GWRC

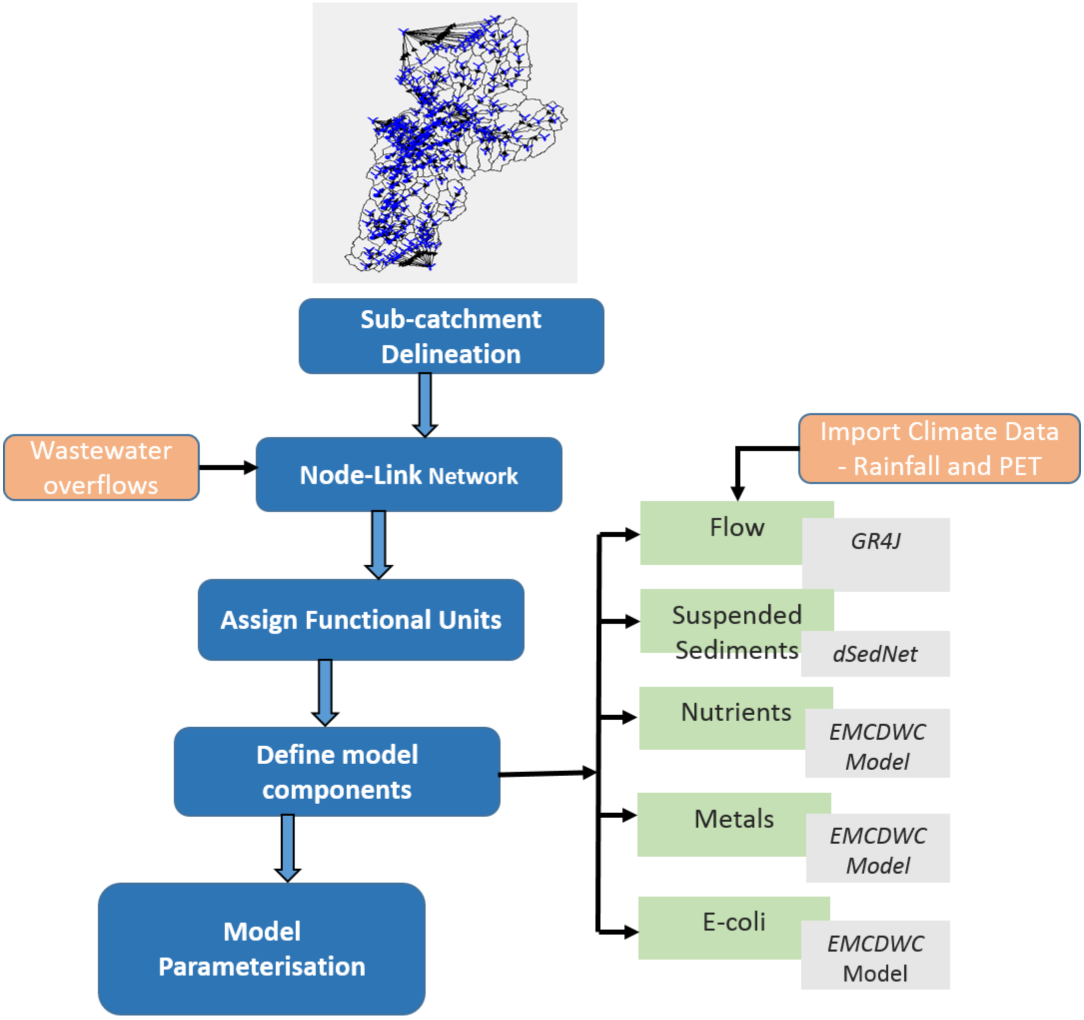

Figure 2.1: Porirua catchment conceptual Source modelling framework

2.2.1 Defining Sub-Catchment Boundaries and Node-Link Network

First, the sub-catchment boundaries and node-link network were defined. Sub-catchment boundaries for catchments that drain to Te Awarua-o-Porirua Harbour were derived from the River Environment Classification (REC) v2.3 database. A sub-catchment area of around 150 ha was adopted for the rainfall-runoff modelling, although smaller sub-catchments were delineated to facilitate inputs to the receiving harbour models. The node-link network was drawn within the Source software based on the REC 2.3 river network. The resulting sub-catchment delineation and node-link is illustrated in Figure 2.2.

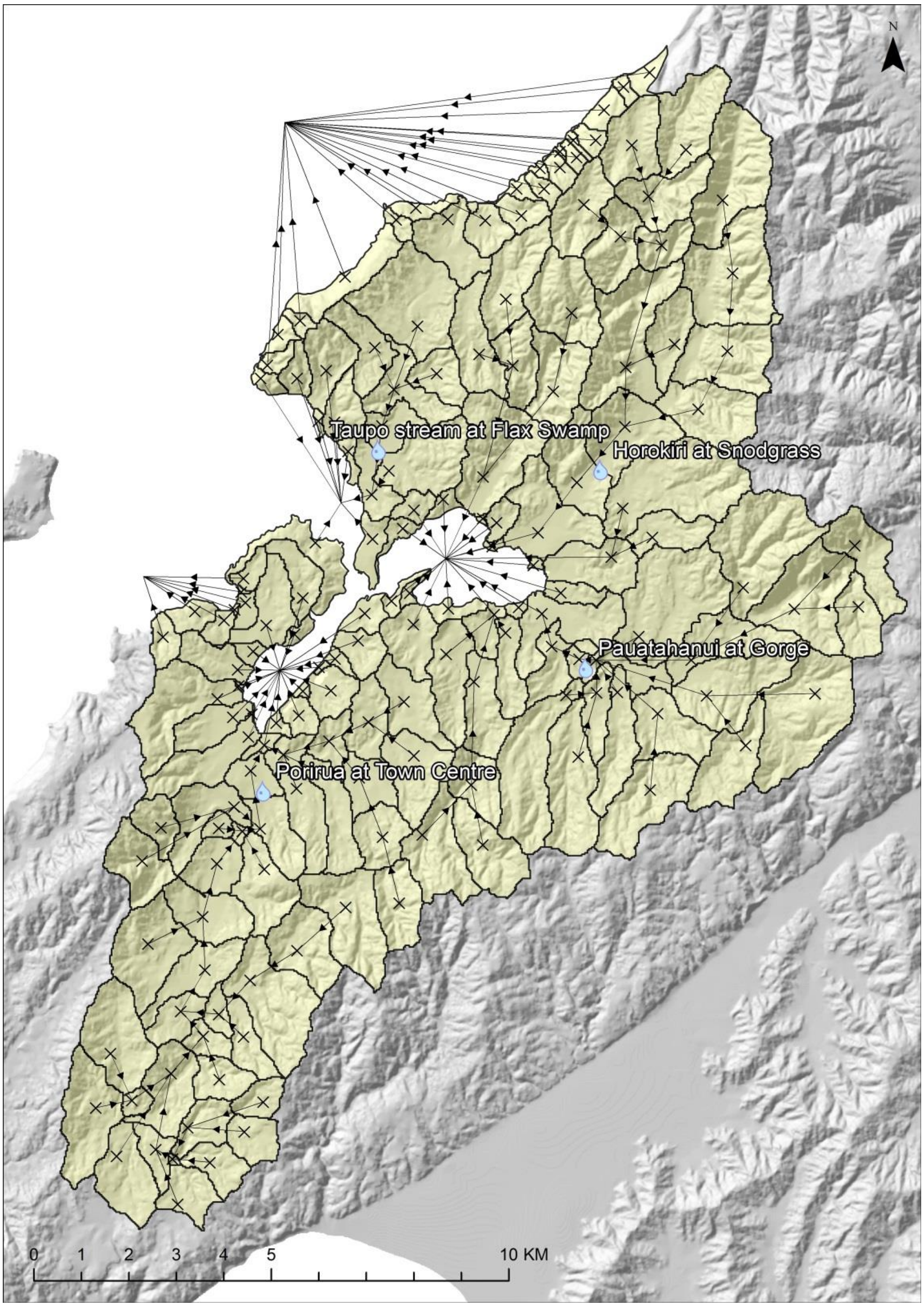

Figure 2.2: Sub-catchment boundaries, node-link network, and flow calibration sites

2.2.1 Functional Unit Characterisation

TAoPW extends to 20,235 ha. It is mostly dominated by rural land uses with grazed pasture, predominantly for sheep, accounting for 41% of the total area of the catchment followed by forest and scrub (33%) as shown in Figure 2.3. Other parts of the catchment are heavily urbanised particularly the Porirua stream, with 23% of the total catchment area comprised of roads, residential, industrial, commercial and urban greenspace land uses.

Functional Units (FUs) were defined for the study area with the Whaitua Modelling Lead Group (MLG) based on a combination of GWRC held land use and zoning information, Porirua City Council (PCC) and Wellington City Council (WCC) building data, CLUES land use data, and satellite imagery classification. The rural/urban divide has been determined by Jacobs using data from GWRC.

23 FUs were identified and assigned based on land use in the model. Table 2.2 lists the FUs assigned in the model and their conceptual group. Figure 2.3 shows the distribution of the conceptual groups within the catchment. Figure 2.4 maps the functional units across the catchment.

The detailed FU mapping represents a 'snapshot' of current land use that is held static during each model run, while rainfall and PET is variable and simulated at a daily time-step based on climate information. During scenario modelling, FUs will be changed to examine how in-stream water quality will change under different land use configuration possibilities.

Roofs

Urban roof area is assumed to be equivalent to building footprint GIS datasets from PCC[1] and WCC[2]. Roofs have been assigned as Residential, Commercial, or Industrial based on local authority zoning information.

Roads

Road areas were determined by buffering a road centreline GIS layer held by Jacobs based upon the number of lanes. Checks against aerial photos were carried out, with minor edits undertaken, e.g. to remove walkways and paper roads. Unsealed roads and pedestrian accessways were not included. Vehicle Per Day (VPD) categories for constituent generation have been derived from the Jacobs SATURN traffic model (2011 baseline).

Urban paved surfaces and grasslands and trees

Paved surfaces and urban grasslands and trees have been defined using supervised aerial imagery classification in ArcGIS from LINZ 0.3 metre resolution imagery captured in 2012 and 2013. Zoning of defined paved surfaces is based on local authority zoning information. Where not defined, paved surfaces are assumed to be residential.

Rural

Rural land use has been derived from CLUES land use information provided by NIWA.

[1] Porirua Building Footprints. 2012. https://koordinates.com/layer/6612-porirua-building-footprints/
[2] Wellington City Building Footprints. 2012. https://koordinates.com/layer/1474-wellington-city-building-footprints/

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Table 2.2: Source Functional Units

Functional Unit	Conceptual Group
Commercial Roof	Commercial & Industrial
Commercial Paved	Commercial & Industrial
Industrial Roof	Commercial & Industrial
Industrial Paved	Commercial & Industrial
Residential Roof	Residential
Residential Paved	Residential
Roads (<1000 VPD)	Roads
Roads (1000 – 5000 VPD)	Roads
Roads (5000 – 20000 VPD)	Roads
Roads (20000 – 50000 VPD)	Roads
Roads (50000 – 100000 VPD)	Roads
Natural Forest	Forest & Scrub
Plantation Forest	Forest & Scrub
Scrub	Forest & Scrub
Urban Grassland	Urban Greenspace
Deer	Grazed Pasture
Sheep & Beef (hill country)	Grazed Pasture
Sheep & Beef (lowland intensive)	Grazed Pasture
Other Animals	Lifestyle & Other
Horticulture	Lifestyle & Other
Other	Lifestyle & Other
Construction Site	Construction
Water	-

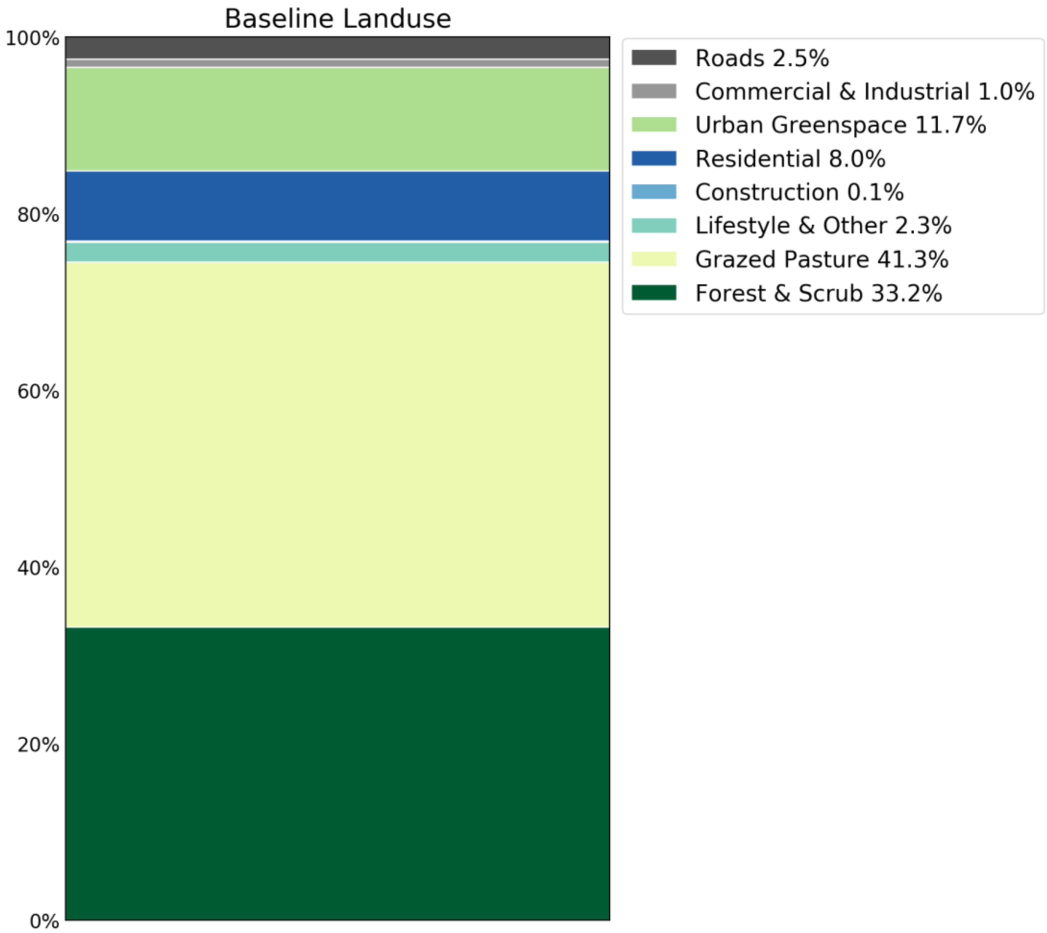

Figure 2.3: Baseline model land use categories (FUs aggregated to conceptual group)

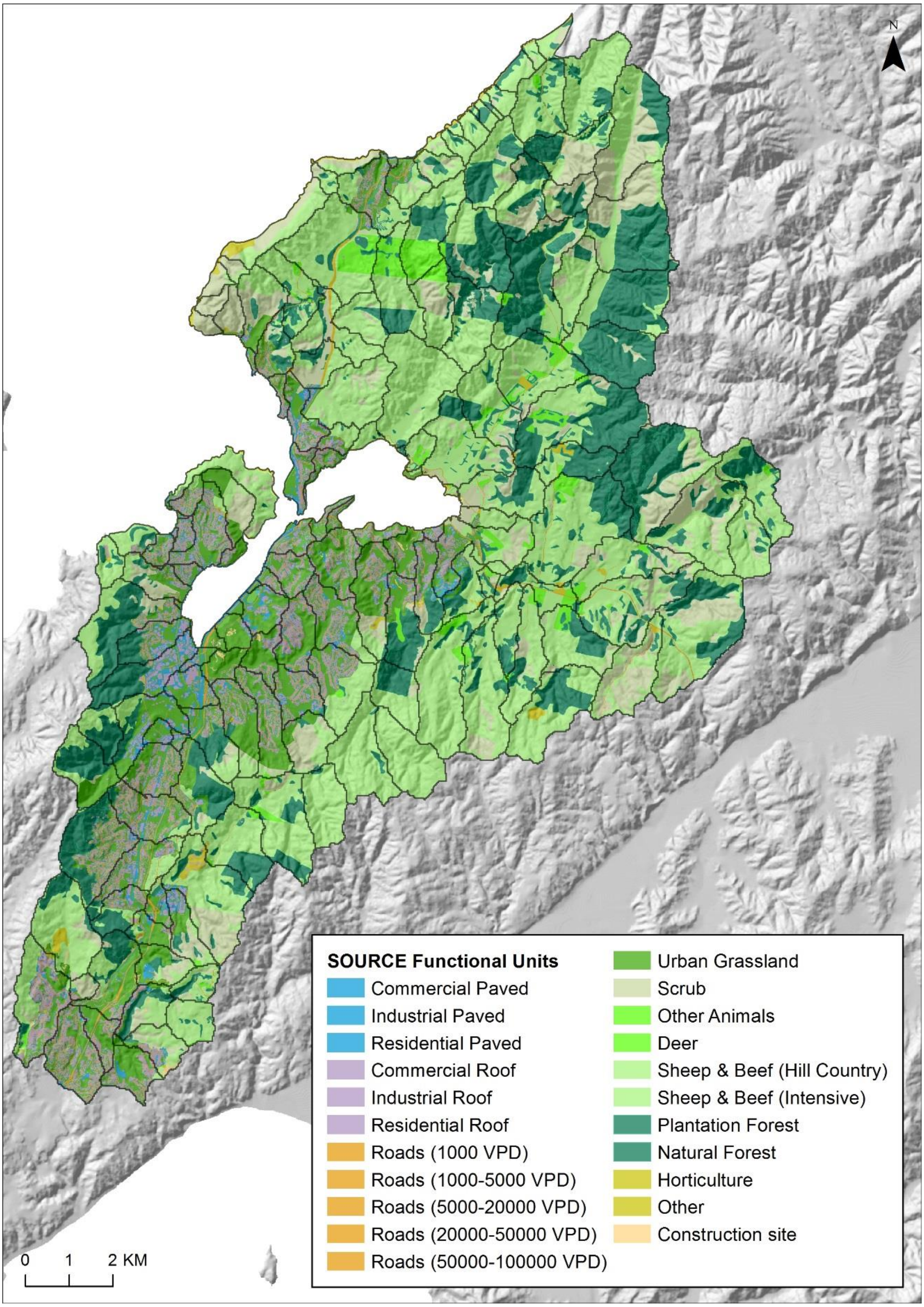

Figure 2.4: Land use categories and functional units in Source

2.2.2 Climate Information

Spatially gridded rainfall and potential evapotranspiration (PET) data at 5 km x 5 km resolution was obtained from NIWA's Virtual Climate Station Network (VCSN) (Tait et al., 2012). VCSN data has been reformatted into ASCII grids for input to the Source model. The Source model then calculates the spatial average daily rainfall and PET from the VCSN grids for each sub-catchment. The VCSN time-series is between 1972 and 2016, inclusive.

2.2.3 Wastewater overflows

The location and frequency of wastewater overflows were modelled in MOUSE by Mott MacDonald for Wellington Water. The provided time-series predicts wastewater overflow volumes at 223 locations for a 10-year period between 2005 and 2014 inclusive, chosen as representative of a range of climatic conditions (Figure 2.5). These predicted wastewater overflows were then represented in the Source model as point-source daily time-series, aggregated at the sub-catchment scale to 48 overflow locations. Average wastewater concentrations for sediment, nutrients, *E. coli,* and metals based on literature (Metcalf and Eddy, 2014) were provided by Wellington Water and are given in Table 2.3. [3]

Table 2.3: Wastewater overflow constituent concentration

Constituent	Average Concentration
Suspended Sediment	248 mg/l
Total Nitrogen	46 mg/l
Nitrate Nitrogen	0 mg/l
Ammoniacal Nitrogen	25 mg/l
Total Phosphorus	6 mg/l
Dissolved Reactive Phosphorus	5 mg/l
E. Coli	1,000,000 cfu/100ml
Copper (Total and Dissolved)	0.077 mg/l
Zinc (Total and Dissolved)	0.48 mg/l

[3] The average concentrations provided are for undiluted wastewater, however dilution is likely to occur during an overflow event. Modelled concentrations can therefore be considered conservative.

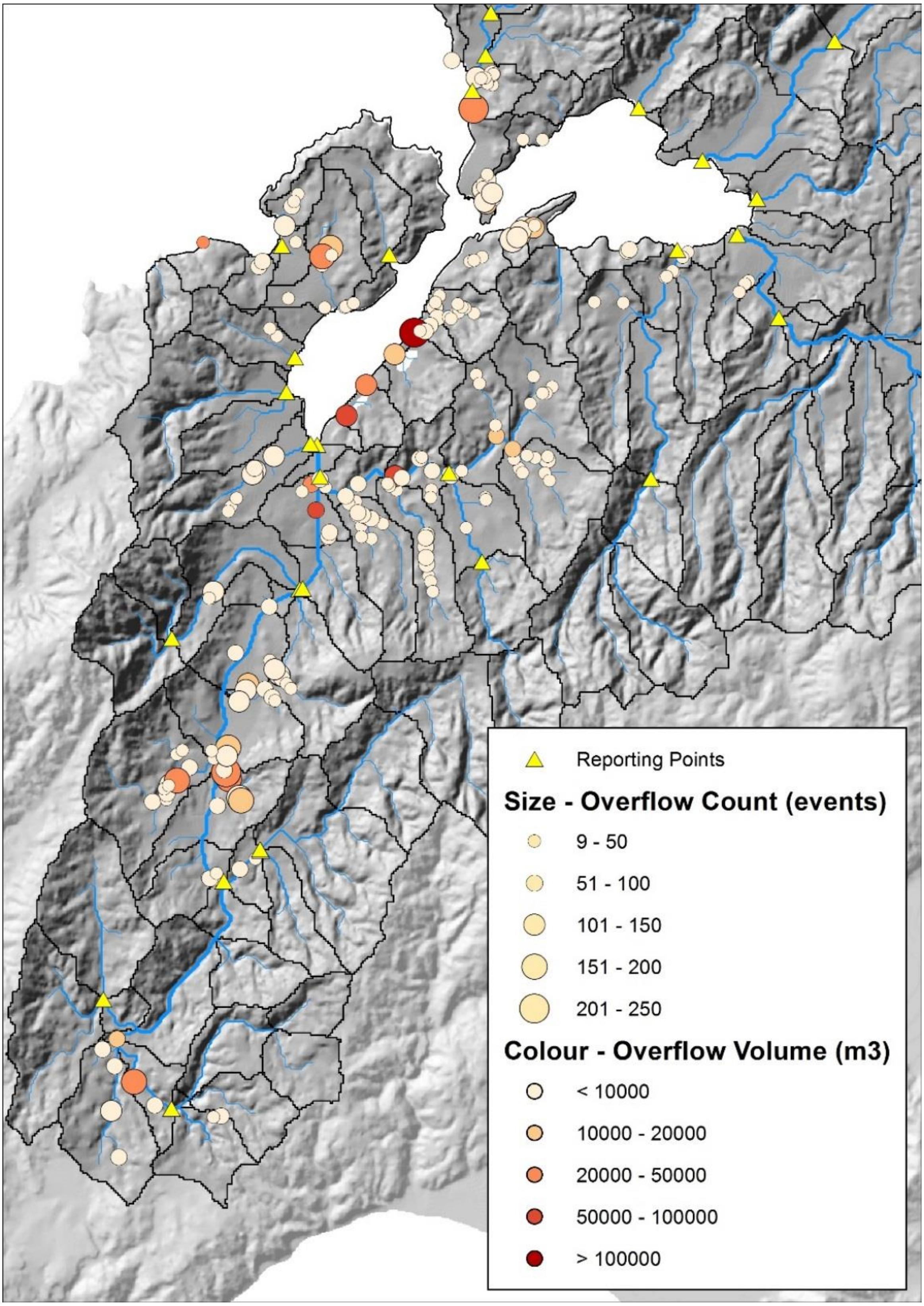

Figure 2.5: Wastewater overflow locations

2.2.4 Flow and constituent model configuration

The Source framework allows the user to combine different rainfall-runoff and constituent sub-models. For this project, rainfall-runoff response was modelled using the GR4J sub-model, and constituents were simulated by means of dSedNet for sediment, and the Event Mean Concentration (EMC) and Dry Weather Concentration (DWC) module for all other contaminants. Details of these modules are described in the respective constituent chapters.

2.2.5 Model parameterisation and calibration

Model parameterisation and data used for calibration are explained in the respective constituent chapters. This section provides an overview of the approach applied to help define input parameters and ultimately calibrate the model. In urban areas, model parameterisation draws heavily from the customised CLM yields developed in the first phase of the TAoPW modelling programme (Moores et al. 2017). In rural areas, model parameterisation is informed by yields derived from CLUES, supplied by NIWA. Observed data for flow, suspended sediment (SS), nutrients, metals and *E. coli* were sourced from GWRC. In general, the water quality data are monthly spot-samples taken for the purpose of state of the environment monitoring. For suspended sediment, sub-daily turbidity information was available.

Calibration performance measures and objective functions generally follow the guidance in Moriasi et al. (2007). Flow calibration aimed to match the observed mean daily flow using Mean Annual Low Flow (MALF), Nash Sutcliffe Efficiency (NSE), and Percent Bias (PBIAS) statistics, and compared for 5, 10, 20, and 50-year Average Return Interval (ARI) events. For SS, calibration aimed to match to the daily load, calculated from sub-daily turbidity and flow observations, using NSE, PBIAS, mean, median, 5^{th} percentile and 90^{th} percentile annual and daily loads. For nutrients, metals, and *E. coli*, calibration initially aimed to match the in-stream observed concentration (monthly spot-sample) to the modelled concentration for that date using PBIAS, mean, median, 5^{th} percentile and 95^{th} percentile concentration comparisons. A successful calibration for *E. coli* was achieved in this manner.

For nutrients and metals, an adequate match to the monthly spot-sample data was unable to be achieved without the use of localised parameter sets. Instead, the monthly mean from the modelled time-series was matched to the observed monthly spot-sample to achieve a satisfactory calibration using global EMC/DWC parameters. This is advantageous for scenario modelling as relative changes in contaminant yield following land use change will be consistently represented across the whaitua.

3. Baseline Flow Model

Source provides a library of rainfall-runoff models for hydrological model development. The GR4J (Perrin et al., 2003) model was selected based on its strong performance in numerous settings around the world (Perrin et al., 2003; Vaze et al., 2011), its parameter parsimony, and previous rainfall-runoff modelling with GR4J for the Porirua stream catchments that produced a well calibrated model.

GR4J is a conceptual daily time-step rainfall-runoff model which can be applied in a lumped or semi-distributed fashion. The structure of GR4J is illustrated in Figure 3.1; rainfall can be discharged to two stores, a production store (x_1) and a routing store (x_3) or routed overland. Water stored in the routing store is partitioned into quick (overland flow) and slow flow (baseflow) components which are routed by a unit hydrograph for each partition, the time base of which is controlled by x_4. Water can also be exchanged (gained or lost) from a conceptual groundwater store which is represented by x_2.

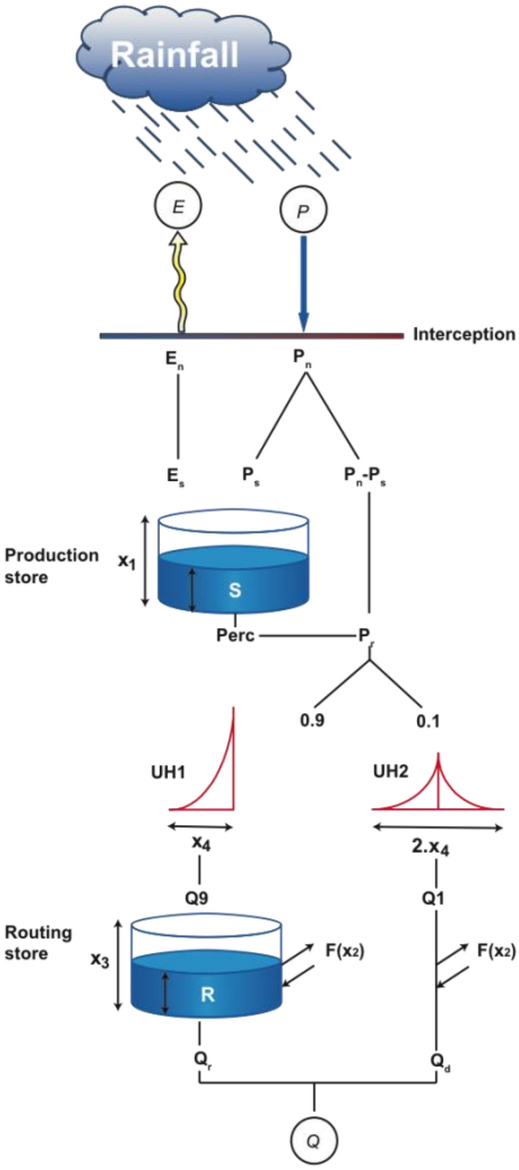

Figure 3.1: GR4J Rainfall-Runoff schematic (eWater, 2015)

3.1 FUs and Metagroups

As described in section 2.2.1, 23 FUs were assigned in the model. These FUs were grouped into 5 rainfall runoff meta-parameter groups (Table 3.1) of similar hydrological characteristics to facilitate calibration.

