Freshwater Management Tool

August 2021 FWMT Report 2021/2

Report 2
Baseline Configuration and Performance

Auckland Council
Te Kaunihera o Tāmaki Makaurau

Freshwater Management Tool:
Report 2. Baseline Configuration and Performance

August 2021

Contributing authors:

Healthy Waters – Regional Planning

Nick Brown, Tom Stephens, Theo Kpodonu, Mahesh Patel

Paradigm Environmental

Dustin Bambic, John Riverson, Khalid Alvi, David Rosa, Xiaomin Zhao

Morphum Environmental

Caleb Clarke, Hana Judd, Andrew Rosaak

Auckland Council

Healthy Waters Department, FWMT Report 2021/2

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Approved for Auckland Council publication by: Name: Nick Brown Position: Manager, Regional Planning, Healthy Waters

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Freshwater Management Tool: Baseline Configuration and Performance Report Overview

Freshwater Management Tool

- FWMT is a freshwater accounting and decision-making tool for water quality, integrating all catchments from mountain to sea (rural and urban) throughout the Auckland region.
- FWMT utilises open-sourced, peer-reviewed US-EPA tools for continuous and process-modelling.

Baseline reporting

- This report is 2 of 5 documenting baseline (2013-17) water quality for freshwater receiving environments in the Auckland region.
- This report should be read alongside [FWMT Baseline Input] to understand how climate, land use and network discharges are represented in the FWMT Stage 1.
- This report should be read alongside [FWMT Baseline State – Rivers] to understand model performance for continuous and graded measures.

Report scope

- This report documents the configuration of 5,465 sub-catchments and associated stream network from regional LiDAR. Time series spanning 2002-17 are aligned to each sub-catchment from 228 unique meteorological stations (observed and modelled). Climate time series drive a range of hydrological and contaminant processes in the FWMT Stage 1 within each sub-catchment, responding to differences in up to 106 land or Hydrological Response Units (HRUs). Outputs from HRUs are transformed instream for erosional/depositional and nutrient processes.
- Calibration and validation are undertaken on 46 continuous flow and 36 discrete (monthly) State of Environment monitoring stations for water quality during the baseline period, using continuous performance metrics (r2, PBias, NSE). Performance metrics were assigned into bands using recommendations from Moriasi et al. (2015).

Report messages

- FWMT Stage 1 uses best available data (as of mid-2017) to account for water quality conditions in the Auckland region. Configuration commences with sub-catchment and stream delineation. 5,465 sub-catchments of varying size (~40-100 Ha) span 4,803 km^2 and 3,085 km of permanent and intermittent stream.
- All sub-catchments are configured with up to 106 unique HRUs on a 2x2m basis. HRUs stratify differing soil, slope, surface and activity (impact) effects on rainfall and contaminant response. All model reaches are classified into one of three

erosional or two nutrient groups. Both HRU and reach groups are regionally parameterised. Horticultural HRUs include additional interflow and active groundwater TN contributions for farms overlying the Franklin aquifer.

- FWMT Stage 1 was calibrated and validated over the 2012-16 period – 2017 was an unusually wet year whose inclusion would bias model performance to the latter year. A top-down approach assessing quality and coverage of boundary data was combined with a selective (upstream-downstream) approach to identifying key stations for calibration (e.g., on basis of dominance by HRU and/or reach group).
- Parameterisation is informed by underlying hydrological, seasonal and event-based patterns. Sediment and heavy metals exhibit similar non-linear patterns with streamflow, indicating likelihood of scour at higher flow. Nitrogen concentrations exhibited seasonal, hydrological and spatial patterns with greatest concentrations in Manukau watershed at lower flow and autumn-winter.
- Multiple performance metrics are tested by the FWMT Stage 1 using increasingly conservative thresholds for hydrology and loading than concentration. Observational records are also tiered by quality.
- Continuous model performance is reported for TSS, TN, TON, TAM, TP, DRP, TCu, TZn and *E. coli* as well as wide-ranging measures of flow – noting limitations of such approaches (e.g., comparison of inequivalent discrete observed and continuous modelled data; limited temporal and spatial resolution of observed data; accuracy and representativity assumed of observational data; continuous measures being inequivalent to grading).

Quality assurance

- FWMT Stage 1 baseline modelling has been externally peer reviewed by Prof. David Hamilton [Griffith University], Dr. Kit Rutherford [NIWA] and Nic Conland [Taiao Consulting]. Findings of the external peer review are contained in [FWMT Baseline Peer Review].

Continuous improvement

- FWMT Stage 1 is the first generation of a paradigm shift in water quality accounting for Auckland – an advance on simpler, empirical and non-continuous modelling (CLM; C-CALM).
- Ongoing changes to the FWMT Stage 1 are expected in light of external peer review and end-user needs. Please contact the FWMT team to request data and updates to the FWMT.

Contact – fwmt@aucklandcouncil.govt.nz

Executive summary

The Freshwater Management Tool (FWMT) is a continuous and process-based water quality accounting framework for the Auckland region. In its first iteration (Stage 1) contaminants simulated include total suspended solids (TSS), total and dissolved forms of nutrients (TN, DIN, TON, TAM, TP, DRP), total forms of heavy metals (TCu, TZn) and faecal indicator bacteria (*E. coli*). The FWMT Stage 1 simulates the generation, transport and fate of contaminants in multiple flow paths across and through land, and ultimately through instream freshwater environments.

This report documents the configuration and subsequent continuous performance of the Load Simulation Programme in C++ (LSPC) to represent instream freshwater flow and contaminant conditions. The FWMT Stage 1 hydrology and water quality model was configured using the best available data (as of mid-2017) to account for water quality conditions in the Auckland region over the calibration/validation period (2012-2016). Datasets used for configuration included high-resolution meteorology, soils, land cover and use, topography, wastewater and stormwater networks, consented water takes and discharges, spanning several years of effort by multiple New Zealand and Auckland Council agencies.

Configuration commenced by delineating sub-catchments and an associated stream network from a regional LiDAR-based DEM, resulting in 2,567 of 5,465 sub-catchments possessing a single modelled reach. A total of 2,898 sub-catchments were delineated as headwater catchments or draining straight to sea or neighbouring region (Waikato). Sub-catchments lacking a modelled stream segment are still subject to hydrological and contaminant modelling (from land) but not then assigned instream grades. Approximately 2,377 km^2 of the 4,803 km^2 Auckland region is either within a headwater sub-catchment or drains directly to the ocean and was not simulated for instream contaminants in the FWMT Stage 1.

Meteorological time series inputs were developed using a combination of observed rain gauge information and modelled VSCN data, for the period 2002-2017. Additional inputs to the model included data on the existing wastewater network, reservoirs, lakes, and dams, and surface water takes. HRUs, representing the combination of landscape characteristics likely to govern hydrological and relevant contaminant processes in the region, were developed to express a range of parameterisation deemed relevant (e.g., of soils, topography, land cover and use). HRU stratification was limited in the FWMT Stage 1 to a level representative of sub-catchment variability across hydrologic and contaminant processes without excessive classes or complexity for best available datasets in later calibration and validation. Each HRU was configured or parameterised regionally, to enable local (sub-catchment) climatic variation to be represented amidst a diverse typology of landscape (i.e., resulting in unique sub-catchment profiles of varying extent of up to

106 HRUs driven by up to 228 unique climate time series to generate sub-catchment time series of hydrology and contaminant concentration or load).

HRU development involved comparative analysis and corroboration across diverse datasets to derive new information to enable a region-wide raster layer to be developed for 106 unique HRUs (2x2m resolution). Soil and slope spatial raster data were intersected with land use/land cover data to create unique combinations of each base factor. The HRUs were further refined into “Impact” classes for intensity of human activity within a land cover type. For example, traffic data were also used to stratify contaminant impacts among different types of road cover. Similarly, simulated meteorological data from NIWA's virtual climate station network were used to fill spatial gaps in the observed data coverage. The higher the resolution and accuracy of the data used to configure the FWMT, the better the model can simulate hydrology and water quality processes.

Instream nutrient and sediment processes were also regionally parameterised into several reach groups, based on modelled reach characteristics (e.g., shade, upstream extent of agriculture/horticulture, bed/bank material, bed slope and stream order). For both nutrient and stream erosional/depositional processes, three reach groups were configured to enable their unique calibration. Reach groups were assigned to modelled segments much like HRUs, through use of best available datasets (e.g., WAR, FENZ, NZLRI).

Following configuration, calibration of the FWMT developed parameters for all processes in LSPC, fixed by HRU and reach group. In addition, calibration involved developed of additional parameterisation for total nitrogen (TN) in active groundwater from horticultural HRUs overlying the Franklin Aquifer Zone. The latter are the only sub-regional process-parameterisation for the FWMT Stage 1, with all other parameters regionalised to permit later increased complexity are purposes and new observational data permit.

Hydrological calibration and validation occurred at 46 continuously (15-min) monitored stations whose data records have been tiered for quality (e.g., against assumed free-flow within LSPC). For each, a raft of calibration/validation outputs have been produced spanning temporal bias, seasonal bias, rainfall bias and antecedent period. The observed vs simulated time series were analysed to generate performance metrics across the full calibration period (2012-2016) as well as subsets of season and flow. Continuous performance metrics were generated for both concentration and loading (r2, PBias, NSE). Performance was assessed utilising recommended bands in continuous metric from Moriasi et al. (2015). The latter were selected to be purposely conservative to ensure future Stage 2 and 3 development can be assessed using equivalent thresholds.

The hydrologic calibration and validation exercise demonstrated the regional parameterisation of the FWMT Stage 1 achieved “satisfactory” or better performance at a majority of stations and conditions. Amongst better quality hydrological stations (Tiers 1 and 2) "satisfactory" or better performance was demonstrated for all flows at 82-86% of stations (varying across the three metrics). Satisfactory or better performance across all flows was reported at a minimum of 76% of hydrological stations (e.g., Tiers 1 to 5).

Contaminant calibration and validation was limited by the lack of continuous or integrated observations (e.g., relying on monthly discrete [grab] samples; 16 of 36 SoE stations having paired flow records; 17 of 36 SoE stations having relatively homogenous upstream HRU composition; metal concentrations limited to 24 urbanised SoE stations). Equally, contaminant performance was limited to comparison of daily flow-weighted average instream concentration and daily load for total suspended solids (TSS), TN, TON, total ammoniacal nitrogen (TAM), total phosphorus (TP), dissolved reactive phosphorus (DRP), total copper (TCu), total zinc (TZn) and *E. coli*. Observational records were limited to 16 flow-paired sites, with daily loading estimated either as product of observed continuous flow by discrete observed concentration or modelled continuous flow by discrete observed concentration. A strong recommendation is made for targeted and flow-paired, integrated or continuous contaminant monitoring to be implemented to better support ongoing FWMT development, and resolve uncertainty in the representativity of observational records (e.g., their fit for comparative purpose to a regionalised continuous model).

As per hydrological performance, a raft of calibration and validation outputs have been produced for each of the 36 SoE stations (e.g., temporal bias, rainfall bias, flow bias, seasonal bias, concentration bias). Whilst performance varied by contaminant and gradient, across "all" flow and seasons r2 was more frequently assessed as "satisfactory" or better (than PBias or NSE). Equally, model performance was markedly better for loading than concentration.

Overall, across "all" flows for the five-year period 2012-2016 and across the three performance metrics, the number of SoE stations continuously modelled with "satisfactory" or better performance varied[1]:

- TSS concentration 0-12% for calibration (0-32% validation) and TSS load 0-65% for calibration (10-100% validation).
- TN concentration 6-53% for calibration (0-42% validation) and TN load 40-90% for calibration (0-100% validation).
- TON concentration 0-47% for calibration (5-26% validation) and TON load 30-60% for calibration (17-100% validation).

[1] Noting concentration performance is estimated at varying numbers of the 36 SoE stations (depending on metric and varying from 9-17 stations for calibration through to 5-19 stations for validation). Satisfactory or better defined by modification of Moriasi et al. (2015).

- TAM concentration 0-24% for calibration (0-5% validation) and TAM load 25-100% for calibration (0-100% validation).
- TP concentration 0-47% for calibration (0-21% validation) and TP load 10-100% for calibration (17-100% validation).
- DRP concentration 0-42% for calibration (0-26% validation) and DRP load 20-100% for calibration (0-100% validation).
- TCu concentration 0-44% for calibration (0-31% validation) and TCu load 0-67% for calibration (0-100% validation).
- TZn concentration 0-56% for calibration (0-44% validation) and TZn load 33-100% for calibration (20-100% validation).
- *E. coli* concentration 0-42% for calibration (6-26% validation) and *E. coli* load 22-67% for calibration (33-100% validation).

Limitations need to be carefully considered, not simply in the quality and representativity of existing contaminant sampling (e.g., upstream composition and sizes of SoE catchments) but in the value of *continuous* performance assessment (e.g., r2, PBias, NSE). The FWMT Stage 1 is intended primarily for use in reporting on grading and optimisation of management to grading-based outcomes. LSPC is naturally likely to be limited by inherent complexity in any assessment of NSE, whilst continuous performance is not alike to grading-based performance (correctly grading sites) and not preferential to enriched (degraded) sites when otherwise regional planning must prioritise degraded sites for managed improvement (i.e., that lower accuracy in A-graded sites is less concerning than lower accuracy in D-graded sites, for FWMT purposes).

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Glossary of key terms

Term	Abbreviation	Definition
Aquifer		An underground layer of water-bearing rock or sand from which groundwater can be extracted.
Attenuation		The storage of excess stormwater during the peak of a storm, followed by controlled release of the stored water.
Attribute		A measurable characteristic of fresh water, including physical, chemical and biological properties, which supports particular values.
Attribute measure		One of several statistics for an attribute, each of which is graded and from which overall grade is determined as the least of measures (e.g., median, 95^{th}%).
Attribute state		The level to which an attribute is to be managed for those attributes specified in Appendix 2 of the National Policy Statement for Freshwater Management (2014).
Auckland Unitary Plan	AUP	The Auckland Unitary Plan Operative in part providing the land use zonation for Auckland Region.
Bank height		The average vertical distance between the stream bed and the top of the bank (immediate bank associated with the watercourse) measured in metres.
Best Management Practices	BMPs	BMPs are structural, vegetative or managerial practices used to treat, prevent or reduce water pollution.
Brownfield		Previously developed land that may be available or have potential for redevelopment, often for more intensive or different land use.
Catchment Land Use for Environmental Sustainability	CLUES	CLUES is a GIS based modelling system which assesses the effects of land use change on water quality and socio-economic indicators. It was developed by NIWA and is an amalgamation of existing modelling and mapping procedures.
Coastal Receiving Environment	CRE	The marine area where freshwaters discharge to.
Combined Sewer Overflow	CSO	Overflows from combined sewers that are designed to collect rainwater runoff, domestic sewage, and industrial wastewater in the same pipe. These overflows contain not only storm water but also untreated human and industrial waste, toxic materials, and debris. They are a major water pollution concern.
Contaminant		Chemicals and particles within a water sample that degrade the water quality
Contaminant Load Model	CLM	The Contaminant Load Model (CLM) is an annual stormwater contaminant load spreadsheet model developed for the Auckland region of New Zealand. It was first developed by Auckland Council's predecessor in 2006 to enable estimation of stormwater contaminant loads on an annual basis.

Term	Abbreviation	Definition
Contributing Catchment Area	Asset_Ac	Area of contributing catchment to the treatment device measured in meters squared.
Dam		Built to store stormwater to control flooding, water for drinking supply, power generation, or irrigation.
Digital Elevation Model	DEM	The digital representation of the land surface elevation with respect to any reference datum.
Directly Connected Impervious Area	DCIA	The portion of impervious with a direct hydraulic connection to a waterbody or drainage network
Distributed Structural Device		Structural Device installed in private property or at the inlet to the public stormwater network or otherwise with inflows from a small catchment.
Drainage catchment		An area of land where stormwater runoff flows to a discharge point at a watercourse, treatment device or the coast.
Drainage class	DRAIN_CLAS	Drainage class values (1-5) are based on New Zealand Soil Classification's hydromorphic classes (1993). They are assigned predominantly on the depth to the seasonally high-water table within the soil profile, which describes the available volume of the soil for retention of water at saturation.
Existing forestry operation		All parcels classified as 'forestry' in Agribase.
Floodplain		The land bordering a stream, built up of sediments from stream overflow and subject to inundation when the stream floods.
Fluvial deposits		All sediments, past and present, deposited by flowing water.
Fractured Basalt Aquifer		Basalt is a finely granulated igneous rock, which is usually black or gray in colour. These rocks are formed due to lava flow. Basaltic rocks are the most productive aquifers in volcanic rocks as they are highly porous and permeable. In Auckland, the basalt aquifers are used to dispose stormwater via drilled soakholes, serve as groundwater supply in the Onehunga aquifer and disperse industrial and commercial sites across the city, and feed important springs in Western Springs and Onehunga.
Future Urban Zone	FUZ	Development area for township expansion in the AUP to be included into the urban area.
Grade		The lesser of any attribute measure's grades under the National Objective Framework (NOF) or any regional objective framework. Interchangeable with attribute state for purposes of report.
Greenfield		Land that has not been previously developed and therefore has little to no existing infrastructure.

Term	Abbreviation	Definition
Gross Pollutant Trap	GPT	Device used for water quality control that removes solids typically greater than five millimetres conveyed by stormwater runoff. GPTs can operate in isolation to reduce pollutant effects within immediate downstream receiving waters, or as part of a more comprehensive treatment train system to prevent overload of downstream infrastructure or treatment devices
Groundwater		Water in the zone of saturation where all open spaces in sediment and rock are filled with water.
Groundwater recharge		Water added to the aquifer through the unsaturated zone after infiltration and percolation following any storm rainfall event.
Gully erosion		Erosional process occurring when sediment is mobilised from an HRU through scouring due to overland flow.
Hydrological Response Unit	HRU	A watershed area assumed to be homogeneous in hydrologic response due to similar land use and soil characteristics and used in the LSPC model.
Hydrological Soil Groups	HSG	Soils grouped by their runoff-producing characteristics. Soils are assigned to five groups in the FWMT: group A+ – D where A+-HSGs have a high infiltration rate and low runoff potential through to D-HSGs that have a low infiltration rate and high runoff potential. HSGs are determined by drainage, permeability,
Impoundment		A body of water confined within an enclosure, as a reservoir.
Interflow		Shallow subsurface flow that contributes to streamflow through the upper soil layer as opposed to recharging aquifers.
Intervention		A measure put in place through either capital investment operational activity, regulation, education
Land cover		The material covering the earth, being vegetation, water, asphalt etc.
Land Information New Zealand	LINZ	land titles, geodetic and cadastral survey systems, topographic information, hydrographic information, managing Crown property and supporting government decision-making around foreign ownership
Land use		Activity undertaken on the land, usually grouped into classes
Livestock units	LSU	The standard unit to compare the feed requirements of different classes of stock or to assess the carrying capacity and potential productivity of a given farm or area of grazing land. The reference unit used for the calculation of livestock units (=1 LSU) is used to express the annual feed requirement of a "standard" 55 kg breeding ewe rearing a single lamb (dry sheep equivalent).
Load reduction factor	LRF	Treatment or control efficiency

Term	Abbreviation	Definition
Loading Simulation Program in C++	LSPC	The watershed modelling system used to characterise the state (concentrations and loads) of freshwater quality and recharge rates of shallow aquifers across the Auckland region. LSPC is an open-source, process-based watershed modelling system developed by the U.S. EPA for simulating watershed hydrology, sediment erosion and transport, and water quality processes from both upland contributing areas and receiving streams
Local Government Act 2002	LGA	The Local Government Act 2002 is an act of Parliament that defines local government in the New Zealand.
Mapped Impervious Area	MIA	The spatial representation of area identified as impervious from available information
Mean High Water Springs 10	MHWS10	Mean high water spring (MHWS) describes the highest level that spring tides reach, on average, over a long timescale. MHWS10 is the mean high-water spring tide exceeded 10 per cent of the time.
The National Policy Statement for Freshwater Management	NPS-FM	Policy providing direction about how local authorities should carry out their responsibilities under the Resource Management Act 1991 for managing fresh water. It's particularly important for regional councils, as it directs them to consider specific matters and to meet certain requirements when they are developing regional plans for fresh water. The NPS-FM came into effect on 1 August 2014.
Northern Allochthon		The Northern Allochthon is characterised by weak, highly sheared mudstones, siltstones, sandstones and limestones. Permeability is typically very low, with northern allochthon rocks forming an aquitard in most areas.
On-Site Wastewater Treatment	OSWW	Onsite wastewater treatment systems are decentralised systems that are used to treat wastewater from a home or business and return treated wastewater back into the receiving environment.
Overland flow		Stormwater that flows overland until it enters the formal stormwater network, stream or the sea.
Overland flow path	OLFP	The route followed by stormwater which runs over the surface of the ground (overland flow) when it becomes concentrated as it makes its way downhill following the path of least resistance towards streams and watercourses, or the sea.
Overseer		Overseer is New Zealand software that enables farmers and growers to improve nutrient use on farms, delivering better environmental outcomes and better farm profitability. Also used by some councils to manage nutrient loadings on the environment.
Pastoral		Land use for keeping and grazing livestock.
Peat soils		Soils with high levels of organic material as a result of decaying vegetation.

Term	Abbreviation	Definition
Permeability	PERMEABILI	Permeability is based on grain size and porosity, which describes the soil's ability to transmit flow. The permeability of a soil profile is related to potential rooting depth, depth to a slowly permeable horizon and internal soil drainage.
Pervious		Natural ground surfaces including trees, shrubs, grass and soil which allow water to pass through and soak into the ground, reducing the volume of runoff flowing over the ground.
Potency factor		Potency reflects the behaviour of pollutants, such as phosphorus, which are assumed to be sorbed to soil. The potency factory of a pollutant indicates to quantity of pollutant per quantity of soil (i.e. mg/kg).
Pour point	PP	A sub-catchment outlet point that represents the reporting node of the FWMT. Otherwise known as [Node]
Regional retrofit		Structural Device installed on the stormwater network to treat a larger area by take-off or inlet from the live network
Resource Management Act 1991	RMA	The Resource Management Act 1991 promotes the sustainable management of natural and physical resources such as land, air and water in New Zealand.
Riparian		Relating to, or situated on, the bank of a river or other water body.
Runoff		Water flows which result from rainwater which is not absorbed by permeable surfaces or that which falls on impermeable surfaces
Rural		Outside of the defined urban area under the Auckland Unitary Plan HRUs with land uses classified as forest, horticulture, pasture or open space
Rural Urban Boundary	RUB	Zoned extent of the urban area and associated rules under the AUP
Sewage fungus		Sewage fungi consists of filamentous bacteria, associated with fungi and protozoa. It is the slimy growth found in sewage and sewage polluted water.
Soak holes		Belowground pit to collect runoff and allow it to soak naturally into the soil. An alternative drainage method for rainwater and is similar to a Retention tank or Detention tank.
Source Control Strategy		Non-structural intervention either rural or urban usually targeted at avoiding an impact on the hydrological cycle by more closely matching a hydrological process to the natural baseline.
Special Housing Area	SHA	To address Auckland's housing crisis, areas established across the city where fast-track development of housing, including affordable housing is undertaken
Stormwater assets		
Stormwater catchment		The authoritative stormwater catchment extents as defined by Auckland Council datasets dated August 2014.
Stormwater network		The pipes, associated assets and watercourses associated with the treatment and conveyance of stormwater.

Term	Abbreviation	Definition
Structural device		Generic term to cover a wide range of devices to remove contaminants from runoff. A physical asset installed in the stormwater network to provide a quality or quantity function Sometimes referred to as a BMP or Stormwater Treatment Device.
Sub-catchment		Area of land in which rainfall drains toward a common stream, river, lake, or estuary. Sub-catchments in the FWMT function as spatial accounting units for the model and are nested within Auckland Council's 233 Stormwater Catchments.
Surface Water Takes		Water take involves abstracting water from a stream, lake or river for land use activities. A water permit is needed to take water unless it is for human consumption or stock water.
System for Urban Stormwater Treatment and Analysis IntegratioN	SUSTAIN	SUSTAIN is a decision support system that assists stormwater management professionals with developing and implementing plans for flow and pollution control measures to protect source waters and meet water quality goals. SUSTAIN allows watershed and stormwater practitioners to develop, evaluate, and select optimal best management practice (BMP) combinations at various watershed scales based on cost and effectiveness.
Topography		Description of the geographical surface features of a region.
Treatment performance	Asset_treatment	A measure of the effectiveness of the asset with respect to its ability to remove stormwater pollutants; TSS, Zinc, and Copper.
Urban area		HRUs with land uses classified as residential, commercial, industrial, or otherwise developed
Vehicles Per Day	VPD	Land use impact measure calculated by average annual daily traffic (AADT) count
Waste Water	WW	Water that has been used in the home, in a business, or as part of an industrial process. Also known as sewage.
Waterbody		Distinct and significant volume of water. For example, for surface water: a lake, a reservoir, a river or part of a river, a stream or part of a stream.
Watershed		Planning units that refer to the area from which surface water drains into a common lake or river system or directly into the ocean; also referred to as a drainage basin or catchment basin. Stormwater management across Auckland is organised into 10 major watersheds.

1.0 Introduction

The Auckland region includes an estimated 16,650 km of permanent streams and rivers, and an additional 4,480 km of intermittent streams (Storey and Wadhwa 2009). The nature of these rivers and their water quality is influenced by a variety of factors including geology, land use, impervious surface type, canopy cover, climate, and soil type. Anthropogenic influences, particularly land use and activities in watersheds, can strongly affect water quality in New Zealand (Larned et al., 2016; PMCSA, 2017). While Auckland has extensive networks of high-quality streams, water quality degradation has been documented in both urban and rural areas (Larned et al., 2016).

New Zealand is facing ongoing pressure from historic and continuing decline of water quality. New Zealanders are engaged and concerned by water quality issues. In 2019, Stats NZ revealed that freshwater quality concerned 80% of New Zealanders, building on prior surveys by a range of agencies highlighting water quality as of high or highest environmental concern (e.g., Hughey et al., 2016; PMSCA, 2017; WaterNZ, 2017; Fish and Game, 2019; Stats NZ, 2019). Concerns are likely to grow as pressures on freshwater increase from development, food security, climate change resilience, social mobility and remediation of historic degradation) (PMSCA, 2017).

In 2011, the Government signalled freshwater quality improvement was needed throughout New Zealand and in 2014 introduced the National Policy Statement for Freshwater Management (NPS-FM) – revised in 2017 and currently undergoing further revision. The latest NPS-FM 2020 version is operative but awaiting detail on several clauses.

Management of freshwater has become a matter of national significance requiring notification and/or operative plans implementing the NPS-FM by 31 December 2024, in all regions of New Zealand (RMA Subpart 4, Section 80A). Underpinning the NPS-FM is an acknowledgment of a freshwater pollution crisis in New Zealand, requiring change, improved management and more robust evidence underpinning all water quality decision-making.

Auckland Council is a unitary authority with both responsibilities to manage the protection and use of water under the Resource Management Act 1991 and Local Government Act 2002. Appropriate management of the hydrological cycle is fundamental to integrating both acts and achieving wellbeing outcomes, adapting to climate change, managing urban growth and biodiversity.

To meet this challenge, the Healthy Waters Department of Auckland Council, in partnership with the wider Auckland Council family and stakeholders, is developing a Freshwater Management Tool (FWMT).

The FWMT will also enable delivery of adaptive planning for stormwater management under the Healthy Waters Network Discharge Consent. It will support decision-making and communication, facilitating the development of water quality investment strategies through the Long-term Plan (LTP), including for the prioritised allocation of funding sources such as the Water Quality Targeted Rate (WQTR).

The FWMT is therefore an important part of the development of Auckland's Water Strategy, as described in the *Our Water Future – Tō tātou wai ahu ake nei* discussion document, which promotes best practice "integrated" water management (Figure 1-1).

With that in mind, the FWMT is designed so it can assist in building common understanding of surface hydrology and baseline water quality (contaminant) conditions, helping also to focus community interest on optimal management (e.g., prioritised reduction in contamination sources). Simulating future scenarios supported on integrated water management principles can provide a fast track towards implementing innovative solutions, such as multifunctional or green infrastructure, and evaluate contributions to wellbeing in the environmental, cultural, social, and economic facets of our society. Consequently, the FWMT holds the opportunity to integrate outcomes in Climate Action and Biodiversity that are of critical importance to Auckland.

Figure 1-1 summarises the Values contributing to te mauri o te wai – the life supporting capacity of Auckland's waters and the heart of Auckland's Water Strategy.

Our Water Values

1. Ecosystems: healthy water systems nourish the natural environment.
2. Water use: we can meet our everyday water needs safely, reliably and efficiently.
3. Recreation and amenity: we enjoy being in, on and near the water.
4. Culture: water contributes to our identities and beliefs, as individuals and as part of communities.
5. Resilience: our communities, catchments and coastlines are resilient to natural hazards and the impacts of climate change

Figure 1-1. Our Water Values as described in *Te mauri o te wai o Tamaki Makaurau* (*Our Water Future*)

The FWMT connects to te mauri o te wai through expanding concentric circles as indicated in Figure 1-2, contributing to wider management of water quality and hydrology, influencing outcomes for ecosystem health, and thence supporting a wider set of values of te mauri o te wai, incorporating needs for urban development, carbon action and biodiversity.

Figure 1-2. FWMT connections to wider objectives

1.1 National Policy Statement for Freshwater Management (NPS-FM)

The NPS-FM directs all regional councils and unitary authorities, to follow a consistent approach in managing water quality. Notably, to consult with their communities and identify: (1) the values for fresh waterways; (2) objectives to underpin maintaining or improving such values; and (3) attributes for objectives on which any assessment must be objectively and consistently made to demonstrate maintenance or improvement of water quality. This is the so-called National Objective Framework (NOF; MfE, 2017a). The NOF requires supplementation by regional attributes for broader community-held values.

To support both the needs for integrated and efficient water management, the NPS-FM also requires Auckland Council develop a freshwater accounting system (Clause 3.29).

Freshwater accounting refers to the collection of information about pressures on resources within Freshwater Management Units (FMUs), the spatial scale set by regional councils for freshwater management.

The NPS-FM (2020: Clause 3.29, 5) defines the requirements of freshwater quality accounting systems to "*record, aggregate and keep regularly update information on the measured, modelled or estimated:*

- *Loads and/or concentration of relevant contaminants; and*

- *Where a desired contaminant load has been set as part of a limit on resource use, or identified as necessary to achieve a target attribute state, the proportion of the contaminant load that has been allocated; and*
- *Sources of relevant contaminants; and*
- *Amount of each contaminant attributable to each source*".

Freshwater accounting systems must therefore account for the type and amount of relevant contaminants affecting freshwater quality, including pathway for contaminants, from natural, diffuse and point sources.

Prior guidance for the NPS-FM (MfE, 2017:82) noted that freshwater accounting systems, are intended to:

- "*Inform decisions on setting freshwater objectives and limits (providing information on sources and amounts of contaminants; testing economic and social impacts of various scenarios);*
- *Inform decisions on managing within limits (determine most equitable and cost-effective methods to achieve objectives);*
- *Report on progress to meeting freshwater objectives*".

The NPS-FM (2020: Clause 3.29, 2) clarifies this further, stating the purpose for accounting systems is "*to provide the baseline information required:*

- *For setting target attribute states, environmental flows and levels, and limits; and*
- *To assess whether an FMU is, or is expected to be, over-allocated; and*
- *To track over time the cumulative effects of activities (such as increases in discharges and changes in land use)*".

Any regional freshwater accounting system therefore needs to be resolved to sufficient detail for objective setting, determining management actions and reporting on implementation (e.g., "commensurate with the significance of the water quality or quantity issues applicable to each FMU or part of an FMU" [NPS-FM, 2020 Clause 3.29, 3]). Equally therefore, regional accounting systems must be flexible enough to support varying scales of accounting resolution from sub-catchment to FMU. MfE (2015:12) recommend that nine high-level principles of freshwater accounting become standard practice for councils implementing the NPS-FM, to assure the quality of baseline information used in decision-making (Table 1-1).

Freshwater accounting systems are not explicitly recognised by the NPS-FM as either modelling- or monitoring-based. However, accompanying guidance by the Ministry for the Environment (MfE, 2015) notes that for the sake of practicality, it is unfeasible to monitor everything, everywhere, at all times and that monitoring costs are often disproportionate to catchment modelling for equivalent or lesser information. For the purpose of NPS-FM freshwater accounting, modelling is a likely and supported approach to set freshwater objectives and limits (MfE, 2015, 2017b, 2020).

Table 1-1. Principles of freshwater accounting (MfE, 2015:12, Table 3:1)

Principles	Descriptors
Risk-based	Accounting systems should allow for accounts to be generated using methods appropriate to the scale and significance of issues in a freshwater management unit (FMU). Identification of relevant contaminant sources should be linked to risks faced in an FMU.
Transparent	The purpose of the accounting system should be clearly stated. Accounting information should be easily accessible by water users, iwi and the community. All methods used for accounting should be clearly documented, so that calculations are repeatable.
Technically robust	Accounting systems should use good practice methods based on relevant science. Accounting systems should allow comparison between years (or reporting periods) and with other FMUs. Any errors and uncertainties of methods used should be clearly documented. Quality assurance steps should be documented, and methods for handling any data issues that may come to light outlined.
Practical	Accounting systems should allow for councils to collate information from various existing systems or models (e.g., consents databases, monitoring databases). The systems should allow reports to be generated and displayed for water users, iwi and the community. Accounting systems should be future-proofed, so they remain practical, capable of being replicated, understood and upgraded over time.
Effective and relevant	Accounting systems should be fit for purpose – that is, they should allow for the four potential uses of accounting information (see section 1.3) for regional freshwater management. Accounting systems should produce meaningful information (accurate, appropriate to the spatial scale of the issues and useful to the intended end users), noting that this may vary with the purpose of the accounts being produced. Accounting systems should be cost-effective.
Timely	Accounting systems should allow a council to produce regular accounts in a suitable form for water quantity and water quality for the FMUs, where freshwater objectives and limits are being set or reviewed. Accounting systems should allow councils to collect and analyse information at frequencies that are relevant to the intended management use (e.g., seasonally, to be relevant to ecological systems and variability in flows; daily, if data will be used for operational water take and/or restriction management).
Partnership	Accounting systems should be developed, and information collected in partnership with stakeholders, iwi and the community. This will help to ensure that the accounts produced are well understood and accepted. It will also help to minimise duplication

Principles	Descriptors
	of resources and ensure that appropriate aggregation is used to protect individual and commercial privacy
Adaptable	Accounting systems should allow for flexibility to accommodate different methods appropriate to the scale and significance of the issues in different FMUs. The systems should allow for improvements in methods and the accuracy of measurements, estimates and/or modelling results over time. Accounting systems should allow for the integrated and iterative nature of freshwater management. Where considered appropriate or necessary, systems should allow for reporting that is scalable from FMUs (or water management zones, if this is different) to the regional level.
Integrated	Where appropriate, the system should allow for the consideration and combined reporting of, for example, surface water and groundwater interactions or discharges to different receiving waters, such as estuaries

1.2 Auckland Council Freshwater Accounting

In developing a freshwater quality accounting framework, it is important to note the progress and investment that Auckland has already made to improved water management, including its prior quantity and quality accounting systems. Figure 1-3 outlines some of the important milestones in Auckland's Water management history, representing the journey to the FWMT since 1990.

Targeted and State of the Environment (SoE) monitoring by Auckland Council has also compiled a body of freshwater accounting knowledge including:

- SoE Monitoring with continuous flow and several physicochemical indicators (e.g., pH, turbidity, dissolved oxygen) coupled with grab sampling for most water quality indicators.
- Edge of field and end of pipe studies to contribute to contaminant load and concentration understanding.
- Consent compliance data and metering of takes and discharge quantity/quality.

Prior to the amalgamation of Auckland's local government into a unitary authority, the Auckland Regional Council (ARC) established, amongst other resources, Low Impact Design Guidance (ARC TP 124), Stormwater Treatment Device Design Guidelines (ARC TP10) and the ARC Contaminant Load Model (ARC CLM, 2006, 2010). The guidance and standards have been replaced by Auckland Council technical publications GD01 and GD04.

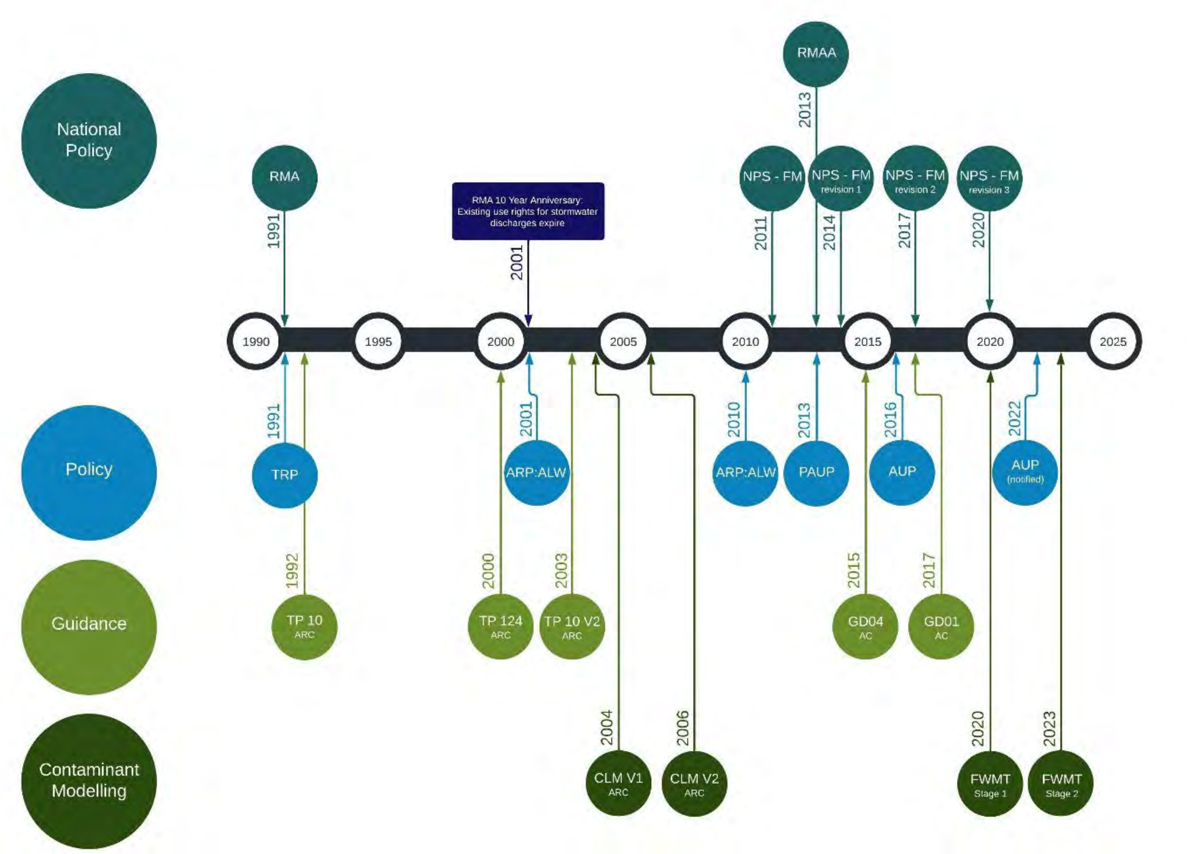


Figure 1-3. Timeline of policy, guidance and contaminant modelling in Auckland from 1990-2025

The Contaminant Load Model (CLM; TR 2010/003 and 004) was developed to by the legacy Auckland Regional Council (ARC) in 2006 as part of the Stormwater Action Plan (SWAP). The CLM is an excel-based spreadsheet model developed to estimate stormwater contaminant loads on an annual basis, based on edge of stream yields derived from monitoring studies applied to a set of standardised land cover types. The period between 2006 and 2010 resulted in significant use of the CLM to support stormwater infrastructure planning across Auckland urban areas, including a new variant with static, steady-state intervention capability. The CLM was modified in 2013/14 for broader use in New Zealand urban environments and published by NIWA as C-CALM (Semadeni-Davies and Wadhwa, 2014).

Both CLM and C-CALM are relatively simple, resolving annual load only, and from generalisation of a source yield by area of source (land use) within the area being studied (catchment), with all output being cumulative and steady-state (i.e., not able to simulate variation in yield and/or concentration discharged, by time nor too for any instream transformation, or by differing flow paths). Both marked a progression for decision support tools to understand general changes to contaminant loading from stormwater management in New Zealand, but do not directly simulate instream contaminant concentrations, grade water quality for concentration-based effect (e.g., NOF attributes) nor integrate a wide library of sources with varying contaminant load (i.e., limiting integrated water management). Hence, neither CLM nor C-CALM meet various NPS-FM requirements for water quality effects assessment.

In preparation for the development of the Auckland Unitary Plan (Notified 2013, Operative in part 2019), the concepts of hydrology and contaminant management were advanced with various evidential studies (Fassman-Beck et al. 2013, Auckland Council 2013) to support Stormwater Management Areas: Flow (SMAF) and Design Effluent Quality Requirements (DEQR) in the proposed plan. The DEQR standards did not carry through the Independent Hearing Process. Although, several water quantity and quality measures were included in the Auckland Unitary Plan (Operative in Part 2019) from which to base further plan changes, to implement NPS-FM.

The FWMT supports a range of rules and implementation programs for the NPS-FM building on earlier contaminant modelling led by the Auckland region. Combined, the sources of freshwater quality accounting available to Auckland Council include:

- 'Observed' data from the State of the Environment (SoE) river water quality network managed by Auckland Council's Research and Evaluation Unit. The SoE river water quality monitoring network includes 36 stations across Auckland's 10 major watersheds. A key purpose for the SoE river water quality monitoring network is trend analysis (e.g., changes in contamination over time) with lesser purposes for loading analysis since a lack of direct monitoring of tracers for source assessment limits calibration. The objective of this network is to help characterise the quality of the region's freshwater resources including changes therein, and to adaptively evaluate the efficacy of council's policy initiatives and management approaches under the Resource Management Act 1991.
- Various past targeted monitoring exercises into contaminant concentration, loading and sources, which have effectively become incorporated into the FWMT via configuration and performance assessment (e.g., FWMT Configuration and Calibration report – Healthy Waters Environmental, 2020).
- 'Predicted' outputs from the Freshwater Management Tool (FWMT), which is a continuous and integrated accounting framework (rural and urban, spanning all freshwater management units in the Auckland region) for hydrological and contaminant processes resulting from the use and development of land upon freshwater and coastal receiving environments. To simulate water quality in monitored and unmonitored watersheds, the FWMT uses the Loading Simulation Program in C++ (LSPC) (Shen et al., 2004). LSPC was developed by the U.S. Environmental Protection Agency and is built on an open-source platform to simulate watershed hydrology, sediment erosion and transport, as well as water quality processes from both upland contributing areas and

receiving streams (the code for LSPC can be downloaded here: LSPC Code). The FWMT accounts for approximately 490,000 Ha of land, 3,085 km of permanent streams, and 2,761 sub-catchment outlets or "nodes" (~18% of the regional permanent and intermittent stream network).

This report documents the configuration of the LSPC base module in the FWMT Stage 1, including the representation of hydrological and contaminant processes across hydrological response units (HRUs) for water quality prediction across the Auckland region. The report also documents calibration and validation for observed flow and contaminants (concentration and load), across full and subsets of flow and seasonal gradients at 26-46 instream stations (varying with contaminant). Limitations of the configuration and performance are also noted, including a reliance only on discrete rather than continuous or integrated contaminant observations in the existing State of Environment monitoring network.

1.3 FWMT Purpose

The FWMT has been developed to serve multiple purposes shown in Figure 1-4 Associated objectives required achieve "fit for purpose" outcomes are also listed and described in Sections 1.4 to 1.7.

Figure 1-4. FWMT value chain of purposes and objectives. The FWMT supports four linked purposes, each with a range of objectives listed beneath

1.4 FWMT Objectives

The FWMT has a set of objectives relating to its role as Auckland Council's freshwater quality accounting framework under the NPS-FM (2020). This modelling approach integrates the principles of freshwater accounting as provided in the Guide to Freshwater Accounting under the National Policy Statement for Freshwater Management 2014 (MfE 2015) listed in Table 1-1.

The current SoE freshwater monitoring network guides configuration of the FWMT Stage 1. The SoE network records the state of freshwater at many monitored sites across the region, for stream hydrology and quality. However, the SoE monitoring network lacks continuous data on quality and offers limited regional coverage or resolution. To support continuous modelling improvement, future FWMT iterations will be supported by both SoE and dedicated monitoring programmes.

1.4.1 Adaptable Hydrology

The process-based routines used by the FWMT are applied at a 15-minute time step, continuously across a multi-year period to produce flow and contaminant concentration time series throughout a modelled stream network spanning the entire Auckland region. FWMT time series output support a range of analyses, including water quality load and concentration reporting. The key features of this hydrology framework for the FWMT are the methods of continuous simulation and process simulation described below.

Continuous simulation uses time series of boundary conditions to represent the variability of climate at high-resolution (spatially and temporally), including rainfall intensity, rainfall duration and antecedent period. Thereby able to better simulate first-flush behaviour and acute contaminant events. Continuous simulation with a high resolution of actual or virtual climate enables both improved understanding of state and variable sizing of interventions for optimal benefit in scenarios. Equally, time series output enables rapid accounting should guidance change (i.e., NOF and regional attribute guidance focusses largely on median and 95^{th}% contaminant concentration, but could in future shift to other percentiles; the FWMT can be used to generate information on any contaminant concentration percentile);

Process-simulation uses equations and parameters to simulate hydrological and contaminant processes (on land and instream for the FWMT). Process-simulation enables accounting to represent the hydraulic routing and physicochemical performance of devices under the influence of important variables such as friction, gradient, volume, residence time, settling velocity, infiltration rates and erosion. Process-simulation also contrasts with statistical or stochastic modelling techniques that apply observed distributions generalised against governing factors (e.g., CLUES, eSource). Process-simulations thereby enable greater understanding of the causes for and behaviour of contaminants, with greater capability to demonstrate how and why interventions will deliver water quality outcomes.

1.4.2 Risk-based Contaminants

The NPS-FM requires accounting of all relevant sources of freshwater contaminants. Numerous studies in the Auckland region have highlighted that amongst stormwater, wastewater and diffuse discharges, contributions of nutrients, sediment, faecal matter and heavy metals are likely the most widespread and serious risk to coastal and freshwater quality outcomes (e.g., Mills and Williamson, 2008; Green 2008a, b; Hewitt and Ellis, 2010). Accordingly, Stage 1 FWMT has been limited to simulations of nutrients, heavy metals, sediment and human faecal contaminants, with the following accounted for across the Auckland region:

1. Nitrogen (N) – total and dissolved forms (directly both)
2. Phosphorus (P) – total and dissolved forms (directly both)
3. Copper (Cu) – total (directly) and dissolved forms (indirectly)
4. Zinc (Zn) – total (directly) and dissolved forms (indirectly)
5. Sediment – total suspended solids (TSS) (directly)
6. Faecal indicator bacteria – *E. coli* (directly)

Future FWMT iterations might simulate instream ecological outcomes (e.g., periphyton, macrophytes, macroinvertebrates, fish). However, Stage 1 FWMT has a clear focus simply on flow and contaminant processes, for the most pressing regional contaminants (e.g., “relevant contaminants” for the NPS-FM – see MfE, 2015).

1.4.3 Robust Contaminant Sources

Diverse natural, point and diffuse contaminant sources are accounted for by the FWMT. All contaminant sources are tiered into a typology of 106 unique Hydrological Response Units (HRU) derived from combinations of soil, slope, land cover and intensity classes. All contaminants are accounted by HRU to edge-of-field (prior to instream processing) but subject to overland or through-soil processes, as well as to downstream receiving environments (following instream processing). Major reticulated wastewater networks operated by Watercare Services Ltd. (Watercare) in the Auckland region and major stormwater networks operated by Auckland Council are separately configured within the FWMT. Natural geological sources of contaminants are not directly accounted for with information on geology not incorporated into the HRU typology. Deep or old groundwater processes are also not directly accounted for; only active groundwater is simulated within the Stage 1 FWMT.

1.4.4 Practical Performance

Freshwater quality accounting performance of the FWMT has been assessed through calibration and validation to State of Environment monitoring stations (e.g., 46 continuous flow and 36 discrete [monthly] contaminant stations). Both calibration and validation has been undertaken only at instream locations, albeit for a lengthy period (up to 15 years, 2003-2017) and in numerous reporting envelopes for conditions (e.g., lower through to greater flow and seasons). In both calibration and validation, numerous measures are also utilised for the varied reporting envelopes (e.g., r^2, Nash-Sutcliffe Efficiency, bias). Collectively, the mix of varying envelopes and measures of performance have been identified as necessary to support the use of the continuous simulation capability of the FWMT. For instance, as continuous time series are produced by the FWMT, these can be queried for changes to contaminant contribution by source, under varying conditions of flow and time. Meaning information on model performance is needed across such gradients to ensure appropriate use of FWMT accounting.

Output from the FWMT is modelled but informed by measured data through performance assessment (e.g., in calibration and validation). Doing so ensures region-wide spatial coverage (of all sub-catchments and watersheds), continuous temporal coverage (of all events) and provenance of contaminants (to relevant sources). All three outcomes are otherwise impossible within the limitations of Auckland Council's State of the Environment monitoring network (i.e., monthly grab-samples for most contaminants, limited to 36 locations only). Importantly, freshwater accounting for the NPS-FM does not require use of measured *or* modelled data, with both combined being best practice (MfE, 2015).

1.4.5 Inform Hydrological Understanding

Due consideration of the complex issues and opportunities for freshwater management requires an informed understanding of the hydrological and contaminant cycle (i.e. interactions between systems influenced by and influencing water movement and quality). The FWMT simulates rainfall-runoff processes in the water cycle, describing the full range of conditions for surface hydrology across long term, predicted climate including the water balance across seasonal variability, but exclusive of deep or old groundwater processes. This comprehensive picture of water quality and quantity provides a wealth of information to support enhanced understanding by stakeholders and water managers to better understand and manage freshwater resources.

1.4.6 Leverage Stakeholder Inputs

The FWMT development is intended to lead through iterative phases including direct engagement of stakeholders, iwi and community to leverage stakeholder inputs of targeted information to improve freshwater quality accounting. Engagement is essential to utilising input data from a wide range of sources and testing assumptions.

1.5 FWMT Scenario Assessment Objectives

Auckland Council has a range of responsibilities under the RMA and LGA to make effective and prudent decisions for investment and sustainable management of freshwater. These require forecasting future water quality contaminant load and concentrations instream and to coast, for consideration of management options (e.g., for effect, efficiency and equitability).

The FWMT can model a variety of future growth scenarios through **integrated forecasting** of changes to land cover, impact, discharges and climate change (i.e., changes in both landscape, via altered HRU composition, and to overlying climate). Furthermore, the FWMT can represent the type of interventions that may be required to achieve a target contaminant state for freshwater quality (e.g., concentration or load-based outcome). Interventions span both rural and urban sources of contaminant including, “structural devices” and “source control” options. Structural devices include stormwater ponds, wetlands and any edge-of-field device (e.g., delivered by subdivision and development processes, policy instruments on rural or urban land, or by public investment). Source control includes changes to land use and/or practices affecting contaminant generation or interception (e.g., delivered by policy instruments, subsidies or management programmes including education and outreach).

Scenario (“future state”) and baseline (“baseline state”) accounting within the FWMT are alike in terms of contaminants, units, sources and process simulation. The continuous and **process simulation** of hydrology and contaminants, enables structural devices and source controls to be accounted for as **dynamic interventions** (i.e., varying in performance over time with climate and flow).

1.6 FWMT Optimised Strategy Development Objectives

Auckland Council as a Unitary Authority holds responsibility for regulatory policy under the RMA and for infrastructure and service provision under the LGA. FWMT water quality accounting to HRU enables inspection not simply of net cost for intervention strategies but also the spread in cost across land users (e.g., agriculture, developers, local government). Auckland Council has developed the FWMT especially to identify integrated solutions that **optimise investment** (target solutions to contaminant provenance in sub-catchment) with **equitable burden** (across sectors and generations) to maximise surety of strategies delivering outcomes, **efficiently**. Scenario optimisation was identified as critical for the FWMT to deliver efficiently on NPS-FM requirements within the Auckland region, where considerable and diverse urban contaminant sources and options exist, with projections for extensive future conversion of rural to urban land.

Through continuous and process-based simulation, the FWMT can tailor the treatment of contaminants to be most cost-effective (optimal) and better integrated as part of a catchment system (i.e., optimised to a sub-catchment and across numerous sub-catchments for ki uta ki tai). The FWMT includes optimisation routines to simulate **life cycle costs** of alternative intervention options, varying cost not simply between intervention type but also by size and location (i.e., for land cover, property value, topography, contaminant loading, variation in discharge). Similarly, the FWMT enables intervention to vary in benefit across type, size and location due to factors such as loading, as well as between chronic and acute contaminant concentrations.

For the purpose of informing best practicable methods to achieve water quality outcomes and limits under the NPS-FM, scenario-modelling objectives for the FWMT include optimisation of contaminant outcomes (concentration and load) from:

- Interventions (devices, practices and land use change);
- Optimised for cost (within and between sub-catchments);
- Targeted to receiving environment (instream, to lake, to coast);
- Accountable to relevant sources (natural, point and diffuse).

The FWMT includes capability to vary both effect and cost of interventions, by type, location and contaminant (throughout the Auckland region) for concentration or load based objectives, generating optimised abatement curves for each sub-catchment (Tier 1) and to downstream locations (Tier 2 – higher order streams, lakes, coast).

1.7 FWMT Effective Communication Objectives

Freshwater is a taonga (treasure) whose effective management is a responsibility for all including Auckland Council. Auckland’s iwi, local boards and communities are increasingly requiring information on baseline conditions, future conditions and optimal freshwater management.

Due consideration of the complex issues and opportunities for freshwater management requires an informed understanding of the hydrological and contaminant cycle (i.e., interactions between systems influenced by and influencing water movement and quality). The FWMT simulates rainfall-runoff processes in the water cycle, describing the full range of conditions for surface hydrology across long term, predicted climate but exclusive of deep or old groundwater processes.

FWMT development is intended to lead through iterative phases including direct engagement of stakeholders, iwi and community to leverage stakeholder inputs of targeted information to improve freshwater quality accounting. Engagement is essential to utilising input data from a wide range of sources and testing assumptions. Accounting by the FWMT will inform and engage stakeholders in strategy development including objective-setting and implementation decision-making for the NPS-FM.

Councils must specifically engage in discussion with communities and tangata whenua to determine local understandings of Te Mana o te Wai, as a "fundamental concept" of the NPS-FM (2020) (e.g., of relevance to all freshwater management whether referred to explicitly in the NPS-FM). Engagement on evidence from the FWMT offers Auckland Council the ability to deliver on several policies of the NPS-FM (2020):

- *Policy 1: Freshwater is managed in a way that gives effect to Te Mana o te Wai;*
- *Policy 2: Tangata whenua are activity involved in freshwater management;*
- *Policy 3: Freshwater is management in an integrated way that considers the effects of the use and development of land on a whole-of-catchment basis, including the effects on receiving environments;*
- *Policy 4: Freshwater is managed as part of New Zealand's integrated response to climate change;*
- *Policy 5: Freshwater is managed through a National Objectives Framework;*
- *Policy 11: Freshwater is allocated and used efficiently, all existing over-allocation is phased out, and future over-allocation is avoided;*
- *Policy 12: The national target for water quality improvement is achieved;*
- *Policy 14: Information about the state of water bodies and freshwater ecosystems, and the challenges to their health and well-being, is regularly reported on and published;*
- *Policy 15: Communities are enabled to provide for their social, economic, and cultural well-being*.

Auckland Council has developed both baseline and scenario capability in the FWMT, to ensure robust evidence is available for communication of current and future water quality state, causes for degradation, benefits of intervention and optimal strategies to reach improved state. By clearly demonstrating efficacy, cost and equity of interventions required to meet future attribute states, the FWMT will support better freshwater decision-making across Auckland. In so doing, better enabling NPS-FM (2020) implementation of an objective hierarchy (e.g., of first the health and wellbeing of waterways, then the health of the people and only then, the ability of communities to provide for their social, economic and cultural well-being, now and into the future – Objective 2.1)

1.8 FWMT Scope

The FWMT serves dual purposes for the NPS-FM and WQTR outlined in Section 1.3. Specifically, to fulfil freshwater accounting system requirements, decision-making and implementation requirements for Auckland Council as a unitary authority (i.e., regional and district government functions of the RMA and LGA). The FWMT is therefore required to support both policy development and infrastructure planning.

The FWMT scope includes both current (2013-2017) and future state freshwater accounting, region-wide at sub-catchment scale via continuous process-based modelling (i.e., to reasonably foresee the effects of targeted investment, development and climate change on freshwater quality, integrated across the Auckland region).

The FWMT scope is supported by an iterative build programme to accommodate revisions to national policy statements, improved regional evidence (including monitoring datasets) and community engagement in decision-making. For Stage 1, the FWMT scope is limited to accounting for six contaminants in varying forms (dissolved, total): N, P, Cu, Zn, TSS and *E. coli*.

The Stage 1 FWMT is also limited in scope to *direct* accounting from land to stream, lake and coast environments, *direct* accounting instream (e.g., contaminants continuously transformed for instream processes), and *indirect* accounting for in-lake via optimised-Vollenweider equations (i.e., FWMT predicted external nutrient loads transformed to steady-state in-lake TN, TP, Chl-a and SD, graded by NOF guidance).

***Note**: the above and following introductory sections are adapted from the FWMT baseline reports to ensure consistency of context and purpose for the FWMT is clear to readers of inputs, configuration and performance, and outputs.*

1.8.1 FWMT Staging – Iterative approach to development

Accommodating the FWMT's ambitious scope for a process-based and comprehensive (continuous, region-wide, sub-catchment resolved) freshwater contaminant accounting model, is not feasible within a short timeframe and single modelling stage. Instead, a prioritised and iterative approach underpins the FWMT development, of both baseline and scenario capability (e.g., for concentration and/or load grading and optimisation).

An iterative approach enables the FWMT to better accommodate (ongoing) changes to the NPS-FM, inform a targeted monitoring programme for greater understanding of freshwater contaminant processes, incorporate such data in revised configuration (for improved performance) and provide an increasingly strengthened evidence base for freshwater objective-setting, limit-setting and implementation decisions.

Development of FWMT Stage 1 commenced in November 2017 using data collected up to 30 June 2017, with a multi-year and incremental programme for Baseline and Scenario Modelling. FWMT Stage 1 baseline state capability is anticipated for delivery by early 2020 and scenario state including optimisation capability, by late 2020[2].

Design and development of Stage 2 FWMT will occur in response to delivery, engagement, policy, regional planning and operational planning uptake of Stage 1 output. Scenario and sensitivity testing using FWMT Stage 1 will proceed only after development is complete (Figure 1-5).

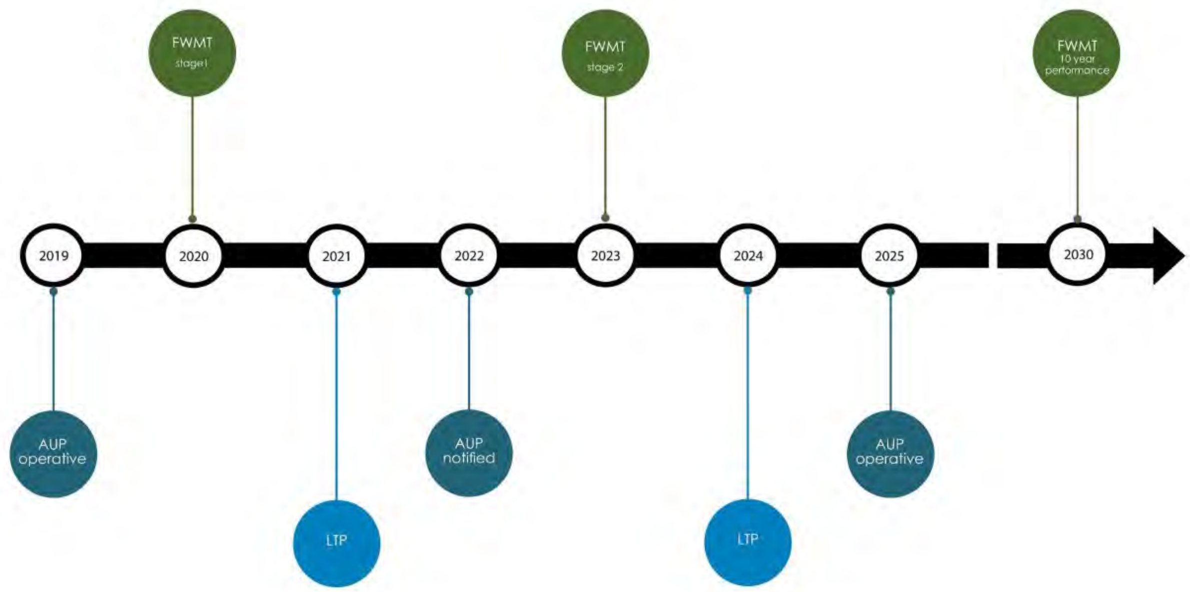


Figure 1-5. Delivery timeline of the FWMT through three iterative stages, with consistent scope between to deliver both baseline and scenario evidence on freshwater quality attribute states under existing and alternate management actions

1.8.2 Baseline Modelling

Catchment modelling of baseline freshwater quality typically aims to establish the baseline state of hydrological and contaminant distributions, across a catchment and either as generalised or continuous state. Baseline modelling is acknowledged in NPS-FM supporting guidance (MfE, 2015) as necessary to ensure variation in contaminant concentration or loading, is understood: throughout an FMU/watershed,

[2] Development timeframes have adjusted since completion of this report and delayed publication by Auckland Council internal engagement processes.

across acute and chronic conditions, and for variation in natural and anthropogenic drivers (soil, land cover, intensity of use, climate).

The objectives for baseline modelling can include:

- Simulation of a historical period matching the best flow and contaminant concentration records available to allow calibration against monitored data.
- Simulation of un-monitored conditions, across time and space, to allow improved understanding of baseline conditions across the regional gradients in driving factors.
- Establish a suitable tool with an appropriate level of confidence for use in scenario modelling.

In practice, catchment modelling requires a range of existing datasets, of varying quality and resolution, nested in a hierarchy reflecting modelling objectives. Where synthesis of data is required, a focus on transparency, repeatability and producing useful data assets for wider business processes is essential.

Baseline modelling can be expected to result in the identification of deficiencies of existing datasets (i.e., in response to testing model performance and/or understanding the spread of likely conditions in contrast to any existing monitoring network). The iterative development of the FWMT is intended to enable continuous improvement of baseline accounting performance by identifying any dataset deficiencies.

The primary unit for FWMT accounting varies by focus, including for:

- Contaminant, by load and/or concentration (from land and instream) – for rivers and to-lake, available continuously from-land as load and/or concentration. For rivers only, also available as transformed instream concentration and load throughout the modelled stream network (inclusive of cumulative and continuous transformation process);
- Space, by sub-catchment through to watershed – for river and lake alike;
- Time, continuously from 15-minute through to multi-year period – for river and to-lake alike whereas in-lake accounting is limited to steady-state only (i.e. not continuously transformed in-lake).

The FWMT thereby generates a mix of continuous time series from land and instream, as well as steady state in-lake, resolved to sub-catchment and stream network. Both continuous time series and steady-state output are suitable to account for a range of grading concentration metrics (e.g., median, 95^{th}%) and for *E. coli*, additional grading metrics (e.g., %>260 MPN/100ml; % >540 MPN/100ml).

Baseline state for FWMT Stage 1 is the period 2013 to 2017, representing a near-recent period of sufficient length to determine a range of acute and chronic responses to resource use but with sufficient high-quality data for robustness of freshwater quality accounting. During this period the underlying landscape is static whilst overlying climate is varied alongside point-sourced discharge from reticulated wastewater networks.

1.8.3 Scenario Modelling

Scenario catchment modelling adapt baseline conditions, including representation of a range of interventions, to represent future conditions driving water quality. Scenario capability is required of the NPS-FM to avoid further impairment and/or improve water quality for the reasonably foreseeable growth and development of Auckland. Configuration of scenarios will likely undergo change in response to FWMT findings (i.e., including or excluding options for contaminant loss reduction or updating costs associated with different land uses). Optimised scenario modelling in the FWMT will also require an a-priori understanding of limiting contaminant(s), targets and attainment points to deliver on NPS-FM objectives.

Much like baseline modelling, scenario modelling capability can be therefore expected to require improvement as datasets, planning instruments and attainment objectives are varied. Equally, sensitivity testing of scenarios can be expected to identify further modelling needs, especially for optimised future scenarios (i.e., where intervention types, effects, costs and opportunities can each alter optimal management strategies).

1.9 FWMT Modelling Approach

Numerous water quality models can simulate the complex range of interactions that generate and transform water quality containments from land to water. Auckland Council technical officers explored both national and international options to meet the FWMT purposes (Section 1.3). Despite recent advancements in the state of water quality modelling in New Zealand, locally developed models do not meet Auckland Council's freshwater quality accounting requirements (e.g., process-based, continuous simulation, baseline and scenario capability, optimised strategy development, integrated modelling from land to sea, region-wide across urban and rural conditions). For instance, CLUES, SedNet, ROTAN and TRIM all lack some part of the process-based and/or continuous capabilities required for the FWMT scope; only internationally developed modelling frameworks have been successfully applied to continuous, process-based freshwater contaminant simulations in New Zealand (e.g., eSource in Greater Wellington's Whaitua process – Jacobs, 2019a, b).

A detailed review and comparison of 11 physically based, watershed-scale hydrologic and nonpoint-source pollution models were given in Borah and Bera (2003). This review found that AGNPS, AnnAGNPS, DWSM, LSPC, MIKE SHE, and SWAT were more fully developed and comprehensive process-based modelling systems, having three major components of freshwater contaminant accounting: hydrology, sediment, and chemical (with varying ecological capability). Among these models, AnnAGNPS, LSPC, and SWAT and MIKE SHE are continuous simulation models useful for analysing acute and chronic events from watershed management (e.g., simulation of hydrology and contaminant concentration and loading). MIKE SHE, the most physically based model, is data and computationally intensive for efficient applications. Therefore, among the physically based long-term continuous models reviewed, LSPC and SWAT were the most comprehensive but *efficient* continuous watershed models; SWAT for agricultural watersheds and LSPC for mixed agricultural and urban watersheds. LSPC integrates with the System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN) model, which provides a system for modelling of structural and non-structural interventions (e.g., devices and source control). Both LSPC and SUSTAIN are open-sourced modelling packages, developed by the US Environmental Protection Agency for objective setting and implementation strategy determination under the US Clean Waters Act (1972) (e.g., for derivation of and attainment of total maximum daily loads for freshwater contaminants in urban and rural catchments). Under that purpose, LSPC and SUSTAIN applications have undergone peer-review for regulatory use, supporting similar application in NZ for the NPS-FM. Combined with the requirements of its freshwater quality accounting scope, Auckland Council thereby elected to utilise LSPC and SUSTAIN as the modelling framework in the FWMT; peer review and prior reporting for contaminant accounting being assessed as integral to extension and communication of FWMT outputs with decision-makers and those tasked with implementing management strategies.

The FWMT is being developed by the Healthy Waters Department with an inter-disciplinary and international team of subject-matter experts under an iterative approach, including:

- Paradigm Environmental Ltd – model design, development (LSPC, SUSTAIN) and reporting;
- Morphum Environmental Ltd – data input, model development (LSPC, SUSTAIN) and reporting;
- Hydraulic Analysis Ltd – data input and reporting;
- Koru Environmental Ltd – data input, model development (SUSTAIN) and reporting;
- Manaaki-Whenua Landcare Research Ltd – data input, model development (SUSTAIN) and reporting;
- Perrin Ag Ltd – data input, model development (SUSTAIN) and reporting.

This team is supported by various departments of Auckland Council (Plans and Places, Natural Environment Strategy, Research and Evaluation Unit) and council-controlled organisations (Watercare, Auckland Transport).

1.10 FWMT Reporting Approach

Reporting is an integral requirement of freshwater quality accounting under the NPS-FM (Policy 2, 14 and 15 – especially Clauses 3.2 to implement Te Mana o te Wai, 3.7 to follow the NOF process transparently, 3.10 to identify baseline attribute states using best available information, 3.15 to prepare and share action plans for achieving environmental outcomes and 3.29 to operate, maintain and publish information on freshwater accounting systems regularly). Reporting is required both to inform decision-makers and for engagement with community in implementation of objective- and limit-setting decisions. For both outcomes, engagement will depend on clarity about the purpose, scope and objectives of the FWMT as well as the model development process and accounting outcomes (e.g., inputs, configuration, performance, outputs under both baseline and scenario conditions).

The reporting framework for the Stage1 FWMT is indicated in Table 1-2. This framework has been developed to allow the model development processes to remain transparent and flexible.

Table 1-2. FWMT Reporting Framework

Report #	Report	Purpose
1	**Integration**	Defines the context, purpose, objectives, development and reporting approach for the FWMT. Included is discussion of how to integrate the FWMT with wider Auckland Council planning and operational functions (e.g., wider national policy statements, local government functions).
2	**Baseline Data Inventory**	References and documents all pre-existing datasets used in baseline modelling. Describes how all other modified or new datasets were generated, describes limitations. Includes meteorology, topography, stream network and geometry, soil, land cover and use, impervious surfaces, on-site wastewater, reticulated wastewater, stormwater, pre-existing devices.
3	**Baseline Configuration and Calibration**	Describes the configuration of LSPC to represent baseline. Describes which processes are accounted for and how these are generalised. Acknowledges limitations of configuration. Documents calibration performance against a range of metrics.

Report #	Report	Purpose
4	**Baseline State (rivers)**	Describes output of baseline accounting. Assesses spread of predicted hydrology, distribution of yields and instream loads – describing that by watershed, source and pathway, for 5-year baseline state interval (2013-17). Assesses instream gradings by contaminant over full 5-year interval (2013-17) and subsets of (wet vs. dry years; storm vs. base flow) – linking back to calibration findings on robustness of such output for FWMT purposes and objectives.
5	**Baseline State (lakes)**	Describes output of LSPC and post process assessment on baseline lake conditions utilising optimised Vollenweider equations for predicting steady-state in-lake TN, TP, Chl-a and SD from continuous external TN and TP inputs.
6	**Scenario Data Inventory**	References and documents all pre-existing datasets used. Describes how all other modified or new datasets were generated. Describes limitations thereof. Includes future climate, future land use, structural device menu and maximum opportunity, source control menu, future wastewater network performance, rural interventions, intervention cost and benefit.
7	**Scenario Configuration and Optimisation**	Describes configuration of LSPC to represent future state or scenarios (e.g., AUP, development, climate change). Describes configuration of SUSTAIN to represent mitigation strategies, costs and effects as well as optimisation process (e.g., for nodes instream or downstream, for which limiting contaminant or hydrology).
8	**Scenario Outcomes**	Frames changes in contaminant outcomes (loads, grading) resulting from climate change, development, and interventions including regulation, non-regulatory policy, infrastructure delivery and lifecycle management. Limited as per Baseline state – Rivers and Lakes reports, to relevant contaminants, sources and interventions.

2.0 Model Background

This section describes the models that compose the FWMT and their applications and numerically represented processes.

The FWMT is composed of two linked models (LSPC; SUSTAIN see Figure 2-1) – a Baseline State model and a Future State model – both of which are open-source, process-based continuous simulation platforms developed by United States Environmental Protection (USEPA). The primary application of these models has been addressing water quality-impaired waterways per requirements of U.S. Clean Water Act (CWA, per Code 40 CFR 130.7; link). Both models have undergone peer-review and successful applications have been found to be appropriate for use in supporting development of integrated catchment management plans for water quality outcomes. The LSPC and SUSTAIN models within the FWMT are considered state-of-the-art for watershed-scale, water quality planning and the result of decades of research and applications. Figure 2-2 illustrates the 60-year timeline of model development and applications that led to the current code base for LSPC and SUSTAIN, originating from the Stanford Watershed Model (Crawford and Linsley, 1966), EPA Stormwater Management Model (SWMM; USEPA, 2015b), and the Hydrological Simulation Program – FORTRAN (HSPF) (Bicknell et al., 1997).

The Baseline State hydrologic and water quality model within the FWMT is the Loading Simulation Program in C++ (LSPC) (Shen et al., 2005). LSPC is built for simulating watershed hydrology, sediment erosion and transport, and water quality processes from both upland contributing areas and receiving streams (the code for LSPC can be downloaded here: LSPC Code). LSPC has been extensively applied throughout the United States, as shown in Figure 2-3, to calculate existing and future contaminant loads as part of CWA requirements under Section 303 (d) (Total Maximum Daily Loads (TMDLs)) of the CWA and EPA's Water Quality Planning and Management Regulations (40 CFR Part 130). Shown in Figure 2-3 are locations across the U.S. where LSPC has been applied for TMDL development (normally by states and EPA) and TMDL implementation (normally by municipalities). Generally, TMDLs are prepared for water bodies listed as 'impaired,' meaning they are over-allocated and do not meet water quality standards for a designated use, such as contact recreation or aquatic life health. There are many analogues between the U.S. CWA and NPS-FM (MfE, 2014), and thus LSPC has been selected for Auckland's NPS-FM water quality accounting framework – to better understand how freshwater quality can be maintained at its current level or improved.