Table 3.1: Mapping of Source FU to Rainfall Runoff parameter group

Functional Unit	Rainfall Runoff meta-parameter group
Commercial Roof	Impervious
Commercial Paved	Impervious
Industrial Roof	Impervious
Industrial Paved	Impervious
Residential Roof	Impervious
Residential Paved	Impervious
Roads (< 1000 VPD)	Impervious
Roads (1000 – 5000 VPD)	Impervious
Roads (5000 – 20000 VPD)	Impervious
Roads (20000 – 50000 VPD)	Impervious
Roads (50000 – 100000 VPD)	Impervious
Natural Forest	Forest
Plantation Forest	Forest
Urban Grassland	Scrub & Grass
Scrub	Scrub & Grass
Deer	Scrub & Grass
Sheep & Beef (hill country)	Scrub & Grass
Sheep & Beef (lowland intensive)	Scrub & Grass
Other Animals	Scrub & Grass
Horticulture	Horticulture & Other
Other	Horticulture & Other
Construction Site	Construction
Water	nil Runoff

3.2 Flow Calibration Approach

Four flow gauge sites were chosen for hydrological calibration (Figure 2.2):

1) Porirua Stream at Town Centre,
2) Pauatahanui at Gorge,
3) Horokiri at Snodgrass, and
4) Taupo at Flax Swamp.

The cumulative upstream area contributing to these gauges is 11,519 ha, accounting for 57% of the total modelled area of 20,234 ha. Model flow is compared to the mean daily flow recorded at the calibration sites. Table 3.2 shows the observed data range, calibration, and validation period for each site. The warm-up period for each site was between the beginning of the data period and beginning of the calibration period.

Table 3.2: Rainfall-Runoff calibration periods

Site	Data period	Calibration period	Validation period
Horokiri at Snodgrass	16/02/2002 - 19/08/2016	14/01/2004 - 2/11/2010	3/11/2010 - 19/08/2016
Pauatahanui at Gorge	31/05/1975 - 31/12/2016	14/03/1980 - 31/12/1999	1/01/2000 - 31/12/2016
Taupo at Flax Swamp	18/08/1979 - 8/02/2016	7/08/1984 - 31/12/1999	1/01/2000 - 8/02/2016
Porirua at Gorge	1/01/1972 - 20/09/2016	31/12/1977 - 31/12/1999	1/01/2000 - 20/09/2016

Initially, the Source automatic calibration tool was used to calibrate the flows at each gauge, using a combined log flow duration curve Nash-Sutcliffe Efficiency (NSE) and daily NSE statistic (Nash & Sutcliffe, 1970) (equal weighting). Following automatic calibration, some parameters were manually calibrated where necessary to ensure that values across parameter groups maintained expected physical relativity. The simulated catchment flows at the four flow gauge locations were assessed for performance against observed and gauged data using the following statistical analyses:

- Comparison of daily flows using summary statistics:
  - NSE statistic (Nash & Sutcliffe, 1970). NSE is a measure of goodness-of-fit, where less than 0 is poor, 0 indicates an equivalent fit to using the mean of the observed data, and 1 is a perfect fit to observed data;
  - Percent bias (PBIAS) (Gupta et al. 1999). PBIAS is the deviation of data being evaluated, expressed as a percentage. The optimal value is 0, with low-magnitude values indicating accurate model simulation.
  - Mean Annual Flow (MAF) and 7-day Mean Annual Low Flow (MALF).
- Comparison of observed and simulated flow duration curves.
- Comparison of observed and modelled annual maxima at key Annual Recurrence Intervals (ARI) as an evaluation of simulated peak flows. ARIs were calculated using Hilltop software.

Wastewater overflow information was not available at the time of flow calibration. The additional flow associated with wastewater overflows is not expected to be significant.

3.3 Flow Calibration Results

Moriasi et al. (2007) suggests that streamflow model simulations are deemed satisfactory if the NSE statistic is greater than 0.6 and PBIAS is ± 25%. Horokiri at Snodgrass and Pauatahanui at Gorge sites fall within the ‘good’ calibration criteria (Table 3.3), however for the Porirua at Town Centre and Taupo at Flax Swamp sites NSE is slightly lower than 0.6 and fall within the ‘satisfactory’ criteria. Both are heavily urbanised catchments and may be influenced by ‘flashy’ hydrology that is challenging to simulate with a daily model. Nevertheless, for the validation period all sites achieved a ‘good’ calibration criteria.

The flow duration curves for each calibration site for the calibration and validation periods (Figure 3.2 to Figure 3.9) demonstrates that the model generally simulates high to medium flows well, but underestimates low flows. This can be observed in the comparison of the daily modelled and observed flow time-series (Appendix A). Underestimation of low flows is acceptable in this context as the assessment of constituent loads will be driven by peak flow events within the catchment, particularly in urban areas. Therefore, calibration focused on achieving a good fit to peak flows.

The Flood Frequency analysis (Table 3.3) shows that the calibrated model can adequately replicate the 10 and 5-year ARI events. Calibration to these high flow events is important in capturing the high flows that transport the majority of contaminant loads to receiving waterbodies. However, the model generally underestimates flood events with a greater than 20-year ARI.

Overall, validation results indicate that the model replication of the observed flow record is acceptable, with all sites achieving a 'good' calibration (as indicated by the NSE statistic and PBIAS results).

Table 3.3: Flow calibration results

Period	Measure	Horokiri at Snodgrass		Pauatahanui at Gorge		Porirua at Town Centre		Taupo at Flax Swamp	
		OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM
Calibration	MAF (m^3/s)	207.9	259.0	246.0	250.0	262.4	301.0	27.4	34.0
	Mean MALF (m^3/s)	0.08	0.07	0.09	0.04	0.15	0.07	0.01	0.01
	NSE	0.73		0.70		0.53		0.55	
	PBIAS	25%		2%		15%		25%	
	NSE Flow duration curve	0.98		0.98		0.95		0.85	
	Combined NSE / NSE flow duration curve	0.86		0.84		0.74		0.70	
Validation	MAF (m^3/s)	188.1	200.0	244.5	238.0	266.6	266.0	34.6	37.0
	Mean MALF (m^3/s)	0.09	0.05	0.09	0.04	0.15	0.06	0.01	0.00
	NSE	0.71		0.74		0.63		0.65	
	PBIAS	6%		-3%		0%		7%	
	NSE Flow duration curve	0.85		1.00		0.95		0.85	
	Combined NSE flow duration curve	0.78		0.87		0.79		0.75	
Flood Frequency	50 ARI (m^3/s)	28.8	22.6	28.9	26.0	24.8	19.7	3.98	4.6
	20 ARI (m^3/s)	23.7	19.0	24.4	22.0	20.1	17.0	3.36	3.9
	10 ARI (m^3/s)	19.7	16.1	21.0	19.0	16.8	14.8	2.89	3.3
	5 ARI (m^3/s)	15.6	13.2	17.41	15.8	13.6	12.6	2.39	2.8

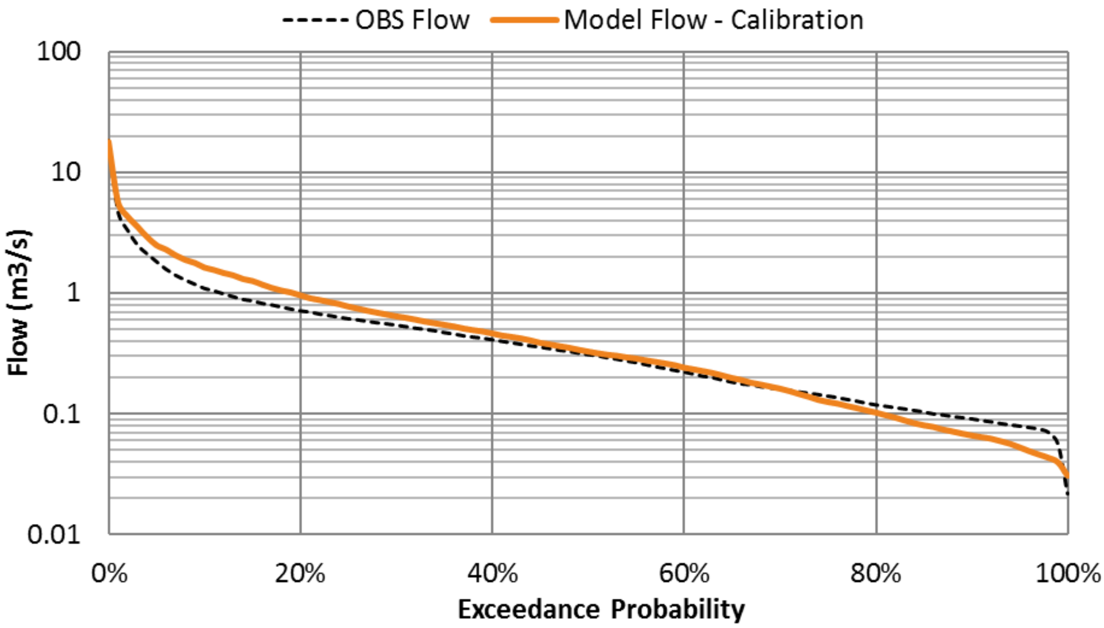

Figure 3.2: Horokiri at Snodgrass Calibration Flow Duration Curve

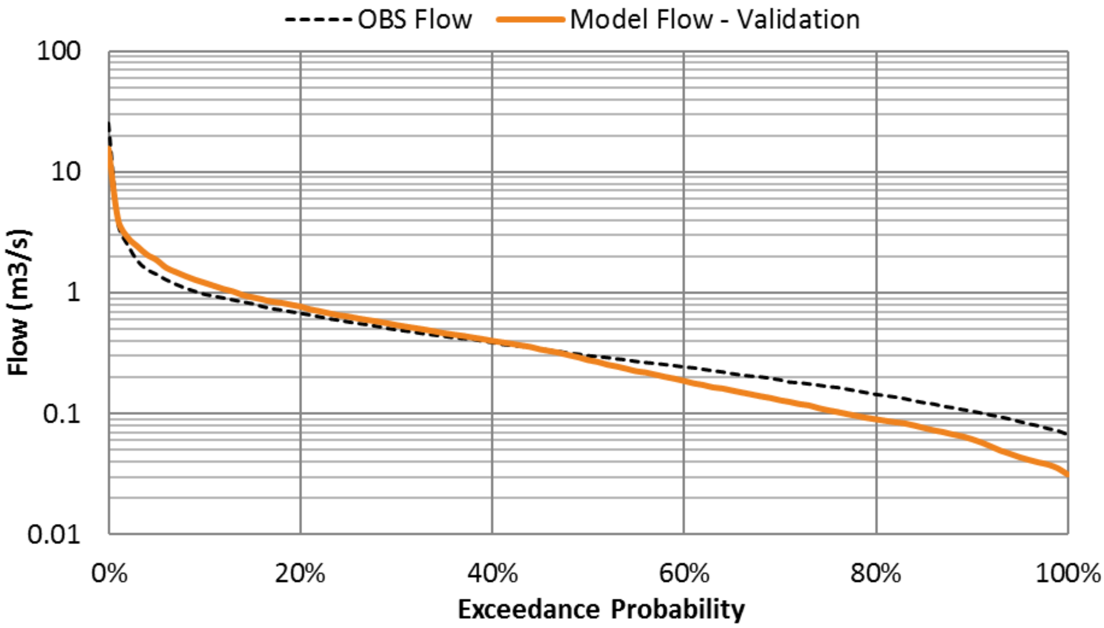

Figure 3.3: Horokiri at Snodgrass Validation Flow Duration Curve

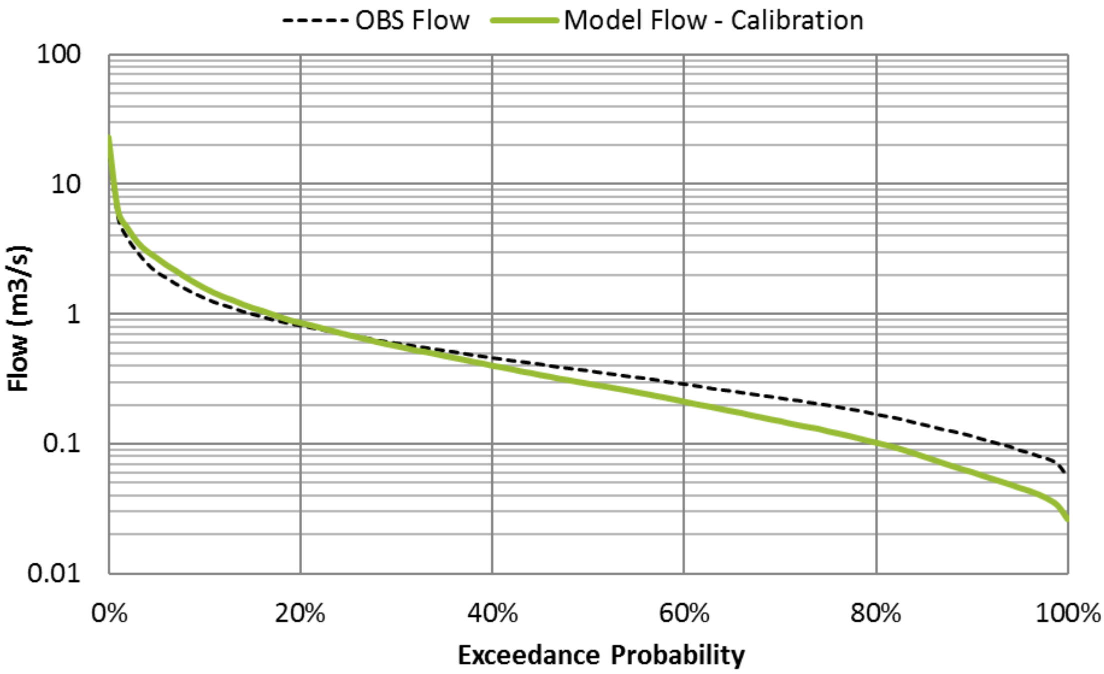

Figure 3.4: Pauatahanui at Gorge Calibration Flow Duration Curve

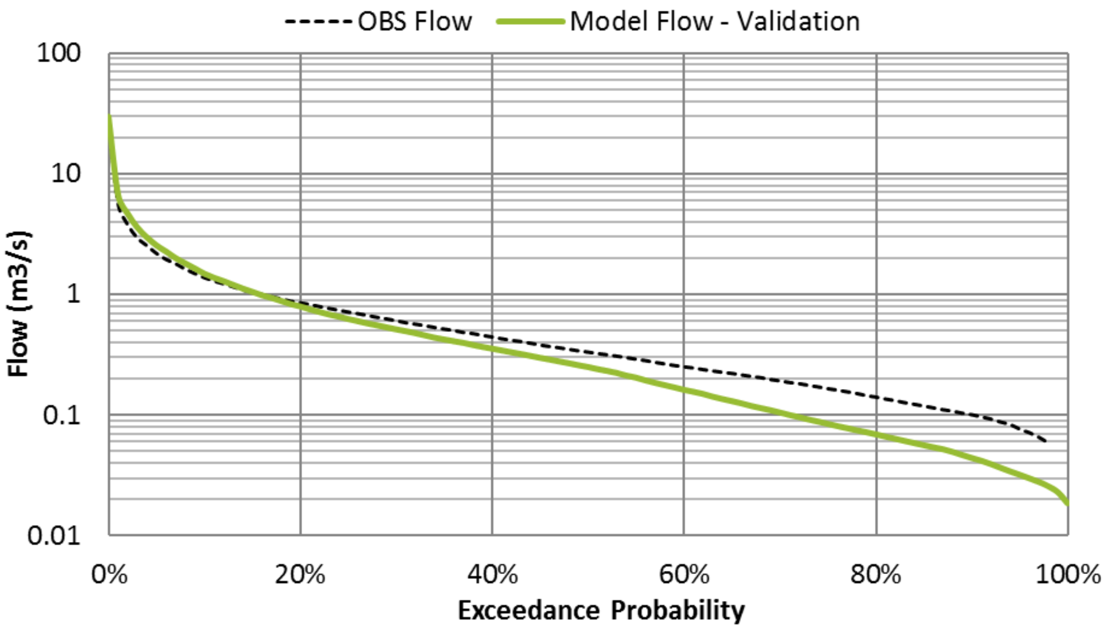

Figure 3.5: Pauatahanui at Gorge Validation Flow Duration Curve

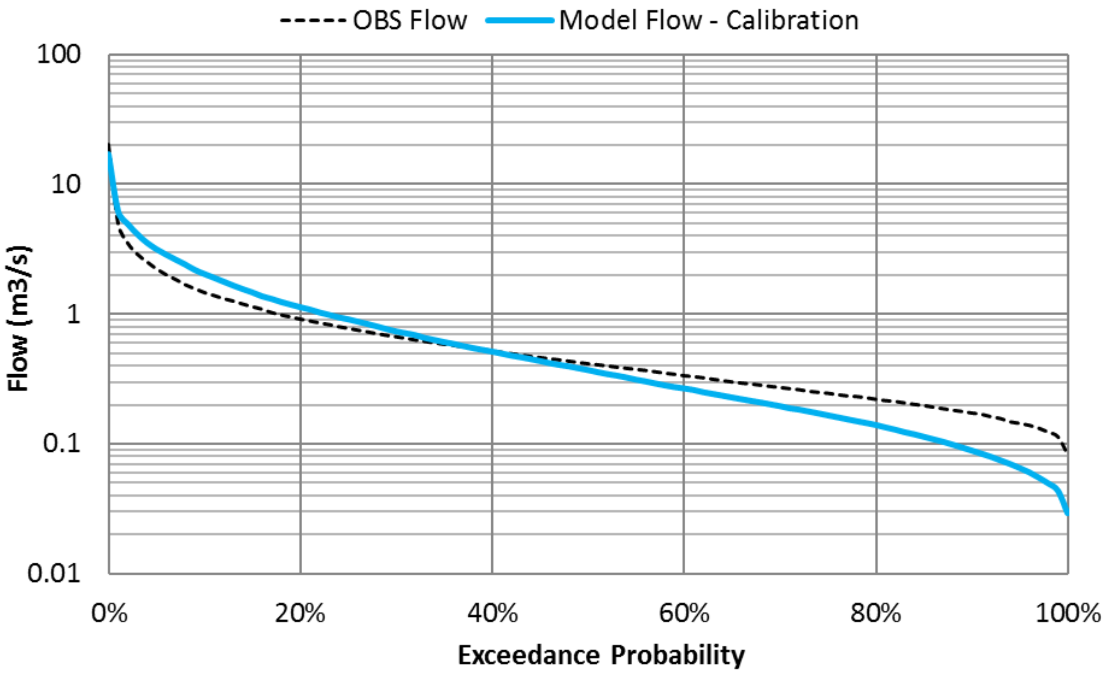

Figure 3.6: Porirua at Town Centre Calibration Flow Duration Curve

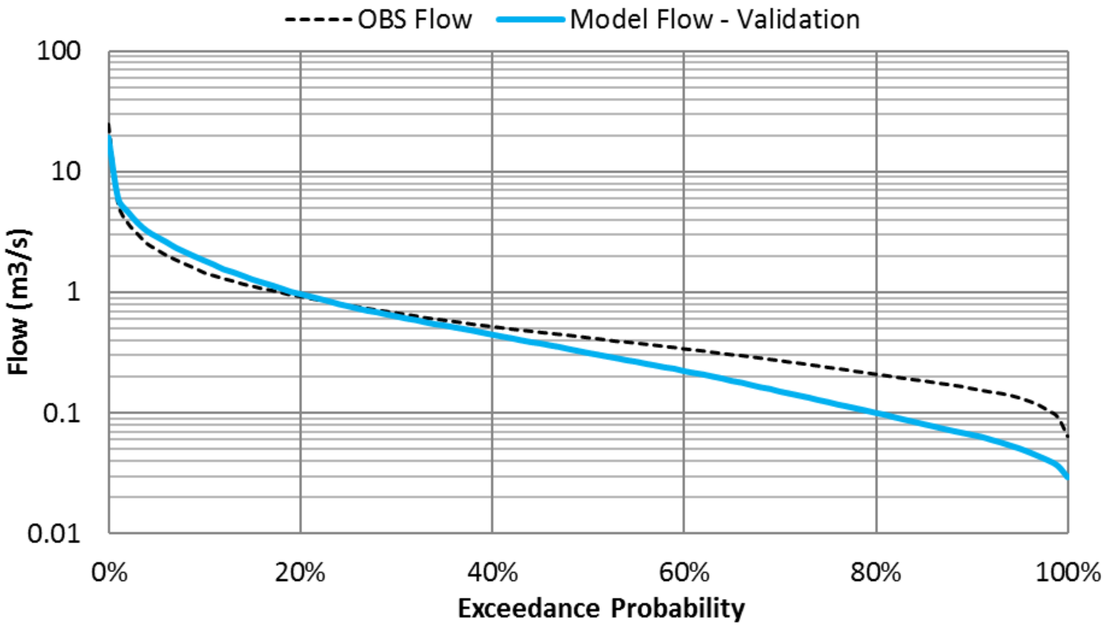

Figure 3.7: Porirua at Town Centre Validation Flow Duration Curve

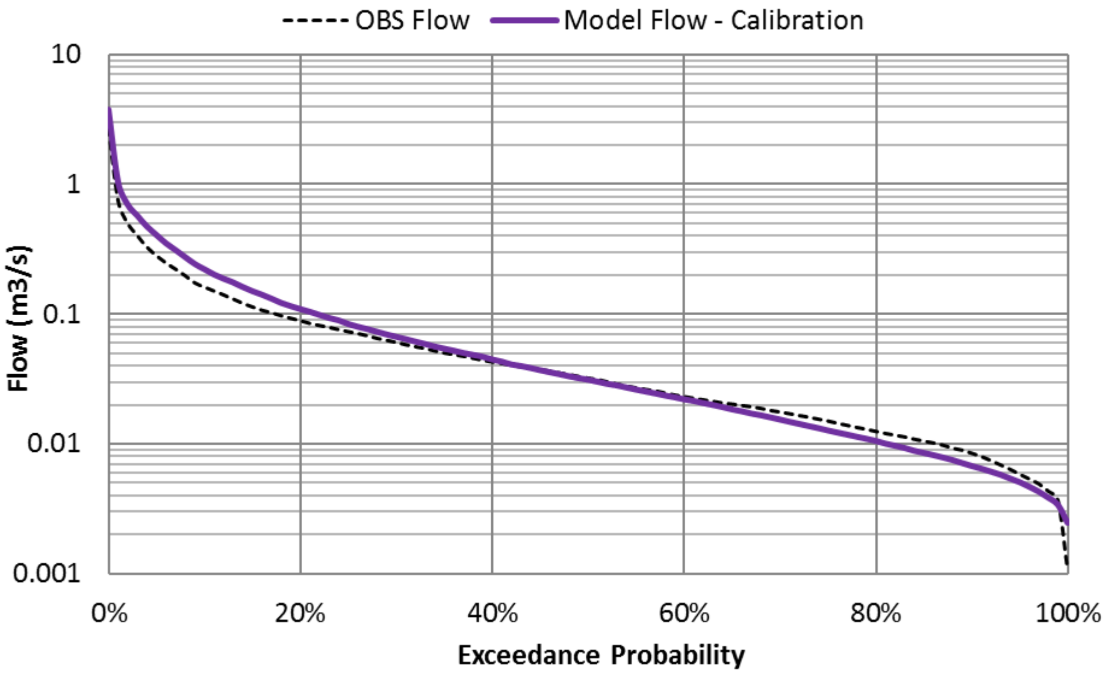

Figure 3.8: Taupo stream at Flax Swamp Calibration Flow Duration Curve

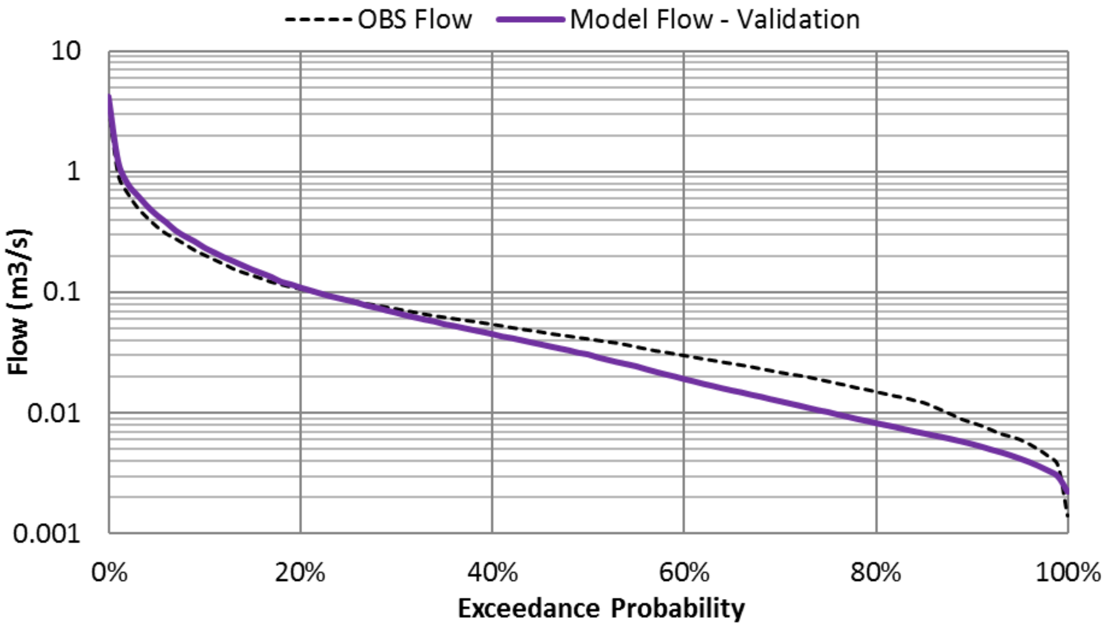

Figure 3.9: Taupo stream at Flax Swamp Validation Flow Duration Curve

4. Baseline Sediment Model

4.1 Model Configuration

Suspended Sediment (SS) load generation has been simulated for surficial erosion (hillslope erosion), streambank erosion, and shallow landslide processes. Additional suspended sediment load in urban areas from modelled wastewater overflow data has also been applied for the period 2005-2015.

4.1.1 Surficial Erosion

Surficial erosion is simulated using the Source dSedNet plugin. The dSedNet hillslope module implements a spatially distributed form of the Revised Universal Soil Loss Equation (RUSLE), which predicts surficial erosion according to:

$$E = R \times K \times S \times L \times C \times P$$

Equation 4.1

where *E* is the soil erosion per unit area (t/ha/year);

R is the rainfall erosivity (EI30) (MG.mm/ha.h.day);

K is the soil erodibility (t.ha.h/ha.MJ.mm);

S is slope steepness (dimensionless);

L is slope length (dimensionless);

C is cover management factor (dimensionless); and

P is the practice factor (conservation measures) (dimensionless).

The product of the K, L, S, and C factors are imported into dSedNet as a raster grid (4 m resolution). The P factor is related to farm management practices (contouring, terracing etc.); because there is negligible arable farmland in the project catchments, the P factor is assumed to be equal to 1.

The rainfall erosivity factor (R) is calculated within Source for each day using NIWA VCSN rainfall data:

$$EI30 = \propto \times (1 + \eta \times TimeOfYearFactor) \times R^{\beta}, when\ R > R_0$$

Equation 4.2

where *EI30* is daily rainfall erosivity (MJ.mm/ha.h);

R is daily rainfall amount (mm);

R_0 is the threshold rainfall amount (12.7 mm);

η is time of year scaling factor;

β is an erosion scaling factor;

α is a calculated constant – utilised as a calibration factor; and

Time of Year Factor determines the peak intensity.

4.1.2 Sediment Delivery Ratio

A sediment delivery ratio (SDR) is commonly used to account for the proportion of eroded sediment that reaches the stream network. In New Zealand, an SDR of 0.5 is generally accepted (ARC, 2014). Globally, an SDR based on catchment area is widely used because of its simplicity (Lim et al., 2005).

A generalised SDR power function based on catchment area derived has been developed by the American Society of Civil Engineers (Vanoni, 1975, reported in Lim et al., 2005):

$$SDR = 0.4724\ A^{-0.125}$$

Equation 4.3

where *A* is watershed area (km^2).

Equation 4.3 has been applied to the project catchments at the scale of the River Environments Classification 2 (REC2) sub-catchments. The calculated SDR ranges between 0.44 and 0.99 for the project catchments, with a mean of 0.56.