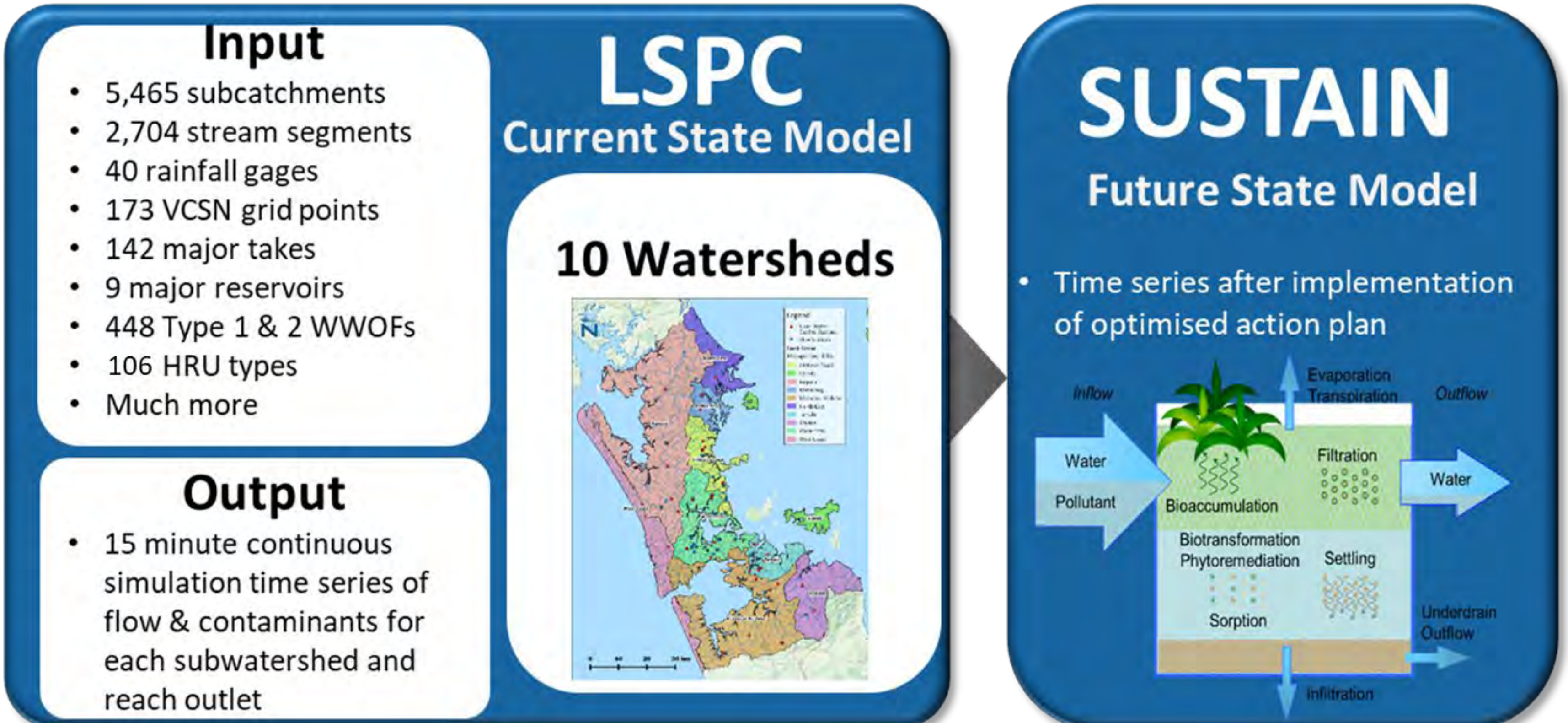


Figure 2-1. Current and Future State Models within the FWMT

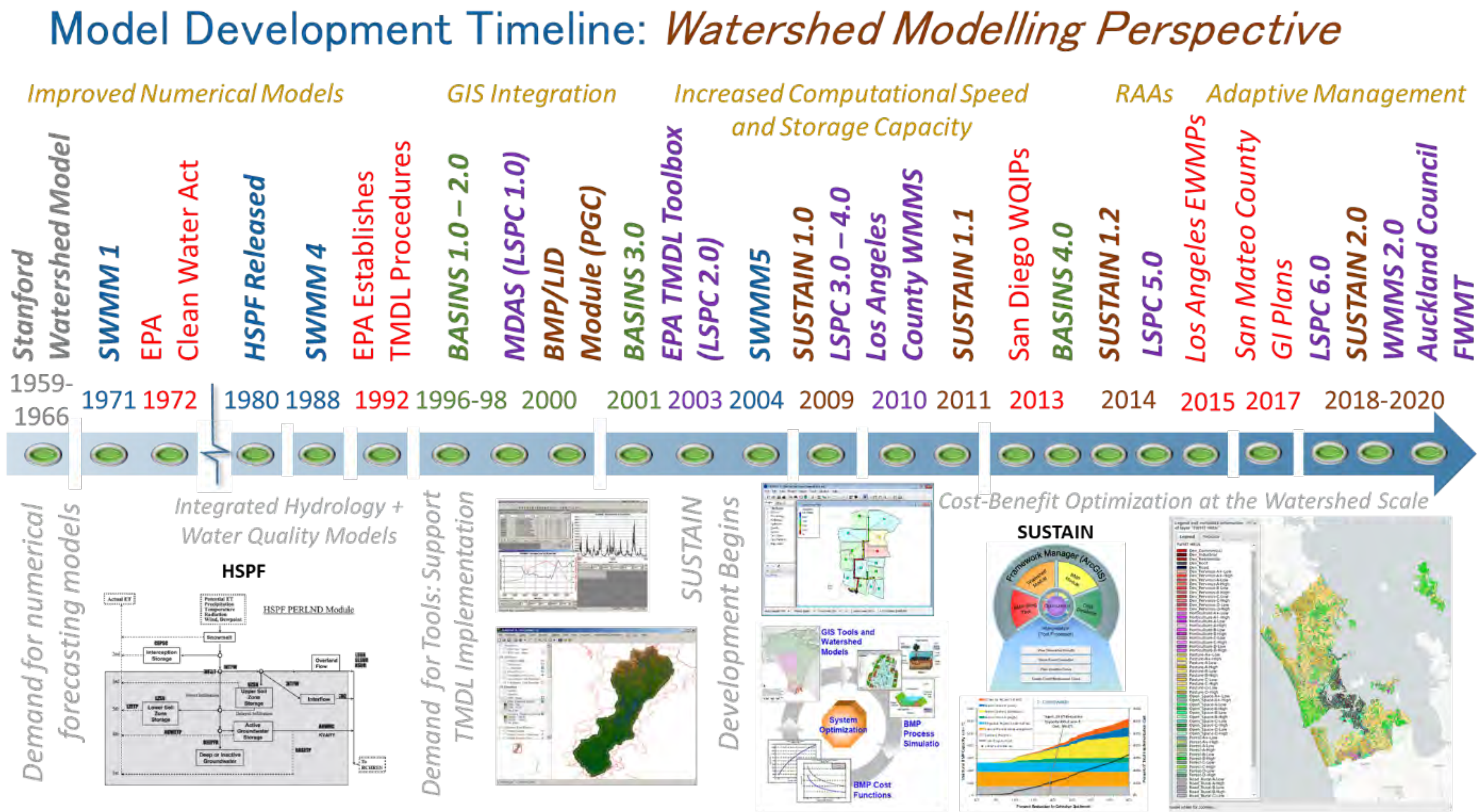


Figure 2-2. Model development timeline for watershed assessment and planning including LSPC, SUSTAIN, and various applications

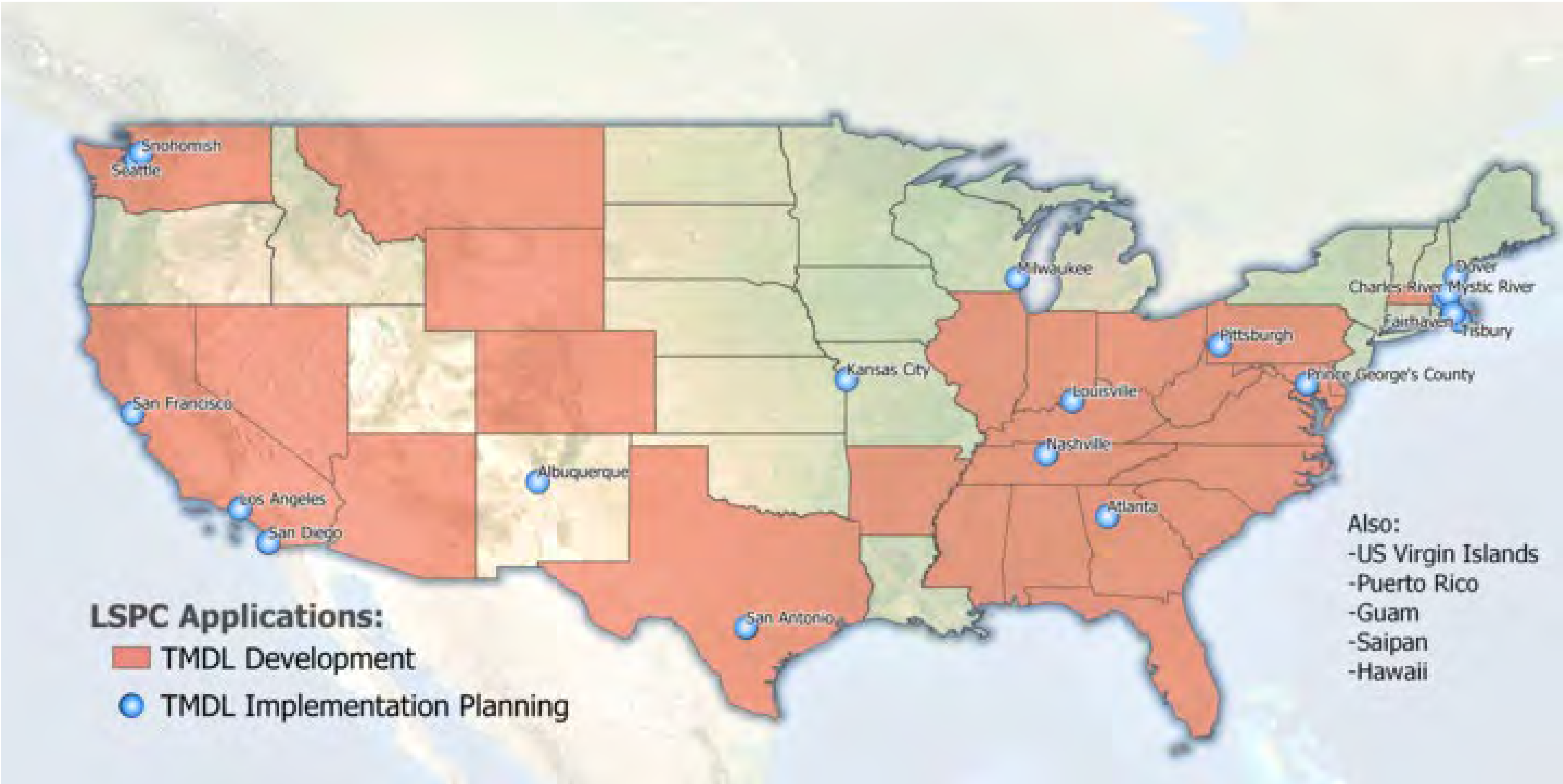


Figure 2-3. LSPC Applications for TMDL Development and Implementation in the United States

The Future State model, which will be configured and described in separate reports, is the System for Urban Stormwater Treatment and Analysis IntegratioN (SUSTAIN) (Shoemaker et al., 2009). SUSTAIN is a decision-support system designed to assist stormwater management agencies in developing implementation plans to protect surface waters and meet instream water quality goals. The SUSTAIN model receives unit-area time series from LSPC to simulate hydrology (fill-up and drawdown) and contaminant treatment of structural stormwater devices and also includes algorithms to simulate the potential effects of non-structural and source control programmes (on hydrology and contaminants). An important feature within SUSTAIN is an optimisation engine that can support decisions regarding the cost-effectiveness of alternative implementation strategies (e.g., varying intervention type, design and location). As shown by the circles in Figure 2-3, SUSTAIN has been used by several major municipalities in the U.S. to develop watershed-scale water quality strategies for CWA compliance including Los Angeles Enhanced Watershed Management Programs (EWMPs; link), San Diego Water Quality Improvement Plans (WQIPs; link), and San Mateo Green Infrastructure Plans (GI Plans; link), plus applications in San Antonio, Seattle, Atlanta, and other large municipal areas.

Together, the models within the FWMT can support an array of programmes, planning, and policy decisions in Auckland Council (and externally) by assessing the baseline state of Auckland's freshwater quality and exploring scenarios for improving water quality, testing each for their associated costs and benefits across stakeholders.

2.1 LSPC Overview

A watershed model like LSPC is essentially a series of algorithms for representing the interaction between meteorology and land surfaces, resulting in surface and subsurface flows that generate and distribute contaminants to streams, lakes or coastal waters. The LSPC model simulates flow accumulation and transport of contaminants instream, subject to a range of transformational processes (e.g., deposition, resuspension, scour, desorption, nitrification, denitrification). Through the combination of erosion, build-up, wash-off, and transformational processes, LSPC is capable of dynamically simulating flow, sediments, nutrients, metals, dissolved oxygen, temperature, and other contaminants for pervious and impervious land and streams of varying order.

The algorithms of LSPC were developed from a subset of those in the Hydrological Simulation Program – FORTRAN (HSPF) (Bicknell et al., 1997). The hydrologic portion of HSPF/LSPC is based on the Stanford Watershed Model (Crawford and Linsley, 1966), which was one of the pioneering watershed models (see left side of Figure 2-2). Over time, there have been several upgrades to LSPC with the latest version being v6.0, which is the 64-bit version created in 2019. The most recent version of the LSPC user manual can be downloaded from the open source repository: LSPC User Manual).

LSPC is built upon a relational database platform, meaning that process-based parameters are organised or associated with physical characteristics of the model at various layers (i.e., sub-watershed, land type, stream type) (Shen et al., 2004). LSPC integrates GIS outputs, comprehensive data storage and management capabilities, the original HSPF algorithms, and a data analysis/post-processing system into a convenient PC-based Windows environment.

2.2 Overview of FWMT Baseline Development Process

The Baseline State model provides the “baseline” for establishing existing hydrology and contaminant profiles (concentrations, loads) in Auckland’s watersheds. The process to develop the Baseline State model has been iterative and adaptive, in response to FWMT purpose and objective learnings. For example, over the last 18 months the FWMT modelling team has: incrementally increased the functional and contaminant scope of the model to better represent nutrient and stream erosion dynamics; expanded the list of stations used for calibration to better represent regional predicted conditions; incrementally incorporated data and findings from wider modelling and monitoring studies in the Auckland region; and adjusted parameters or reorganise parameter associations to improve the calibration based on comparisons to observed data.

Figure 2-4 is a conceptual schematic for the proposed model development cycle for the FWMT. The cycle can be summarised in six interrelated steps, defining each FWMT iteration:

1. **Assess Available Data**: these data are used for land representation, source characterisation, meteorological boundary conditions and more.
2. **Delineate Project Extent**: which refers to model segmentation and discretisation needed to simulate hydrology and water quality at temporal and spatial scales appropriate for supporting decisions across the watershed.
3. **Set Boundary Conditions**: spatial and temporal model inputs, especially meteorological data, for establishing the conditions that drive variation in hydrology and water quality.
4. **Represent Processes:** these are the processes represented by the algorithms in the model, and selection of the processes to use for the application (e.g., which contaminants to simulate).

5. **Confirm Predictions**: refers to adjustment of model rates and constants to mimic observed physical processes of the natural system, mostly through comparison to observational data.
6. **Assess Performance, Sensitivity and Data Gaps**: modelled responses and/or poor model performance can indicate the influence of unrepresented physical processes in the modelled system. A well-designed model can be adapted for future applications as new information about the watersheds becomes available. The impact of the new information can be assessed through sensitivity testing and leveraged through updated calibration and validation. Depending on the study objectives, data gaps sometimes provide a sound basis for further data collection efforts to refine the model, which cycles back to Step 1.

These steps are organised into two primary efforts: model configuration (green boxes) and model calibration (blue), which are detailed respectively in Section 3.0 and 4.0.

2.3 LSPC Model Processes

The hydrology and water quality processes in LSPC are detailed in the LSPC User's Manual (USEPA, 2017), including details on each major simulation module within LSPC and the corresponding routines and parameters. Many of the routines in LSPC are built upon HSPF, but with more integrated organisation of the HSPF modules. For example, in LSPC, pervious and impervious lands are not handled by separate modules (as they are in HSPF, called PERLND and IMPLND); rather, they are grouped together in the input file and a flag is used to designate whether the land is pervious or impervious. And when a component is invoked in LSPC, both the upland and reach processes are simulated (rather than being handled in separate RCHRES module as they are in HSPF).

Table 2-1 presents a summary of major LSPC features and comparison to select water quality models. Unlike receiving water models, which focus only on processes in lakes, streams, estuaries and the like, LSPC simulates entire watersheds including instream processes (but omitting in-lake and in-estuarine processing). The contributing areas to streams and lakes are delineated and characterised using existing data about land use/land cover, soils, slopes etc. Processes governing contaminant generation and transport are parameterised and simulated on the land. Rainfall drives overland and subsurface flows, and associated contaminants from the landscape to streams and lakes, where additional processes account for routing and fate and transport.

LSPC is organised within the following components:

- Snow: accumulation and melting of snow and ice (as applicable)
- Hydrology: upland hydrology and reach hydraulics plus irrigation

- Water Temperature: upland soil and water temperature and reach heat exchange/water temperature
- Sediment: upland production/accumulation and removal of sediment and reach sediment behaviour
- Water Quality GQUAL: generalised quality constituent for uplands and reaches
- Water Quality RQUAL: Simulation of constituents involved in biochemical transformations
    - DO – BOD: primary DO and BOD balances.
    - Nutrients: primary inorganic nitrogen and phosphorus balances (DO – BOD must also be activated).
    - Plankton: plankton populations and associated reactions (DO – BOD and Nutrients must also be activated).
    - pH – CO_2: pH, carbon dioxide, total inorganic carbon, and alkalinity (DO – BOD, Nutrients, and Plankton must be activated)

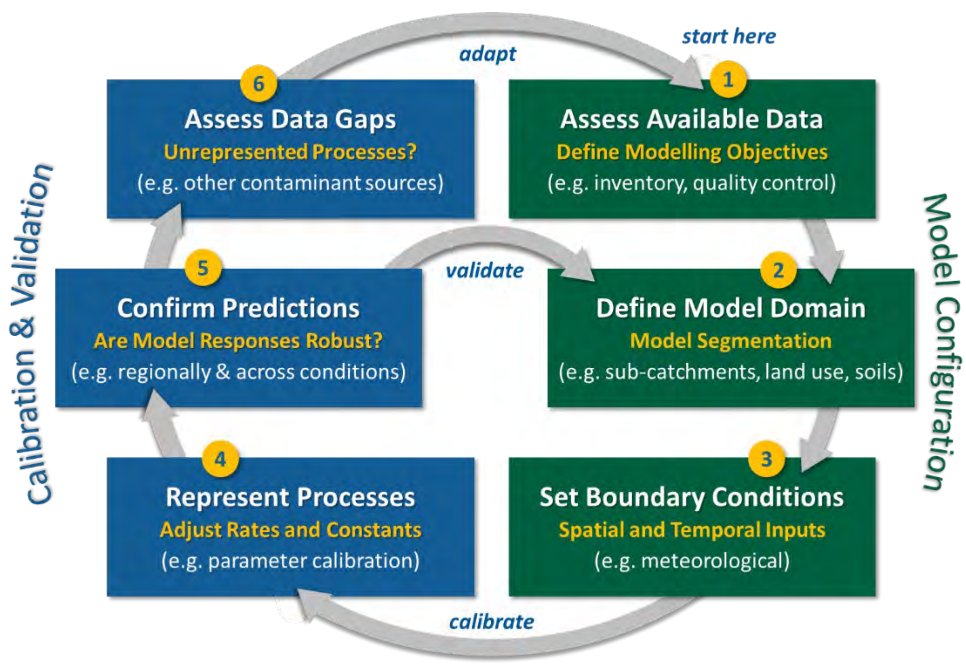


Figure 2-4. Conceptual schematic of a LSPC model development cycle for the FWMT

Table 2-1. LPSC Functionality and Comparison to Select Models

	Type			Spatial Discretisation			Water Quality							
Model	Steady state	Quasi-dynamic	Dynamic	One-dimensional	Two-dimensional	Three-dimensional	User-defined contaminant	Sediment	Nutrients	Toxics	Metals	BOD	Dissolved Oxygen	Bacteria
LSPC			●	●			●	●	●	●	●	●	●	●
MIKE 11			●	●				●	●	●	●	●	●	●
DELFT3D			●	●	●	●	●	●	●	●	●	●	●	●
QUAL2K		●		●			●		●			●	●	●

Land and water features supported*									
	Urban	Rural	Agriculture	Forest	River	Lake	Reservoir/ Impoundment	Estuary (tidal)	Coastal (tidal/ Shoreline)
LSPC	●	●	●	●	●	●	●		
MIKE 11	●	●	●	●	●	●	●		
DELFT3D					●	●	●	●	●
QUAL2K					●				

*Support may range from medium-moderate to high-detailed level of simulations of processes

The LSPC components that have been activated during Stage 1 include:

- Hydrology (see Figure 2-6)
- Sediment (see Figure 2-7)
- Water Quality RQUAL for nitrogen and phosphorous (Figure 2-8 and Figure 2-9) DO-BOD and Plankton to support simulation of nutrients (not reported)
- Water Quality GQUAL for zinc, copper and *E. coli*
- Water Temperature to support simulation of above contaminants (not reported)

Within LSPC, precipitation falls onto units of land called Hydrological Response Units (HRUs) which comprise sub-catchments, with HRUs routed into model stream segments (Figure 2-5). Each of these model components – HRUs, sub-catchments and model stream segments – has a set of parameters that arise from configuration and calibration. A watershed and its associated sub-catchments can consist of several HRUs (e.g., in the case of FWMT, up to 106 HRUs).

HRUs represent land units with unique combinations of several factors: land cover, soil type, slope, as well as intensity or impact. Based on these factors, numerous combinations or classes of HRU are configured for parameter responses to climate. Rainfall is partitioned at the HRU level between evapotranspiration, runoff, interflow and groundwater. Runoff, interflow and groundwater are the means by which water is routed through the watershed along with suspended and dissolved contaminants. The aggregated contributions of all HRUs within a sub-catchment dictate the hydrology and water quality at its downstream outlet. Once in the stream channel, LSPC routes the runoff downstream using stage-storage relationships and simulates contaminant fate during transport by stream segment classes (e.g., settling, resuspension and instream transformations). Flows and contaminants discharged from sub-catchments continue to accumulate or attenuate during downstream transport until they reach the terminal catchment outlet (e.g., pour point into the coastal environment).

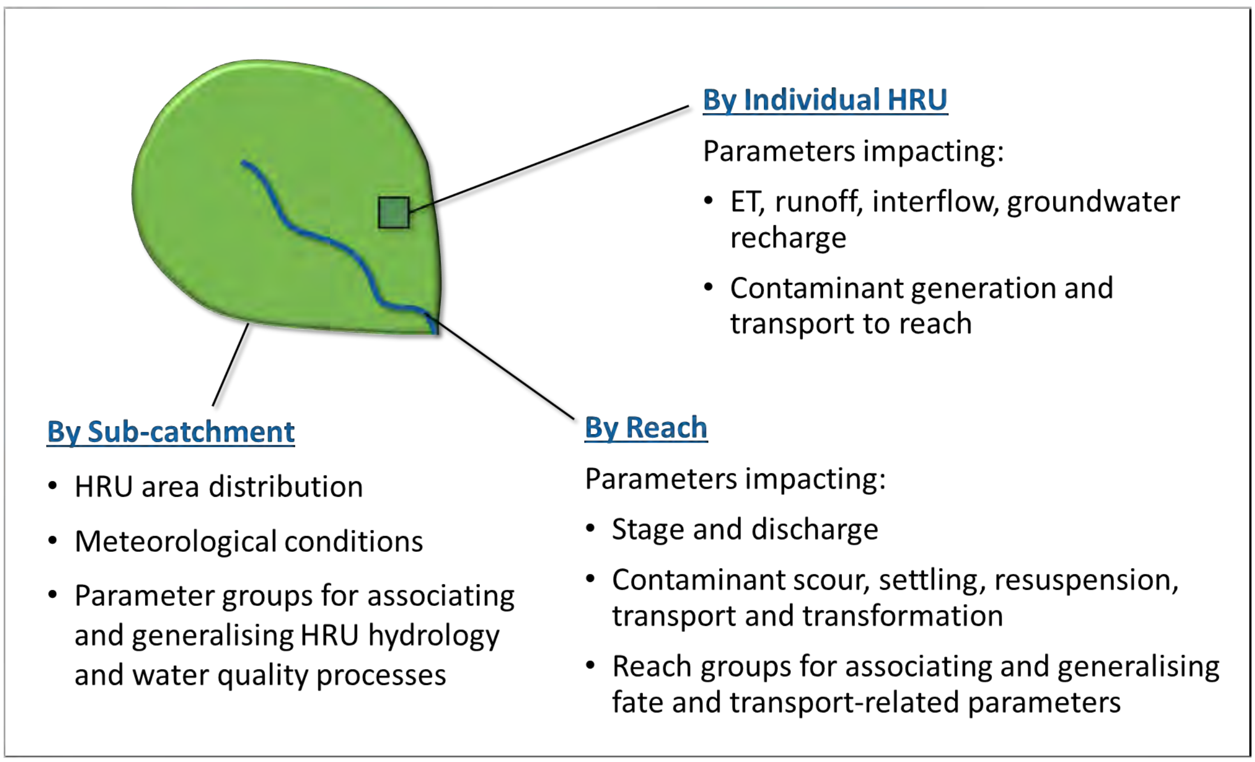


Figure 2-5. Schematic of major LSPC components for model configuration and parameterisation

To illustrate the model processes within LSPC and the parameters that affect hydrology, sediment and nutrient simulations, a series of figures and parameter tables are presented as follows:

- Figure 2-6 presents a hydrology schematic representing land-based processes for a single HRU in the model. The denoted parameters govern the transfer and storage of water through the HRU and are adjusted to improve agreement between predicted hydrological outputs and observations.
- Figure 2-7 is a generalised schematic of the underlying sediment routines, including instream sediment processes used in LSPC, while outlines the listed parameters for sediment dynamics. Table 2-3 presents sediment parameters names and descriptions.
- Figure 2-8 and Figure 2-9 present nitrogen and phosphorus schematics, respectively, with illustration of land-based and instream processes while Table 2-3 presents RQUAL parameter names and descriptions of nutrient dynamics.

The key parameters adjusted during the configuration and calibration process are described in relevant sections of Section 3.0 (Model Configuration) and Section 4.0 (Model Calibration and Validation) to provide context within the overall LSPC processes. Initial parameter values were based on recommended values provided in Bicknell et al. (1996) and USEPA (2000), final, calibrated parameter values are presented in Appendix A.

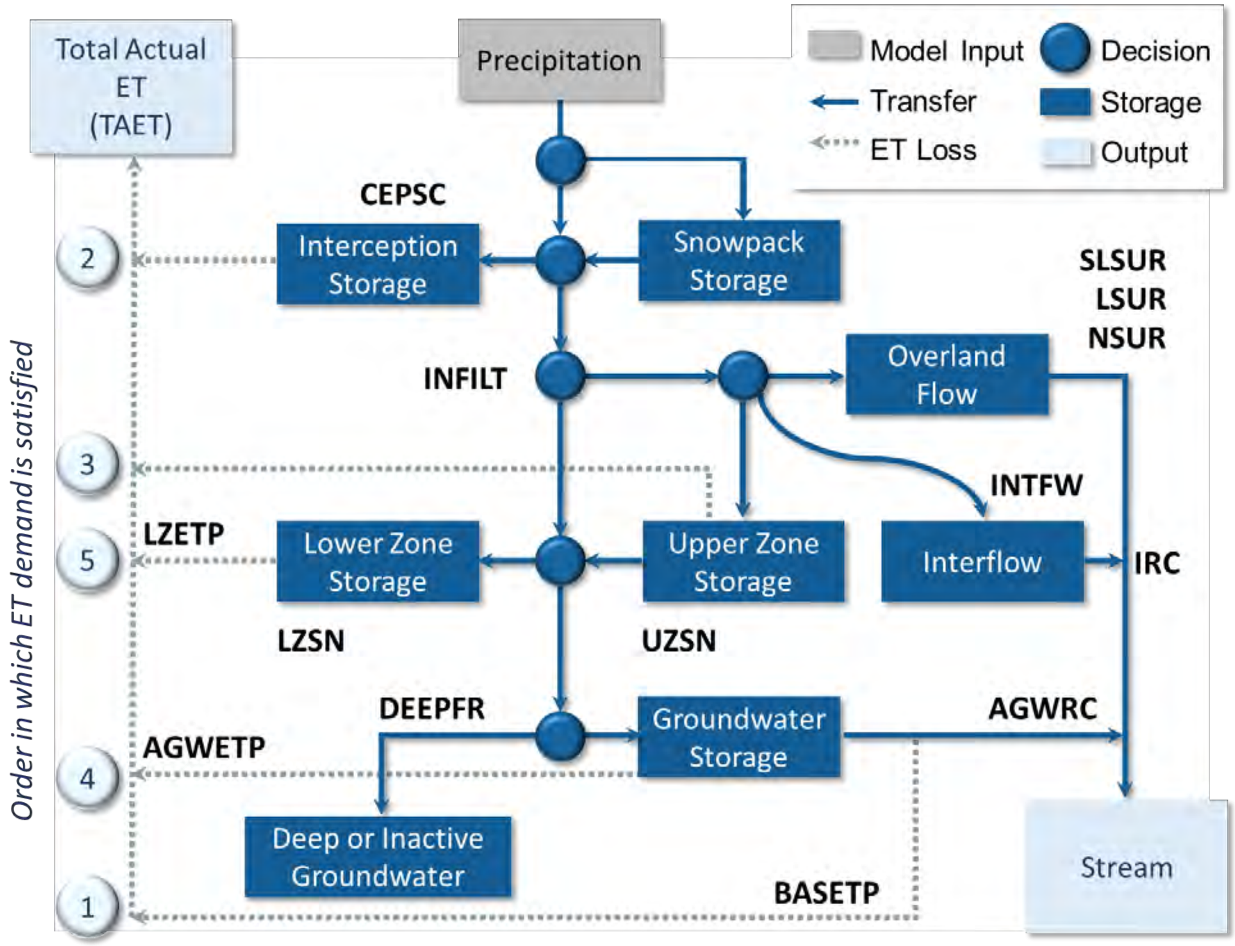


Figure 2-6. Schematic of hydrology component and routines/parameters in LSPC

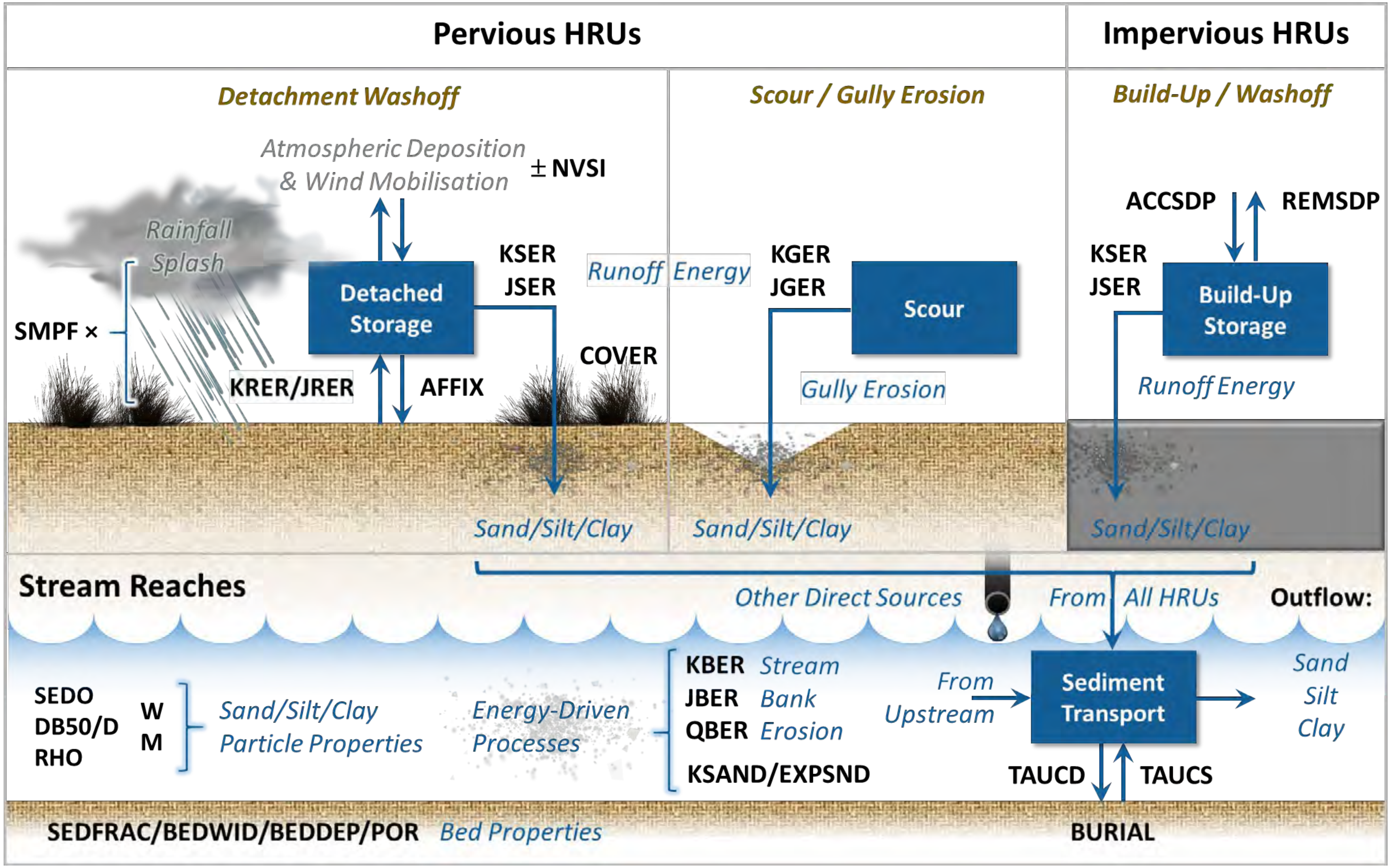


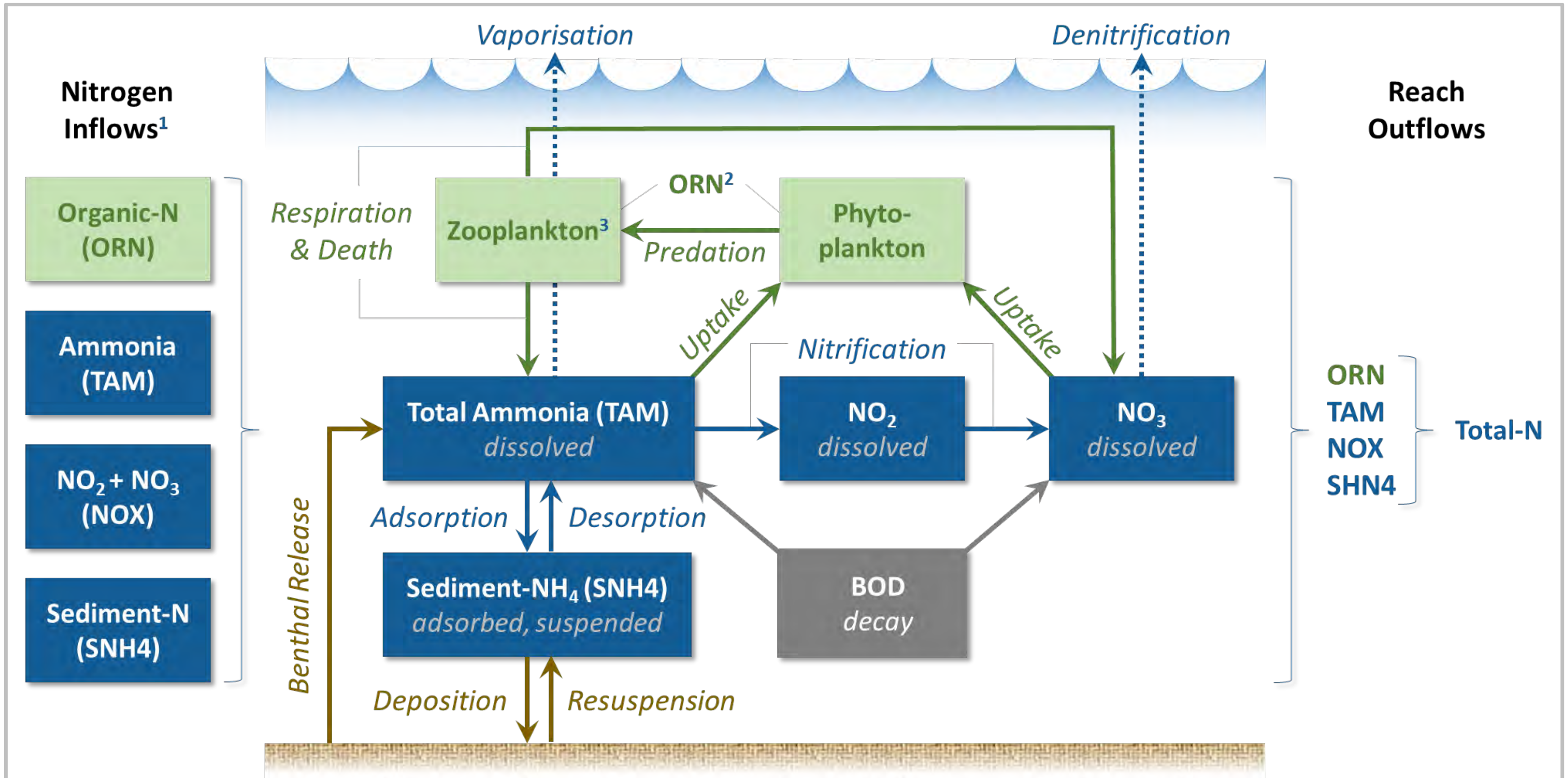
Figure 2-7. Schematic of sediment routines and parameters in LSPC

Table 2-2. HRU-based sediment model parameters in LSPC (as shown in Figure 2-7)

Parameter		Description
Pervious HRUs	SMPF	Supporting management practice factor, default value is 1.0
	KRER	Coefficient in the soil detachment equation
	JRER	Exponent in the soil detachment equation
	AFFIX	Fraction by which detached sediment storage decreases each day as a result of soil compaction (1/day)
	COVER	Fraction of land surface which is shielded from rainfall erosion
	NVSI	Rate at which sediment enters detached storage from the atmosphere (lb/ac/day); negative value may be used to simulate removal by human activity or wind
	KSER	Coefficient in the detached sediment wash-off equation
	JSER	Exponent in the detached sediment wash-off equation
	KGER	Coefficient in the matrix soil scour equation, which simulates gully erosion
	JGER	Exponent in the matrix soil scour equation, which simulates gully erosion
Impervious HRUs	ACCSDP	Rate at which solids accumulate on the land surface
	REMSDP	Fraction of solids storage which is removed each day when there is no runoff, e.g., due to wind and/or traffic
	KSER	Coefficient in the detached sediment wash-off equation (equivalent to KEIM in HSPF for impervious land)
	JSER	Exponent in the detached sediment wash-off equation (equivalent to JEIM in HSPF for impervious land)
Land-to-Stream Splitter (Sediment Particle Size)		
Sed_i …		Fraction of total sediment from land that is SAND (i=1)
		Fraction of total sediment from land that is SILT (i=2)
		Fraction of total sediment from land that is CLAY (i=3)

Table 2-3. Stream-reach sediment model parameters in LSPC (as shown in Figure 2-7)

Parameter		Description
Bed Properties	BEDWID	Bed width (ft) used for sediment deposition—this is constant for the entire simulation period and fixed by stream class or type
	BEDDEP	Initial bed depth (ft)
	POR	Porosity (volume voids/total volume), used to estimate bed depth
	BURIAL	Burial rate of aggregated sediment layer (in./day)
	SEDFRAC	Initial sediment fractions (by weight) in the bed material
Particle Properties	DB50/D	Sand: Median diameter of the non-cohesive sediment (in.) Silt/Clay: Effective diameter of the cohesive particles (in.)
	W	Corresponding fall (settling) velocity of the particle in still water (in./s)
	SEDO	Initial sediment concentration in fluid phase (mg/L)
	RHO	Density of the particles (gm/cm^3)
	M	Erodibility coefficient for cohesive particles (lb/ft^2/day)
Energy-Driven Processes	KSAND	coefficient in the sandload power function formula
	EXPSND	exponent in the sandload power function formula
	QBER	Bank erosion flow threshold causing channel bank soil erosion (cfs)
	KBER	Coefficient for scour of the bank matrix soil (calibration)
	JBER	Exponent for scour of the bank matrix soil (calibration)
	SED_i …	Bank erosion sediment splitter (i: 1=Sand, 2=Silt, 3=Clay)
	TAUCD	Critical bed shear stress for deposition of the cohesive particle (lb/ft^2)
	TAUCS	Critical bed shear stress for scour of the cohesive particle (lb/ft^2)



1: *Nitrogen inflows vary by HRU type and flow pathway (i.e., surface, interflow, groundwater; point sources & upstream reaches)*
2: *ORN, Organic-P (ORP), Organic-C (ORC), and BOD are updated with phytoplankton death*
3: *Zooplankton is not simulated in Freshwater Management Tool*

Figure 2-8. Schematic of nitrogen / RQUAL routines and parameters in LSPC[3]

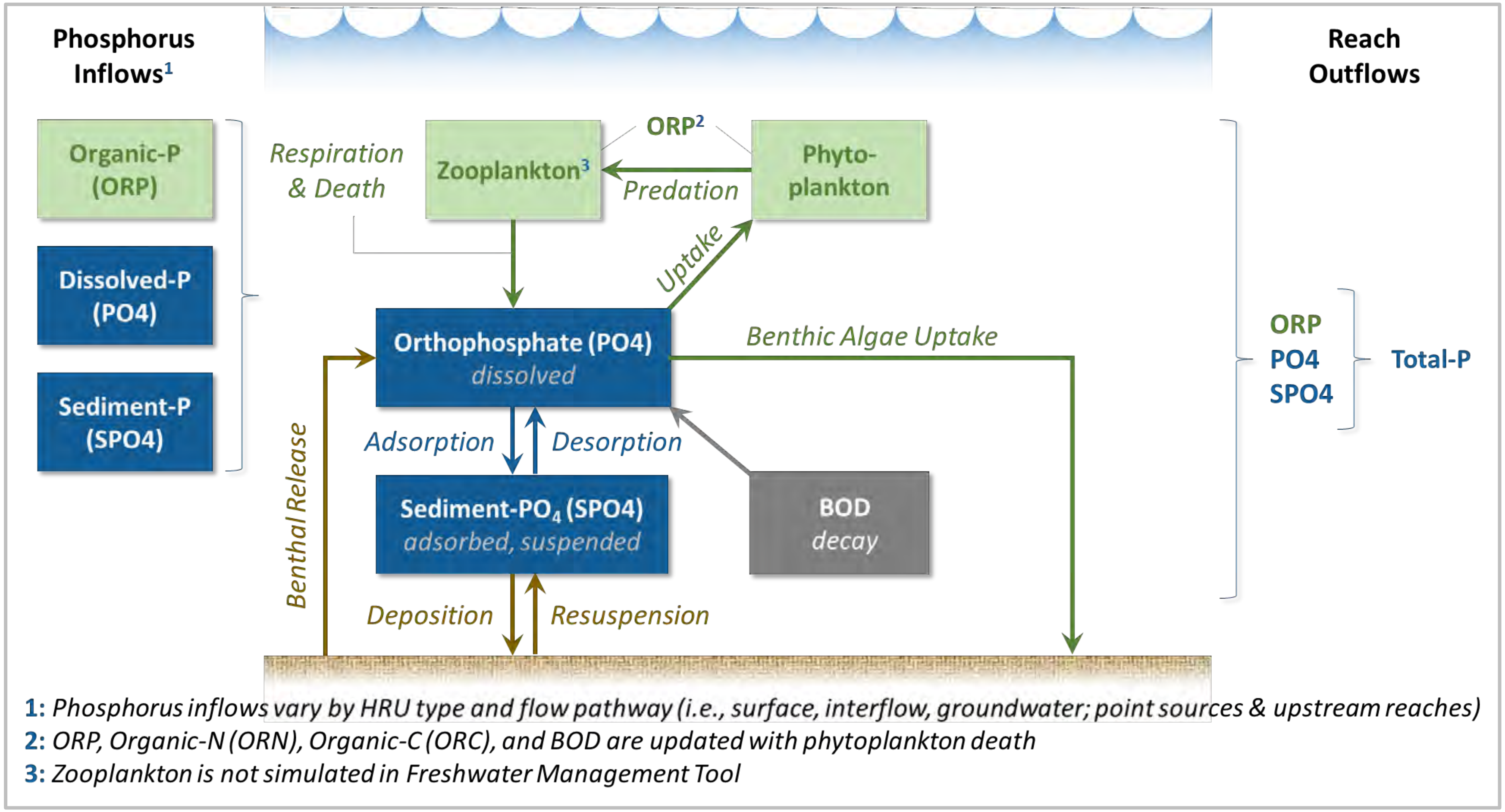


Figure 2-9. Schematic of phosphorus / RQUAL routines and parameters in LSPC

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[3] Ammonia release from sediments is a function of scouring, which is dependent on the average velocity of the water and does not account for stoichiometry. Biomass stoichiometry is addressed using default values for parameters indicating biomass carbon:nitrogen:phosphorus ratio and the percent-by-weight carbon (Table 2-4)

Table 2-4. Stream-reach nutrient model parameters in LSPC RQUAL module

Modelled Contaminants		
NOX		Nitrate and nitrite fraction of TN loading from land entering stream
TAM		Total ammonia fraction TN loading from land entering stream (equivalent to ammoniacal-N)
ORN		Organic nitrogen fraction TN loading from land entering stream
PO4		Orthophosphate fraction of TN loading from land entering stream
ORP		Organic phosphorus fraction of TN loading from land entering stream
Parameter		**Description**
Mass Conversions and Rate Constants	CVBO	Conversion from milligrams biomass to milligrams oxygen demand (mg/mg), default value is 1.98
	CVBPC	Conversion from biomass expressed as phosphorus to carbon (mols/mol), default value is 106.0
	CVBPN	Conversion from biomass expressed as phosphorus to nitrogen (mols/mol), default value is 16.0
	BPCNTC	Percentage of biomass which is carbon (by weight), default value is 49.0 percent
	KTAM20	Nitrification rate of ammonia at 20 °C (1/hr)
	KNO220	Nitrification rate of nitrite at 20 °C (1/hr)
	TCNIT	Temperature correction coefficient for nitrification, default value is 1.07
	KNO320	Nitrate denitrification rate at 20 °C (1/hr)
	TCDEN	Temperature correction coefficient for denitrification, default value is 1.07
	DENOXT	Dissolved oxygen concentration threshold for denitrification, default value is 2.0 mg/L
Benthic Release	BRTAM_1	Benthic release rate of ammonia under aerobic condition (mgN/m^2/hr)
	BRTAM_2	Benthic release rate of ammonia under anaerobic condition (mgN/m^2/hr)
	BRPO4_1	Benthic release rate of orthophosphate under aerobic condition (mgP/m^2/hr)
	BRPO4_2	Benthic release rate of orthophosphate under anaerobic condition (mgP/m^2/hr)
	BNH4(1-3)	Constant bed concentrations of ammonium-N adsorbed to sand, silt, and clay (mg/kg)
	BPO4(1-3)	Constant bed concentrations of orthophosphate adsorbed to sand, silt, and clay (mg/kg)
Anaerobic conditions and adsorp	ANAER	Concentration of DO below which anaerobic conditions are assumed to exist (mg/L)
	ADNHPM(1-3)	Adsorption coefficients (Kd) for ammonia-N adsorbed to sand, silt, and clay (cm3/g)

	ADPOPM(1-3)	Adsorption coefficients for orthophosphate-P adsorbed to sand, silt, and clay (cm3/g)
Initial conditions	NO3	Initial concentration of nitrate (mgN/L)
	TAM	Initial concentration of total ammonia (mgN/L)
	NO2	Initial concentration of nitrite (mgN/L)
	PO4	Initial concentration of orthophosphorus (mgP/L)
	SNH4(1-3)	Initial suspended concentration of ammonia-N adsorbed to sand, silt, and clay (mg/kg)
	SPO4(1-3)	Initial suspended concentration of orthophosphorus-P adsorbed to sand, silt, and clay (mg/kg)
Plankton	RATCLP	Ratio of chlorophyll *a* content of biomass to phosphorus content, default value is 0.6
	NONREF	Non-refractory fraction of algae and zooplankton biomass, default value is 0.5
	LITSED	Multiplication factor to total sediment concentration to determine sediment contribution to light
	ALNPR	Fraction of nitrogen requirements for phytoplankton growth that is satisfied by nitrate, default value is
	EXTB	Base extinction coefficient for light (1/m)
	MALGR	Maximum unit algal growth rate (1/hr), default value is 0.3
	CMMLT	Michaelis-Menten constant for light limited growth (ly/min), default value is 0.033
	CMMN	Nitrate Michaelis-Menten constant for nitrogen limited growth (mg/L), default value is 0.045
	CMMNP	Nitrate Michaelis-Menten constant for phosphorus limited growth (mg/L), default value is 0.0284
	CMMP	Phosphate Michaelis-Menten constant for phosphorus limited growth (mg/L), default value is 0.015
	TALGRH	Temperature above which algal growth ceases (°C), default value is 35.0
	TALGRL	Temperature below which algal growth ceases (°C), default value is 6.1
	TALGRM	Temperature below which algal growth is retarded (°C), default value is 25.0
	ALR20	Algal unit respiration rate at 20 °C (1/hr), default value is 0.004
	ALDH	High algal unit death rate (1/hr), default value is 0.01
	ALDL	Low algal unit death rate (1/hr), default value is 0.001
	OXALD	Increment to phytoplankton unit death rate due to anaerobic conditions (1/hr), default value is 0.03

	NALDH	Inorganic nitrogen concentration below which high algal death rate occurs (as nitrogen) (mgN/L)
	PALDH	Inorganic phosphorus concentration below which high algal death rate occurs (as phosphorus)
	PHYCON	Constant inflow concentration of plankton from land to reach (mg/L)
	SEED	Minimum concentration of plankton not subject to advection (i.e., at high flow) (mg/L)
	MXSTAY	Concentration of plankton not subject to advection at very low flow (mg/L)
	OREF	Velocity/outflow at which the concentration of plankton not subject to advection is midway between
	CLALDH	Chlorophyll *a* concentration above which high algal death rate occurs (µg/L), default value is 50.0
	PHYSET	Phytoplankton settling rate (m/hr)
	REFSET	Settling rate for dead refractory organics (m/hr)
	CFSAEX	CFSAEX This factor is used to adjust the input solar radiation to make it applicable to the RCHRES; for example, to account for shading of the surface by trees or buildings
	MBAL	Maximum benthic algae density (as biomass) (mg/m2), default value is 600.0
	CFBALR	Ratio of benthic algal to phytoplankton respiration rate, default value is 1.0
	CFBALG	Ratio of benthic algal to phytoplankton growth rate, default value is 1.0

3.0 Model Configuration

This section describes the configuration of LSPC to represent hydrological conditions and contaminant generation and transport from the landscape and through the Auckland region stream network. Model configuration was followed by hydrology and water quality calibration for the period 2012-2016. After model calibration, hydrological predictions for a 15-year period between 1 January 2002 and 31 December 2017[4] was assessed via visual inspection of hydrographs. Baseline State analysis and grading for both lakes and rivers for the time period 2013-2017 is addressed in separate reports. Further detail on the collation of necessary datasets, including their development where otherwise novel, is provided in a stand-alone FWMT Stage 1 Baseline Data Inputs Report.

Model configuration refers to using available data to establish boundary conditions and physical characteristics of watersheds (e.g., meteorology, soils, land cover and use, topography, infrastructure, wastewater and stormwater networks, water takes and discharges). The Stage 1 configuration of the Baseline State model for the FWMT involved assembling best available datasets (as of 30 June 2017) for Auckland watersheds. The higher the resolution and accuracy of the data used to configure the FWMT, the better the model can simulate hydrology and water quality processes. Additionally, a more detailed configuration can reduce the 'burden' of later calibration efforts. Over time and through the staged model development process, it is envisioned that many of the datasets used for the FWMT Stage 1 configuration will be updated with higher resolution/higher quality data and incorporated into the FWMT Stage 2. Later variants might also be reconfigured for added complexity to better resolve processes or expand the scope of contaminants and environments to better encapsulate an evolving policy and value-base for water quality (e.g., as uncertainty is better understood; community engagement accelerates).

The FWMT Stage 1 has been configured solely to represent land and climate-driven contaminant processes to, and subsequent transformational processes within, freshwater streams, across each of 10 watersheds. The FWMT Stage 1 is also configured to represent contaminant loading to moderate-sized freshwater lakes and the coast to better enable integrated decision-making of fresh and coastal water quality FWMT Lake configuration is detailed in the [FWMT Baseline State Lakes Report].

[4] Although observed data existed through 2017, it was not included in calibration as it was an abnormally wet year compared to other calibration years

Key elements of the FWMT model configuration include: (1) model domain and sub-catchment delineation, (2) meteorological boundary conditions, (3) hydrologic response unit classification to represent all major types of land cover and activity, (4) stream routing and cross sectional geometry, (5) structural device representation, and (6) representation of 'reach groups' for simulation of instream sediment and nutrient processes. These elements are described in the subsection below.

3.1 Baseline Simulation Period

Within the FWMT Stage 1, LSPC was configured using a variety of data (Table 3-1) to allow for hydrological simulation of a 15-year period, between 1 January 2003 and 31 December 2017. The period of 15 years was selected to provide an array of wet and dry years to evaluate the impact of a range of climate on hydrology and water quality.

Table 3-1. Summary of baseline LSPC inputs

Physical characteristic of watershed	Primary data source(s) for representation in LSPC	Report Section
Stream network	Auckland Council Underground Services, Watercourse Assessment Report and OLFP conditioned DEM	0, 3.3, and 3.4
Stormwater network	Auckland Council Underground Services	
Channel Geometry	Watercourse Assessment Report	
PEVT, solar radiation, temperature	NIWA – Virtual Climate Station Network	3.5
Precipitation	Auckland Council Rain Gauges and VCSN	
Discharges from wastewater network	Watercare	3.6
Extraction by water takes	Auckland Council consents and Watercare	
Impoundment by reservoirs, lakes, and dams	Watercare	3.7
Impoundment by stormwater devices	Auckland Council inventory	
Soil	Multiple	3.8
Slope	Auckland Council	
Land cover	Multiple	
Impact	Multiple	

The configuration approach of LPSC for FWMT is fundamental when considering its outputs: the land cover / HRU area distribution is a snapshot in time, while the weather varies dynamically over 15 years. For example, the LCBD4 land cover dataset represented land cover in the region for the period 2012/2013. The resulting model configuration was a static representation of the landscape coupled with a dynamic representation of meteorological conditions, to produce the predicted time-variable hydrology and water quality responses. The value of such a configuration is that it allows for calibration of land and stream parameters that govern hydrological and water quality responses over time, thereby improving understanding of contaminant generation and transport across the region under varying meteorological conditions. As discussed in Section 4.0, a recent 5-year period (2012-2016) was used as the calibration / model performance evaluation period to align with the land use snapshot.

3.2 Model Domain and Sub-catchment Delineation

The physical domain of the regional LSPC model is the entire Auckland region, 4,788 square kilometres and the 3,085 kilometres of modelled freshwater stream network therein – the FWMT Stage 1 does not simulate lake or estuarine environments, although the model accounts for external contaminant loads to both waterway types. Stormwater management across Auckland is organised into 10 major watersheds, as shown in Figure 3-1, The FWMT databases are organised to be able to simulate and report to these 10 major planning units, which can also be aggregated to provide outputs (e.g., contaminant yields) that represent the entire Auckland region.

Within the 10 watersheds, the delineated model sub-catchments are important accounting units for the model, within which aggregation of watershed hydrology and water quality processes occur. A finely resolved sub-catchment delineation provides for increased spatial resolution of hydrologic characteristics within a watershed, improved routing of flows and accounting for contaminant loads (i.e., representing unique sub-catchment mixes of HRU and climatic boundary conditions).

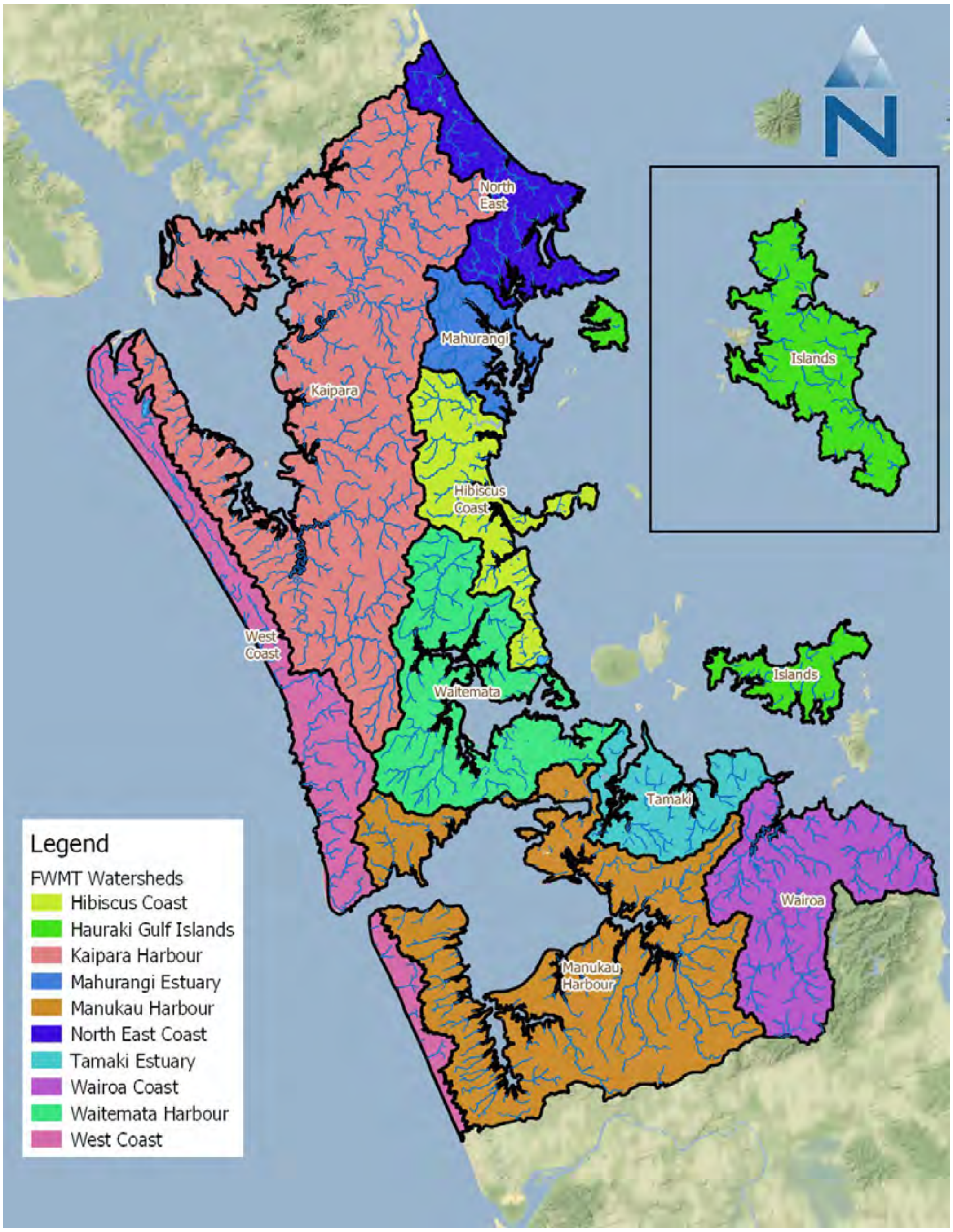


Figure 3-1. FWMT 10 watersheds and sub-catchment reach segments (reaches shown in blue features) delineated from 2-m LiDAR spanning entire Auckland region

Sub-catchments were delineated based on a 2x2 m digital elevation model (DEM) developed in 2012 for Auckland Council. While the DEM was created in 2012, it was based on LiDAR data obtained in 2006, 2008, 2009, and 2010 for various parts of the region. The various datasets were combined into a single DEM in 2012. Additional information on the DEM can be found in the [FWMT Baseline Input Report, Section 3.1].

Sub-catchment delineation began with identifying sub-catchment outlet nodes, delineating hydrological (topographic) catchments from the DEM that drain to those nodes, and identifying a representative watercourse reach for each delineated catchment. The process does not simulate the full complexities of surface-groundwater interactions, but instead relies on topographically defined watersheds. Outlet nodes were established that resulted in delineated catchments that generally ranged in size from 1-2 km^2.

Catchments of 1-2 km^2 were selected to maximise the effectiveness of the LSPC operating timestep within the FWMT Stage 1. LSPC operates within the FWMT Stage 1 on a 15-minute timestep, and a conservative time of concentration for a 1 km^2 sub-catchment was estimated to be greater than or equal to 15 minutes.

This can be demonstrated based on calculating time of concentration using the equations presented in Chow et al., (1988). For instance:

$$T_c = G(1.1 - C)L^{0.5}/(100 * S)^{1/3}$$

where T_c is the time of concentration, G is a constant 1.8, C is the Rational method runoff coefficient, L is the length of overland flow and S is the average slope of the watershed. The runoff coefficient C was approximated as average annual runoff depth (SURO) divided by average annual precipitation depth (PREC) for each sub-catchment. Overland flow L was approximated for each sub-catchment by first calculating drainage density as the length of the modelled stream segment divided by sub-catchment area. The average length of overland flow (L) was then calculated as the reciprocal of two times drainage density (Chow et al., 1988). For sub-catchments without modelled reaches, overland flow was estimated as ~0.7*sqrt(area); for sub-catchments where L could be calculated, the average ratio of L to sqrt(area) was ~0.7. Finally, the slope (S) was calculated at the HRU level and summarised by sub-catchment as both a mean and a median. Figure 3-2 presents the results of the analysis. Using mean slope, the average time of concentration was about 29 minutes, with the lower 5th percentile equal to 15 minutes and upper 95th percentile equal to 64 minutes. A cumulative distribution of Tc shows that the 5th percentile (5% of catchments with < 15-min Tc) make up only 1.3% of the total FWMT model area, and account for about 2.3% of the total edge-of-field sediment load, so represent a small portion of overall loading (Figure 3-3). Therefore, within a sub-catchment 1 km^2 in size, mass (water and contaminant) is expected to be conserved between sub-catchments during timesteps. The process of establishing outlet nodes to generate 1 km^2 sub-catchments resulted in 5,465 LSPC sub-catchments across the Auckland region as shown in Table 3-2. Of the 5,465 sub-catchments, 2,165 drain directly to the coastal receiving environment or to a neighbouring region (Waikato, Northland), as shown Figure 3-4. Such sub-catchments had contributing areas less than 1 km^2, lacked moderate streams (3^{rd} order or greater) and did not therefore, undergo simulation of instream contaminant processes (i.e., cannot be graded). However, flow and contaminant loads were accounted for at nodes with catchment area between 1 and 0.4 km^2 and for the remainder by stormwater catchment, to enable management of whole-of-watershed or coastal contaminant objectives. The total area of coastal draining sub-catchments was 907 square kilometres, or 19% of the total modelled area.

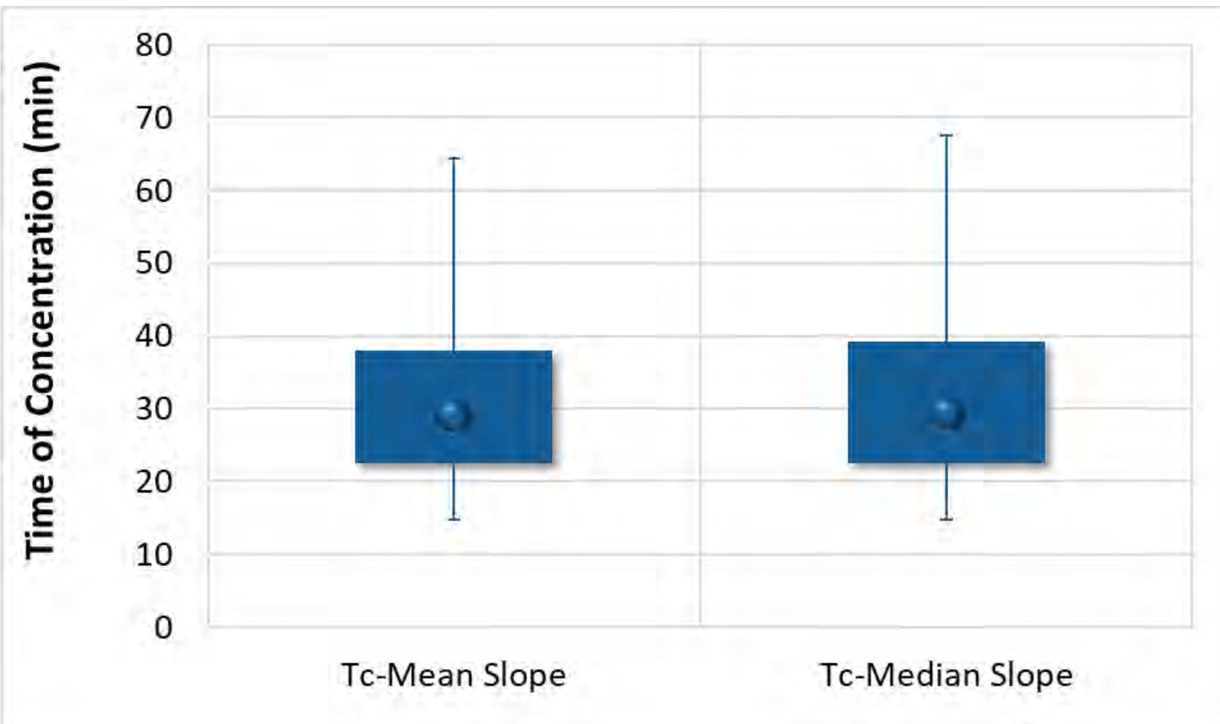


Figure 3-2. Time of concentration (Tc) for all FWMT watersheds based on mean and median HRU slope within each sub-catchment. Lower and upper bounds represent 5^{th} and 95^{th} percentiles, respectively

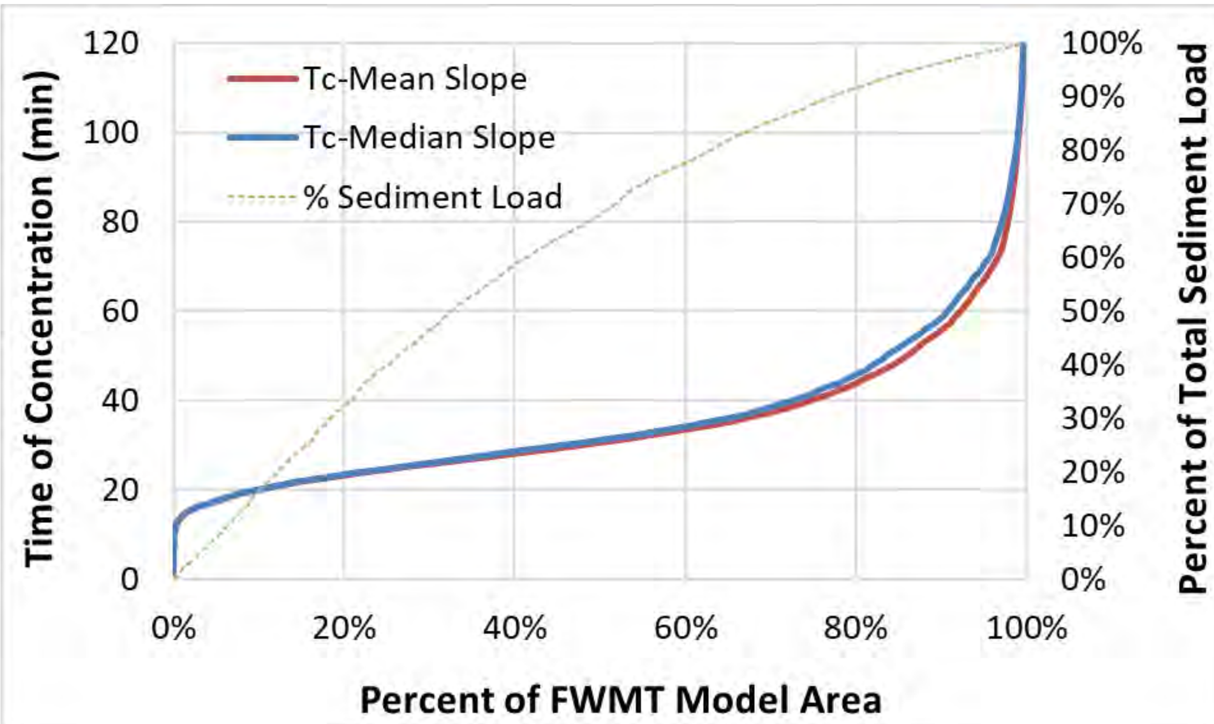


Figure 3-3. Cumulative distribution functions of time of concentration (Tc) and sediment load for all FWMT watersheds based on mean slope, median slope overland flow length and per cent runoff by each sub-catchment

To account for sub-catchments with hydrological modifications, such as road embankments and large consented dams (>5,000 m^3) that otherwise would not have been captured from the elevation dataset, additional sources were used to inform catchment delineation. Adjustments included manually altering sub-catchments if a stormwater pipe of diameter >500 mm intersected the sub-catchment boundary. Sub-catchment boundaries were also adjusted around the six major monitored lakes in the Auckland Region: Lake Kereta, Lake Wainamu, Lake Rototoa, Lake Tomarata, Lake Spectacle, Lake Kuwakatai, and Lake Pupuke. Outside of the regional configuration and for the [FWMT Baseline State Lakes Report], a further 11 lake catchments were refined. Additionally, some sub-catchments around Karepiro and Okura North were adjusted based on information received on current development occurring in the area. More detailed information on manual changes to sub catchment delineations can be found in the [FWMT 1 Baseline Data Inputs Report, Section 3.2].