4.1.3 Streambank Erosion

Streambank erosion is related to high-flow events and has been modelled simplistically using a custom function that relates streambank SS load to flow in each link where applied. The custom function calculates streambank erosion as:

$$SE\ =\ aQ^b, when\ Q \geq MF$$

Equation 4.4

where *SE* is streambank suspended sediment load (kg/day);

a is the calibrated constant;

b is the calibrated exponent;

Q is the modelled link flow (m^3/s); and

MF is the 2.33 ARI flow for the modelled reach.

Equation 4.4 has been applied to all links for catchments containing second-order or higher streams, where streambank erosion is more likely to occur. Streambank erosion load is calibrated to annual loads calculated following Dymond *et al.* (2016) (see section 4.2.1). Mean annual flood for each link is estimated as the 99.8th percentile flow due to model architecture limitations (Figure 4.1).

Reduction of streambank erosion to account for stabilisation from existing stock exclusion (fencing) and riparian vegetation has been applied in a spatially weighted manner. A GIS layer of existing vegetated riparian margins was developed from the REC2 stream reach information and satellite imagery (acquired in 2012) in collaboration with the GWRC. The vegetated proportion of eroding stream lengths is also assumed to exclude stock via fencing. This riparian managed length has a load reduction of 80% applied to the generated streambank load (Equation 4.4) following Mueller & Dymond (2015). It is expected that the impact of different riparian planting regimes on sediment load will be investigated during scenario testing, therefore it was important to establish existing riparian and stock exclusion areas.

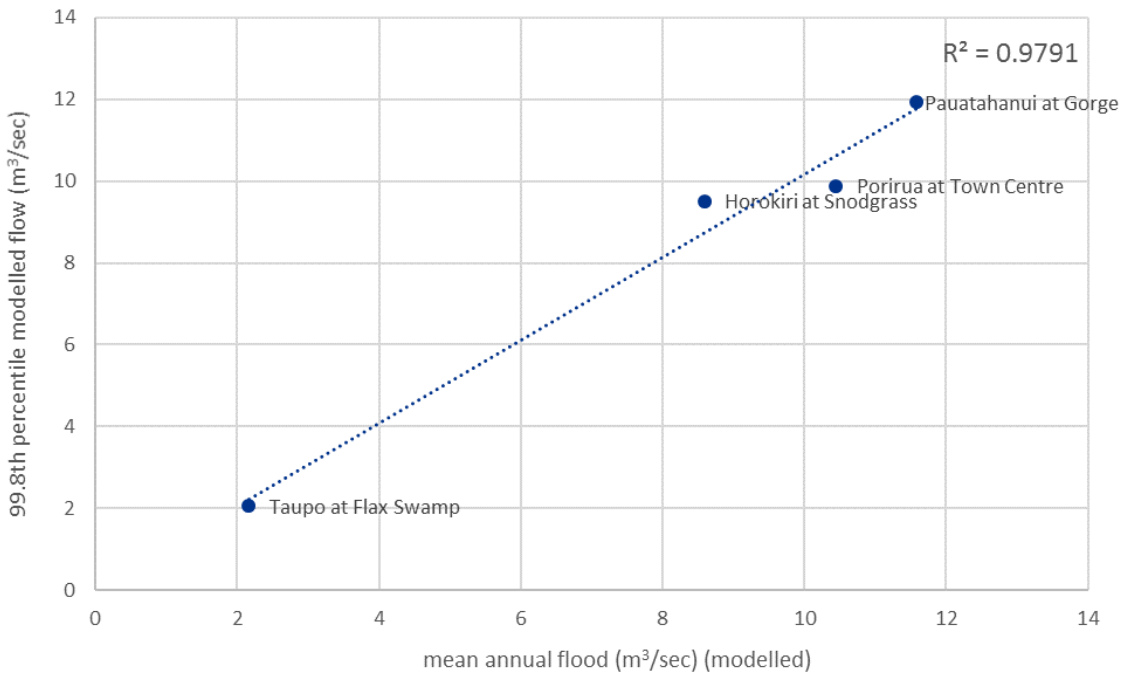

Figure 4.1: Relationship between mean annual flow and 99.8th percentile flow

4.1.4 Landslide Erosion

Observed data shows that landslides are a significant contributor to sediment delivery to the Porirua Harbour. Work in New Zealand shows that landslides are generally confined to steep slopes greater than 26 degrees (DeRose 1995, 1996, 2013; Dymond et al. 2016), with the highest number of landslides per area occurring in pastureland (Glade, 1998). A simple approach has been adopted in the model as a rainfall-triggered power function to represent shallow landslides, applied to all rural grassland and scrub and urban grassland FUs that occur over steep land as defined by the NZLRI (> 26 degrees).

$$LE = aQ_{quick}{}^{b}, when\ R_3 \geq threshold$$

Equation 4.5

where LE is the Landslide Erosion SS concentration generated (mg/l);

a is the calibrated constant;

b is the calibrated exponent;

Q_{quick} is the modelled FU generated quick flow (m^3/s);

R_3 is the average rainfall over the preceding 3 days;

threshold is the rainfall threshold; 30 mm has been adopted.

4.2 Sediment Calibration Approach

Daily suspended sediment loads have been calibrated to observed data recorded by GWRC at three sites: Porirua Stream at Town Centre, Pauatahanui Stream at Gorge, and Horokiri Stream at Snodgrass. Continuous turbidity at these sites have been converted to suspended sediment concentration (SSC) using the formulae presented in Morar & Oliver (2016). The longest record is for Porirua at town Centre (Table 4.1). No validation period was used due to the short observation records. Calibration encompassed hillslope, streambank, and landslide processes, aimed to minimise the daily PBIAS and match daily mean, median, 5th percentile, 90th percentile, and exceedance probability curve to observed daily load values.

The surficial erosion component was calibrated first, accounting for baseflow and small-medium events (i.e. where flows are below the 2.33 ARI event trigger for the streambank function). The streambank erosion and landslide components were then calibrated with the aim to match peak loads that were underestimated by the surficial erosion component only.

Table 4.1: Observed turbidity record

Site Name	Observed turbidity record	Calibration / validation
Porirua at Town Centre	1/05/2012-21/07/2016	Calibration
Horokiri at Snodgrass	01/06/2013-21/07/2016	Calibration
Pauatahanui at Gorge	13/06/2013-07/09/2016	Calibration

4.2.1 Streambank Erosion Calibration

Streambank erosion was calibrated to annual loads as estimated following the methodology in SedNetNZ (Dymond et al., 2016) for the three calibration sites. SedNetNZ estimates streambank erosion from the product of the bank migration rate, bank height, and length of the stream link:

$$B_j = \rho \, M_j \, H_j \, L_j$$

Equation 4.6

where B_j is the total mass of soil eroded by bank erosion in the *j*th stream link (t yr),

ρ is the bulk density of soil (t m^{-3}),

M_j is the bank migration rate of the *j*th stream link (m yr),

H_j is the mean bank height of the *j*th stream link (m), and

L_j is the length of the *j*th stream link (m).

The bank migration rate is estimated from an empirical relationship with the mean annual flood (Dymond et al., 2016; Mueller & Dymond, 2015). Estimates of bank height are also derived from a relationship to modelled discharge developed from bank height field observations following Dymond et al. (2016). Stream length is calculated as the sum of second order or higher REC 2 stream length represented by each model link. Soil bulk density is estimated as 1.5 t/m^3 following Mueller & Dymond (2015), and a net fraction of 0.2 of the gross load calculated in Equation 4.6 has been adopted (Dymond et al. 2016).

Equation 4.4 was calibrated to match the mean annual load estimated by Equation 4.6 through adjustment of the *a* and *b* factors. Table 4.2 shows the average annual modelled streambank erosion loads for modelled links contributing to the calibration points, prior to reductions for riparian vegetation/streambank fencing (section 4.1.3). The adopted streambank parameters are calibrated to the calibration sub-catchments, with these parameters then being regionalised to uncalibrated catchments as in Figure 4.2.

Table 4.2: Streambank erosion annual loads

Method	Porirua at Town Centre	Pauatahanui at Gorge	Horokiri at Snodgrass
Annual load estimated following SedNetNZ	513 t	424 t	392 t
Average annual load modelled using Equation 4.4	512 t	426 t	391 t

4.2.2 Surficial and Landslide Erosion Calibration

Surficial erosion and landslide erosion, as well as the background streambank erosion, is calibrated to observed daily sediment loads. Surficial erosion is calibrated through the β erosion scaling factor and α constant in Equation 4.2. A surficial DWC has been applied globally in the model to account for suspended sediment load during baseflow.

Landslide erosion is calibrated to the observed daily sediment loads through the *a* and *b* factors (Equation 4.5) as a combined sediment load with the surficial erosion. Parameters have been regionalised to uncalibrated catchments as in Figure 4.2.

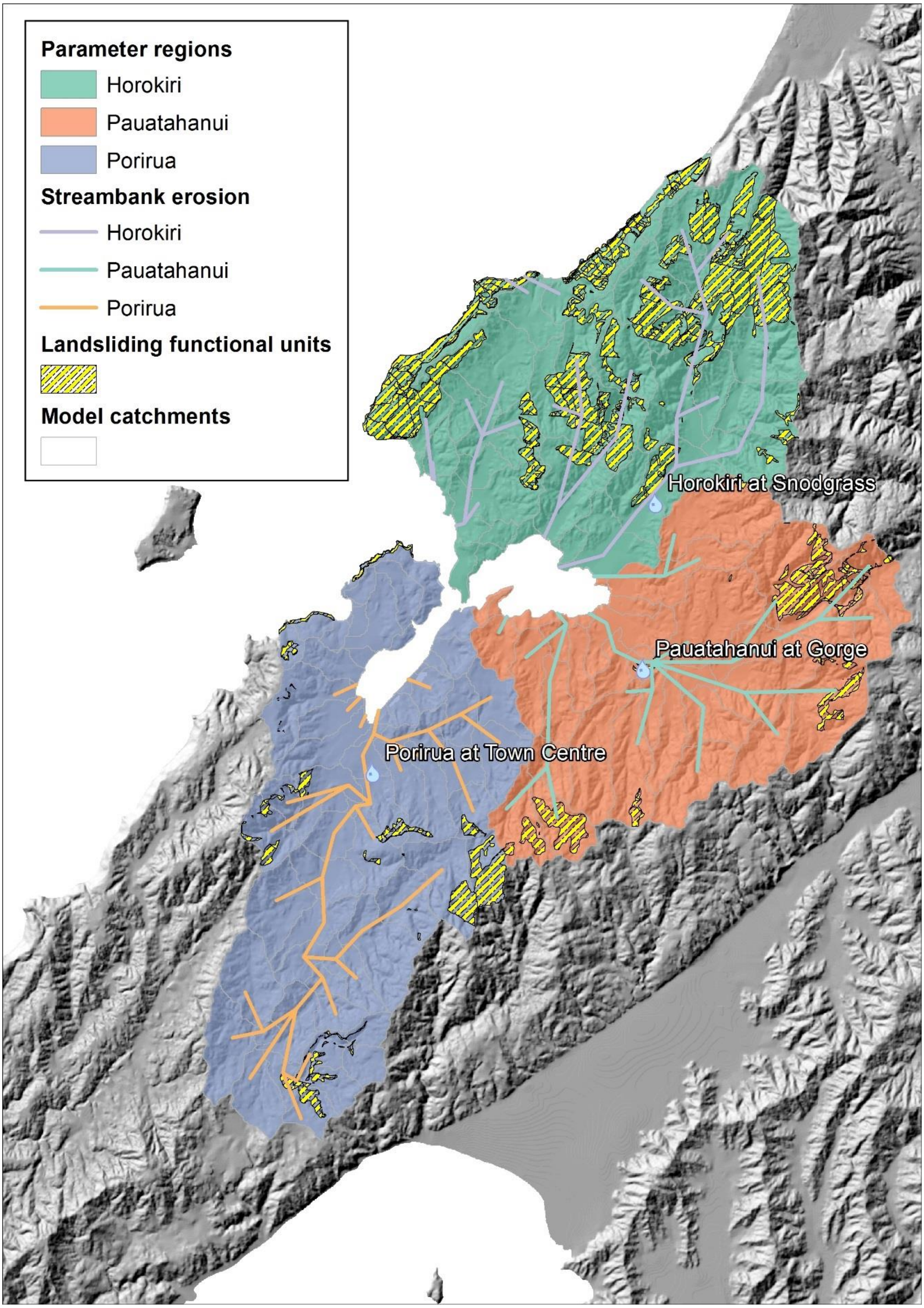

Figure 4.2: Erosion model overview and parameter regionalisation

4.3 Sediment Calibration Results

Calibration results show a good match to observed data for all three calibration sites. Table 4.3 shows the daily SS load results compared to observed data, and Table 4.4 shows the monthly average SS load PBIAS and NSE statistics. Evaluation ratings of PBIAS and NSE statistics follow Moriasi et. al. (2007); sediment calibration is deemed 'very good' if the NSE statistic is greater than 0.7 and PBIAS is ± 15%, 'good' if the NSE statistic is greater than 0.65 and PBIAS is ± 30%, and 'satisfactory' if the NSE statistic is greater than 0.5 and PBIAS is ± 50%. Pauatahanui at Gorge achieves a 'satisfactory' rating for PBIAS, and 'very good' for NSE, while Porirua at Town Centre and Horokiri at Snodgrass achieve 'very good' for PBIAS and NSE.

Figure 4.3, Figure 4.4 and Figure 4.5 show the exceedance curves of SS loads for the three calibration sites. Figure 4.6 aggregates the annual load for the three calibration sites. The relative proportion of modelled surficial, streambank, and landslide erosion sources for each calibration site is shown in Figure 4.7, Figure 4.8, and Figure 4.9.

Table 4.3: Daily load calibration statistics

Daily statistics	Porirua at Town Centre		Pauatahanui at Gorge		Horokiri at Snodgrass	
	1/05/2012 - 21/07/2016		13/06/2013 - 07/09/2016		01/06/2013 - 21/07/2016	
	OBS	SIM	OBS	SIM	OBS	SIM
Mean (t/day)	5.73	5.22	7.17	5.94	4.06	4.21
Median (t/day)	0.14	0.15	0.15	0.15	0.09	0.16
90th percentile (t/day)	5.26	5.41	3.85	6.14	1.03	1.76
5th percentile (t/day)	0.03	0.02	0.01	0.01	0.02	0.01
PBIAS	-1%		-32%		-8%	
Mean annual load (t/yr)	2092	1907	2616	2168	1483	1537

Table 4.4: Mean monthly calibration statistics

Monthly statistics	Porirua at Town Centre		Pauatahanui at Gorge		Horokiri at Snodgrass	
	1/05/2012 - 21/07/2016		01/07/2013 - 07/09/2016*		01/07/2013 - 21/07/2016*	
	Performance Rating	Value	Performance Rating	Value	Performance Rating	Value
PBIAS	Very Good	-3%	Satisfactory	-34%	Very Good	-8%
NSE	Very Good	0.87	Very Good	0.83	Very Good	0.98
*June 2013 not included due to gap in observation record during large event						

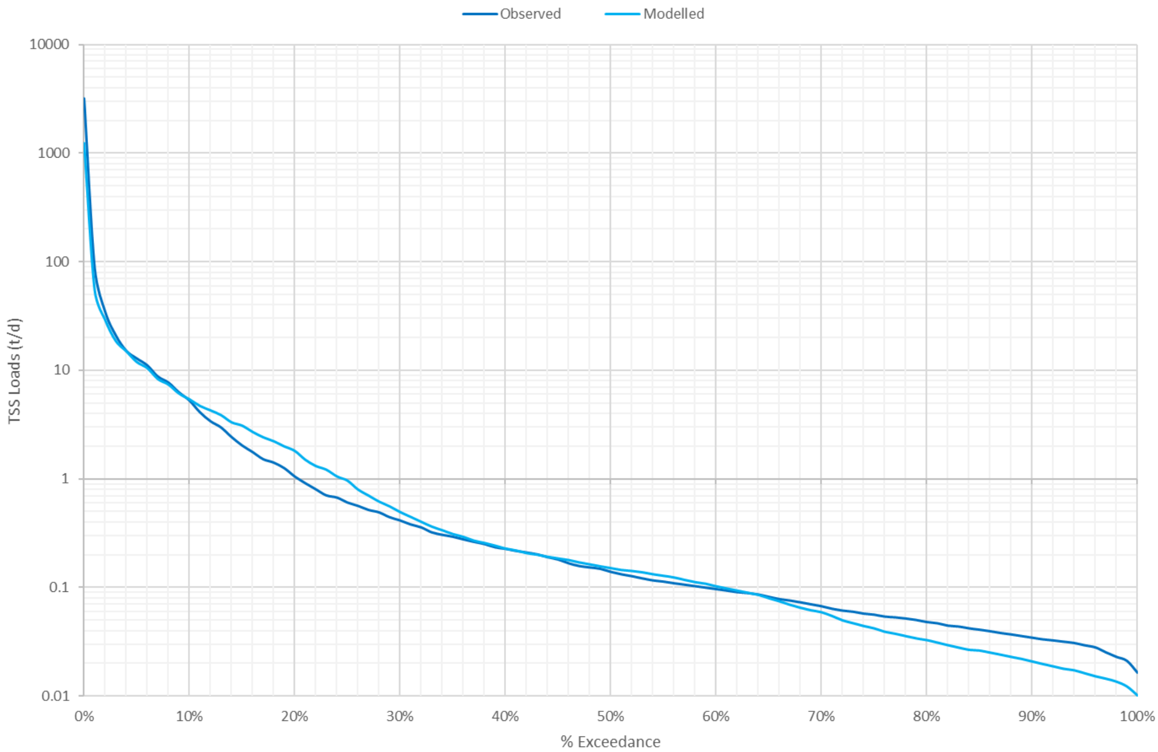

Figure 4.3: Suspended sediment load exceedance curve at Porirua at Town Centre

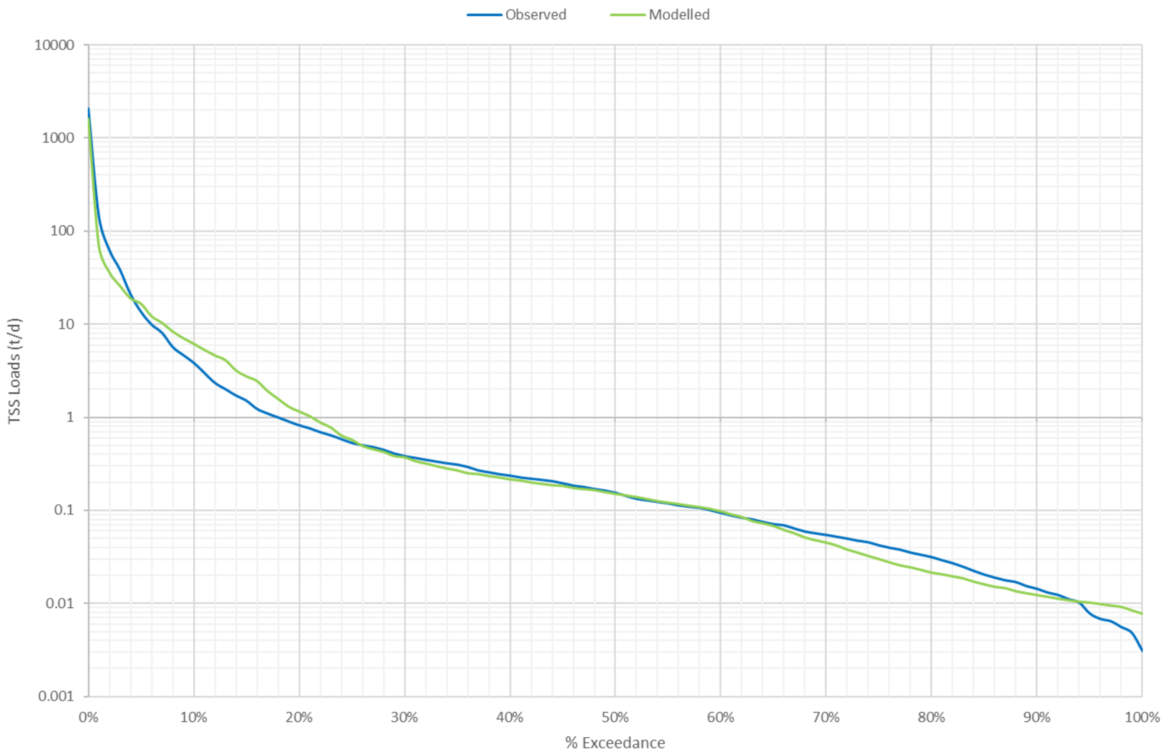

Figure 4.4: Suspended sediment load exceedance curve at Pauatahanui at Gorge

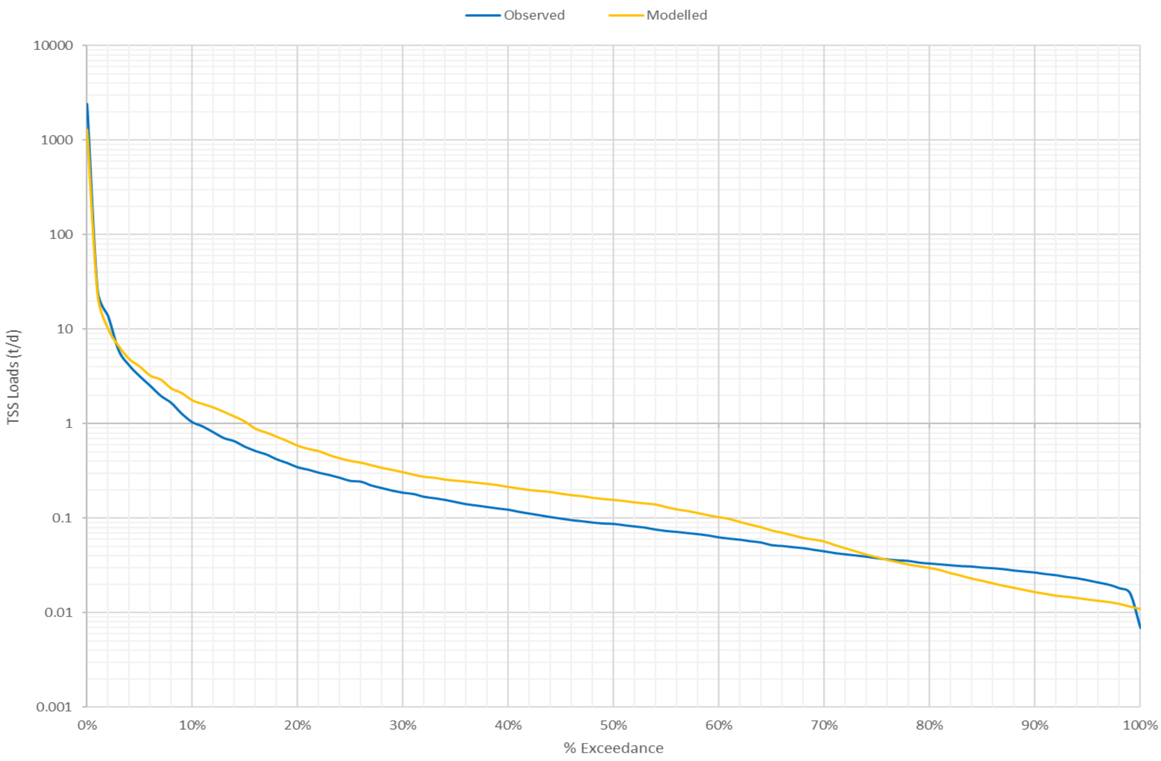

Figure 4.5: Suspended sediment load exceedance curve at Horokiri at Snodgrass

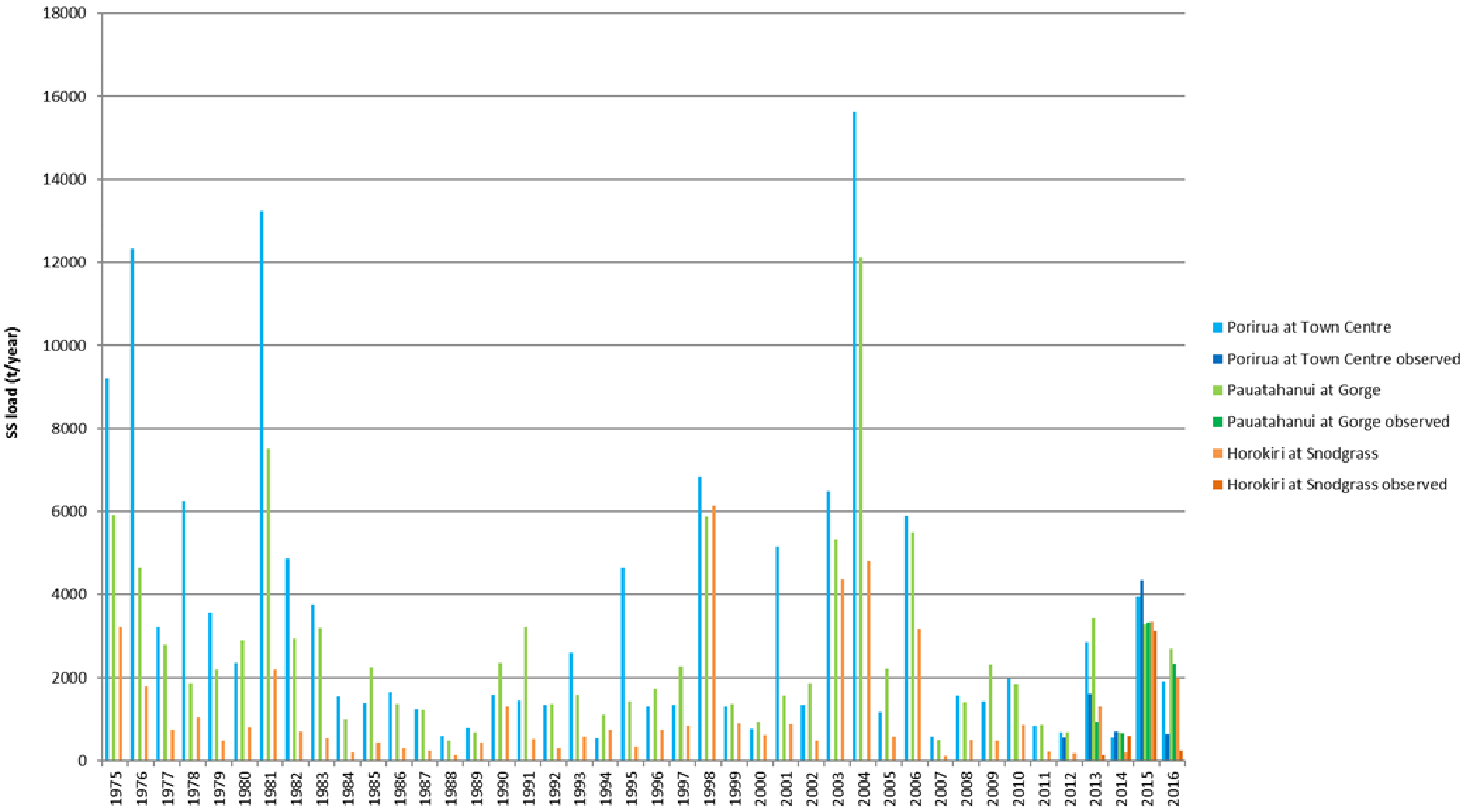

Figure 4.6: Modelled and observed annual sediment loads (t/year) (observed data incomplete – see Table 4.4)

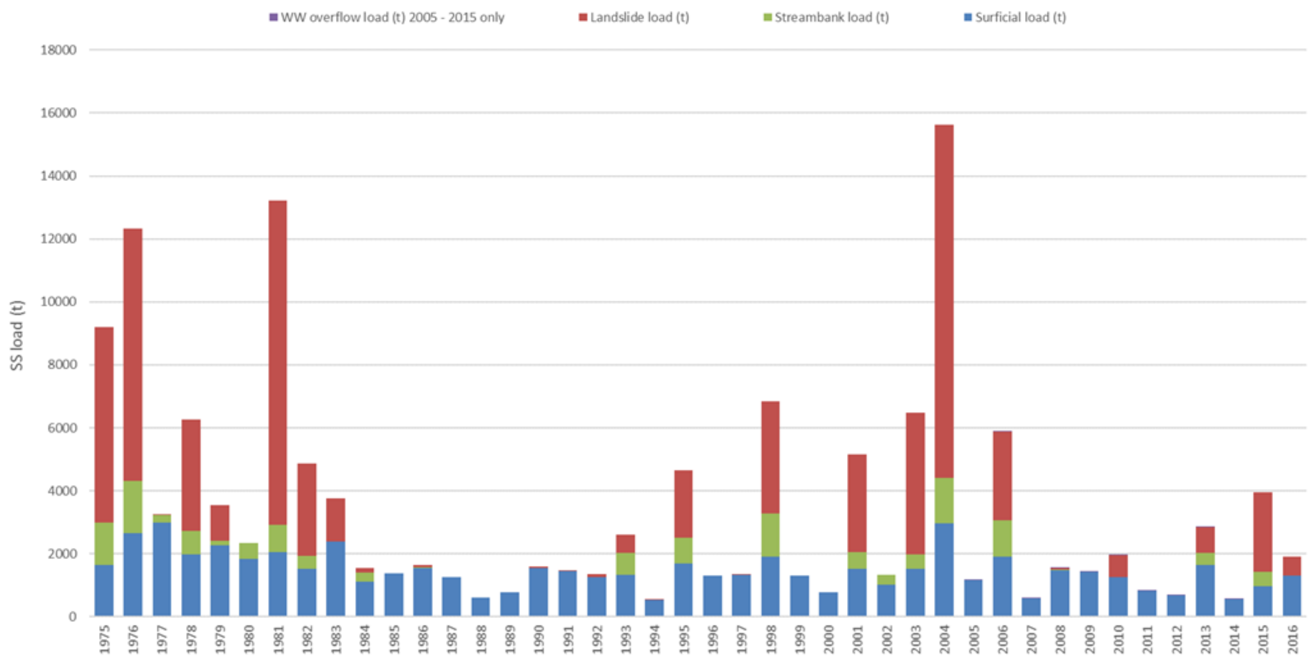

Figure 4.7: Modelled sediment sources for Porirua at Town Centre

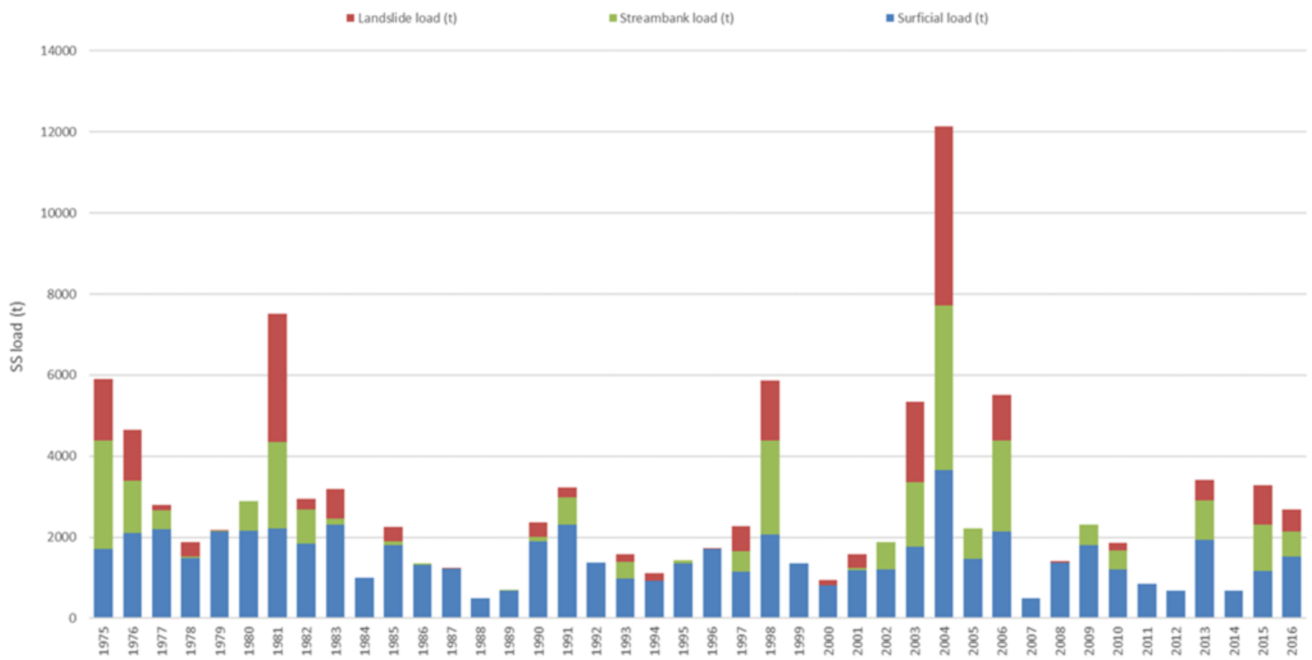

Figure 4.8 Modelled sediment sources for Pauatahanui at Gorge

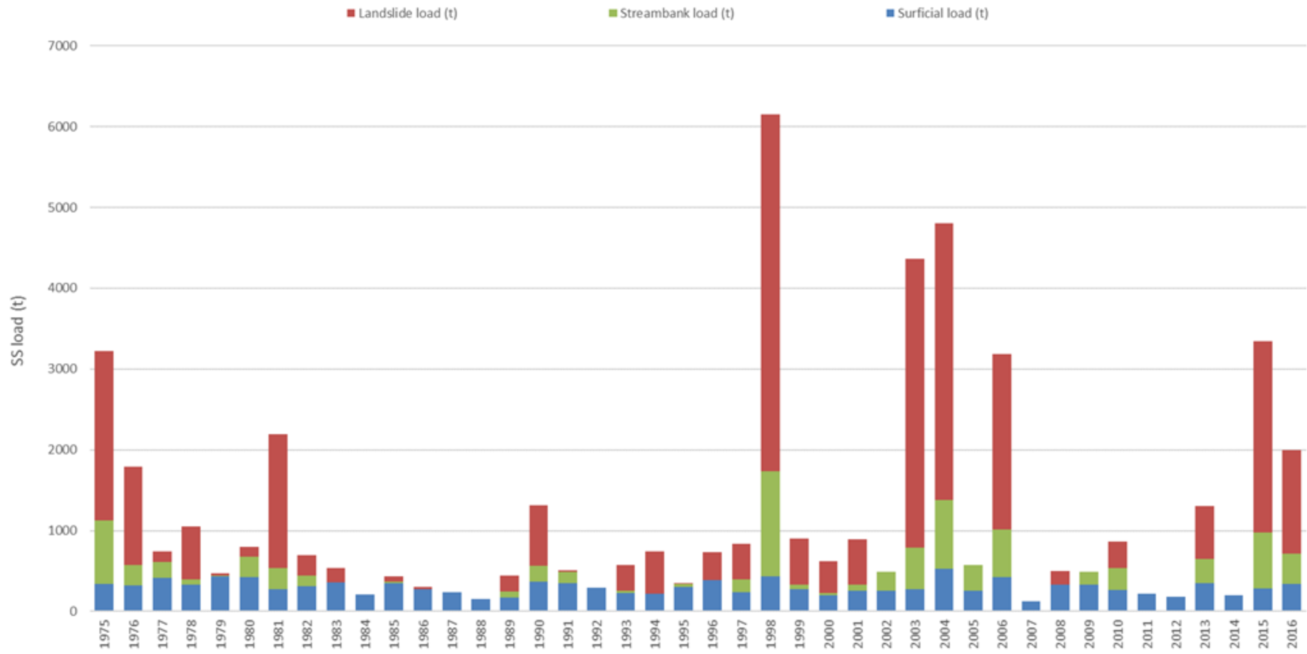

Figure 4.9: Modelled sediment sources for Horokiri at Snodgrass

4.3.1 Comparison to annual estimates

In general, the modelled loads match observed loads well. A comparison of modelled loads to reported annual models is provided in Table 4.5.

Annual sediment load estimates vary widely, as does the relativity between the three monitoring sites. The Suspended Sediment Yield Estimator (SSYE) GIS layer, modified CLUES (Green et al. 2014), and SedNetNZ (GIS layers) all predict average annual loads greater than observed data for all three sites, significantly so for CLUES and SedNetNZ. It should be noted that the CLUES modelled loads cover a larger area than the Source model. The higher load estimates from these models compared to the dSedNet model estimates may be partially attributed to the relatively low rainfall during the observation period compared to the long-term average; the annual average 2012-2016 rainfall is 87% of the long-term annual average rainfall between 1973-2011 for the Porirua at Town Centre site in the VCSN.

The SSYE and modified CLUES estimate roughly equal (CLUES) or higher (SSYE) loads to the Horokiri at Snodgrass site relative to the Porirua or Pauatahanui sites, in contrast to the observed loads and those estimated by SedNetNZ, indicating uncertainty of erosive potential across the project catchments. Calibration to observed loads (Table 4.3 and Figure 4.5) has resulted in the adoption of a lower erosion scaling factor (β) for the Horokiri catchments compared to the Porirua and Pauatahanui.

Table 4.5: Annual load model comparison

Model	Porirua at Town Centre	Horokiri at Snodgrass	Pauatahanui at Gorge
Area (ha)	3,992	2,884	3,838
Observed load[1] (2012/13-2016) (t/year)	2,092	1,483	2,616
Suspended Sediment Rating[2] (t/year)	N/A	N/A	2,958
Jacobs modelled (1975-2016) (t/year)	3,377	1,187	2,634
SSYE (t/year)	3,924	4,937	2,999
SedNetNZ Total Hill Erosion (t/year)	13,682	7,813	17,105
CLUES[3] area (ha)	4,108	3,306	4,168
CLUES[3] load (t/year)	8,206	8,162	8,066

Notes
1. Converted from observed continuous turbidity, see Table 4.1 for dates of record
2. Hicks et al., 2011.
3. Green et al. 2014, table 2.8. Loads are to the stream mouth.

4.3.2 Discussion

The greatest source of uncertainty in the modelled loads is likely the large, infrequent sediment loading events that have been attributed to landslide and streambank erosion processes. The large May 2015 event contributed more than three quarters of the total sediment load for the first six months of 2015 and more sediment than the combined loads for 2013 and 2014 for the Porirua stream (Morar & Oliver, 2016). Calibration to this event has resulted in spatially varied landslide parameters across the project catchments, which may be an oversimplification across a longer observation period.

The relative contribution of modelled surficial, landslides, and streambank erosion for the three calibration sites is shown in Table 4.6. The relatively low proportion of landslide contribution to the Pauatahanui at Gorge site can be attributed to the small landslide prone area identified in the contributing sub-catchments (Figure 4.2). Horokiri at Snodgrass is characterised by the largest landslide prone area, and subsequently the largest proportion of predicted sediment load from landslides (58%). A satisfactory calibration to observed SS loads was achieved for the combined modelled surficial, landslide, and bank erosion processes. However, a lack of observed data means that the relative contribution between surficial, landslide, and bank erosion processes is uncertain.

Despite the identified uncertainties, the described sediment modelling approach represents a novel methodology that offers increased utility and resolution of erosion processes than previous annual scale models (compared in 4.3.1). The approach allows mitigation options such as pole planting, retirement, and constructed wetlands to be tested during scenarios, with model outputs expressed as daily in-stream SS concentrations and loads to Te Awarua-o-Porirua receiving environment. The comparison of model results as load and concentration time-series provides for wider ecosystem health assessment and linkage to other models, e.g. hydrodynamic harbour modelling for sediment deposition and stream habitat assessment.

Table 4.6: Modelled sediment load proportions for the period 1975 - 2016

Sediment source	Porirua at Town Centre	Horokiri at Snodgrass	Pauatahanui at Gorge
Surficial proportion	58 %	25 %	58 %
Landslide proportion	32 %	58 %	19 %
Streambank proportion	9 %	17 %	23 %

5. Baseline Nutrient Model

Nutrient generation and transport are simulated using an EMC and DWC approach. EMC/DWC model parameters are specified for each Functional Unit (FU) land use type. The modelled nutrients are Total Nitrogen (TN), Nitrate-Nitrogen (NO_3), Ammoniacal-Nitrogen (NH_4), Total Phosphorus (TP) and Dissolved Reactive Phosphorus (DRP). EMC's are applied to quickflow while DWC's are applied to baseflow, for the flow generated off each functional unit.

Four monitoring sites with monthly observed in-stream nutrient data were available for calibration from GWRC and are described in Table 5.1. Three stations were used for calibration and one as an independent verification site to test the reliability of the spatial performance of the calibrated model for the Porirua Catchment (Figure 5.1).

Table 5.1: Calibration and validation sites for nutrient modelling

Site name	Date range	Calibration / Validation
Horokiri Stream at Snodgrass	July 2002 – June 2016	Calibration
Pauatahanui Stream at Elmwood Bridge	July 2001 – June 2016	Calibration
Porirua Stream at Wall Park (Milk Depot)	July 2001 – June 2016	Calibration
Porirua Stream at Glenside Overhead Cables	July 2001 – June 2016	Validation

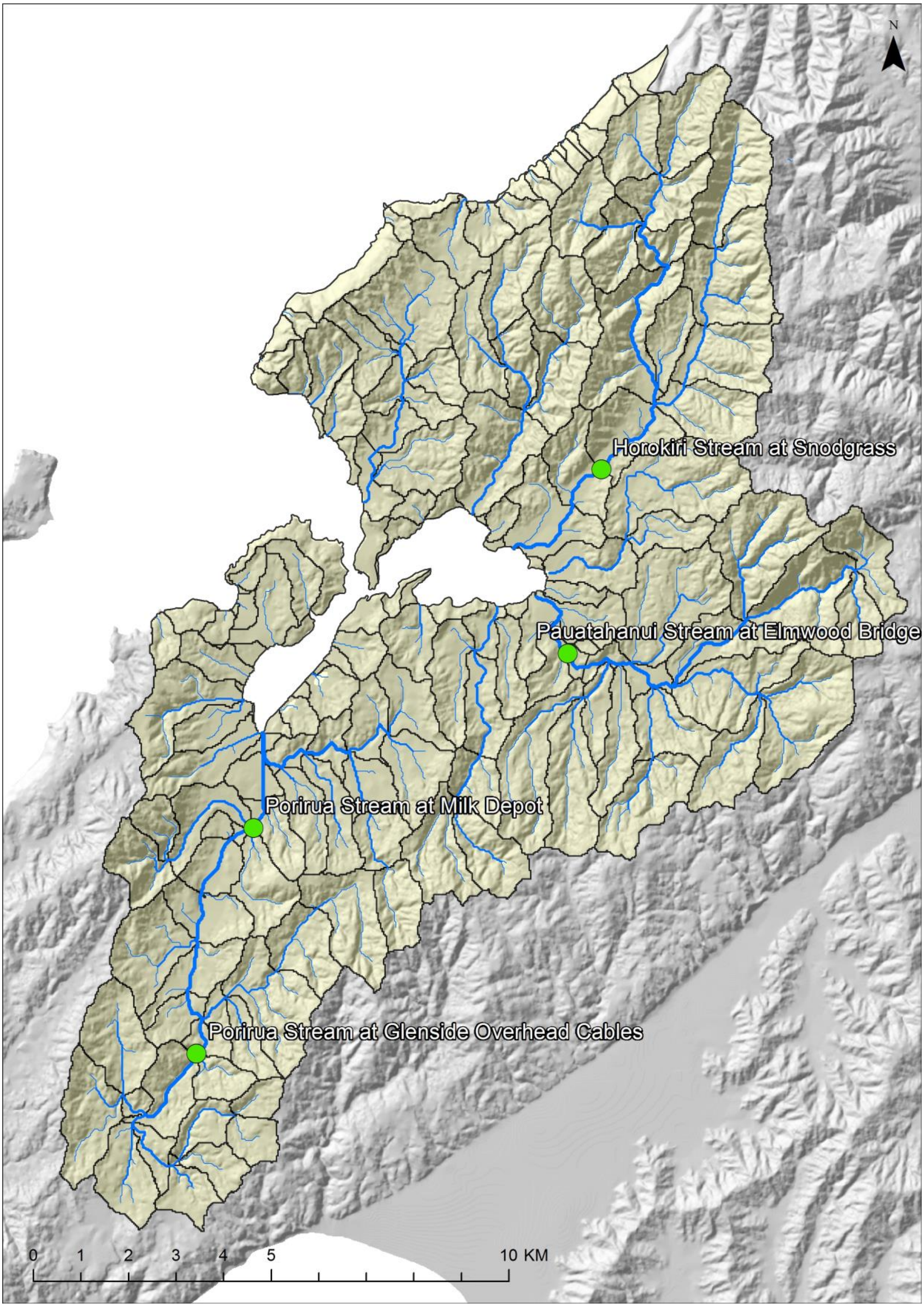

Figure 5.1: Nutrient model calibration locations

5.1 Nutrient Generation Rates

The preliminary EMC and DWC concentration for each FU was estimated from the corresponding annual average nutrient yield provided by literature, CLUES and the customised CLM (Moores et al. 2017).

- The customised CLM model estimates the annual TN and TP yields for urban areas. The CLM derived urban yields were translated into EMC values, as yields largely represent stormwater generated (runoff) loads.
- CLUES annual nutrient yields were used to estimate nutrient yields from rural FUs. CLUES yields have been translated into DWC values for TN as a leaching rate and EMC values for TP as a runoff generation rate, reflecting the physical pathway from land to stream of the respective nutrient.

For each FU for each sub-catchment, the yields from CLM/CLUES were multiplied by the FU's total area and runoff, extracted from the calibrated rainfall-runoff model, to estimate the EMC/DWC concentration. Initial EMC and DWC values not derived from the CLM/CLUES annual yields were estimated from literature sources:

- urban FUs (urban, roofs and roads) used literature values from Fletcher et al. (2004);
- rural FUs (forestry, native land cover, dairy, livestock grazing, irrigated horticulture) used literature values from Barlow et al. (2009).

The concentration of nutrients in the wastewater overflows were adopted based on data provided by Wellington Water and is provided in Table 5.2. The modelling configuration of the wastewater overflows is described in section 2.2.3.

Table 5.2: Average wastewater overflow concentrations

Nutrients	Concentration (mg/l)
Total Nitrogen	46
Nitrate Nitrogen	0
Ammoniacal Nitrogen	25
Total Phosphorus	6
Dissolved Reactive Phosphorus	5

5.2 Nutrient Calibration Approach

The model was calibrated over the period of 2001 - 2016 for three monitoring stations for TN and TP in the first instance. The EMC/DWC concentration values derived from the CLM/CLUES were kept fixed as much as possible, while calibrating the literature values only. However, some of these derived concentration values were modified slightly to obtain the best calibration result.

After calibrating for TN and TP, corresponding nutrient speciation factors were used to estimate the preliminary EMC/DWC values of the remaining nutrient analytes NO_3, NH_4 and DRP. For each of the calibration sites the proportion of median NO_3-N and NH_4-N concentration to TN and DRP to TP was calculated from the observed record to provide a range in factors, then averaged to estimate the corresponding speciation factors. The calculated speciation factors were 0.63, 0.2 and 0.6 for NO_3, NH_4 and DRP respectively. The estimated EMC/DWC for these analytes were later fine-tuned within the range calculated from monitoring data to obtain satisfactory calibration results.

To account for in-stream processes of nutrient transformations and loss, decay functions (half-life algorithm) were incorporated into the model links. Lower half-life values indicate increased in-stream nutrient attenuation process.

Initial calibration aimed to match the in-stream observed concentration (monthly spot-sample) to the modelled concentration for that date. However, an adequate match to the monthly spot-sample data was unable to be achieved without the use of localised parameter sets. Instead, the monthly mean from the modelled time-series was matched to the observed monthly spot-sample to achieve a satisfactory calibration using global EMC/DWC parameters. This is advantageous for scenario modelling as relative changes in contaminant yield following land use change will be consistently represented across the whaitua.

Calibration first focussed on achieving satisfactory PBIAS as a measure of fit between the observed and modelled concentration. The model is deemed satisfactory if PBIAS for nutrients is ± 75 % as suggested by Moriasi et al. (2007). The model was further evaluated using descriptive statistics such as median, 95th percentile, mean, and time-series graphical analysis. In addition, the calibrated model was independently verified at the Porirua at Glenside Overhead Cables site, which is upstream of the heavily urbanised areas in the Porirua Catchment and is mostly rural land use with minimal urban areas.

5.3 Calibration Results and Discussion

The final calibrated EMC/DWC parameters are given in Table 5.3, all sub-catchments are assigned the same EMC and DWC concentration for a particular FU.

Table 5.3: Calibrated EMC/DWC parameter values (mg/l)

Land use	TN (mg/l)		NO_3-N (mg/l)		NH_4-N (mg/l)		TP (mg/l)		DRP (mg/l)	
	EMC	DWC	EMC	DWC	EMC	DWC	EMC	DWC	EMC	DWC
Commercial Paved	1.5	0.4	1.21	0.32	0.03	0.008	0.18	0.04	0.07	0.02
Industrial Paved	1.5	0.4	1.21	0.32	0.03	0.008	0.15	0.03	0.06	0.01
Residential Paved	1.5	0.4	1.21	0.32	0.03	0.008	0.18	0.04	0.07	0.02
Roads[1] (all)	1.5	0.4	1.21	0.32	0.03	0.008	0.15	0.03	0.06	0.01
Roof[2] (all)	1.5	0.4	1.21	0.32	0.03	0.008	0.07	0.02	0.04	0.01
Urban Grassland	4	3.59	3.2	2.87	0.08	0.072	0.36	0.02	0.1	0.01
Other	1	0.38	0.8	0.3	0.02	0.008	0.03	0.03	0.01	0.01
Natural Forest	1	0.55	0.8	0.44	0.02	0.011	0.03	0.03	0.01	0.01
Plantation Forest	1	0.53	0.8	0.42	0.02	0.011	0.03	0.03	0.01	0.01
Scrub	1	0.85	0.8	0.68	0.02	0.017	0.05	0.05	0.02	0.02
SB Hill	8	1.16	6.4	0.93	0.12	0.023	0.4	0.18	0.11	0.07
Other Animals	6	0.69	4.8	0.55	0.12	0.014	0.05	0.04	0.02	0.02
SB Intensive	10	1.35	8	1.08	0.16	0.027	0.3	0.18	0.1	0.07
Deer	6	1.9	4.8	1.52	0.12	0.038	0.28	0.18	0.1	0.07
Horticulture	4	3.57	3.2	2.86	0.08	0.071	0.02	0.02	0.01	0.01
Construction Site	2.5	1.33	2	1.06	0.05	0.027	4.78	0.04	1.75	0.02

Notes

1 – Roads includes All Roads VPD (<1000, 1000-5000, 5000-20000, 20000-50000 and 50000-100000)

2 – Roof covers Commercial Roof, Industrial Roof and Residential Roof

The calibrated half-life factors are similar for rural catchments (Horokiri and Pauatahanui) and higher in Porirua, suggesting greater nutrient attenuation within rural streams (Table 5.4). Half-life factors are applied to the remaining catchments following the parameter regions shown in Figure 4.2.

Table 5.4: Calibrated half-life parameters (in days)

Calibration site	Half-life in days				
	TN	NO_3	NH_4	TP	DRP
Horokiri at Snodgrass	0.8	0.7	0.8	0.8	0.8
Pauatahanui at Elmwood Bridge	0.65	0.55	0.8	0.8	0.8
Porirua at Milk Depot	2.2	2.2	1.8	1.8	1.8

5.3.1 Nitrogen Calibration and Validation

The PBIAS for TN, NO_3-N and NH_4-N at all calibration sites are within ± 75% as shown in Table 5.5, and fall into the 'good' calibration performance rating given by Moriasi *et al.* (2007). Furthermore, comparing the mean, median and 95th percentiles in Table 5.5 shows that the model agrees well with the observed data, which are all within ± 75%.

A comparison of box-whisker plots for observed and modelled results is shown in Figure 5.2. These exclude the outliers for ease of interpretation as the maximum value is often ten times greater than the 95th percentile. The box plots show that nitrogen species concentrations are higher in the Porirua catchment compared to the other two rural sites. For the Horokiri and Pauatahanui sites the model is in good agreement with the observed data, however, for the Porirua site the model generally underestimates the variability in NO_3-N and NH_4-N concentrations.

A graphical comparison between the observed and simulated data (Figure A.9, A.10, and A.11 in Appendix A) demonstrates that the model is able to simulate seasonal TN fluctuations well for all sites. The model underestimates NO_3-N event concentrations at the Porirua site, and generally performs poorly in predicting NH_4-N concentration fluctuations at all three sites. Spikes in NH_4-N in the observed data may be a result of localised sewer leaks or some other unaccounted for point-source that cannot be captured in a catchment-scale model adequately as these peaks do not coincide with the provided wastewater overflow time-series (Section 2.2.3). Further calibration of localised EMC/DWC values for the Porirua stream may improve the model simulations for NO_3-N, however non-localised parameters were preferred to ensure consistent contaminant generation response following land use change during later scenario testing.

The upstream catchment of the Porirua at Glenside was used as a verification site for this study to test the performance of the model given the sparsity of calibration sites. Table 5.5 gives the summary statistics and PBIAS between the observed and simulated data for Porirua at Glenside, which show the model performs well, albeit with an underestimation in median NH_4-N. The box plots also demonstrate reasonably good agreement between observed and modelled nitrogen components (Figure 5.2). Graphical comparisons of observed and modelled nitrogen species at the Porirua at Glenside site follow similar trends as for the Porirua at Milk Depot site, which further suggests that localised EMC/DWC values may be necessary for the sheep & beef land uses that dominate the upstream catchment.

Table 5.5: Mean monthly statistical comparison for observed and simulated TN, NO_3-N, and NH_4-N.

Calibration / validation site	Statistic	TN (mg/l)		NO_3-N (mg/l)		NH_4-N (mg/l)	
		OBS	SIM	OBS	SIM	OBS	SIM
Horokiri at Snodgrass (Calibration)	Median	0.64	0.71	0.46	0.5	0.01	0.01
	95th Percentile	1.3	1.08	1.05	0.78	0.05	0.02
	Mean	0.7	0.68	0.49	0.49	0.02	0.01
	PBIAS (%)	2%		-2%		-21%	
Pauatahanui at Elmwood Bridge (Calibration)	Median	0.56	0.59	0.26	0.36	0.02	0.01
	95th Percentile	1.11	1.12	0.73	0.72	0.05	0.02
	Mean	0.57	0.61	0.3	0.38	0.02	0.01
	PBIAS (%)	8%		28%		-41%	
Porirua at Milk Depot (Calibration)	Median	1.25	0.95	0.93	0.76	0.02	0.02
	95th Percentile	2.35	1.56	1.76	1.24	0.13	0.04
	Mean	1.35	0.97	0.99	0.76	0.04	0.02
	PBIAS (%)	-28%		-23%		-44%	
Porirua at Glenside (Validation)	Median	1.25	1.09	0.97	0.86	0.01	0.03
	95th Percentile	2.22	1.77	1.84	1.4	0.07	0.05
	Average	1.36	1.11	1.05	0.88	0.02	0.03
	PBIAS (%)	-18%		-17%		3%	

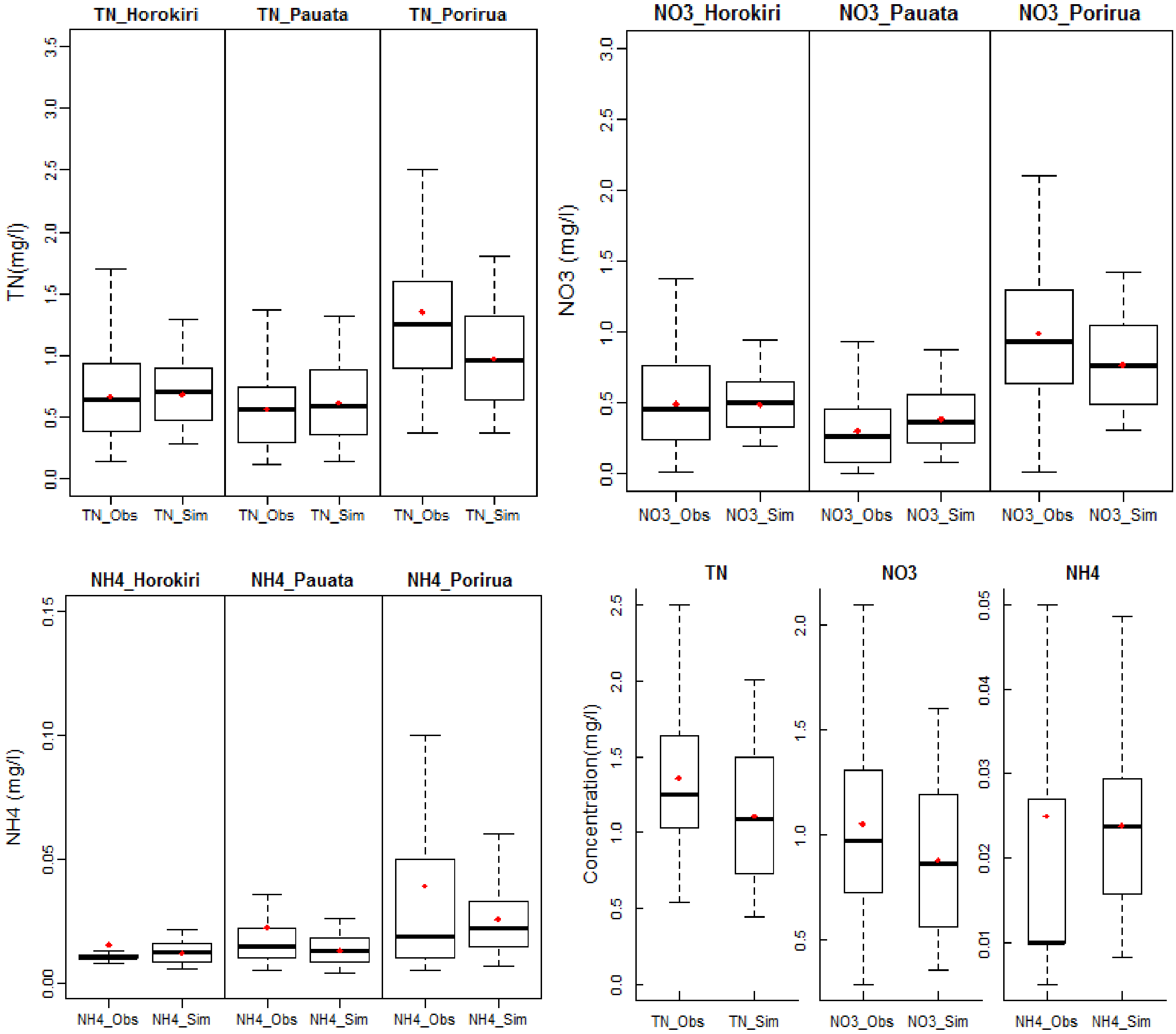

Figure 5.2: Comparison between monthly observed and simulated Box and whisker plot for a) TN, b) NO_3-N and c) NH_4-N for each calibration site; and d) for the Porirua at Glenside verification site.