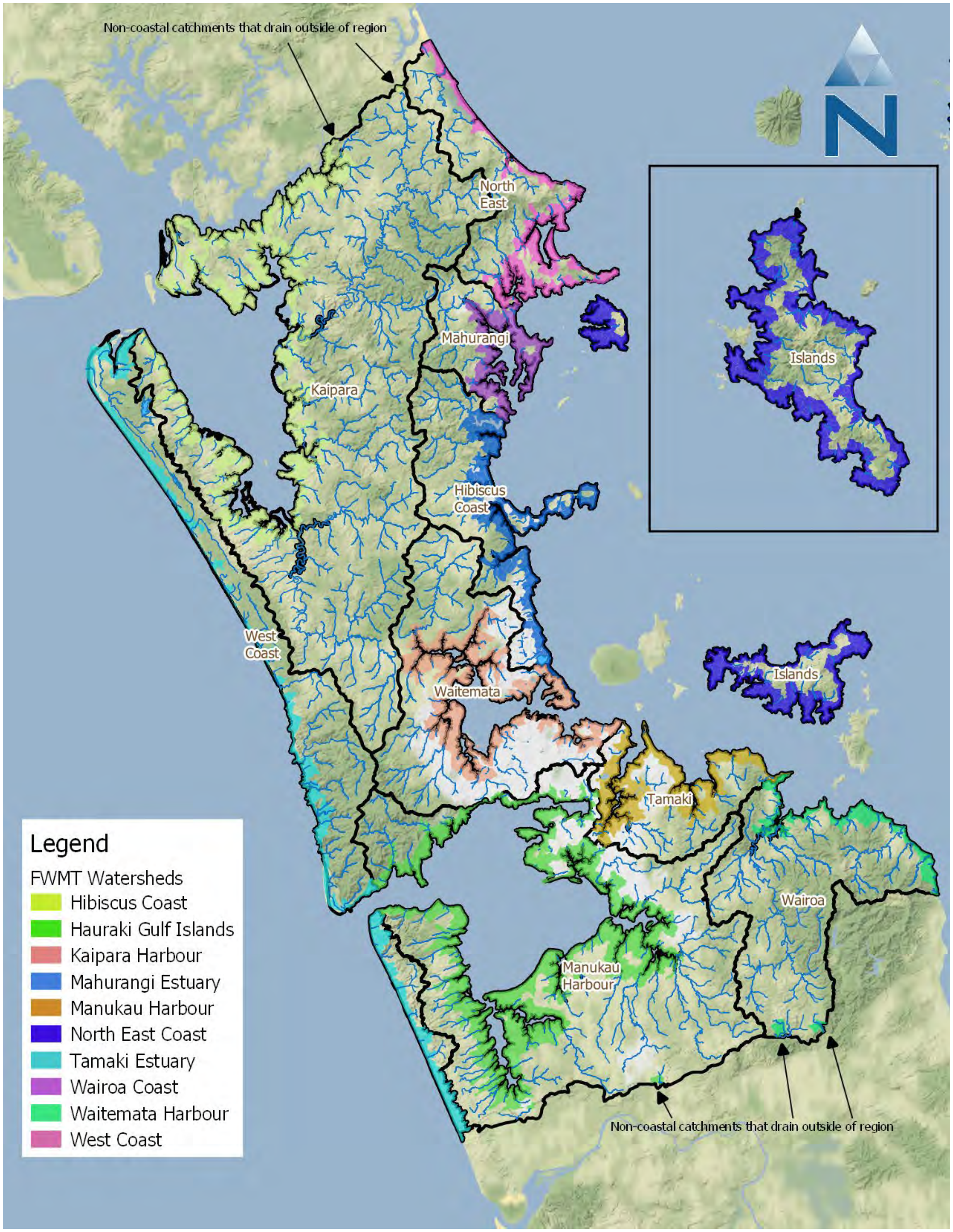


Figure 3-4. FWMT sub-catchments within 10 watersheds that drain directly to the coastal receiving environment (indicated by shading). Coastal-draining sub-catchments are those of <40 Ha extent with all others possessing pour-points to freshwater

Table 3-2. Summary statistics of sub-catchment delineations for Auckland's 10 watersheds

Watershed	Total Area (sq. km.)	Sub-catchments								
		Count	Mean Size (ha.)	Median Size (ha.)	Minimum Size (ha.)	Maximum Size (ha.)	Area Draining Straight to Sea (ha.)	Area Draining Straight to Sea (% of total)	Area within Headwater Catchments (ha.)	Area within Headwater Catchments (% of total)
Hibiscus Coast	255.96	373	68.62	68.32	0.05	252.19	5,329	20.8%	8,569	33.5%
Hauraki Gulf Islands	386.04	442	87.34	89.40	0.07	524.67	16,295	42.2%	8,838	22.9%
Kaipara Harbour	1,406.51	1,417	99.26	103.73	0.24	322.57	15,340	10.9%	45,601	32.4%
Mahurangi Estuary	128.59	140	91.85	95.12	0.02	347.03	4,042	31.4%	3,112	24.2%
Manukau Harbour	917.84	1,060	86.59	90.65	0.14	297.37	18,918	20.6%	28,174	30.7%
North-East Coast	240.54	278	86.53	91.08	0.56	287.09	5,433	22.6%	8,204	34.1%
Tamaki Estuary	189.97	294	64.62	59.33	0.28	273.16	6,593	34.7%	4,601	24.2%
Wairoa Coast	419.83	419	100.20	102.31	1.76	385.40	2,157	5.1%	15,135	36.0%
Waitematā Harbour	448.96	607	73.96	71.44	0.10	359.44	9,114	20.3%	12,110	27.0%
West Coast	409.02	435	94.03	98.69	1.20	414.64	7,490	18.3%	12,647	30.9%
Total	**4,803.25**	**5,465**	**87.89**	**93.71**	**0.02**	**524.67**	**90,7010**	**18.9%**	**146,991**	**30.6%**

3.3 Stream Network – Delineation

The process of stream network delineation undertaken for the FWMT is described in the [FWMT Baseline Data Inputs Report, Section 5.0]. LSPC is configured to allow a single routing reach per sub-catchment to represent lag, transformation, erosion and deposition processes instream (i.e., max of a single modelled reach per sub-catchment). In order to equally represent the interaction of catchment processes with instream processes for upstream and downstream catchments, headwater catchments were not assigned a modelled reach length to match the lack of tributary reach routing within downstream sub-catchments (i.e., headwater catchments also lack the ability to be graded for instream concentrations).

Figure 3-5 indicates the configuration of sub-catchments and stream routing segments within the FWMT. The process to digitise streams followed the Auckland Council Watercourse Digitisation Methodology (Lowe et al., 2016). This adopted the Auckland Council overland flow path layer (OLFP) and was corrected using a hierarchy of data sources. Stream and piped network were combined within sub-catchments, using a length-weighted average reach (e.g., with properties weighted to both pipes and streams). Further information stream network delineation is found in [FWMT Baseline Data Inputs Report, Section 5.0].

Digitisation of the trunk stream network in this way resulted in 3,085 km of streams in the routing network of the FWMT, which represents approximately 18% of the 16,650 km of permanent streams in the region (Storey and Wadhwa, 2009). Stream representation provided coverage of the majority of generally second order streams and all 3rd order and greater (as defined from the River Environment Classification [REC] following dominant neighbour analysis – assessing the dominant equivalent REC reach and assigned information by length, for a 100m buffer on FWMT modelled reach). Note the REC and FWMT modelled reach networks are not identical with latter digitised from a higher-resolution LiDAR-based DEM.

The initial digitisation used the AC Stormwater Catchment polygons to define the coastal extent of the sub-catchments and therefore stream network. These were then adjusted to be defined by the Mean High-Water Springs 10% (MHWS10) exceedance water level GIS-layer (ARC, undated). Consequently, terminal freshwater stream nodes in the FWMT are at the MHWS10 boundary and are likely to be tidally-influenced (e.g., water level, salinity).

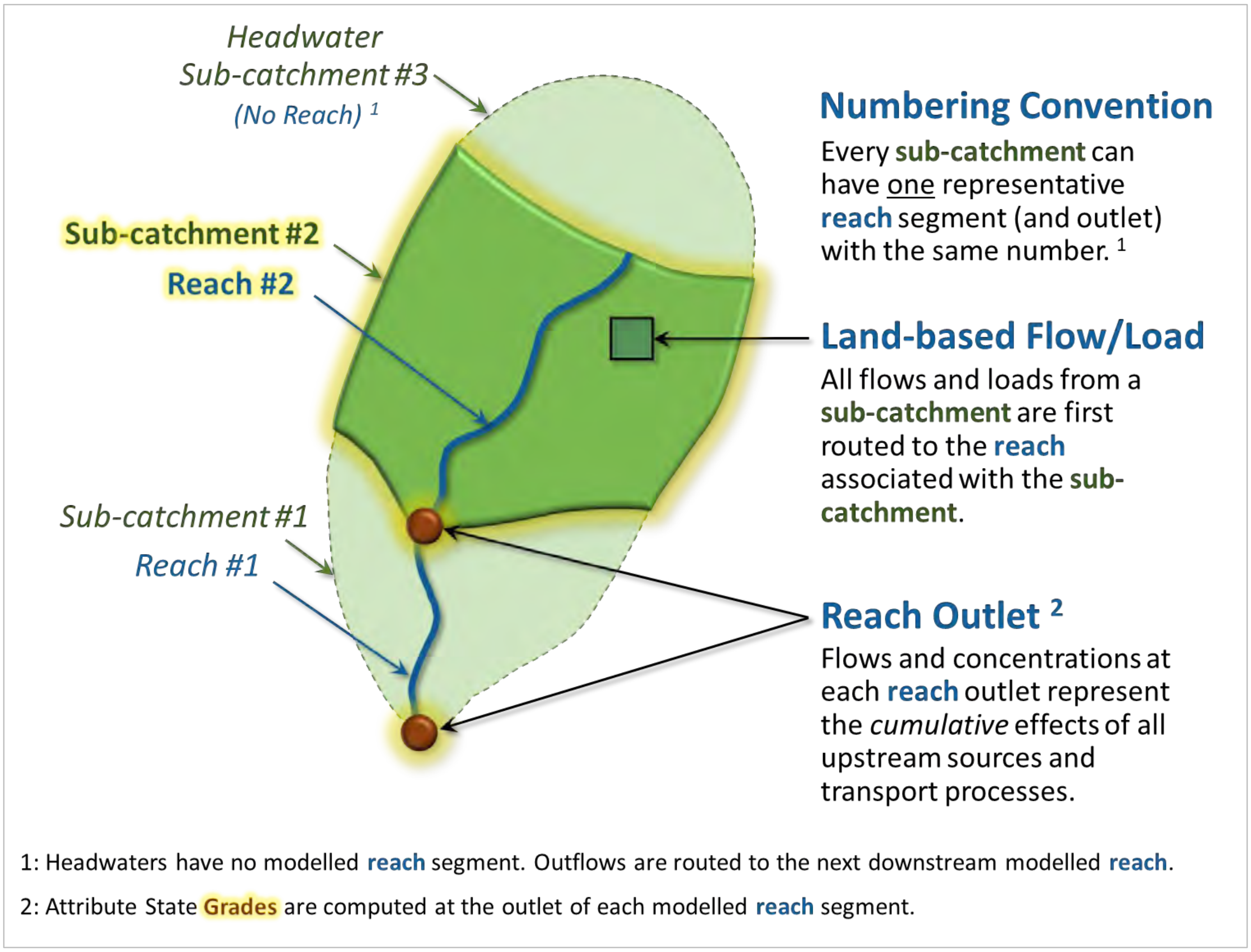


Figure 3-5. Relationship of sub-catchments and stream routing segments in FWMT. Adjacent and upstream edge-of-stream loads are subject to instream processes prior to reporting at a reach outlet

3.4 Channel Geometry

LSPC routes streamflow and contaminants downstream using stage-discharge relationships. By altering stage, the cross-sectional geometry of the mainstem segments represented in LSPC affects the shape of the hydrograph through each sub-catchment. By altering the hydrograph, the channel geometry also alters the timing of contaminant delivery to downstream nodes.

Channel geometry parameters were adopted using a hierarchy of data sources. Three methods were used to define channel geometry for each model sub-catchment (listed below in the order used to assign stream geometry to mainstem segments). Methods and sources are detailed in the [FWMT Baseline Data Inputs Report, Section 5.1].

1. Several parameters could be calculated from regional datasets including ground and non-ground DEM and floodplains. Length (from delineated channels),

channel slope, floodplain width ratio, floodplain Manning's *n* and floodplain edge slope were calculated for all reaches. Estimates for Manning's *n* for floodplain roughness accounted for vegetation determined from non-ground LiDAR (ARC, 2012) as a percentage of floodplain extent for all reaches.

2. Watercourse Assessment Report parameters (WAR; Lowe et al., 2016) defining channel width, depth, height, angle and substrate material were used to determine channel geometry and roughness; if not,
3. Derived relationships between catchment size, catchment slope and land use and other parameters were developed for estimating mainstem channel geometry. Relationships derived from WAR data correlated against catchment size for three channel slope classes (<3°, 3-5° and >5°); These were applied as follows:
    a. Channel width vs catchment size relationships were applied for rural and urban reaches.
    b. Average Manning's *n* per slope band was applied separately to rural and urban reaches.
    c. Average bank angle and bank height were applied separately for rural and urban reaches.
    d. Derived relationships were then applied to all reaches where no WAR data exists.

Together, the sub-catchments, mainstem segments, cross-sectional and longitudinal geometry as well as wider floodplain characteristics dictated the routing algorithms for flow (and contaminants) in the FWMT.

3.5 Meteorological Boundary Conditions

This section presents the LSPC model requirements, the data used, and the approach applied to configure weather boundary conditions into the FWMT. Meteorological data are needed to drive the modelled hydrologic processes within LSPC and generate flow for three separate pathways across the regional landscape: runoff, interflow and active groundwater. Both the mass and intensity of rainfall are key determinants of the flow and contaminant processes simulated by LSPC, with consequent effects on the generation, routing and concentration of contaminants instream. Contaminant concentrations determine associated modelled reach grades, whether from the National Objective Framework or regional guidance (e.g., Gadd et al., 2019), which demonstrates the importance of meteorological boundary condition time series to model configuration.

As shown in Figure 2-6, precipitation is the primary input to the water budget (top middle) and drives runoff due to rainfall (overland flow and interflow outflow). Overland flow and interflow outflow are two of three flow-paths discharging to modelled stream reaches; the third being active groundwater outflow (see Figure 2-6 for conceptual link to upper vadose zone storage). Additionally, infiltrated rainwater can be lost to groundwater through the DEEPFR parameter (Figure 2-6). The DEEPFR is typically used in cases when baseflow calibration and local data suggests a need to lose more water from the system to deep groundwater. The FWMT Stage 1 did not use DEEPFR.

The water budget in the FWMT Stage 1 resolves the partitioning of rainfall to total actual evapotranspiration (TAET), interflow, and overland flow determined for each of the 5,465 sub-catchments on an HRU-basis. The amount of TAET is in part determined by potential evapotranspiration (PET), a user input. The interaction of model parameters will ultimately determine how much PEVT becomes TAET. Sources of evapotranspiration include groundwater outflow, interception storage and soil moisture storage. Interflow and overland flow are then determined based on HRU characteristics, including soil infiltration rate, surface roughness, and slope. The outputs of the hydrology module drive the water quality modules to simulate contaminant generation and transport processes.

Table 3-3 presents a summary of the LSPC modules activated for the FWMT Stage 1 and associated climate data dependencies.

Based on a review of available data (including non-climate data such as land use, water take and discharge information) and consideration of the planning objectives with the FWMT, a five-year simulation period between 1 January 2012 and 31 December 2016 was selected for the hydrology and water quality calibration while the full simulation period for FWMT Stage 1 is between 1 January 2003 and 31 December 2017. Based on the size of the sub-catchments (~1-2 km^2) and the 15-minute model time step, discussed in Section 0, climate data were compiled and processed to a 15-minute time step. These 15-minute climate data are the key boundary conditions that drive the hydrology and water quality modules.

The primary climate data used in the model configuration are precipitation, potential evapotranspiration, air temperature, and solar radiation. While not required for any of the modules used in Auckland, Table 3-3 presents additional meteorological time series that LSPC can potentially use (see the cells with ‘--‘). Those non-essential climate datasets were nonetheless processed and included to provide flexibility for future model updates (e.g., simulation of climate change impacts on future contaminant grading).

Precipitation inputs were developed through a hybrid approach that used observed point data from Auckland Council rain gauges (AC gauges), augmented with Virtual Climate Station Network (VCSN) data provided by NIWA (downloaded March 2018). The VSCN data were at a daily timestep and required disaggregation to 15-minute intervals. When available, observed hyetographs from AC gauges were used to downscale the VCSN precipitation data. If no observed data was available, a statistically derived hyetograph that was typical of observed average volume, duration, and peak timing of rainfall for the corresponding month was used. Daily rainfall values were disaggregated based on these observed or synthetic rainfall distributions while ensuring that the distributed rainfall matched the daily rainfall totals matched exactly. The hybrid approach adopted by the FWMT Stage 1 utilised observed rain gauge time series over the gridded VCSN data where gauges are locally available for a sub-catchment (e.g., <5km from sub-catchment centroid). Doing so enabled a full regional meteorological coverage of all 5,465 sub-catchments spanning the Auckland region. Notably, each sub-catchment received a uniform rainfall time series that, whilst able to vary between sub-catchments and over time, was uniform across a sub-catchment for each 15-minute time-step.

Table 3-3. Summary of climate data input requirements by LSPC module

LSPC Module	Precipitation	Potential Evapotranspiration	Temperature	Dew Point	Wind Speed	Solar Radiation	Cloud Cover
Hydrology	●	●	--	--	--	--	--
Sediment Erosion and Transport	●	--	--	--	--	--	--
Water Quality (GQUAL)	●	●	--	--	--	--	--
Water Quality (RQUAL)	--	--	●	--	--	●	--

Precipitation magnitude within the VCSN time series was scaled by elevation whereas no scaling was used for gauged data. The hybrid precipitation approach was applied to the 15-year period of data, 2003-2017 used in the FWMT Stage 1 as follows:

- For LSPC sub-catchments with centroids within 5 km of the selected AC rain gauges, the observed time series are used directly with no scaling. Note that within the Waitematā Harbour watershed the gauge network is most dense and was used to cover all such sub-catchments with no scaling.
- For LSPC sub-watersheds with centroids beyond 5 km from any AC rain gauges (and outside of Waitematā), the monthly VCSN rainfall totals were used and nearest point gauges were used to disaggregate to the 15-minute/hourly distributions prior to elevation scaling.

All other non-rainfall meteorological parameters including PEVT, solar radiation, and temperature, were derived from the VCSN time series, using the nearest grid node for all sub-catchments. These parameters required disaggregation from daily values. The FWMT Stage 1 Baseline Data Inputs Report, Section 4.0 contains additional information on weather time series inputs.

Table 3-4 summarises the combinations of climate time series used for LSPC configuration. The selected AC gauges are shown in Figure 3-6 and the VCSN grid location are shown in Figure 3-7. The monthly precipitation totals at observed gauges versus VCSN grid locations generally showed strong agreement ($R^2 > 0.8$) – an example comparison is shown in Figure 3-8. Additional information on the agreement between observed and VCSN derived data can be found in the [FWMT Baseline Input Report Section 4.0].

The selection of AC gauges was based on: coverage across the calibration/validation period (2012-2016), hourly or finer time step continuity of data, spatial coverage across the region, and guidance from AC on which gauges have generally high quality coding according to National Environmental Monitoring Standards (NEMS) (Milne, 2019). Some gauges had gaps across the 15-year record, in which case the nearest rainfall gauge was used to directly replace missing observations. In a few cases, this resulted in several observed gauges with recent, shorter records having their earlier observations replaced with a more distant gauge (for example, the gauge on Great Barrier Island covers the most recent five years and was used for that period). Additional data, including a complete list of AC and VCSN gauges and corresponding mapped VCSN grid IDs can be found in the [FWMT Baseline Data Input Report, Section 4.0].

Table 3-4. Summary of climate datasets used by the FWMT Stage 1 for watersheds

Watershed	Summary of Selected Rainfall Gauges		Summary of FWMT Model Rainfall Time series				Secondary Climate Time series[2]
	Locations		Number of Sub-catchments Assigned[1]		Per cent of Sub-catchments		
	Auckland Council	NIWA VCSN	Observed Data	VCSN Adjusted	Observed Data	VCSN Adjusted	
Hibiscus Coast	4	12	206	167	47%	53%	18
Hauraki Gulf Islands	2	15	98	344	18%	82%	16
Kaipara Harbour	7	56	290	1,127	23%	77%	69
Mahurangi Estuary	2	4	98	42	67%	33%	8
Manukau Harbour	9	35	452	608	43%	57%	50
North East Coast	2	9	131	147	41%	59%	13
Tamaki Estuary	3	8	220	74	71%	29%	12
Wairoa Coast	2	17	81	338	20%	80%	23
Waitematā Harbour	9	15	607	0	100%	0%	26
West Coast	0	17	48	387	12%	88%	27
Total	40	188	2,231	3,234	41%	59%	262

1. Sub-catchments with centroids ≤ 5km from observed data used Auckland Council rainfall time series directly, this resulted in places like West Coast, which does not have observed rain gauges, having some portion of nearby observed data attributed to applicable subbasements. Otherwise, VCSN was used to scale the rainfall depths, except in Waitemata, which used only observed precipitation time series.
2. Secondary climate time series derived from NIWA VCSN data include potential evapotranspiration, air temperature, solar radiation, dew point temperature, wind speed, and cloud cover, which required downscaling from daily values.

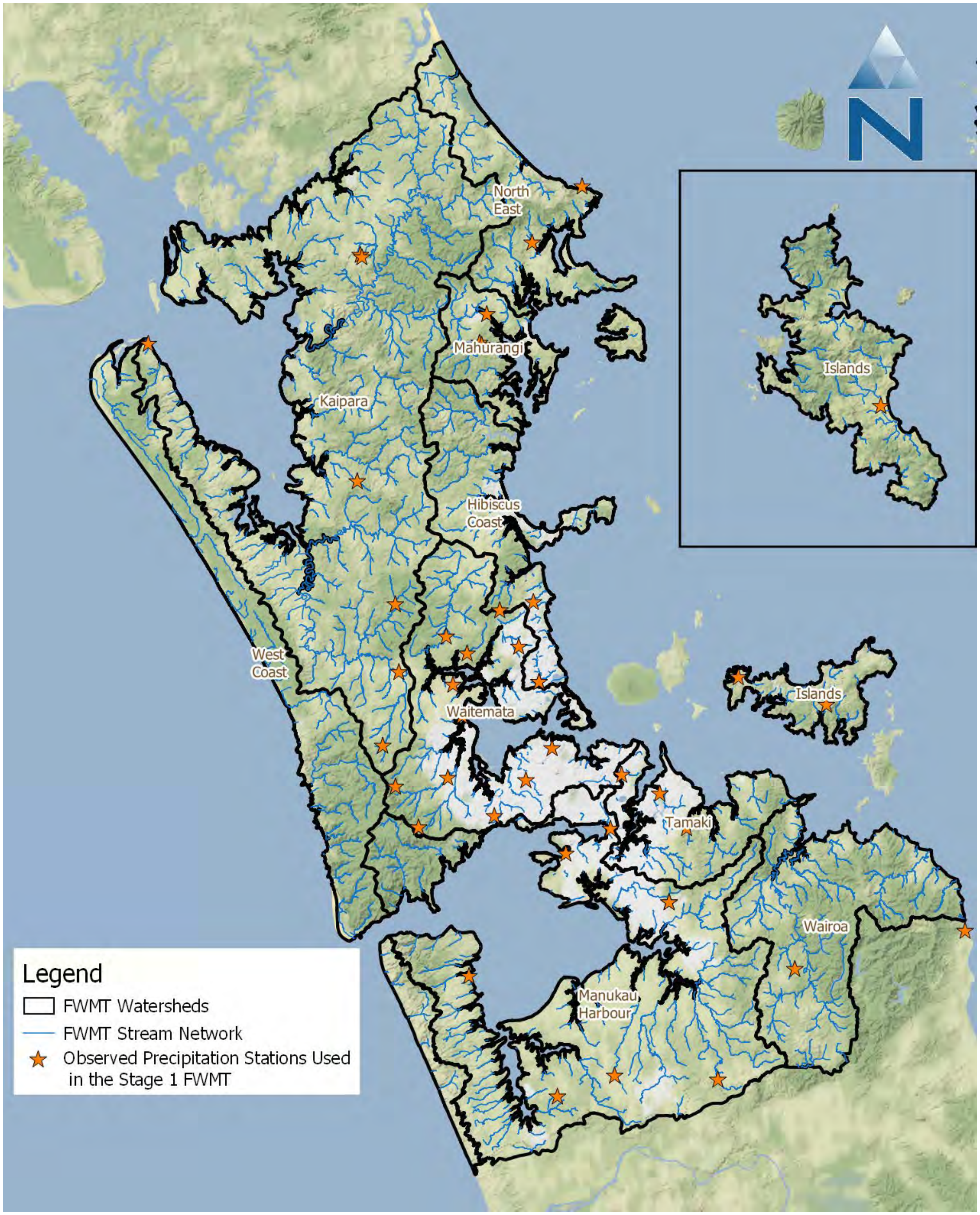


Figure 3-6. Observed precipitation gauges used for LSPC configuration of FWMT Stage 1

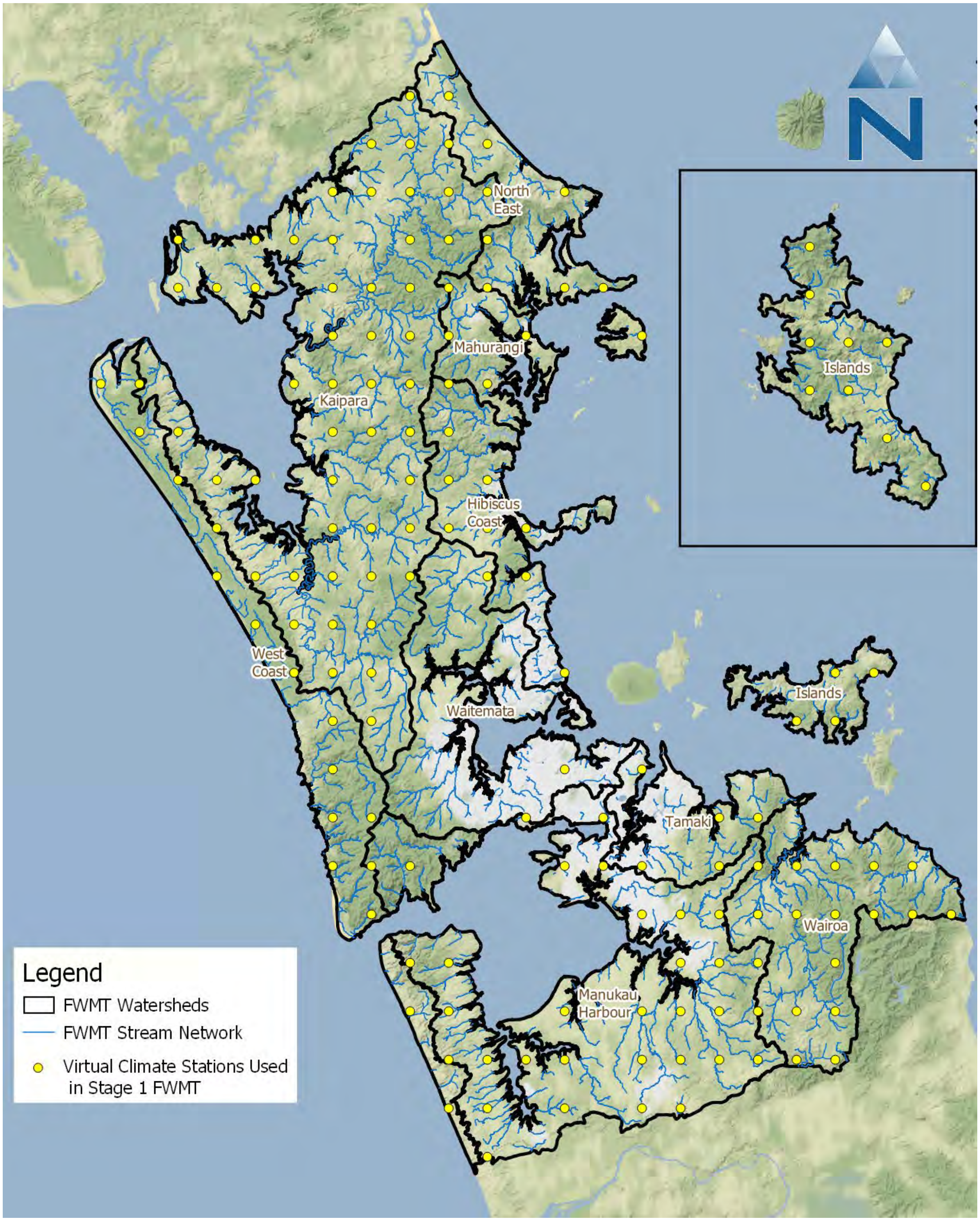


Figure 3-7. Coverage of NIWA gridded virtual climate station network (VCSN) within Auckland watersheds and used in the FWMT Stage 1

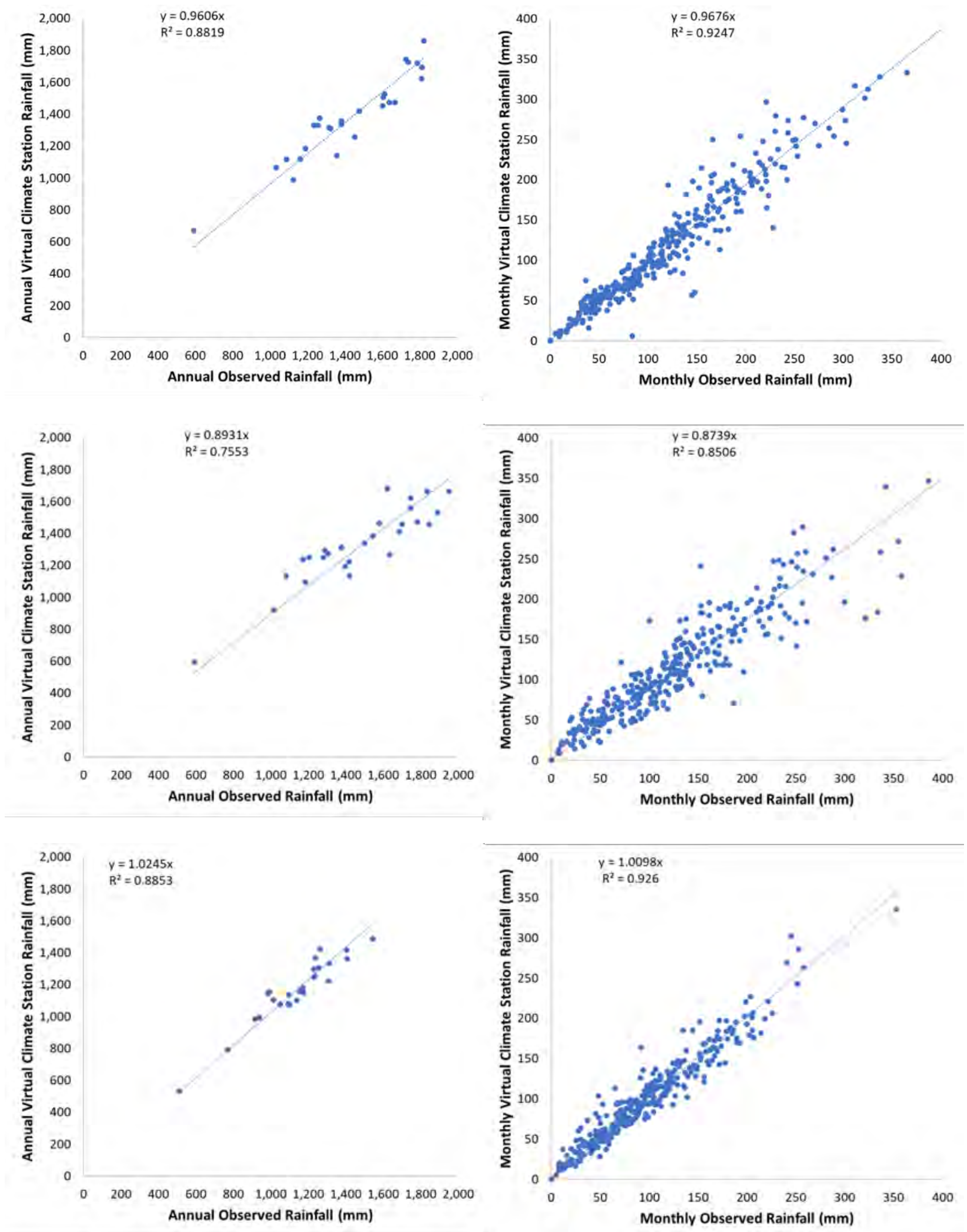


Figure 3-8. Example comparison of annual and monthly rainfall between observations at the observed AC gauges Mahurangi at Warkworth Wastewater Treatment Plant weather station and its nearest VCSN station (21651) (Top); Hoteo at Oldfields weather station and its nearest VCSN station (25736) (middle); and Tamaki weather station and its nearest VCSN station (29687) (bottom)

3.6 Point Sources and Takes

3.6.1 Wastewater Network and Discharge

There are occasions where stormwater flows are contaminated with wastewater. Urban wastewater sources may include point source network overflows and non-point source contributions, which could include network exfiltration, cross connections, or dry weather overflows. Figure 3-9 presents a map of the wastewater network service areas and outfall locations where contaminated overflows can occur. Because runoff within the service areas enters the wastewater conveyance system (intended for treatment), it can only discharge during overflow events. To avoid double-counting the runoff contribution, the HRUs that intersect the service area boundaries were removed from the FWMT Stage 1 and replaced by time series of wastewater overflows that are mixed with stormwater[5].

Overflows were represented using Watercare models, operated by HAL for the Auckland Council Healthy Waters Department, over 15-year continuous rainfall time series duration consistent with the FWMT Stage 1. These models provide estimated information on where, when and how-much volume (and contaminant load) of wastewater and combined stormwater entered the stormwater network. The Watercare models also generate the estimated proportion of dry-weather overflow volume (and load), effectively the raw effluent component of combined overflow events at engineered overflow points. These models were developed for six reticulated networks using either MIKE URBAN or Infoworks ICM models covering the time period from 1 July 2002 to 30 June 2017.

[5] HAL generated wastewater time series for raw effluent mass discharged per unit time at EOPs over the full modelling 15-year period coincident with hydrology simulation within the FWMT Stage 1 (2003-2017). The latter were then combined within LSPC with the runoff-derived masses from “service area” HRUs to create a mixed effluent and stormwater time series at each EOP.

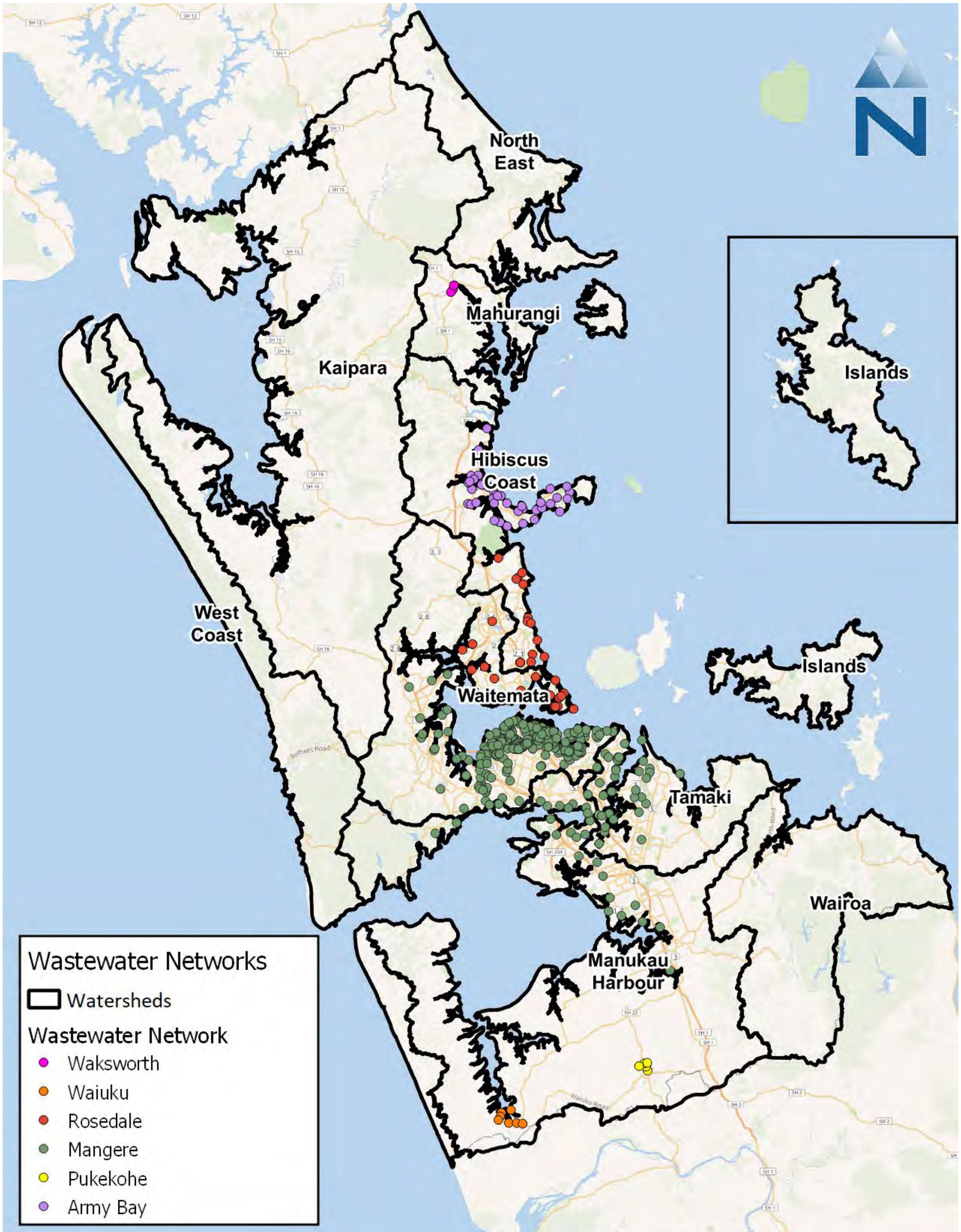


Figure 3-9. Wastewater conveyance network service areas and all engineered overflow points (EOPs) represented in the FWMT Stage 1

Table 3-5. Summary of modelled wastewater network discharges

Hydraulic Model	Wastewater Network	No. of Rainfall Gauges Used	No. of Overflow Points	No. of Overflow Points with Volume
MIKE URBAN	Rosedale [1]	1	39	31
	Warkworth [2]	1	3	3
	Army Bay [3]	1	44	20
Infoworks ICM	Mangere [4]	6	348	301
	Pukekohe [5]	1	2	2
	Waiuku [5]	1	7	2
Total			**443**	**359**

1. Rosedale wastewater model was run using rainfall time series for Wairau at Testing Station NSCC07 (647722)
2. Warkworth wastewater model was run using rainfall time series for Mahurangi @ Warkworth Sewage Treatment Plant (644626)
3. Army Bay wastewater model was run using rainfall time series for Orewa @ Treatment Ponds (646619)
4. Mangere wastewater model was run using five different rainfall time series for Keeling Road @ Utilitech Training Centre (648612), Mt Albert Grammar rainfall (648717), Tamaki rainfall (648850), Pakuranga @ Sunnyhills Village (649820), Anns Ck @ Acc Abattoir Rainfall (649818), Puhinui @ Botanics (740815)
5. Pukekohe and Waiuku wastewater models were run using rainfall time series for Whangamaire @ Culvert (741813)

Wastewater volume entering stormwater networks were combined with statistics derived from dry weather wastewater influent to Watercare's Mangere and Rosedale treatment plants (2002-2017) to generate time series of combined wastewater and stormwater contaminant to downstream receiving environments within the FWMT Stage 1 (Table 3-5). The Rosedale concentrations are considered more typical of a mixed residential catchment, while the Mangere wastewater concentrations are considered more representative of commercial and industrial sources. In the FWMT Stage 1, represented outfalls that are part of the Mangere wastewater conveyance network were assigned concentrations consistent with Mangere wastewater while all other outfalls (i.e., Rosedale, Warkworth, Army Bay, Pukekohe, and Waiuku) were assigned concentrations derived from Rosedale monitoring data, consistent with residential networks. The adopted concentrations and calculation methods are presented in Table 3-6.

Table 3-6. Adopted representative concentrations

Parameter	Mangere (industrial)		Rosedale (residential)	
Total Suspended Solids (TSS)	7-day antecedent dry period median statistic using 2002-2017 influent monitoring data.	467 mg/L	7-day antecedent dry period median statistic using 2002-2017 influent monitoring data	471 mg/L
Total Kjeldahl Nitrogen (TKN)	7-day antecedent dry period median statistic using 2002-2017 influent monitoring data.	68.39 mg/L	Not reported. Calculated as Total Nitrogen minus Nitrate.	77.36 mg/L
Total Nitrogen (TN)	Not reported. Calculated the ratio of TKN between Mangere and Rosedale; used this ratio to proportionally adjust the TN value from Rosedale.	68.65 mg/L	7-day antecedent dry period median statistic using 2002-2017 influent monitoring data.	77.65 mg/L
Soluble Reactive Phosphorus (SRP)	7-day antecedent dry period median statistic using 2002-2017 influent monitoring data.	5.4 mg/L	Not reported. Median from Mangere used for Rosedale.	5.4 mg/L
Total Phosphorus (TP)	Not reported. Median from Rosedale used for Mangere.	11.28 mg/L	7-day antecedent dry period median statistic using 2002-2017 influent monitoring data.	11.28 mg/L
Total Zinc (Zn)	7-day antecedent dry period median statistic using 2002-2017 influent monitoring data.	244.07 µg/L	7-day antecedent dry period median statistic using 2002-2017 influent monitoring data.	177.14 µg/L
Total Copper (Cu)	7-day antecedent dry period median statistic using 2002-2017 influent monitoring data.	86.37 µg/L	7-day antecedent dry period median statistic using 2002-2017 influent monitoring data.	68.55 µg/L
Ammonia (NH3+NH4)	7-day antecedent dry period median statistic using 2002-2017 influent monitoring data.	41.51 mg/L	7-day antecedent dry period median statistic using 2002-2017 influent monitoring data.	52.28 mg/L

Parameter	Mangere (industrial)		Rosedale (residential)	
Nitrate	Not reported. Calculated as Total Nitrogen minus TKN.	0.26 mg/L	7-day antecedent dry period median statistic using 2002-2017 influent monitoring data.	0.29 mg/L
E. coli	Median from Rosedale used for Mangere.	1,091,429 cfu/100ml	Concentration listed in influent monitoring dataset as 'Enterococci', however, confirmed with Watercare that data are for *E. coli* 7-day antecedent dry period median statistic using 2002-2017 influent monitoring data.	1,091,429 cfu/100ml

A 7-day antecedent dry period was used to conservatively estimate contaminant concentrations in wastewater that is not influenced by stormwater inflow and infiltration. Rainfall derived inflow may dilute the concentrated wastewater, thereby influencing the wastewater influent analysis. The US Environmental Protection Agency recommends average dry weather flow analysis to be conducted during an extended period of 7 to 14 dry days (EPA, 2014). The 7-day dry period follows a conservative approach that is within the standard dry weather range, while still allowing enough samples for estimation of wastewater influent concentrations.

Auckland Council precipitation gauges for North Shore (4) and ACC-West (6) were used to perform a dry-weather flagging analysis for the Rosedale and Mangere service areas, respectively. Any day with total precipitation over 0 cm was considered “wet”, whereas only days with zero precipitation were considered “dry.” Total rainfall was summed across the entire period of record (2002-2017) using 1-day, 3-day, and 7-day increments to analyse the variability in antecedent conditions. For example, on 28 August 2012, precipitation totals for the 7-day increment would include precipitation for 28 August plus the previous six days. For any of these rolling increments, if the total precipitation across the respective window of days was 0 cm, that day was flagged as a “dry” day. Finally, wet days were filtered out and only dry days included in the statistical analysis.

3.6.2 Surface Water Takes

Surface water takes were obtained from Auckland Council as a shapefile of consented take locations and a time series of meter readings associated with some of these consents (Surface Take Consent List Provided by Auckland Council 2 May 2018). These meter readings were transformed into volumes by subtracting each reading from the reading at the previous timestep. The time series collectively spans the period from 2 January 2003 through 29 November 2018, though the start and end dates of individual takes varied by consent. Watercare also provided a spreadsheet of abstractions from their water resources dams spanning a period from 1 July 2001 to 30 June 2017. These features were configured in the FWMT Stage 1 as withdrawals extracting surface water from the reach of the sub-catchment in which the consent is located. Withdrawals were considered consumptive so none of the extracted volume in the model was explicitly returned to the system. Table 3-7 presents a summary of the number of individual consented water takes by watershed. Figure 3-10 presents geographic locations of takes, grey dots represent unmetered takes that were not included in the model.

Table 3-7. Number of consented surface water takes in the FWMT Stage 1 by summarised by watershed

Watershed	No. of Water takes	No. of Impacted Subwatersheds	Minimum Daily Volume (m^3/day)	Average Daily Volume (m^3/day)	Maximum Daily Volume (m^3/day)
Hibiscus Coast	3	2	0.3	1,553	305,552
Hauraki Gulf Islands	4	4	1.0	49	8,147
Kaipara Harbour	32	24	0.2	2,719	2,135,172
Mahurangi Estuary	1	1	24.5	1,049	78,046
Manukau Harbour	63	50	< 0.1	4,539	2,280,180
North East Coast	7	3	6.0	773	206,197
Tamaki Estuary	8	5	1.0	1,619	417,997
Wairoa Coast	7	6	0.1	15,757	1,821,668
Waitematā Harbour	10	10	1.0	773	321,798
West Coast	7	5	0.5	629	130,476
Total	**142**	**110**			

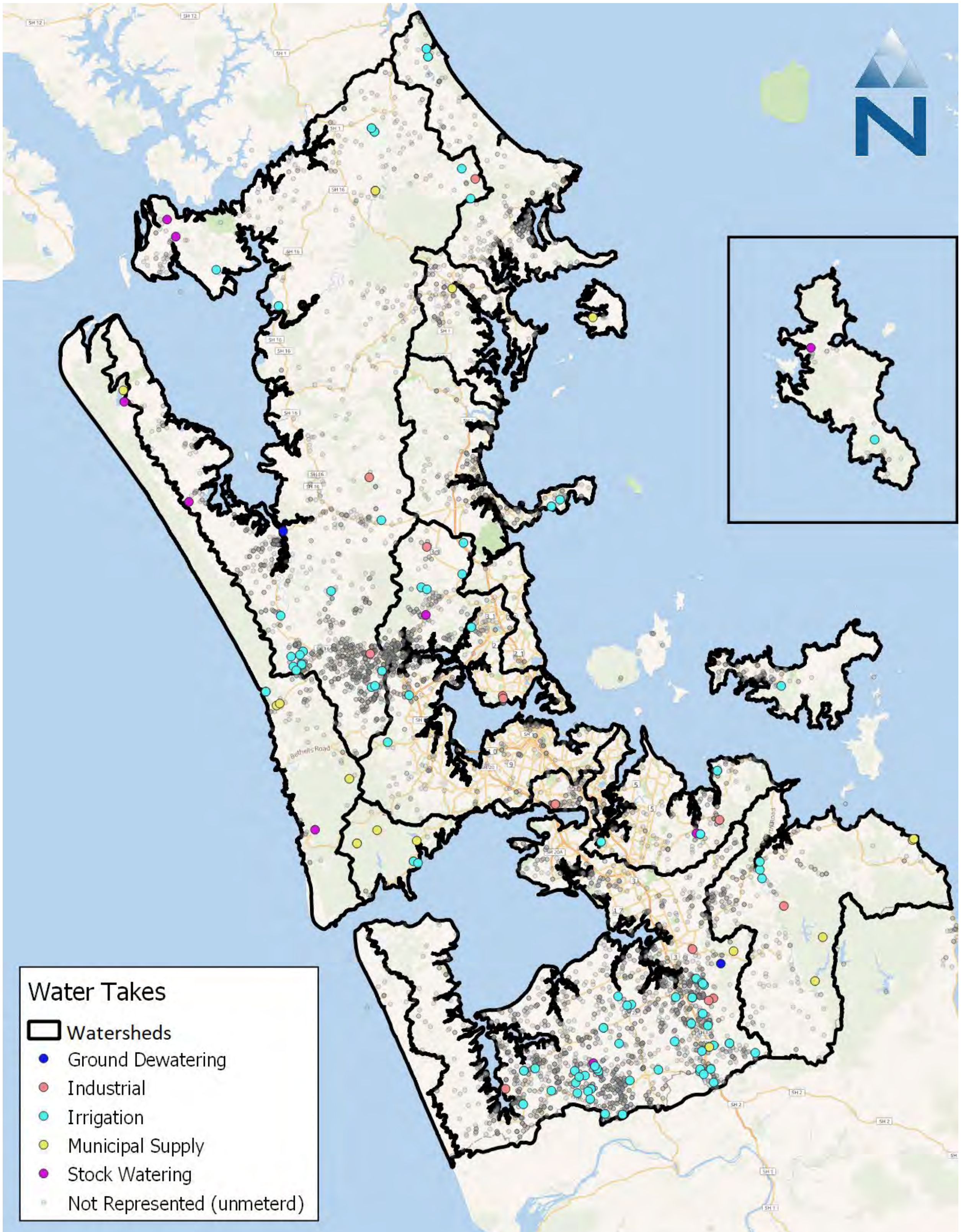


Figure 3-10. Locations and types of water takes represented in the FWMT Stage 1

3.7 Impoundments

Impoundments in the watershed affect hydrology and water quality (e.g., intercepting runoff and interflow, reducing velocity to reduce contaminant generation and enhance sedimentation). Two types of impoundments are explicitly represented in the FWMT as below.

3.7.1 Reservoirs and Lakes

Seven (7) major lakes and ten (10) Watercare-managed reservoirs (Figure 3-11) were represented in the FWMT Stage 1 using a combination of functional tables (f-tables) defining the storage-discharge relationship and time series of documented releases. These f-tables govern the simulation of outflow from each impoundment. Water quality simulation within the impoundments was subject to the same contaminant processes represented in modelled reaches. No specific lake processes or internal loading from sediments were represented.

F-tables were developed based on the dam sizing configuration, depth, volume, and surface area. Records were available for takes (e.g., water supply) and releases (controlled discharge downstream) for the reservoirs. These were represented explicitly as withdrawals in the model which extracted the recorded volume at each time step. Withdrawals representing takes were received from Watercare (Watercare Dams Takes and Releases 20020701 – 20170630 c/o Maria Utting 3 September 2018). These were abstracted from reservoirs at each timestep based on the documented withdrawal rate, then routed to the downstream sub-catchment in the model network. When a reservoir was full, the overflow is estimated using the volume-discharge relationship defined in the F-table. Overflows only occurred when the reservoir is full after satisfying the takes and release outflows.

FWMT Stage 1 f-tables are presented in Appendix G. Further lake baseline assessment has been undertaken and is detailed in the FWMT Baseline State – Lakes Report.

3.7.2 Structural Devices – Ponds

Structural devices such as ponds, wetlands and inline treatment devices constructed during greenfield and brownfield development and present on rural land can affect hydrology and water quality (e.g., intercepting runoff and interflow, reducing velocity to reduce contaminant generation and enhance sedimentation). In the Stage 1 development of the FWMT, limited available data on structural devices meant only surface ponds were accounted for within LSPC. Over 11,000 waterbody features were incorporated into the FWMT Stage 1, including their effects on stormwater hydrology and contaminant processes (covering combined ~17,000 Ha; 768 structural devices). Data sources for ponds included the 2011 Research and Evaluation Unit wetland extent dataset. Additional information on the pond datasets can be found in the [FWMT Baseline Data Inputs Report, Section 7.1]. Figure 3-12 presents an example of pond locations in a sub-catchment of the Kaipara Harbour watershed. Pond uses included farm, stormwater, golf course, and ornamental. Within the pond inventory, 768 stormwater treatment ponds were identified, along with 1,994 farm ponds. These types were selected for carrying forward into the configuration because they have the highest likelihood of impounding/managing runoff (and runoff-derived contaminants).

The stormwater treatment ponds and farm ponds were combined into a single layer and dataset, with the following key findings:

- 98% of the pond footprints were less than one hectare in size
- 7% of sub-catchments (n=383) contain stormwater ponds
- 21% of sub-catchments (n=1,198) contain stormwater or farm ponds

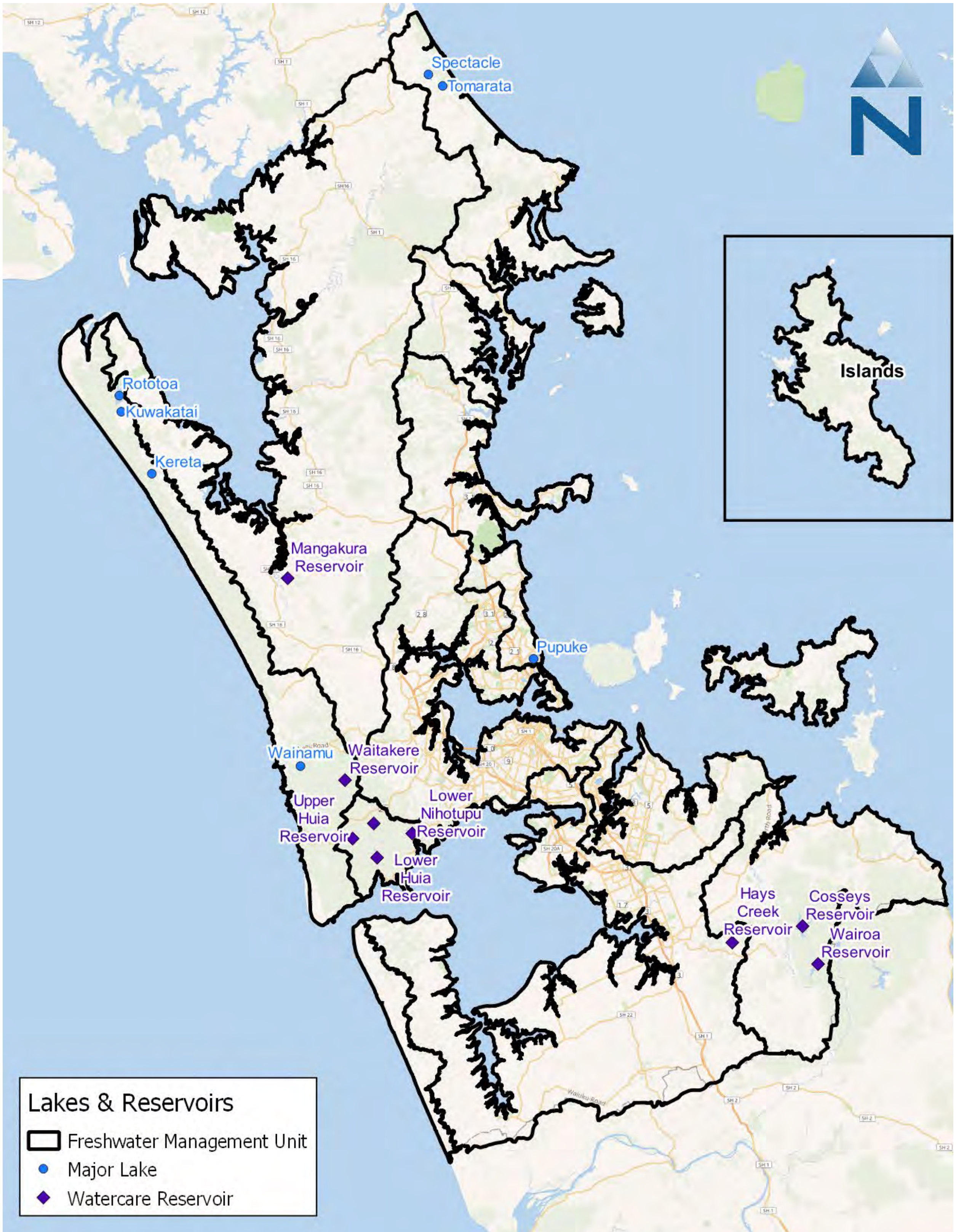


Figure 3-11. Map of major lakes and reservoirs across the Auckland region

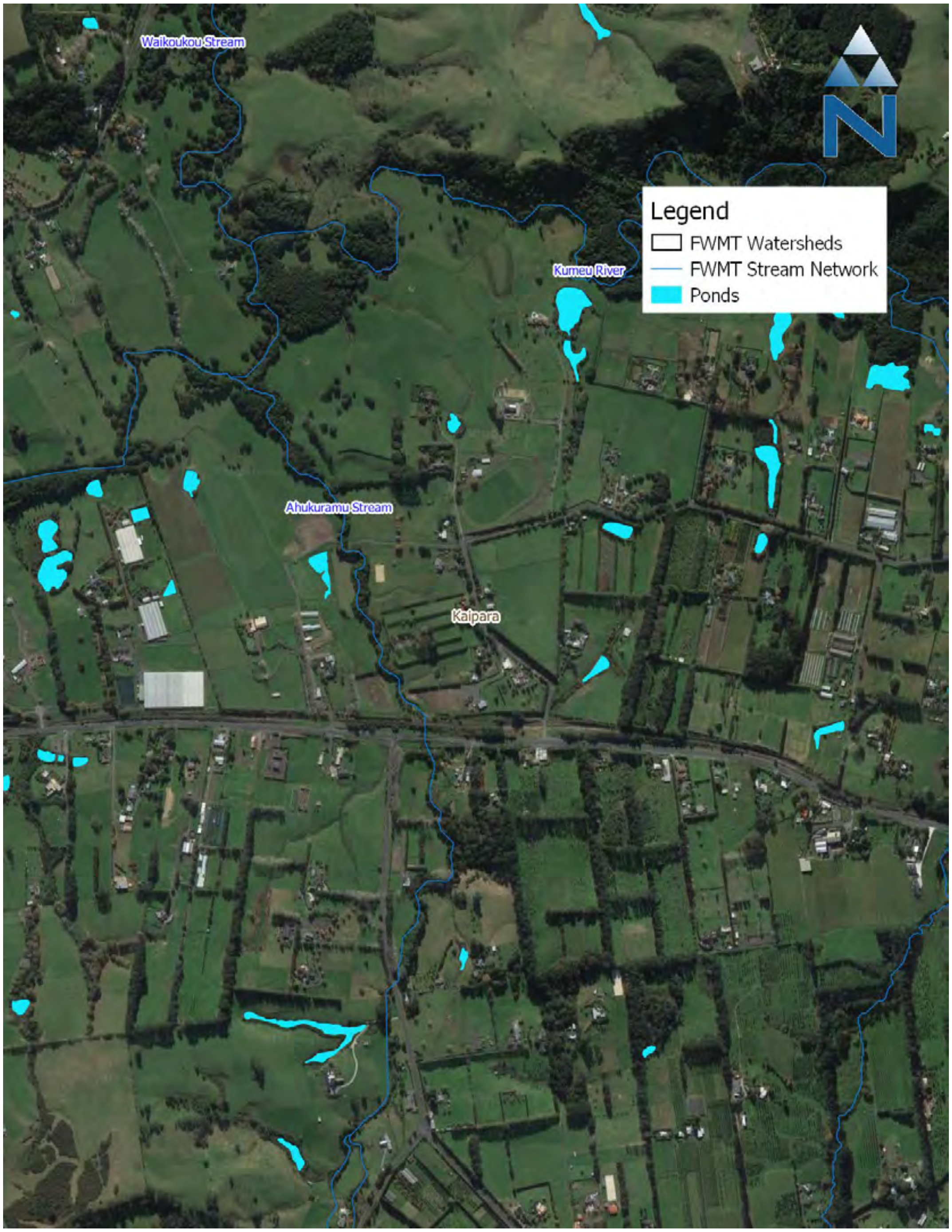


Figure 3-12. Example of farm ponds represented in the FWMT Stage 1 within the Kaipara Harbour watershed

3.8 Hydrologic Response Units (HRUs)

A key part of the configuration of the FWMT Stage 1 was the development of a high-resolution raster dataset to represent spatial differences in landscape factors that influence water quantity and quality in the Auckland region. A raster grid containing 2×2 m cells was developed with each cell assigned a Hydrologic Response Unit (HRU) class. The HRU is the core hydrologic modelling unit within LSPC. The single HRU raster dataset was constructed by overlaying several individual raster datasets containing information on HRU factors. The 2×2 m HRU cells were assigned a numeric code representing the specific combination of factors combined into each overall HRU class.

Three factors, soils, slope, and land use/land cover are the basic HRU components typically used in LSPC modelling application and are referred to here as HRU base factors. Each factor can have several classes, for example, a land use/land cover factor likely includes several classes such as pasture, horticulture, residential, commercial, etc. The land use/land cover factor can be further refined to establish a qualitative measure of the relative intensity of the corresponding land use/land cover. These additional HRU components are referred to as HRU impact factors. Impact factors use information relevant to the model purpose, specifically the FWMT regional accounting purpose (i.e., relevant contaminants for the Auckland region). For the FWMT Stage 1, HRU impact factors included information on grazing management, roof material, traffic, forestry practices, and septic systems. Impact factors facilitate model calibration by characterising and categorising the intensity of human activities on the landscape, allowing for the modeler to consistently adjust parameter values within HRUs with specific impact factors. The number and extent of HRUs within a sub-catchment varied but could never exceed a maximum of 106 possible types.

HRUs are classified within LSPC to effectively integrate the multiple characteristics affecting runoff and contaminant generation and to enable regionalisation of parameters (e.g., HRU-based parameterisation). This HRU-based parameterisation occurred through the utilisation of parameter groups, which were sets of parameter values assigned to a group of HRUs during configuration. These HRUs thereby share similar processes and water quantity/quality responses to meteorological conditions.

Figure 3-13 shows the organisational relationship between HRU components, meteorological data, and modelled land responses. The classification and accounting for HRUs within each sub-catchment is a key determinant of contaminant predictions by the FWMT, and consequently, calibrated performance. HRUs in the FWMT have been developed in line with the model objectives to account for contaminant processes related to nutrients (N, P), heavy metals (Cu, Zn), sediment (TSS) and faecal indicator bacteria (*E. coli*). The wider water quality literature in New Zealand has identified numerous factors governing loss of contaminants from land-based activities to waterways, but whose consistent findings highlight soil characteristics, topography, land cover and intensity of land use all being key determinants (e.g., Larned et al., 2004, 2016; McDowell et al., 2009, 2013; PCE, 2013, 2015). The factors used to develop the HRUs for the FWMT Stage 1 are presented in Table 3-8. The table also provides the report section where additional details about the HRU factors can be found. More detailed information can be found in the [FWMT Baseline Data Input Report Section 8.0].

Often, impact factors were used to further refine the pervious and impervious land uses/land covers. Impact factors allow for additional characterisation of the land by using available data on the intensity of human activities. For instance, impact factor data on grazing rates was used to segment pastoral land cover, established from base factor data, into tiers of varying stocking-rates to predict the greater contaminant loading typically associated with greater stocking rates, agricultural production and stock-associated degradation of ecosystem services responsible for attenuation of contaminant loss.

Table 3-8. Summary of datasets used for HRU classification

HRU Factor type	Description	Data Source(s)	Report Section
HRU Base Factors	Slope (based on 2-m DEM)	Auckland Council	3.8.2
	Land cover (including imperviousness)	Auckland Council Landcare Research Agribase Land Information New Zealand (LINZ)	3.8.2 3.8.3
	Hydrologic Soil Group (HSG)	New Zealand Fundamental Soil Layer S-Map Fact Sheets	3.8.5
HRU Impact Factors	Septic condition (for non-reticulated dwellings)	Tonkin and Taylor Onsite Wastewater Risk Assessment	3.8.4
	Grazing livestock density	Agribase	
	Horticulture (Irrigation needs)	Agribase	
	Vegetation height	LiDAR	
	Road (Vehicles per Day)	RAMM Annual Average Daily Traffic Data – Vehicles per Day (VPD) (2017)	
	Roof Materials	Auckland Council District Valuation Roll (2018)	

Noting greater stocking rate resulting in greater contaminant loading is then modified by base factors (i.e., less intensively-stocked pastoral land will generate greater contaminant loading on steeper slopes). The combination of HRU-factors enables a matrix of HRUs to be developed for LSPC spanning gradients in land and activity types, for which contaminant generation and transport processes are uniquely parameterised across the wider region. Note the HRUs do not limit the parameterisation as much as guide the range of unique hydrological and contaminant process coefficients within the FWMT.

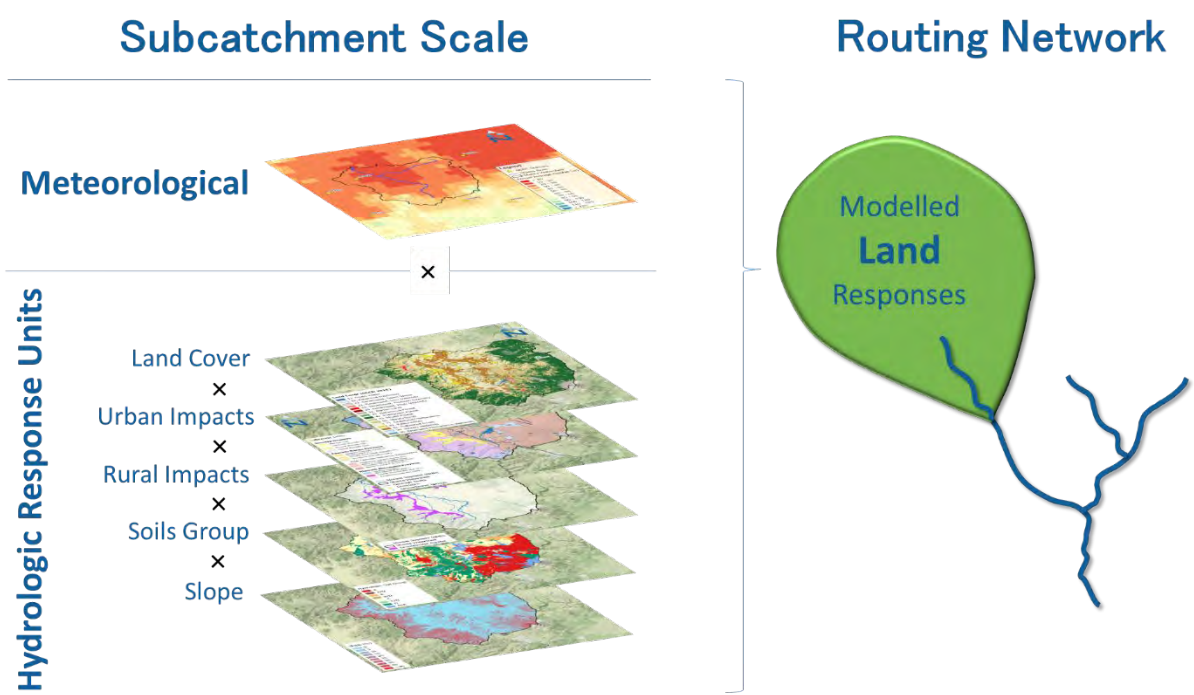


Figure 3-13. Organisation of HRUs and their interaction with meteorological data to produce land responses

3.8.1 HRU Classification Approach

The HRU distribution in each sub-catchment was held constant over the period of calibration (e.g. “static” configuration). Consequently, baseline output is broadly representative of 2013-2017, representing the period from which data were collected on

HRU factors. FWMT Stage 1 simulations do not directly[6] therefore, account for seasonal variation in land use and omit inter-annual variation altogether. Instead capturing a range of water quality contaminant process-based responses to broadly current land use, under varying recent climate.

The HRU development process involved integrating each HRU factor dataset into a single, intersected HRU raster dataset with a resolution of 2×2 m for the entire Auckland region, with full coverage of each sub-catchment. As detailed below, that process involved scaling across sub-catchments to account for areas devoid of information on any one factor (i.e., scaling proportionately for areas within each sub-catchment that had information, to the full extent of a sub-catchment). Generally, HRU factor datasets covered the entirety of the FWMT Stage 1 model domain.

The following subsections detail the approach taken for processing the HRU factors into their various classes (HRU type), including maps of HRU distribution within the 10 watersheds spanning the Auckland region.

3.8.2 Slope

Slope has been typically used as a base HRU factor because of its importance in determining surface runoff and associated contaminant processes. Within LSPC, greater slope results in an increased proportion of rainfall transferred from the land as runoff (USEPA, 2017), although runoff generation is also impacted by other factors including the soil infiltration rate, the amount of available surface storage, and the roughness of the land surface. Within LSPC, the amount of overland flow generated from an HRU directly impacts the amount of contaminants generated from that area (see section 3.9 for additional discussion), therefore adjustments in slope lead to changes in runoff which result in changes to contaminant export.

Slope across the Auckland region was derived from a digital elevation model (DEM) developed in 2012 for Auckland Council. While the DEM was created in 2012, it was based on LiDAR data obtained in 2006, 2007, 2008, and 2010 for various parts of the region. The various datasets were combined into a single DEM in 2012. The LiDAR DEM was a raster-based dataset describing the elevation of the landscape across a regular grid. Table 3-9 presents the details of these DEMs and the generated slope raster for the FWMT.

[6] Indirect effects from seasonal variation in cover and/or practices can be captured through the parameterisation, as required to improve calibration (i.e., if climate demonstrated seasonal patterns coeval with seasonal changes in cover or practice, the variation in flow or contaminant processes can be captured in the parameterisation process for HRUs).

Table 3-9. Summary of input datasets detailing data source and type

GIS Layer	Data Source	Description
Digital Elevation Model (DEM)	AC	2-m Raster (c. 2012)
Slope (derived from above DEM)	FWMT project (derived from above DEM)	2-m Raster (c. 2019)

Figure 3-14 presents the regional cumulative distribution function for slope. This curve was used to assign slopes throughout the watersheds to either a ‘Low’ or ‘High’ slope category based on a breakpoint (i.e., < 10% and ≥ 10% – equivalent to ~6 degrees). This HRU breakpoint was used during calibration to generalise parameterisation of processes that are impacted by slope; however, the classification did not change the computed slope value of any HRU raster cell. All relevant algorithms used slope values represented in the distribution in Figure 3-14 (e.g., sub-catchment specific slope estimates used to drive HRU contaminant and hydrological processes).

Gully erosion occurs when sediment is mobilised from an HRU through scouring due to overland flow. The gully erosion equation within the sediment module was one process that impacted the establishment of the breakpoint in slope. Within the FWMT Stage 1, the breakpoint of 10% was used to differentiate the parameter values for gully erosion such that HRUs that were categorised in the High slope category could generate more gully erosion than HRUs categorised as Low slope, although those processes were governed by the computed aggregated slope of all HRU raster cells within each sub-catchment. A 10% threshold for simulating higher levels of gully erosion thereby appears to be reasonable (e.g., Katz et al., 2013). Section 3.9.3.3 contains detailed discussion on the gully erosion process. Figure 3-15 through Figure 3-24 presents maps showing the spatial distribution of the classified slope categories for HRU development.