The box represents the 25th percentile, median and 75th percentiles, the whiskers represent the 1.5×IQR (interquartile range) above or below the 25th and 75th percentiles. Mean concentration is given as a single red point

5.3.2 Phosphorus Calibration

The model achieved acceptable PBIAS values for TP and DRP at all three calibration sites, in addition to achieving a good agreement between median, mean and 95th percentile concentrations (Table 5.6). Median and mean TP concentrations at Horokiri are overestimated by the model.

Box and whisker plot comparisons in Figure 5.3 shows that Horokiri site has the lowest observed median TP concentration compared to the Porirua and Pauatahanui sites. As for Nitrogen species, both TP and DRP exhibit higher median concentrations for Porirua compared to the two rural sites. Overall, the box plots demonstrate that the model can simulate the distribution of observed TP and DRP concentrations reasonably well.

The time-series analysis for TP and DRP at the calibration sites (Figure A.12 and Figure A.13 in Appendix A) gives a reasonably good correspondence between the observed and simulated concentration. As for nitrogen species, the timing is well represented by the model, but the magnitude of the peak events are underestimated for both TP and to a lesser extent for DRP. The peak TP events observed in the data at all sites may be due to particulate phosphorus bound to sediment mobilised during extreme rainfall events, which is challenging to model with an EMC/DWC approach. Adjustment of the EMCs derived from the annual loads to fit the model to these peak events subsequently resulted in an overall increase in simulated median TP concentration, which was reverted in favour of good estimation of median TP concentration.

The verification site at Porirua at Glenside illustrates that the model performs reasonably well for TP and DRP (Table 5.6), although concentrations are generally overestimated (Figure 5.3c).

Table 5.6: Mean monthly statistical comparison for observed and simulated TP and DRP at monitoring sites.

Calibration / validation site	Statistic	TP (mg/l)		DRP (mg/l)	
		OBS	SIM	OBS	SIM
Horokiri at Snodgrass (calibration)	Median	0.02	0.04	0.01	0.01
	95th Percentile	0.05	0.05	0.02	0.02
	Mean	0.02	0.04	0.01	0.01
	PBIAS (%)	53.6%		-7%	
Pauatahanui at Elmwood Bridge (calibration)	Median	0.03	0.04	0.02	0.01
	95th Percentile	0.08	0.07	0.03	0.02
	Mean	0.03	0.04	0.02	0.01
	PBIAS (%)	23%		-9%	
Porirua at Milk Depot (calibration)	Median	0.04	0.06	0.02	0.02
	95th Percentile	0.12	0.08	0.04	0.03
	Mean	0.05	0.06	0.02	0.02
	PBIAS (%)	16%		-0.4%	
Porirua at Glenside (validation)	Median	0.03	0.07	0.02	0.03
	95th Percentile	0.15	0.1	0.03	0.04
	Average	0.04	0.07	0.02	0.03
	PBIAS (%)	56%		34%	

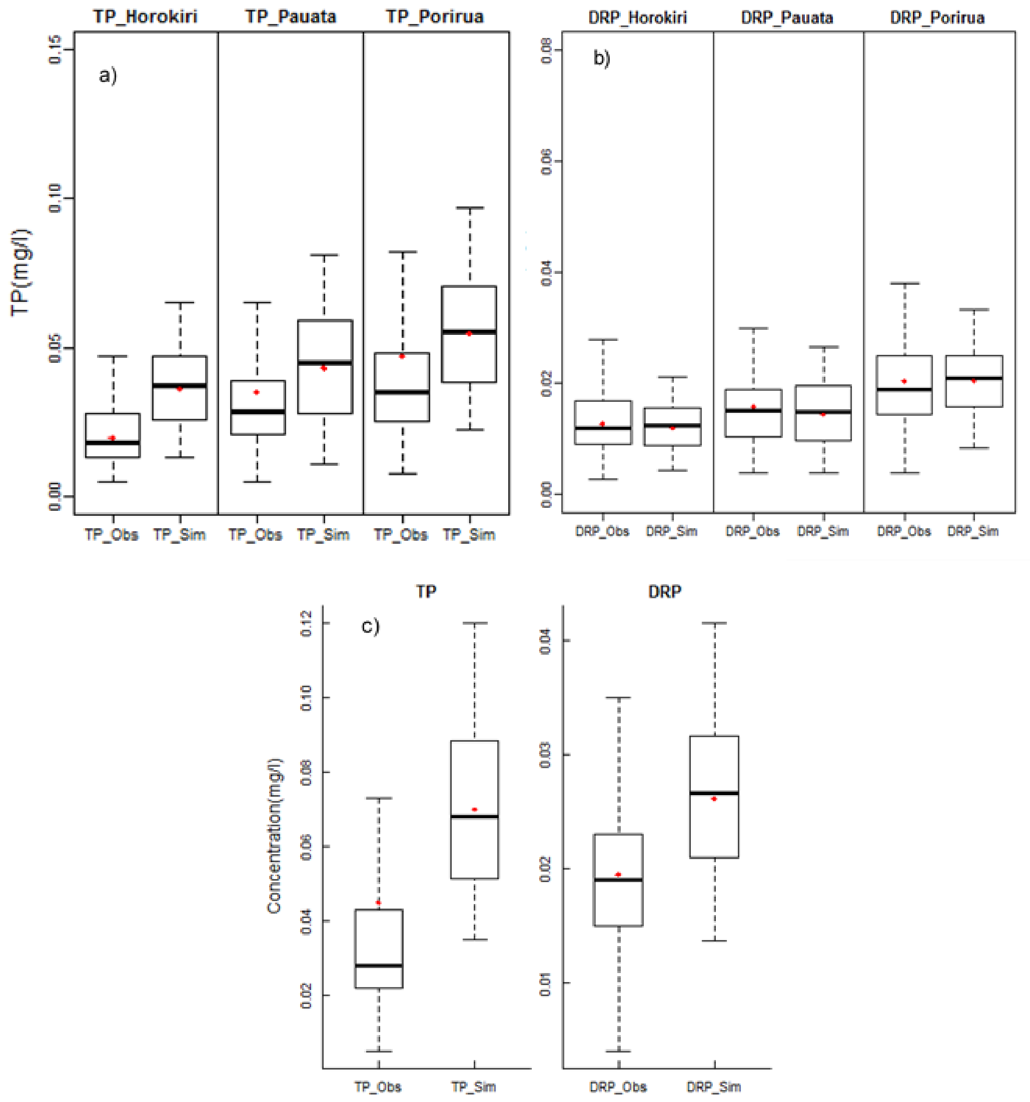

Figure 5.3: Comparison between observed and simulated Box and whisker plot for a) TP and b) DRP for each calibration site, and c) for the Porirua at Glenside verification site.

The box represents the 25th percentile, median and 75th percentiles, the whiskers represent the 1.5×IQR (interquartile range) above or below the 25th and 75th percentiles. Mean concentration is given as a single red point.

6. Baseline Metal Model

Dissolved and total Copper (Cu), and dissolved and total Zinc (Zn) generation and transport are simulated using an EMC/DWC approach. EMC/DWC model parameters are specified for each FU.

In-stream dissolved Cu and Zn data are available for four monitored sites in the Whaitua area; Porirua stream at Glenside, Porirua stream at Milk Depot, Kenepuru stream at Mepham Crescent, and Mitchell stream at Porirua stream (Figure 6.1). Two sites, Porirua stream at Glenside and Porirua stream at Milk Depot, are on the main stem of the Porirua stream and are sampled on the same day from 2008. These two sites have been used for model calibration. The records for Mitchell stream at Porirua and Kenepuru stream at Mepham Crescent are only for one year, from July 2011 to June 2012, and have been utilised as verification sites.

Observed data for all locations are dissolved Zn and Cu only. The model is therefore calibrated to dissolved concentration only. Total Zn and Cu estimation is discussed in section 6.3.

Table 6.1: Observed metal data overview

Monitoring Location	Date Range	Number of samples	Interval	Calibration / Validation
Porirua stream at Glenside	9/01/2008-16/06/2016	102	Monthly	Calibration
Porirua stream at Milk Depot	9/01/2008-19/12/2016	108	Monthly	Calibration
Kenepuru stream at Mepham Crescent	12/07/2011-7/06/2012	12	Monthly	Validation
Mitchell stream at Porirua stream	12/07/2011-7/06/2012	12	Monthly	Validation

Figure 6.1: Location of monitoring sites for metals

6.1 Metal Generation Rates

Initial values for the EMC were derived from the customised CLM yields (Moores et al., 2017) for total metals. Table 6.2 shows the derived concentrations from the customised CLM. Total loads (product of yield and area) were divided by the total flow generated from each FU to produce a concentration. Yields for Construction Sites and Urban Grassland were derived using the background metal soil concentration as in the CLM customisation (52.2 mg/kg Zn and 9 mg/kg Cu) as a proportion of the calibrated sediment yield. Rural FU concentration was calculated in the same manner, using the local background soil concentrations for each land use from Sorensen (2012) (Table 6.3).

Table 6.2 Concentration derived from customised CLM

Functional Unit	Zinc concentration (g/m^3)	Copper concentration (g/m^3)
Commercial Paved	0.1631	0.0296
Industrial Paved	0.6069	0.1101
Residential Paved	0.1974	0.0364
Roads (1000 VPD)	0.0043	0.0009
Roads (1000-5000 VPD)	0.0257	0.0052
Roads (5000-20000 VPD)	0.1281	0.0256
Roads (20000-50000 VPD)	0.2978	0.0595
Roads (50000-100000 VPD)	0.4909	0.0982
Commercial Roof	0.5951	0.0344
Industrial Roof	1.5417	0.0009
Residential Roof	0.5053	0.0017
Urban Grassland	0.0035	0.0006
Other	0.0033	0.0006
Natural Forest	0.0022	0.0004
Plantation Forest	0.0011	0.0002
Scrub	0.0048	0.0009
Sheep and Beef Hill	0.0134	0.0022
Other Animals	0.0021	0.0003
Sheep and Beef Intensive	0.0034	0.0006
Deer	0.0019	0.0003
Horticulture	0.0009	0.0002
Construction Site	0.1731	0.0298

Table 6.3: Median total recoverable trace element concentrations from Soresen (2012)

Metal	Cropping	Dairying	Drystock	Exotic forest	Horticulture	Vegetables	Native forest
Zinc (mg/kg)	80.0	79.0	58.0	44.5	69.0	84.0	66.0
Copper (mg/kg)	9.8	13.0	9.8	7.0	19.0	25.0	12.0

6.2 Calibration Results and Discussion

Modelled concentrations were calibrated to the observed median, mean, 95th percentile, and PBIAS. To assess the performance of the model, criteria from Moriasi et al. (2007) for TN and TP was adopted given the model is calibrating to dissolved metals and to maintain consistency with other modelled contaminants. Moriasi et al. (2007) suggests that monthly model simulations for TN and TP are 'satisfactory' if the PBIAS statistic is ± 70%, 'good' if PBIAS is ± 40%, and 'very good' if PBIAS is ± 25%.

As described in Section 5.2, calibration considered the monthly mean from the modelled time-series matched to the observed monthly spot-sample. This is advantageous for scenario modelling as relative changes in contaminant yield following land use change will be consistently represented across the whaitua. Because the calibration data is collected during dry weather, additional Cu and Zn load from wastewater overflows have not been included in model simulations.

Initial EMC and DWC values presented in Table 6.4 were derived from Table 6.2. The EMC concentration for industrial and commercial roof FUs are maintained from Table 6.2 for Zn and Cu. This is justified as much of the Cu and Zn yield from these FUs is expected to occur in the dissolved form. Calibration was required for the remaining FUs to fit the customised CLM derived total metal yields to the observed in-stream dissolved metal time-series. The adopted EMCs for the remaining FUs are 10% of the concentration calculated in Table 6.2 for Zn and 30% for Cu. DWCs for Zn and Cu are equal to 20% of the EMC for each FU. The EMC and DWC values for Sheep & Beef Intensive FU have been adopted from the Sheep & Beef Hill Country FU. Final calibrated EMC/DWC values are provided in Table 6.4.

Table 6.4: Calibrated EMC and DWC values for dissolved Zn and Cu (g/m3)

Functional Unit	Zn EMC	Zn DWC	Cu EMC	Cu DWC
Commercial Paved	0.01631	0.00326	0.00888	0.00178
Industrial Paved	0.06069	0.01214	0.03302	0.00660
Residential Paved	0.01974	0.00395	0.01093	0.00219
Roads (1000 VPD)	0.00043	0.00009	0.00026	0.00005
Roads (1000-5000 VPD)	0.00258	0.00052	0.00155	0.00031
Roads (5000-20000 VPD)	0.01281	0.00256	0.00769	0.00154
Roads (20000-50000 VPD)	0.02978	0.00596	0.01786	0.00357
Roads (50000-100000 VPD)	0.04909	0.00982	0.02945	0.00589
Commercial Roof	0.59512	0.11902	0.03443	0.00689
Industrial Roof	1.54165	0.30833	0.00092	0.00018
Residential Roof	0.05053	0.01011	0.00051	0.00010
Urban Grassland	0.00035	0.00007	0.00018	0.00004
Other	0.00033	0.00007	0.00018	0.00004
Natural Forest	0.00022	0.00004	0.00012	0.00002
Plantation Forest	0.00011	0.00002	0.00005	0.00001
Scrub	0.00049	0.00010	0.00026	0.00005
Sheep and Beef Hill	0.00034	0.00007	0.00017	0.00003
Other Animals	0.00021	0.00004	0.00010	0.00002
Sheep and Beef Intensive	0.00034	0.00007	0.00017	0.00003

Functional Unit	Zn EMC	Zn DWC	Cu EMC	Cu DWC
Deer	0.00019	0.00004	0.00009	0.00002
Horticulture	0.00009	0.00002	0.00008	0.00002
Construction Site	0.01631	0.00326	0.00888	0.00178

6.2.1 Dissolved Zinc Calibration and Validation

Calibration summary statistics are shown in Table 6.5. Based on Moriasi et al. (2007), the calibration achieves a 'very good' result for Porirua at Glenside, and a 'satisfactory' result for Porirua at Milk Depot. Model validation achieves a 'very good' result for Kenepuru at Mepham Crescent and 'satisfactory' result for Mitchell Stream at Porirua. The monthly observed and mean monthly modelled concentrations for the calibration and validation sites are plotted in Figure A.14 to Figure A.17 in Appendix A.

Estimates of the median concentration are conservative except for the Porirua at Milk Depot site (Figure 6.2 and Figure 6.3). The Porirua at Milk Depot site is immediately downstream of the confluence with the Mitchell stream, where the estimated median is higher than the observed. These two sites have a relatively large industrial area (1.6% of total area – Milk Depot and 4.9% - Mitchell stream) within their catchments, suggesting variability in Zn yield across industrial land uses within the Whaitua.

In general, modelled concentrations are less variable than the observed data – the modelled means and medians are higher than the observed (except at Porirua at Milk Depot), while the 95th percentile is lower (except at Mitchell stream at Porirua stream). This is in part due to the averaging of the daily modelled concentrations to compare to the monthly grab samples.

Table 6.5: Dissolved Zinc calibration summary statistics

Statistic	Porirua at Glenside		Porirua at Milk Depot		Kenepuru at Mepham Crescent		Mitchell Stream at Porirua	
	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM
Median (g/m^3)	0.005	0.007	0.024	0.011	0.005	0.007	0.012	0.018
Mean (g/m^3)	0.007	0.007	0.032	0.013	0.008	0.007	0.012	0.019
95th Percentile (g/m^3)	0.016	0.012	0.081	0.022	0.016	0.010	0.018	0.031
PBIAS	9%		-61%		-7%		53%	

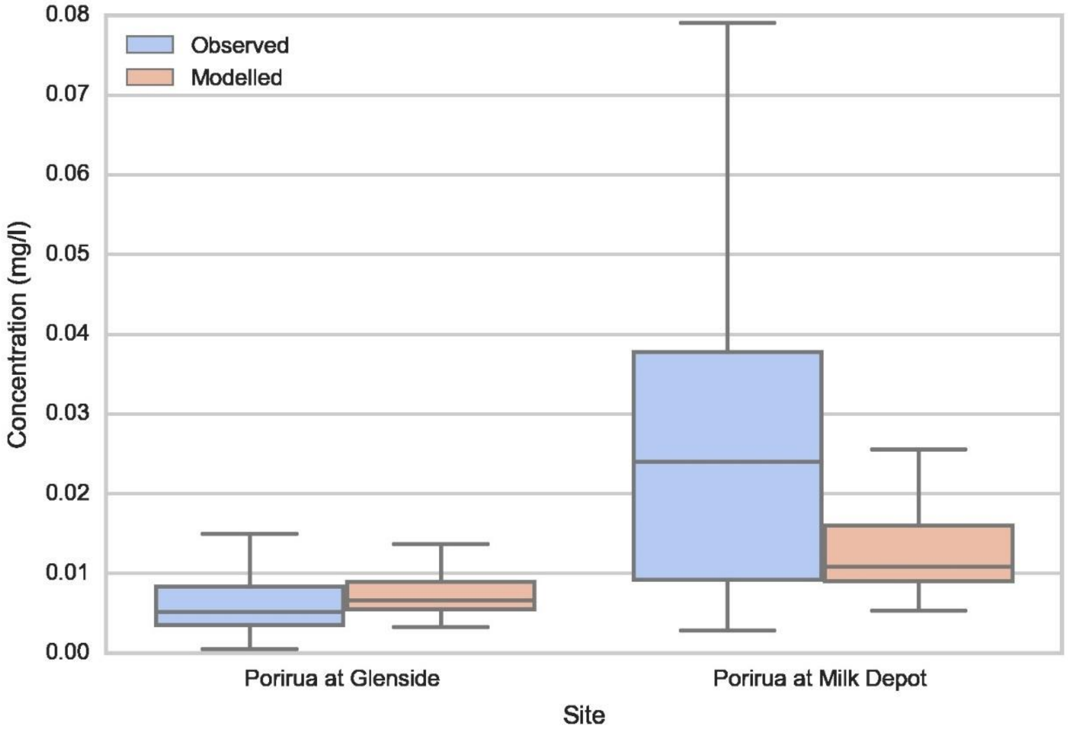

Figure 6.2: Boxplot comparison for Dissolved Zinc concentration at two calibration sites.

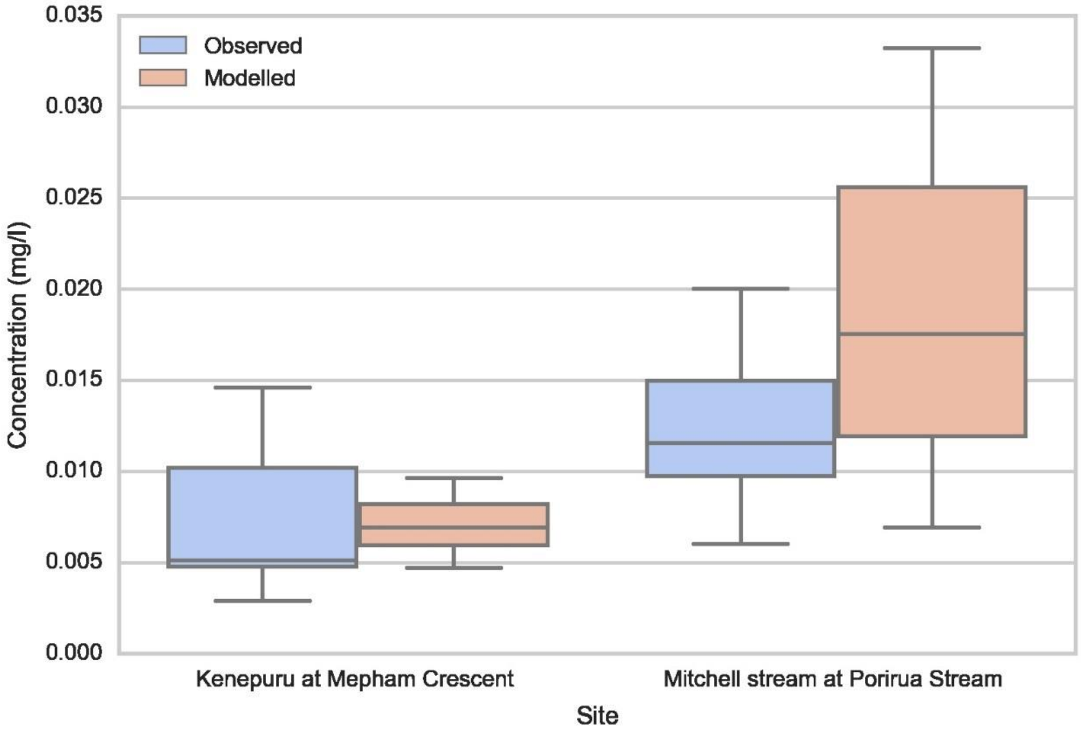

Figure 6.3 Boxplot comparison for Dissolved Zinc concentration at two validation sites.

6.2.2 Dissolved Copper Calibration and Validation

Calibration summary statistics are shown in Table 6.6. Figure A.18 to Figure A.21 in Appendix A plot the monthly observed and mean monthly modelled Cu concentrations for the calibration and validation sites.

Based on Moriasi et al. (2007), the calibration achieves a 'good' result for Porirua at Milk Depot and Porirua at Glenside. Validation achieves a 'good' result for Kenepuru at Mepham Crescent and Mitchell Stream at Porirua. Estimates of the mean and median concentration are conservative (Figure 6.4 and Figure 6.5), except for the Porirua at Milk Depot site. Like the Zn calibration, estimates for Cu are higher than the observed data for the Mitchell Stream at Porirua Stream site, indicating relatively low yielding FUs within the Mitchell Stream catchment.

Table 6.6: Dissolved Copper calibration summary statistics

Statistic	Porirua at Glenside		Porirua at Milk Depot		Kenepuru at Mepham Crescent		Mitchell Stream at Porirua	
	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM
Median (g/m^3)	0.0009	0.0014	0.0017	0.0013	0.0010	0.0017	0.0010	0.0012
Mean (g/m^3)	0.0011	0.0015	0.0025	0.0015	0.0013	0.0017	0.0011	0.0013
95^{th} Percentile (g/m^3)	0.0019	0.0024	0.0086	0.0025	0.0026	0.0023	0.0018	0.0022
PBIAS	31%		-40%		29%		19%	

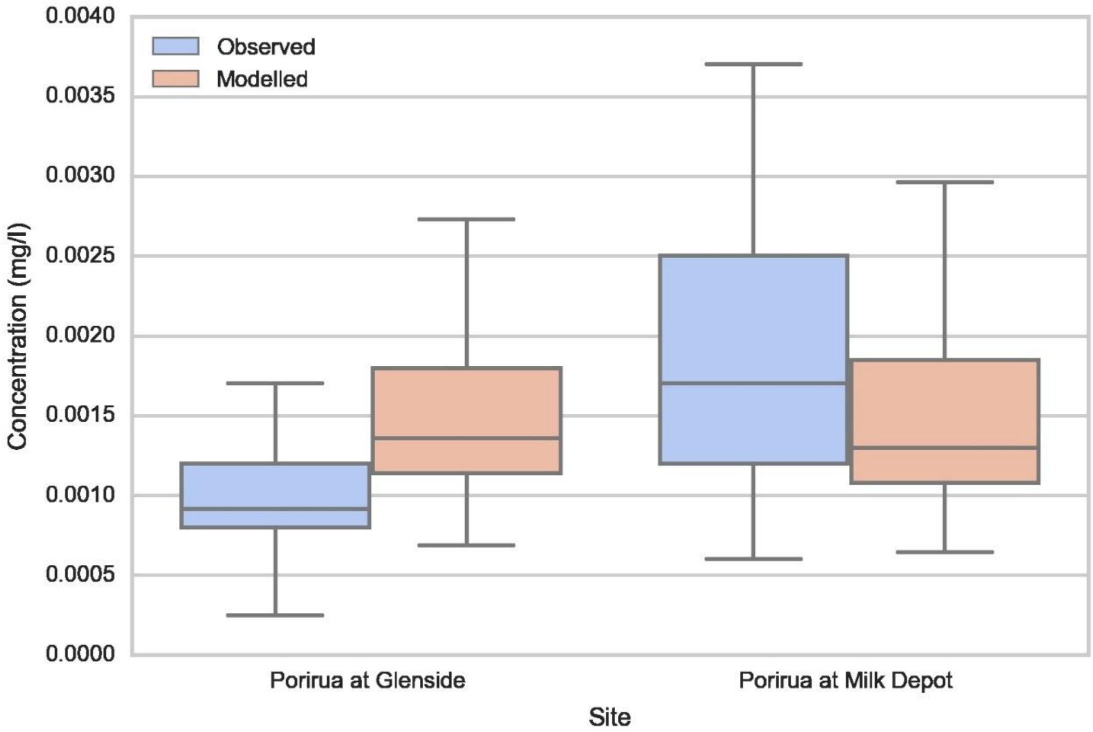

Figure 6.4: Boxplot comparison for Dissolved Copper concentration at two calibration sites

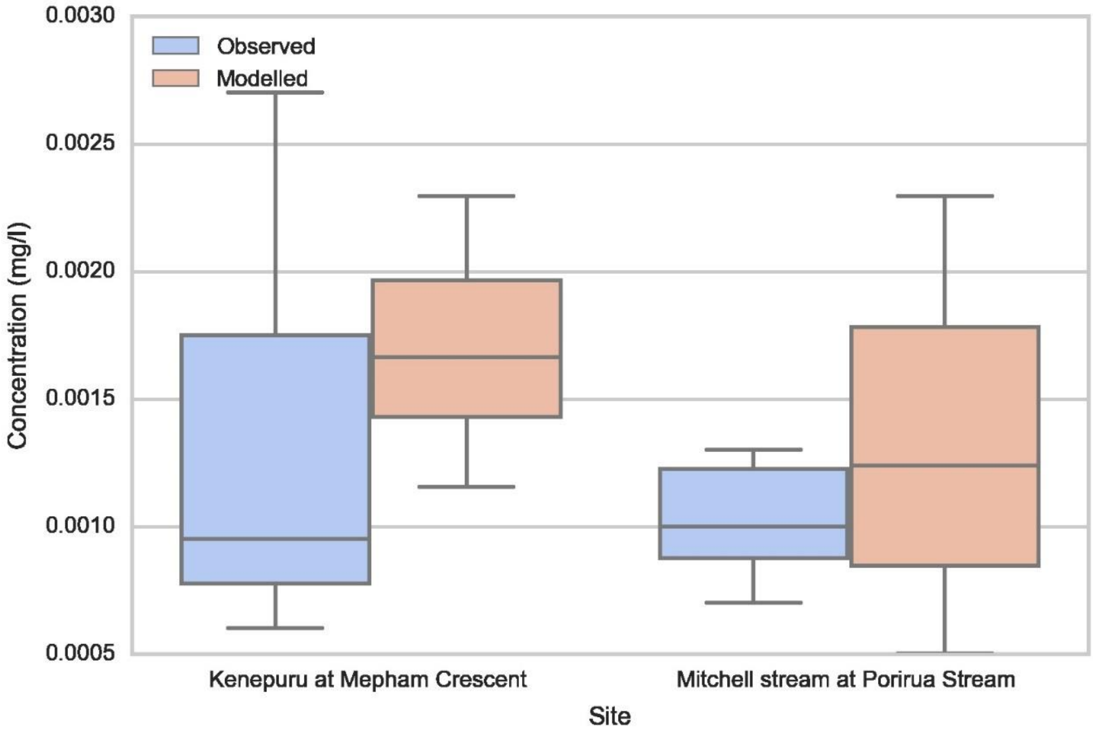

Figure 6.5: Boxplot comparison for Dissolved Copper concentration at two validation sites

6.3 Estimation of Total Metals

EMC and DWC values for total metals have been derived from the CLM customisation (Table 6.2). The EMC values are equal to the CLM derived concentrations and the DWC values are estimated as 20% of the EMC values following the dissolved model calibration. The total metal model is uncalibrated as no observation data are available for comparative purposes.

7. Baseline *E. coli* Model

E. coli generation and transport is simulated using an EMC/DWC approach. EMC/DWC model parameters are specified for each FU. In-stream die-off processes were collectively represented by decay (half-life) functions within the model links. The half-life values are utilised as a calibration factor and encompass multiple attentuation processes including die-off, inactivation in soil, predation, and time of concentration.

Routine monthly *E. coli* data were available at four sites; Horokiri at Snodgrass, Pauatahanui at Elmwood Bridge, Porirua Stream at Milk Depot and Porirua Stream at Glenside Overhead Cables. The number of data observations and date range selected for calibration is provided in Table 7.1.

Table 7.1: Monthly sampled calibration data

Calibration Site	Date Range	Number of Observations	Calibration / validation
Horokiri Stream at Snodgrass	September 2003 – September 2016	154	Calibration
Pauatahanui Stream at Elmwood Bridge	October 2003 – September 2016	155	Calibration
Porirua Stream at Milk Depot	September 2003 – September 2016	155	Calibration
Porirua Stream at Glenside Overhead Cables	September 2003 – June 2016	152	Calibration

7.1 *E. coli* Generation Rates

EMC/DWCs for urban FUs were adopted from mean concentrations derived from the customised CLM (Moores et al., 2017) yields based on regional and national stormwater sampling data. Initially rural *E. coli* concentrations were adopted from annual yields derived from CLUES modelling (converted to concentrations using modelled flows from the Source model). However, these concentrations required adjustment, within literature ranges (Table 7.2), to obtain a better fit to the in-stream observed *E. coli* data. Waste water overflows were represented as point sources (see Section 2.2.3) with an *E. coli* concentration of 1,000,000 cfu/100mL.

Table 7.2: Literature ranges of *E. coli* concentration (cfu/100 ml) for different land uses.

FC or *E. coli* ranges (CFU/100mL)	Min	Max	Reference
General livestock/pasture	1,200	4,350	Long and Plummer (2004)
Agriculture	6,160	40,000	Stein et al. (2008)
Forest	130	400	Long and Plummer (2004)
General urban stormwater	100	1,100,000	Davies and Bavor (2000)
	84	33,800	KCDC sampling data 2006-2015 (Jacobs, 2015)
	2,300	48,000	GWRC Porirua event sampling 2017
	1,255	33,800	GWRC spot sampling 2017 - Harbour sites
General Residential	700	2,600	Long and Plummer (2004)
	8,200	30,000	Stein et al. (2008)
Commercial	4,000	11,000	Stein et al. (2008)
Industrial	1,500	3,800	Stein et al. (2008)
Transportation (roads)		1,400	Stein et al. (2008)
Open space	5,400	7,200	Stein et al. (2008)

7.2 Calibration Results and Discussion

Calibration was performed based on comparisons of the modelled daily concentration to the corresponding day's sample observation for four calibration sites. Simulated *E. coli* concentrations for each calibration site were assessed against observed monitoring data using:

- Percent bias (% difference between modelled and observed concentrations);
- Box-whisker plots (illustrating the median, 25th and 75th percentiles – the box; 1.5× interquartile range above or below the 25th and 75th percentiles – the whiskers); and
- Exceedance curves.

Initial parameters were derived from the customised CLM annual yields as an average concentration and converted to EMC/DWC parameters during calibration (Table 7.3). Half-life parameters were also calibrated (Table 7.4), characterised by increased attenuation in the rural environment compared to urban. A regional half-life value was applied to links downstream of the Porirua at Glenside monitoring site to achieve a satisfactory calibration at Glenside and Milk Depot, both of which are on the main Porirua stream stem.

Simulation of microbial concentrations with a semi-distributed 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.

Overall, the model performed very well, demonstrated by the low PBIAS statistic for each calibration site and a good fit to the overall distribution of *E. coli* concentrations as demonstrated by the summary statistics in Table 7.5 and box-whisker plots in Figure 7.1. The model was also able to perform well in terms of event concentrations as demonstrated by the good fit to observed 95th percentile concentrations and the exceedance curves in Figure 7.2.

Table 7.3 Initial and final calibrated EMC/DWC parameters for *E. coli*.

Land use	*E. coli* (cfu/100ml)		
	Initial concentration derived from customised CLM and CLUES annual yields	Final Calibrated Parameters	
		EMC	DWC
Commercial Paved	8,056*	10,000*	2,000*
Industrial Paved	8,229*	10,000*	2,000*
Residential Paved	8,099*	10,000*	2,000*
Roads 1000	7,854*	10,000*	2,000*
Roads 1000-5000	7,744*	10,000*	2,000*
Roads 5000-20000	7,909*	10,000*	2,000*
Roads 20000-50000	7,909*	10,000*	2,000*
Roads 50000-100000	7,124*	10,000*	2,000*
Commercial Roof	7,869*	10,000*	2,000*
Industrial Roof	8,157*	10,000*	2,000*
Residential Roof	7,926*	10,000*	2,000*
Urban Grassland	19,144*	10,000*	2,000*
Other	52	78	15
Natural Forest	61	92	18
Plantation Forest	62	93	18
Scrub	95	143	29
Sheep and Beef Hill	15,849	23,774	4,755
Other Animals	94	141	29
Sheep and Beef Intensive	17,119	25,679	5,136
Deer	21,825	32,738	6,548
Horticulture	41	62	12
Construction Site	0	0	0

* Assuming urban stormwater is contaminated with wastewater from cross-connections etc. Where wastewater contamination is absent, a lower *E. coli* yield is proposed in the customised CLM (Moores et. al 2017).

Table 7.4: Calibrated half-life values of *E. coli* in links for different land uses

Land use	Half-life (days)
Rural	0.45
Urban	0.65
Porirua d/s Glenside	1.2

Table 7.5: Statistical comparisons for daily observed and simulated *E. coli* data at different sites (cfu/100ml).

Statistic	Horokiri Stream at Snodgrass		Pauatahanui Stream at Elmwood Bridge		Porirua Stream at Milk Depot		Porirua Stream at Glenside	
	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM
Median (cfu/100ml)	315	182	315	256	900	927	340	654
Mean (cfu/100ml)	617	548	789	2833	1651	1586	823	1238
95th Percentile (cfu/100ml)	2540	2778	3070	2833	6750	5014	2777	4095
PBIAS	-9.1%		-10.9%		-2.2%		54.3%	

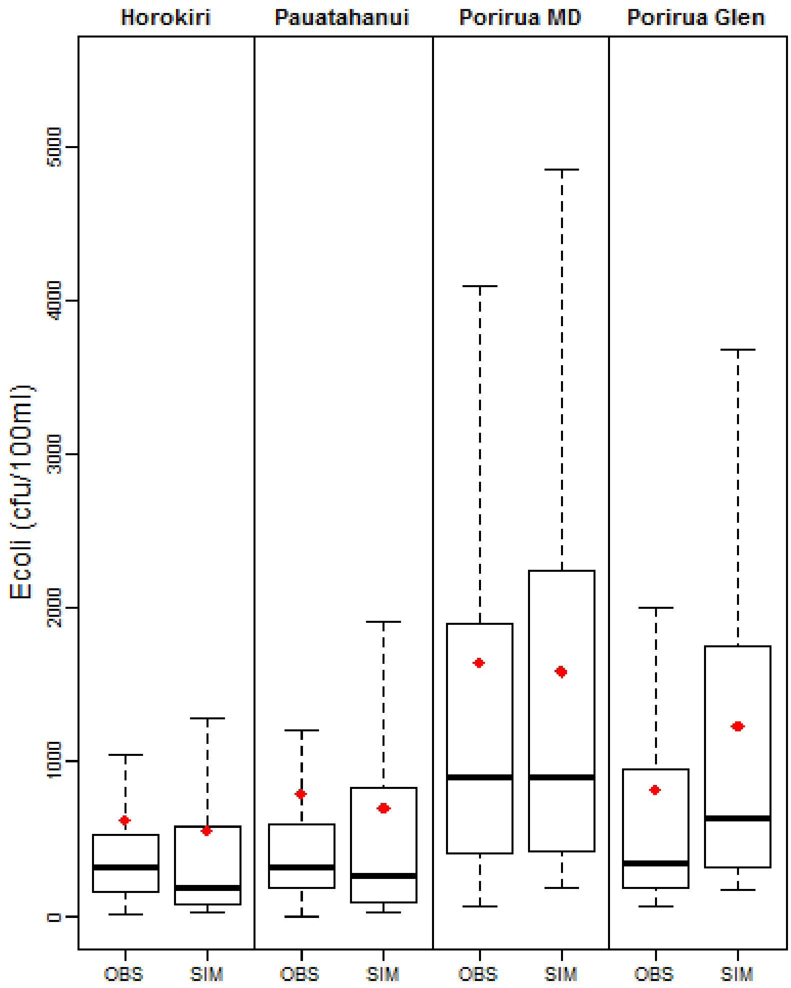

Figure 7.1: Boxplot comparisons of observed and simulated data for *E. coli*.

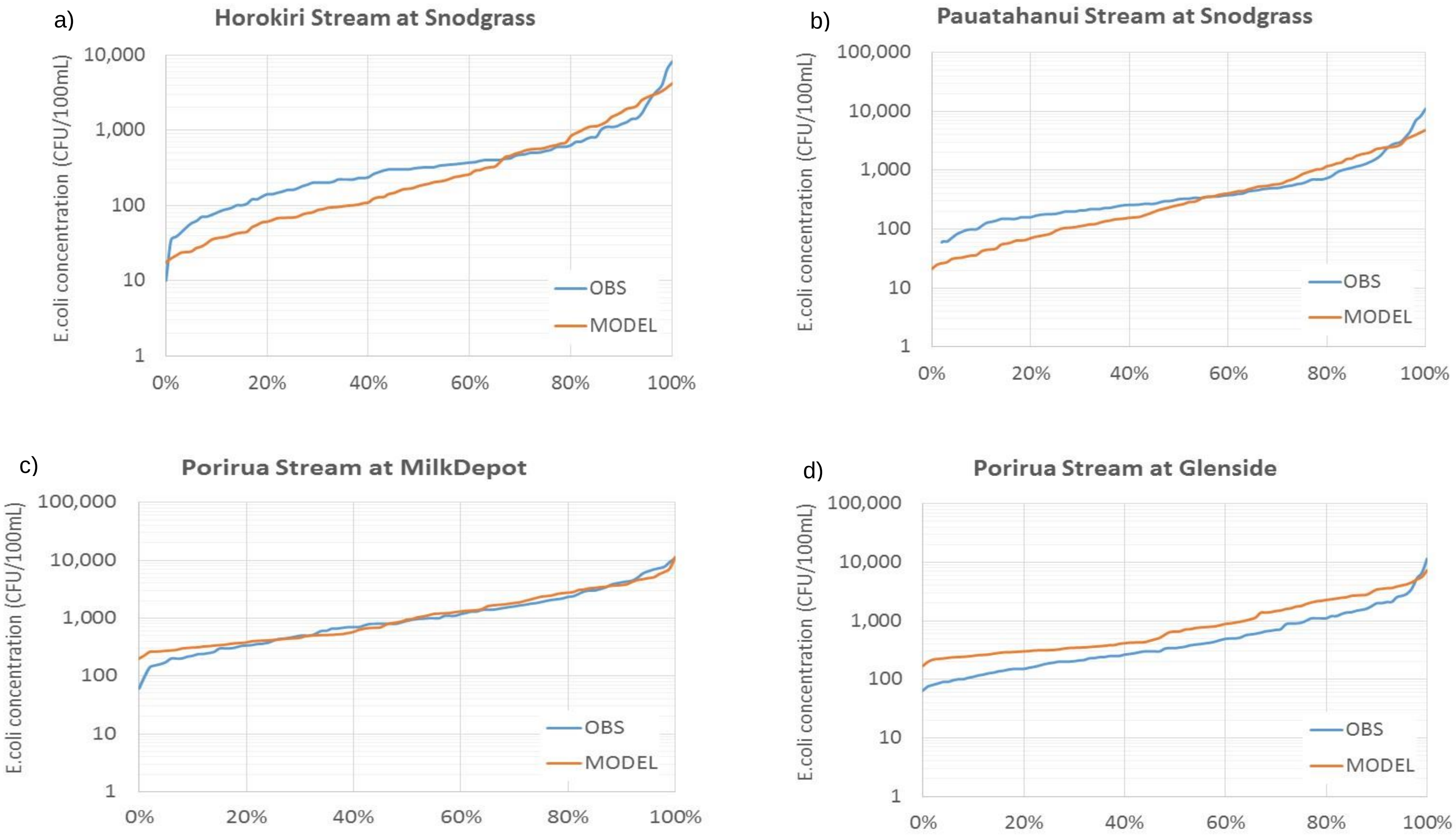

Figure 7.2: Exceedance curve for observed and simulated *E. coli* at: a) Horokiri Stream at Snodgrass; b) Pauatahanui Stream at Elmwood Bridge; c) Porirua Stream at Milk Depot and d) Porirua Stream at Glenside Overhead Cables.

8. Attribute states

The NPSFM (2017) provides an approach for regional councils to establish freshwater objectives that are consistent with the National Objective Framework (NOF) by means of attribute states of freshwaters. For nutrients, the NOF includes defined attribute states for ecological toxicity from Nitrate-Nitrogen and Ammoniacal-Nitrogen in rivers and provides Human Health for Recreation (swimmability) attribute states using E. coli as a measure of primary contact suitability. As dissolved metals are not included in the NOF banding system in the NPSFM at the time of writing, proxy attribute states have been developed by the Whaitua MLG. Proxy attribute states for Cu and Zn are based on ANZECC (2000) guidelines and designed to follow the NOF structure for other contaminants (see section 8.3).

This section assesses and compares the baseline attribute states as predicted by the calibrated Source model and include the wastewater overflow inputs (see section 2.2.3). The data period assessed for the observed and modelled NOF banding is equivalent to the coincident period of the observation record (site and constituent dependent) and the wastewater overflow time-series (2005-2014) to allow comparison between observed data and model results. Modelled NOF bands are derived using the modelled daily water quality time-series, reflecting the intended use of the Source model during scenario modelling.

Comparison of simulated attribute banding to observed data is an important check to ensure information provided to the Whaitua committee is consistent to the regulatory framework under which decisions are to be made. However, the attribute state predicted by the model and observed data may not perfectly align as observed data is collected monthly, generally during dry weather, resulting in a potentially non-representative data series especially for higher concentrations, e.g. 95th percentile and maximum. Similarly, attribute states for the data period to be utilised for scenario modelling, 2005 – 2014, may be different to the period reported here, driven by changes in climate and subsequent runoff response. A different NOF band than displayed here may also be reported for the observed data where a different or more recent data period is used.

8.1 Nutrient Attribute States

Table 8.1 describes the NOF attribute states ranging from A to D for Nitrate and Ammoniacal Nitrogen and the potential effects on aquatic species. Table 8.2 and Table 8.3 compare the observed and predicted NOF bands for NO_3-N and NH_4-N, respectively, using the monthly observed and daily modelled water quality time-series for the period 2005-2014.

Modelled median and 95th percentile values in Table 8.2 and Table 8.3 differ compared to Table 5.5 as they are for a different period, and are derived from the daily timeseries instead of the monthly mean as was utilised for calibration (see section 5.2). Observed median and 95th percentile values in Table 8.2 and Table 8.3 differ compared to Table 5.5 as they are for the period coincident with the available wastewater overflow time-series, rather than the full observation record.

Comparison of the observed and model derived NOF attribute states in Table 8.2 and Table 8.3 shows agreement for median and 95th percentile NO_3-N concentrations, predicting the same overall NOF category as for the observed record. The median NH_4-N concentration is well predicted by the model, while the maximum NH_4-N concentration is overestimated at Porirua at Glenside. For the urban sites on the Porirua stream such as Porirua at Glenside, observed maximums are driven by wastewater overflows that may not captured during monthly spot sampling.

Overall, the model predicts attribute states well for NO_3-N and NH_4-N, predicting within one band of the observed time-series for all sites.

Table 8.1: Description of Attribute state for freshwater body for Nitrate and Ammonia.

Attribute	NPS Attribute State				
Narrative Attribute State	*99% species protection level: No observed effect on any species tested*	*95% species protection level: Starts impacting occasionally on the 5% most sensitive species*	*80% species protection level: Starts impacting regularly on the 20% most sensitive species (reduced survival of most sensitive species)*		*Starts approaching acute impact level (i.e. risk of death) for sensitive species*
Nitrate-Nitrogen (mg/L)	**A** Annual median ≤ 1 Annual 95th percentile ≤ 1.5	**B** Annual median > 1 and ≤ 2.4 Annual 95th percentile > 1.5 and ≤ 3.5	**C** Annual median > 2.4 and ≤ 6.9 Annual 95th percentile > 3.5 and ≤ 9.8	**National Bottom Line** Annual median 6.9 Annual 95th percentile 9.8	**D** Annual median > 6.9 Annual 95th percentile > 9.8
Ammoniacal Nitrogen (mg/L)	**A** Annual median ≤ 0.03 Annual maximum ≤ 0.05	**B** Annual median > 0.03 and ≤ 0.24 Annual maximum > 0.05 and ≤ 0.4	**C** Annual median > 0.24 and ≤ 1.3 Annual maximum > 0.4 and ≤ 2.2	**National Bottom Line** Annual median 1.3 Annual maximum 2.2	**D** Annual median > 1.3 Annual maximum > 2.2

Table 8.2: Nitrate Nitrogen comparison of observed data and modelled outputs following the criteria in National Policy Statement for Freshwater Management, 2017. Concentration (mg/L) given in parentheses.

Calibration Site		Median	95th percentile	Overall attribute State
Horokiri at Snodgrass	OBS	A (0.41)	A (1.06)	A
	MODEL	A (0.28)	A (1.50)	A
Pauatahanui at Elmwood	OBS	A (0.21)	A (0.73)	A
	MODEL	A (0.18)	A (1.32)	A
Porirua Milk Depot	OBS	A (0.92)	B (1.75)	B
	MODEL	A (0.58)	B (1.78)	B
Porirua Glenside	OBS	A (1.00)	B (1.80)	B
	MODEL	A (0.69)	B (2.10)	B

Table 8.3 Ammoniacal Nitrogen comparison of observed data and modelled outputs following the criteria in National Policy Statement for Freshwater Management, 2017. Concentration (mg/L) given in parentheses.

Calibration Site		Median	Maximum	Overall attribute State
Horokiri at Snodgrass	OBS	A (0.01)	A (0.04)	A
	MODEL	A (0.01)	A (0.05)	A
Pauatahanui at Elmwood	OBS	A (0.01)	B (0.16)	B
	MODEL	A (0.01)	B (0.06)	B
Porirua Milk Depot	OBS	A (0.01)	C (0.85)	C
	MODEL	A (0.01)	C (1.79)	C
Porirua at Glenside	OBS	A (0.01)	B (0.22)	B
	MODEL	A (0.02)	C (1.25)	C

8.2 Human Health Attribute States

The NPSFM (amended 2017) provides Human Health for Recreation (swimmability) Attribute States driven by *E. coli* as a measure of primary contact suitability (Table 8.4). Modelled and observed NOF bands are derived for the period 2005-2014 (inclusive), corresponding to the available wastewater overflow timeseries.

Statistical values provided in Table 8.5 differ compared to Table 7.5 as they are for a different period and are derived from the full daily timeseries. Observed statistics in Table 8.5 differ compared to Table 7.5 as they are for the period coincident with the available wastewater overflow time-series, rather than the full observation record.

Table 8.5 shows that the streams within the TAoPW have poor water quality for all statistical measures as calculated from observed data, and the model is generally reproducing these results. The exception is the Horokiri site where the simulated outputs fall into the D category rather than the E category as shown by the observed data.

A contributing reason for the poor swimmability (independent from generation rates from various land uses) is the lack of dilution in streams. In catchments with larger rivers, increased flow can help dilute the *E. coli* concentration, buffering effects from land use.

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Table 8.4: Statistical measures for Human Health for Recreation Attribute States (Ministry for the Environment, 2017)

Category	% of exceedances over 540 cfu/100mL	Median concentration (cfu/100mL)	95th percentile *E. coli* cfu/100mL	% of exceedances over 260 cfu/100mL
A (Blue)	< 5%	≤ 130	≤ 540	< 20%
B (Green)	5 – 10%	≤ 130	≤ 1000	20 – 30 %
C (Yellow)	10 – 20%	≤ 130	≤ 1200	20 – 34%
D (Orange)	20 – 30%	>130	>1200	>34%
E (Red)	>30%	>260	>1200	>50%

Table 8.5: Comparison of observed and simulated statistics for NPS Human Health Attribute States.

Calibration Site		Median (cfu/100ml)	95th Percentile (cfu/100ml)	Exceedances over 260 cfu/100ml (%)	Exceedances over 540 cfu/100ml (%)	Attribute State
Horokiri Snodgrass	OBS	E (300)	D (1720)	E (57%)	C (19%)	E
	MODEL	D (166)	D (2717)	D (41%)	D (28%)	D
Pauatahanui Elmwood	OBS	E (300)	D (2905)	E (55%)	D (23%)	E
	MODEL	D (231)	D (3018)	D (47%)	E (33%)	E
Porirua Milk Depot	OBS	E (800)	D (6910)	E (83%)	E (63%)	E
	MODEL	E (891)	D (5817)	E (96%)	E (65%)	E
Porirua Glenside	OBS	E (290)	D (2565)	E (53%)	E (31%)	E
	MODEL	E (738)	D (4764)	E (99%)	E (62%)	E

8.3 Metal attribute states

As dissolved metals are not included in the NOF banding system in the NPSFM at the time of writing, proxy attribute states have been developed by the MLG. Proxy attribute states are based on ANZECC (2000) guidelines and designed to follow the NOF structure for other contaminants. Proxy attribute states are shown for dissolved Zn in Table 8.6 and Cu in Table 8.7.

For the Porirua at Glenside and Porirua at Milk Depot sites, the data period utilised to derive the observed and modelled NOF bands is between 2008 – 2014, corresponding to the beginning of the observation period and the end of the wastewater overflow timeseries. For the Kenepuru at Mepham Crescent and Mitchell stream sites, the data period is July 2011 – June 2012, corresponding to the full observation record.

Comparison of the observed and model derived attribute states in Table 8.8 and Table 8.9 shows that the model predicts within one band for both Zn and Cu for the calibration sites. Zn attribute states match the observed data for the median but under-predict the 95th percentile banding for Porirua at Milk Depot and over-predict for the Mitchell stream. Cu attribute states are under-predicted for the median at Porirua at Milk Depot, over-predict for the 95th percentile at Porirua Glenside, Kenepuru at Mepham Crescent, and Mitchell stream. For these sites, the monthly spot-sample record may not adequately capture the higher concentrations associated with medium - large rainfall events and wastewater overflows as predicted by the model.

Table 8.6 Proxy attribute state for dissolved Zinc

Attribute State	Species Protection	Median below (mg/l)	95th percentile below (mg/l)
A	50% time protect >99% species from chronic toxicity 95% time protect >95% species from chronic toxicity	0.0024	0.008
B	50% time protect >95% species from chronic toxicity 95% time protect >90% species from chronic toxicity	0.008	0.015
C	50% time protect >80% species from chronic toxicity 95% time protect species from acute toxicity	0.031	0.042
D	Chronic and acute toxicity may occur	>0.031	>0.042

Table 8.7 Proxy attribute state for dissolved Copper

Attribute State	Species Protection	Median below (mg/l)	95th percentile below (mg/l)
A	50% time protect >99% species from chronic toxicity 95% time protect >95% species from chronic toxicity	0.001	0.0014
B	50% time protect >95% species from chronic toxicity 95% time protect >90% species from chronic toxicity	0.0014	0.0018
C	50% time protect >80% species from chronic toxicity 95% time protect species from acute toxicity	0.0025	0.0043
D	Chronic and acute toxicity may occur	>0.0025	>0.0043

Table 8.8 Dissolved Zinc attribute states

Calibration Site		Median	95th percentile	Overall attribute State
Porirua Glenside	OBS	B (0.006)	C (0.016)	C
	MODEL	B (0.005)	C (0.022)	C
Porirua at Milk Depot	OBS	C (0.025)	D (0.078)	D
	MODEL	C (0.008)	C (0.041)	C
Kenepuru at Mepham Crescent	OBS	B (0.005)	C (0.016)	C
	MODEL	B (0.005)	C (0.019)	C
Mitchell stream at Porirua Stream	OBS	C (0.012)	C (0.018)	C
	MODEL	C (0.008)	D (0.076)	D

Table 8.9 Dissolved Copper attribute states

Calibration Site		Median	95th percentile	Overall attribute State
Porirua Glenside	OBS	B (0.0010)	C (0.0019)	C
	MODEL	B (0.0010)	D (0.0044)	D
Porirua at Milk Depot	OBS	C (0.0019)	D (0.0078)	D
	MODEL	B (0.0010)	D (0.0048)	D
Kenepuru at Mepham Crescent	OBS	B (0.0010)	C (0.0026)	C
	MODEL	B (0.0012)	D (0.0044)	D
Mitchell stream at Porirua Stream	OBS	B (0.0010)	C (0.0018)	C
	MODEL	A (0.0006)	D (0.0053)	D

9. Conclusion

An integrated flow and water quality model of the Te Awarua-o-Porirua harbour catchments using the eWater Source framework has been developed to inform GWRC and the Whaitua Committee in their task to develop a Whaitua Implementation Programme. The developed model predicts daily flows and associated loads and concentrations for Suspended Sediment (SS), *E. coli,* Total Nitrogen (TN), Nitrate–Nitrogen (NO_3), Ammoniacal–Nitrogen (NH_4-N), Total Phosphorus (TP), Dissolved Reactive Phosphorous (DRP), Total Copper (Total Cu), Dissolved Copper (Dissolved Cu), Total Zinc (Total Zn), and Dissolved Zinc (Dissolved Zn).

Model architecture and calibration decisions were designed to accurately represent the current conditions in the Whaitua as well as to facilitate the testing of yet to be defined (at the time of baseline model development) alternative scenarios involving stormwater treatment, contaminant source control, and land use change. Constituent generation is driven by diffuse yields associated with detailed land use mapped spatially across the Whaitua. Point source loads associated with wastewater overflows are also accounted for using modelled outputs provided by Wellington Water.

Model parameterisation utilised data from literature sources, local in-stream monitoring, and previously developed average annual yield models. In urban areas, model parameterisation draws heavily from the annual average customised CLM yields developed in the first phase of the Te Awarua-o-Porirua Whaitua modelling programme (Moores et al. 2017). In rural areas, model parameterisation for nutrients and *E. coli* is informed by yields derived from CLUES, supplied by NIWA. Observed data for flow, suspended sediment, nutrients, metals and *E. coli* were sourced from GWRC.

The model generally performed well to represent the temporal and spatial variability of flow, suspended sediment, nutrients, metals, and *E. coli* in the catchment, for both urban and rural land uses.

In general, the model calibrates well to observed flow. Rainfall-runoff parameters were calibrated to four locations representative of the largest catchments in the Whaitua. The application of the calibrated rainfall-runoff parameters to the remaining catchments is justified, however flow predictions for small urban catchments are uncertain, as hydrology for these catchments is likely to be ‘flashy’ with runoff response times difficult to accurately represent in a daily model. Furthermore, flow calibration was most uncertain during low-flows, which may result in contaminant load underestimation when baseflow is dominant. Underestimation of low flows is acceptable in this context as the assessment of constituent loads will be driven by peak flow events within the catchment, particularly in urban areas.

The suspended sediment sub-model simulates sediment generation from three sources – hillslope erosion, streambank erosion, and shallow landslides. The proportionality between these three sources was determined during calibration to the observed time-series based on known physical processes but is uncalibrated due to data scarcity and remains uncertain. The combined suspended sediment loads from the simulated generation processes calibrated well to observed load, particularly average annual loads and the mean, median, 5^{th} percentile and 95^{th} percentile loads for the daily time-series. The Pauatahanui at Gorge site was the most uncertain. The relatively short observed data time-series utilised for calibration also means that peak events, largely attributed to streambank and landslide processes, remain somewhat uncertain due to the lack of calibration points.

Despite the identified uncertainties, the described sediment modelling approach represents a novel methodology that offers increased utility and resolution of erosion processes than previous annual scale models (compared in 4.3.1). The approach allows mitigation options such as pole planting, retirement, and constructed wetlands to be tested during scenarios, with model outputs expressed as daily in-stream SS concentrations and loads to Te Awarua-o-Porirua receiving environment. The comparison of model results as load and concentration time-series provides for wider ecosystem health assessment and linkage to other models, e.g. hydrodynamic harbour modelling for sediment deposition and stream habitat assessment.