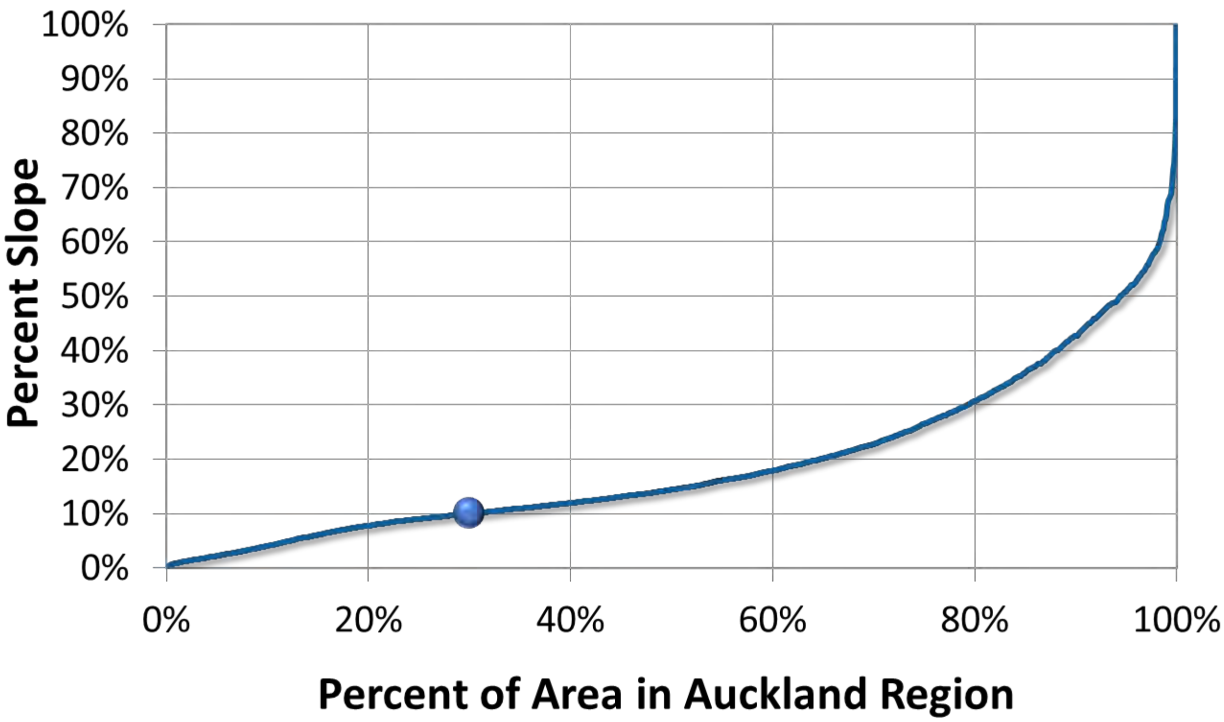


Figure 3-14. Cumulative distribution function that shows the raw slope value as a percentage of total watershed area for the FWMT watersheds

Figure 3-15. Map showing slope classifications for the Kaipara Harbour watershed. Derived from regional 2-m LiDAR DEM

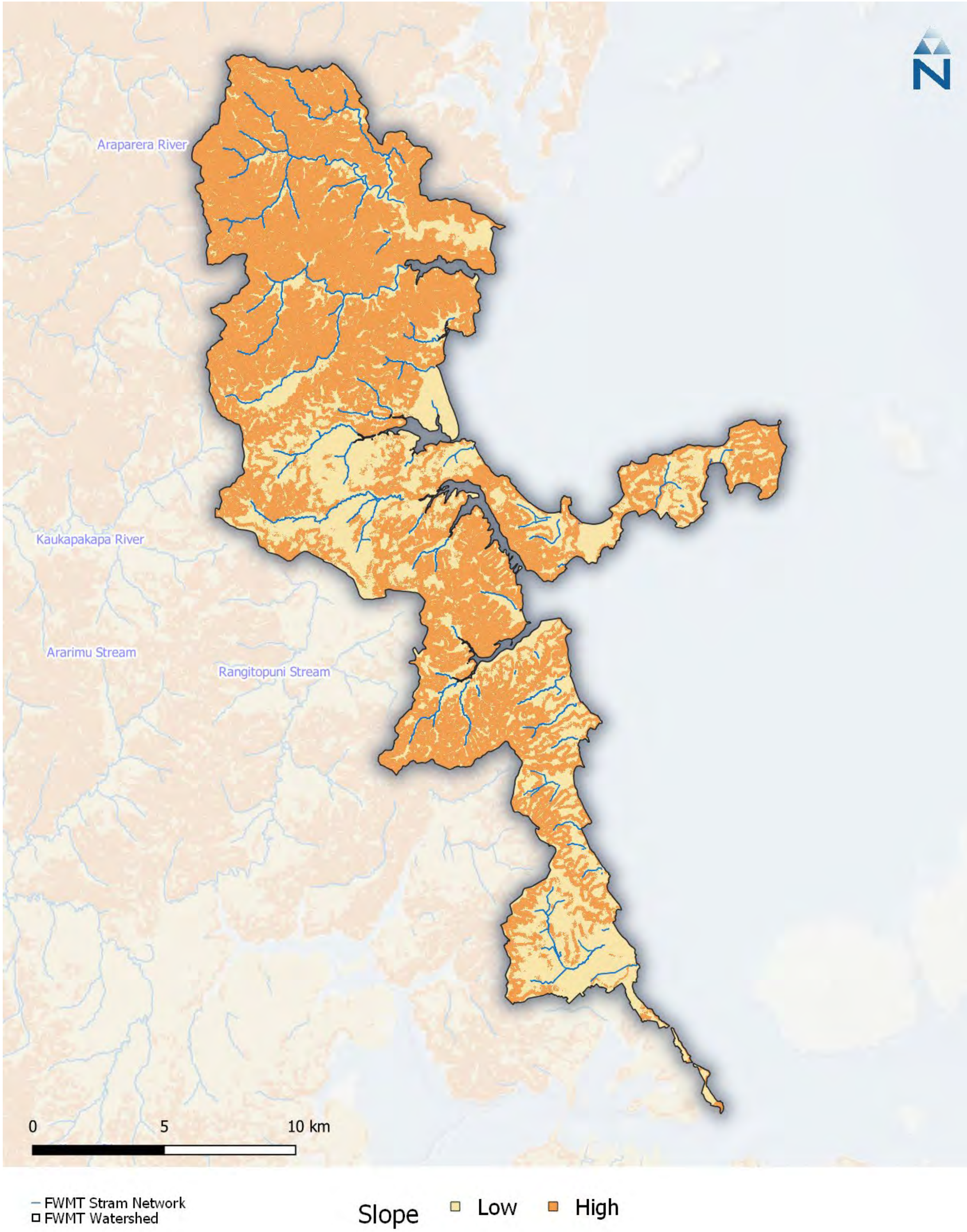


Figure 3-16. Map showing slope classifications for the Hibiscus Coast watershed. Derived from regional 2-m LiDAR DEM

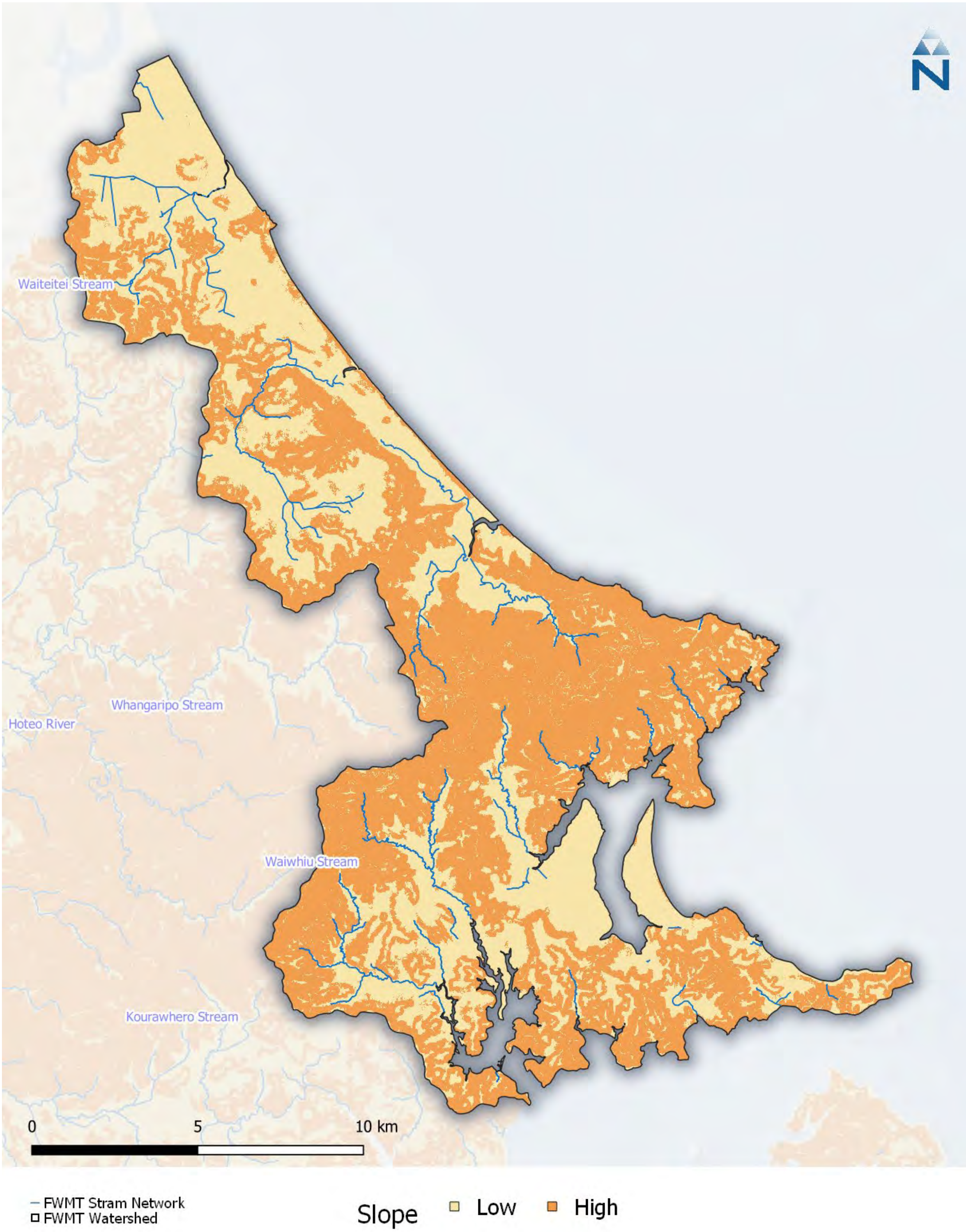


Figure 3-17. Map showing slope classifications for the Northeast Coast watershed. Derived from regional 2-m LiDAR DEM

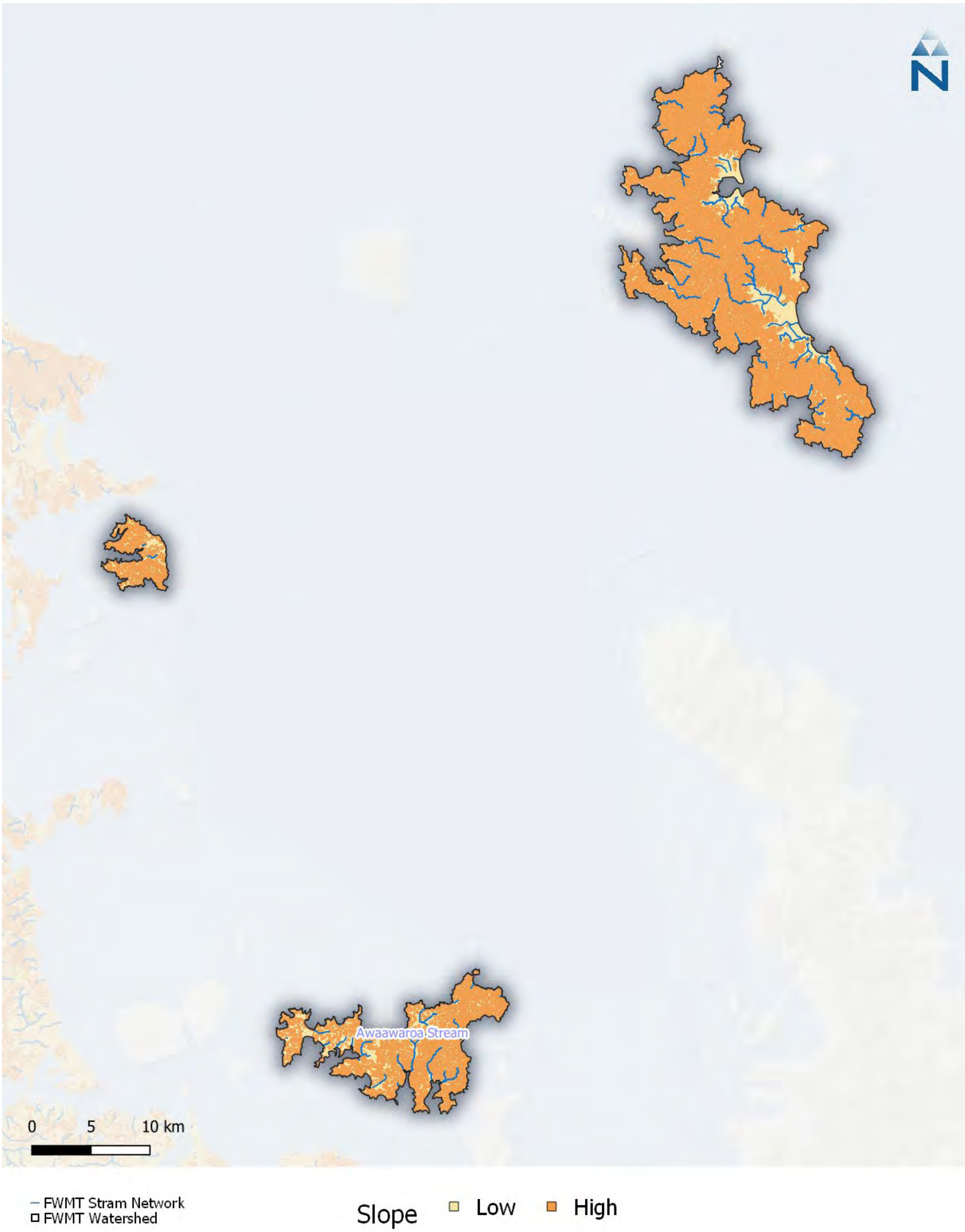


Figure 3-18. Map showing slope classifications the Hauraki Gulf Islands watershed. Derived from regional 2-m LiDAR DEM

Figure 3-19. Map showing slope classifications for Mahurangi Estuary watershed. Derived from regional 2-m LiDAR DEM

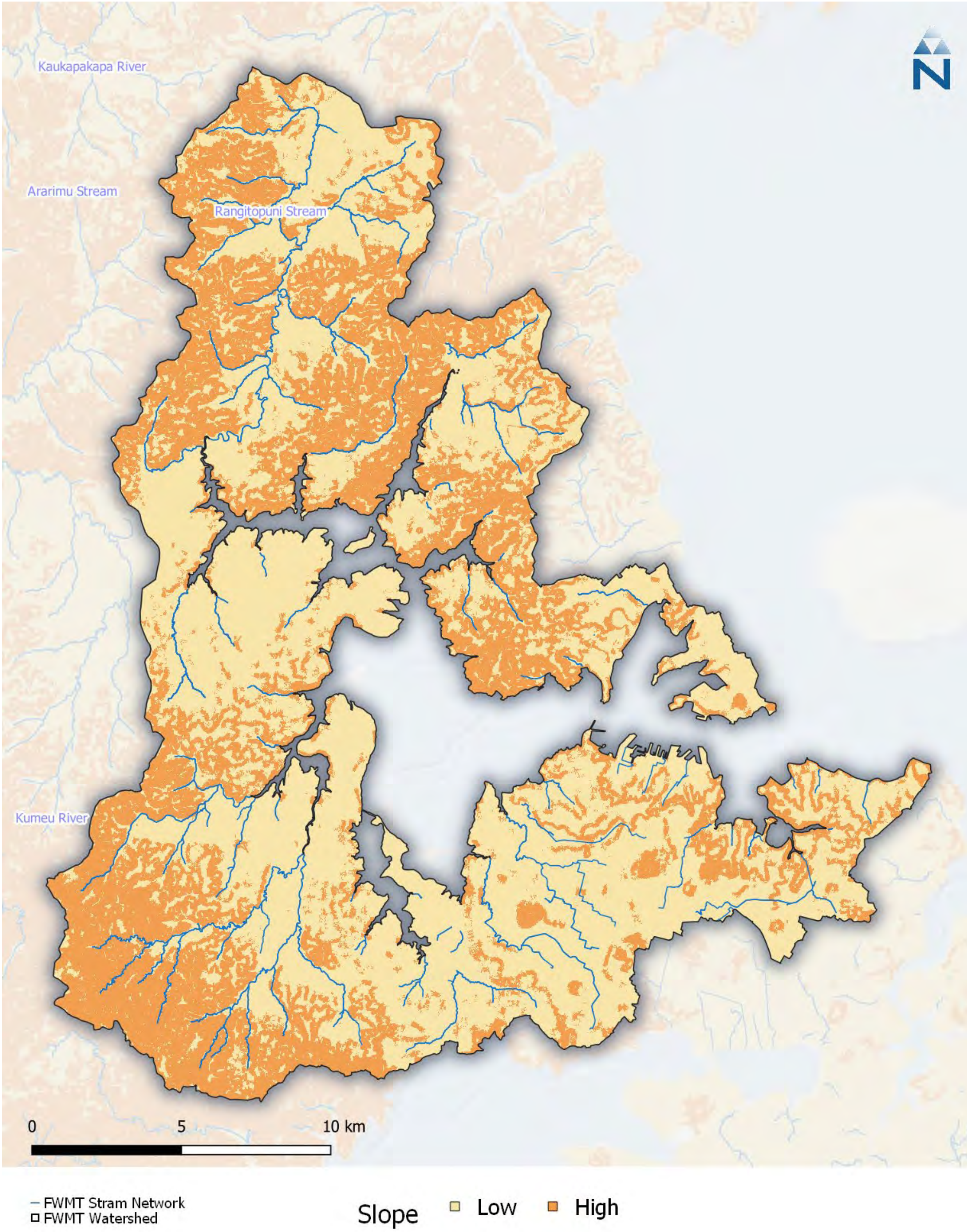


Figure 3-20. Map showing slope classifications for the Waitematā Harbour watershed. Derived from regional 2-m LiDAR DEM

Figure 3-21. Map showing slope classifications for the West Coast watershed. Derived from regional 2-m LiDAR DEM

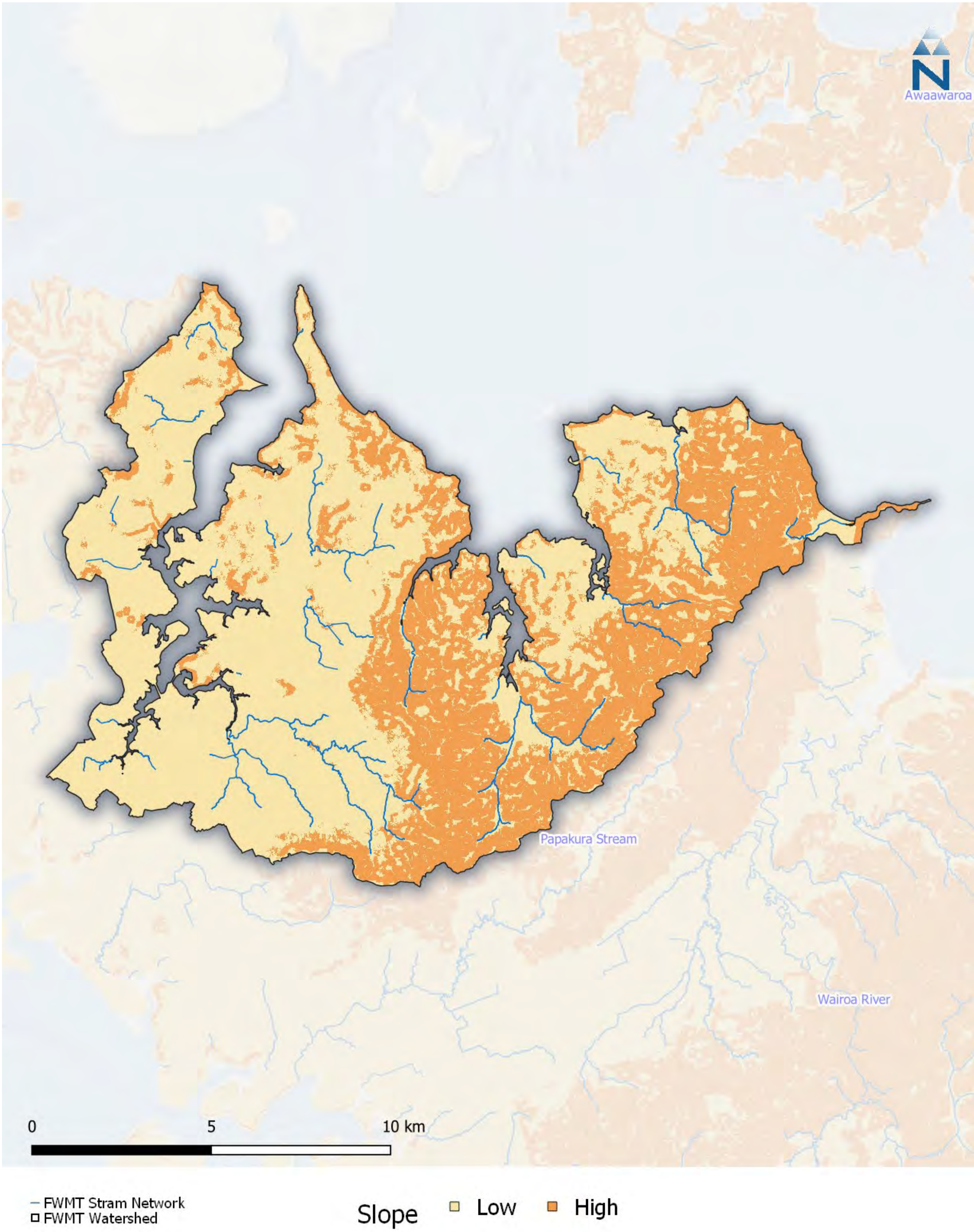


Figure 3-22. Map showing slope classifications for the Tamaki Estuary watershed. Derived from regional 2-m LiDAR DEM

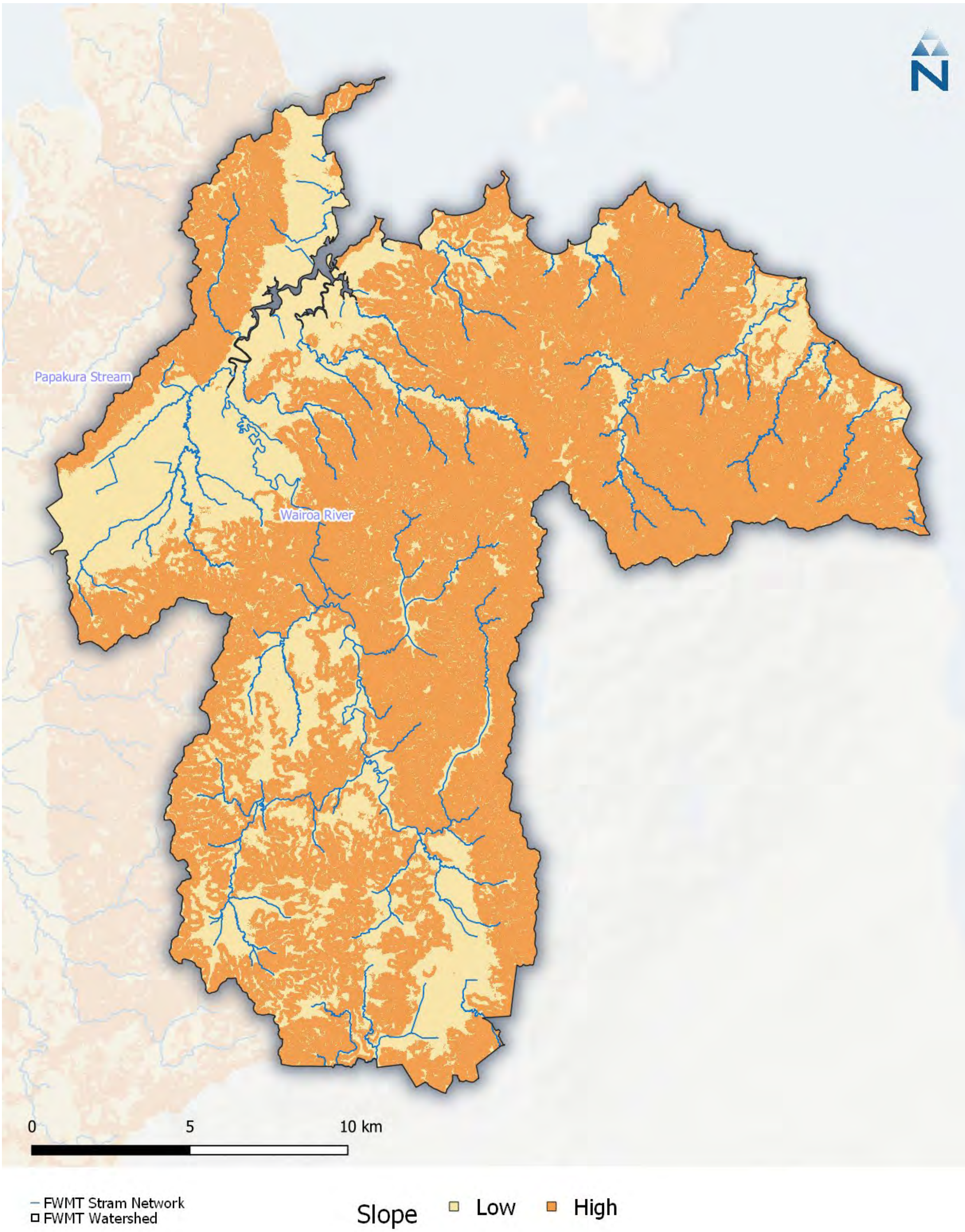


Figure 3-23. Map showing slope classifications for the Wairoa Coast watershed. Derived from regional 2-m LiDAR DEM

Figure 3-24. Map showing slope classifications for the Manukau Harbour watershed. Derived from regional 2-m LiDAR DEM

3.8.3 Land Cover and Use

Land cover and land use data are base layers of HRU development, the data were also used to provide impact attributes, discussed further in Section 3.8.4. Land cover describes the overlying vegetation or impervious cover characteristics (e.g., forest, grasslands, development) while land use describes the functional nature of land cover (e.g., type of impervious cover, use of open space, type of agriculture). Table 3-10 presents the sources of land use and land cover data used to develop the classes within the HRU raster layer for the FWMT Stage 1.

The FWMT existing land use layer incorporates information from 2008-2018, to create a regional and continuous layer at parcel resolution for rural coverage and sub-parcel resolution for urban coverage. This dataset was developed using the best available information from a range of organisations and institutions, including the prior Auckland Regional Council, current Auckland Council, crown research institutes, central Government, and crown agencies. Datasets were cross-referenced with orthophotography via a sub-sampling approach involving each polygon being assigned a land use code and surface type before comparison to aerial imagery. Detailed quality control processes are further explained in [FWMT Baseline Data Inputs Report, Section 8.3].

The land cover dataset was used during HRU development to distinguish pervious from impervious surfaces. Generation of an impervious layer within the FWMT was essential both for driving hydrological and contaminant processes and to ensure capability to target management options (i.e., specific to impervious surfaces within later “scenario” modelling such as altered roofing material, impervious extent, road-sweeping, raingardens). With the high level of spatial detail provided in the dataset (Figure 3-25), the surface type attribute was used directly to represent different types of impervious cover. The FWMT impervious surface extent is an amalgam of information from developed impervious, building outlines, roofing layers, primary parcels, and road centrelines. The FWMT open space HRU is also a combination of several land use categories of both urban and rural activity[7]. Those categories were derived using the sources in Table 3-10 with all “open space” distinguished from “pasture” by Agribase descriptions (i.e., ungrazed and grazed, respectively). In the few instances where

[7] Open space includes land parcels classes as “exotic grassland”, “native grassland and conservation”, “tourism areas”. “ungrazed high producing exotic pasture”, “pervious grasses <50cm”, “pervious grasses <50cm/exotic forest/plantations”, “pervious grasses <50cm/exotic grassland”, “pervious grasses <50cm/native grassland and conservation”, “pervious grass <50cm/pervious”, “pervious grass <50cm/tourism areas”, “pervious grasses <50cm/ungrazed high producing exotic pasture”, “pervious vegetation >50cm/exotic grassland”, “pervious vegetation >50cm/native grassland and conservation”, and “previous vegetation >50cm/native grassland and conservation”.

Agribase polygons reported stocking density of grazed land, but whose LCDB4 class was not exotic producing grassland, the underlying polygon was not classed as a pastoral HRU for accounting purposes but was assigned the corresponding pastoral HRU parameters (e.g., low or high impact).

Figure 3-26 depicts a conceptual overlay of the components used to derive impervious and pervious land cover and the additional refinement to the pervious dataset for impact. The figure shows the relationship between the land cover components and describes the process for integrating these different components into a single rasterized layer describing land cover and impact. Figure 3-27 through Figure 3-36 show combined, generalised land cover and land use map for the 10 watersheds.

Table 3-10. Summary of input datasets used to describe land cover and impact for the FWMT

Type	Data	Description	Data Source	Data type	Date represented
Cover	Developed Impervious	Impervious surfaces mapped for urban areas, expansion areas and some rural catchments draining to urban	Auckland Regional Council (ARC)	Polygon feature class	2008
Cover	Building Outlines	Roof outline of buildings	Land Information New Zealand (LINZ)	Polygon feature class	2008/10*
Cover	Parcel boundaries	Primary Parcel boundaries	LINZ	Polygon feature class	2017
Cover	Road centrelines	Road centrelines	LINZ	Polyline feature class	2017
Cover	Land cover database (LCBD4)	Classification of land cover	Landcare Research	Polygon feature class	2012/13
Cover	Vegetation Height	Regional Li2006/10DAR	Auckland Council (AC)	Raster	2006-2010
Impact	Auckland Unitary Plan Base Zones	Zoning information	AC	Polygon feature class	2016
Impact	Agribase	Land use	Agribase	Polygon feature class	2015/16*
		Animal counts			2015/16*

Type	Data	Description	Data Source	Data type	Date represented
Impact	District Valuation Roll (DVR)	Construction material of roofs	AC	CSV	2018
Impact	Traffic Data	Annual average daily traffic	RAMM Software Ltd (RAMM)	Polyline feature class	2017

*2008 supplemented by 2010 North Shore City building outlines
**Datasets included within Agribase layer whilst valid for the 2015/16 period include information from prior surveys.

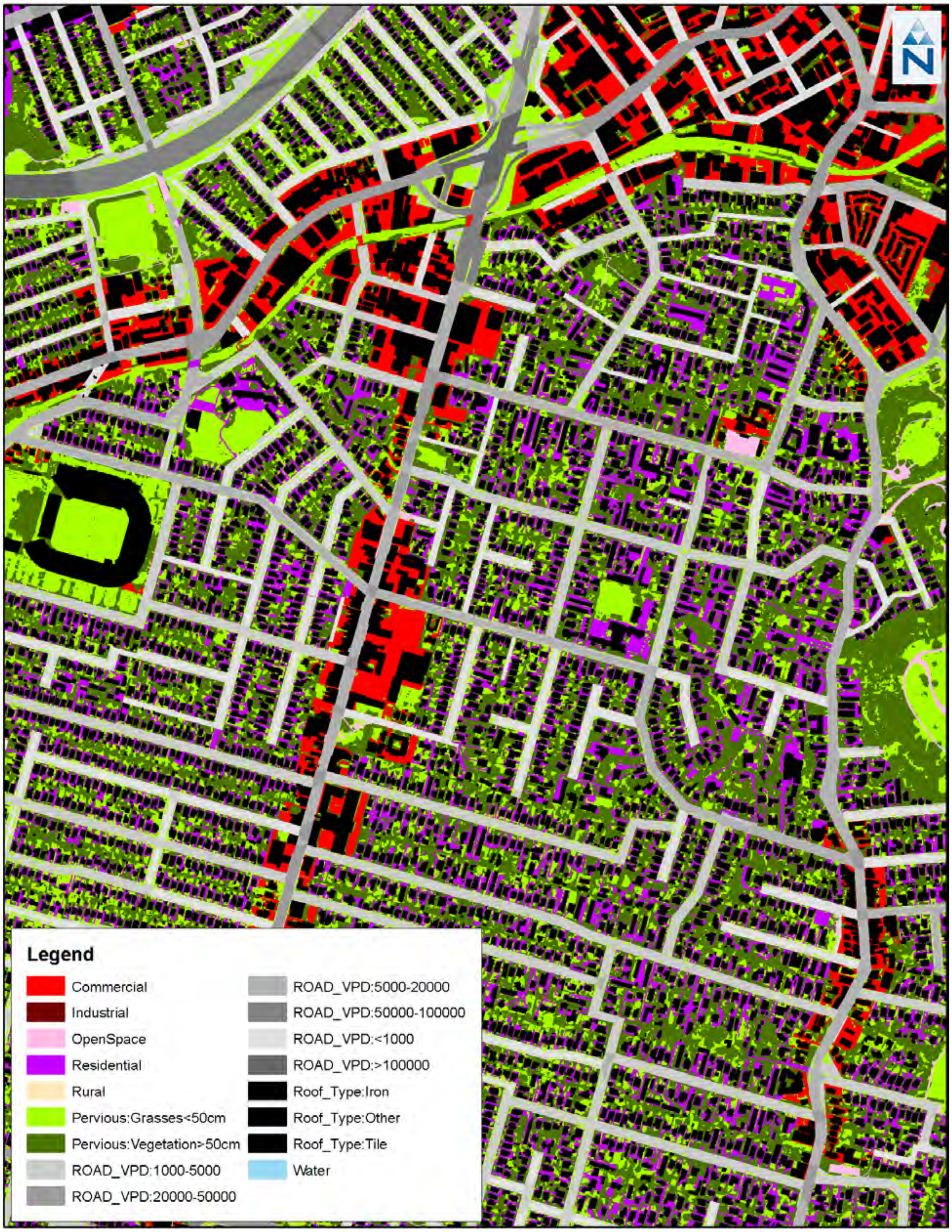
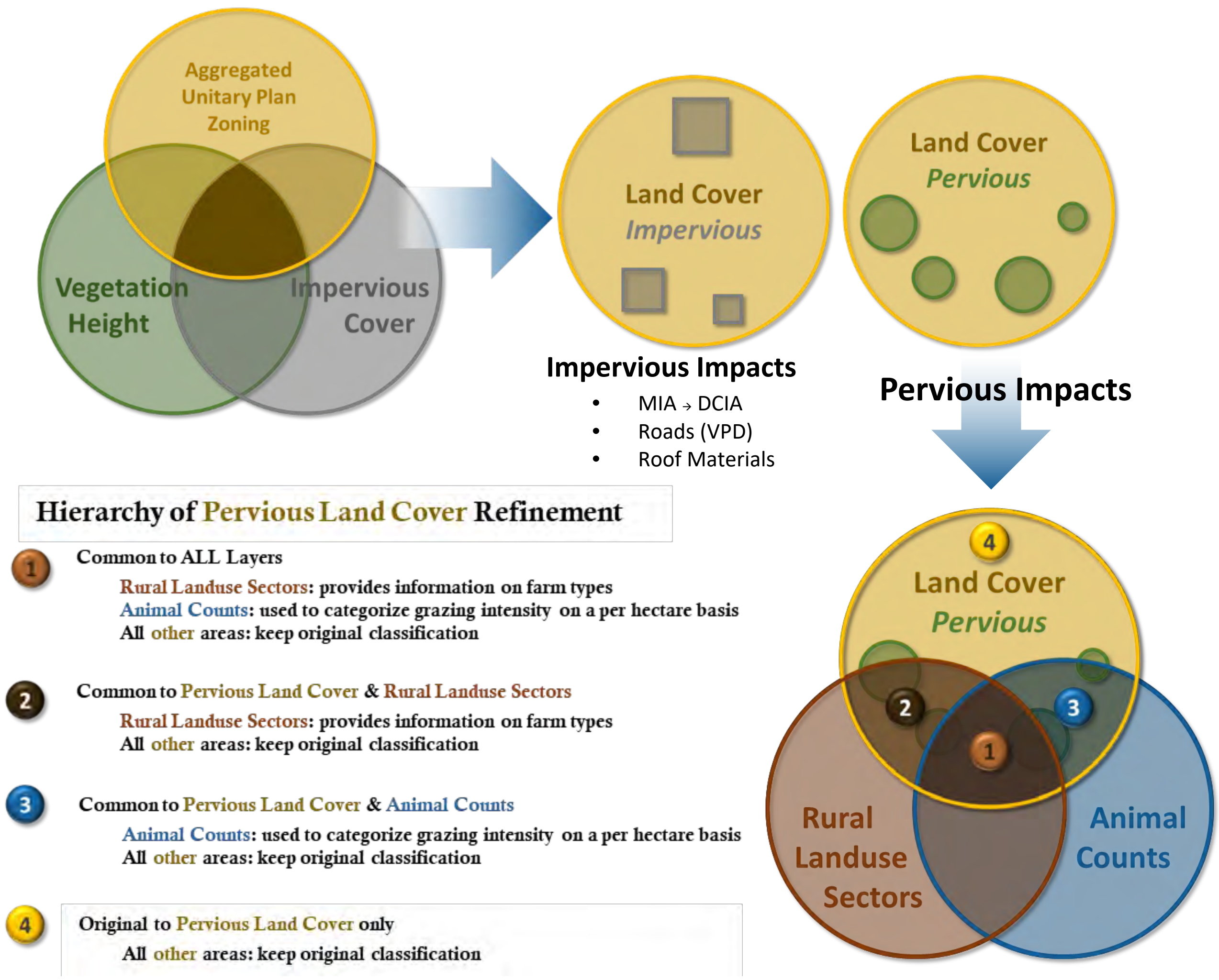


Figure 3-25. Land cover including impervious surface categories for a location in Waitematā Harbour watershed



Conceptual – Not to Scale

Figure 3-26. Conceptual diagram of HRU land cover reclassification process, including refinement of pervious land cover

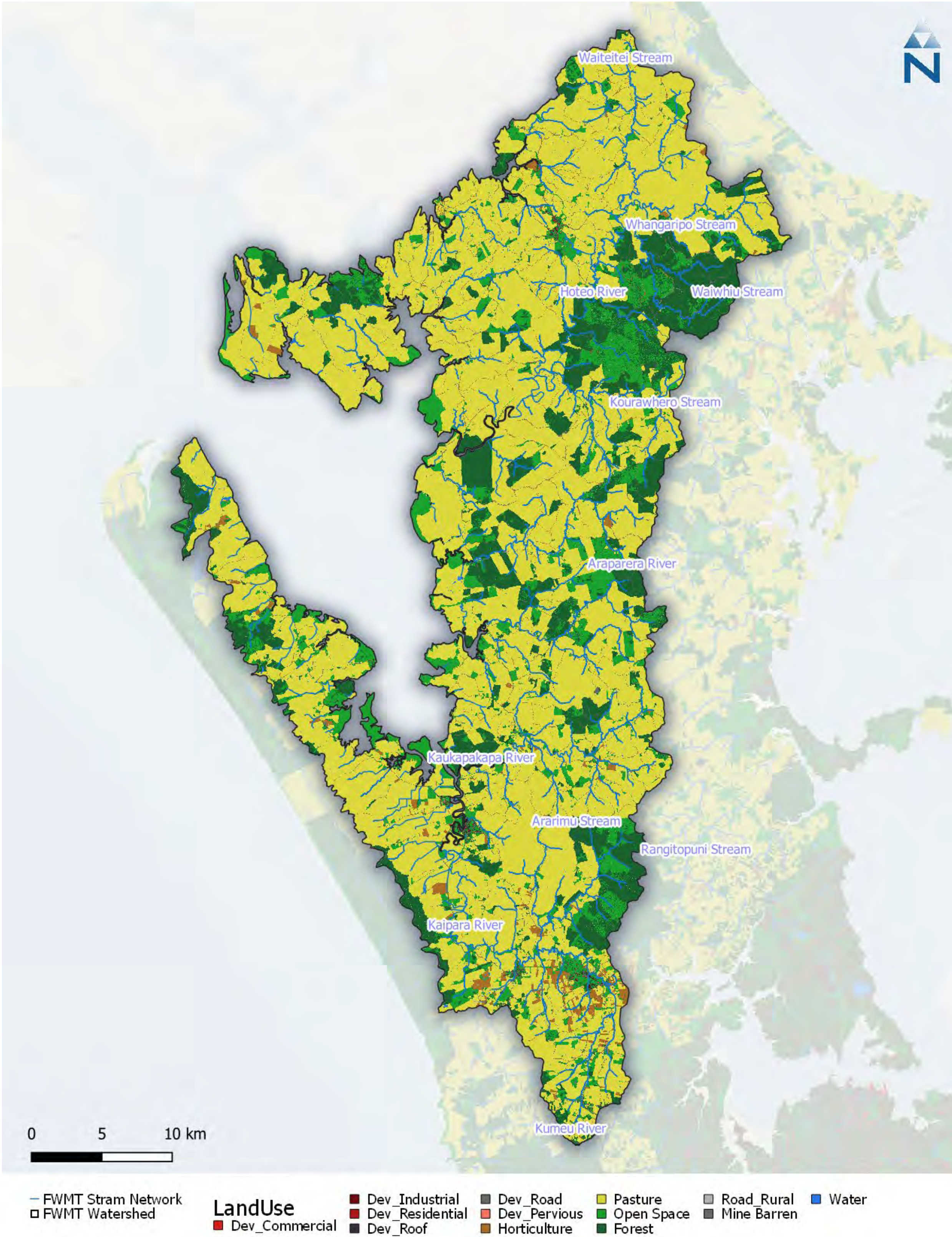


Figure 3-27. Combined major categories based on the land cover and land use datasets for the Kaipara Harbour watershed

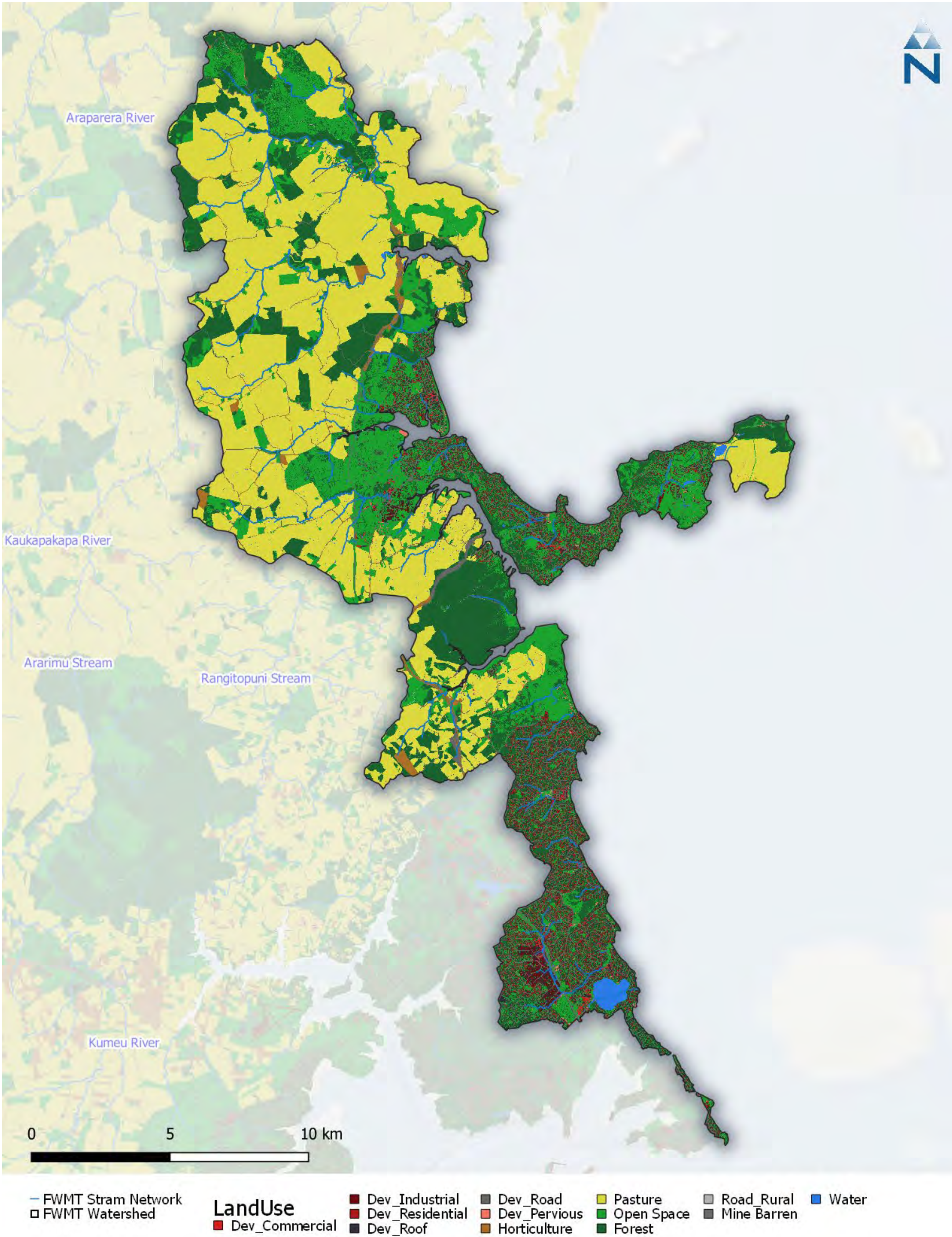


Figure 3-28. Combined major categories based on the land cover and land use datasets for the Hibiscus Coast watershed

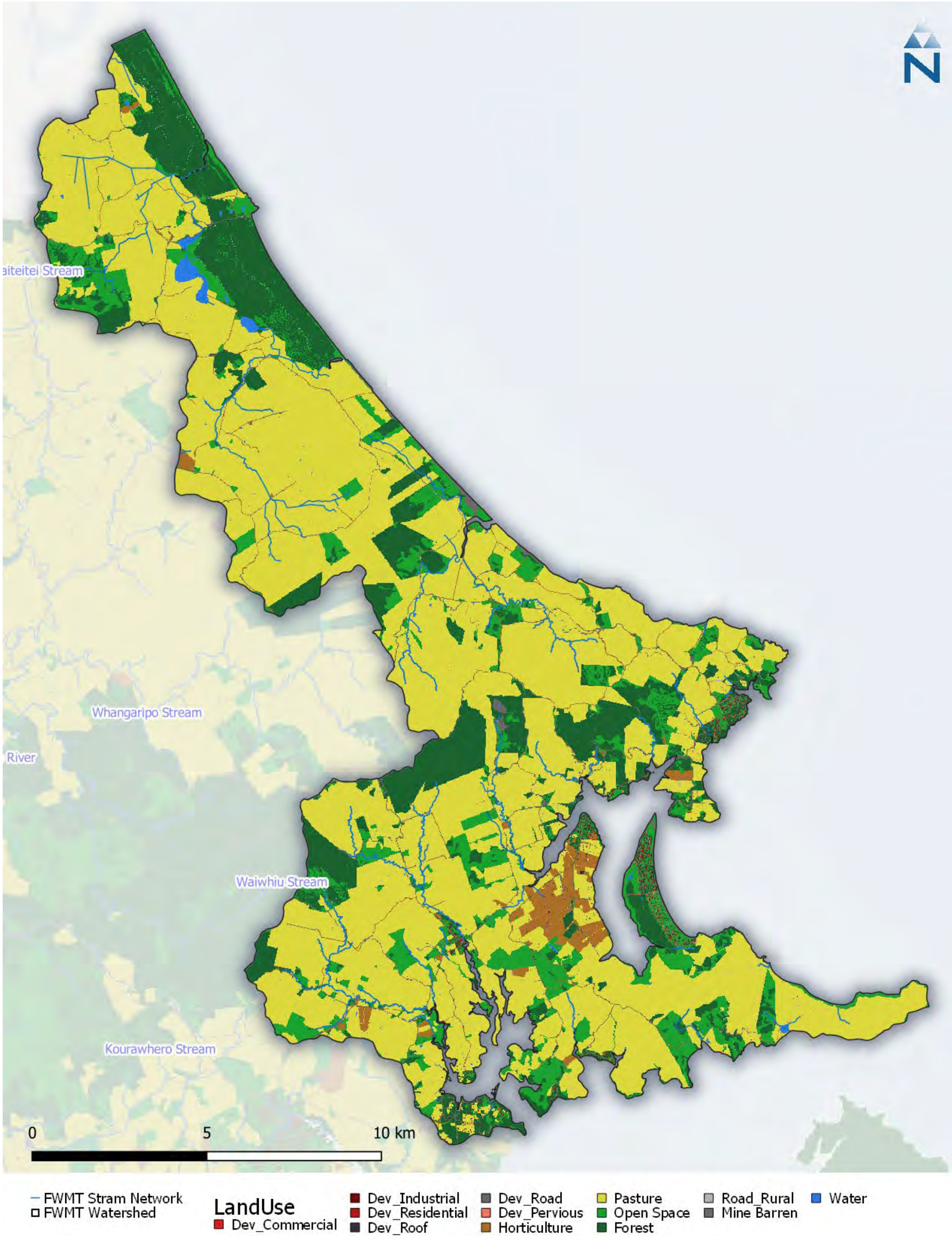


Figure 3-29. Combined major categories based on the land cover and land use datasets for the Northeast Coast watershed

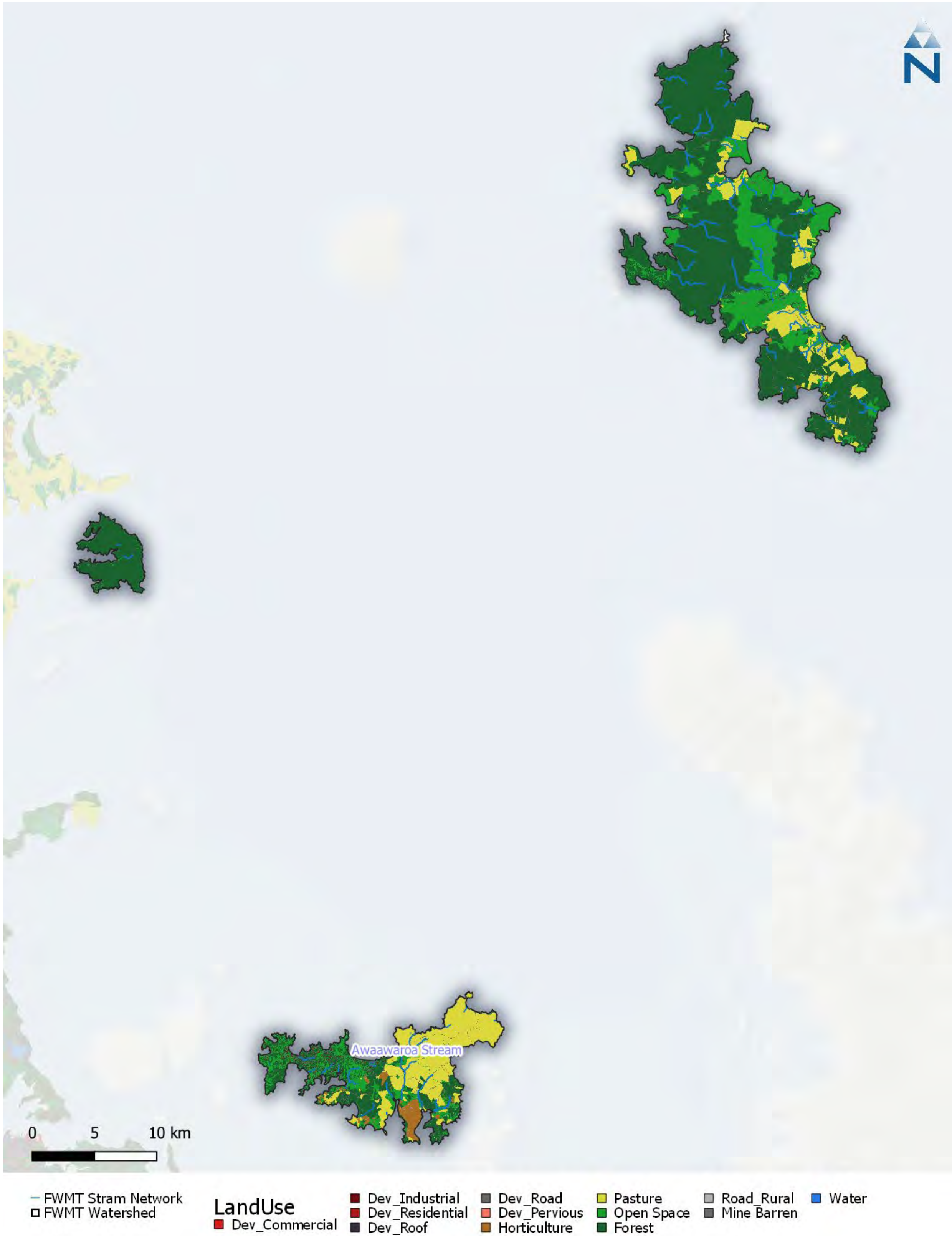


Figure 3-30. Combined major categories based on the land cover and land use datasets for the Hauraki Gulf Islands watershed

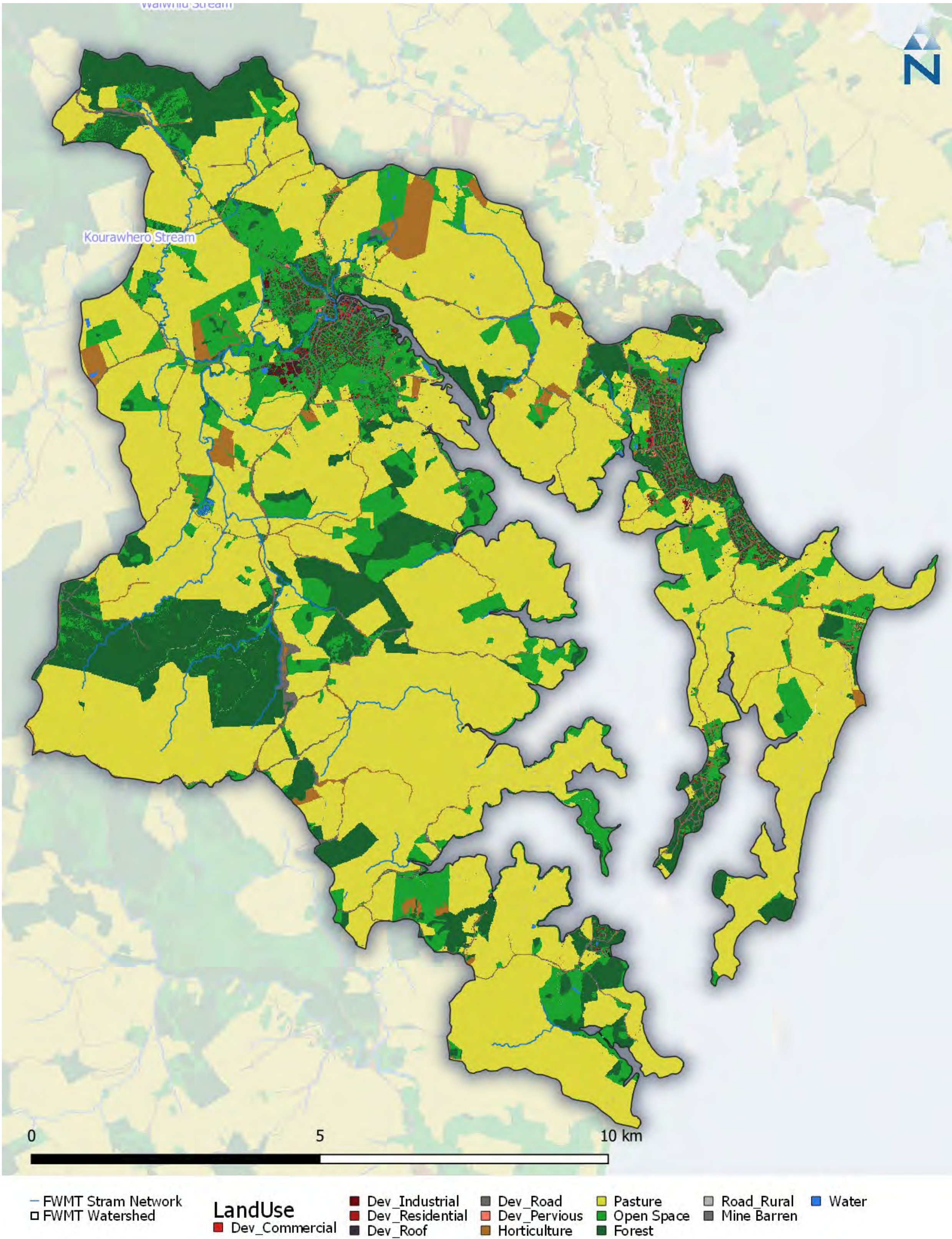


Figure 3-31. Combined major categories based on the land cover and land use datasets for the Mahurangi Estuary watershed

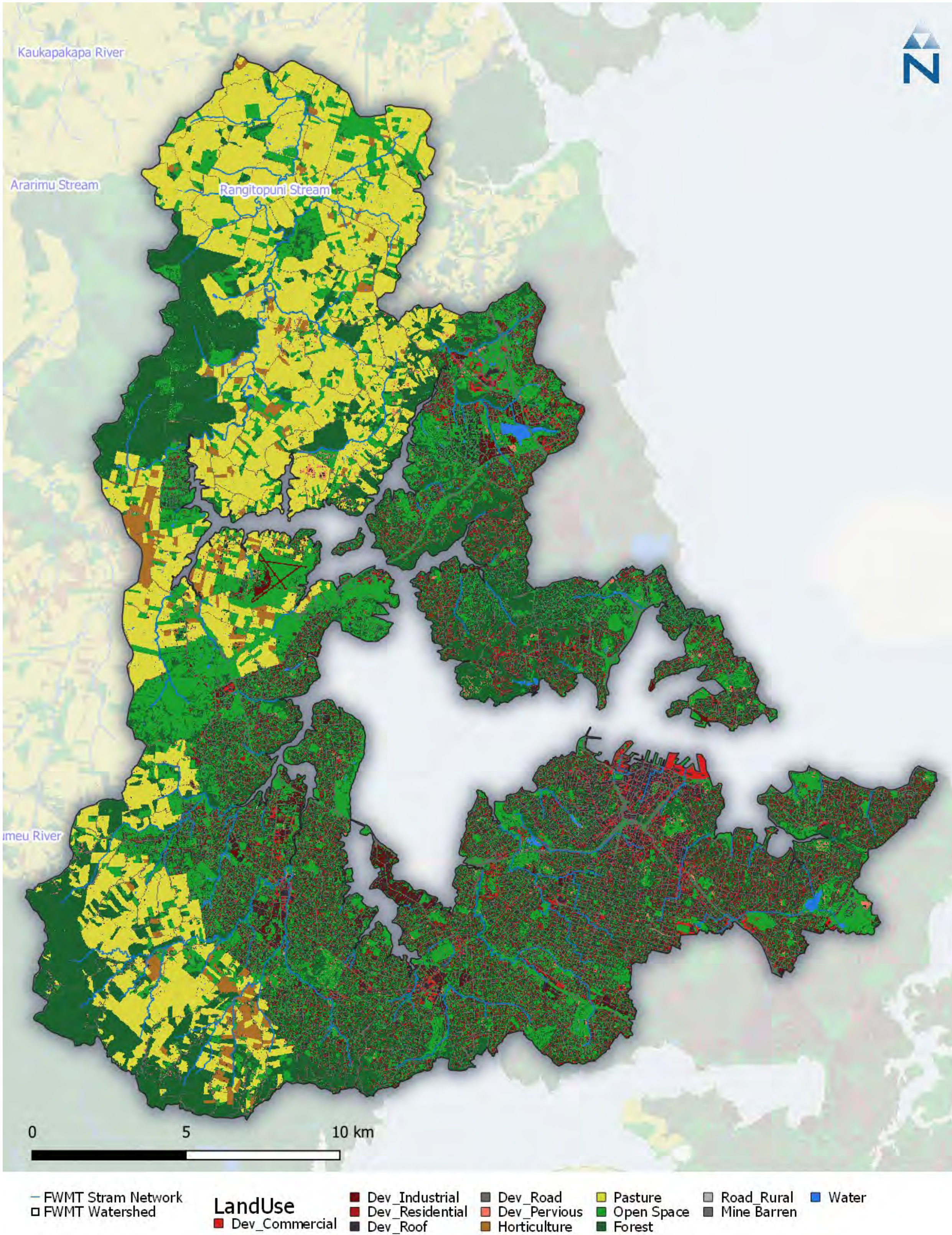


Figure 3-32. Combined major categories based on the land cover and land use datasets for the Waitematā Harbour watershed

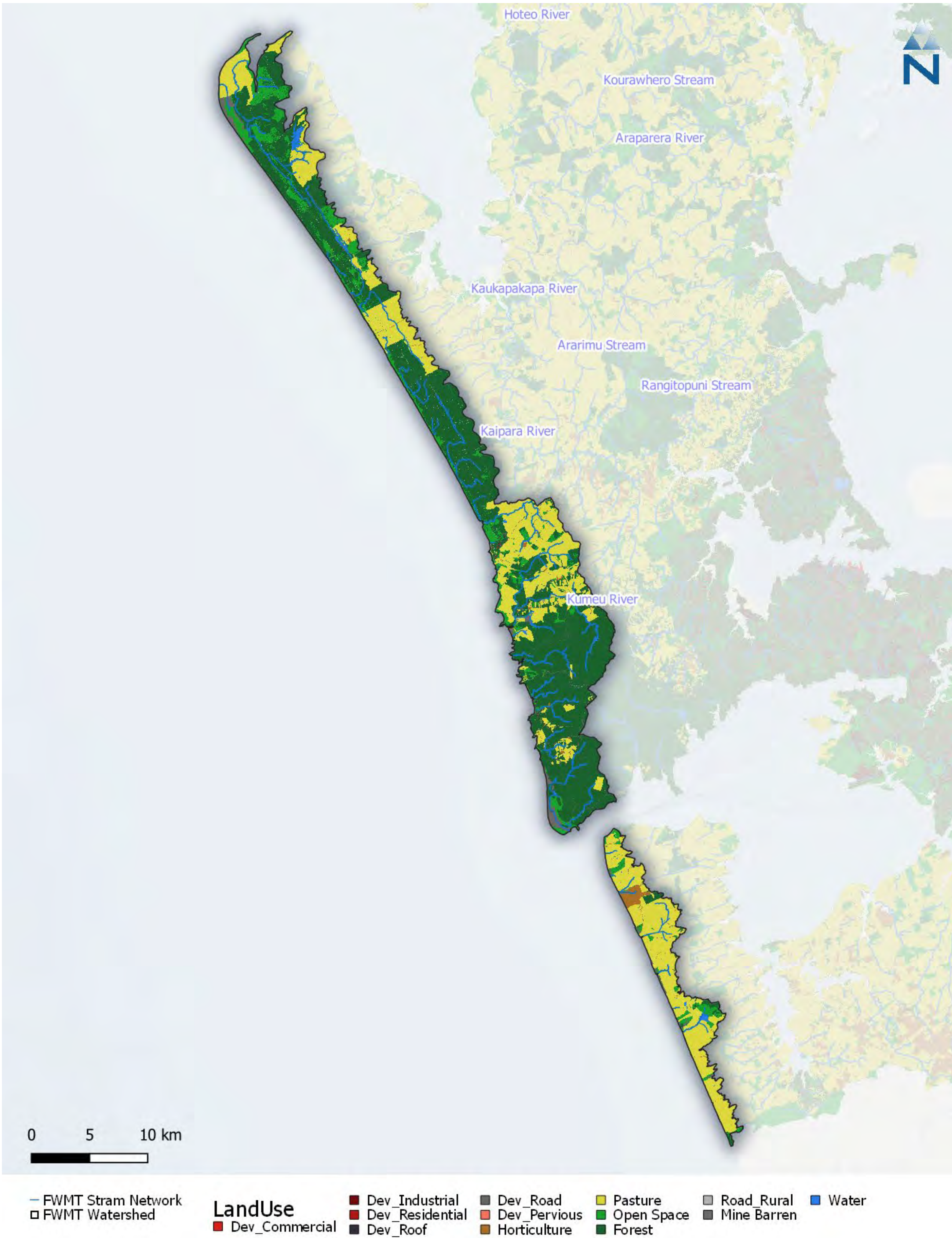


Figure 3-33. Combined major categories based on the land cover and land use datasets for the West Coast watershed

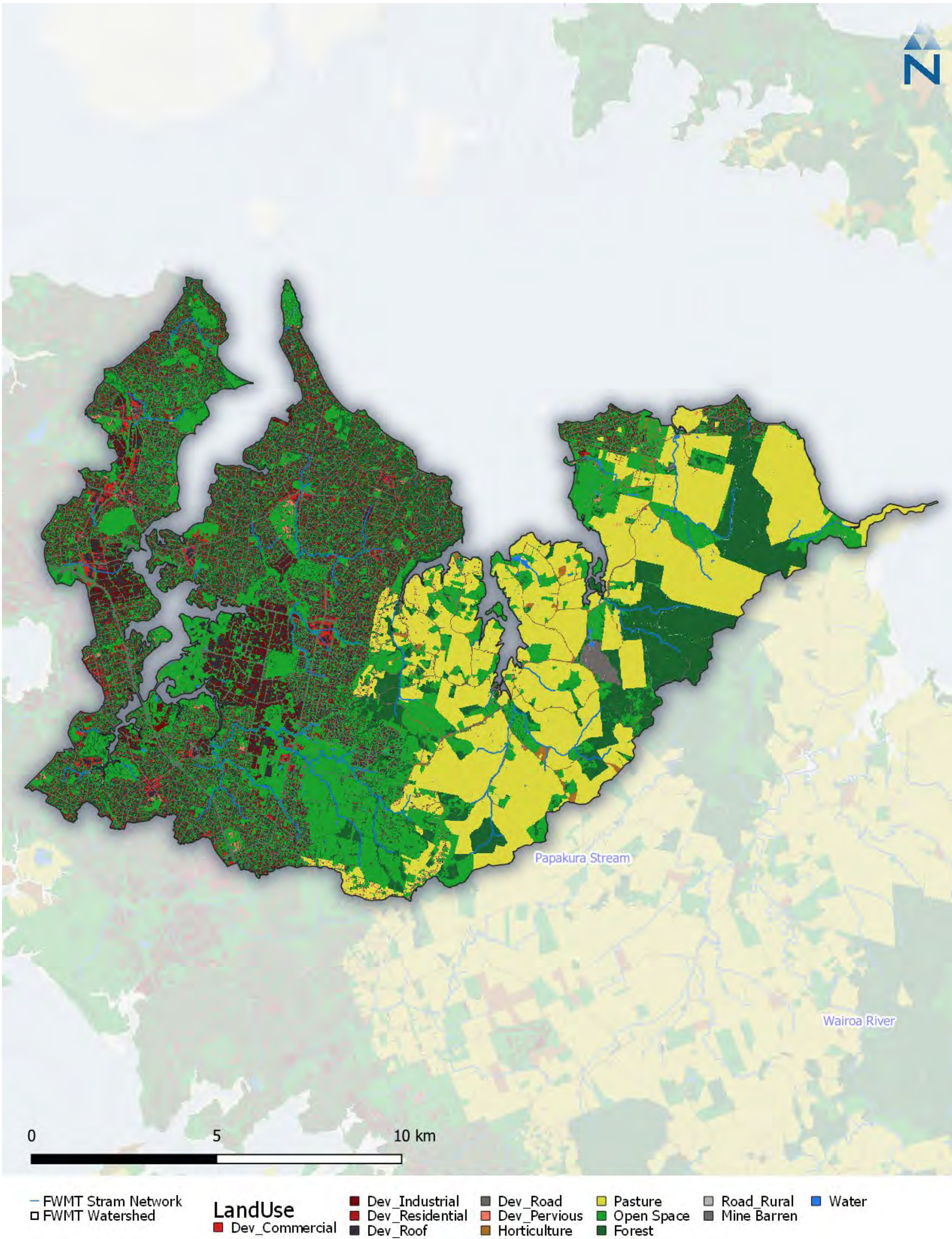


Figure 3-34. Combined major categories based on the land cover and land use datasets for the Tamaki Estuary watershed

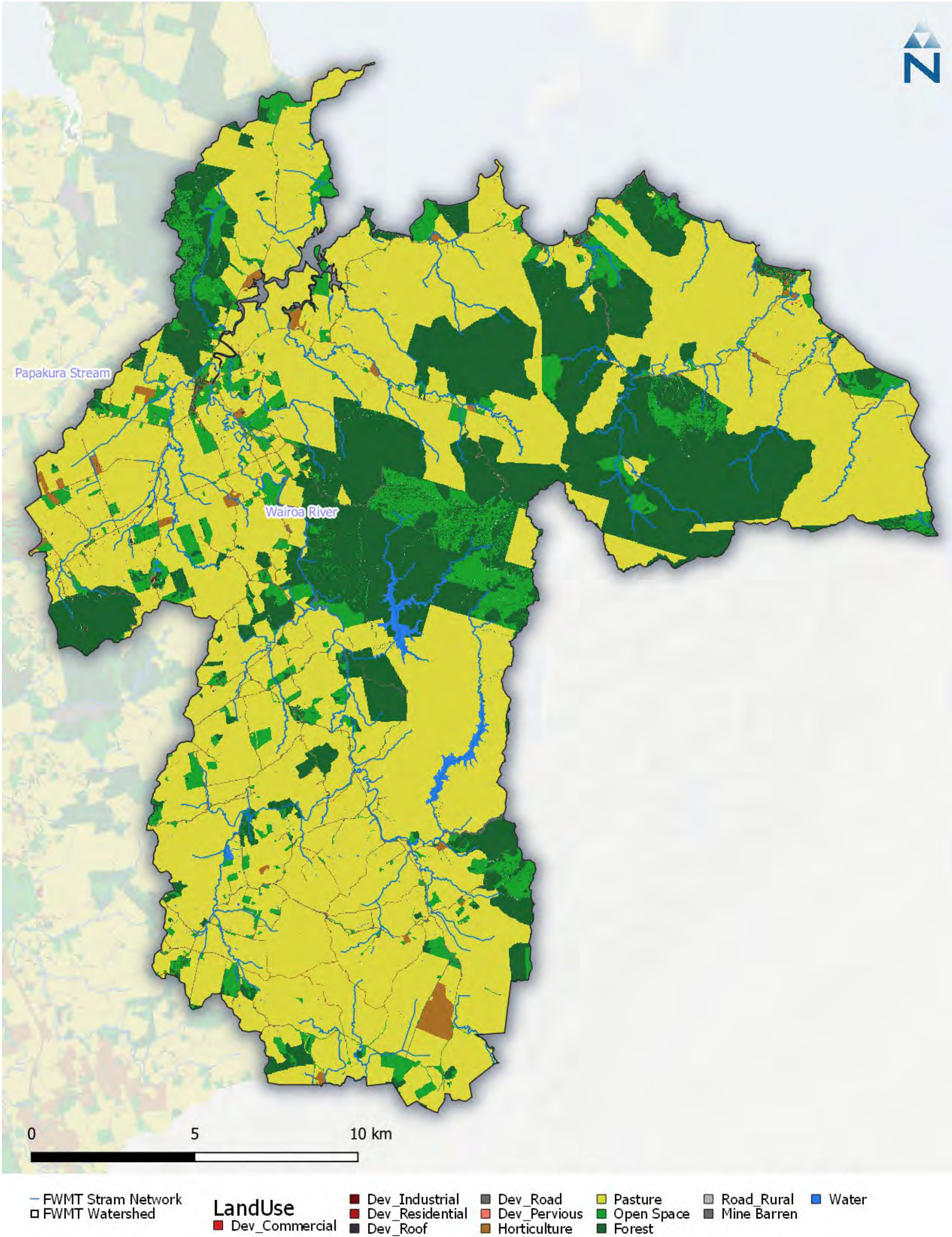


Figure 3-35. Combined major categories based on the land cover and land use datasets for the Wairoa Coast watershed

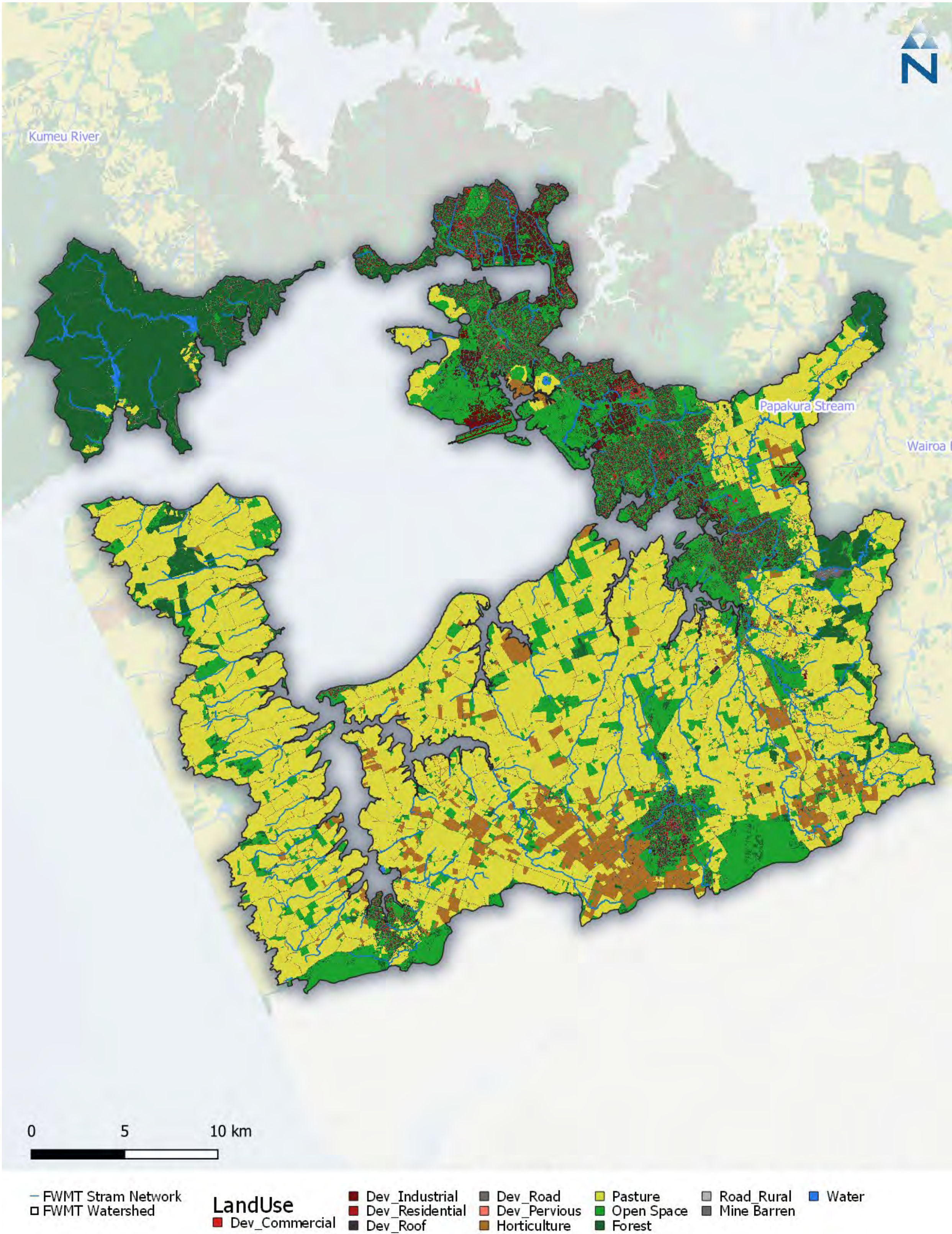


Figure 3-36. Combined major categories based on the land cover and land use datasets for the Manukau Harbour watershed

3.8.4 Impact

HRU impact factors were utilised to vary LSPC processing to better approximate variation in intensity of human activity on pervious and impervious surfaces (Table 3-11). Impact factors allow a modeler to distinguish otherwise identical HRUs based on information about the intensity of land use activity. Examples include road HRUs distinguished by traffic intensity and pastoral HRUs distinguished by stocking intensity. During calibration, one or more parameters may be isolated and adjusted within an HRUs impact level to improve agreement between predictions and observations. The adjustments are targeted to pollutant associated parameters, such as the build-up and wash-off of solids on road surfaces, and nitrogen or the phosphorus concentration in soil and groundwater. Impacts factors are used to target pollutant associated parameters as well as parameters that govern the ability of cover vegetation to reduce erosion. As an example of the latter, high impact pasture would be assumed to have a cover crop that is more grazed or trampled by livestock, reducing the ability of the cover crop to slow erosion compared to low impact pasture.

Table 3-11. HRU impact factors and data sources

Landcover	Impact	Description	Data Source	Data type	Date Represented
Impervious	Roof material	Construction material of roofs	Auckland Council District Valuation Roll	Excel file	2018
	Traffic Data	Annual average daily traffic	RAMM	GIS polyline layer	2017
Pervious	Grazing density	Animal counts	Agribase, landcover basemap,	Table	2016
	Horticulture	Crop type	Agribase	GIS polygon layer	2016
	Forestry	Areas with active forestry practices	Agribase	GIS polygon layer	2016
	Onsite Wastewater System Risk	Risk of discharge of contaminants from septic tanks	Auckland Council	GIS raster layer	2017

The impact factor levels/classifications (low, medium, high) are assigned through calibration and in turn, affect potency for HRU contaminants associated with sediment in all HRU runoff. Potency represents variation in pollutants sorbed to soil, including total phosphorus, total copper and total zinc (i.e., quantity of pollutant per quantity of soil; mg/kg). Potency values are supplied in Appendix A. Nitrogen was not associated with soil, therefore the build-up of nitrogen on the surface was adjusted during calibration instead of via altered potency, but again through a tiered approach (e.g., greater build-up rate on higher impact HRUs).

Impact factors varied groundwater and interflow concentrations of TP and TN, discussed further in Section 3.10. The subsections below provide further details on the impact factors used in the FWMT Stage 1. Notably, in future-state modelling, HRU impact factors also enable discrimination of varying lifecycle costs, contaminant benefits and/or mitigation opportunity between equivalent activities. For instance, variation in riparian management on pastoral HRUs, between drystock farming “low impact pasture” and beef finishing or dairying “high impact pasture”.

3.8.4.1 Impervious Surfaces – Roof material

Roof surfaces impact the volume and quality of stormwater generated by impervious surfaces in New Zealand (Kingett Mitchell Ltd., 2003). Data from the 2018 District Valuation Roll were used to assign roof material types to the LINZ building outlines layer, the building footprints were assumed to be coincidental with building roofs. Impact categories (Table 3-12) were assigned based on water quality observations for roof runoff in Auckland (Kingett Mitchell Ltd., 2003). Within each impact category, the sediment potency factors for zinc were adjusted to reflect greater (lesser) loading of high (low) impact of the roof type. A full list of potency factors can be found in Appendix A. Additional information on the data source processing can be found within the [FWMT Baseline Data Inputs Report, Section 8.3.1.2].

Table 3-12. Roof material impact classification

Roof Material	Impact
Concrete/Tile/Iron, Painted	Low
Iron, Zn-Al alloy coated	Medium
Iron, Unpainted	High

3.8.4.2 Impervious Surfaces – Traffic

Annual average daily traffic data were used to assign an estimate of vehicles per day to roads within the FWMT Stage 1. Impact categories (Table 3-13) were assigned based on relative differences in vehicles per day. Within each impact category, the build-up and wash off parameter values for copper were adjusted to reflect the impact of the road type. Additional information on the approach can be found within the [FWMT Baseline Data Inputs Report, Section 8].

Table 3-13. Traffic impact classification

Vehicles per day	Impact
< 1K	Very Low
1K-5K	Low
5K-20K	Low-Medium
20K-50K	Medium-High
50K-100K	High
≥ 100K	Very High

3.8.4.3 Pasture – Grazing density

The intensity of pastoral grazing can impact the quality of stormwater generated from pervious surfaces in New Zealand (Clothier et al., 2007; Gentile et al., 2014; Menneer, et al., 2004). Figure 3-37 presents the classification of pastureland into low and high impact factors. A threshold of 10 livestock units (LSU) per hectare was used. This threshold was based on a review of existing data and literature, including the online benchmarking tool provided by Beef and Lamb New Zealand (Beef and Lamb New Zealand, 2019) as well as a review of sheep and beef cattle production systems, including those using intensive management (Morris, 2013). For nitrogen, the build-up and wash off parameter values were logically adjusted within each impact category during calibration to improve agreement between observations and predictions (e.g., increased with higher impact class). Since phosphorus is simulated as a sediment bound nutrient in LSPC, the phosphorus potency factors were logically adjusted to improve agreement between observations and predictions. Additionally, groundwater TN and TP concentrations were adjusted based on impact factor and observed stream concentration (See Section 3-10).

Quantitative data from Agribase (2015/16) on both areas of grazed land per property parcel was overlain on pasture areas delineated in the FWMT land cover/use dataset (Section 3.8.3). When the Agribase polygon was smaller than the FWMT pasture area (parcel), the stocking density information applied to the pastoral parcel area falling within the Agribase polygon; the remaining pasture parcel was assigned to the low intensity impact factor. When the Agribase polygon containing stocking data was larger than the available FWMT pasture area, the grazing data was normalised to the available FWMT pasture area. Finally, there were some instances when grazing density data was available for an Agribase polygon, but the underlying property area was not classified as "pasture" in the FWMT land use/cover layer (i.e., remaining "open space"). Instead, equivalent pastoral impact factor (potency and N-build up) were applied to a corresponding area of open space. Table 3-15 presents a summary of the area to which these different scaling approaches were applied. For example 1,548 km^2 of open space had overlapping Agribase data. Of that open space, 64% (991 km^2) was classified as pasture and received "high" impact factor because Agribase data reported stocking >10LSU/ha. Additional information on the land cover and use classifications can be found in the [FWMT Baseline Data Inputs Report, Section 8.3.2.5].

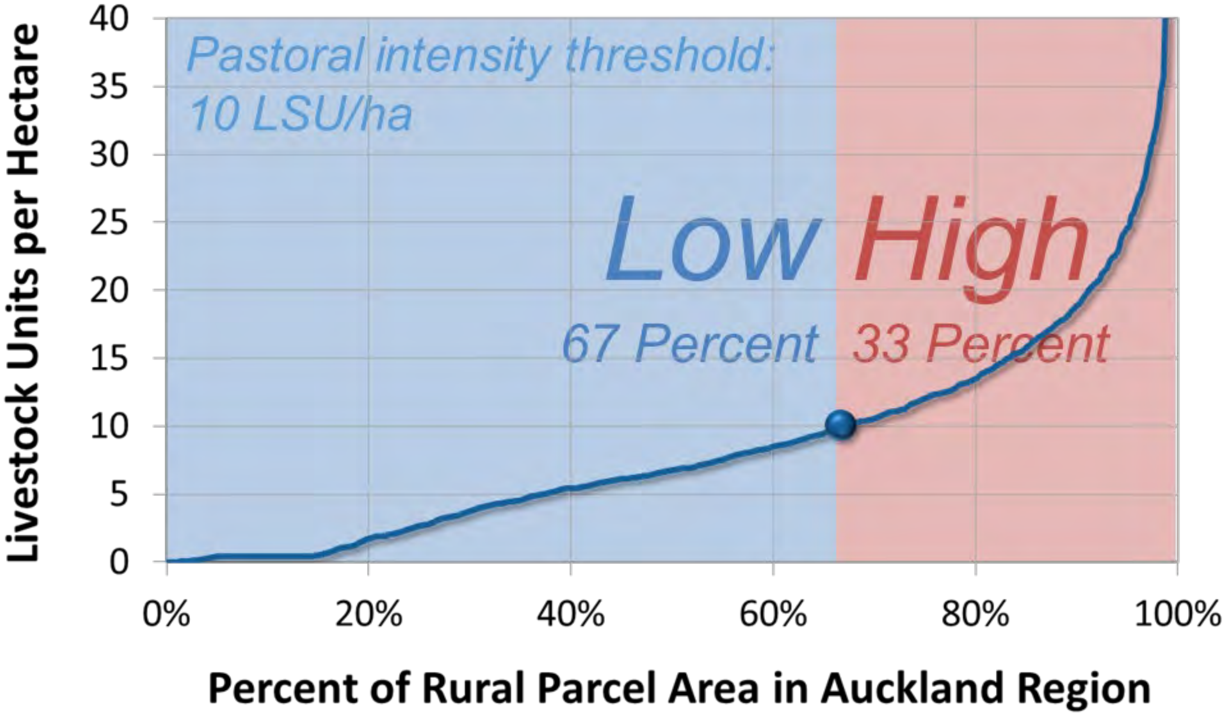


Figure 3-37. Per cent of rural titles by area classified into low and high intensity by livestock unit density (after Agribase, 2015/16)

3.8.4.4 Horticulture – Crop Type

Horticultural crop type can impact the quality of stormwater generated from pervious surfaces in New Zealand (Gentile et al., 2014). Crop type information from Agribase was used to assign horticultural areas specific crop types. Table 3-14 presents the classification of those crop types into impact factors. For nitrogen, the build-up and wash off parameter values were adjusted within each impact category to reflect the expected impact. Since phosphorus is simulated as a sediment bound nutrient in LSPC, the potency factors were adjusted within each category to reflect the relative differences. Additionally, groundwater TN concentrations were adjusted based on horticulture impact factor and observed stream concentrations (See Section 3.10). The FWMT Stage 1 is currently limited in its ability to simulate the timing and intensity of fertilizer application. While not currently utilised in the FWMT Stage 1, monthly adjusted soil potency factors or monthly adjusted build-up and wash off functions can be defined for various agricultural HRUs and pollutants to account for timing and intensity of fertilizer application.

Table 3-14. Horticulture impact classification

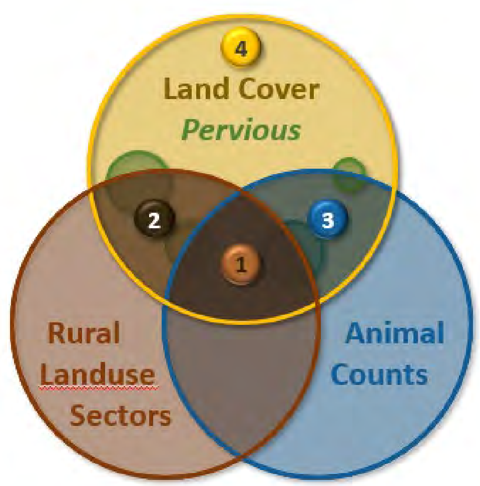
Crop type	Impact
Idle, Orchards, Pervious	Low
Arable land, citrus, fodder, nuts, viticulture	Medium
Berryfruit, flowers, fruit, kiwifruit, pipfruit, stonefruit, other fruit, vegetable, nursery, green houses	High

3.8.4.5 Forest – Forestry practices

Forestry practices can impact the quality of stormwater generated from pervious surfaces in New Zealand (Baillie and Neary, 2015). Forested areas were classified into low and high impact levels based on location data for active forestry operations. Forestry operations were located using Agribase data for 2015/16. The default value for all forested areas identified through the FWMT land use/land cover dataset was Low. Any area overlapping an existing forestry business (identified as “forestry” in Agribase 2015/16) was classified as High. For nitrogen, the build-up and wash off parameter values were adjusted within each impact category to reflect the expected impact. Since phosphorus is simulated as a sediment bound nutrient in LSPC, the potency factors were adjusted within each category to reflect the relative differences. Groundwater TP concentrations were also adjusted with respect to forest impact. Additional information on the approach can be found in the [FWMT Baseline Input Report, Section 8.3.2].

Table 3-15 presents a summary of how impacts were used to refine pervious land and the degree to which the distribution of those impacts were applied with respect to data limitations.

Table 3-15. Refinement of pervious land. Assumption 1 corresponds to aligned Agribase and LCDB, 2 to LCDB only, 3 to Agribase only and 4 to "open space" due to lack of Agribase or LCDB land activity information but that also not classified as impervious



Rural Land Use	Impact	Area (km2)	Area Distribution Assumption			
			1	2	3	4
Forest	Low	1,080	-	-	-	100%
	High	155	73%	27%	-	-
Horticulture	Low	18	-	-	-	100%
	Medium	31	72%	28%	-	-
	High	68	34%	18%	-	48%
Pasture	Low	869	7%	6%	44%	43%
	High	1,548	7%	9%	64%	20%
Open Space	Low	708	13%	2%	-	84%
Total	Percent	100%	10%	5%	25%	60%
	km2	4,477	442	234	1,129	2,672

3.8.4.6 Onsite Wastewater Systems

Onsite wastewater systems (OSWW) facilities (e.g., septic systems), can impact the quality of stormwater generated from pervious surfaces as well as groundwater in New Zealand (MfE, 2008; Chen and Roberts, 2018). A subset of open space areas in sub-catchments without reticulated network access, where potential dwelling structures could be identified (using an overlay of delineated building outlines [FWMT Baseline Data Inputs Report] was converted to OSWW area. The relative risk of contaminant transport from failing systems was also used to estimate the relative OSWW impact area. Using open space, which was abundantly available in rural areas where OSWW were likely to occur, was necessary given that unlike the previous impact factors, there was no explicitly defined land use coverage for OSWW. For nitrogen, phosphorus and *E. coli*, groundwater concentrations for the OSWW HRU were adjusted to reflect the expected elevated impacts. For nitrogen and *E. coli* in overland flow, the build-up and wash off parameter values were also increased relative to open space to represent more surface contaminant loading from leaking or failing systems during runoff events. For phosphorus in overland flow, potency factors were adjusted since phosphorus is simulated as a sediment bound nutrient in LSPC. Additionally, groundwater concentrations of TN and TP were increased in OSWW HRUs to reflect their impact and improve agreement between observed and predicted results.

The OSWW impact HRUs were located in rural areas that did not fall within wastewater network serviced areas. The areas outside of wastewater network serviced catchments are referred to as non-reticulated areas. Thus, OSWW impact HRUs were largely located in rural areas but also some urban non-reticulated areas. Table 3-16 presents a summary of OSWW area by watershed. The OSWW analysis relied on LINZ building outline data Table 3-10 and OSWW risk data. Building outline area was assumed to be coincident with rooftop area. A visual assessment was performed to exclude very large rooftops unlikely to be residential buildings, such as greenhouses. OSWW Risk data was obtained from the Regional OSWW GIS Risk Assessment Tool (Tonkin and Taylor, 2017). The tool was created for Auckland Council to identify communities where there is an elevated likelihood of adverse effects to human health due to on-site wastewater disposal. The tool calculates a risk score based on lot density, building age, slope, and soil type. OSWW Impact was generally located on rural lands, and all rooftops not excluded through visual assessment were assumed to be associated with an OSWW. The OSWW Impact affected wet weather loading through surface, interflow as well as dry weather conditions through baseflow. Figure 3-38 presents a conceptual model of OSWW risk analysis. Table 3-17 presents a summary of OSWW impacts distribution based on the data coverage described in Figure 3-36. The HRU for OSWW Failure Impact Area is considered a subset of the open space land use HRUs. The OSWW area was applied proportionally to well-draining (A+, A, B) and poorly draining soils (C, D). This was necessary to provide area within LSPC for the OSWW impact. The reduction to the open space was minimal, with only 1.7%. of open space being converted to the OSWW impact factor.

Table 3-16. Summary of OSWW Impact Areas by watershed

Watershed	Ha	Per cent of total area
Hibiscus Coast	38.82	5.6%
Hauraki Gulf Islands	9.77	1.4%
Kaipara Harbour	179.65	26.1%
Mahurangi Estuary	24.93	3.6%
Manukau Harbour	159.41	23.1%
North East Coast	49.34	7.2%
Tamaki Estuary	36.06	5.2%
Wairoa Coast	20.43	3.0%
Waitematā Harbour	141.85	20.6%
West Coast	29.30	4.2%

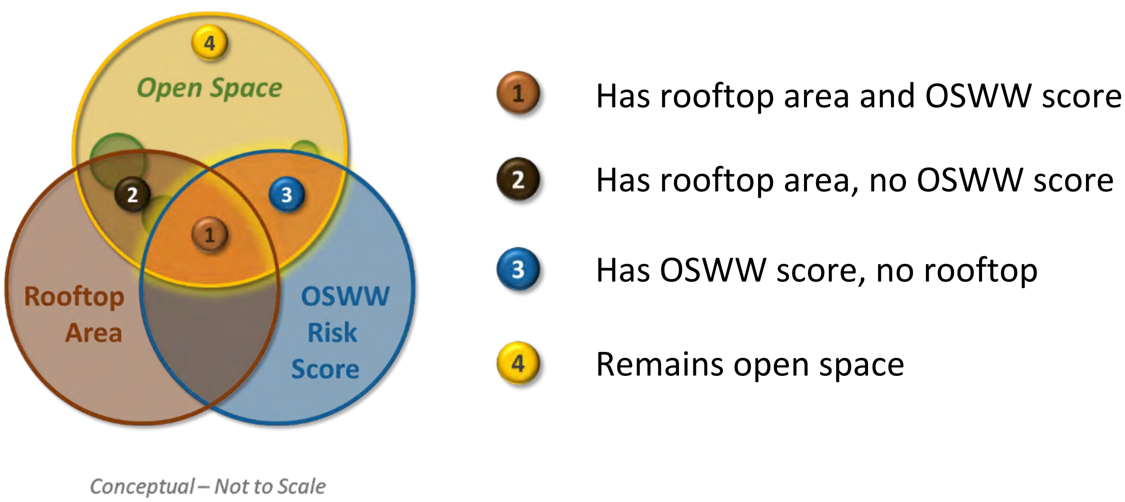


Figure 3-38. Conceptual model for quantifying the impact of OSWW Impact Area

Table 3-17. Summary of OSWW Impact Areas by watershed

Watershed	Condition (Per cent of Pervious Area)				Per cent of total pervious area modelled as OSWW
	1	2	3	4	
Hibiscus Coast	3.4%	0.0%	1.0%	0.7%	0.17%
Hauraki Gulf Islands	2.0%	0.0%	6.5%	0.0%	0.03%
Kaipara Harbour	24.5%	0.0%	6.4%	0.0%	0.13%
Mahurangi Estuary	2.2%	0.0%	0.6%	0.0%	0.20%
Manukau Harbour	9.1%	0.3%	8.0%	1.2%	0.19%
North East Coast	4.4%	0.0%	0.8%	0.0%	0.21%
Tamaki Estuary	1.4%	0.1%	0.7%	1.1%	0.25%
Wairoa Coast	3.3%	0.0%	5.6%	0.2%	0.05%
Waitematā Harbour	4.2%	0.1%	0.6%	2.5%	0.43%
West Coast	2.8%	0.0%	6.1%	0.1%	0.07%
Auckland Region	**57.3%**	**0.5%**	**36.4%**	**5.8%**	0.15%

In non-reticulated areas with both a rooftop area and an OSWW score, OSWW impact area was calculated using the following equation:

$$\text{OSWW Impact Area} = \text{Rooftop Area} \times \text{OSWW Risk}$$

The impact area of an OSWW was assumed to scale directly with rooftop area. The calculated OSWW Impact Area was then created by converting the same amount of open space to OSWW Impact Area. The rooftop layer contained limited data in rural areas, therefore a representative area was calculated in areas with an OSWW score but no rooftop area using the following equation:

$$\text{OSWW Impact Area} = \text{Average Rural Rooftop} \times \text{OSWW Risk Score}$$

Additional information on the approach can be found in the [FWMT Baseline Data Inputs Report, Section 8.3.2.1].

3.8.5 Hydrologic Soil Groups

Hydrologic soils groups (HSG) are used in LSPC to represent soils with different characteristics, particularly, differences in effective infiltration rates. Differing infiltration rates result in differences in the runoff, interflow and active-groundwater response to rainfall on land for various HSGs. In HRU development HSGs are assigned to pervious surfaces only (i.e., impervious surfaces are "sealed" within LSPC, so are unable to represent soil processes on runoff or associated soil-contaminants).

HSGs are based on the U.S. Natural Resource Conservation Service National Engineering Handbook (NRCS, 1997). HSGs are widely adopted to represent the influence of soil infiltration characteristics on the water balance, most notable in Auckland Regional Council TP 108 (ARC, 1999). TP 108 provides guidelines for stormwater runoff modelling and forms the basis for stormwater design in the Auckland Region. The document lists HSGs, along with soil cover, soil treatment, hydrological condition, and antecedent ground conditions as the major factors for determining runoff in catchments in the Auckland Region. The HSGs used in the FWMT are presented in Table 3-18. HSG-A+ has the lowest runoff potential whereas HSG-D has the highest runoff potential. Soil data was obtained from several sources to develop the soil groups (Table 3-19).

Table 3-18. Hydrologic soil group types in the FWMT

Hydrologic Soil Group (HSG)	Drainage description	Infiltration Rate (mm/hr)	HSG Description
A+	Very high infiltration	12.7 - 25.3	Volcanic Geology, medium to high classes soakage areas
A	High infiltration	7.6 - 12.7	Sand, Loamy Sand, or Sandy Loam
B	Moderate infiltration	3.8 - 7.6	Silt, Silt Loam or Loam
C	Low infiltration	1.3 - 3.8	Sandy Clay Loam
D	Very low infiltration	0.0 - 1.3	Clay Loam, Silty Clay Loam, Sandy Clay, Silty Clay, or Clay

Table 3-19. Summary of input datasets detailing the data layer and source for developing soil groups

Preference Order	Data	Description	Data source	Data type	Date represented
1	Volcanic Aquifers	Volcanic Aquifers in the Auckland Region	Research and Evaluation Unit, Auckland Council	Polygon feature class	Technical report, TR2013/040
2	Northern Allochthon	Geological mapping units of all areas in Auckland underlain by the Northern Allochthon	GNS Science	Polygon feature class	2014
3	Soil Drainage Characteristics	Drainage characteristics of soils on different rock types in the Auckland Region	Auckland Regional Council (ARC)	Polygon feature class	1999
4	New Zealand Fundamental Soil Layer (FSL)	FSL classes soil according to fertility/toxicity, physical properties and topography/climate	New Zealand Land Resource Inventory (NZLRI) and National Soils Database (NSD) – Land Care Research	Polygon feature class	1960-2000
5	S-Map	Soil physical properties listed on S-map factsheets	S-Map Online (version 2.0)	PDF	2017

The New Zealand Fundamental Soil Layer (FSL) was used as the primary source of information for classifying soil types into HSGs. The FSL replicates main Soil Type within the New Zealand Land Resource Inventory (NZLRI) and is a single spatial (polygon) layer with national coverage, supplemented with numerous soil survey layers of local coverage. FSL attributes main soils according to topographic, physical and chemical properties. A selection of these properties, including permeability class of topsoil and subsoil, depth to regolith or bedrock, position of water table and the interface with underlying regolith or bedrock, has been evaluated by Auckland Council to group main soil series according to their drainage characteristics. Where soil series were not characterised by drainage properties S-MAP fact sheets on specific soil profiles were instead aligned to HSGs by expert judgement.

While traditional HSG classifications use groups A-D, the HSG layer for the FWMT was modified to include a designation of (A+) for rapidly draining volcanic soils. HSG-D was assigned to all areas underlain by the Northern Allochthon. In urban areas where pervious areas had unknown soil properties in the FSL and excluding volcanic aquifers or soakage areas, HSG-C was applied (e.g., where Permeability = Town to represent compaction resulting from development). Detailed methods for assigning HSGs and infiltration rates are found within the [FWMT Baseline Data Inputs Report Section 8.2].

Table 3-20 summarises the HSG distribution for each of the 10 watersheds. Maps showing the HSG distribution in each watershed presented in Figure 3-39 through Figure 3-48. Overall, no single soil group in the FWMT dominates the soils distribution. Hydrologic soils groups B and C are most dominant, making up 70% of all soils in the FWMT. HSG-A+ represents the smallest portion of area. Manukau Harbour has the highest per cent of HSG-A+ soils, followed by Waitematā Harbour and Tamaki Estuary, representing the rapidly draining volcanic geology present in these areas.

Table 3-20. HSG distribution as per cent of area for Auckland watersheds, including the area-weighted regional average

Watershed	Impervious (DCIA*)	Hydrologic Soil Group[1]				
		A+	A	B	C	D
Hibiscus Coast	7%	1%	1%	16%	51%	24%
Hauraki Gulf Islands	0%	0%	2%	57%	37%	4%
Kaipara Harbour	0%	1%	12%	25%	40%	23%
Mahurangi Estuary	1%	1%	0%	38%	43%	16%
Manukau Harbour	5%	27%	4%	38%	26%	1%
North East Coast	0%	1%	3%	30%	58%	7%
Tamaki Estuary	17%	3%	1%	5%	74%	0%
Wairoa Coast	0%	1%	0%	53%	43%	2%
Waitematā Harbour	15%	5%	0%	24%	45%	9%
West Coast	0%	2%	47%	16%	21%	14%
Auckland region area-weighted average	**4%**	**6%**	**9%**	**31%**	**39%**	**11%**

* Directly connected impervious area (DCIA) is the proportion of impervious area presumed directly connected to a stormwater inlet or receiving waterway. The process of estimating DCIA is described in Section 3.8.7.

[1] Colour gradient shows low (white) to high (dark) percentage of each watershed land classified as each HSG.

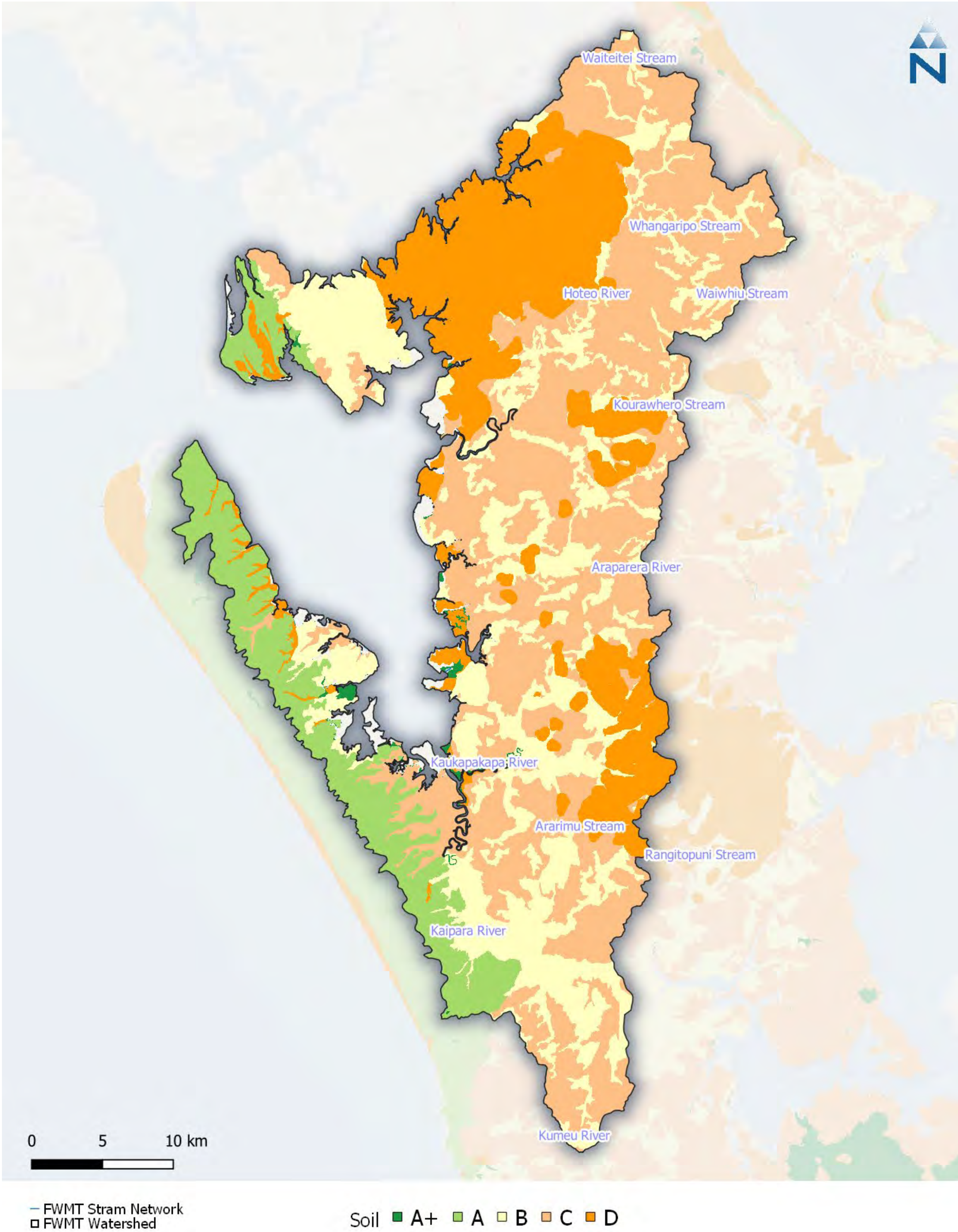


Figure 3-39. Hydrologic soil groups in the Kaipara Harbour watershed

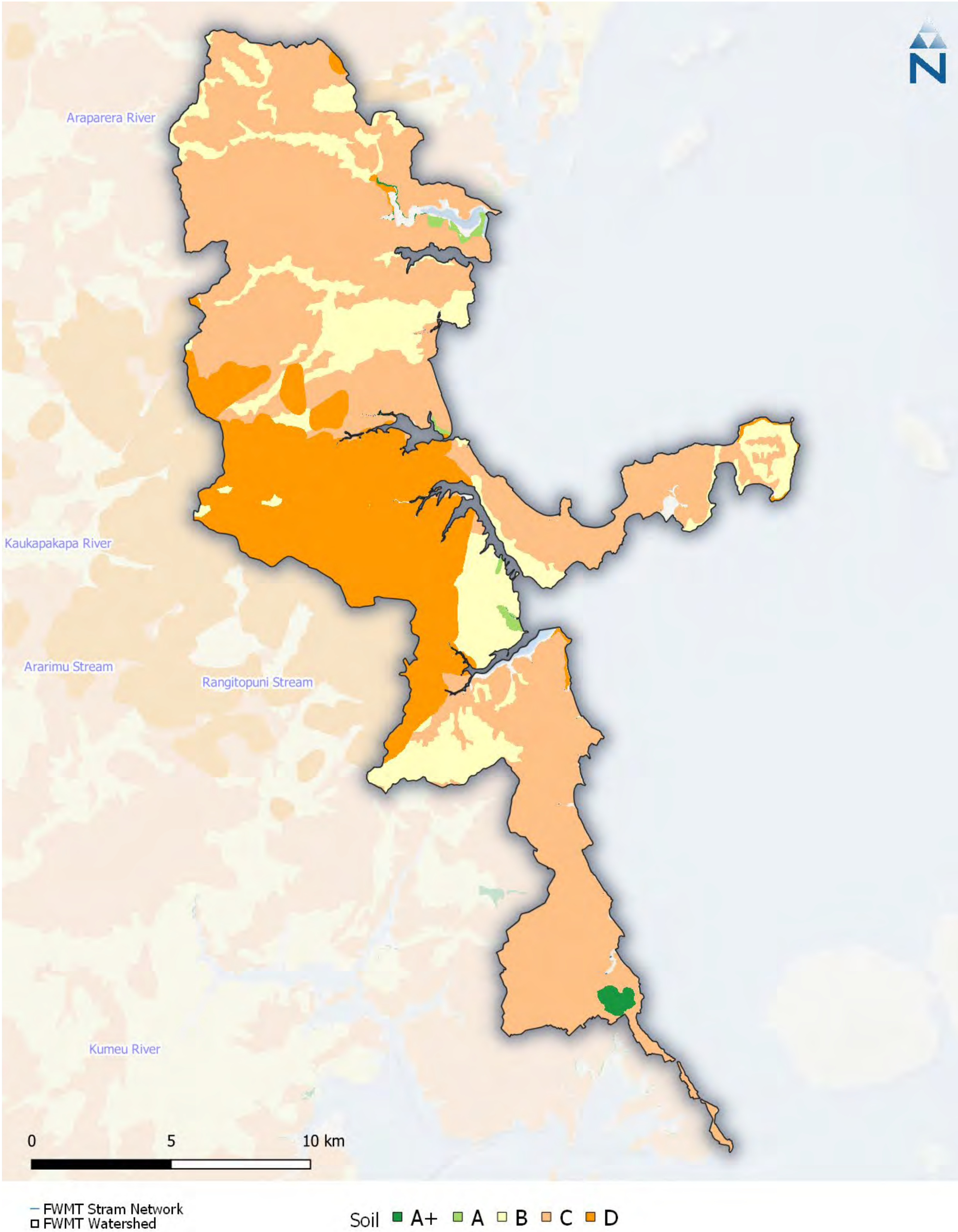


Figure 3-40. Hydrologic soil groups in the Hibiscus Coast watershed

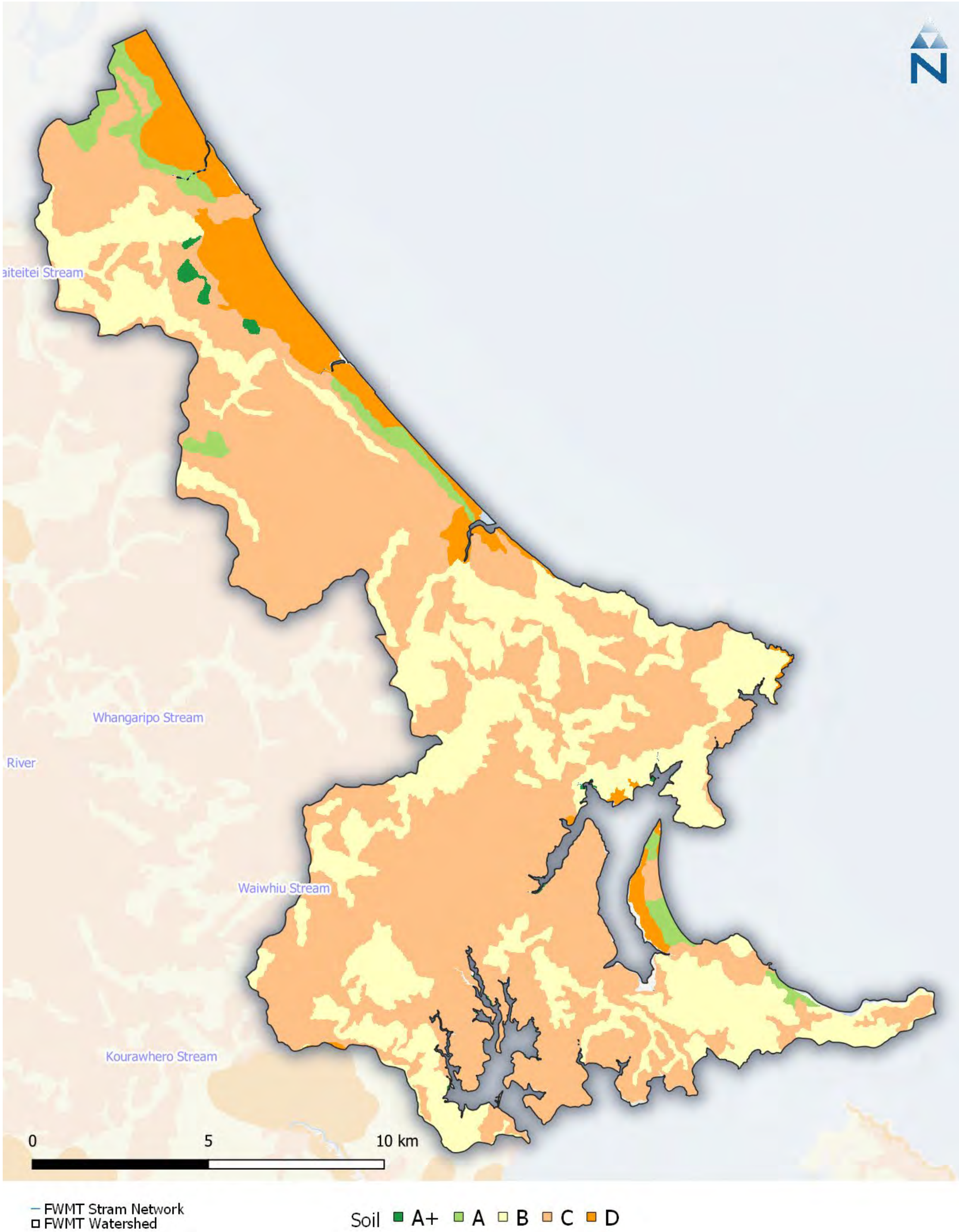


Figure 3-41. Hydrologic soil groups in the Northeast Coast watershed

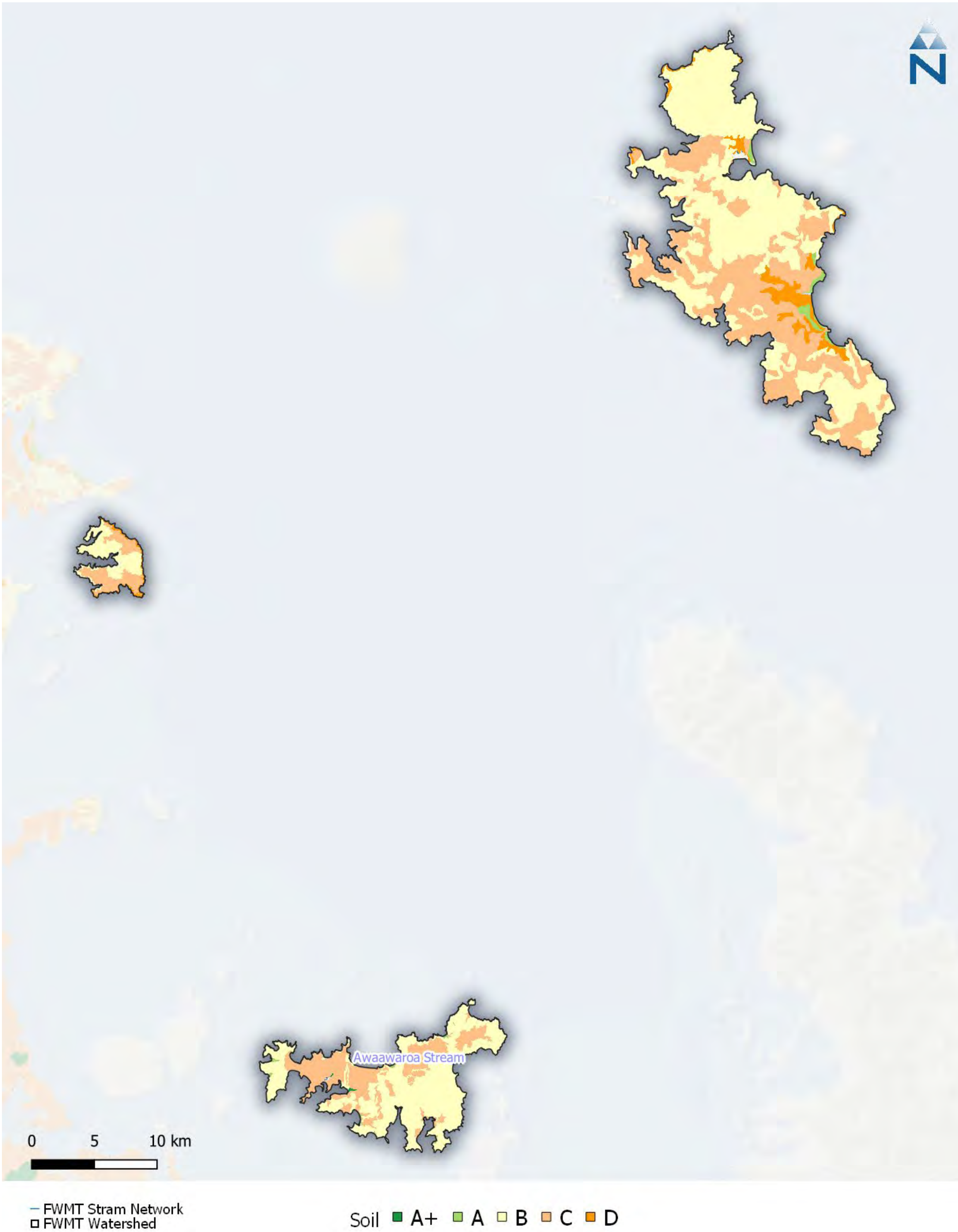


Figure 3-42. Hydrologic soil groups in the Hauraki Gulf Islands watershed

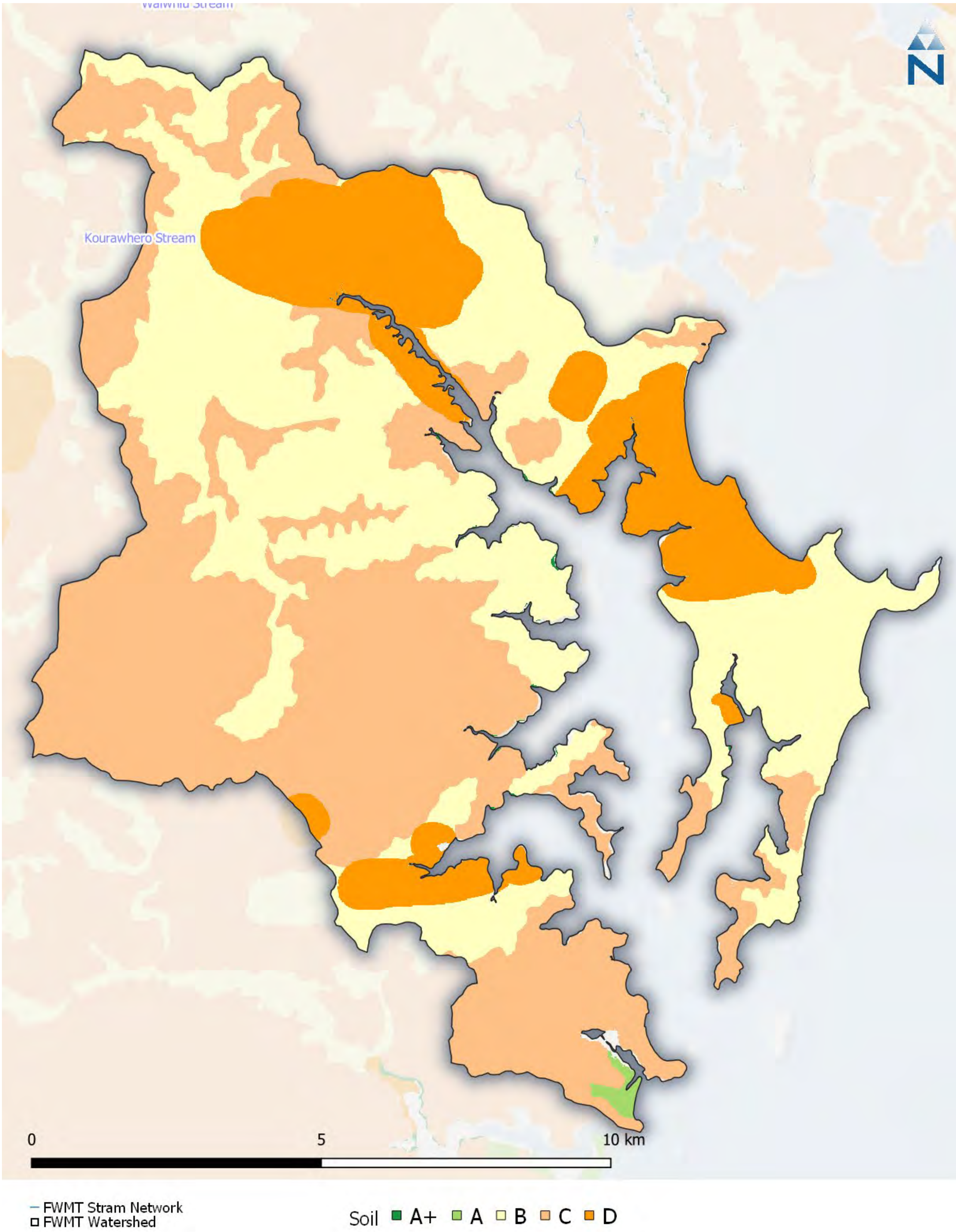


Figure 3-43. Hydrologic soil groups in the Mahurangi Estuary watershed

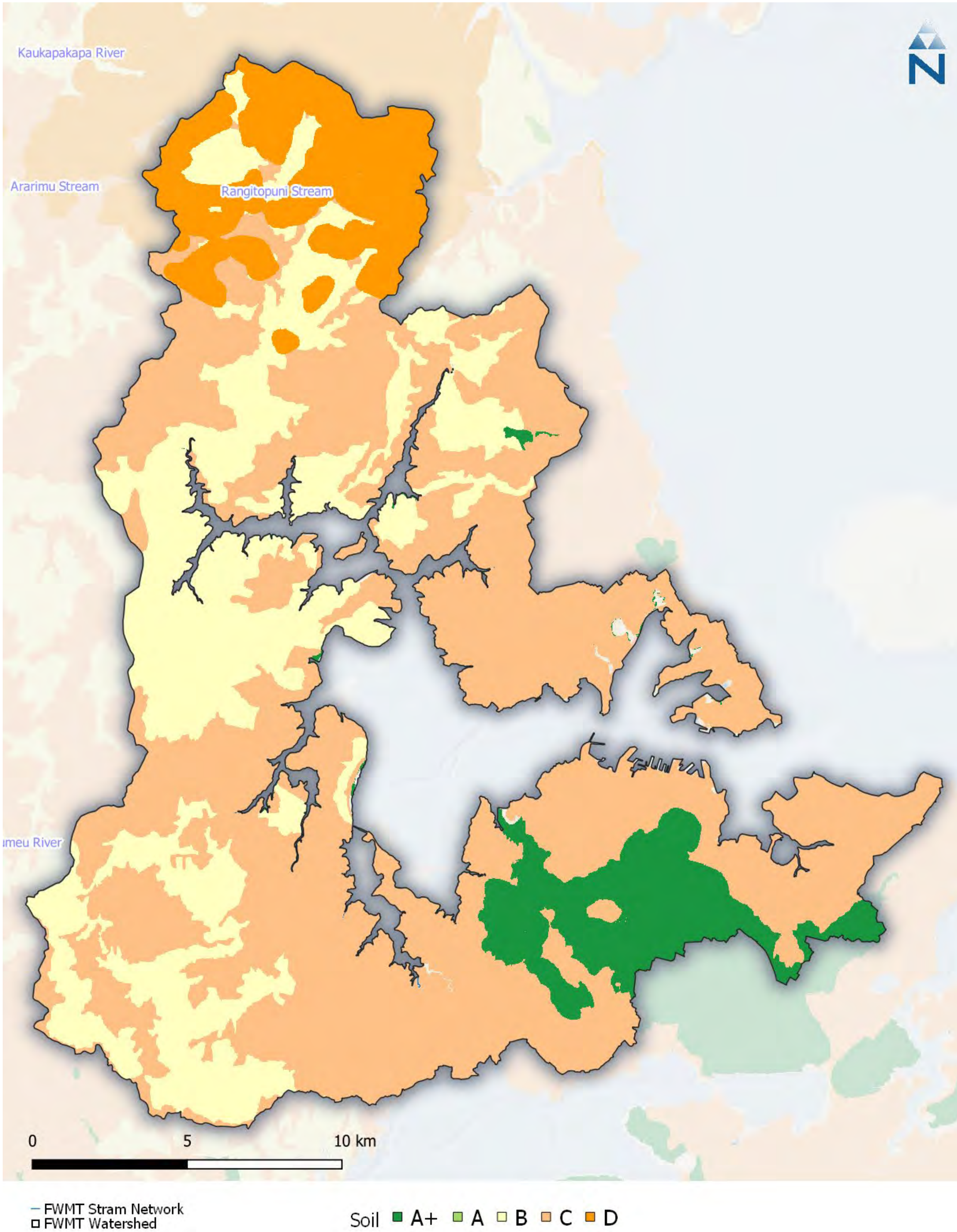


Figure 3-44. Hydrologic soil groups in the Waitematā Harbour watershed

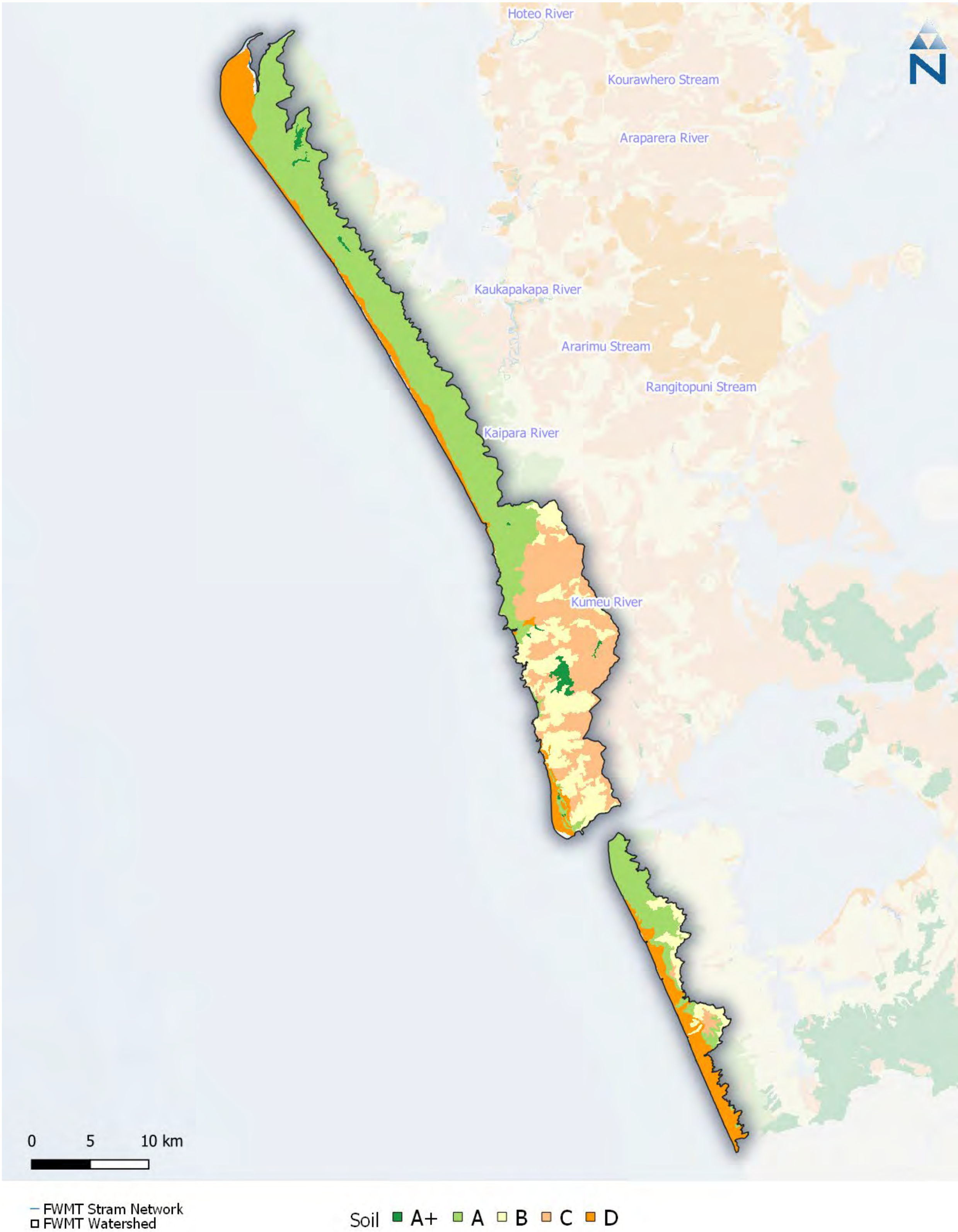


Figure 3-45. Hydrologic soil groups in the West Coast watershed

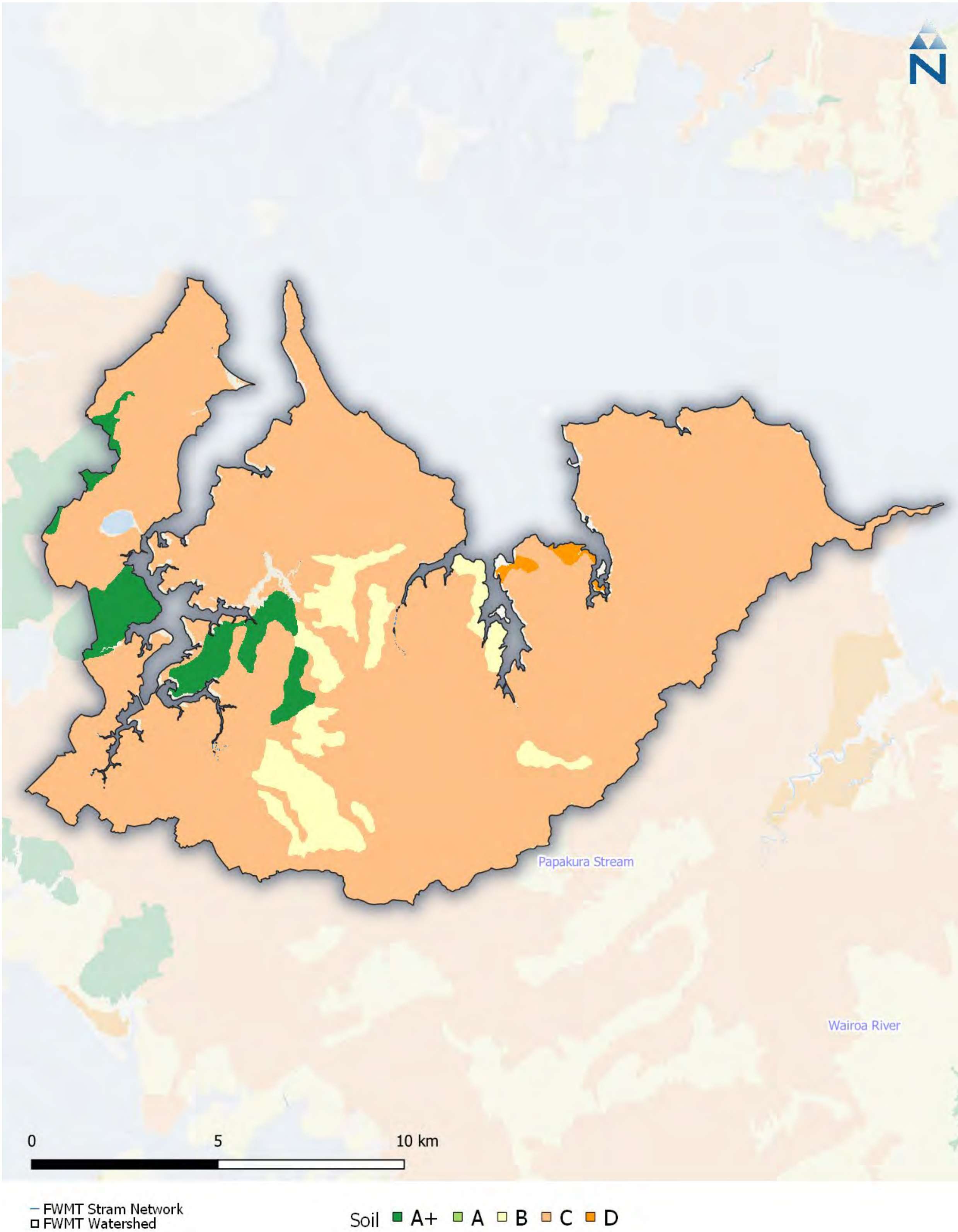


Figure 3-46. Hydrologic soil groups in the Tamaki Estuary watershed

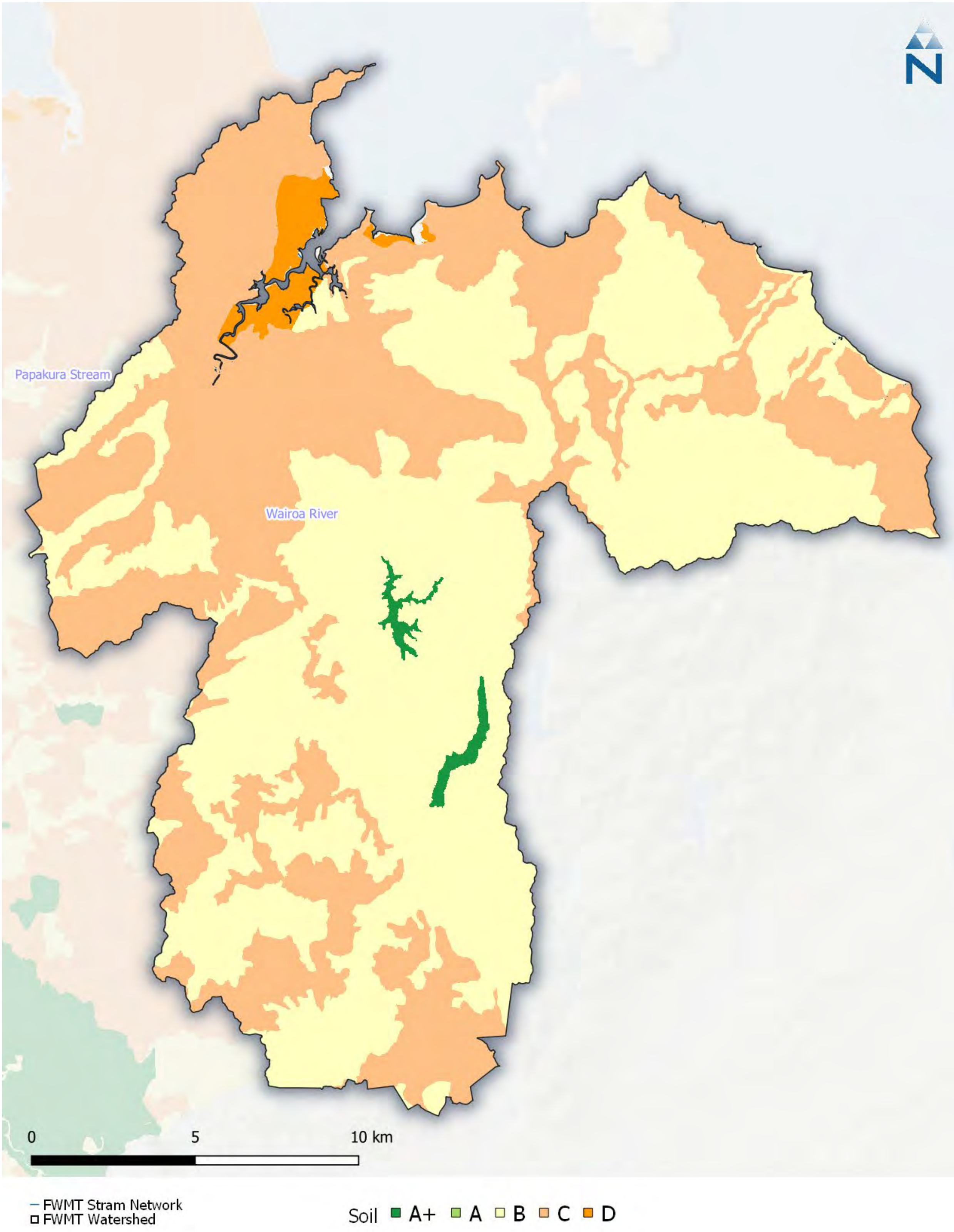


Figure 3-47. Hydrologic soil groups in the Wairoa Coast watershed

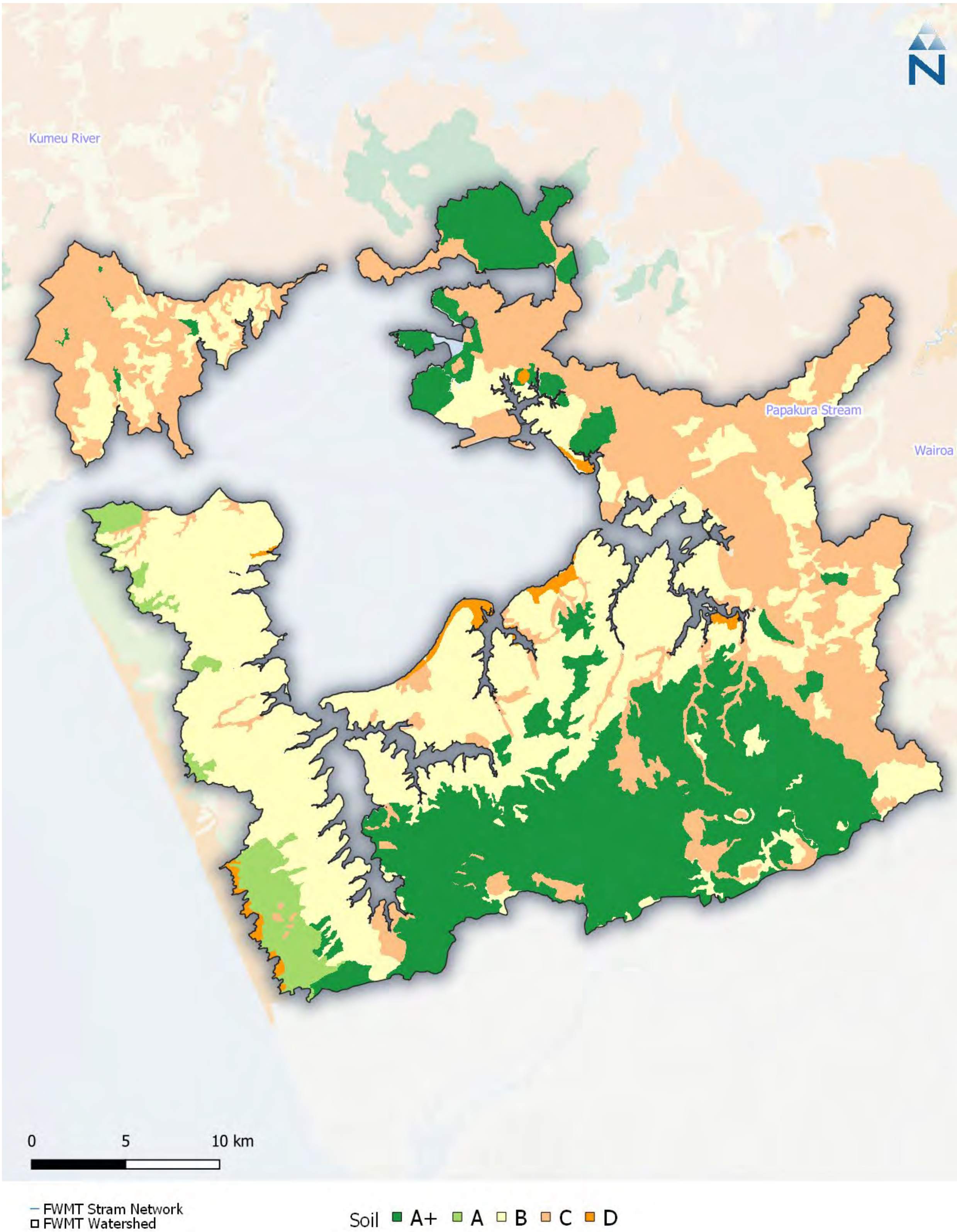


Figure 3-48. Hydrologic soil groups in the Manukau Harbour watershed

3.8.6 HRU Classification Output

Each of the HRU factors discussed in the previous subsections were overlaid in GIS (i.e., slope, cover, use, imperviousness, hydrologic soil group, impact). A single raster dataset with unique HRU was developed regionwide with scaling for missing data or to resolve differences in spatial extents of datasets.

Table 3-21 summarises the HRUs incorporated into the FWMT Stage 1. Table 3-21 also shows the relative impact factors used to further refine the land cover factor. Table 3-22 presents a summary of HRU classes for each of the four factors, as a per cent of total area within the FWMT Stage 1. The information in Table 3-23 was used to adjust the combinations in Table 3-21 to ensure factors were appropriately represented whilst reducing model complexity. As an example, in Table 3-21, most soils (67%) in the developed pervious (Dev_Pervious) land cover category were C soils. Alternatively, only 3.2% of Dev_Pervious soils were D soils. Therefore, All Dev Pervious D soils were classified as C soils in the FWMT Stage 1. As another example, impervious land cover categories have a ‘0’ for soil group categories (Table 3-21) indicating no functional soil type in Table 3-22 (i.e., rainfall does not interact with soil underneath impervious areas within LSPC). Any field where a ‘0’ value is entered indicates that HRUs were not stratified by that factor.

Ultimately, a land typology of 106 HRUs was derived to represent hydrologic and contaminant responses of land, applied to each of the 5,465 sub-catchments within the FWMT Stage 1. From this, up to 106 unique parameter combinations are possible throughout the Auckland region for hydrology and water quality processes (see Section 2.3 for description of all LSPC processes enabled in the FWMT Stage 1). Note, the objective for the FWMT Stage 1 is a regionalised build so all HRU parameterisation will be regional (i.e., equivalently parameterised HRUs assigned to a given climate station will generate equivalent unit-area hydrological and contaminant responses unless the slope differs).

Figure 3-49 presents an example composite of HRUs within a sub-catchment. Figure 3-50 through Figure 3-59 show the actual spatial distribution of HRUs across the 10 watersheds.