Nutrients were calibrated first for TN and TP, before speciation factors based on observed data were used to estimate concentrations of NO_3-N, NH_4-N, and DRP. Despite some challenges in simulating peak TP events in urban streams, and the underestimation of the annual maximum for Ammoniacal-Nitrogen, the model was satisfactorily calibrated and is fit for purpose to assess relative change following mitigation during scenario modelling.

Dissolved metals achieved satisfactory calibration criteria, however uncertainty exists in the yields of Dissolved Zn and Dissolved Cu for urban land uses within the applied FU categorisation. As the model operates at a daily time-step, sub-daily peak concentrations associated with ‘first flush’ responses are not represented. Total Zn and Cu were estimated based on the yields developed for the customised CLM and are uncalibrated to in-stream records.

For *E. coli*, the model calibrated very well to the in-stream observed time-series. Application of the NPS-FM primary contact statistical guidelines show that the water quality in the Whaitua is generally poor and largely unsuitable for primary contact.

The observed water quality data utilised for parameterisation and calibration was generally based on monthly water quality monitoring. Normally, 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. 95^{th} percentiles).

The developed model is fit for purpose to be used to test the relative changes in water quality for alternative development scenarios and inform decision making by the Whaitua committee under the regulatory framework of the NPS-FM.

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Appendix A. Calibration plots

A.1 Flow calibration time-series plots

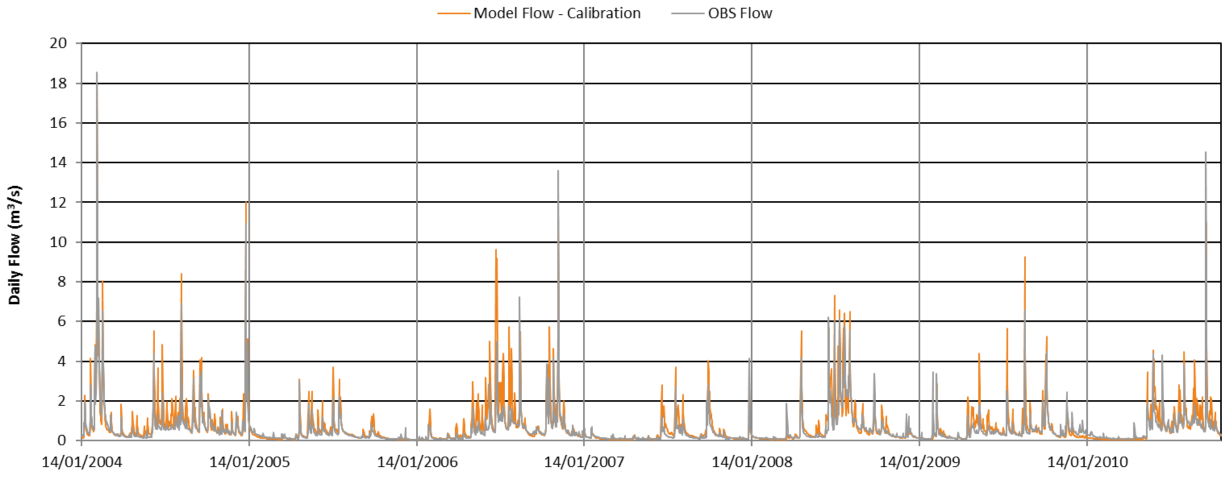

Figure A.1: Horokiri at Snodgrass Flow – Calibration period

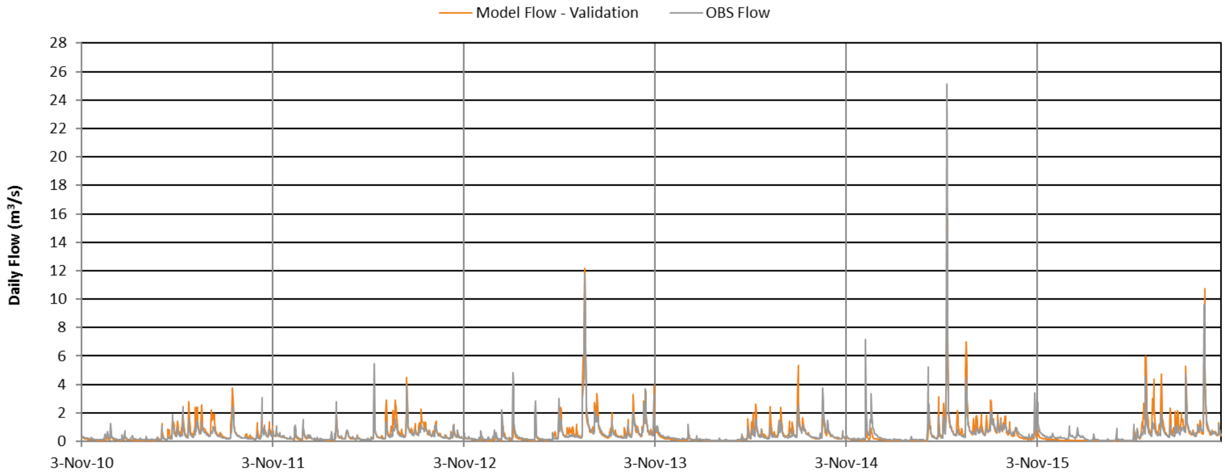

Figure A.2: Horokiri at Snodgrass Flow – Validation period

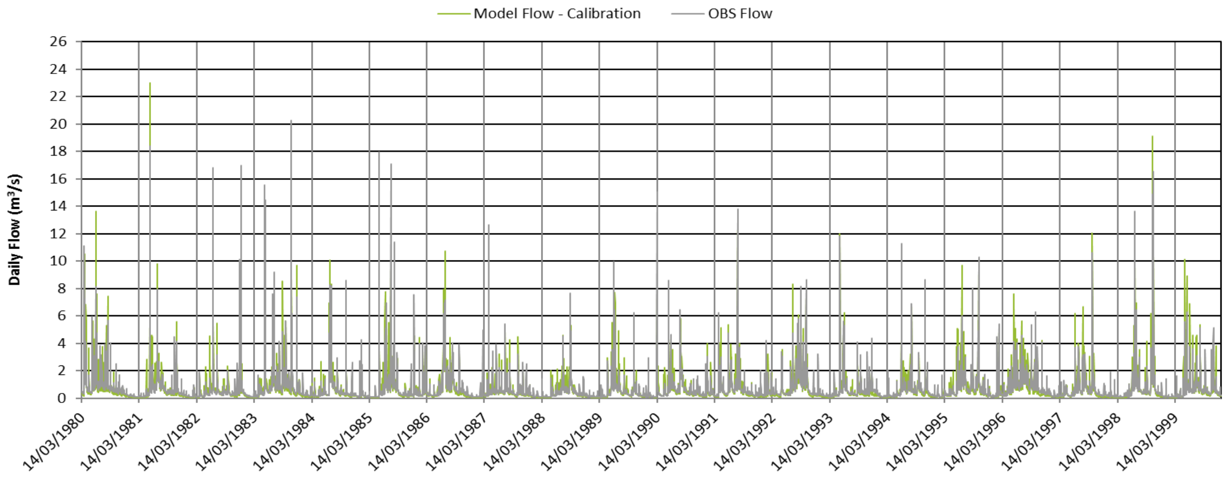

Figure A.3: Pauatahanui at Gorge Flow – Calibration period

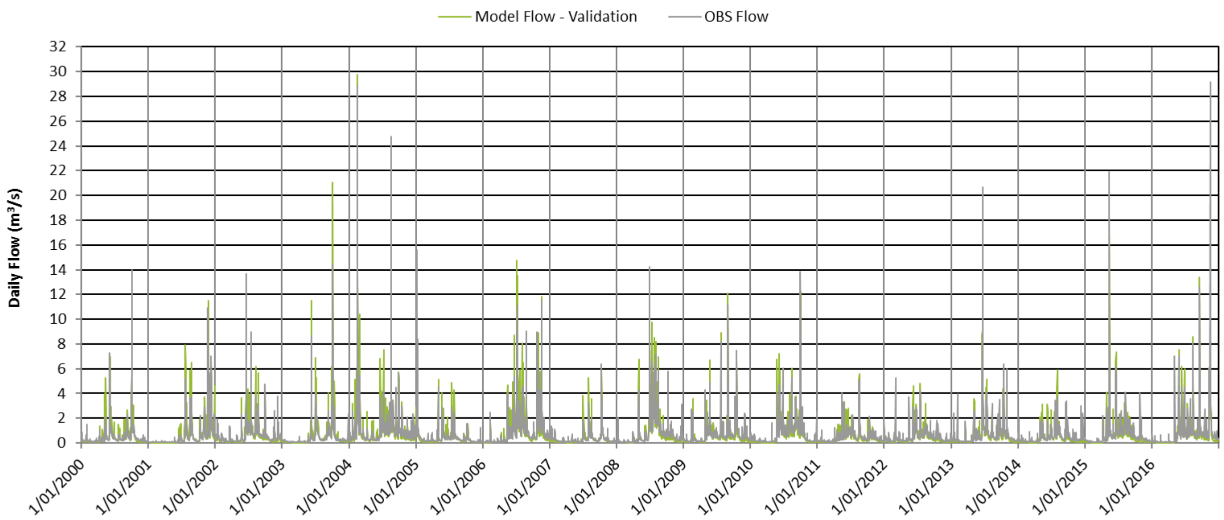

Figure A.4: Pauatahanui at Gorge Flow – Validation period

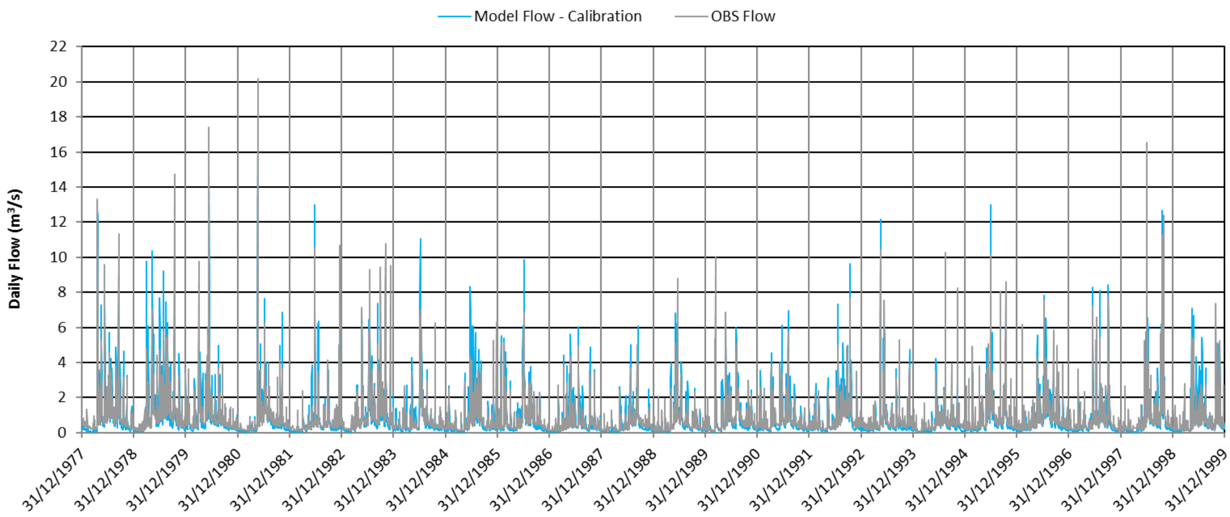

Figure A.5: Porirua at Town Centre Flow – Calibration period

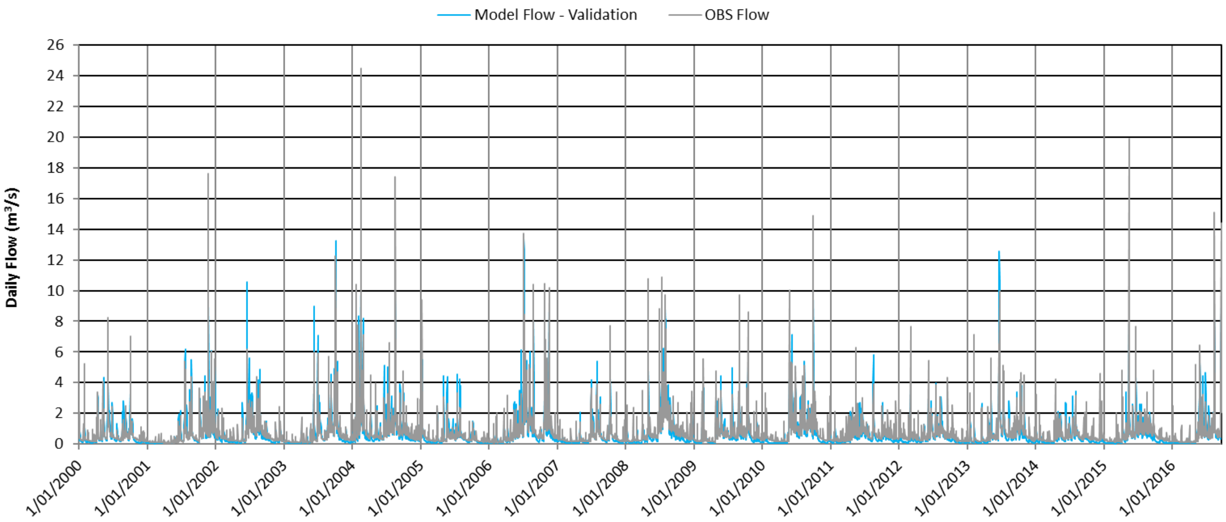

Figure A.6: Porirua at Town Centre Flow - Validation Period

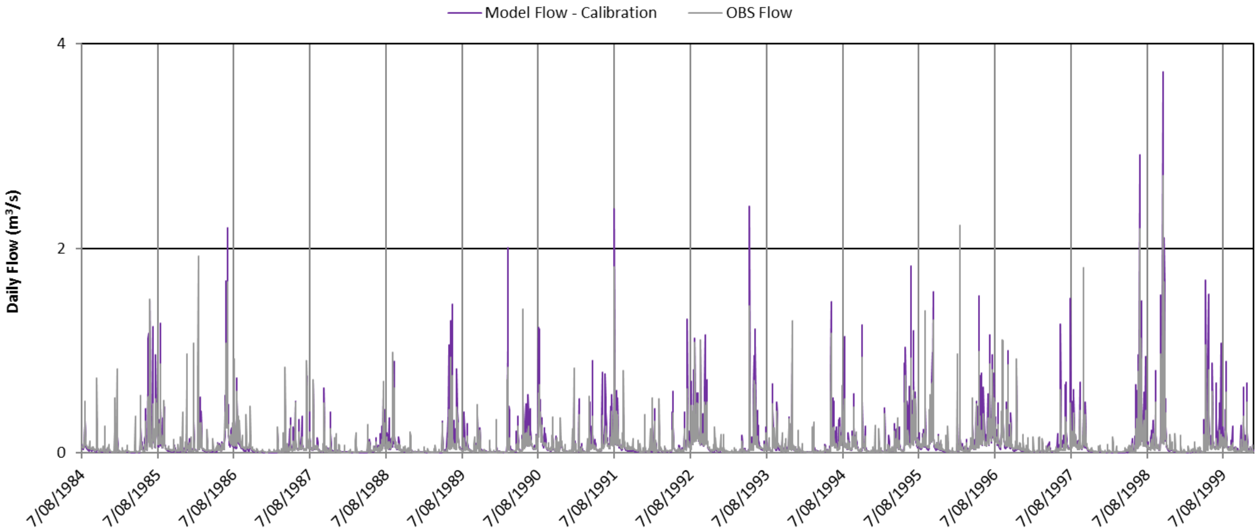

Figure A.7: Taupo stream at Flax Swamp Flow - Calibration Period

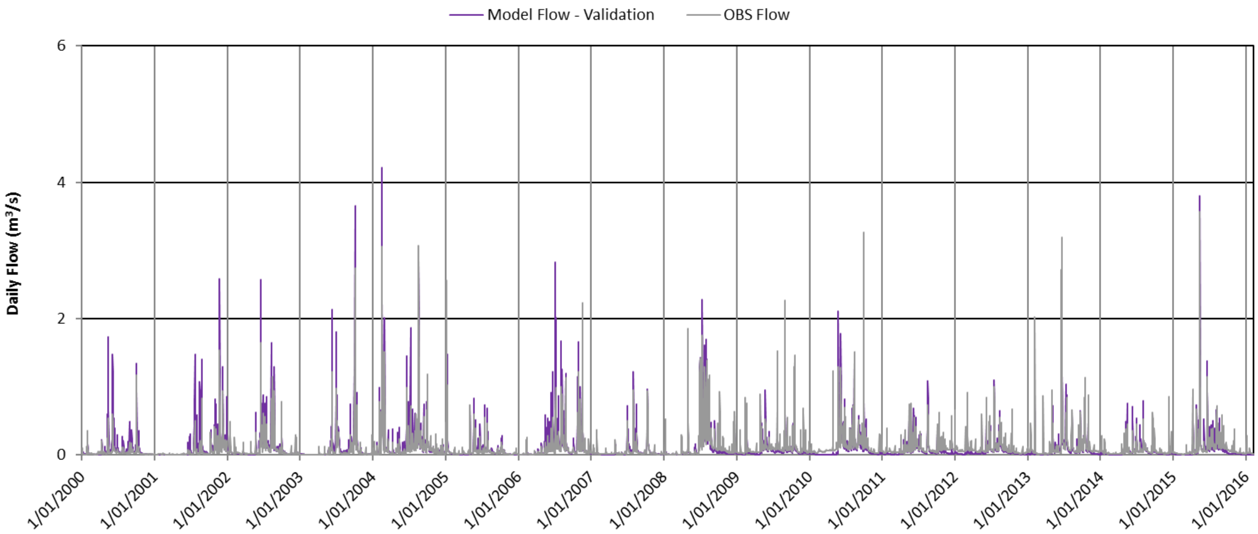

Figure A.8: Taupo stream at Flax Swamp Flow - Validation Period

A.2 Nitrogen calibration plots

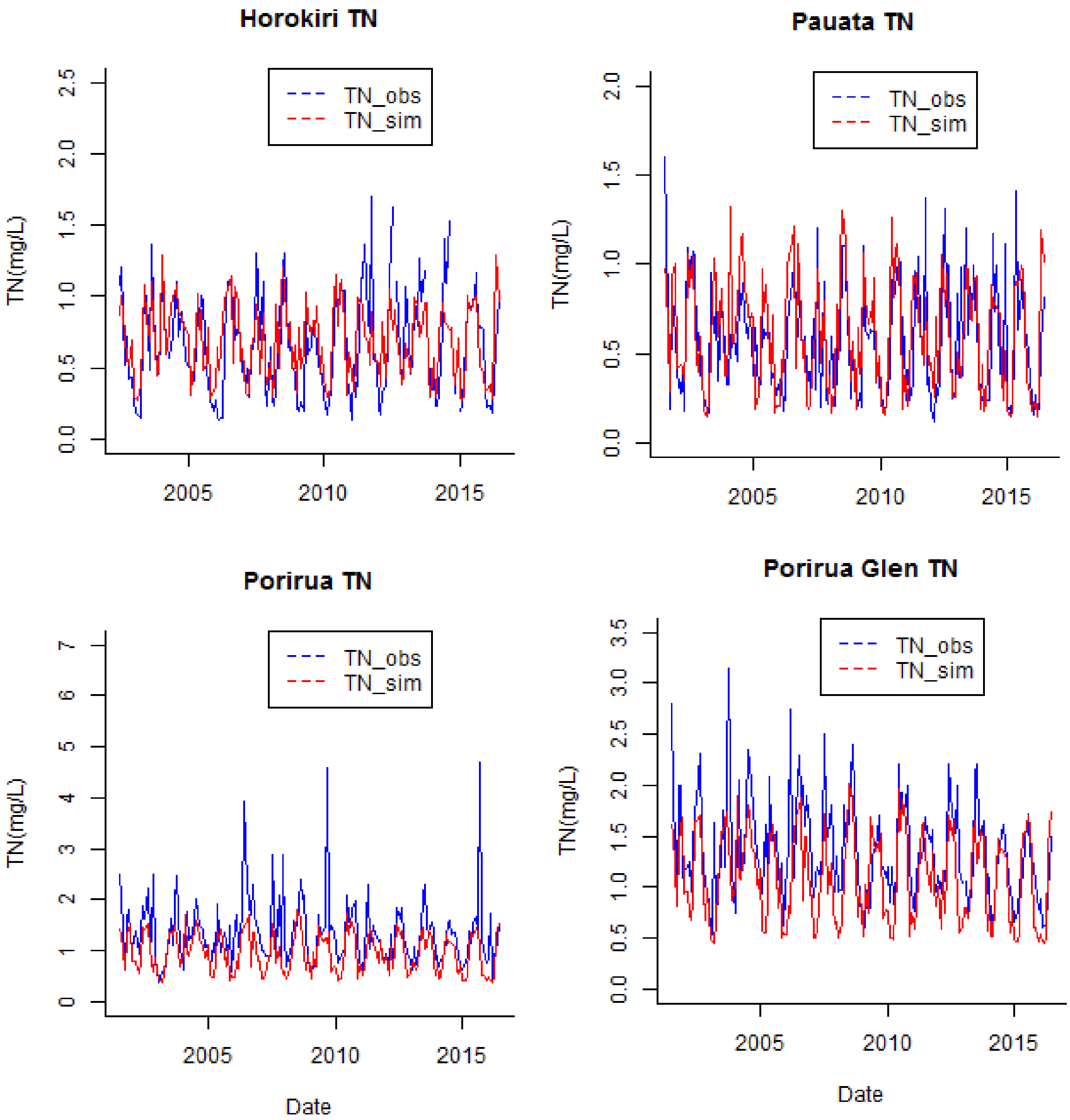

Figure A.9: Comparison of monthly observed and simulated nutrient concentration for Total Nitrogen (TN) at three calibration sites, and the verification site.

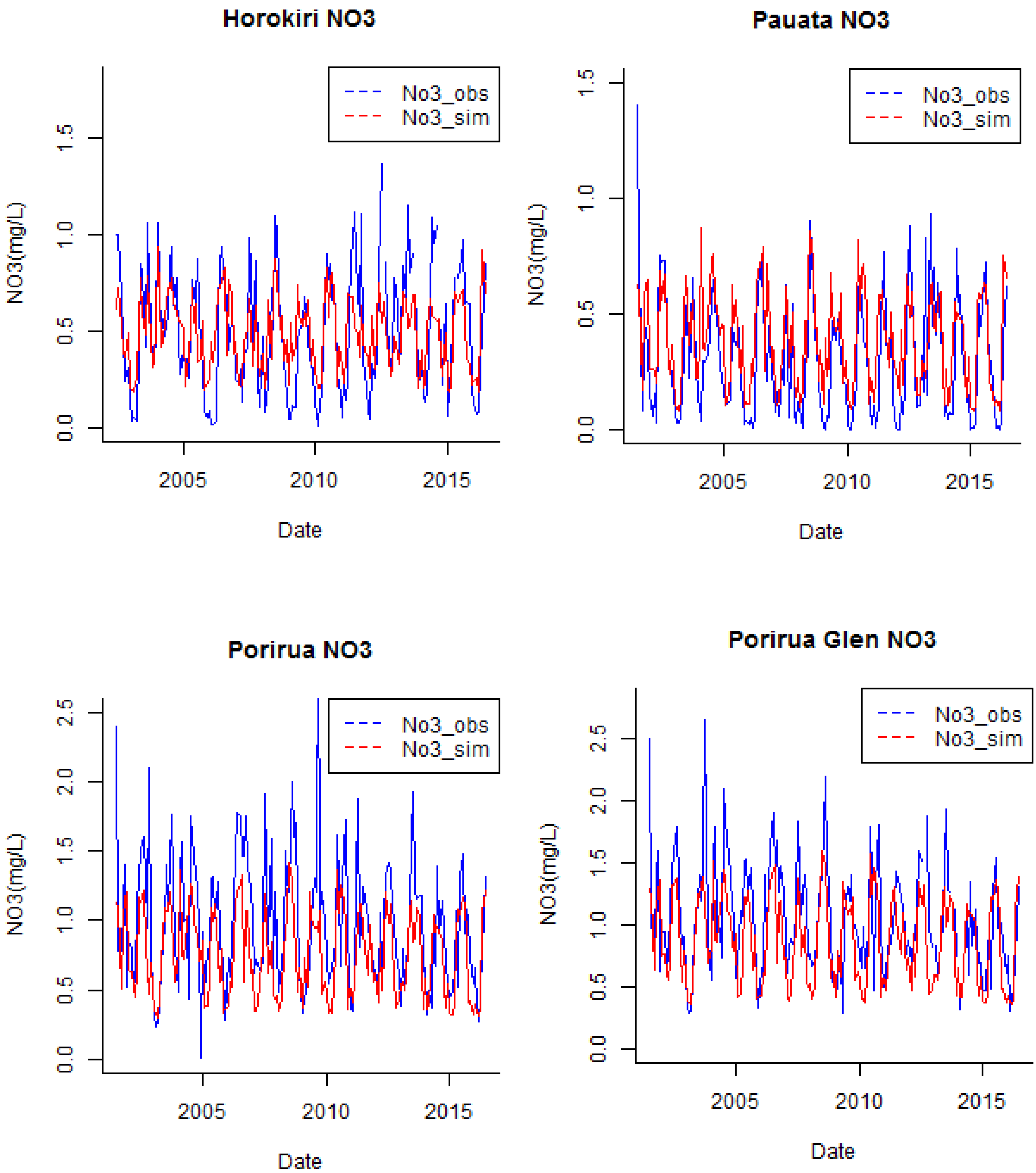

Figure A.10: Comparison of monthly observed and simulated nutrient concentration for Nitrate-Nitrogen (NO_3-N) at three calibration sites, and the verification site.

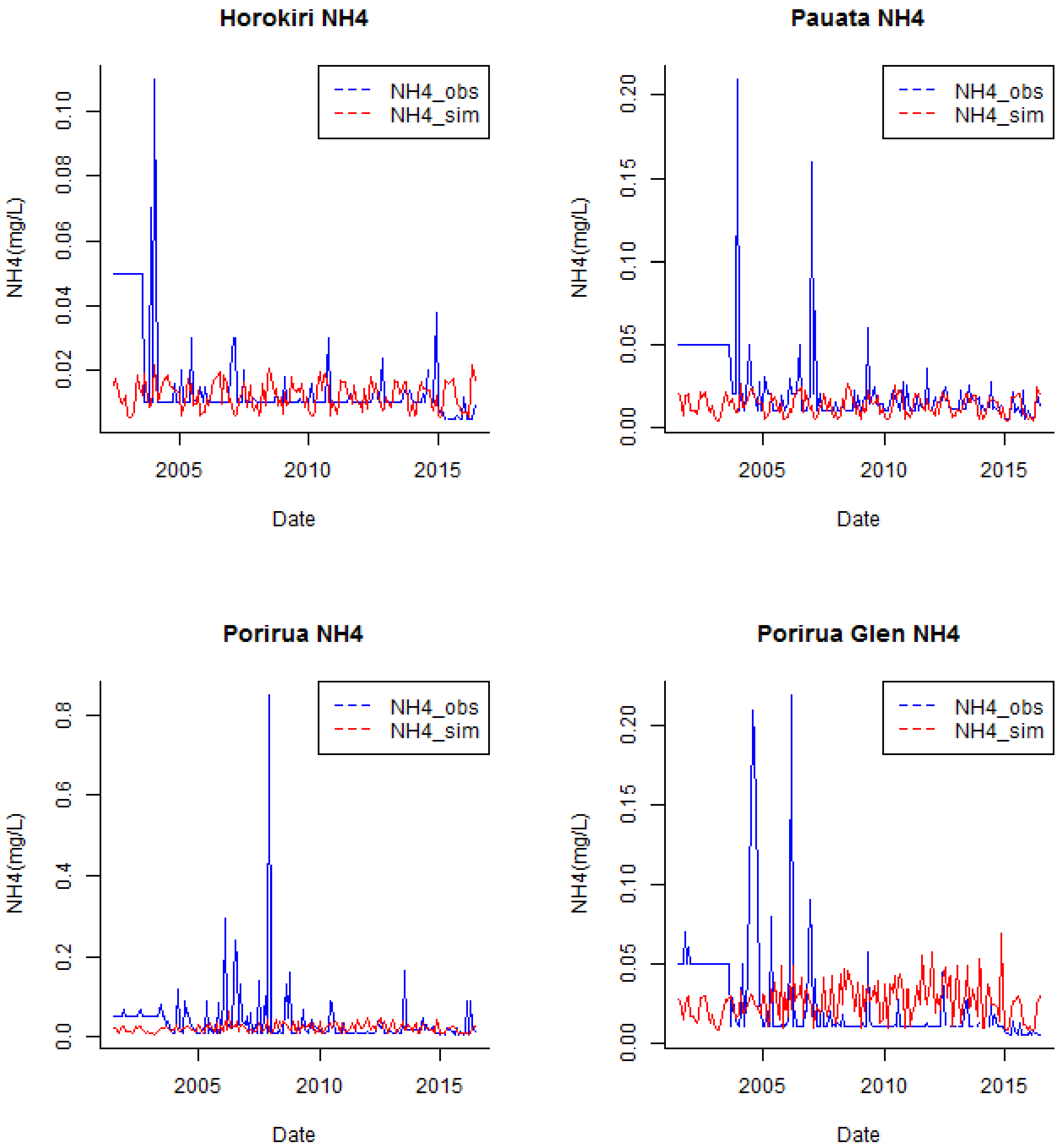

Figure A.11: Comparison of monthly observed and simulated nutrient concentration for Ammoniacal-Nitrogen (NH_4-N) at three calibration sites, and the verification site.

A.3 Phosphorus calibration plots

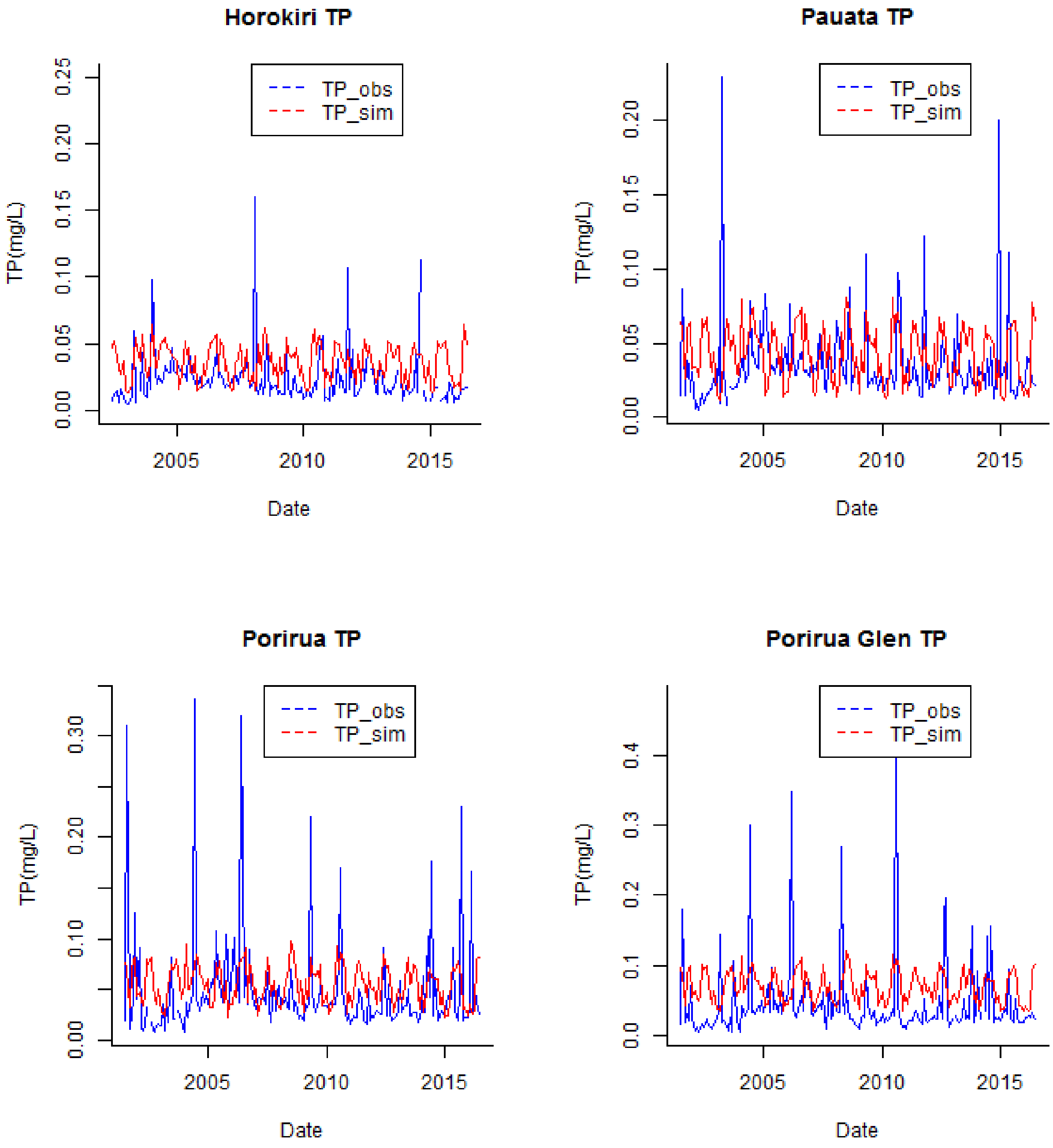

Figure A.12: Comparison of monthly observed and simulated total phosphorus (TP) concentrations at each calibration site and the verification site.

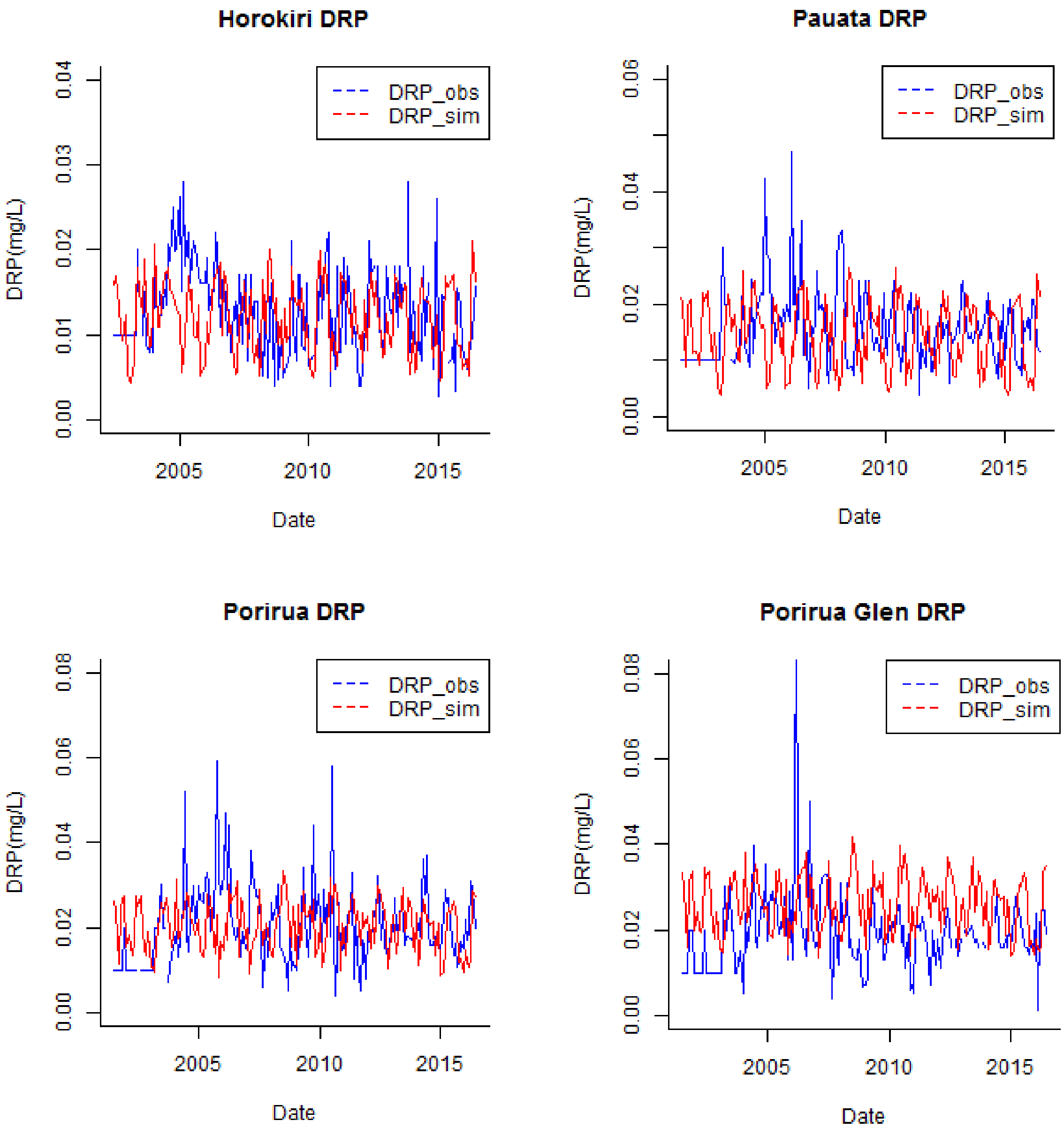

Figure A.13: Comparison of monthly observed and simulated Dissolved Reactive Phosphorus (DRP) concentrations at each calibration site and the verification site.

A.4 Zinc calibration plots

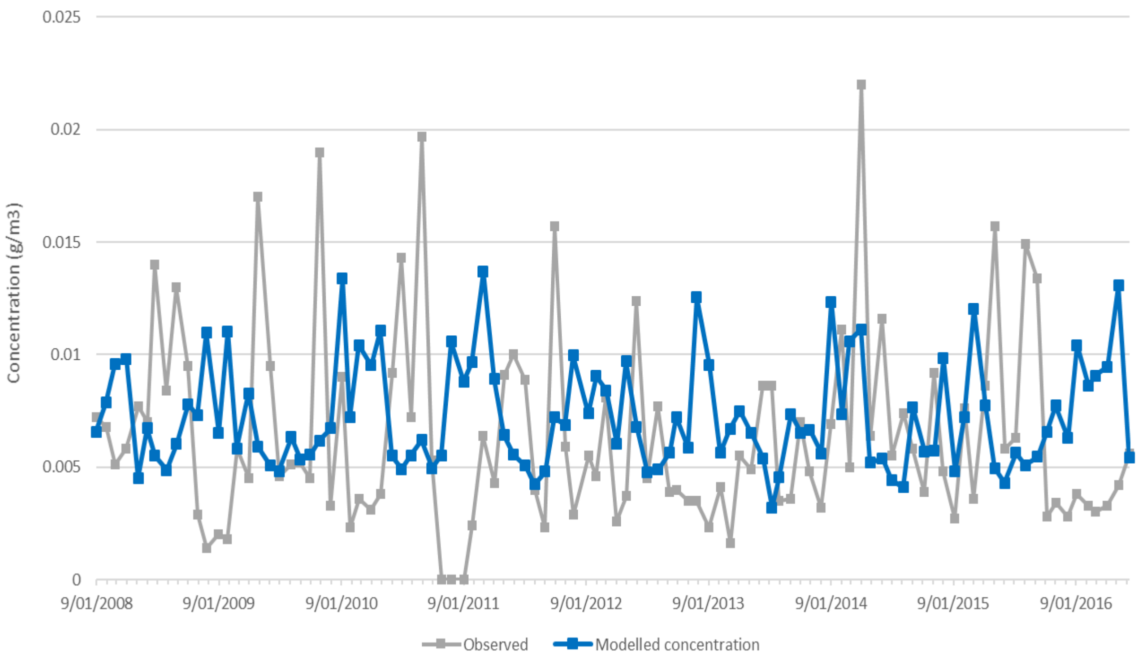

Figure A.14: Comparison of monthly Dissolved Zinc concentration at Porirua at Glenside

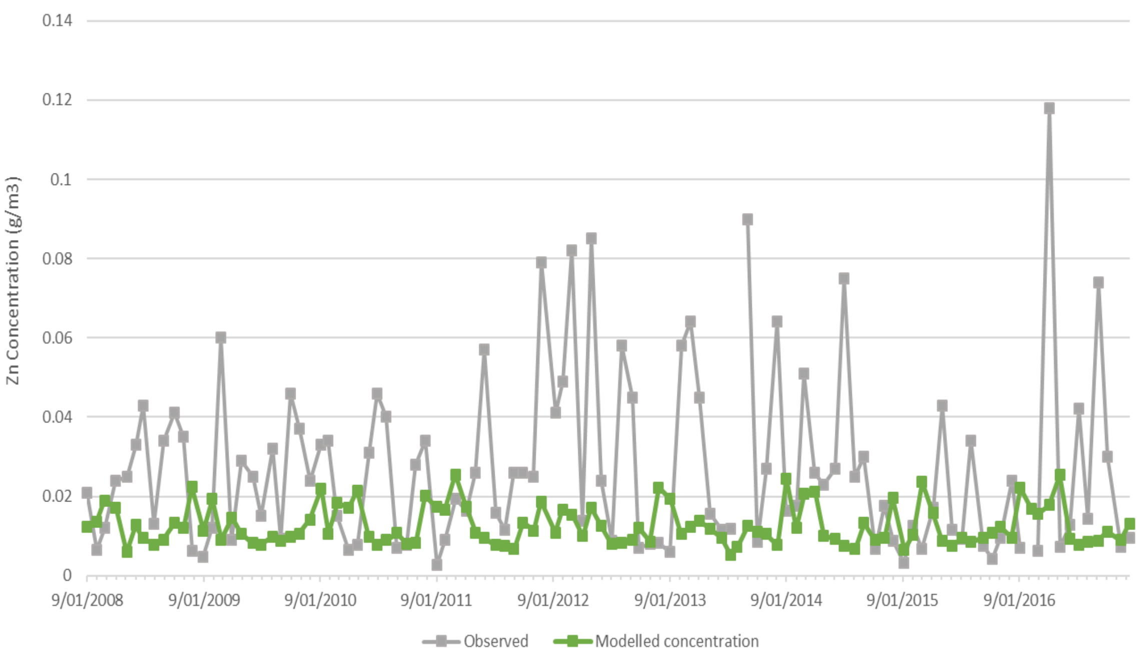

Figure A.15: Comparison of monthly Dissolved Zinc concentration at Porirua at Milk Depot. – Note: two extreme values are not displayed (0.25 g/m^3 on 7/08/2012, 0.33 g/m^3 on 16/02/16)

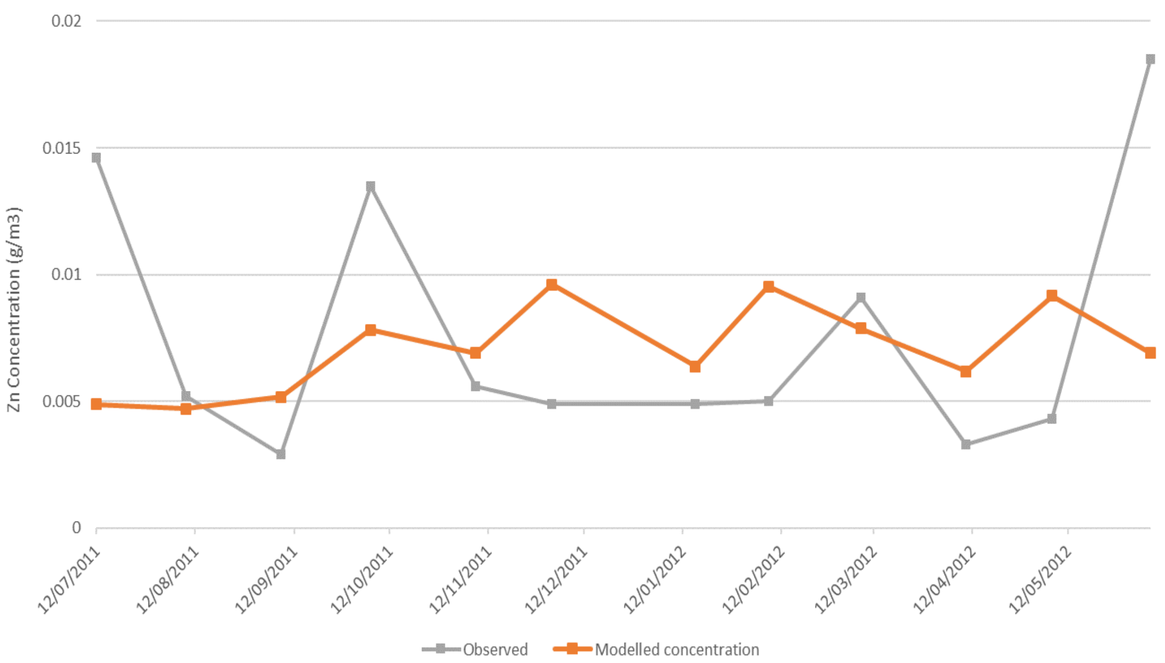

Figure A.16: Comparison of monthly Dissolved Zinc concentration at Kenepuru at Mepham Crescent

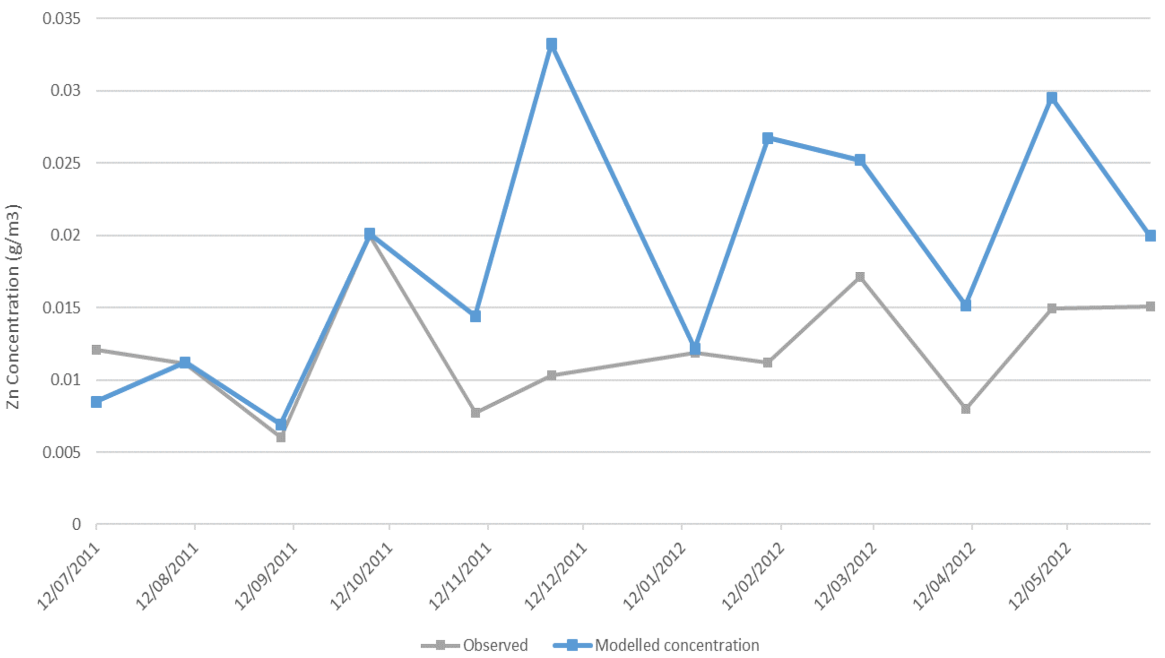

Figure A.17: Comparison of monthly Dissolved Zinc concentration at Mitchell Stream at Porirua Stream

A.5 Copper calibration plots

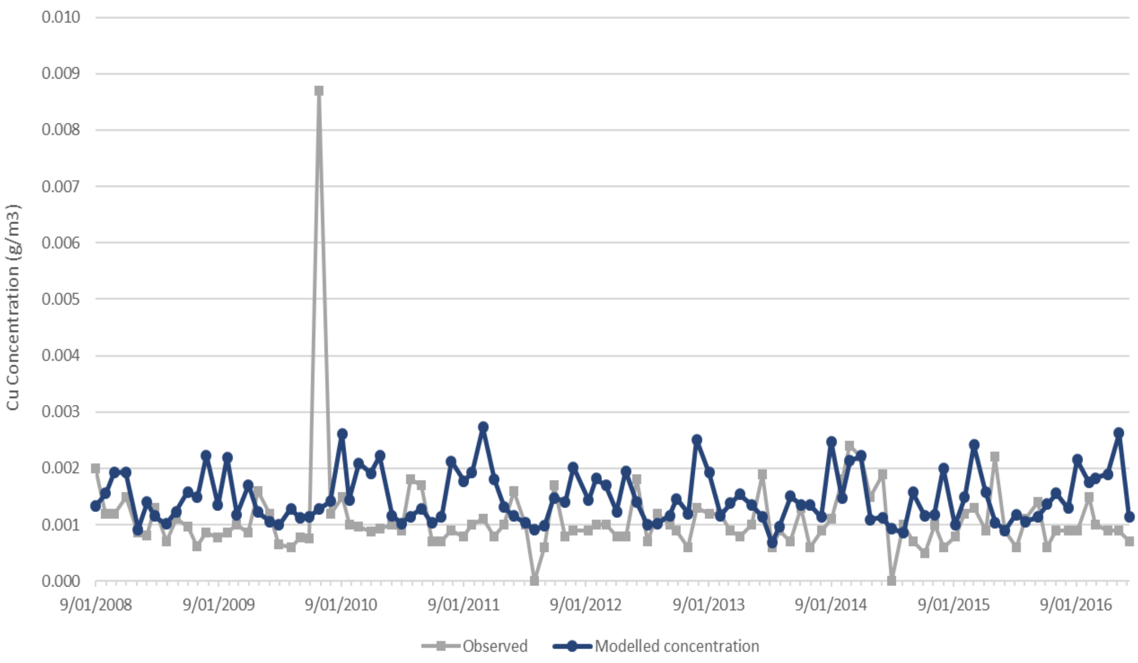

Figure A.18: Comparison of monthly Dissolved Copper concentration at Porirua at Glenside

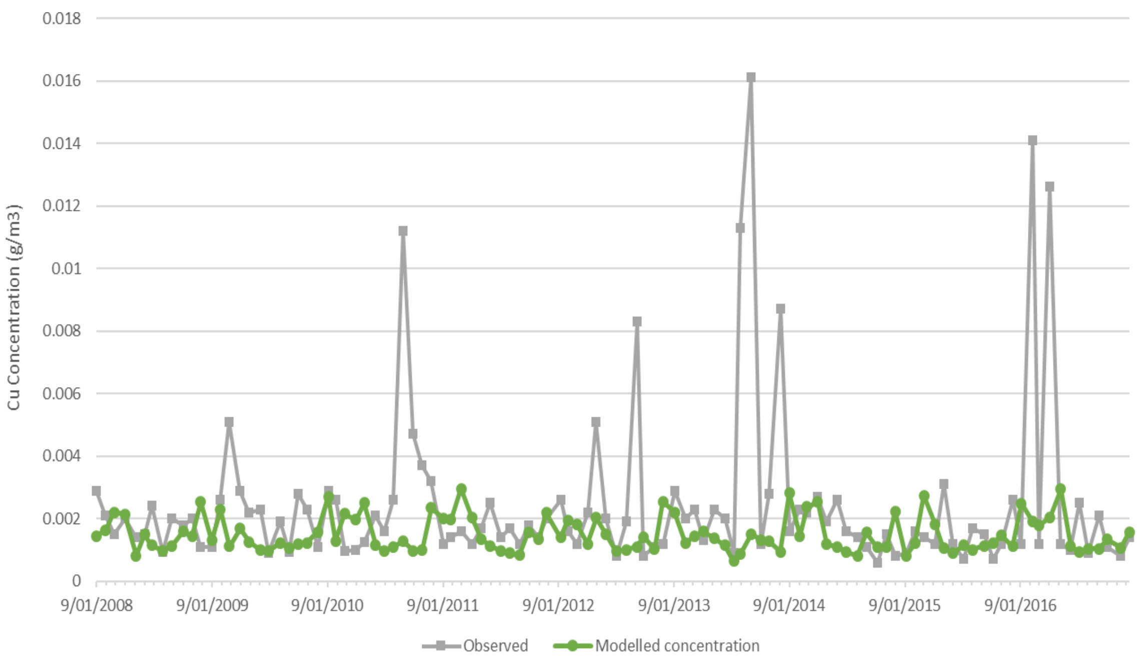

Figure A.19: Comparison of monthly Dissolved Copper concentration at Porirua Stream at Milk Depot

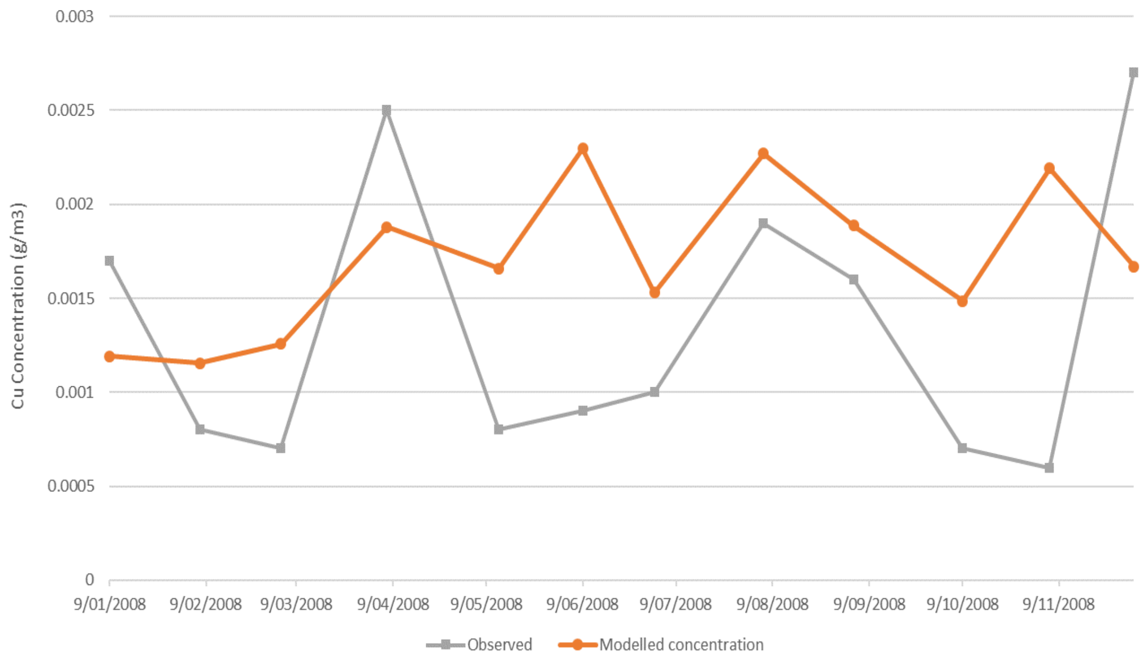

Figure A.20: Comparison of monthly Dissolved Copper concentration at Kenepuru at Mepham Crescent

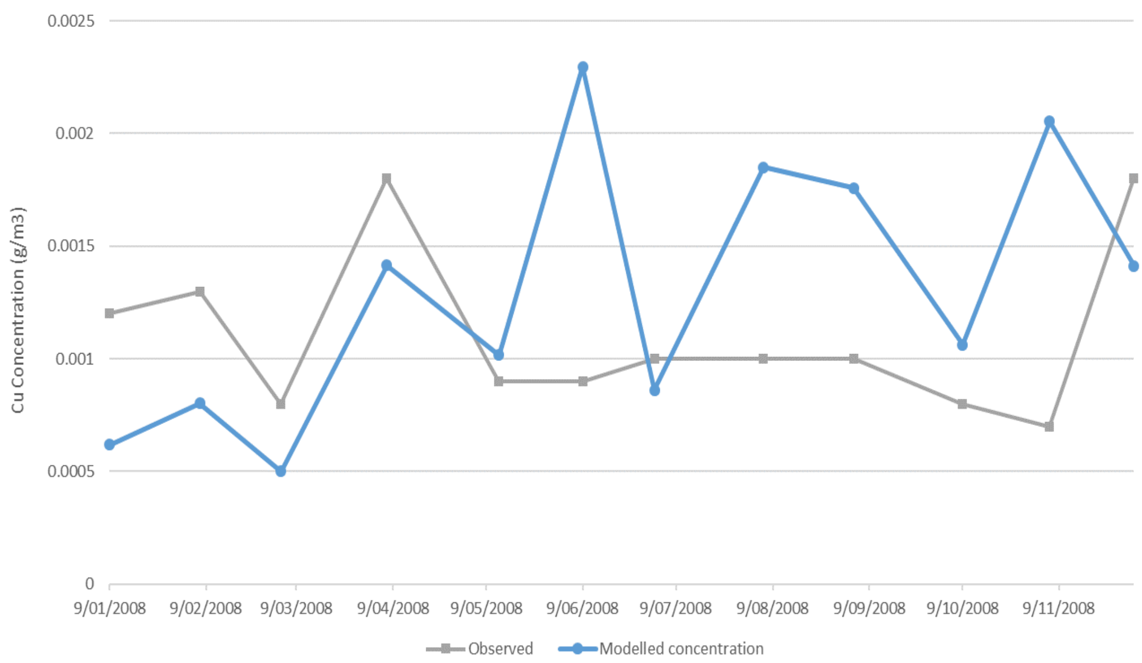

Figure A.21: Comparison of monthly Dissolved Copper concentration at Mitchell Stream at Porirua Stream