Table 3-21. Switchboard of HRUs showing the combinations of land cover across soil group, slope and impact factors

Order	Land Cover	PERIMP	Soil Group						Slope		Relative Impact					
			Imp	A+	A	B	C	D	0-10	>10	Lower → Higher					
		0/1	0	1	2	3	4	5	1	2	1	2	3	4	5	6
1	Dev_Commercial	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Dev_Industrial	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Dev_Residential	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Dev_Roof	1	0	0	0	0	0	0	0	0	1	2	3	0	0	0
5	Dev_Road	1	0	0	0	0	0	0	0	0	1	2	3	4	5	6
6	Dev_Pervious	0	0	1	2	3	4	4	1	2	0	0	0	0	0	0
7	Dev_OSWW	0	0	3	3	3	4	4	0	0	0	0	0	0	0	0
8	Horticulture	0	0	1	2	3	4	4	1	2	1	2	3	0	0	0
9	Pasture	0	0	1	2	3	4	5	1	2	1	2	0	0	0	0
10	Open_Space	0	0	1	2	3	4	5	1	2	1	0	0	0	0	0
11	Forest	0	0	1	2	3	4	5	1	2	1	2	0	0	0	0
12	Road_Rural	0	0	4	4	4	4	4	1	2	1	2	3	4	0	0
13	Mine_Barren	0	0	5	5	5	5	5	0	0	0	0	0	0	0	0
14	Water	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3-22. Summary of HRU components expressed as a per cent of total area across Auckland Council

Order	Land Cover	Total Area	Soil Group (% Area)						Slope (% Area)		Relative Impact (% Area)					
			Imp	A+	A	B	C	D	0-10	>10	Lower → Higher					
		%	0	1	2	3	4	5	1	2	1	2	3	4	5	6
1	Dev_Commercial	0.2%	100%	0.0%	0.0%	0.0%	0.0%	0.0%	90%	9.7%	100%	0.0%	0.0%	0.0%	0.0%	0.0%
2	Dev_Industrial	0.3%	100%	0.0%	0.0%	0.0%	0.0%	0.0%	98%	2.4%	100%	0.0%	0.0%	0.0%	0.0%	0.0%
3	Dev_Residential	0.7%	100%	0.0%	0.0%	0.0%	0.0%	0.0%	68%	32%	100%	0.0%	0.0%	0.0%	0.0%	0.0%
4	Dev_Roof	1.3%	100%	0.0%	0.0%	0.0%	0.0%	0.0%	79%	21%	73%	13%	14%	0.0%	0.0%	0.0%
5	Dev_Road	1.2%	100%	0.0%	0.0%	0.0%	0.0%	0.0%	76%	24%	38%	28%	21%	8.0%	2.4%	2.5%
6	Dev_Pervious	2.1%	0.0%	13%	1.3%	16%	67%	3.2%	66%	34%	100%	0.0%	0.0%	0.0%	0.0%	0.0%
7	Dev_OSWW	0.3%	0.0%	7.1%	3.2%	38%	47%	4.5%	36%	64%	100%	0.0%	0.0%	0.0%	0.0%	0.0%
8	Horticulture	2.5%	0.0%	34%	13%	31%	17%	4.9%	69%	31%	16%	26%	58%	0.0%	0.0%	0.0%
9	Pasture	47.0%	0.0%	5.5%	9.1%	33%	36%	17%	31%	69%	69%	31%	0.0%	0.0%	0.0%	0.0%
10	Open_Space	17.8%	0.0%	7.8%	7.1%	30%	45%	10%	41%	59%	100%	0.0%	0.0%	0.0%	0.0%	0.0%
11	Forest	25.7%	0.0%	2.5%	10%	34%	47%	5.9%	16%	84%	87%	13%	0.0%	0.0%	0.0%	0.0%
12	Road_Rural	0.2%	0.0%	2.6%	17%	28%	37%	16%	39%	61%	99%	1.1%	0.1%	0.0%	0.0%	0.0%
13	Mine_Barren	0.2%	0.0%	5.2%	21%	4.5%	13%	56%	56%	44%	100%	0.0%	0.0%	0.0%	0.0%	0.0%
14	Water	0.6%	100%	0.0%	0.0%	0.0%	0.0%	0.0%	82%	18%	100%	0.0%	0.0%	0.0%	0.0%	0.0%

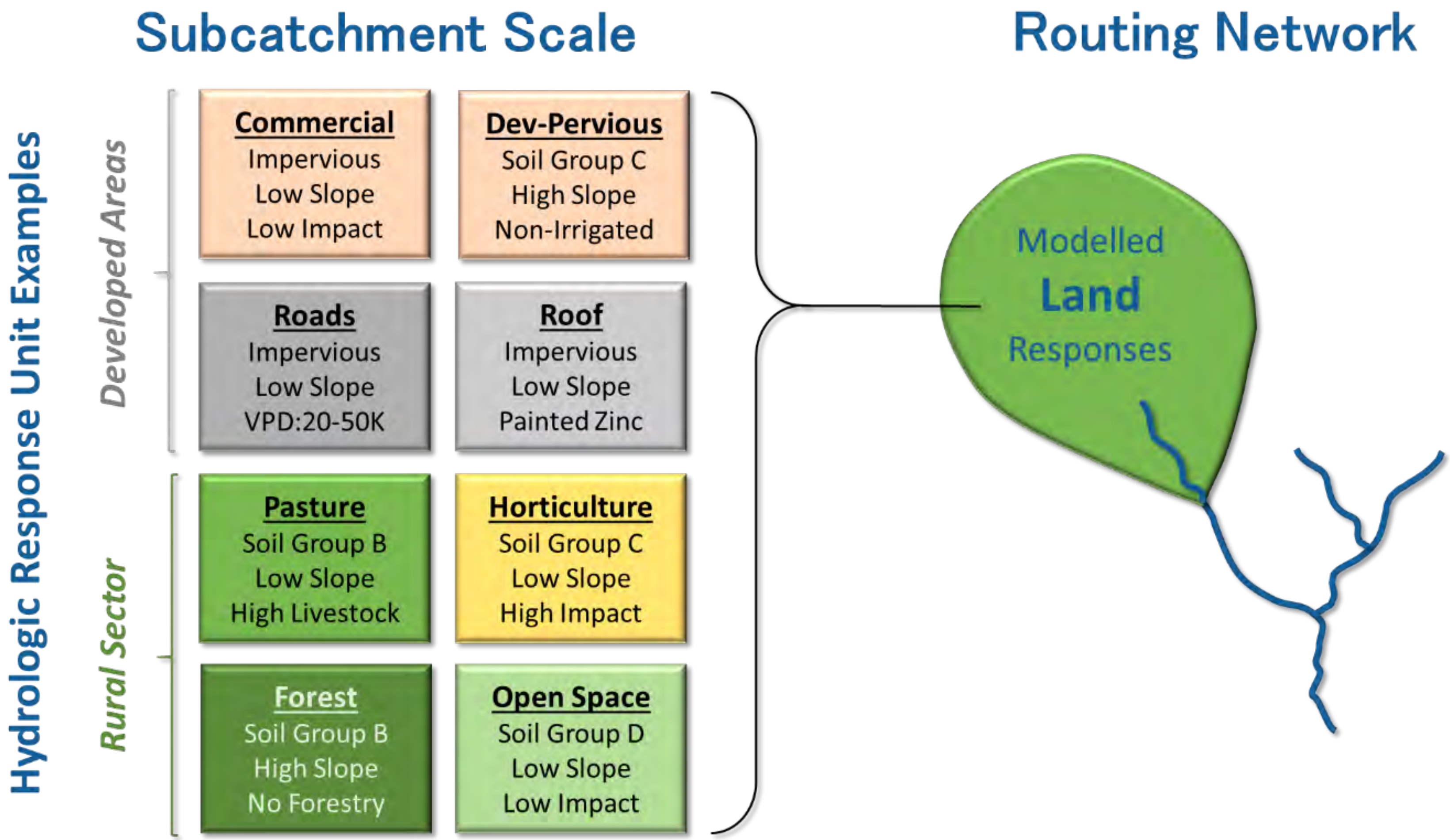


Figure 3-49. Example HRUs within a sub-catchment

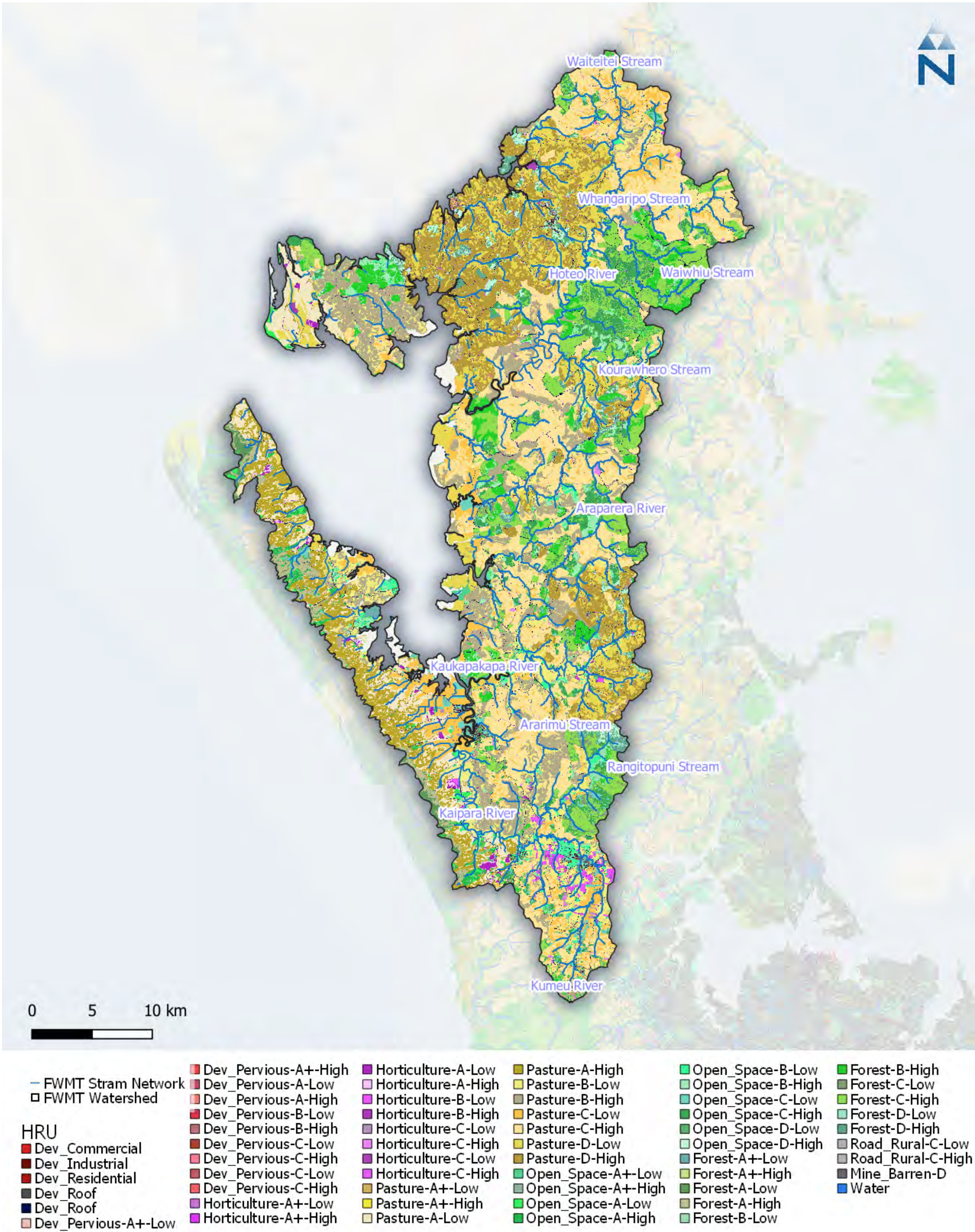


Figure 3-50. Map of FWMT HRUs for the Kaipara Harbour watershed

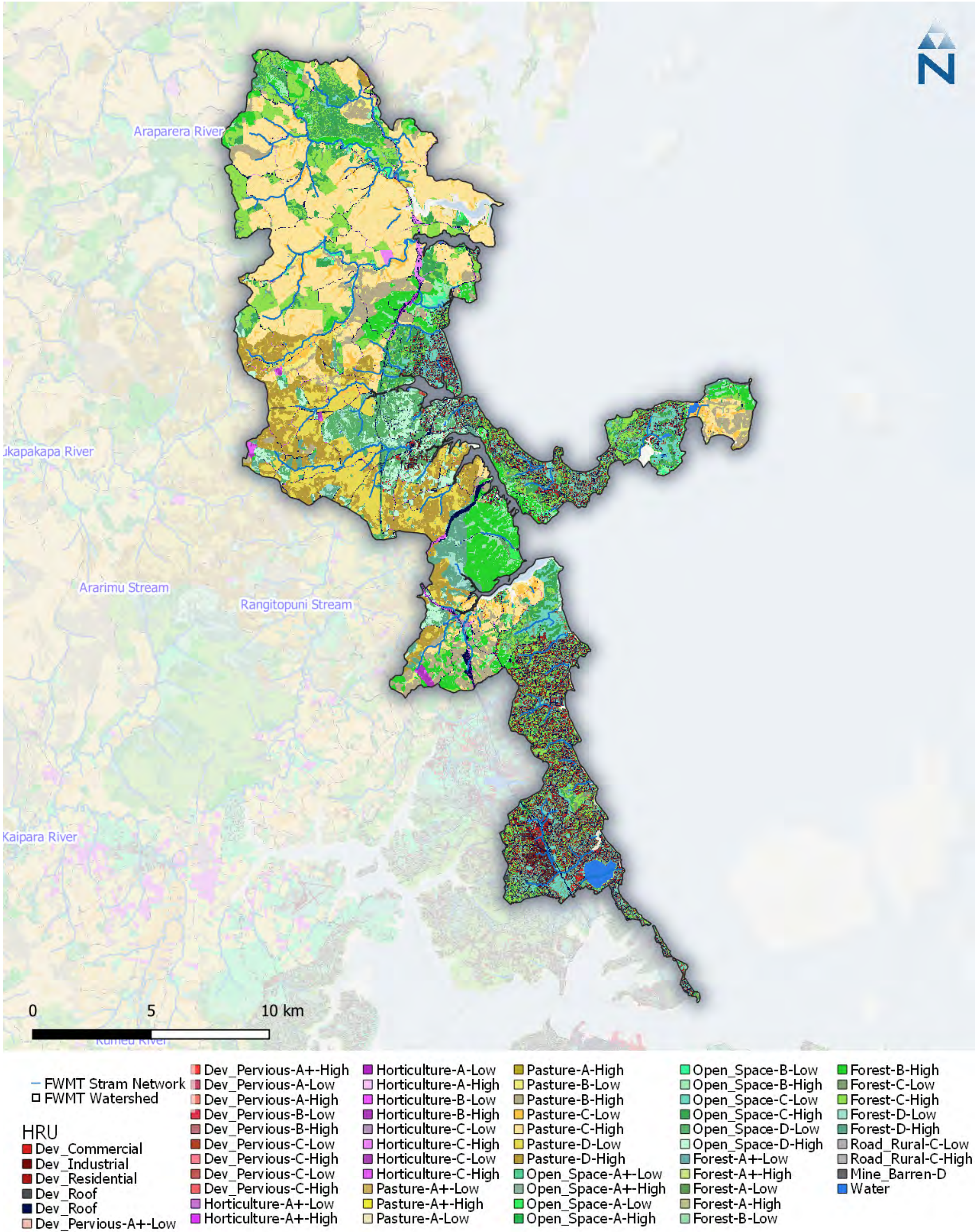


Figure 3-51. Map of FWMT HRUs for the Hibiscus Coast watershed

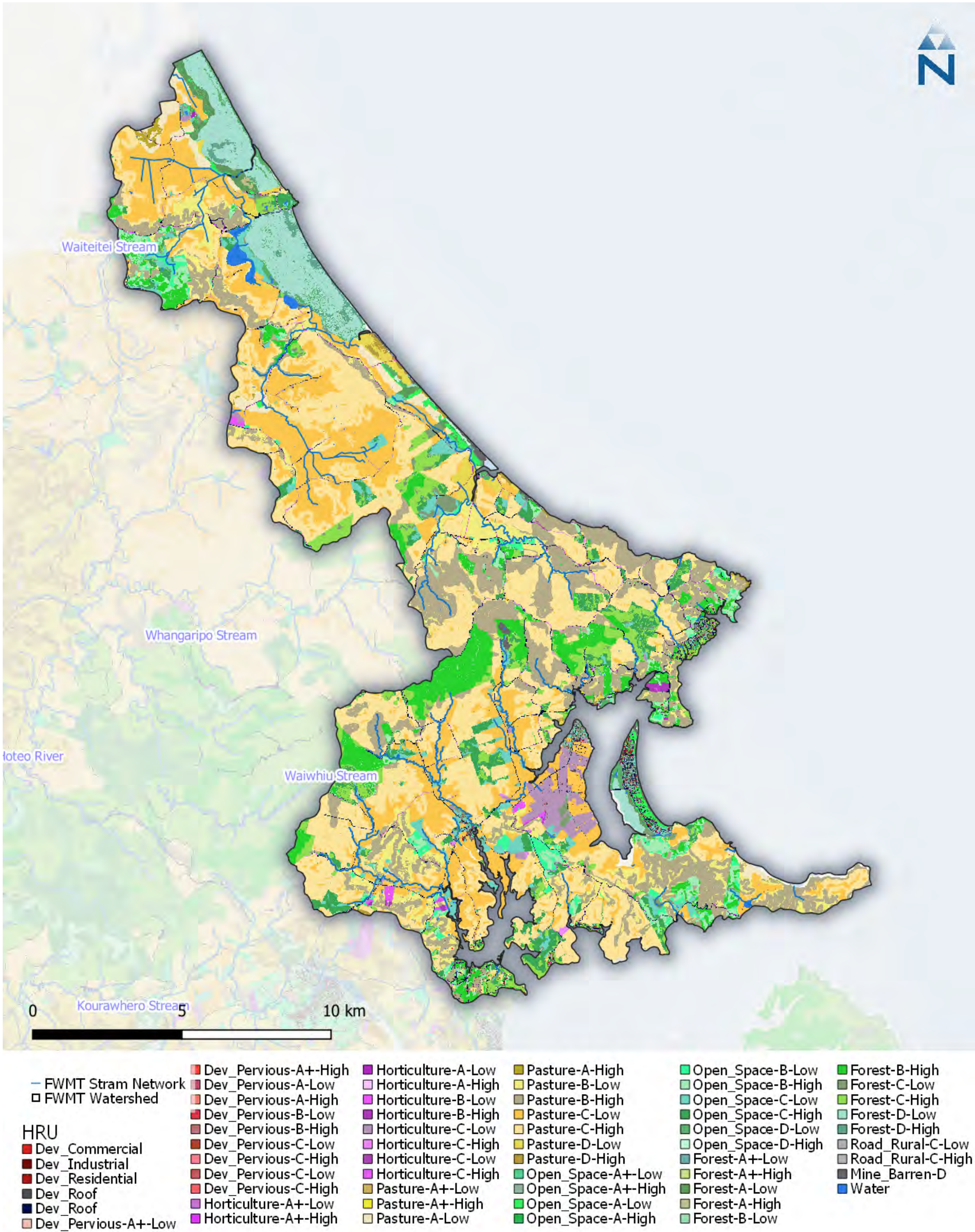


Figure 3-52. Map of FWMT HRUs in Northeast Coast watershed

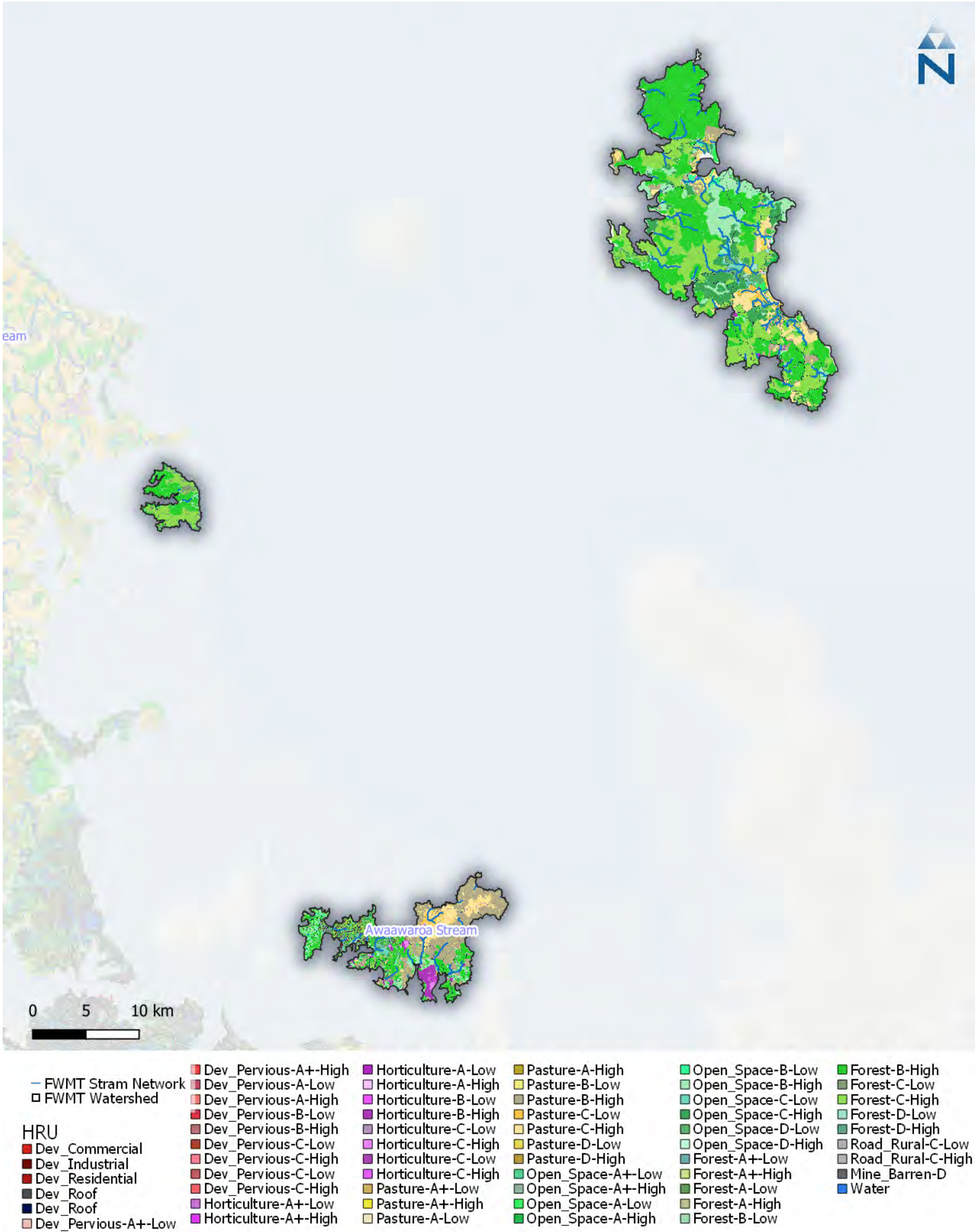


Figure 3-53. Map of FWMT HRUs for the Hauraki Gulf Islands watershed

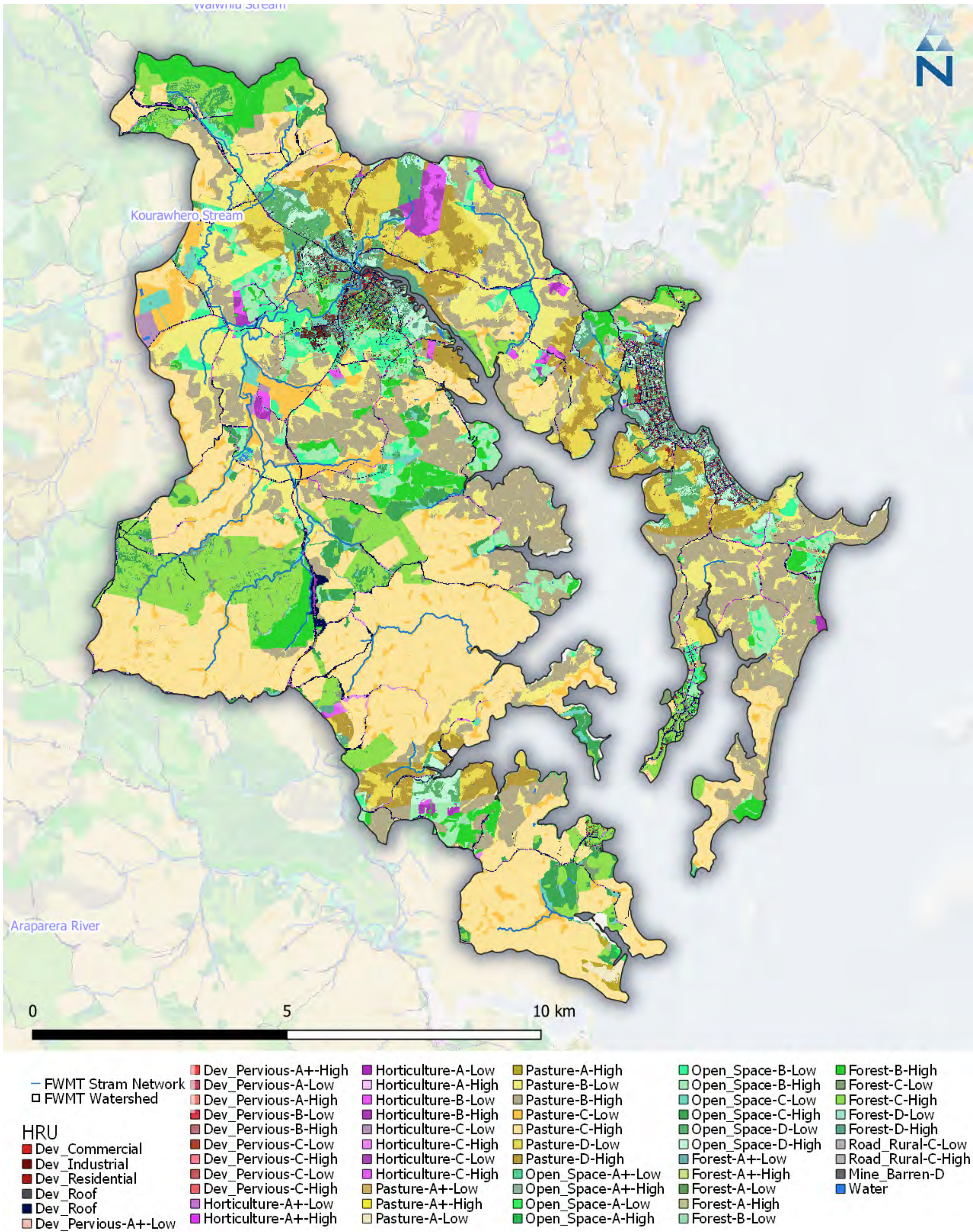


Figure 3-54. Map of FWMT HRUs for the Mahurangi Estuary watershed

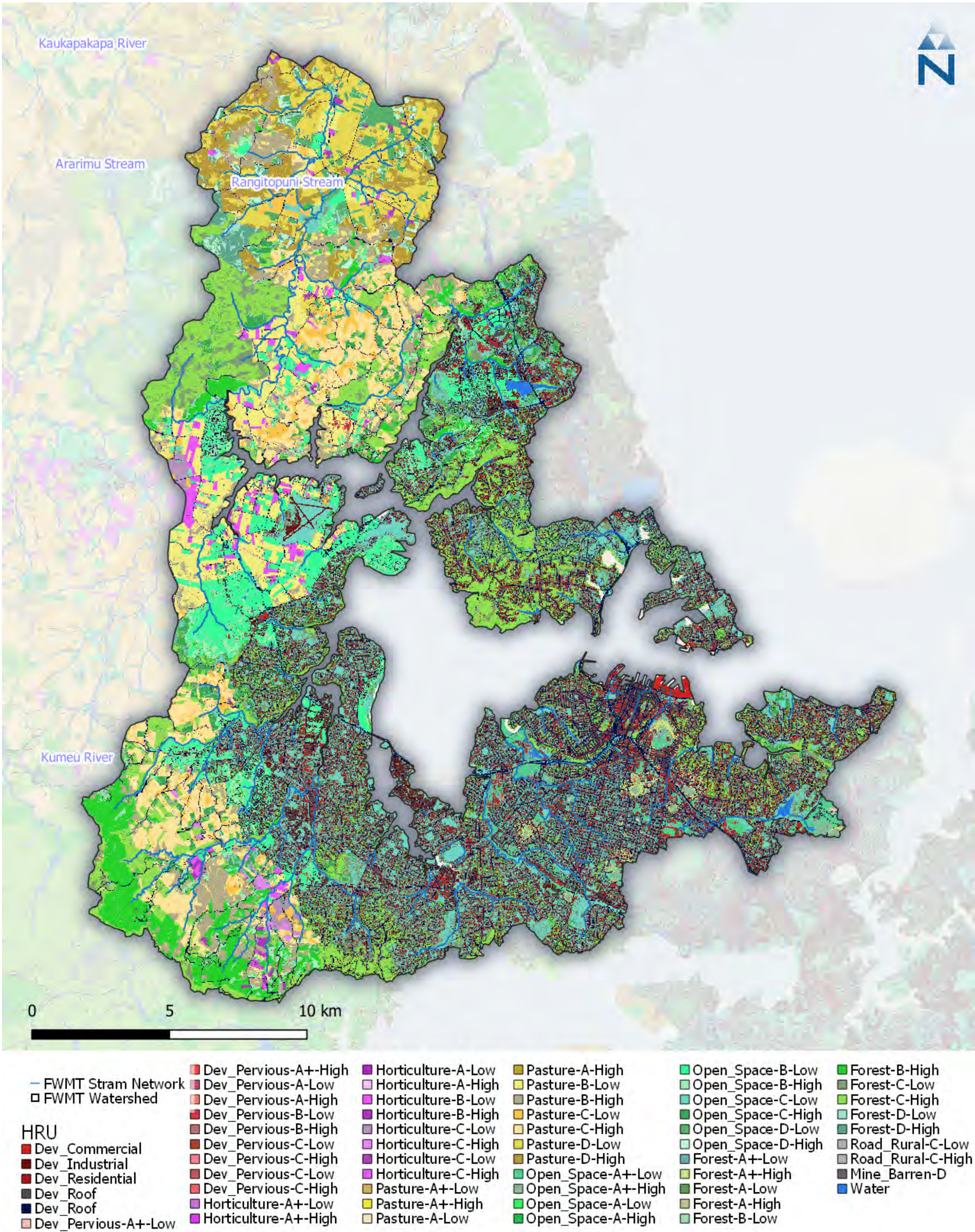


Figure 3-55. Map of FWMT HRUs for the Waitematā Harbour watershed

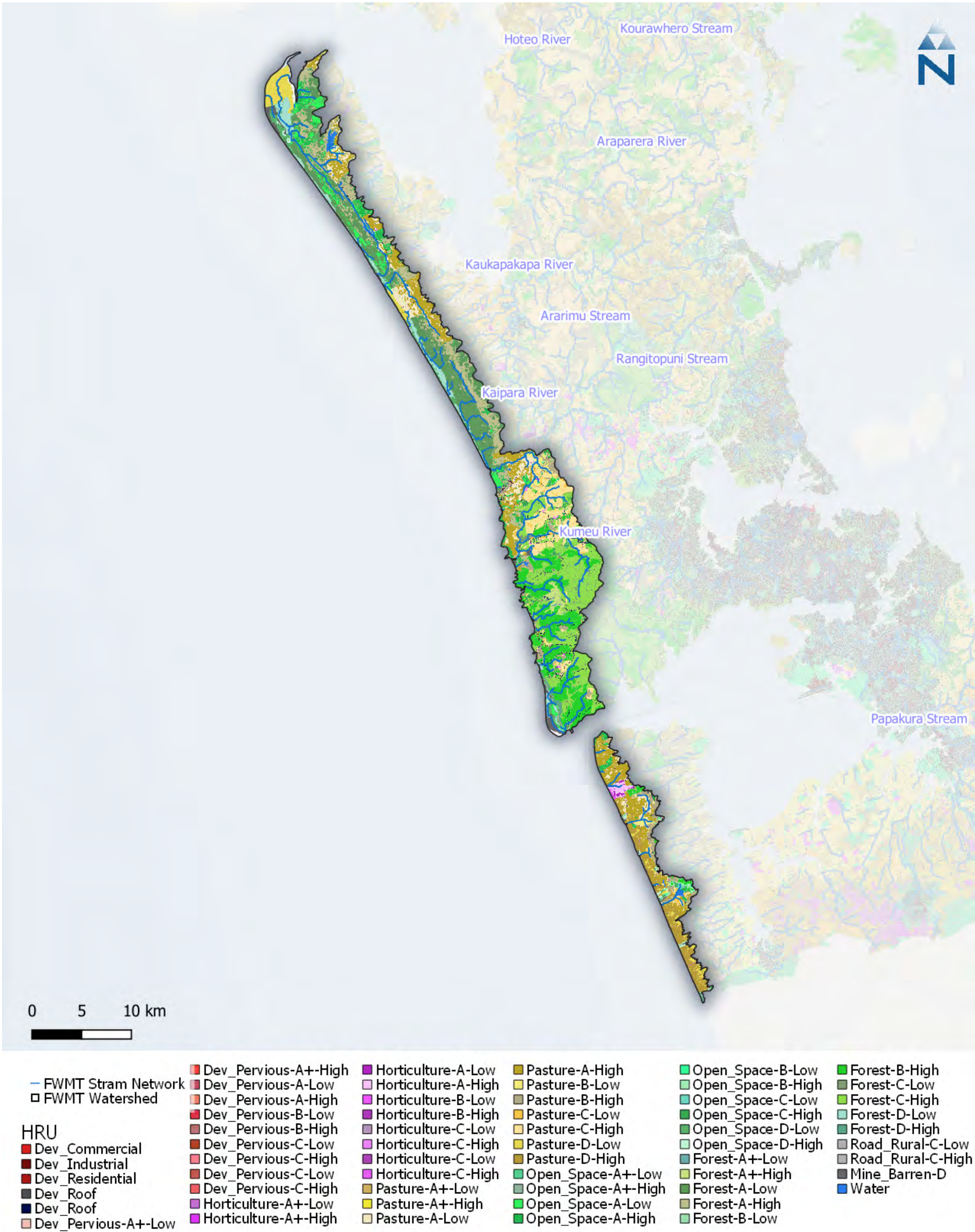


Figure 3-56. Map of FWMT HRUs for the West Coast watershed

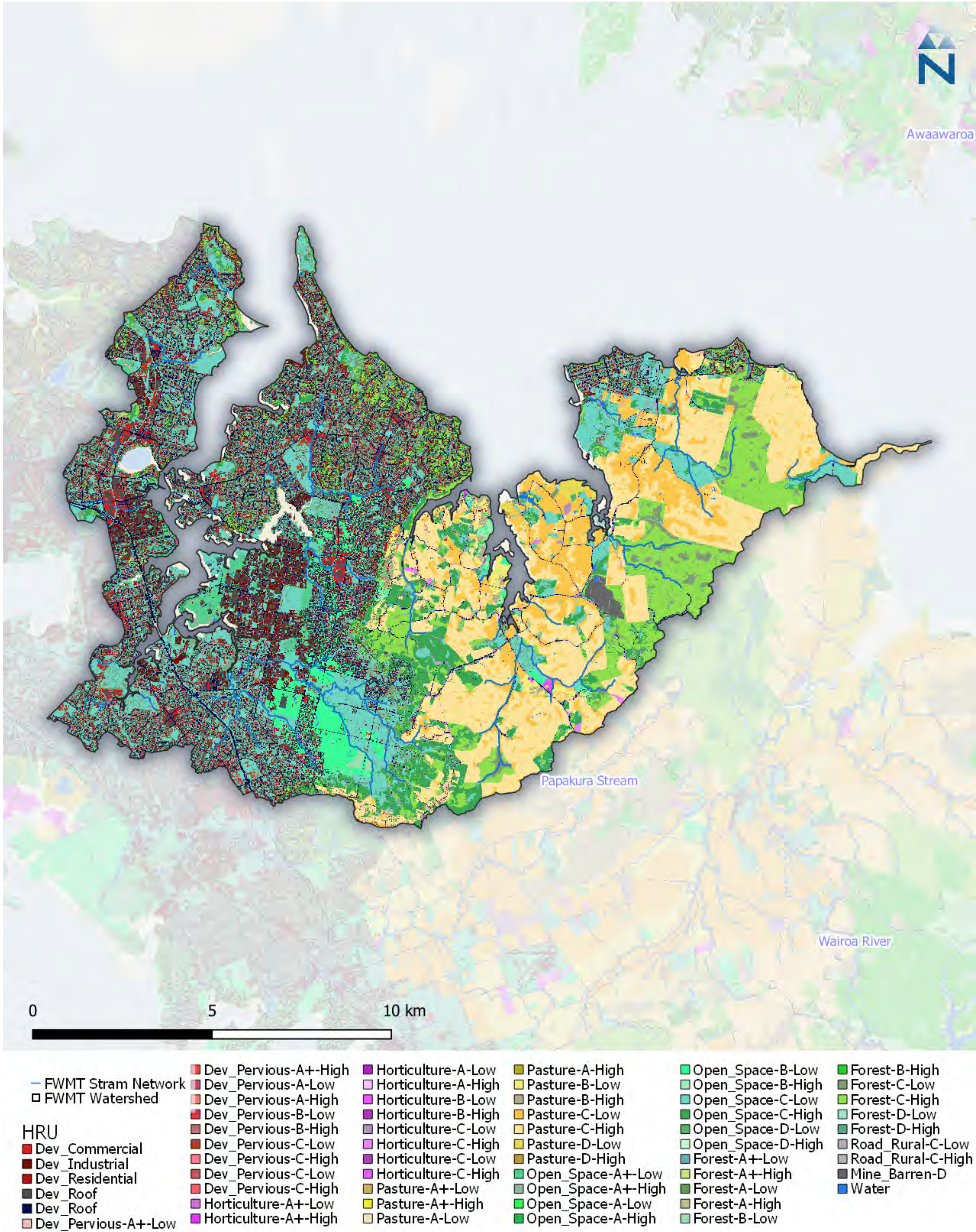


Figure 3-57. Map of FWMT HRUs for the Tamaki Estuary watershed

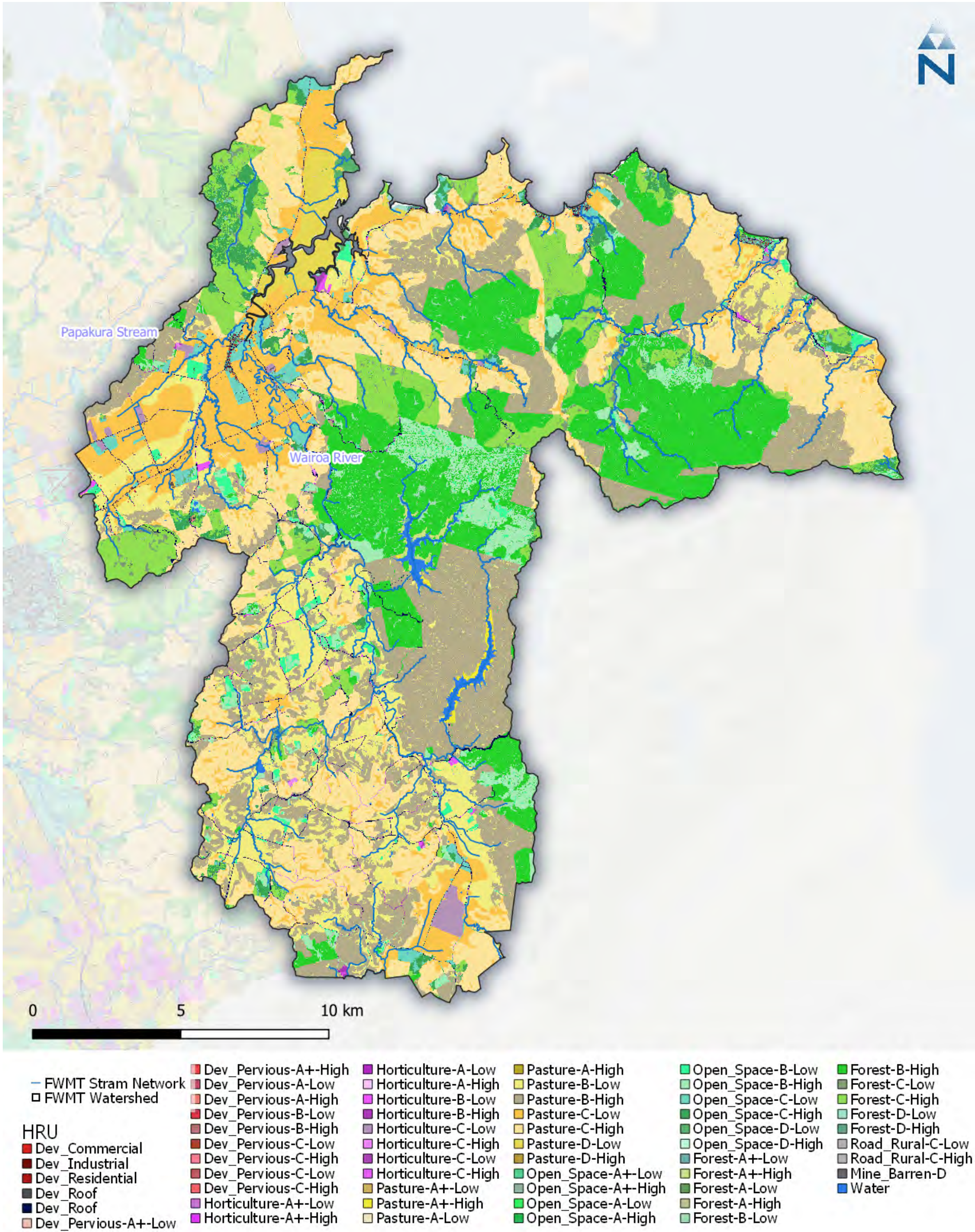


Figure 3-58. Map of FWMT HRUs for the Wairoa Coast watershed

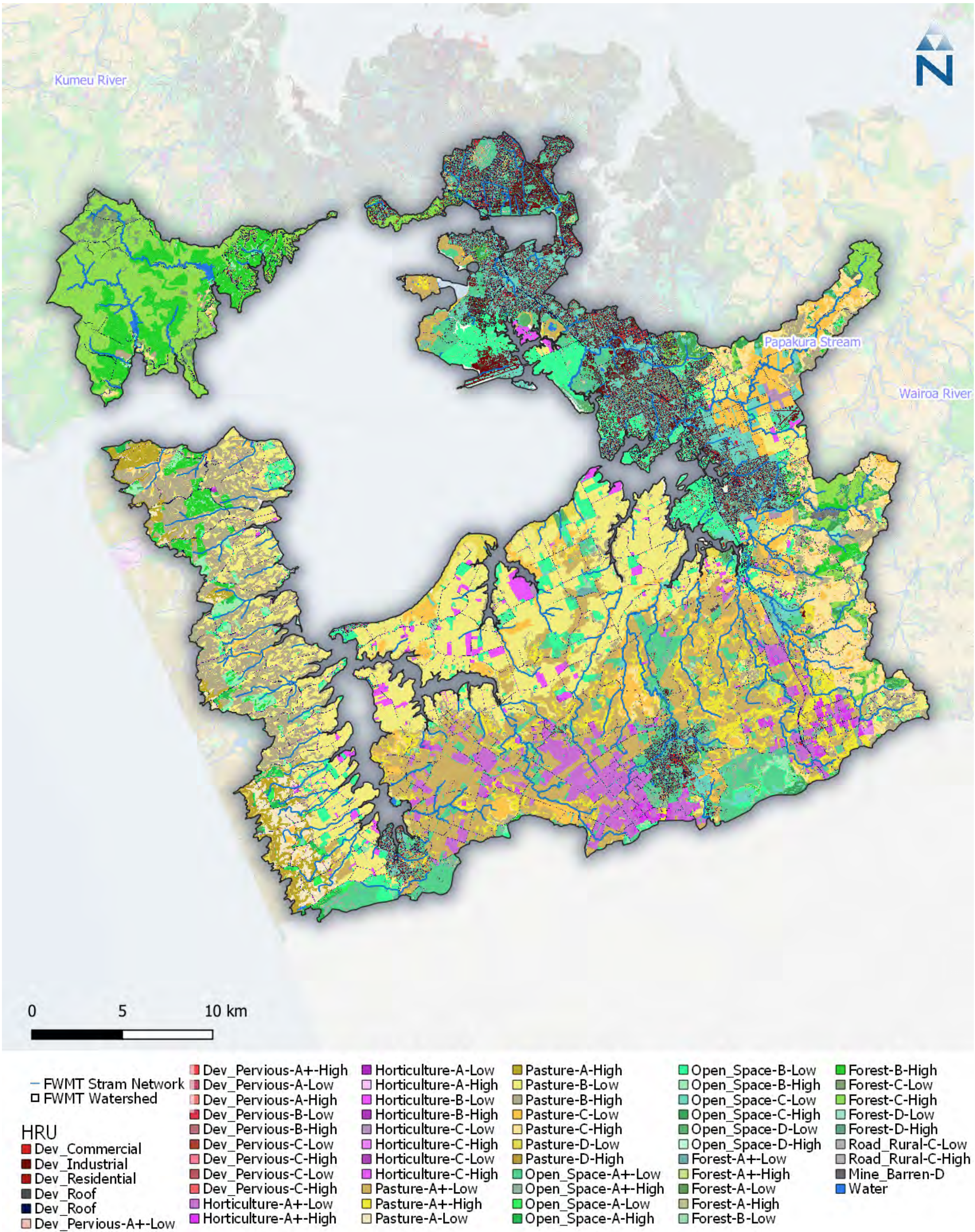


Figure 3-59. Map of FWMT HRUs for the Manukau Harbour watershed

3.8.7 Directly Connected Impervious Area

LSPC representation of impervious cover requires adjustments to account for 'directly connected' imperviousness. In watersheds, the distinction between impervious and pervious land is not clearly distinguished. Runoff from impervious surfaces may flow over pervious land on its way to the stormwater network (or waterway), reducing the hydrological and contaminant effect of the impervious HRU on the receiving environment. Therefore, both the runoff volume and potential contaminant wash off from impervious areas and associated contaminant loading may change as it flows over existing pervious surfaces before being discharged to a downstream waterway.

To incorporate the effects of varying impervious connectivity within hydrological modelling, a translation from Mapped Impervious Area (MIA) to Directly Connected Impervious Area (DCIA) is required. MIA represents the potential maximum impervious cover that can be directly quantified from the impervious HRU layer (see Section 3.8.3). Whereas DCIA, which is adjusted for losses from lateral flow of impervious runoff to pervious area, is the aggregated proportion of MIA that contributes runoff directly lost to the stormwater network. Estimating DCIA is a common practice in hydrological modelling, which otherwise could lead to spurious over-estimates of rainfall-runoff volumes and velocity, and associated over-estimates of contaminant generation and instream hydrology, and/or reduced estimates of contaminant attenuation within LSPC.

Explicit values for DCIA were not available throughout the Auckland region, requiring development of a new layer. Empirical algorithms were used for the FWMT Stage 1. Figure 3-60 illustrates the transitional sequence from MIA to DCIA within the FWMT Stage 1. The amount of the each of these impervious surfaces that directly contributes to the stormwater network was then determined by the Sutherland Equations (2000). The Sutherland Equations (2000), presented in Figure 3-61 are based on a strong correlation between the relative area of imperviousness and corresponding DCIA for runoff. The curve for high-density developed land trends closer to the line of equal value (1:1 or DCIA approximating MIA). Table 3-23 shows the resulting DCIA extent for the 10 watersheds.

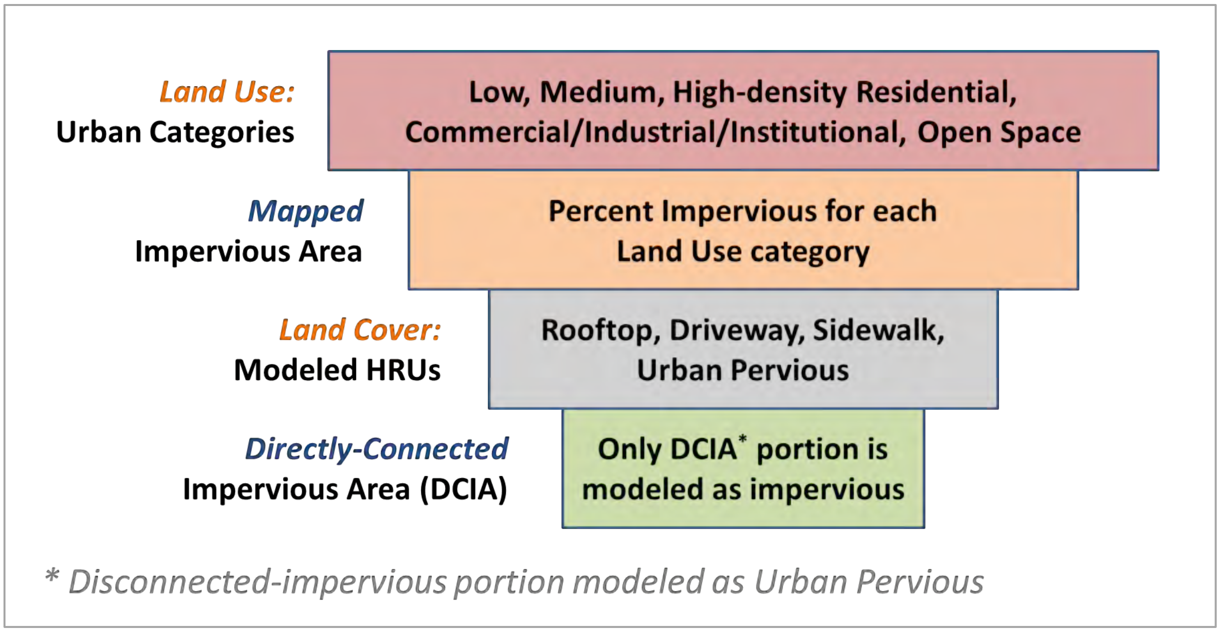


Figure 3-60. Translation Sequence from Mapped Impervious Area to Directly Connected Impervious Area

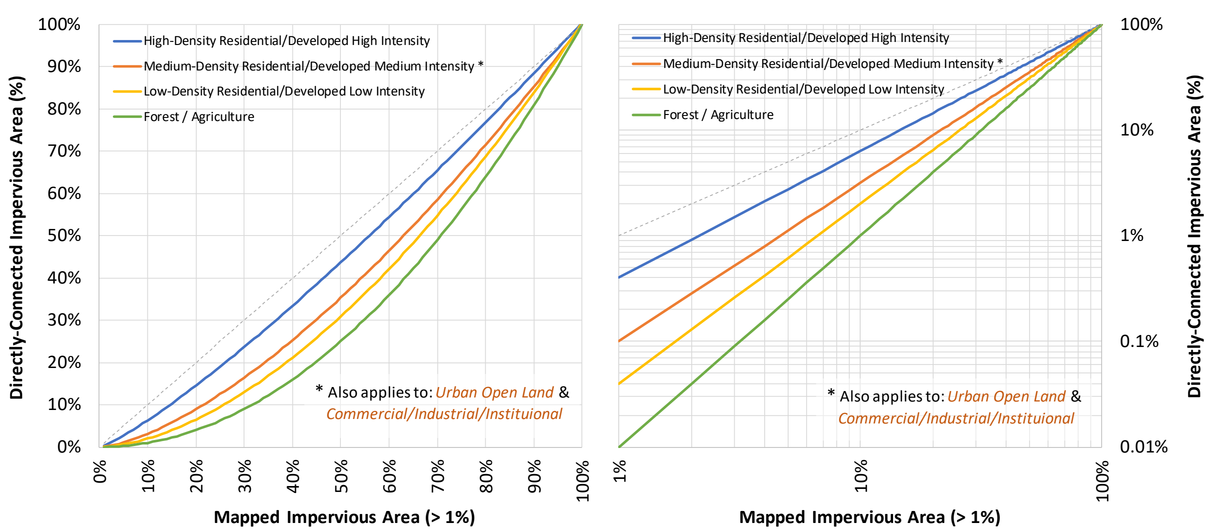


Figure 3-61. Relationships between Mapped and directly connected impervious area (Sutherland 2000)

Table 3-23. Impervious area summary for 10 major watersheds across the Auckland region

Watershed	Area (km^2)			DCIA:MIA	Per cent of Area	
	Total	MIA	DCIA		MIA	DCIA
Hibiscus Coast	256.0	27.3	16.8	61.7%	10.7%	6.6%
Hauraki Gulf Islands	386.0	2.7	0.5	19.0%	0.7%	0.1%
Kaipara Harbour	1,406.5	7.3	2.7	37.8%	0.5%	0.2%
Mahurangi Estuary	128.6	2.7	1.2	43.8%	2.1%	0.9%
Manukau Harbour	917.8	75.3	46.9	62.3%	8.2%	5.1%
North East Coast	240.5	2.0	0.7	36.3%	0.8%	0.3%
Tamaki Estuary	190.0	46.7	31.6	67.6%	24.6%	16.6%
Wairoa Coast	419.8	2.4	1.0	39.9%	0.6%	0.2%
Waitematā Harbour	449.0	105.7	69.4	65.7%	23.6%	15.5%
West Coast	409.0	1.3	0.4	29.9%	0.3%	0.1%
Auckland Council	**4,803.2**	**273.5**	**171.3**	**62.6%**	**5.7%**	**3.6%**

The relative footprints of stormwater green infrastructure (SGI) within sub-catchments were determined as are a key determinant on hydrology and water quality contaminant attenuation (see Pennino et al., 2016). Typically, optimal sizing of impervious area for reduction in channel shaping erosional flows downstream are in the range of 2-5% of catchment area (i.e., ensuring detention of 90% of runoff events and 80% of combined annual runoff volume for >24hr, which aligns well with the threshold for channel-shaping or eroding flows downstream [Auckland Regional Council, 2003]).

Across the region, the 95th percentile estimate of pond-to-catchment area was 0.3%. Using the assumption that ponds manage a land area approximately 15 times greater than their footprint, approximately 5% of sub-catchments had more than 4.5% of their land managed by ponds. All such sub-catchments were subject to parameter adjustment, which involved increasing upper-zone storage and interception storage on pervious land and impervious land, respectively. Therefore, the ponds were not explicitly represented, rather, the impact on 5% of sub-catchments impacted by existing ponds were reflected through parameter changes on pervious and impervious HRUs.

Note that a wider inventory of structural stormwater devices can be incorporated into successive stages of the FWMT. Either approximately (indirectly as above) or directly through SUSTAIN to better simulate the filling and drawdown of those devices in a process-based manner.

3.9 Instream Processes

The LSPC model within the FWMT Stage 1 was configured to represent instream sediment and nutrient processes affecting downstream loading, with the explicit purpose of better enabling freshwater management for coastal contaminant outcomes. The FWMT can thereby enable accounting of contaminant yields to nearest instream receiving environment (within sub-catchments) and to downstream reporting locations (across sub-catchments). Doing so required activation of the sediment, temperature, and RQUAL modules within LSPC. Within RQUAL, subroutines for dissolved oxygen-biological oxygen demand (DO-BOD) and plankton were also activated. Parameters within the DO-BOD and plankton subroutines relied on default values. Section 2.3 contains figures, tables and further discussion of simulated processes.

The RQUAL module within LSPC simulates instream biochemical transformations of nutrients. Biochemical processes represented in RQUAL included nitrification, dentification, benthic releases of nutrients, nutrient adsorption to suspended sediment, and algal growth/death rates and associated nutrient requirements. Although RQUAL contains the main algorithms for quantifying instream nutrient dynamics, the inputs to these algorithms are interconnected with other modules. RQUAL nutrient transformations are a function of simulated instream temperature, which also influences DO-BOD and plankton subroutines (noting temperature simulation is not calibrated owing to a lack of suitable or robust continuous instream temperature observations within the Auckland region). Transformations simulated for the FWMT Stage 1 using RQUAL are presented in Section 2.3 and include deposition, resuspension, adsorption, desorption and benthal release of phosphorus and nitrogen. While RQUAL and its affiliated algorithms represented instream processes, the sediment module was used for simulating land-based processes responsible for the production and removal of sediment from both pervious and impervious land. Previous applications of LSPC using both the sediment and RQUAL modules include studies of the Flathead Lake watershed in Montana USA (Tetra Tech, 2014a) and the James River watershed in Virginia USA (Tetra Tech, 2014b). Both studies successfully utilised those LSPC modules to establish baseline sediment and nutrient loadings to quantify the water quality impacts from both agricultural and urban areas and to assess the impact of various watershed management scenarios.

Some parameters within the temperature, RQUAL, and sediment modules were adjusted within LSPC through a “reach-group” based approach. Similar to how land segments were classified into HRUs, the reach-group construct was used to group and parameterise model reach segments. Initial parameter values were based on recommended values provided in Bicknell et al. (1997) and USEPA (2000), Reach groups related certain physical characteristics—segments within a reach group are assumed to exhibit similar instream processes, which in turn impact responses in nutrient speciation and fate and transport. Three factors were established for characterising reach groups: shade, nutrients, and sediment. Within each group, a reach was designated a classification (e.g., low, medium, or high) to reflect the relative impact of those factors on instream processes. For example, break points for the slope factor included: <2% classified as low, slopes 2%-4% classified as medium and slopes >4% classified as high. As with HRU impacts, reach group factors were used to manage the breath of variability among model parameters while providing physical bases and rationale for how parameters were assigned and/or varied.

The shade reach group factor was used to characterise existing stream shading on a relative basis for stream temperature simulation. Although reach group factors and thresholds were established during configuration, parameters associated with those groups were adjusted during calibration to improve agreement between observed and predicted sediment and nutrient concentrations and loads. Whilst using reach groups prevents each modelled reach within a sub-catchment from having unique parameters assigned to instream processes, it provides a meaningful and systematic way to generalise parameter variation, with up to 5, 25 and 81 unique reach groups for shade, nutrient processes, and sediment processes, respectively.

3.9.1 Stream Shade Nutrient Processes and Reach Group

Temperature dependence is present in nearly all processes impacting nutrient dynamics in streams. Within the FWMT Stage 1, stream temperature impacts saturation levels of DO, the BOD caused by decaying organic matter, and the prevalence of benthic algae. In turn, oxygen levels within a stream affect denitrification as well as algae growth levels. Where available, Watercourse Assessment Report (WAR) GIS data (ARC, 2016b) were extracted to determine the extent of channel shading. The WAR data represented baseline information on the existing condition of waterways, including results of field assessments to visually determine the proportion of the water surface shaded by vegetation or topography. For reaches lacking WAR data, Freshwater Ecosystem of New Zealand (FENZ) data for predicted riparian shading (Leathwick et al., 2010) were used. These data were collected using national, satellite image-based vegetation classifications. The extent of stream shading for streams were separated into five classifications. Based on designated shade classifications, the correction factor for solar radiation (Cfsaex), which represents the fraction of reach surface exposed to radiation within the temperature module, was adjusted during model configuration. Table 3-24 shows the resulting reach groups for shade. Approximately 37% of model stream reaches were classified as medium-high shade, with 28% and 27% of reaches classified as high or medium, respectively. The remaining 8% of reaches were classified as either low-medium or low.

Table 3-24. Shade group classifications and associated Cfsaex value

Categories (per cent of stream reach shaded)	Shade Classification	Cfsaex value
>70%	High	0.225
50%-70%	Medium-High	0.399
30%-50%	Medium	0.584
10%-30%	Low-Medium	0.778
<10%	Low	0.989

3.9.2 Stream Nutrient Processes and Reach Group

To facilitate the calibration of NO3N and DRP based on observed data, as well as the later optimisation of intervention strategies, nutrient groups were established. Model reaches with similar stream and watershed characteristics were assigned to unique nutrient groups; these groups could then be parameterised during calibration to manage the variability of model parameters by associating them with measurable physical characteristics (Figure 3-62). Two factors were chosen for assigning reaches to a nutrient group: shade and the amount of pastoral/horticultural land in the upstream drainage area. Shade categories used to adjust Cfsaex were also used in the nutrient group; however, when combined with information about the amount of upstream agricultural area, the number of combinations increases. Table 3-25 shows high/medium/low nutrient classifications for combinations of shade and upstream agricultural area. Agricultural land cover data were obtained from FWMT Land Use/Cover layer (Section 3.8.3).

Table 3-25. Parameters adjusted during calibration based on nutrient group classification

Parameter	Description	Module	Unit
KTAM20	Nitrification rate of NH4N	RQUAL	1/hr
KNO320	Dentification rate of NO3N	RQUAL	1/hr

The combinations of nutrient reach group factors (and associated model parameterisation) provided a qualitative assessment of expected stream condition. Water quality impacts of contaminants are often moderated by riparian cover (Meals and Hopkins, 2002) as well as the amount of agriculture within the watershed (i.e., as a broad proxy for wider ecosystem functions that can mitigate contaminant effect but which in turn are degraded by land use; Omernik, 1976; PCE, 2013; Larned et al., 2016; PMCSA, 2017; Julian et al., 2017). Low, medium, and high nutrient groups were expected to have dissolved nitrogen and phosphorus concentrations varying in similar order (e.g., lesser for low).

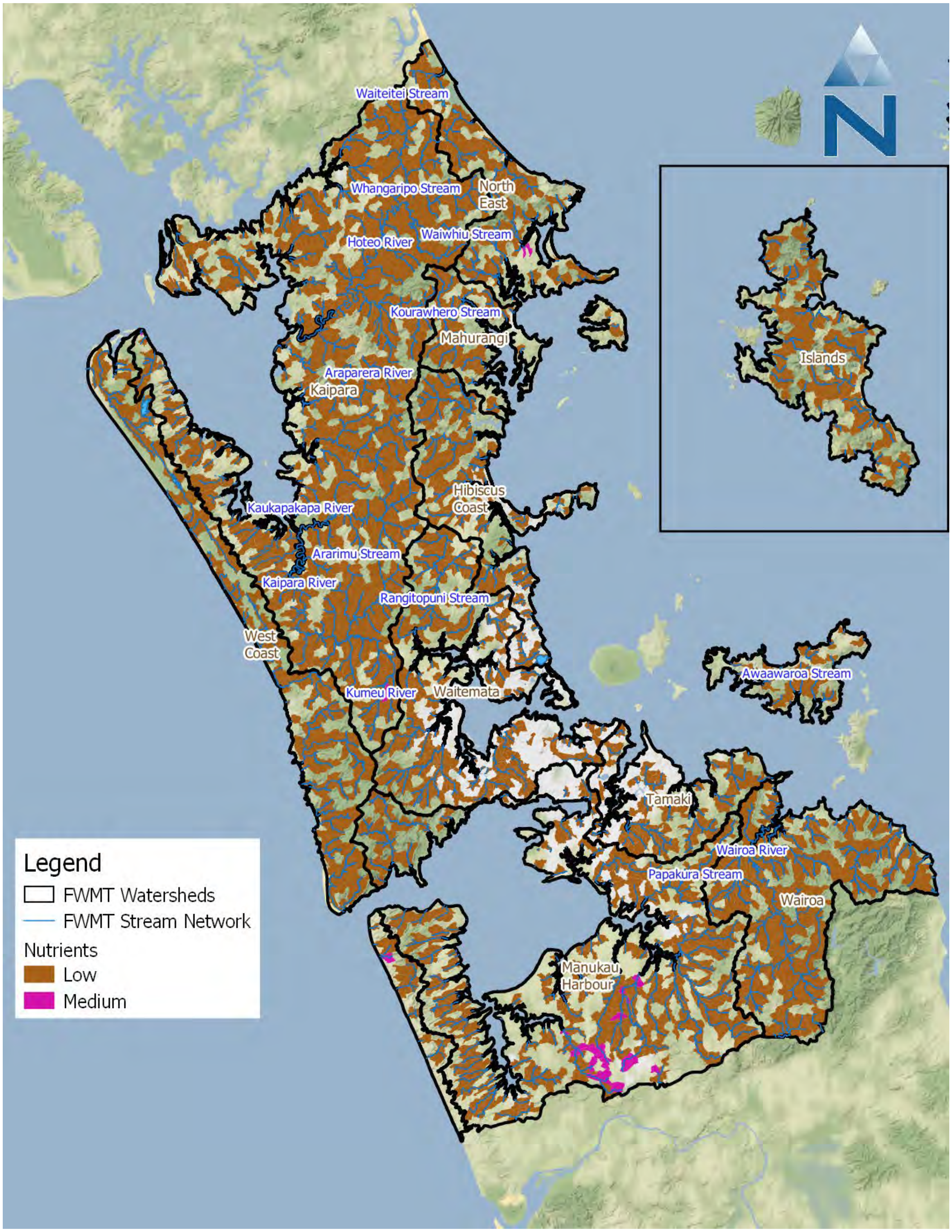


Figure 3-62. Stream nutrient group classifications in the FWMT

3.9.3 Stream Sediment Processes and Reach Group

Within LSPC, sediment can enter water bodies by being detached and washed off land surfaces, scoured from the HRU soil matrix through gully erosion, scoured from the stream bank through stream bank erosion, or introduced through point sources (Figure 2-7). In LSPC, all sources of sediment are partitioned into particle size categories, each of which is modelled as completely mixed within the stream segment. An overview of these processes and a discussion of all sediment sources is provided below.

The FWMT factors affecting erosion from land surfaces include erosion potential, slope, and vegetation. Erosion potential, reflected in the KRER/JRER parameters (Figure 2-7), is typically adjusted based on HSG and other HRU characteristics, but may be modified to account for specific soil characteristics such as particle size. Within LSPC, all sediment, whether washed off from impervious surfaces or eroded from pervious surfaces including in the form of gully and stream bank erosion, is partitioned into sand, silt and clay particle size categories by HRU at the edge-of-stream, prior to routing. Once in the stream, transportation, deposition, and resuspension processes are a function of the particle sizes of sand, silt and clay and associated fall velocities and streamflow energy thresholds (i.e., critical shear stresses). Within any given stream segment, transported sand, silt, and clay from upstream reaches, all HRUs in the immediate sub-catchment, atmospheric deposition, and available point sources are assumed completely mixed.

Each instream sediment size class was also modelled perpetually – that is eroded sand always remained as sand, silt always as silt, and clay always as clay instream (i.e., no further weathering of particles along their instream journey). Eroded sediment mass was estimated as sand/silt/clay portions based on the particle size distributions associated with the HSG assigned to the contributing HRUs (Figure 3-63). The A+ HSG was assumed to have the same portions of sand, silt and clay as the A group (Table 3-26). Nevertheless, the infiltration rate index parameter for A+ soils was modelled with a higher value for A+ soils relative to A soils.

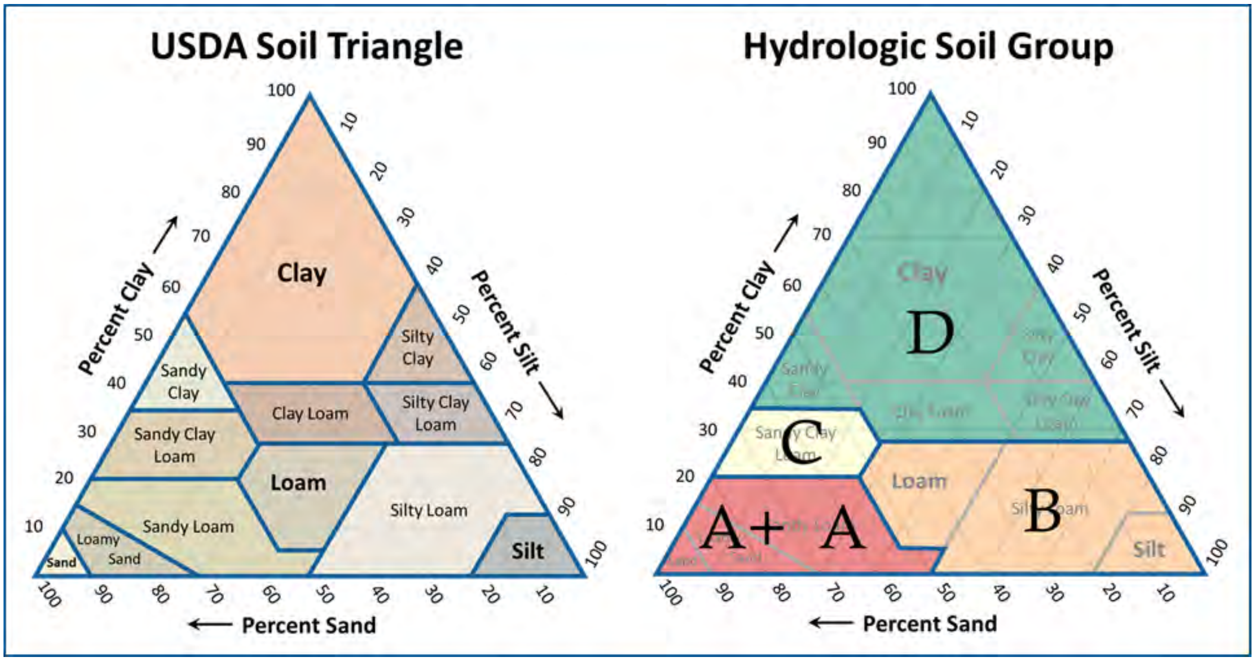


Figure 3-63. Standard USDA Soil Triangle with Hydrologic Soil Group mapping

Table 3-26. Estimated particle size distribution by hydrologic soil group and for impervious surfaces

Hydrologic Soil Group	Sand	Silt	Clay
A+	70%	10%	20%
A	70%	10%	20%
B	20%	65%	15%
C	50%	20%	30%
D	60%	20%	20%
Impervious Surfaces	10%	70%	20%

Resuspension, transport, and deposition of cohesive sediments (silt and clay) depends on the shear stress exerted on the streambed surface. Regionwide critical shear stress was assigned to reach segments for each of silt and clay TSS fractions, as per Table 3-27.

Table 3-27. Calibrated critical sheer stress thresholds by sediment class

Sediment Class	Deposition	Resuspension
Sand	Power Function[1]	Power Function[1]
Silt	5 Pa	14 Pa
Clay	1 Pa	9 Pa

1: Sand transport is modelled using a power function on velocity (coefficient and exponent)

The critical shear stress parameters for settling and resuspension of silt and clay were calibrated to observed values at downstream gauge locations. When boundary shear stresses are below the user-defined critical shear stress, deposition occurs, when shear stresses are greater than critical shear stress, resuspension occurs. Within LSPC, sand movement is modelled using a user-specified power function of velocity. Both boundary shear stress and velocity are derivative values computed as a function of flow volume and channel geometry. Variation in critical shear stress represents physical process effects of smaller grains being more easily resuspended and remaining in suspension longer than larger grains. Streams with higher slopes and flow rates will resuspend sediment more easily and more often, while streams with lower slopes and lower flow rates experience more sediment deposition due to variation in boundary shear stress (e.g., under equivalent critical shear stress). Critical shear stress was assumed to be a function of the material in the bed, varying by sediment class.

Table 3-27 represents the energy required to mobilise silt and clay, respectively, with clay particles requiring less energy to resuspend than silt particles, and only depositing when boundary shear stress is less than 1 Pa. Critical shear stress terms were globally applied by sediment class.

Figure 3-64 shows the per cent of time that silt and clay particles spend in deposition, transport, and resuspension within modelled stream reaches, as estimated from critical shear stress values in Table 3-26 and computed against modelled hydrology and HSG-inferred channel sediment composition. For pond segments, critical shear stress for deposition and resuspension were not applicable, with sediment settling at the particle settling rate for still water.

Figure 3-65 shows how reach slope influences the range and variability of boundary shear stress. Figure 3-66 shows the per cent of time that silt and clay particles remain in deposition, transport, or resuspension. Steeper-sloped streams have more sediment in resuspension and transport, while lower-sloped streams segments have more sediment in deposition. Regardless of slope, the heavier silt particles spend more time in deposition than the lighter clay particles.

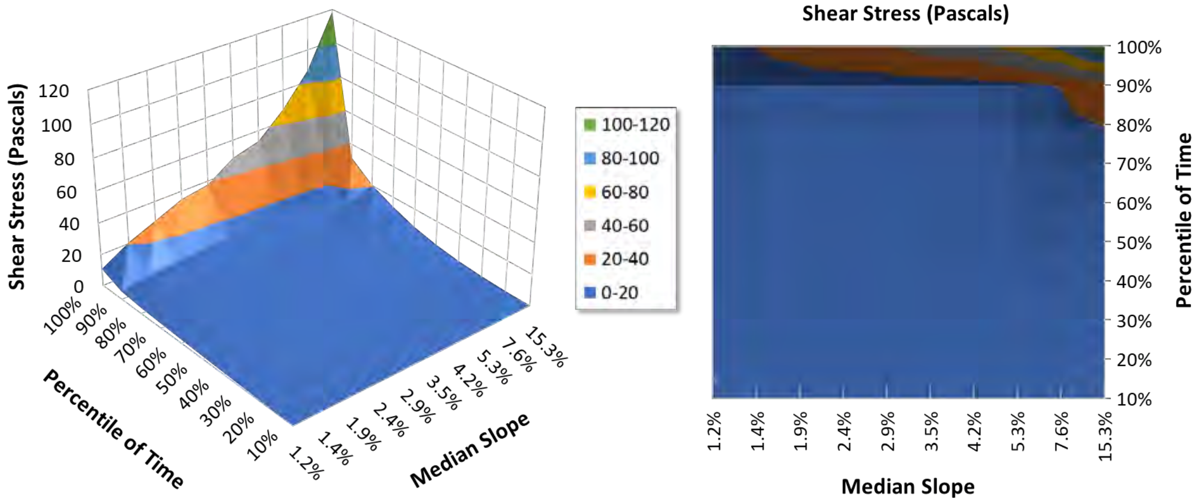


Figure 3-64. Surface of channel boundary shear stress vs. slope and per cent of time (all modelled reaches)

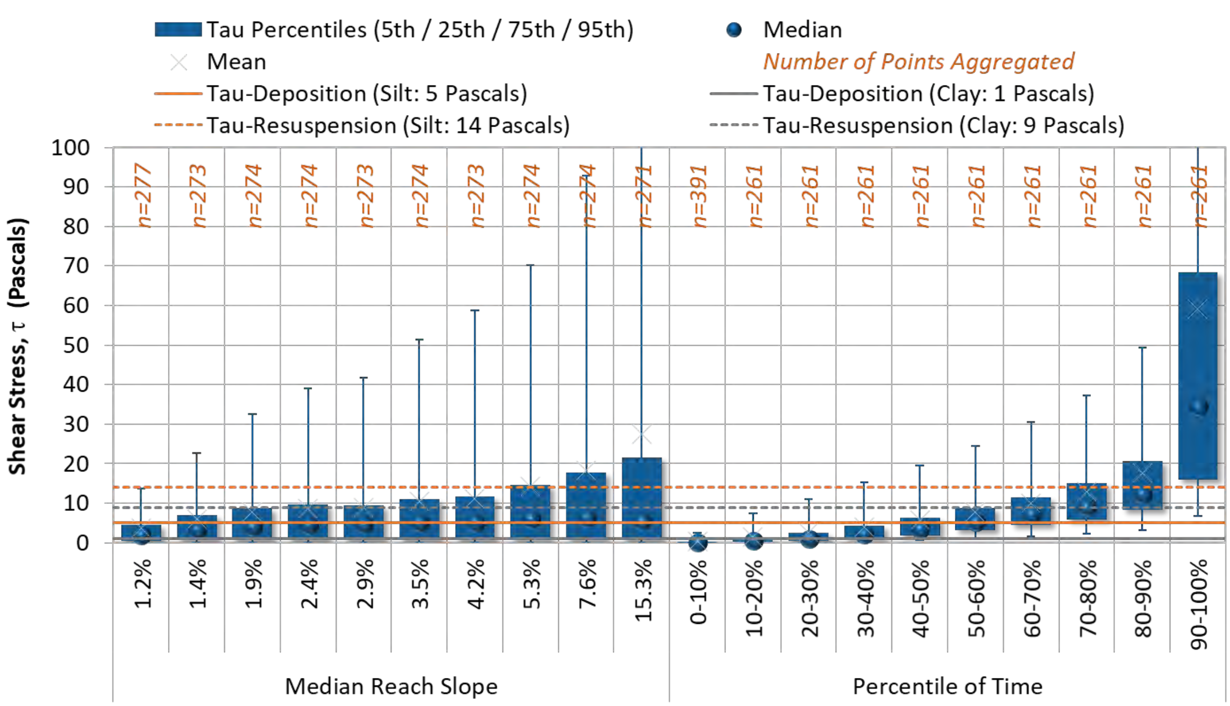


Figure 3-65. Estimated critical shear stress for deposition and resuspension vs. distribution of boundary shear stress by median reach slope and per cent of time for all modelled reaches

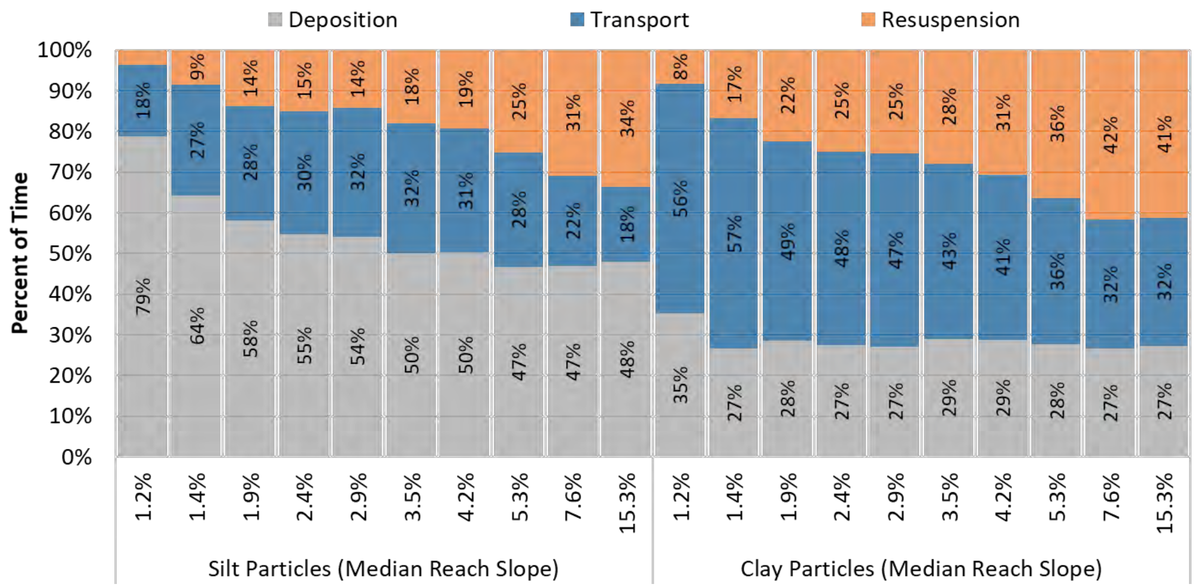


Figure 3-66. Per cent of time that silt and clay particles spend in deposition, transport, and resuspension in the FWMT Stage 1 reach segments, as estimated from critical shear stress values

3.9.3.1 Build-up and wash off from impervious surfaces

Build-up and wash off functions in the sediment module are based on those in the NPS Model (Donigian and Crawford, 1976) and are similar to the equations developed for the accumulation and wash off of dust and dirt on street surfaces (APWA, 1969; Sartor et al., 1974). Figure 3-67 depicts a sediment simulation diagram for impervious surfaces and instream transport. Build-up of sediment (kg/day) on impervious surfaces within the FWMT was simulated using an exponential function. Wash off of sediment (kg/timestep) was estimated by a power equation for overland flow (runoff rate). The amount of sediment available to be washed off could not exceed the amount of sediment that had built up on the impervious surface. Parameters affecting both build-up and wash off were adjusted during calibration.

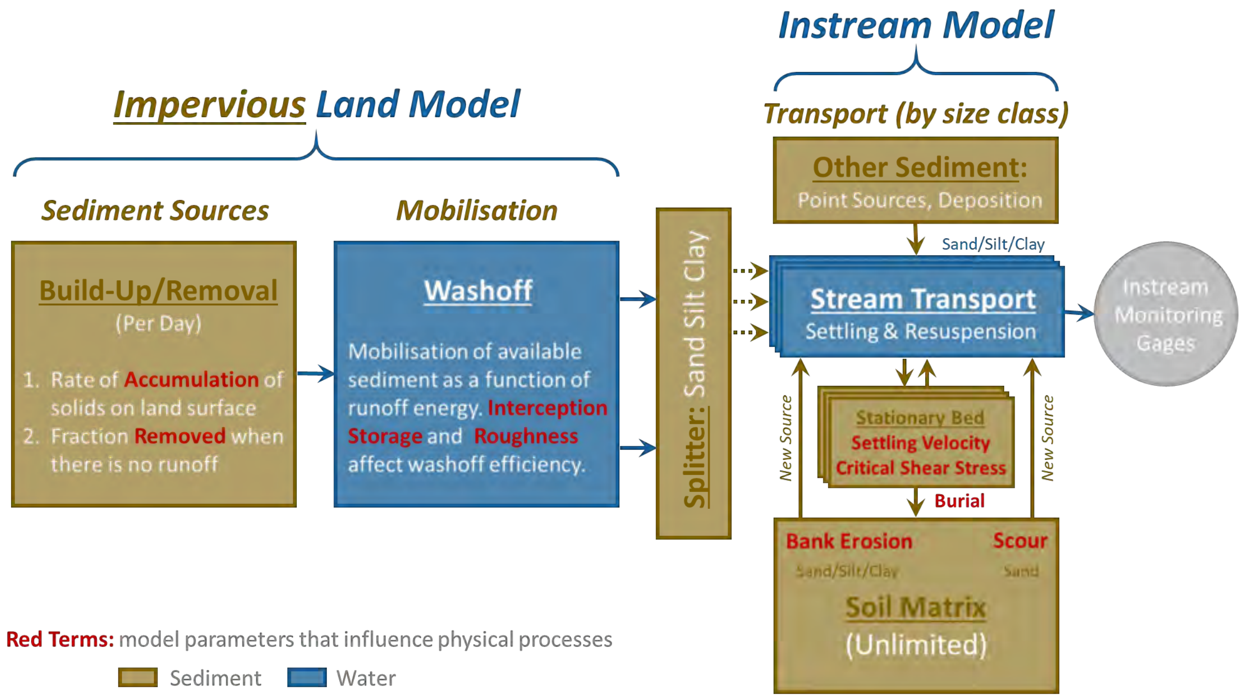


Figure 3-67. Sediment simulation process diagram for impervious surfaces upstream of instream transport

3.9.3.2 Sediment detachment and wash off

On pervious land, LSPC sediment export processes are governed by equations developed by Negev (1967) and also incorporated into the Stanford Watershed Model (Crawford and Linsley, 1966). The algorithms for sediment detachment and runoff have similar parameters to the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) including those representing soil erodibility, rainfall erosivity, management practices, and vegetation cover. Detachment of soil due to the impact of rainfall is governed by a detachment coefficient and exponent. Kinetic energy from rain falling on an HRU detaches soil particles which are then available to be transported by overland flow. The equation for detachment is given as:

$$(1) \qquad DET = DELT60\,(1.0 - CR) * SMPF * KRER * \left(\frac{RAIN}{DELT60}\right)^{JRER}$$

where DET is the sediment detached from the soil matrix by rainfall (mass/area/time), DELT60 is hours per timestep (unitless), CR is the fraction of the HRU with vegetative or other cover, SMPF is the supporting management practice factor, KRER is the detachment coefficient for the HRU, RAIN is the rainfall (depth/time), and JRER is the detachment exponent for the HRU.

To simulate the wash off of detached sediment generated from Equation 1, the transport capacity of overland flow is estimated and compared to the amount of detached sediment available. The transport capacity is calculated by the equation:

$$(2) \qquad \mathrm{STCAP} = DELT60 * KSER * \left(\frac{SURS+SURO}{DELT60}\right)^{JSER}$$

where STCAP is the capacity for removing detached sediment (mass/area/time), DELT60 is hours/timestep (unitless) SURS is the initial surface storage (volume), SURO is the surface outflow (volume/time), KSER is the transport coefficient for the HRU, and JSER is the transport exponent for the HRU. When STCAP is greater than the amount of detached sediment in storage, wash off is calculated by:

$$(3) \qquad \mathrm{WSSD} = DETS * \left(\frac{SURO}{(SURS+SURO}\right)$$

if the storage is enough to fulfil the transport capacity, the wash off is calculated as:

$$(4) \qquad \mathrm{WSSD} = STCAP * \left(\frac{SURO}{(SURS+SURO}\right)$$

where WSSD is the wash off of detached sediment (mass/area/time) and DETS is the detached sediment storage (mass/area). WSSD is then subtracted from DETS.

3.9.3.3 Gully Erosion

In addition to soil becoming detached due to the impact of rainfall, sediment can also be mobilised from an HRU through scouring due to overland flow. Like the equations for sediment detachment and wash off, the equation representing scouring of the matrix soil is based on the sediment model component of the Stanford Watershed Model (Negev, 1967). Within LSPC, scour from the land surface of an HRU is calculated as:

$$(5) \qquad \boldsymbol{SCRSD} = \frac{\boldsymbol{SURO}}{(\boldsymbol{SURS}+\boldsymbol{SURO})} \times \boldsymbol{DELT60} \times \boldsymbol{KGER} \times \left(\frac{\boldsymbol{SURS}+\boldsymbol{SURO}}{\boldsymbol{DELT60}}\right)^{\boldsymbol{JGER}}$$

where SCRSD is HRU scour sediment yield (mass/area/time), SURO is surface runoff outflow (vol/time), SURS is surface water storage (vol), DELT60 is hours per timestep (unitless), KGER is coefficient for HRU matrix soil scour (unitless), JGER is the exponent for HRU matrix soil scour (unitless), SURS and SURO were previously defined for equation (2).

Scouring is independently simulated from other sources of sediment, such as build up and wash off from impervious land. Scouring mobilises sediment from an unlimited source and is driven by the amount of overland flow. The ability of runoff to scour is not diminished due to energy losses from mobilising other sources of sediment.

3.9.3.4 Streambank Erosion and Reach Group

A process to specifically estimate streambank erosion was added to LSPC for the FWMT Stage 1 using an equation analogous to the one used for gully erosion and included a coefficient and exponent to characterise scour from the stream bank soil matrix. While both gully and soil detachment due to rainfall occur at the HRU level, stream bank erosion occurs within a reach. Figure 3-68 depicts a sediment simulation diagram for pervious surfaces upstream of instream transport. Sediment sources, including detachment by rainfall, scour, and erosion from stream banks are highlighted in red. Although gully erosion was associated with the rate of overland flow on an HRU, streambank erosion was associated with a “runoff” depth calculated as the cumulative flow into the reach segment divided by the cumulative drainage area upstream of the reach. Dividing cumulative streamflow by upstream area produced a term that not only took into account the cumulative-aggregated streamflow in the reach segment, but also, preserved the numerical form of water depth per unit area of land segment, analogous to the characterisation of gully erosion in Negev’s (1967) equations. Within LSPC stream bank erosion was calculated as:

$$(6) \qquad BERSD = DELT60 \times KBER \times \left(\frac{UARO}{DELT60}\right)^{JBER}$$

where BERSD is model reach bank erosion sediment yield (mass/area/time), DELT 60 is hours/timestep (unitless), UARO is the unit-area outflow (vol/time) of the cumulative-aggregated upstream flow, KBER is equal to a coefficient of stream bank matrix soil scour, and JBER is an exponent governing the scouring from the stream bank matrix soil. UARO was calculated as follows:

$$(7) \qquad UARO = \frac{Cumulative\ Flow}{Cumulative\ Drainage\ Area}$$

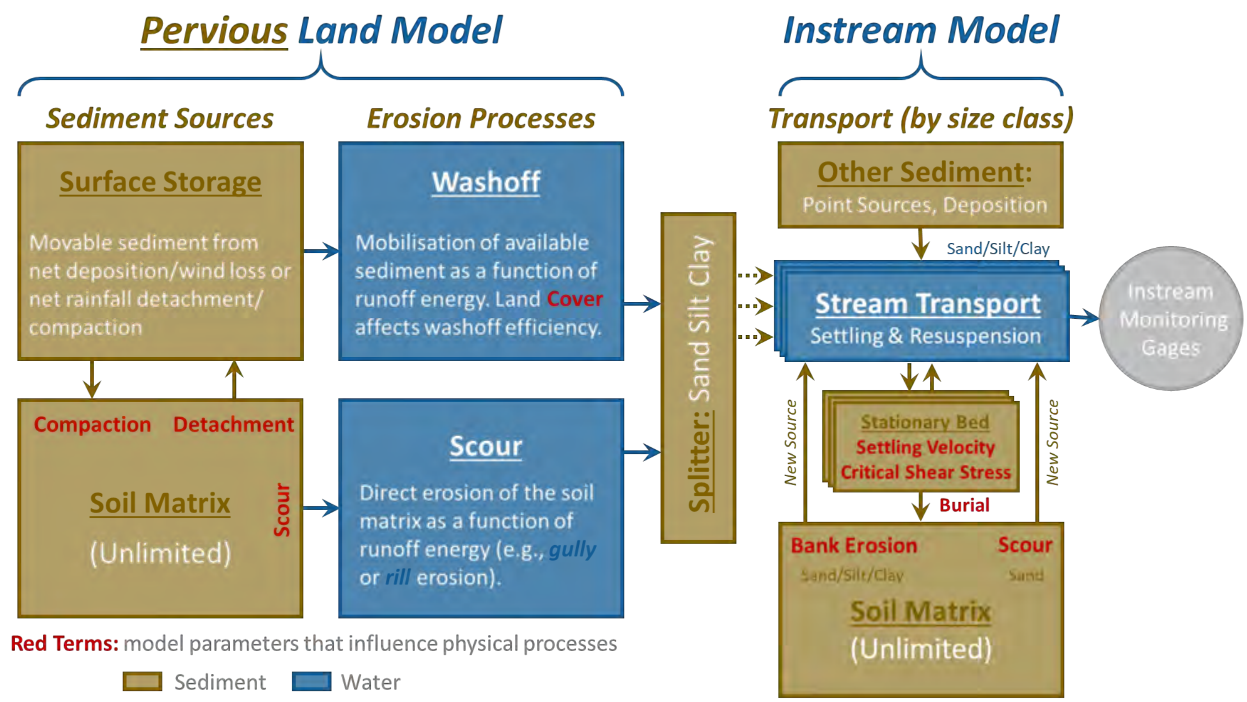


Figure 3-68. Sediment simulation process diagram for pervious surfaces upstream of instream transport

Stream erosion groups were established to facilitate the calibration of sediment export in the FWMT by adjusting the coefficient of scour from the stream bank soil matrix (KBER) in equation (6). Stream reaches were classified based on their likely susceptibility to erosion. Factors affecting stream sediment erodibility were bank material, cover, slope, and stream order (Table 3-28). Bank cover was estimated through GIS analysis by generating a 20 m buffer on either side of stream reaches and intersecting that buffer with the FWMT vegetation layer. The FWMT vegetation layer was generated from a 2006/10 LiDAR-derived vegetation height layer provided by Auckland Council. Bank material was classified as being soft, intermediate, and hard/lined categories.

Several datasets were used to classify bank material, with priority given to WAR data where available, followed by AC SW watercourse/channel data, FENZ data, and NZLRI data. When no other data was available GNS – NZ geology data was used for classification. Further information on data sources utilised for erosion reach groups is presented in [FWMT Baseline Data Inputs, Section 9.3]. Table 3-29 presents how the material, cover, slope and stream order were combined to generate erosion classifications of low, medium, and high. Figure 3-69 displays the sediment group classifications by sub-catchment.

Table 3-28. Parameters adjusted during calibration based on nutrient group classification

Factors	Categories	Data source	Description
Material	Soft, Intermediate, Hard/Lined	Auckland Council Watercourse Assessment Report (WAR)	Stream substrate material
		Auckland Council SW channel network layer	Streams recorded as artificially lined
		NZ Dept. of Conservation Freshwater of New Zealand (FENZ) geodatabase	Stream substrate material
		GNS Science – Geology	Geology layer
		NZ Land Resource Inventory	Geology layer
Bank Cover	<30%; 30-70%; >70%	FWMT Vegetation layer (vegetation >1.5m)	Per cent cover of vegetation > 1.5 m in height
Slope	<2%; 2%-4%; >4%	FWMT streams layer	Reach slope
Stream order	1 and 2, 3 and 4, >5	FWMT streams layer	Stream order
		NZ Ministry for the Environment River Environment Classification (REC) database	

Table 3-29. Erosion group classifications

Material	Cover	Slope	Stream Order	Erosion Group Classification
Intermediate	<30%	High (>0.04)	Low (1 and 2)	High
Soft	<30%	Med (0.02-0.04)	Low (1 and 2)	High
Soft	<30%	High (>0.04)	Low (1 and 2)	High
Soft	<30%	High (>0.04)	Middle (3 and 4)	High
Soft	30-70%	High (>0.04)	Low (1 and 2)	High
Intermediate	<30%	Med (0.02 - 0.04)	Low (1 and 2)	Medium
Intermediate	<30%	Med (0.02 - 0.04)	Middle (3 and 4)	Medium
Intermediate	<30%	High (>0.04)	Middle (3 and 4)	Medium
Intermediate	<30%	High (>0.04)	High (>= 5)	Medium
Intermediate	30-70%	Med (0.02 - 0.04)	Low (1 and 2)	Medium
Intermediate	30-70%	Med (0.02 - 0.04)	Middle (3 and 4)	Medium
Intermediate	30-70%	High (>0.04)	Low (1 and 2)	Medium
Intermediate	30-70%	High (>0.04)	Middle (3 and 4)	Medium
Soft	<30%	Low (<0.02)	Low (1 and 2)	Medium
Soft	<30%	Med (0.02 - 0.04)	Middle (3 and 4)	Medium
Soft	<30%	Med (0.02 - 0.04)	High (>= 5)	Medium
Soft	<30%	High (>0.04)	High (>= 5)	Medium
Soft	30-70%	Med (0.02 - 0.04)	Low (1 and 2)	Medium

Material	Cover	Slope	Stream Order	Erosion Group Classification
Soft	30-70%	Med (0.02 - 0.04)	Middle (3 and 4)	Medium
Soft	30-70%	High (>0.04)	Middle (3 and 4)	Medium
Soft	30-70%	High (>0.04)	High (>= 5)	Medium
Soft	>70%	High (>0.04)	Low (1 and 2)	Medium
Hard/Lined	<30%	Low (<0.02)	Low (1 and 2)	Low
Hard/Lined	<30%	Low (<0.02)	Middle (3 and 4)	Low
Hard/Lined	<30%	Low (<0.02)	High (>= 5)	Low
gHard/Lined	<30%	Med (0.02 - 0.04)	Low (1 and 2)	Low
Hard/Lined	<30%	Med (0.02 - 0.04)	Middle (3 and 4)	Low
Hard/Lined	<30%	Med (0.02 - 0.04)	High (>= 5)	Low
Hard/Lined	<30%	High (>0.04)	Low (1 and 2)	Low
Hard/Lined	<30%	High (>0.04)	Middle (3 and 4)	Low
Hard/Lined	<30%	High (>0.04)	High (>= 5)	Low
Hard/Lined	30-70%	Low (<0.02)	Low (1 and 2)	Low
Hard/Lined	30-70%	Low (<0.02)	Middle (3 and 4)	Low
Hard/Lined	30-70%	Low (<0.02)	High (>= 5)	Low
Hard/Lined	30-70%	Med (0.02 - 0.04)	Low (1 and 2)	Low
Hard/Lined	30-70%	Med (0.02 - 0.04)	Middle (3 and 4)	Low
Hard/Lined	30-70%	Med (0.02 - 0.04)	High (>= 5)	Low
Hard/Lined	30-70%	High (>0.04)	Low (1 and 2)	Low
Hard/Lined	30-70%	High (>0.04)	Middle (3 and 4)	Low
Hard/Lined	30-70%	High (>0.04)	High (>= 5)	Low
Hard/Lined	>70%	Low (<0.02)	Low (1 and 2)	Low
Hard/Lined	>70%	Low (<0.02)	Middle (3 and 4)	Low
Hard/Lined	>70%	Low (<0.02)	High (>= 5)	Low
Hard/Lined	>70%	Med (0.02 - 0.04)	Low (1 and 2)	Low
Hard/Lined	>70%	Med (0.02 - 0.04)	Middle (3 and 4)	Low
Hard/Lined	>70%	Med (0.02 - 0.04)	High (>= 5)	Low
Hard/Lined	>70%	High (>0.04)	Low (1 and 2)	Low
Hard/Lined	>70%	High (>0.04)	Middle (3 and 4)	Low
Hard/Lined	>70%	High (>0.04)	High (>= 5)	Low
Intermediate	<30%	Low (<0.02)	Low (1 and 2)	Low
Intermediate	<30%	Low (<0.02)	Middle (3 and 4)	Low
Intermediate	<30%	Low (<0.02)	High (>= 5)	Low
Intermediate	<30%	Med (0.02 - 0.04)	High (>= 5)	Low
Intermediate	30-70%	Low (<0.02)	Low (1 and 2)	Low
Intermediate	30-70%	Low (<0.02)	Middle (3 and 4)	Low
Intermediate	30-70%	Low (<0.02)	High (>= 5)	Low
Intermediate	30-70%	Med (0.02 - 0.04)	High (>= 5)	Low
Intermediate	30-70%	High (>0.04)	High (>= 5)	Low
Intermediate	>70%	Low (<0.02)	Low (1 and 2)	Low
Intermediate	>70%	Low (<0.02)	Middle (3 and 4)	Low

Material	Cover	Slope	Stream Order	Erosion Group Classification
Intermediate	>70%	Low (<0.02)	High (>= 5)	Low
Intermediate	>70%	Med (0.02 - 0.04)	Low (1 and 2)	Low
Intermediate	>70%	Med (0.02 - 0.04)	Middle (3 and 4)	Low
Intermediate	>70%	Med (0.02 - 0.04)	High (>= 5)	Low
Intermediate	>70%	High (>0.04)	Low (1 and 2)	Low
Intermediate	>70%	High (>0.04)	Middle (3 and 4)	Low
Intermediate	>70%	High (>0.04)	High (>= 5)	Low
Soft	<30%	Low (<0.02)	Middle (3 and 4)	Low
Soft	<30%	Low (<0.02)	High (>= 5)	Low
Soft	30-70%	Low (<0.02)	Low (1 and 2)	Low
Soft	30-70%	Low (<0.02)	Middle (3 and 4)	Low
Soft	30-70%	Low (<0.02)	High (>= 5)	Low
Soft	30-70%	Med (0.02 - 0.04)	High (>= 5)	Low
Soft	>70%	Low (<0.02)	Low (1 and 2)	Low
Soft	>70%	Low (<0.02)	Middle (3 and 4)	Low
Soft	>70%	Low (<0.02)	High (>= 5)	Low
Soft	>70%	Med (0.02 - 0.04)	Low (1 and 2)	Low
Soft	>70%	Med (0.02 - 0.04)	Middle (3 and 4)	Low
Soft	>70%	Med (0.02 - 0.04)	High (>= 5)	Low
Soft	>70%	High (>0.04)	Middle (3 and 4)	Low
Soft	>70%	High (>0.04)	High (>= 5)	Low

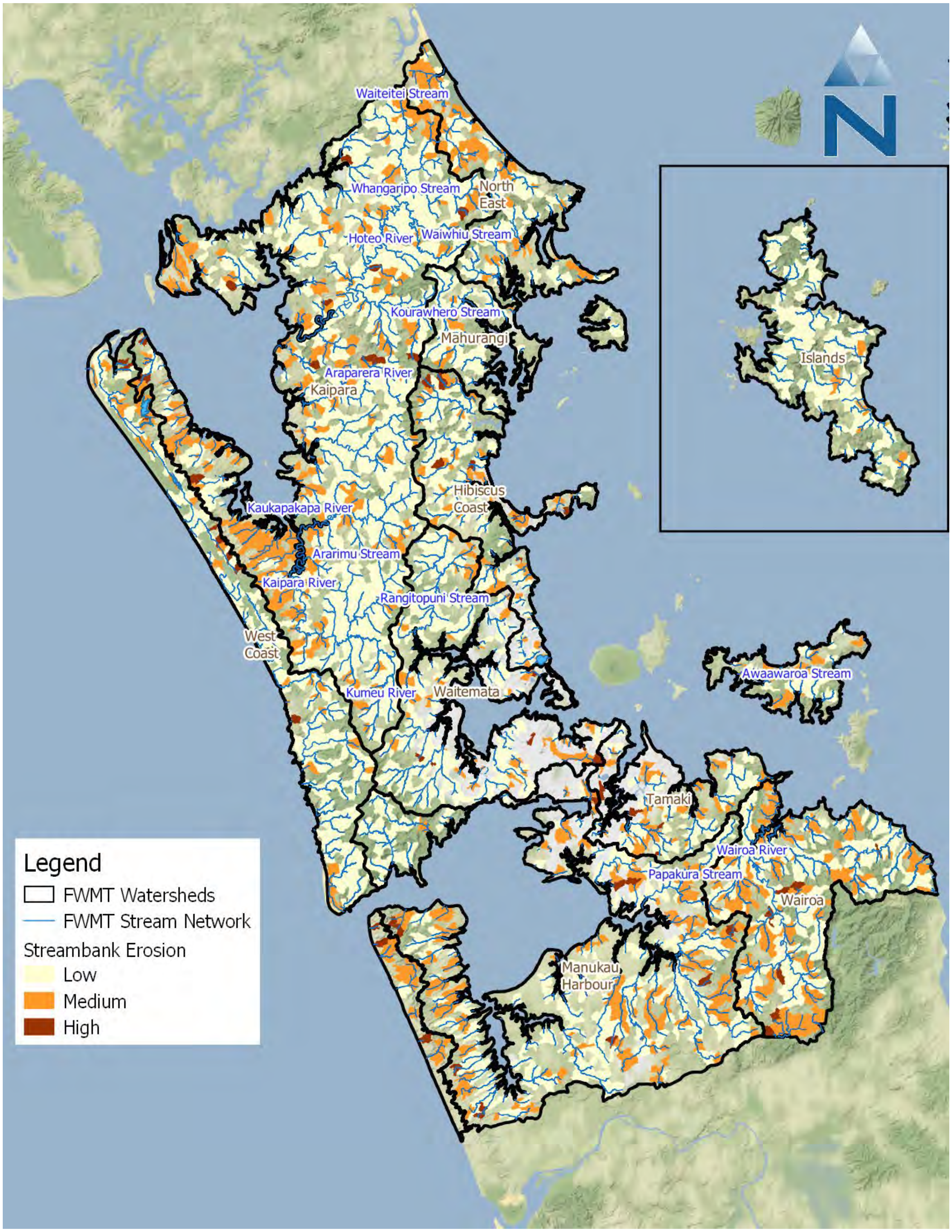


Figure 3-69. Streambank erosion susceptibility classifications in the FWMT

3.10 Groundwater Impacts on Surface Waters

Groundwater and interflow concentrations for TN, TP, Cu, Zn, and *E. coli* were adjusted during calibration to represent subsurface contributions and improve agreement between observations and predictions. Satisfactory calibration results could not be achieved by adjusting overland flow parameters alone, suggesting that subsurface contributions play a substantial role in regional surface water quality. These adjustments occurred at the HRU level and were applied across the region. The area of the Franklin Volcanic Aquifer was calibrated separately and based on more detailed groundwater nitrogen sampling. Groundwater adjustments included metals given observed trace amounts in New Zealand aquifers (Pang et al., 2004). The addition of simulated groundwater *E. coli* concentrations whilst unusual is an accepted approach to modelling bacteria fate and transport in watershed models (e.g., Benham et al., 2006).

Table 3-30 presents regionwide, flow-weighted average interflow and groundwater concentrations for Cu, Zn, and *E. coli* (2013-2017). Agreement between observations and predictions for TN and TP were further improved by applying monthly variations to subsurface concentrations from pasture, horticulture and forest by month (Figure 3-70 and Figure 3-71). The full set of regional and Franklin Aquifer values can be found in Appendix A.

Table 3-30. Interflow and active groundwater outflow for Cu, Zn, and *E. coli*

	Copper (mg/L)		Zinc (mg/L)		*E. coli* (#/100ml)	
Land Use	**Interflow**	**Groundwater**	**Zinc (mg/L)**	**Groundwater**	**Interflow**	**Groundwater**
Developed Impervious	0	0	0	0	0	0
Developed Pervious	0.0015	0.001	0.009	0.006	138	92
OSWW	0.0015	0.001	0.009	0.006	15,000	10,000
Horticulture	0.00009	0.00006	0.00144	0.00096	138	92
Pasture	0.00009	0.00006	0.00144	0.00096	69 - 690	46 - 460
Open Space	0.00009	0.00006	0.00144	0.00096	46	46
Forest	0.00009	0.00006	0.00144	0.00096	46	46
Rural Road	0.00009	0.00006	0.00144	0.00096	138	92

The groundwater in the shallow Franklin Volcanic Aquifer (Glenbrook, Pukekohe, Bombay aquifers within the Manukau Harbour watershed) has notably elevated nitrate concentrations (Meijer et al., 2016) (Figure 3-72). As shown in Figure 3-73, analysis of observed nitrate concentrations at SoE river stations within the recharge zones of the Franklin Volcanic Aquifer suggest that the Whangamaire River (SoE station), which drains the Pukekohe portion of the aquifer, possessed higher NO3N concentrations than the Ngakoroa River (SoE station, Bombay aquifer) and Waitangi River (SoE station, Glenbrook aquifer) (Buckthought, 2019).

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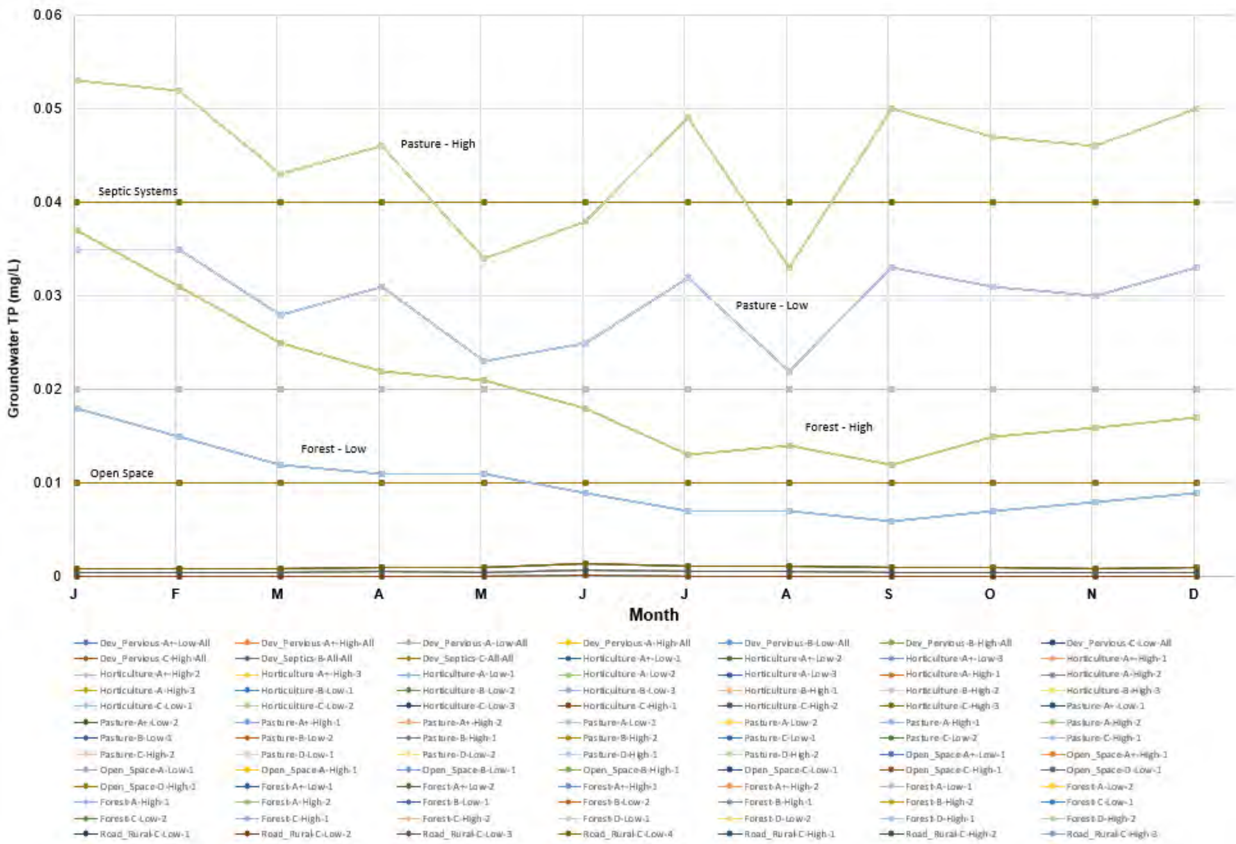


Figure 3-70. Regionwide Groundwater TP Concentrations (flow-weighted over full baseline period 2013-2017 by HRU)

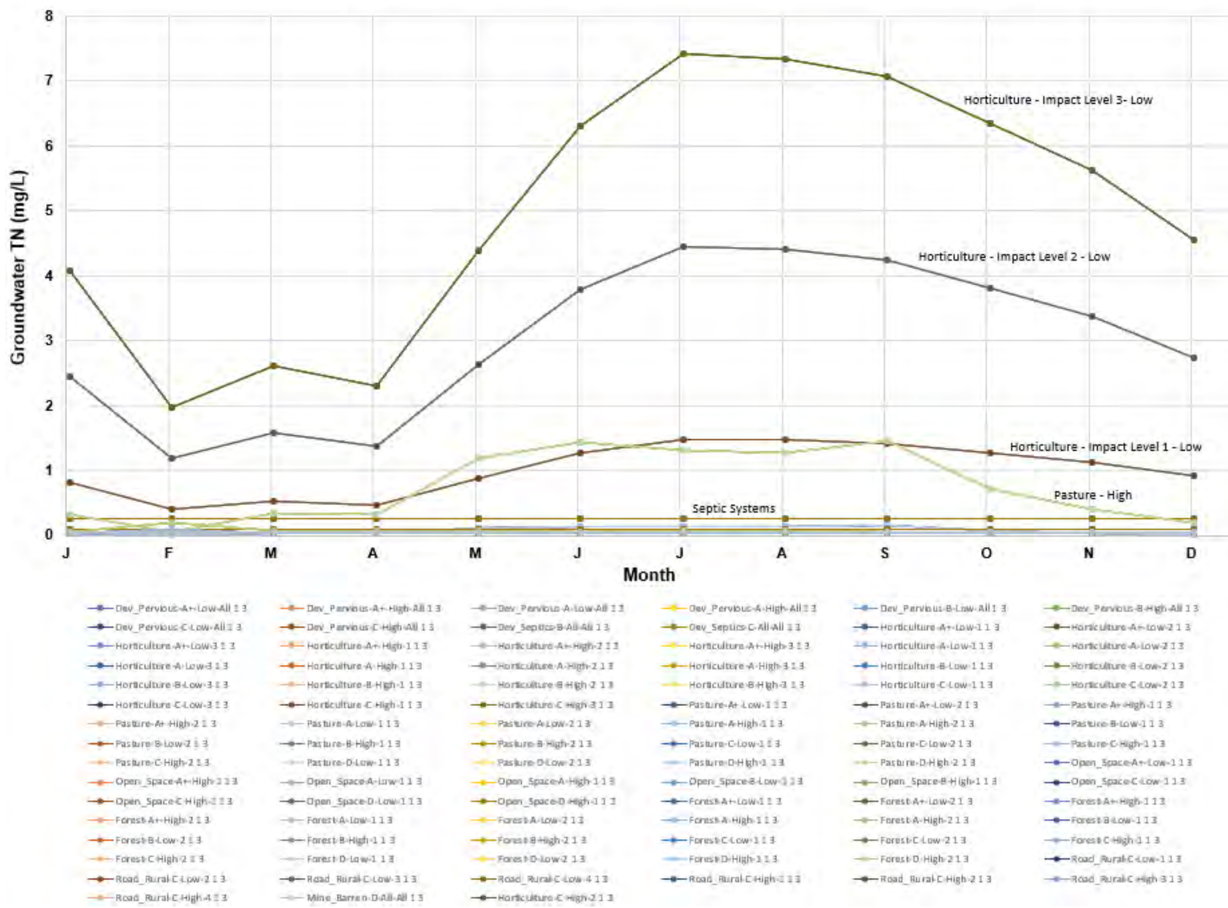
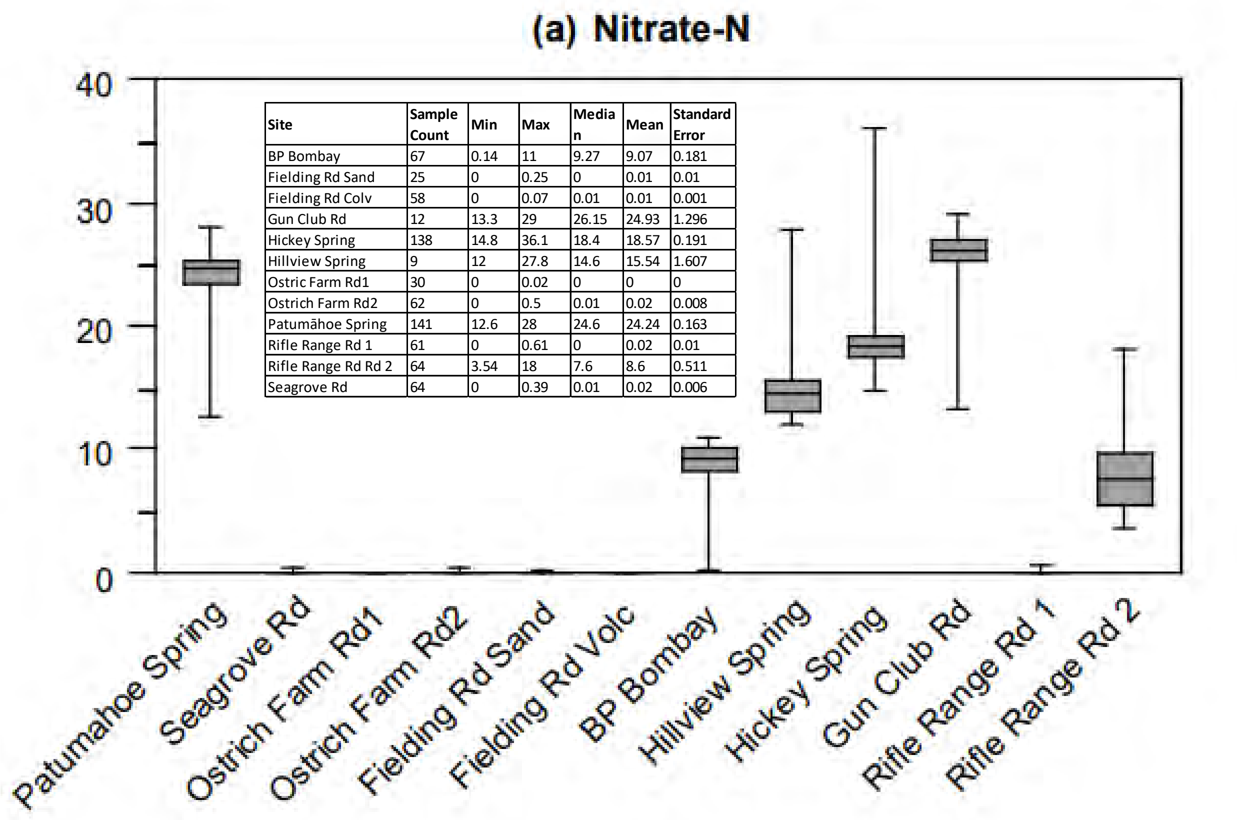


Figure 3-71. Regionwide Groundwater TN Concentrations (flow-weighted over full baseline period 2013-2017 by HRU)



Site	Sample Count	Min	Max	Median	Mean	Standard Error
BP Bombay	67	0.14	11	9.27	9.07	0.181
Fielding Rd Sand	25	0	0.25	0	0.01	0.01
Fielding Rd Colv	58	0	0.07	0.01	0.01	0.001
Gun Club Rd	12	13.3	29	26.15	24.93	1.296
Hickey Spring	138	14.8	36.1	18.4	18.57	0.191
Hillview Spring	9	12	27.8	14.6	15.54	1.607
Ostric Farm Rd1	30	0	0.02	0	0	0
Ostrich Farm Rd2	62	0	0.5	0.01	0.02	0.008
Patumāhoe Spring	141	12.6	28	24.6	24.24	0.163
Rifle Range Rd 1	61	0	0.61	0	0.02	0.01
Rifle Range Rd Rd 2	64	3.54	18	7.6	8.6	0.511
Seagrove Rd	64	0	0.39	0.01	0.02	0.006

Figure 3-72. Groundwater well sampling for Nitrate-N in the Franklin Volcanic Aquifer 1998-2013 (concentrations in mg/l). Patumahoe Spring is upstream of Whangamarie stream sampling site and is fed by discharge from the Pukekohe Volcanic aquifer. BP Bombay and Hillview Spring are both fed by discharge from the Bombay Volcanic Aquifer. Hillview Spring is fed by discharge from the Bombay Volcanic Aquifer. Hickey Spring is the source of the Whāngapōuri Stream. Boxes represent interquartile range, mid-lines the median, and the bars show the maximum and minimum values (Graphic Source: Meijer et al. (2016)

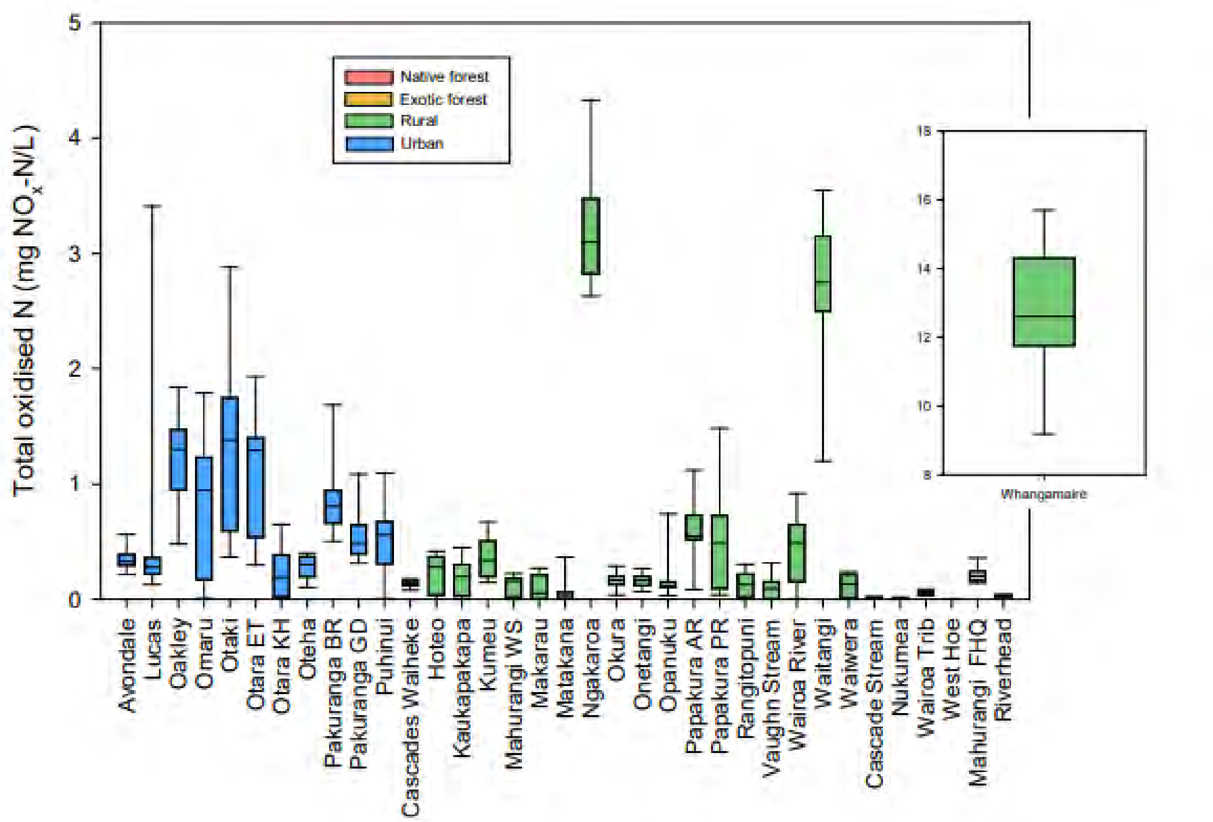


Figure 3-73. Box plots showing the variation in total oxidised nitrogen at the 36 monitored river sites using data collected during the 2017 calendar year. The results for Whangamarie stream (Pukekohe Volcanic Aquifer) are separated out to accentuate the difference in scale of TON reported for this stream. Also note the higher TON concentrations measured at both the Ngakoroa (Bombay Volcanic Aquifer) and Waitangi (Glenbrook Volcanic Aquifer) stream sites. Graphic Source: Buckthought (2019)

Previous studies and inspection of instream nitrogen concentrations observed at downstream gauges suggest strong seasonal variability (Figure 3-74). Observed nitrate concentrations were highest in sub-catchments with greater horticulture. Hence, a decision was made to increase groundwater nitrate yield (and concentration) from horticulture HRUs for parcels overlying the Franklin aquifer. Two additional classes of low, medium and high impact types of horticulture were configured and calibrated (i.e., three variant parameter groups for each horticultural impact class were created, one each for the various sub-aquifer zones of the Franklin Aquifer (e.g., Bombay Volcanic; Glenbrook Volcanic; Pukekohe Volcanic sub-aquifer). Of those, the Pukekohe Volcanic sub-aquifer parameter group generated most enriched concentrations of TN in active groundwater. The Bombay and Glenbrook Volcanic sub-aquifer parameter groups were calibrated for greater TN-concentration in horticultural active groundwater than the broader regional parameter group, but otherwise of lesser concentration than the Pukekohe parameter set. (Noting, horticultural active groundwater parameter groups also vary by impact class within each sub-aquifer and broader regional configuration).

A GIS layer of the Franklin Volcanic Aquifer was used to perform a spatial query of the sub-catchments that intersected the sub-aquifer boundaries to “medium” and “high” parameter groups; horticultural HRUs outside of the Franklin Volcanic Aquifer were assigned to the regional “low” parameter group. See Figure 3-75 for where “low”, “medium” and “high” active groundwater groups apply to horticultural HRUs.

Table 3-31 records the flow-weighted, baseline groundwater TN concentrations for horticultural HRUs across impact and parameter groups, demonstrating the increasing concentrations assigned to medium (Bombay and Glenbrook sub-aquifers) and high groups (Pukekohe sub-aquifer).

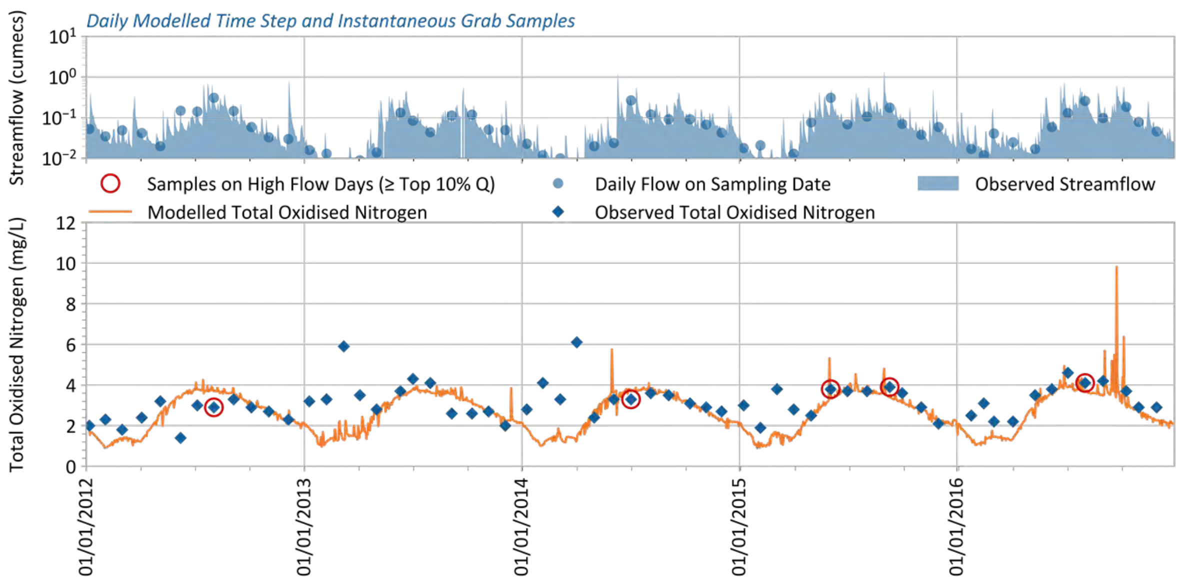


Figure 3-74. Ngakoroa Stream @ Mill Rd (43829), located east of Pukekohe and influenced by the Franklin volcanic aquifer – Total oxidised nitrogen calibration: Simulated daily modelled time series vs observed grab sample concentrations

Table 3-31. Interflow and active groundwater outflow for horticulture TN (mg/l) concentrations by model parameter group (low, medium, high) in the area of the Franklin Aquifer

Month		Impact 1			Impact 2			Impact 3		
		Low	Medium	High	Low	Medium	High	Low	Medium	High
Interflow Outflow	Jan	1.2	1.2	1.6	3.7	3.7	7.8	6.1	12.2	31.2
	Feb	0.6	0.6	1.6	1.8	1.8	7.9	3.0	5.9	31.5
	Mar	0.8	0.8	1.5	2.4	2.4	7.3	3.9	7.9	29.1
	Apr	0.7	0.7	1.6	2.1	2.1	8.1	3.4	6.9	32.3
	May	1.3	1.3	1.6	3.9	3.9	8.0	6.6	13.1	31.9
	Jun	1.9	1.9	1.3	5.7	5.7	6.6	9.5	18.9	26.4
	Jul	2.2	2.2	1.4	6.7	6.7	6.9	11.1	22.2	27.5
	Aug	2.2	2.2	1.3	6.6	6.6	6.4	11.0	22.0	25.6
	Sep	2.1	2.1	1.4	6.4	6.4	6.9	10.6	21.2	27.4
	Oct	1.9	1.9	1.5	5.7	5.7	7.7	9.5	19.1	30.7
	Nov	1.7	1.7	1.7	5.1	5.1	8.4	8.4	16.9	33.5
	Dec	1.4	1.4	1.6	4.1	4.1	8.2	6.8	13.6	32.8
Month		Impact 1			Impact 2			Impact 3		
		Low	Medium	High	Low	Medium	High	Low	Medium	High
Active Groundwater Outflow	Jan	0.8	0.8	1.0	2.4	2.4	5.2	4.1	8.2	41.6
	Feb	0.4	0.4	1.1	1.2	1.2	5.3	2.0	3.9	42.0
	Mar	0.5	0.5	1.0	1.6	1.6	4.8	2.6	5.2	38.8
	Apr	0.5	0.5	1.1	1.4	1.4	5.4	2.3	4.6	43.1
	May	0.9	0.9	1.1	2.6	2.6	5.3	4.4	8.8	42.5
	Jun	1.3	1.3	0.9	3.8	3.8	4.4	6.3	12.6	35.2
	Jul	1.5	1.5	0.9	4.4	4.4	4.6	7.4	14.8	36.6
	Aug	1.5	1.5	0.9	4.4	4.4	4.3	7.3	14.7	34.1
	Sep	1.4	1.4	0.9	4.2	4.2	4.6	7.1	14.2	36.6
	Oct	1.3	1.3	1.0	3.8	3.8	5.1	6.4	12.7	41.0
	Nov	1.1	1.1	1.1	3.4	3.4	5.6	5.6	11.3	44.7
	Dec	0.9	0.9	1.1	2.7	2.7	5.5	4.5	9.1	43.7

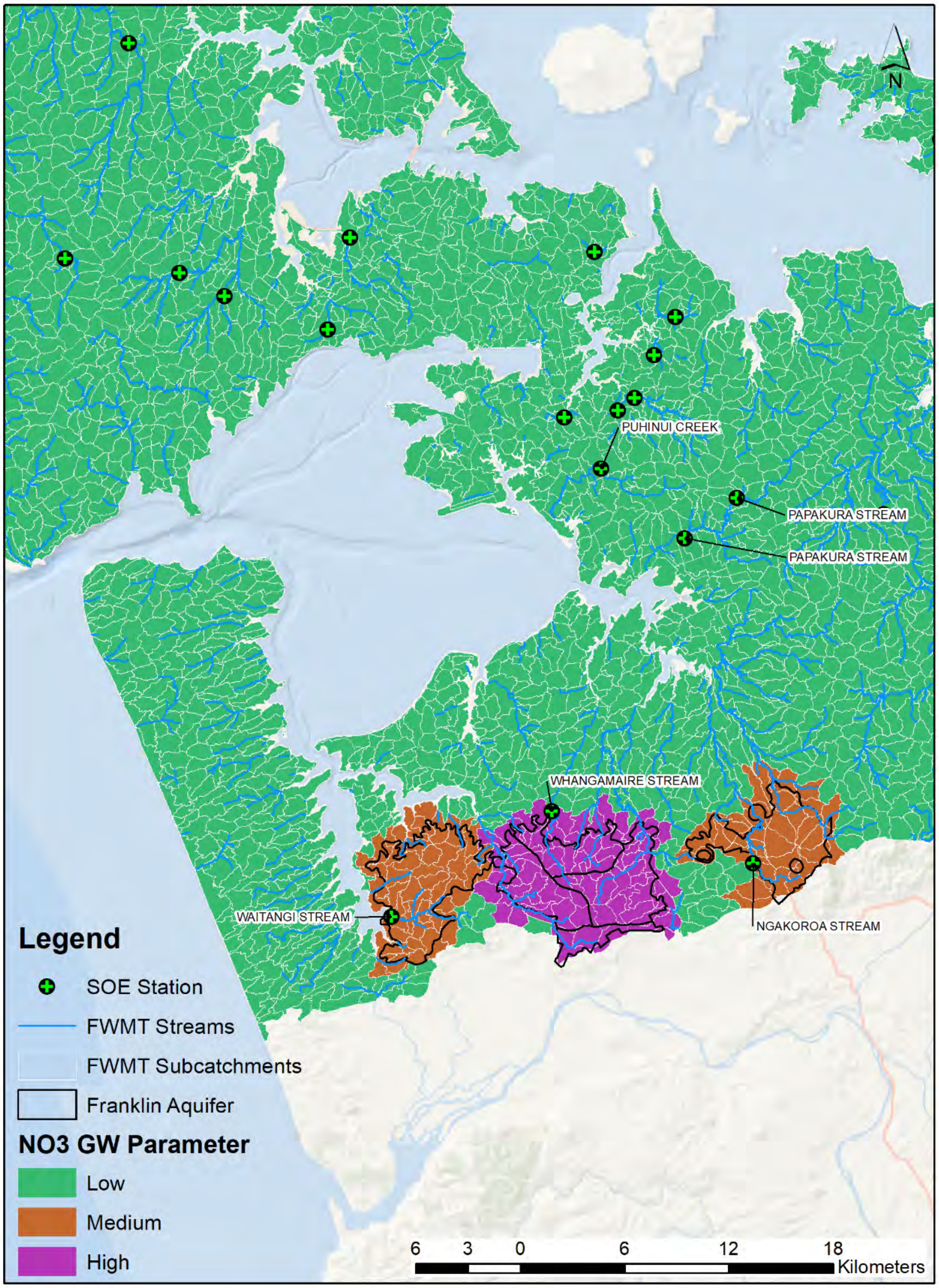


Figure 3-75. Parameter group assignments by sub-catchment to represent low, medium, and high levels of NO3-N concentrations in groundwater

3.11 Summary

The FWMT Stage 1 hydrology and water quality model was configured using the best available data (as of mid-2017) to account for water quality conditions in the Auckland region over the calibration/validation period (2012-2016). Latter datasets included high-resolution meteorology, soils, land cover and use, topography, wastewater and stormwater networks, consented water takes and discharges, spanning several years of effort by multiple New Zealand and Auckland Council agencies.

Configuration commenced by delineating sub-catchments and associated stream network with a regional LiDAR DEM, resulting in 2,567 of 5,465 sub-catchments possessing a single modelled reach. A total of 2,898 sub-catchments were delineated as headwater catchments or draining straight to sea or neighbouring region. Sub-catchments lacking a modelled stream segment are still subject to hydrological and contaminant modelling (from land) but not then assigned instream grades. Approximately 2,377 km^2 of the 4,803 km^2 Auckland region is either within a headwater sub-catchment or drains directly to the ocean and was not simulated for instream contaminants in the FWMT Stage 1.

Meteorological time series inputs were developed using a combination of observed rain gauge information and modelled VSCN data, for the period 2002-2017. Additional inputs to the model included data on the existing wastewater network, reservoirs, lakes, and dams, and surface water takes. HRUs, representing the combination of landscape characteristics likely to govern hydrological and relevant contaminant processes in the region, were developed to express a range of parameterisation deemed relevant (e.g., of soils, topography, land cover and use). HRU stratification was limited in the FWMT Stage 1 to a level representative of sub-catchment variability across hydrologic and contaminant processes without excessive classes or complexity for best available datasets in later calibration and validation. Each HRU was configured or parameterised regionally, to enable local (sub-catchment) climatic variation to be represented amidst a diverse typology of landscape (i.e., resulting in unique sub-catchment profiles of varying extent of up to 106 HRUs driven by up to 228 unique climate time series to generate sub-catchment time series of hydrology and contaminant concentration or load).

HRU development involved comparative analysis and corroboration across diverse datasets to derive new information to fill data gaps and augment the resolution to 2x2 m cells assigned one of the 106 unique HRUs. For example, soil and slope spatial raster data were intersected with land use/land cover data to create unique combinations of base factors for HRU classification, of land use, soil, and slope. The HRUs were further refined by Impact factors representing the intensity of human activity within a land cover type. For example, traffic data were also used to stratify contaminant impacts among different types of road cover. Similarly, simulated meteorological data from NIWA's virtual climate station network were used to fill spatial gaps in the observed data coverage. The higher the resolution and accuracy of the data used to configure the FWMT, the better the model can simulate hydrology and water quality processes. A detailed configuration of spatial features reduces the 'burden' of later calibration efforts. Representing observed variability among physical properties during model configuration provides a sound basis for generalisation of associated parameters during model calibration.

Instream nutrient and sediment processes were also regionally parameterised into several reach groups, based on modelled reach characteristics (e.g., shade, upstream extent of agriculture/horticulture, bed/bank material, bed slope and stream order). For both nutrient and stream erosional/depositional processes, three reach groups were configured to enable their unique calibration. Reach groups were assigned to modelled segments much like HRUs, through use of best available datasets (e.g., WAR, FENZ, NZLRI).

Over time and through the staged model development process, it is envisioned that many of the datasets used for the FWMT Stage 1 configuration will be updated with higher resolution/higher quality data and incorporated into the FWMT and/or added complexity created to better resolve processes or expand the scope of contaminants and environments (e.g., as uncertainty is better understood).

4.0 Model Calibration and Validation

Calibration of the FWMT attempted to improve performance at simulating streamflow and contaminants, creating a set of parameters for all processes in LSPC, fixed by HRU and reach group. Those parameters regulate a range of processes presented in Figure 2-6 to Figure 2-9. The process of calibration also generates an understanding of baseline modelling capabilities of the FWMT Stage 1 model (e.g., performance under different conditions and seasons). Performance of baseline simulations is useful for identifying potential changes to configuration and data input, ranked in order of importance, which could include a targeted programme to collect additional data (as discussed in Section 2.2).

It is important to note the FWMT calibration process is for a regionalised Stage 1 model; configuration did not include parameterisation for specific watersheds, conditions or years. Instead, all process parameters were adjusted and set identically within HRU or stream reach groups (sediment and nutrient) for the full calibration period. Given evidence for differences in groundwater concentrations within the Franklin Volcanic Aquifer, two new parameter groups were introduced for horticultural HRUs during the course of model calibration and validation to provide flexibility for varying groundwater TN concentrations levels (see Section 3.10). That modification is an example of the feedback loop where new information, combined with a rigid response from the model, supported a refinement of the model configuration. Nevertheless, the generalised parameterisation approach accords with our regional objectives and the requirement for greater parsimony, by reducing an already complex process-based model for the regional use of FWMT Stage 1. In future stages, the regional parameterisation could serve as a starting point for detailed analyses/studies, perhaps including compilation of expanded datasets for individual watersheds and further parameter adjustments at the watershed-level.

The hydrologic and water quality calibration period was the 5-year period between 1/1/2012 and 31/12/2016, which is a subset of the total output simulation period that spans 1/1/2002 to 31/12/2017. As described in Section 3.1 a recent 5-year period was used because the HRUs represent a ‘snapshot’ in time based on the available land cover and use layers (Section 3.8.3), and thus including the early simulation period (before 2012) could introduce additional error associated with the land cover datasets as opposed to model processes. Further, the recent 5-years generally represent higher data quality for defining boundary conditions (e.g., surface water takes and contaminant concentrations). The full 15-year simulation period was used to assess hydrological calibration based on visual assessment of hydrographs representing simulated and observed daily streamflow and simulated and observed normalised monthly streamflow.

The 2017 calendar year was excluded from the calibration period because the annual rainfall was exceptionally high (Table 4-1) and flooding events were relatively frequent during that year. An increased amount of precipitation and streamflow occurring in 2017 can be seen in Figure 4-1. However, the 2012-2016 period still contained relatively high flows, therefore model calibration reflects the influence of these flows. For sediment yield comparisons presented in Section 4.3.4.1.1, results were assessed both with and without data from the year 2017 to facilitate comparisons to periods when sediment mobilisation and streambank scour was relatively high as described in Section 4.5.

Table 4-1. Precipitation summary for Tamaki

Year (Jul-Jun)	Rainfall (mm)	Percentile (1991-2017)
1991	1,296	68%
1992	1,137	32%
1993	1,253	64%
1994	793	4%
1995	1,416	86%
1996	1,362	79%
1997	1,222	57%
1998	1,076	18%
1999	1,333	75%
2000	1,156	43%
2001	1,182	54%
2002	1,246	61%
2003	1,157	46%
2004	1,426	89%
2005	986	7%
2006	1,368	82%
2007	994	11%
2008	1,165	50%
2009	1,306	71%
2010	1,145	36%
2011	1,489	93%
2012	1,101	25%
2013	1,148	39%
2014	1,103	29%
2015	1,080	21%
2016	1,075	14%
2017	1,618	96%

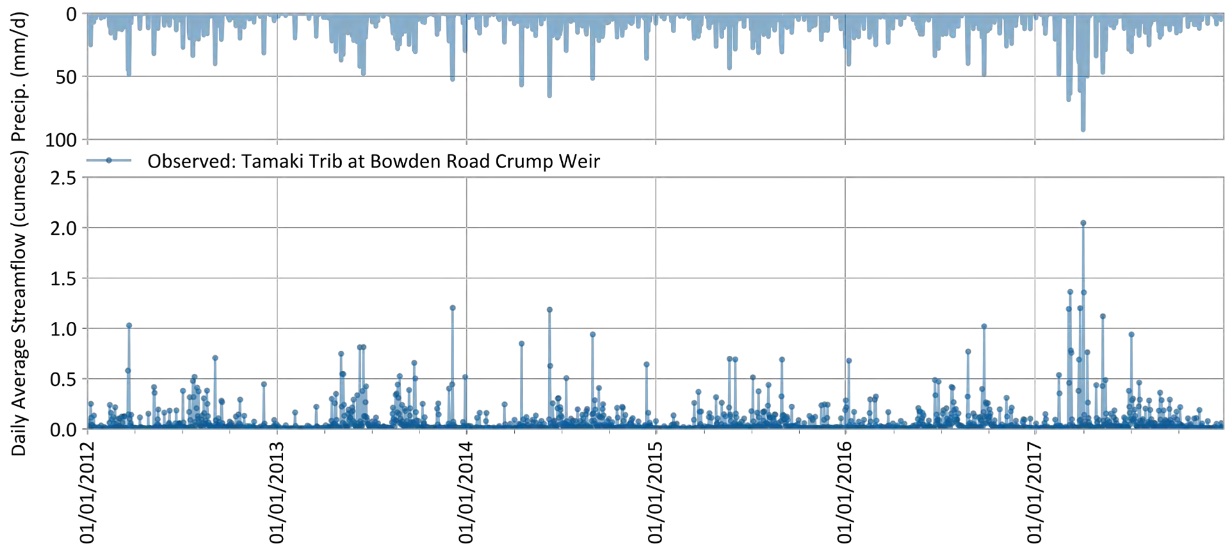


Figure 4-1. Precipitation and Stream Flow – Tamaki Trib at Bowden Road Crump Weir (8222)

4.1 Calibration and Validation Approach

The FWMT Stage 1 calibration exercise was accomplished across four steps:

- ***Top-down data approach to calibration:*** the calibration sequence began with QA and review of the boundary condition data (especially weather data), then progressed to hydrologic calibration and then water quality calibration (see Figure 4-2). This sequencing aims to minimise the propagation of uncertainty/error through the modelled parameters. Within the water quality calibration, sediment was calibrated before other contaminants, many of which are sediment-associated/bound.
- ***Upstream-downstream approach to calibration:*** the calibration sequence initially emphasised data collected from stations where upstream land uses / HRUs are relatively homogenous (see Figure 4-3). This sequencing aims to isolate the varying parameterisation of HRUs, and the upstream stations are where HRU characteristics are most homogeneous and thus can most readily be distinguished. Within this process, reach group parameter adjustments were also an important calibration tool for sediment and nutrients. Adjustments to parameters (Appendix A) to improve model performance at upstream stations, referred to as 'calibration stations' in this document, primarily drove parameterisation. As an initial set of HRU parameters were developed, the model performance downstream at mixed HRU stations was evaluated. These downstream stations are referred to as 'validation stations' – some regional parameter adjustments were made to improve performance across the validation

stations (e.g., if baseflow predictions were biased high across a high proportion of stations, as presented ins Section 4.2.3), but those adjustments represented a small proportion of the parameterisation effort.

- ***Comparison to other estimates and literature:*** regional estimates and literature values are also an important point of reference for evaluation of outputs. Unit-area results (yields and concentrations) were summarised and compared relative to each other and against representative published literature values. Evaluation of unit-area responses across HRU factor gradients is an important evaluation point to understand the relative contribution of land to instream conditions (i.e., all factors held constant, an HRU type should incrementally generate more sediment on steeper slopes, as shown in Appendix E). Unit area responses were also compared to observed ‘end-of-pipe’ data and the relative contaminant levels were used as a starting point for model parameterisation (which also follows the ‘upstream’ approach, as these levels are set prior to mixing with receiving waters). Finally, for sediment there were available estimates from AC of sediment yield from several upstream watersheds (Haddadchi and Hicks, 2016; Holwerda, N., pers. comm. 2019), and the LSPC outputs were processed to allow direct comparisons of sediment generation from watershed outlets.
- ***Multiple performance metric approach to calibration:*** quantitative statistics of model calibration are key to model development, forming the basis of error/uncertainty quantification in model predictions (e.g., highlighting conditions and seasons associated with varying predictive performance). A set of calibration metrics were developed for hydrology and water quality, based on published references on catchment-scale, continuous simulation model performance evaluation. Performance across flow regimes and seasons was evaluated, reporting performance metrics as grades of “Very Good”, “Good”, “Fair” and “Unsatisfactory” using thresholds also recommended by the modelling literature. The calibration effort for FWMT Stage 1 greatly expands on earlier LSPC builds to include r^2, Nash-Sutcliffe efficiency and per cent bias metrics across the various data envelopes, discussed further in Section 4.2.

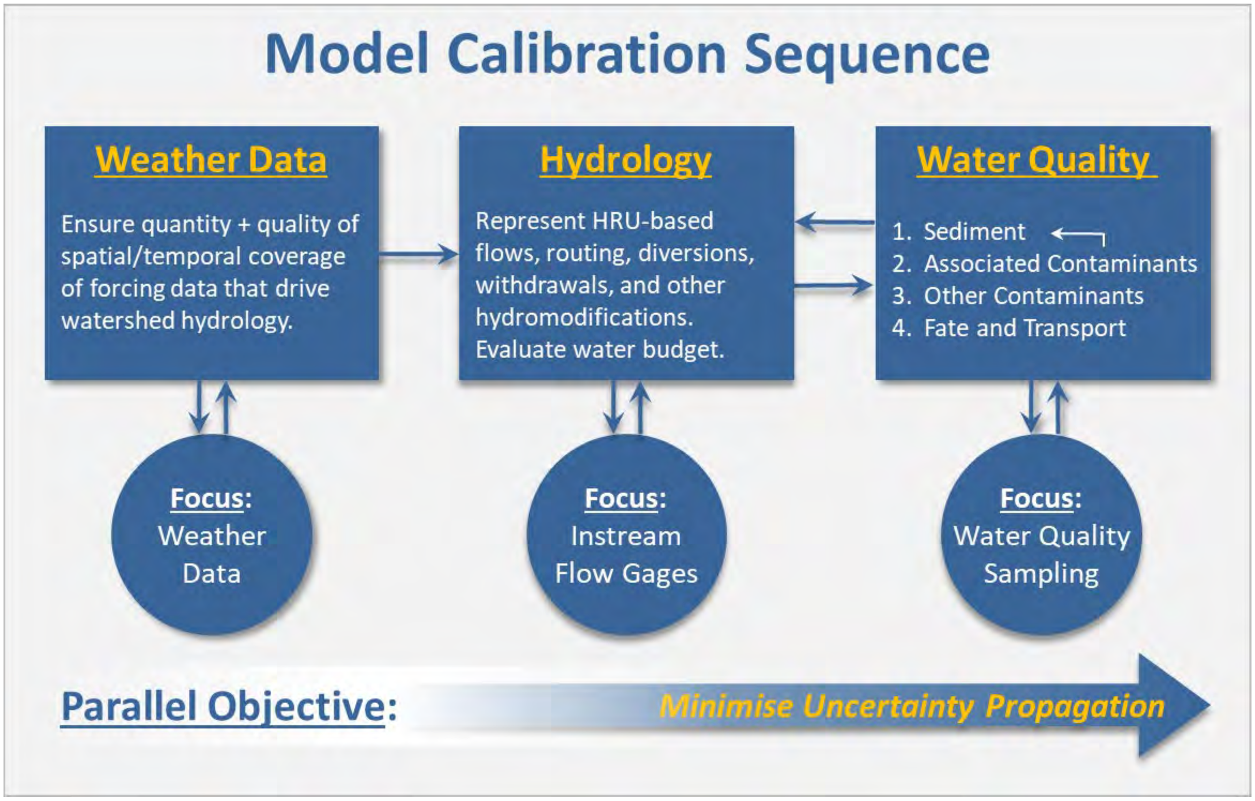


Figure 4-2. Top-down calibration sequence used for FWMT calibration

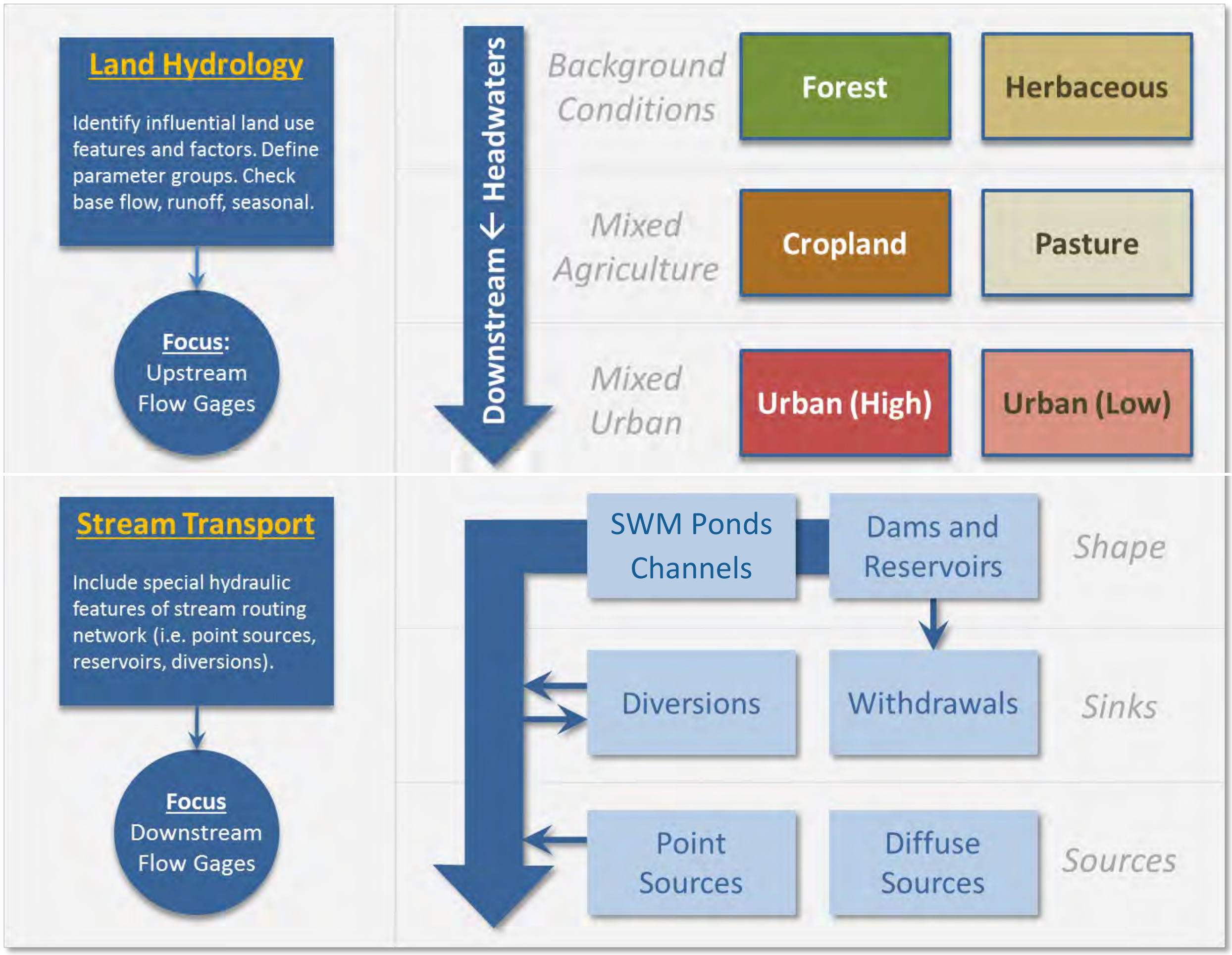


Figure 4-3. Upstream-downstream sequence used for FWMT calibration

The calibration effort has relied upon daily averaged LSPC outputs. Daily averages were utilised in calibration assessments for several reasons:

- Daily timestep likely reflects the highest resolution at which planning decisions would be made using the FWMT;
- Outputting daily timestep data makes run times more reasonable between parameter adjustments. For reference, as of 2019, the run time for the regional LSPC model outputting daily timestep data is approximately 72 hours on a high-performance modelling workstation (the modelling team generated regionwide outputs in 14 hours for the 5-year simulation by parallelising 52 runs across 5 modelling computers). To support calibration effort, cloud servers on Amazon Web Services (two servers with 16 CPUs and one with 8 CPUs) were leveraged for a few regionwide runs which reduced runtime to approximately 9 hours.

- Daily timestep data helps resolve short-term event-based variation in rainfall and contaminant behaviour, important to grading contaminant state (i.e., influencing 95^{th}%), but without excessive and increasingly erroneous variation (e.g., 15-minute time series will be more variable than averaged daily outputs, introducing increasing error to 95^{th}% concentrations at reporting nodes). That error extends not simply into the contaminant mass generated but its temporal distribution and delivery to a site where observed data is available, which if treated as sub-daily could readily result in "timing error" (e.g., right peak concentration, right loading, but delivered too soon or too late to a location to be exactly coeval with a 15-minute interval when compared to a time-stamped observation).

4.1.1 Performance Statistics

Calibration was assessed using a combination of visual assessments and computed numerical evaluation metrics. Grading of LPSC performance was assessed using performance metrics and grading thresholds recommended by Moriasi et al. (2015) and Donigian (2000) – an approach in line with catchment water quality modelling in New Zealand (e.g., Greater Wellington: Jacobs, 2019a, b). The performance metrics used to evaluate the FWMT are considered highly conservative, and it is very rare to receive "Very Good" evaluations across all metrics – "Satisfactory" is deemed a reasonable outcome for FWMT Stage 1 (i.e., for regionalised, continuous output). Moriasi et al. (2015) assign narrative grades for water quality modelling to the coefficient of determination (r-Squared), Nash-Sutcliffe model efficiency (NSE), and per cent bias (PBIAS), as follows:

- The **coefficient of determination (r-Squared)** describes the degree of collinearity between simulated and measured data. The correlation coefficient is an index that is used to investigate the degree of linear relationship between observed and simulated data. r-Squared describes the proportion of the variance in observed data that is explained by a model. Values for r-Squared range from 0 to 1, with 1 indicating a perfect fit. The r-Squared metric was calculated and presented within graphical evaluation panels for contaminants by site (Appendix F1 – Appendix F9). Note that 'r-Squared' is used in calibration panels for the performance metric whereas 'r^2' is used for regressions used in some of the panels such as streamflow vs contaminant concentrations (the r^2 regressions do not indicate model performance, instead they convey whether the relationship exists in the observed and simulated data).
- The **per cent bias (PBIAS)** quantifies systematic overprediction or underprediction of observations. A bias towards underestimation is reflected in positive values of PBIAS while a bias towards overestimation is reflected in

negative values. Low magnitude values of PBIAS indicate better fit, with a value of 0 being optimal.

- The **Nash-Sutcliffe efficiency (NSE)** is a normalised statistic that determines the relative magnitude of the residual variance compared to the measured data variance (Nash and Sutcliffe, 1970). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. Values for NSE can range between -∞ and 1, with NSE = 1 indicating a perfect fit.

For each metric, the resulting value was compared to performance thresholds, which differ for hydrology and water quality (see Table 4-2 and Table 4-3). Flows for each day at each station were categorised as 'Stormflow' or 'Baseflow' by applying the baseflow separation and recession technique developed by the U.S. Geological Survey (link) to the observed streamflow time series. The Moriasi et al. (2015) thresholds for nutrients were applied to all contaminants to simplify the comparisons and because there were no published thresholds for metals. The performance thresholds established by Moriasi et al. (2015) were modified based on performance criteria established by Donigian (2000) to account for targeted 'bins' of conditions based on season and flow rate; Moriasi et al. (2015) only provided metrics for evaluation of all conditions across the model time series. Donigian (2000) included metrics for model predictions within flow regimes, such as the highest 10% of flows and baseflow. After modification in line with Donigian (2000), the Moriasi-based thresholds were effectively scaled one tier up (less conservatively) for assessing all bin-stratified calibration (e.g., within a smaller bin of sub-samples, performance thresholds for "Very Good" were equivalent to those of "Good" when considering all the data within a single pool). Moriasi et al. (2015) anticipated adjustments to their thresholds: "these [thresholds] can be adjusted within acceptable bounds based on additional considerations, such as quality and quantity of available measured data, spatial and temporal scales, and project scope and magnitude, and updated based on the framework presented herein."

The assessment of combined, regional performance requires some subjective interpretation to account for varying record lengths, gradient coverage and quality of differing SoE stations. Here, the FWMT Stage 1 is assessed from:

- A weight-of-evidence approach, where the multiple metrics and conditions are considered across multiple stations and conditions, in line with the regional purpose and modelling objectives.
- Greater weighting to hydrology calibration over water quality, acknowledging greater resolution, coverage and extent of observed hydrological records than monthly grabs for water quality. Equally, that many processes within LSPC are linked strongly to hydrology so errors therein are compounded through process-responses for contaminants.

- The rate of uncertainty in water quality observations can be relatively high due to data collection methods, sample storage and preservation, and laboratory analysis methods. Harmel et al., (2006) estimated the cumulative uncertainty in water quality measurements due to these factors for typical and worst-case scenarios (see Figure 4-4).

From the weight-of-evidence approach, overall regional performance is determined from summary plots of individual site performance and interpretation of these for hydrology and each of the contaminants, as described in Section 4.2 for Hydrology and Section 4.3 for water quality.

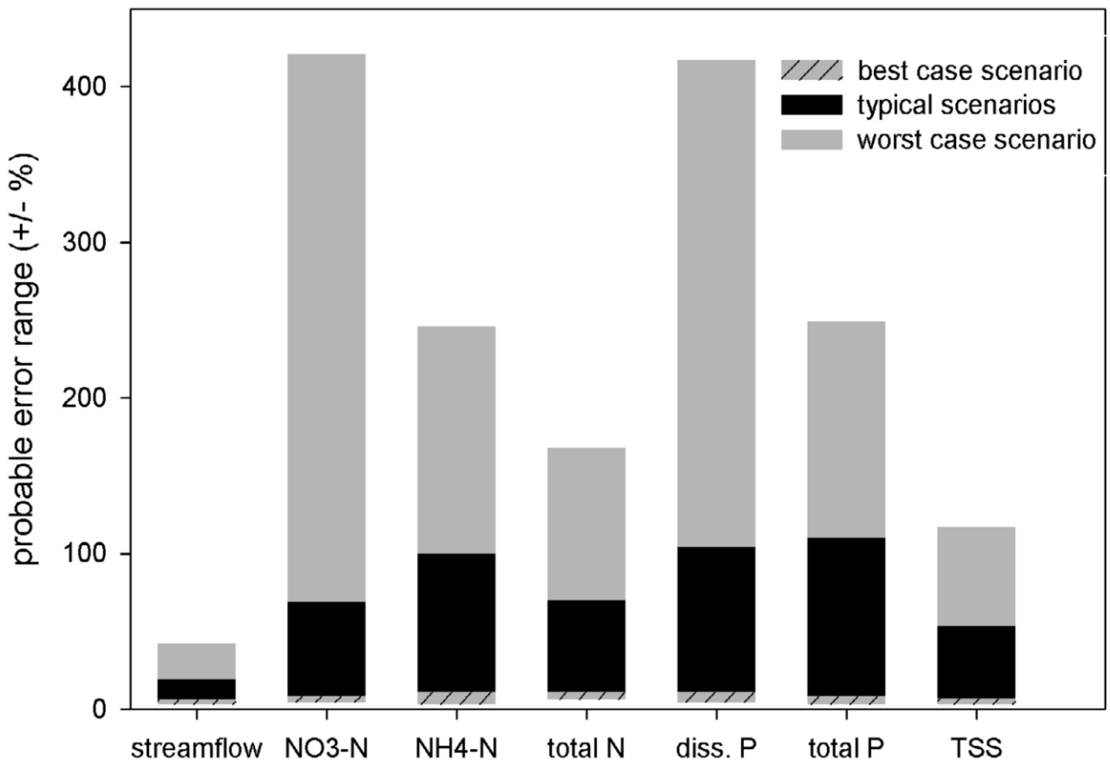


Figure 4-4. Estimated error in water quality measurements (graphic source: Harmel et al., 2006)

Table 4-2. Summary of performance metrics used to evaluate hydrology calibration

Performance Metric	Hydrological Condition	Comparison Type	Performance Threshold for Hydrology Simulation				Reference
			Very Good	Good	Satisfactory	Unsatisfactory	
r-Squared (R^2)	All Conditions [1]	Compare All Observed vs Simulated Daily Flow Rates that Occur During Selected Season-Conditions	>0.85	0.75 - 0.85	0.60 - 0.75	≤0.60	Moriasi et al. (2015)
	Seasonal Flows [2]		>0.75	0.60 - 0.75	0.50 - 0.60	≤0.50	
	Highest 10% of Daily Flow Rates [3]						
	Lowest 50% of Daily Flow Rates [4]						
	Days Categorised as Storm Flow [5]						
	Days Categorised as Baseflow [5]						
Nash-Sutcliffe Efficiency (E)	All Conditions [1]		>0.80	0.70 - 0.80	0.50 - 0.70	≤0.50	
	Seasonal Flows [2]		>0.70	0.50 - 0.70	0.40 - 0.50	≤0.40	
	Highest 10% of Daily Flow Rates [3]						
	Lowest 50% of Daily Flow Rates [4]						
	Days Categorised as Storm Flow [5]						
	Days Categorised as Baseflow [5]						
Per cent Bias (PBIAS)	All Conditions [1]		<5%	5% - 10%	10% - 15%	>15%	
	Seasonal Flows [2]		<10%	10% - 15%	15% - 25%	>25%	
	Highest 10% of Daily Flow Rates [3]						
	Lowest 50% of Daily Flow Rates [4]						
	Days Categorised as Storm Flow [5]						
	Days Categorised as Baseflow [5]						

1. All Flows considers all daily time steps in the model time series.
2. Seasonal Flows considers daily flows during a predefined, three-month seasonal period (e.g., Winter, Spring, Summer, and Fall). Winter included the months of July, August, and September. Spring included the months of October, November, and December. Summer included the months of January, February, and March. Fall included the months of April, May, and June.
3. Highest 10% of Flows considers the top 10% of daily flows by magnitude as determined from the flow duration curve.
4. Lowest 50% of Flows considers the bottom 50% of daily flows by magnitude as determined from the flow duration curve.
5. Baseflows and Storm flows were determined from analysing the daily model time series by applying the USGS hydrograph separation approach (Sloto et al., 1996) This approach parses the volume of the hydrograph at each time step (i.e., daily) into baseflow and stormflow components. Daily model time series were classified as a Storm Flows condition if the stormflow portion of the model hydrograph was greater than zero, and the baseflow recession rate was null. Baseflow recession rate was calculated by dividing baseflow from the following day (Q_{t+1}) by baseflow from the current day (Q_t) such that both Q_t and Q_{t+1} are greater than zero and Q_{t+1}/ Q_t is less than 1.0. If either Q_t or Q_{t+1} was zero or Q_{t+1}/ Q_t >= 1.0 then the baseflow recession rate was considered null. All days not classified as Storm Flows condition were considered Baseflows condition.

Table 4-3. Summary of performance metrics used to evaluate water quality calibration

Performance Metric	Condition	Performance Threshold for WQ Simulation				Reference
		Very Good	Good	Satisfactory	Unsatisfactory	
R-squared	All Conditions (Combined) [1]	>0.70	0.6 - 0.70	0.30 - 0.60	<0.30	Moriasi et al. (2015)
	Seasonal and High/Low Flows [2,3,4]	> 0.60	0.30 - 0.60	0.20 - 0.30	<0.20	
Per cent Bias (PBIAS, %)	All Conditions (Combined) [1]	<15%	15% - 20%	20% - 30%	>30%	
	Seasonal and High/Low Flows [2,3,4]	<20%	20% - 30%	30% - 40%	>40%	
Nash-Sutcliffe Efficiency (E)	All Conditions (Combined) [1]	>0.65	0.50 - 0.65	0.35 - 0.50	<0.35	
	Seasonal and High/Low Flows [2,3,4]	>0.50	0.35 - 0.50	0.25 - 0.35	<0.25	

1. All Flows considers all daily time steps in the model time series.
2. Seasonal Flows considers daily flows during a predefined, three-month seasonal period (e.g., Winter, Spring, Summer, and Fall). Winter included the months of July, August, and September. Spring included the months of October, November, and December. Summer included the months of January, February, and March. Fall included the months of April, May, and June.
3. Highest 10% of Flows considers the top 10% of daily flows by magnitude as determined from the flow duration curve.
4. Lowest 50% of Flows considers the bottom 50% of daily flows by magnitude as determined from the flow duration curve.

4.1.2 Performance Envelopes

For hydrology and water quality, data were binned into seasons and flow conditions to help elucidate patterns related to differential model performance. Observed data were binned into different conditions based on the day of observation – either by season according to the time stamp or by flow condition based on the daily average observed streamflow. Streamflow percentiles were based on the records during the calibration period (2012-2016). Binned streamflow conditions for application of the performance metrics included percentiles of daily average streamflows of 'Highest 10%' (to isolate model performance during high flows) and 'Lowest 50%' (to isolate model performance during low flows). For water quality calibration, the 'Highest 10%' of flows was replaced with 'Highest 25%' to increase the number of samples in that bin.

For hydrological performance assessment, in addition to the various performance metrics derived from Moriasi et al., (2015), the reviewed observed vs simulated flow statistics included the mean annual flood (MAF), mean annual low-flow (7-day MALF), frequency of "freshes" three times the median flow (FRE3) as well as flow percentiles (5^{th}%, 25^{th}%, median, 75^{th}%, 95^{th}%). The latter were selected for assessment owing to their use in the wider NZ literature as being important predictors of stream geomorphology and ecology (e.g., Clausen and Biggs, 1997; Clausen and Biggs, 2000; Kilroy et al., 2018; Graham et al., 2019). Following Booker (2013), FRE3 was calculated using the median flow over calendar years 2012-2016. The number of consecutive days with flow below 3*median flow for each year were identified and the occurrence of consecutive days that were larger than five days were counted. The FRE3 value was derived as the average of the count of consecutive days that were larger than five days in each year.

4.1.3 Parameter Selection

Parameter selection is the culmination of the modelling configuration and calibration. Prior to calibration, an initial set of HRU model parameters were derived and stratified by HRU with guidance from the BASINS Technical Note 6: *Estimating Hydrology and Hydraulic Runoff Parameters* (USEPA 2000). In selecting various parameters to adjust and others to remain globally constant across all HRUs, the calibration exercise sought to characterise the key processes likely to vary across HRU combinations (e.g., factors of land cover, impact, HSG and slope). The exercise involved adjusting HRU and reach group parameters using the upstream-downstream approach so that performance metrics achieved "Satisfactory" or better grades across the greatest number of calibration stations. Large watersheds were emphasised over small watersheds during calibration given the regional nature of the model.

The key selected parameters are detailed in Appendix A. In the sections below, the parameters that were relied upon most heavily during calibration routines are also itemised. Note that Appendix A reports imperial units, as that is the 'native' set of units in LSPC. All LSPC outputs are post-processed to convert to metric units outside of LSPC.

4.2 Hydrology Calibration and Validation

As described in Section 4.1, the top-down calibration approach highly emphasised the hydrologic calibration, as runoff and streamflow drive erosion, scour, wash off, travel time, settling, resuspension and a variety of other factors that affect water quality conditions.

4.2.1 Monitoring Stations and Data

River flow and water quality monitoring programmes operated by Auckland Council over the past decade were essential to the calibration of FWMT. Table 4-3 shows the complete list of stations used for FWMT performance assessment, with stations marked by dots under the 'Flow' column were used for hydrologic assessment. The daily flow records from each of these stations over the 2012-2016 period was the basis of hydrologic calibration and validation (i.e., 1825 flow records for most stations).

A total of 46 stations were used to assess the FWMT's hydrologic performance, 16 of which were designated as calibration stations due to relatively homogeneous HRU composition upstream. The watershed areas upstream of hydrologic calibration (shaded) and validation stations are shown in Figure 4-5. The watershed area and HRU composition upstream of the hydrologic assessment stations are detailed in Table 4-4 and Table 4-5.

The hydrologic stations were labelled with 'Tiers' of hydrologic data quality based on review by Fordham (2019) (see Appendix H). The Tiers were based upon five factors:

1. % of level measurements flagged as high quality
2. Whether the site is tidally influenced or affected by nearby structure (subjective 'No' used as 'Pass')
3. Whether the site is impeded by macrophytes (subjective 'No' used as 'Pass')
4. Days recorded greater than a 2-year flow (fewer than 3 days of flows > 2-year over a 5-year period as 'Pass')
5. Maximum gauged flow as % 2 year flow (≥75% used as 'Pass')

And the data quality Tiers were defined as follows:

- Tier 1: all 5 factors pass (n = 7 stations)

- Tier 2: At least 90% of Factor 1 and No for both Factor 2 and Factor 3 (n = 15 stations)
- Tier 3: at least 80% for Factor 1 and No for Factor 2 (n = 11 stations)
- Tier 4: at least 80% for Factor 1 (n = 6 stations)
- Tier 5: reported but ignored for performance assessment (n = 7 stations)

The resulting Tiers for all stations are shown in Table 4-4. For hydrologic performance reporting, summaries are presented for both 'All' tiers (n = 46) and Tier 1 and 2 stations (n = 22).

Table 4-4. HRU Distribution and Watershed Size for All Stations used for FWMT Calibration and Validation (both Hydrology and Water Quality)

Group	Monitoring Locations: Hydrology Calibration (predominant Land Use) and Model Validation (Hydrology and Water Quality)	Hydro Quality Tier	Available Data: Flow	Available Data: WQ	Available Data: Sed. Yield	Drainage Area (km^2): Observed	Drainage Area (km^2): Model	Percent of Area – Land Use/Land Cover: Developed	Forest	Horticulture	Open Space	Pasture	Other	Percent of Area – Slope: High	Low	Percent of Area – Hydrologic Soil Group: A+	A	B	C	D	Impervious	Water
Forest	Cascades Stream @ Confluence	-		●		-	11	0	97	0	0	0	3	96	4	0	0	10	87	0	0	3
Forest	Okura @ Weiti Forest	4	●		●	-	1.7	0	73	0	6	20	0	100	0	0	0	0	0	100	0	0
Forest	Opanuku Stream @ Candia Road Bridge	2	●	●	●	16	15	3	54	2	7	33	1	95	5	0	0	54	45	0	0	1
Forest	Riverhead @ Ararimu Valley Road	-		●		-	4.6	1	70	0	24	5	0	91	9	0	0	6	93	0	0	0
Forest	Vaughn Stream @ Lower Weir	4	●	●	●	2.3	2.4	6	45	0	49	0	0	92	8	0	0	14	85	0	1	0
Forest	West Hoe @ Halls	2	●	●	●	0.5	0.5	0	63	0	1	35	0	99	1	0	0	73	27	0	0	0
Pasture	Kaukapakapa @ Taylors	3	●	●	●	62	62	1	8	1	15	75	1	68	32	0	0	20	16	64	0	1
Pasture	Mangawheau Stream @ Weir	3	●			30	32	1	8	1	10	80	1	82	18	0	0	52	47	0	0	1
Pasture	Orewa @ Kowhai Ave	2	●		●	9.7	9.7	1	3	1	12	82	1	64	36	0	0	7	9	83	0	0
Pasture	Papakura @ Alfriston/Ardmore Rd	-		●		-	23	1	20	1	16	61	1	78	22	0	0	19	80	1	0	0
Pasture	Papakura @ Great South Road Bridge	4	●			52	53	9	13	4	21	53	1	39	61	0	0	27	68	0	5	0
Pasture	Wairoa Trib @ Caitchons Rd	-		●		-	2.2	0	1	0	0	99	0	100	0	0	0	100	0	0	0	0
Hort.	Ngakoroa Stream @ Mill Rd	2	●	●		4.7	4.8	2	2	24	12	59	1	50	50	90	0	7	1	0	1	1
Hort.	Oratia @ Parrs Cross Road	5	●	●	●	17	17	8	41	14	16	21	0	81	19	0	0	63	34	0	2	0
Hort.	Waitangi @ S H Bridge	5	●			18	18	1	2	14	11	72	0	15	85	87	0	5	8	0	0	0
Hort.	Waitangi @ Waitangi Falls Bridge.	-		●		-	19	1	2	14	11	72	0	14	86	87	0	5	7	0	0	0
Hort.	Whangamaire @ Woodhouse Road	-		●		-	8.0	3	3	35	12	47	0	19	81	98	0	0	0	0	1	0
Developed	Lucas @ Gills Road	2	●	●		6.3	6.1	30	27	0	42	0	1	59	41	0	0	18	62	0	19	1
Developed	Oakley Creek at Richardson Road	3	●	●		-	5.9	45	19	0	36	0	0	2	98	16	0	0	54	0	30	0
Developed	Otara @ East Tamaki Rd	-		●		-	9.4	43	20	0	37	1	0	4	96	0	0	10	62	0	28	0
Developed	Oteha River @ Days Bridge	2	●	●		12	12	41	21	0	34	0	4	34	66	0	0	21	44	0	30	4
Developed	Puhinui @ Drop Structure	3	●	●		12	13	34	19	0	40	6	1	36	64	0	0	6	70	0	23	0
Developed	Wairau Creek @ Motorway	1	●			11	11	52	25	0	23	0	0	31	69	0	0	0	62	0	38	0
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Ararimu River @ Old North Rd Bridge	3	●			67	71	0	35	1	19	45	1	85	15	0	0	34	58	8	0	0
	Avondale Stream @ Shadbolt Park	-		●		-	3.0	29	46	0	24	0	0	41	59	0	0	0	84	0	16	0
	Awaruku stream at Glenvar Road	2	●			1.7	1.9	45	41	0	14	0	0	69	31	0	0	12	59	0	29	0
	Cascades @ Whakanewha	-		●		-	0.6	0	49	1	41	8	1	99	1	0	0	52	48	0	0	0
	Eskdale Stream at Lauderdale Reserve	2	●			3.9	4.0	26	57	0	16	0	0	83	17	0	0	0	85	0	14	0
	Hoteo River @ Gubbs	1	●		●	268	270	0	25	1	15	58	1	81	19	0	0	18	65	17	0	1
	Kaipara River @ Waimauku	3	●		●	155	156	2	20	5	16	55	1	66	34	0	0	41	54	4	1	0
	Kaipatiki Stream at Kaipatiki road	2	●			1.5	1.4	37	40	0	23	0	0	78	22	0	0	0	79	0	21	0
	Kumeu @ Maddrens Weir	5	●	●		-	45	3	10	6	14	67	1	53	47	0	0	34	65	0	1	0
	Mahurangi @ College	1	●			47	48	1	35	2	17	44	1	78	22	0	0	40	55	4	0	1
	Mahurangi Argonaut @ College	2	●	●		47	50	2	35	2	18	43	1	78	22	0	0	41	54	4	1	1
	Mairangi Bay Stream at Tennis Club	2	●			0.6	1.0	51	32	0	17	0	0	61	39	0	0	0	66	0	34	0
	Makarau at Coles	5	●	●		54	49	0	23	0	17	58	1	90	10	0	0	20	50	30	0	0
	Mangemangeroa	2	●		●	4.6	4.3	3	23	0	58	16	0	98	2	0	0	0	100	0	0	0
	Matakana @ Wenzlicks Farm	-		●		-	13	0	31	1	24	44	0	90	10	0	0	33	67	0	0	0
	Meola Creek at Motions Road Weir	3	●			15	8.6	51	27	0	21	0	0	10	90	57	0	0	6	0	37	0
	Motions Stream @ Western Springs.	2	●			7.5	4.3	57	23	0	18	0	2	10	90	20	0	0	32	0	46	2
	Newmarket Stream @ AYR Street crump weir	4	●			5.5	5.0	56	27	0	17	0	0	20	80	55	0	0	2	0	43	0
	Nukumea @ Upper Site	-		●		-	1.0	0	75	0	19	6	0	99	1	0	0	100	0	0	0	0
	Oakley Creek @ Carrington.	-		●		-	12	44	22	0	34	0	0	3	97	28	0	0	42	0	30	0
	Okura Creek @ Awanohi Rd	5	●	●	●	-	5.8	2	25	5	24	43	1	94	6	0	0	48	15	37	1	0
	Omaru @ Maybury Street	-		●		-	3.5	49	19	0	32	0	0	11	89	9	0	0	54	0	37	0
	Onetangi @ Waiheke Rd	-		●		-	0.7	4	86	0	5	4	0	99	1	0	0	70	29	0	1	0
	Opanuku @ Vintage Reserve	1	●			27	25	9	41	3	14	32	1	81	19	0	0	45	50	0	4	1
	Oratia @ Millbrook Road	1	●			23	28	18	42	8	19	13	0	69	31	0	0	41	50	0	9	0
	Otaki @ Middlemore Crescent	-		●		-	1.0	45	25	0	30	0	1	0	100	0	0	0	72	0	27	1
	Otara @ Hills Road Bridge	1	●			19	19	18	14	0	57	10	1	40	60	1	0	20	68	0	10	1
	Otara Stream @ Kennel Hill	-		●		-	18	17	14	0	58	11	1	41	59	1	0	21	68	0	9	1
	Pakuranga @ Botany Rd	-		●		-	6.6	53	21	0	24	2	0	2	98	0	0	18	45	0	37	0
	Pakuranga @ Greenmount Drive	-		●		-	2.4	47	15	0	35	3	0	20	80	18	0	16	34	0	31	0
	Papakura Stream @ Porchester Road Bridge	-		●		-	45	4	12	5	18	61	1	46	54	0	0	29	69	0	1	0
	Rangitopuni River @ Walkers	3	●	●		82	82	1	19	2	18	58	1	62	38	0	0	21	29	49	0	1
	Swanson Stream @ Woodside Reserve	2	●		●	23	23	9	33	1	22	35	1	78	22	0	0	32	64	0	3	0
	Taiaotea stream at Freyberg Park	4	●			2.2	2.4	47	34	0	19	0	0	62	38	0	0	0	70	0	30	0
	Taiorahi Stream at Westbourne ave	5	●			1.0	1.0	45	39	0	16	0	1	70	30	0	0	0	71	0	28	1
	Tamahunga River @ Quintals Falls	3	●			8.0	8.2	0	39	0	8	50	3	87	13	0	0	44	53	2	0	1
	Tamaki Trib at Bowden Road Crump Weir	2	●			3.1	2.9	61	14	0	25	0	0	1	99	11	0	0	38	0	50	0
	Wairau Creek @ Chartwell Road	3	●			1.4	1.1	37	38	0	25	0	0	76	24	0	0	0	78	0	22	0
	Wairoa River @ Tourist Road	1	●	●	●	161	149	0	23	0	11	63	2	83	17	1	0	74	23	0	0	2
	Waiteitei River @ Sandersons	3	●		●	81	82	0	4	1	9	85	1	70	30	0	0	17	72	10	0	0
	Waiwera Stream @ Upper Waiwera Road	-		●		-	30	0	16	1	21	61	1	92	8	0	0	15	68	16	0	1
	Waiwhiu Stream @ Dome Shadow	5	●		●	-	8.6	0	90	0	7	2	1	99	1	0	0	32	68	0	0	0
	Whau Stream at Blockhouse Bay Road Crump Wier	4	●			4.7	4.8	43	26	0	31	0	0	13	87	0	0	0	73	0	27	0

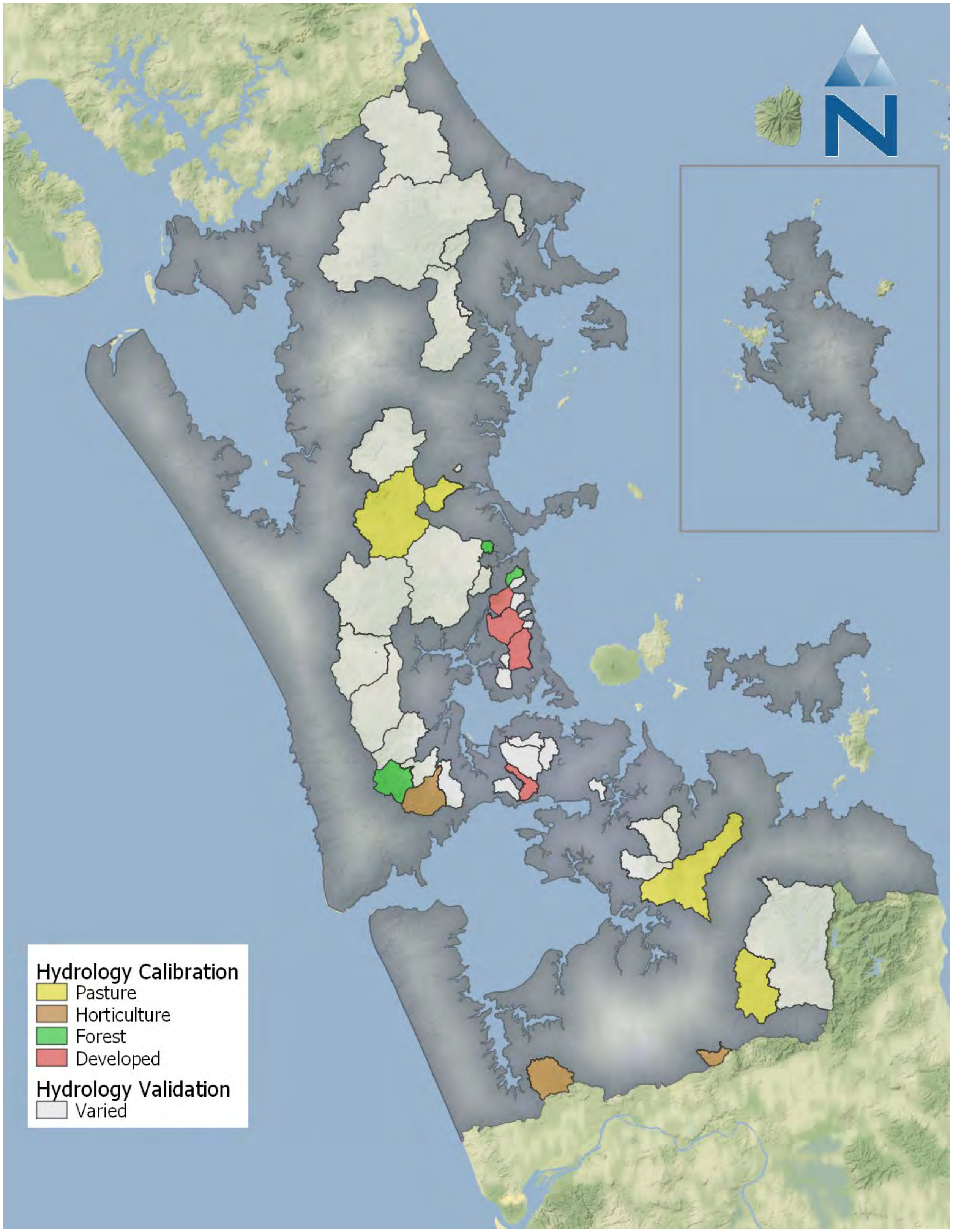


Figure 4-5. Watersheds Upstream of Hydrology Calibration and Validation Stations

Table 4-5. HRU Distribution and Watershed Size for Stations used for FWMT Hydrologic Calibration and Validation

Monitoring Locations: Hydrology Calibration (Land Use of Interest) and Model Validation (Hydrology)		Hydro Quality Tier	Available Data			Drainage Area (km^2)		Percent of Area: Land Use/Land Cover						Percent of Area: Slope		Percent of Area: Hydrologic Soil Group						
			Flow	WQ	Sed. Yield	Observed	Model	Developed	Forest	Horticulture	Open Space	Pasture	Other	High	Low	A+	A	B	C	D	Impervious	Water
Forest	Okura @ Weiti Forest	4	●		●	-	1.7	0	73	0	6	20	0	100	0	0	0	0	0	100	0	0
Forest	Opanuku Stream @ Candia Road Bridge	2	●	●	●	16	15	3	54	2	7	33	1	95	5	0	0	54	45	0	0	1
Forest	Vaughn Stream @ Lower Weir	4	●	●	●	2.3	2.4	6	45	0	49	0	0	92	8	0	0	14	85	0	1	0
Forest	West Hoe @ Halls	2	●	●	●	0.5	0.5	0	63	0	1	35	0	99	1	0	0	73	27	0	0	0
Pasture	Kaukapakapa @ Taylors	3	●	●	●	62	62	1	8	1	15	75	1	68	32	0	0	20	16	64	0	1
Pasture	Mangawheau Stream @ Weir	3	●			30	32	1	8	1	10	80	1	82	18	0	0	52	47	0	0	1
Pasture	Orewa @ Kowhai Ave	2	●		●	9.7	9.7	1	3	1	12	82	1	64	36	0	0	7	9	83	0	0
Pasture	Papakura @ Great South Road Bridge	4	●			52	53	9	13	4	21	53	1	39	61	0	0	27	68	0	5	0
Hort.	Ngakoroa Stream @ Mill Rd	2	●	●		4.7	4.8	2	2	24	12	59	1	50	50	90	0	7	1	0	1	1
Hort.	Oratia @ Parrs Cross Road	5	●	●	●	17	17	8	41	14	16	21	0	81	19	0	0	63	34	0	2	0
Hort.	Waitangi @ S H Bridge	5	●			18	18	1	2	14	11	72	0	15	85	87	0	5	8	0	0	0
Developed	Lucas @ Gills Road	2	●	●		6.3	6.1	30	27	0	42	0	1	59	41	0	0	18	62	0	19	1
Developed	Oakley Creek at Richardson Road	3	●	●		-	5.9	45	19	0	36	0	0	2	98	16	0	0	54	0	30	0
Developed	Oteha River @ Days Bridge	2	●	●		12	12	41	21	0	34	0	4	34	66	0	0	21	44	0	30	4
Developed	Puhinui @ Drop Structure	3	●	●		12	13	34	19	0	40	6	1	36	64	0	0	6	70	0	23	0
Developed	Wairau Creek @ Motorway	1	●			11	11	52	25	0	23	0	0	31	69	0	0	0	62	0	38	0
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Ararimu River @ Old North Rd Bridge	3	●			67	71	0	35	1	19	45	1	85	15	0	0	34	58	8	0	0
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Awaruku stream at Glenvar Road	2	●			1.7	1.9	45	41	0	14	0	0	69	31	0	0	12	59	0	29	0
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Eskdale Stream at Lauderdale Reserve	2	●			3.9	4.0	26	57	0	16	0	0	83	17	0	0	0	85	0	14	0
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Hoteo River @ Gubbs	1	●		●	268	270	0	25	1	15	58	1	81	19	0	0	18	65	17	0	1
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Kaipara River @ Waimauku	3	●		●	155	156	2	20	5	16	55	1	66	34	0	0	41	54	4	1	0
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Kaipatiki Stream at Kaipatiki road	2	●			1.5	1.4	37	40	0	23	0	0	78	22	0	0	0	79	0	21	0
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Kumeu @ Maddrens Weir	5	●	●		-	45	3	10	6	14	67	1	53	47	0	0	34	65	0	1	0
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Mahurangi @ College	1	●			47	48	1	35	2	17	44	1	78	22	0	0	40	55	4	0	1
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Mahurangi Argonaut @ College	2	●	●		47	50	2	35	2	18	43	1	78	22	0	0	41	54	4	1	1
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Mairangi Bay Stream at Tennis Club	2	●			0.6	1.0	51	32	0	17	0	0	61	39	0	0	0	66	0	34	0
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Makarau at Coles	5	●	●		54	49	0	23	0	17	58	1	90	10	0	0	20	50	30	0	0
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Mangemangeroa	2	●		●	4.6	4.3	3	23	0	58	16	0	98	2	0	0	0	100	0	0	0
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Meola Creek at Motions Road Weir	3	●			15	8.6	51	27	0	21	0	0	10	90	57	0	0	6	0	37	0
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Motions Stream @ Western Springs.	2	●			7.5	4.3	57	23	0	18	0	2	10	90	20	0	0	32	0	46	2
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Newmarket Stream @ AYR Street crump weir	4	●			5.5	5.0	56	27	0	17	0	0	20	80	55	0	0	2	0	43	0
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Okura Creek @ Awanohi Rd	5	●	●	●	-	5.8	2	25	5	24	43	1	94	6	0	0	48	15	37	1	0
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Opanuku @ Vintage Reserve	1	●			27	25	9	41	3	14	32	1	81	19	0	0	45	50	0	4	1
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Oratia @ Millbrook Road	1	●			23	28	18	42	8	19	13	0	69	31	0	0	41	50	0	9	0
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Otara @ Hills Road Bridge	1	●			19	19	18	14	0	57	10	1	40	60	1	0	20	68	0	10	1
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Rangitopuni River @ Walkers	3	●	●		82	82	1	19	2	18	58	1	62	38	0	0	21	29	49	0	1
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Swanson Stream @ Woodside Reserve	2	●		●	23	23	9	33	1	22	35	1	78	22	0	0	32	64	0	3	0
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Taiaotea stream at Freyberg Park	4	●			2.2	2.4	47	34	0	19	0	0	62	38	0	0	0	70	0	30	0
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Taiorahi Stream at Westbourne ave	5	●			1.0	1.0	45	39	0	16	0	1	70	30	0	0	0	71	0	28	1
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Tamahunga River @ Quintals Falls	3	●			8.0	8.2	0	39	0	8	50	3	87	13	0	0	44	53	2	0	1
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Tamaki Trib at Bowden Road Crump Weir	2	●			3.1	2.9	61	14	0	25	0	0	1	99	11	0	0	38	0	50	0
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Wairau Creek @ Chartwell Road	3	●			1.4	1.1	37	38	0	25	0	0	76	24	0	0	0	78	0	22	0
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Wairoa River @ Tourist Road	1	●	●	●	161	149	0	23	0	11	63	2	83	17	1	0	74	23	0	0	2
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Waiteitei River @ Sandersons	3	●		●	81	82	0	4	1	9	85	1	70	30	0	0	17	72	10	0	0
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Waiwhiu Stream @ Dome Shadow	5	●		●	-	8.6	0	90	0	7	2	1	99	1	0	0	32	68	0	0	0
Other Monitoring Locations (for Hydrology and Water Quality Validation)	Whau Stream at Blockhouse Bay Road Crump Wier	4	●			4.7	4.8	43	26	0	31	0	0	13	87	0	0	0	73	0	27	0

4.2.2 Hydrologic Performance Assessment

The outcome of the hydrologic calibration and validation process is a set of performance metrics for each of the 46 stations along with an extensive series of hydrology panels for each station. Regionwide performance of the FWMT is assessed through summary figures, whilst performance at each station can be assessed through output panels that analyse residuals and per cent differences across time periods, seasons and flow conditions for each station. Also, for each station hydrologic metrics (7-day MALF, MAF, and FRE3) are reported for both observed and simulated time series.

The regionwide hydrologic performance of the FWMT is presented as the following:

- Table 4-6: reports the station-by-station hydrologic performance assessment for different seasons (left performance columns) and flow conditions (right performance columns) for r-Squared, PBIAS and NSE.
- Figure 4-6: summarises the per cent of Tier 1 and 2 (n = 22) stations achieving different performance categories across seasonal and flow-based conditions for r-Squared, PBIAS and NSE.
- Figure 4-7: summarises the per cent of all stations (n = 46) achieving different performance categories across seasonal and flow-based conditions for r-Squared, PBIAS and NSE.

The hydrologic performance panels are presented for each of the 46 stations in Appendix B. An example series of panels for the Hoteo River validation station is presented as the following for observed vs simulated time series:

- Figure 4-8 to Figure 4-9: Raw time series comparison of daily and monthly values for the entire simulations period (2003-2017).
- Figure 4-9 to Figure 4-11: Raw and aggregated monthly time series comparison
- Figure 4-12: Flow duration curve comparison
- Figure 4-13: Area-normalised daily time series comparison
- Figure 4-14 to Figure 4-17: Residuals and per cent differences of daily flow across time periods and months
- Figure 4-18 to Figure 4-20: Residuals and per cent differences of daily flow sorted by flow conditions
- Table 4-7 to Table 4-10: Detailed reporting of performance metrics for r-Squared, NSE and PBIAS across seasons and flow conditions.
- Table 4-11 to Table 4-14: Flow rate statistics including percentile, 7-day MALF, MAF and FRE3.

Combined, the hydrologic performance panels total over 1000 pages of detailed information regarding model performance and streamflow statistics.

4.2.3 Hydrologic Calibration Outcomes and Discussion

The hydrologic calibration exercise has demonstrated the ability of the regional configuration and calibration methodology to create a hydrologic model that achieves 'Satisfactory' or better performance in a majority of stations and conditions across all three performance metrics. For the 'All' condition which analyses performance across all seasons and flow conditions, the following outcome represents an important milestone in water quality planning for the Auckland region (Figure 4-6):

- 86% of Tier 1 and 2 stations achieve Satisfactory or better for the PBIAS metric
- 82% of Tier 1 and 2 stations achieve Satisfactory or better for the r-Squared metric
- 86% of Tier 1 and 2 stations achieve Satisfactory or better for the NSE metric

Even when considering all stations including Tier 5 stations which are known to have data quality issues, at least 76% of stations achieve Satisfactory or better in the 'All' category for PBIAS, r-Squared and NSE. The 'All' category is highlighted because it covers all seasons and conditions and because water quality planning is expected to improve water quality over continuous, long-term periods (as opposed to be targeted or limited to certain conditions). A visual assessment comparing observed and predicted daily and monthly streamflow for the full 15 year simulation period (Figure 4-8 and Figure 4-9) suggests that the hydrological calibration is robust enough to capture much of the variation of the same time.

Table 4-6. Hydrologic Performance Evaluation Across All Stations by Flow Regime and Season

Tier	Hydrology Monitoring Locations	Drainage Area (km2)	Performance Metrics (Seasonal) PBIAS All	Winter	Spring	Summer	Fall	Performance Metrics (Flow Regime) PBIAS All	Top 10%	Storms	Low 50%	Baseflow
Tier 1	Hoteo River @ Gubbs	268	+	+	+	+	+	+	+	+	+	+
	Wairoa River @ Tourist Road	161	-	-	+		-		-		+	
	Mahurangi @ College	46.8	+	+	+		+	+	+	+	+	
	Opanuku @ Vintage Reserve	26.5	+	+	+	+	+	+	+	+		
	Oratia @ Millbrook Road	22.9	-	-		-	-	-	-	-	-	-
	Otara @ Hills Road Bridge	18.9	+	+	+	+	+	+	+	+	-	
	Wairau Creek @ Motorway	11.1	+	+	+	+	+	+	+	+	-	+
Tier 2	Mahurangi Argonaut @ College	46.8	-	-	+		-		+	+	+	-
	Swanson Stream @ Woodside Reserve	22.8	+	+	+	+	+	+	+	+	+	
	Opanuku Stream @ Candia Road Bridge	15.9	+	+	+	+	+	+	+	+		
	Oteha River @ Days Bridge	12.2	+		+	+	+	+	+	+	-	
	Orewa @ Kowhai Ave	9.7	+	+		-	-	+	+	-	-	+
	Motions Stream @ Western Springs	7.5	-	-	+	+	-			-	+	+
	Lucas @ Gills Road	6.3	+	+	+	+	+	+	+	+	-	
	Ngakoroa Stream @ Mill Rd	4.7	+	+	+		+	+	+	+		
	Mangemangeroa	4.8		+	+				+		-	
	Eskdale Stream at Lauderdale Reserve	3.9			+	+	+		+	+	+	-
	Tamaki Trib at Bowden Road Crump Weir	3.1	-	-						-	+	+
	Awaruku stream at Glenvar Road	1.7	-	-		-	-	-		-	-	
	Kaipatiki Stream at Kaipatiki road	1.5	-	-	+	+	-			-	+	+
	Mairangi Bay Stream at Tennis Club	0.6	-	-		-	-	-	-	-	-	-
	West Hoe @ Halls	0.5	+	-	+	+	+	+	+	+	+	+
Tier 3	Kaipara River @ Waimauku	155.4	+	+	+	+	+	+	+	+	-	+
	Rangitopuni River @ Walkers	81.5	+	+	+			+	+	+	-	
	Waiteitei River @ Sandersons	80.6	-	-	+		-	-	+	-	-	-
	Ararimu River @ Old North Rd Bridge	66.8	-	-	+		-			-	-	+
	Kaukapakapa @ Taylors	61.9	-	-			-	-		-	-	-
	Mangawheau Stream @ Weir	30.4	+	-	+	+	-	+	-		+	+
	Meola Creek at Motions Road Weir	14.7	-	-	-	-	-	-	-	-	-	-
	Puhinui @ Drop Structure	11.6	-	-			-		-		+	
	Tamahunga River @ Quinlans Falls	8	+	+	+	+	-	+	+	+	-	-
	Oakley Creek at Richardson Road	6.1	+	+	+	+	+	+	+	+	+	+
	Wairau Creek @ Chartwell Road	1.4	+	+	+	+	+	+	+	+	+	+
Tier 4	Papakura @ Great South Road Bridge	51.6	-	+	+	-	-		+	-	-	+
	Newmarket Stream @ AYR Street	5.5	-	-			-	-	-	-	-	-
	Whau Stream at Crump Wier	4.7	-	-				-	+	+		-
	Vaughn Stream @ Lower Weir	2.3	-	-	+		-	-	+	+	-	-
	Taiaotea stream at Freyberg Park	2.2	+	+	+	+	-	+	+	+	-	-
	Okura @ Weiti Forest	1.7			+	+	-		+	-	-	-
Tier 5	Makarau at Coles	53.7	+	+	+	+	+	+	+	+	+	-
	Kumeu @ Maddrens Weir	44.9	+	+	+	+	-	+	+	+	-	+
	Waitangi @ S H Bridge	17.6	-	+	-				+	+	-	-
	Oratia @ Parrs Cross Road	16.7	-	-	+		-		+	+	-	-
	Waiwhiu Stream @ Dome Shadow	8.6	+	+	+	+	+	+	+	+	+	+
	Okura Creek @ Awanohi Rd	5.8	-	-			-	-	+	-	-	-
	Taiorahi Stream at Westbourne ave	1	+	+	+	+	+	+	+	+	-	+

Very Good | Good | Satisfactory | Unsatisfactory

+ Overpredicts | - Underpredicts

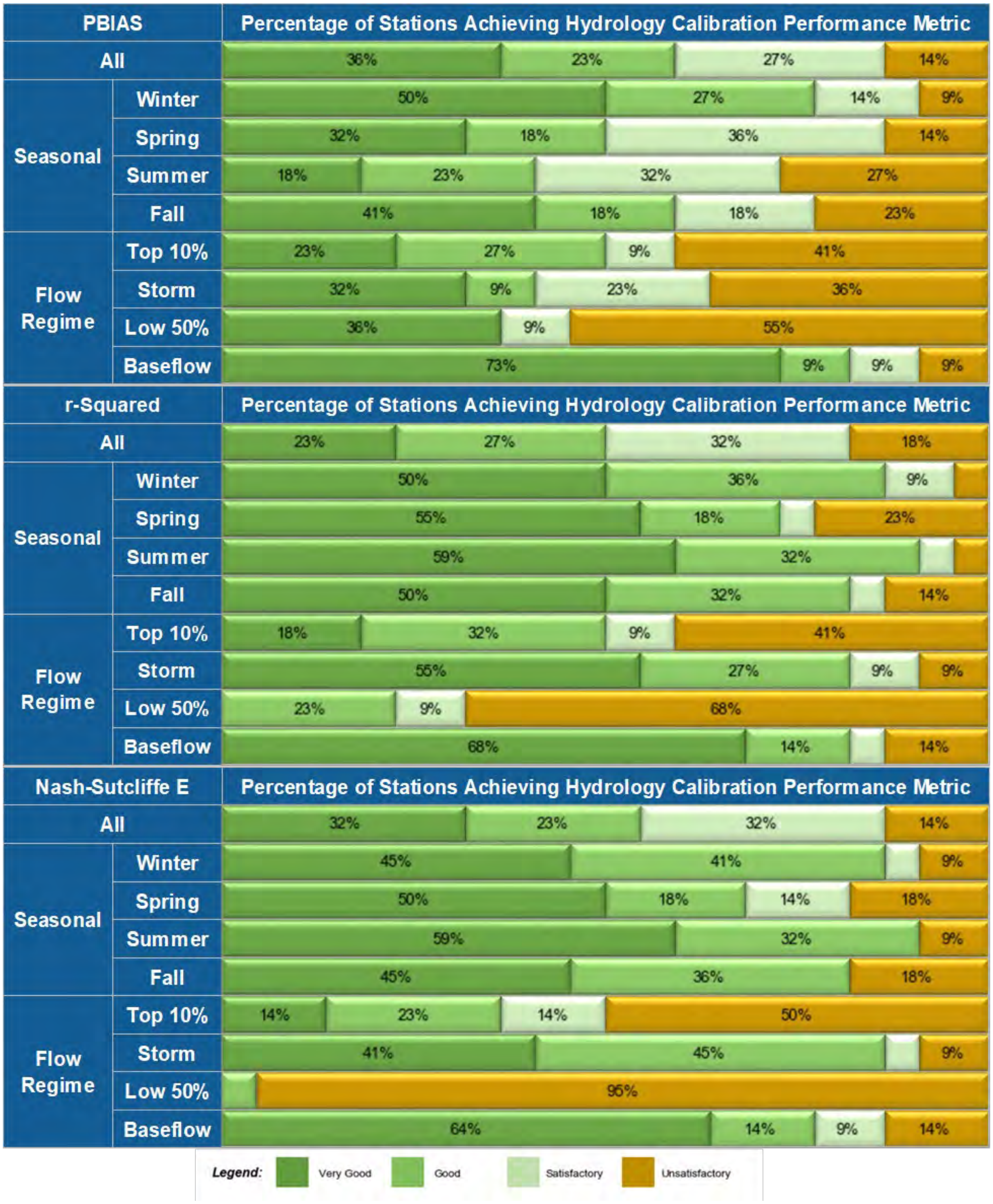


Figure 4-6. Regionwide FWMT Hydrologic Performance Evaluation for Tiers 1 and 2 Stations (n=22)

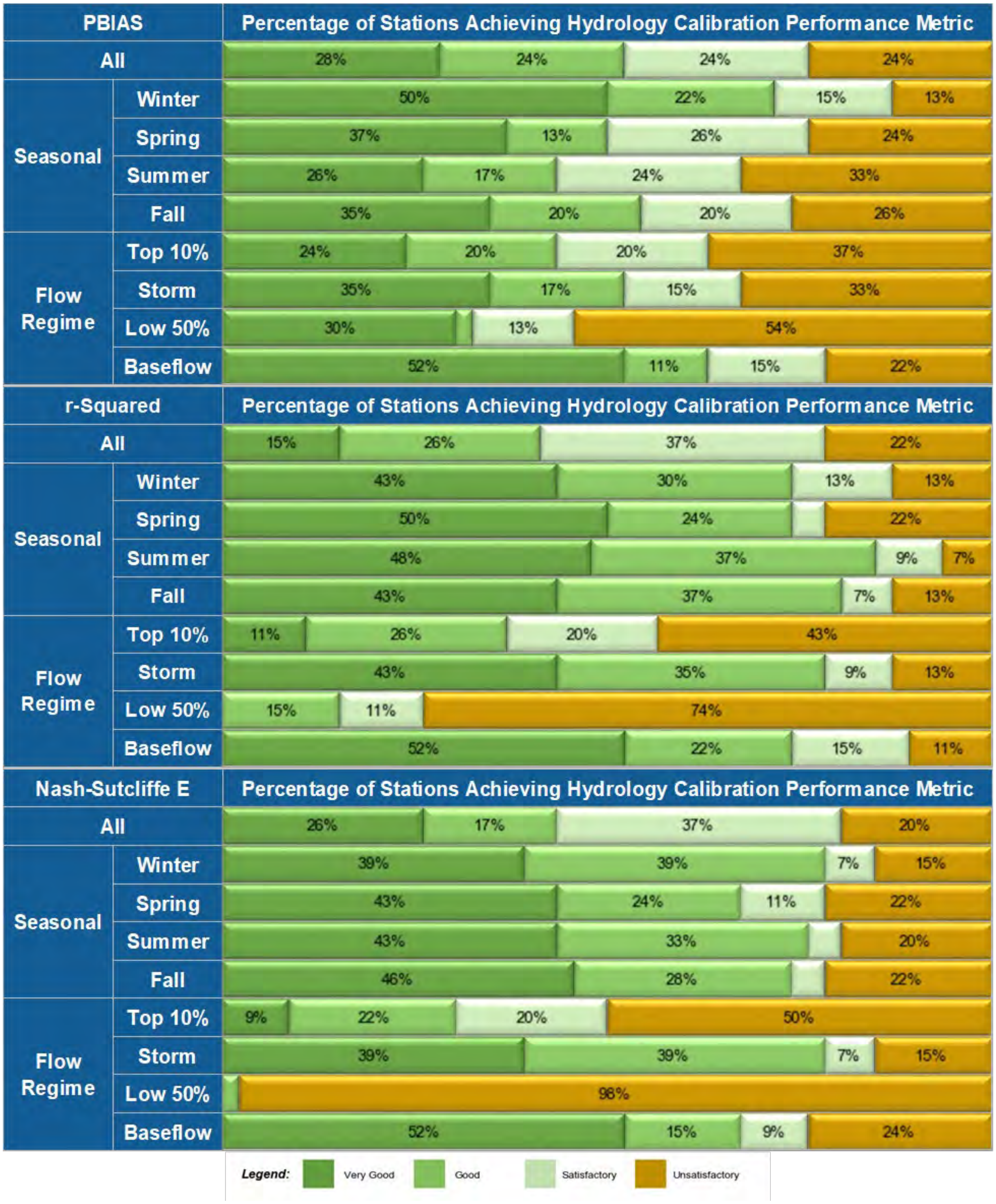


Figure 4-7. Regionwide FWMT Hydrologic Performance Evaluation for All Stations (n = 46)

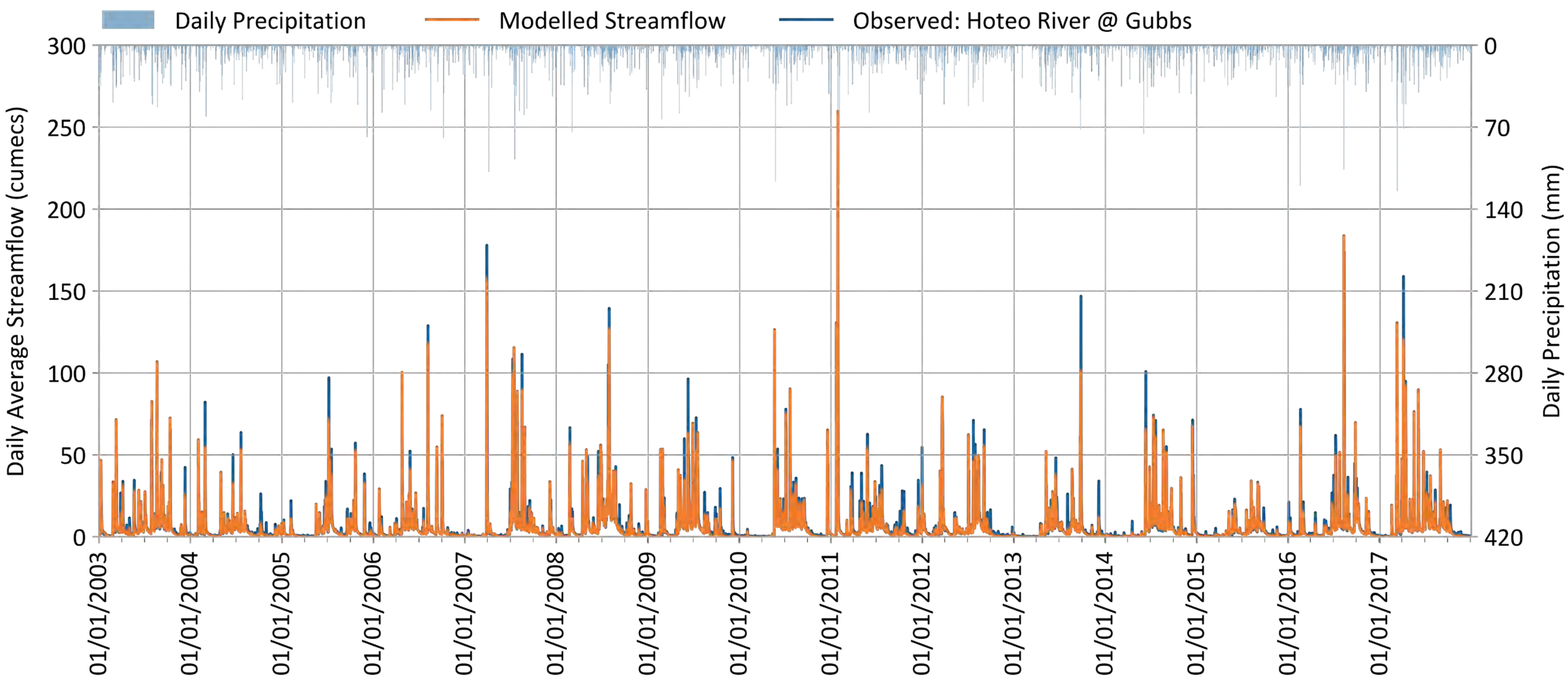


Figure 4-8. Example Panel from Hydrologic Validation: Hoteo River @ Gubbs (45703) – Hydrology calibration: Simulated vs. daily observed streamflow

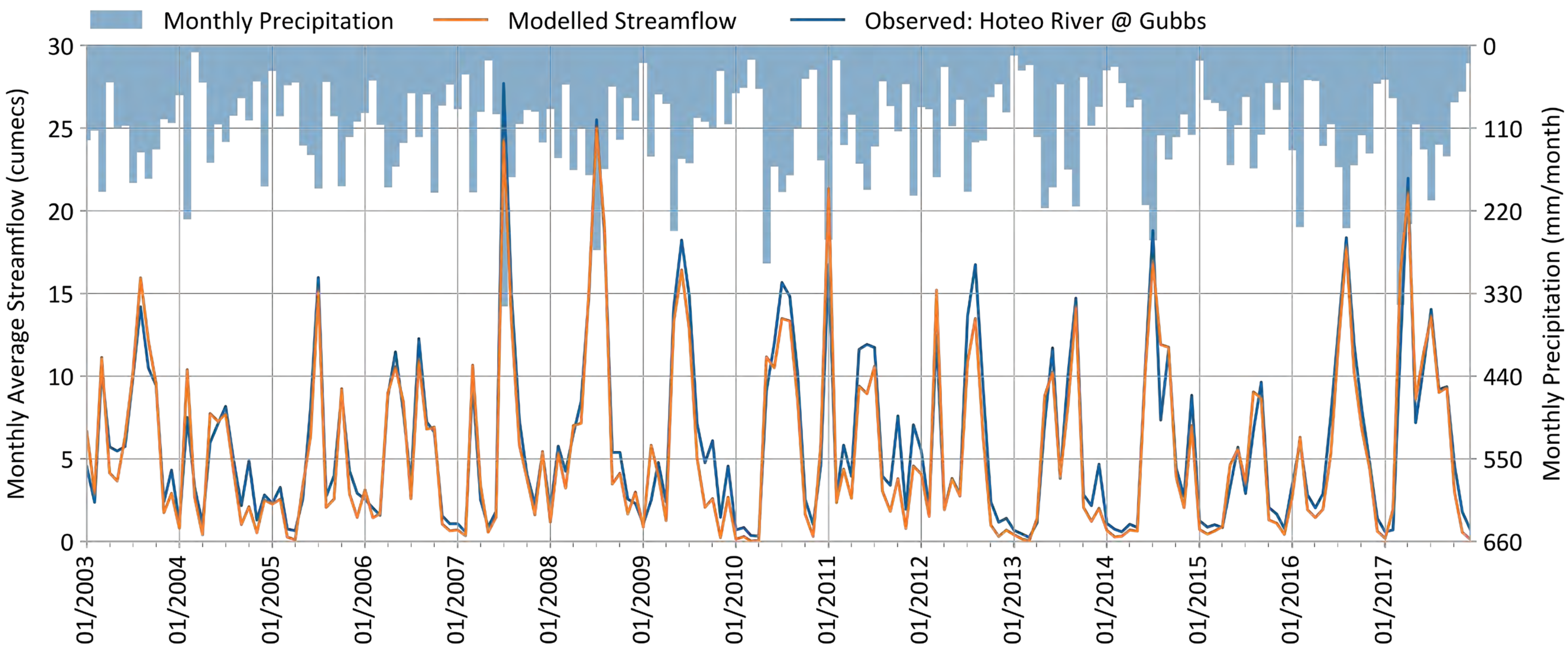


Figure 4-9. Example Panel from Hydrologic Validation: Hoteo River @ Gubbs (45703) – Hydrology calibration: Simulated vs. observed normalised monthly streamflow

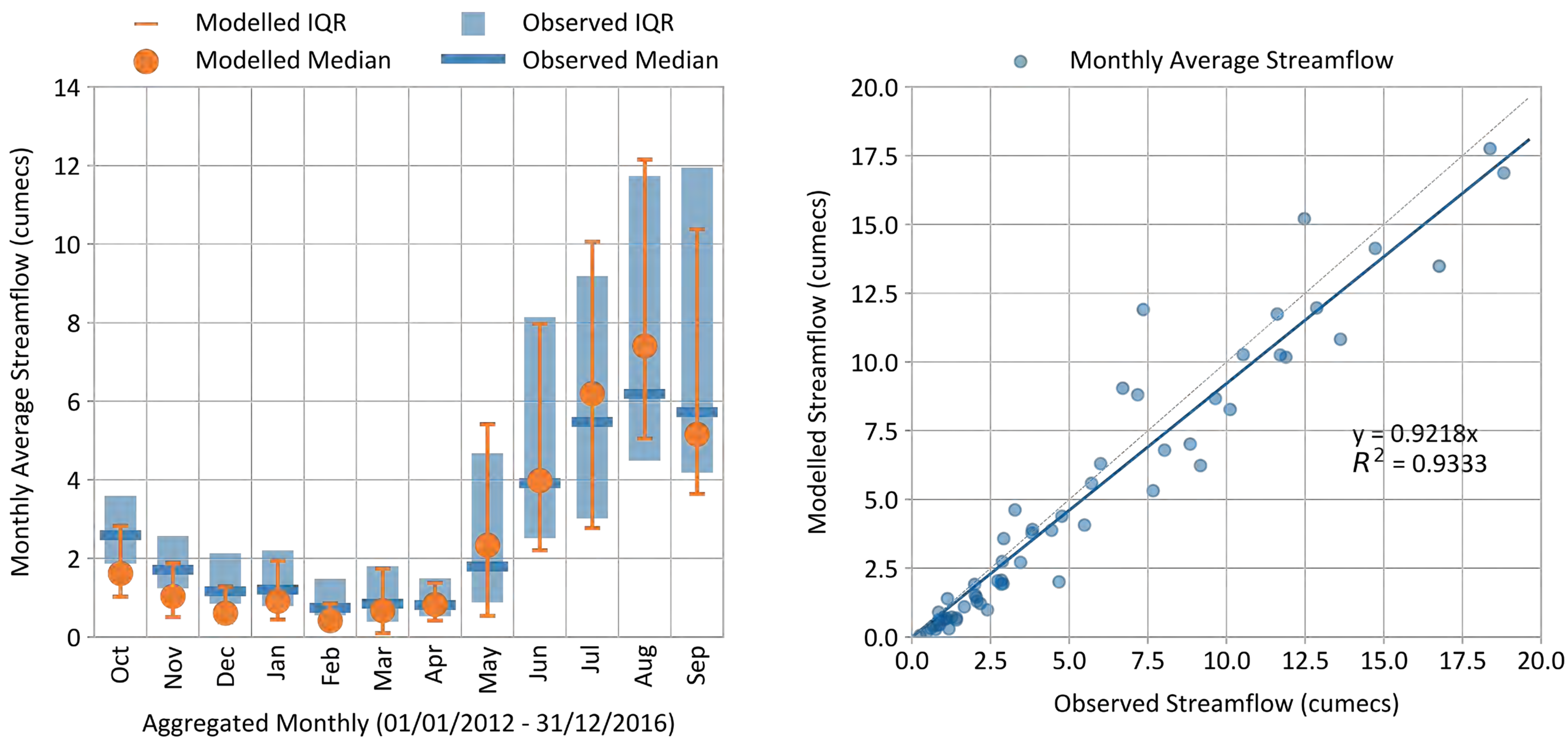


Figure 4-10. Example Panel from Hydrologic Validation: Hoteo River @ Gubbs (45703) – Hydrology calibration: Simulated vs. observed normalised monthly streamflow IQRs

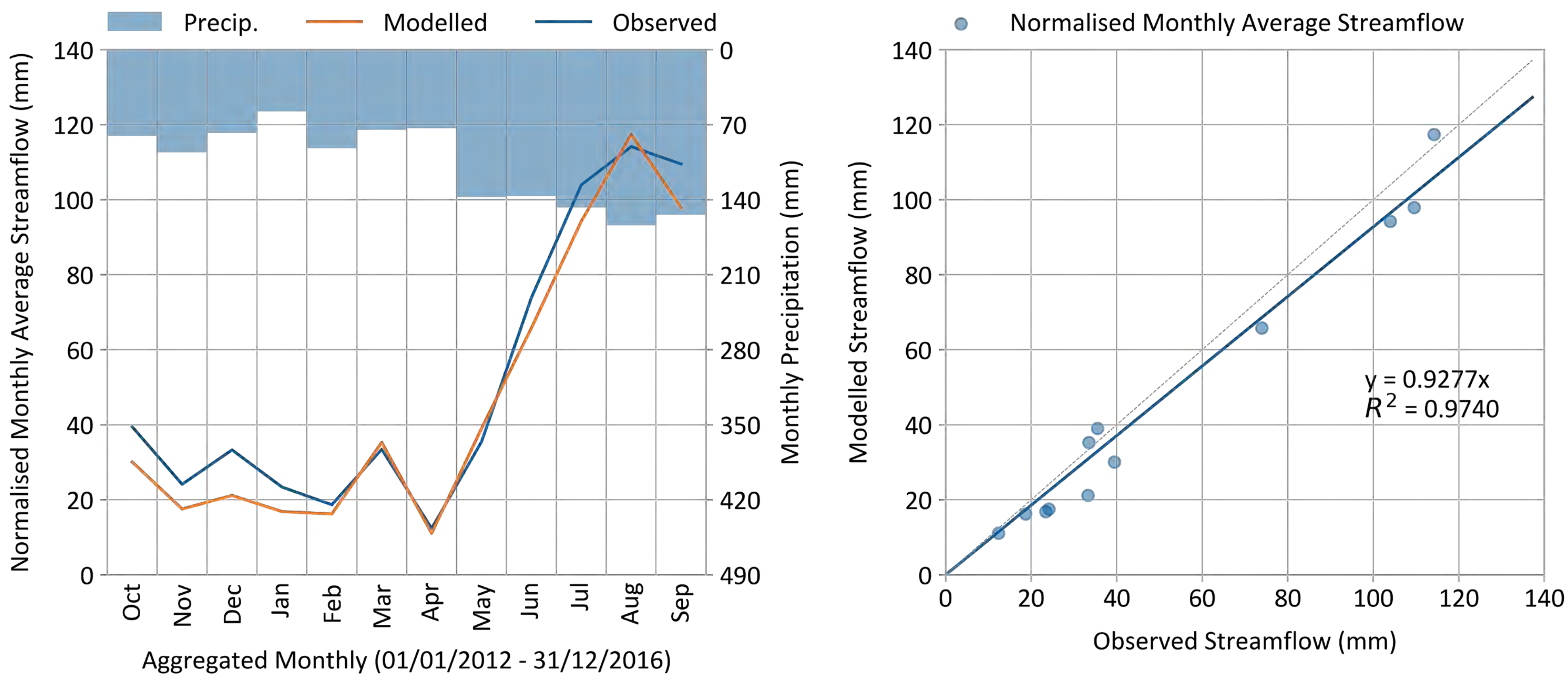


Figure 4-11. Example Panel from Hydrologic Validation: Hoteo River @ Gubbs (45703) – Hydrology calibration: Simulated vs. observed annualised monthly streamflow

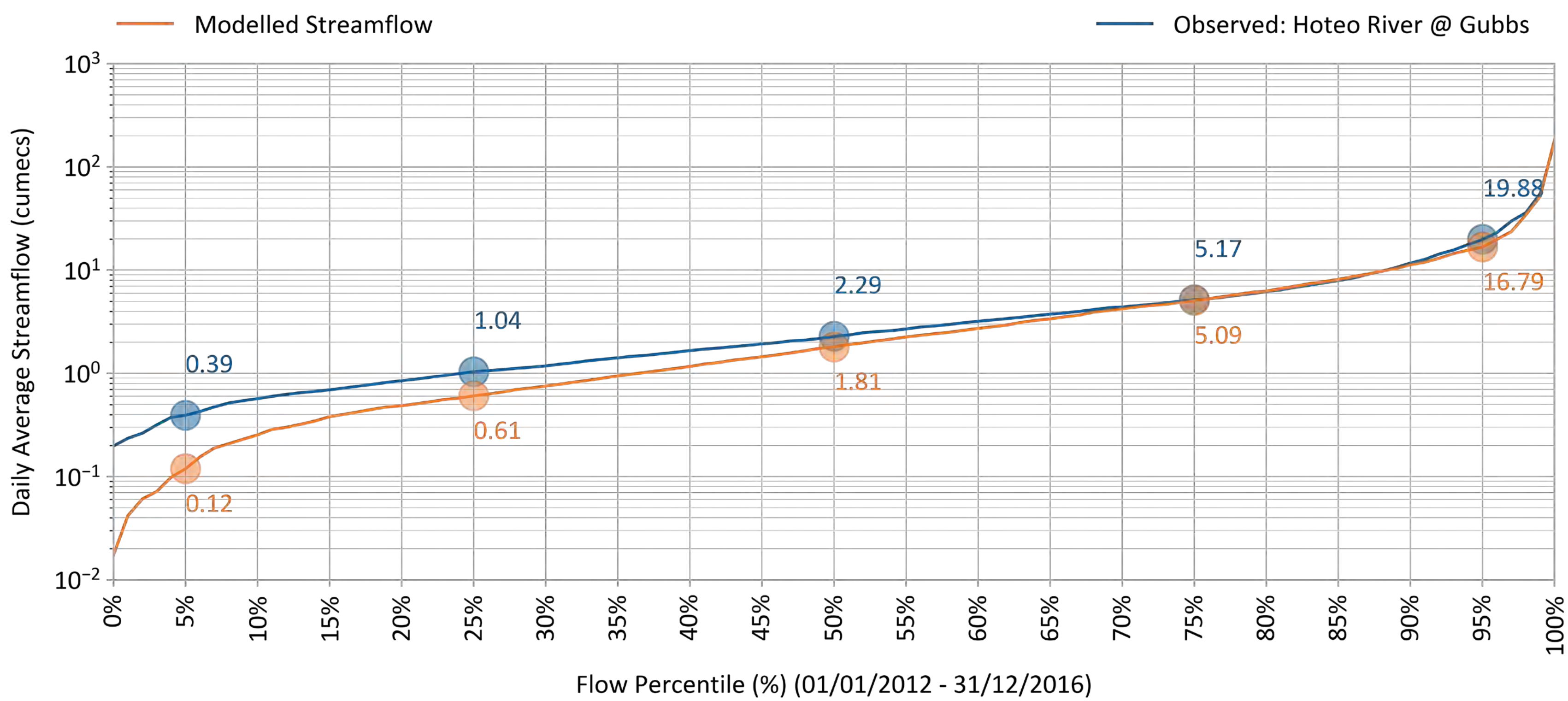


Figure 4-12. Example Panel from Hydrologic Validation: Hoteo River @ Gubbs (45703) – Hydrology calibration: Simulated vs. observed streamflow duration curves

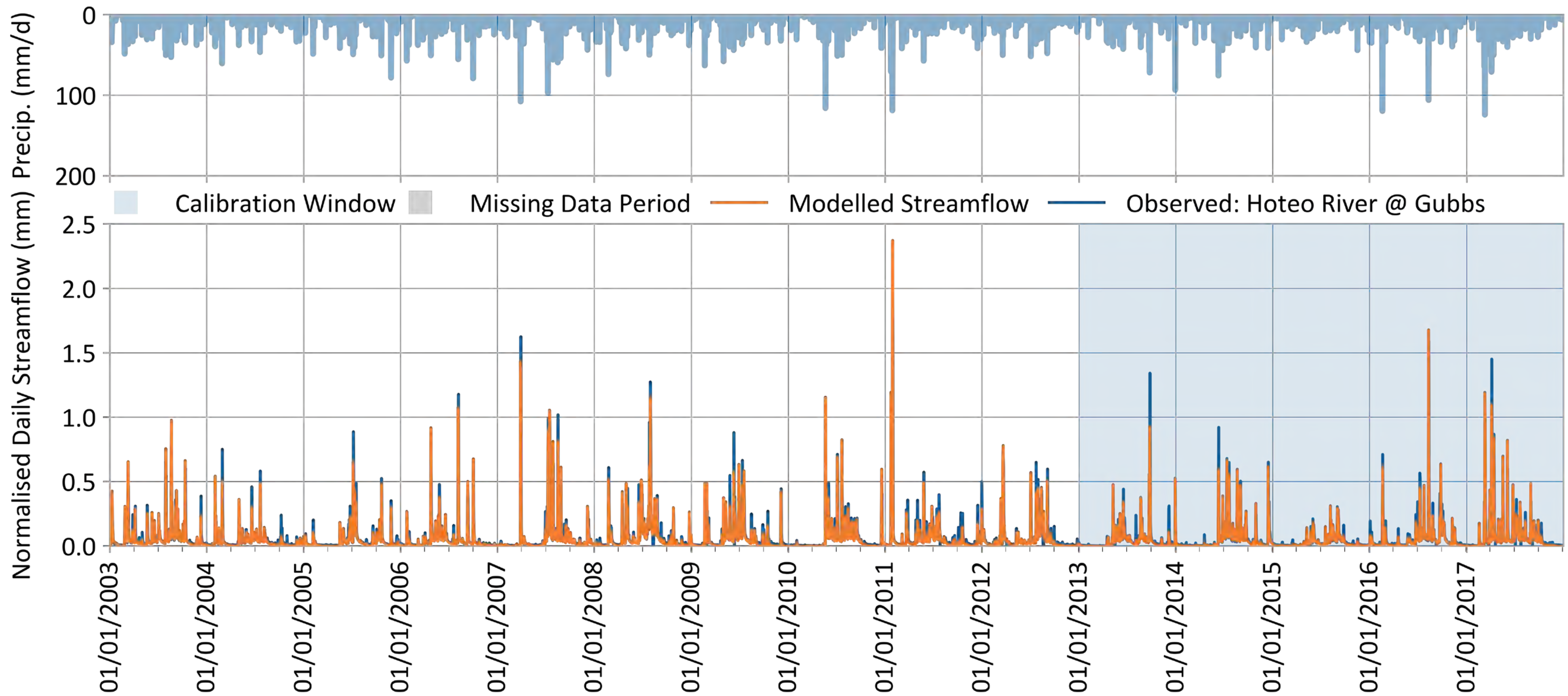


Figure 4-13. Example Panel from Hydrologic Validation: Hoteo River @ Gubbs (45703) – Hydrology calibration: Simulated vs. observed normalised daily streamflow

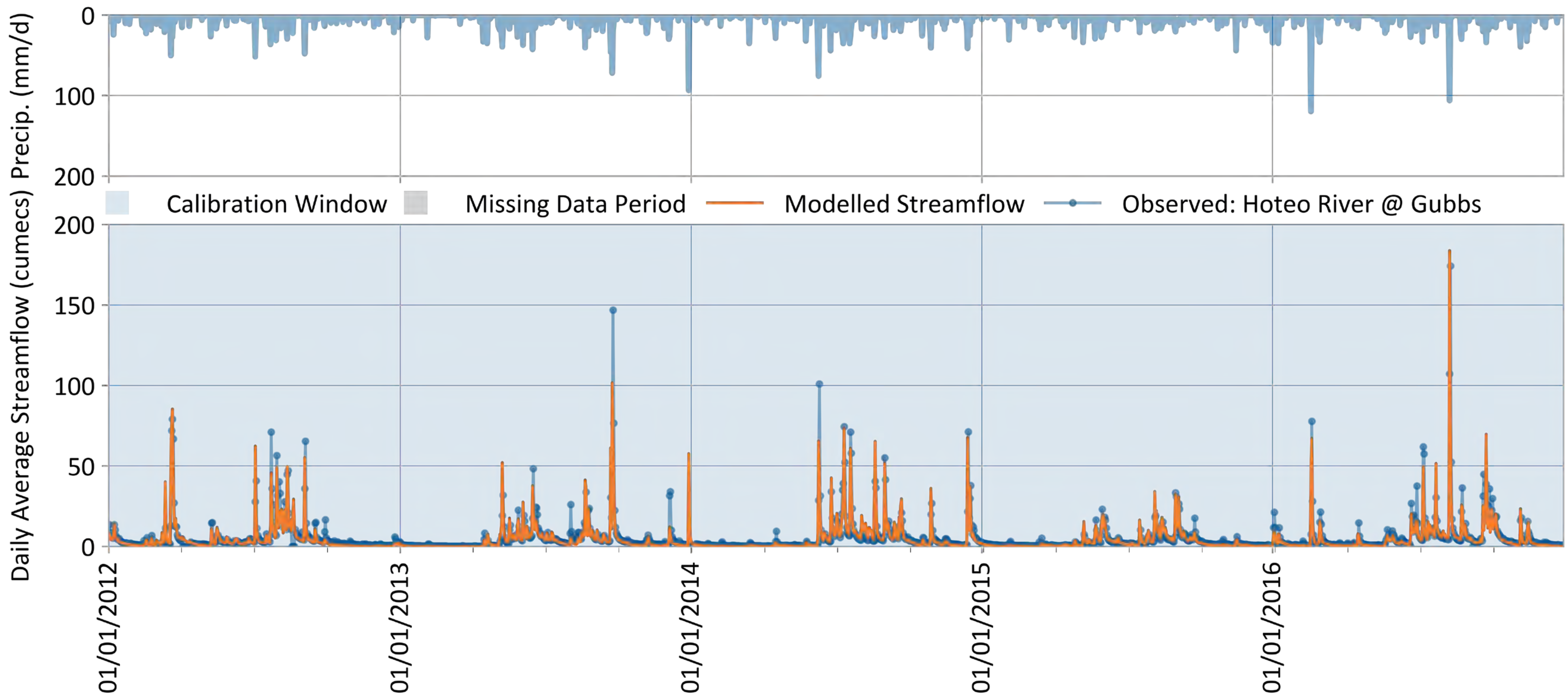


Figure 4-14. Example Panel from Hydrologic Validation: Hoteo River @ Gubbs (45703) – Hydrology calibration: Simulated vs. observed normalised daily streamflow

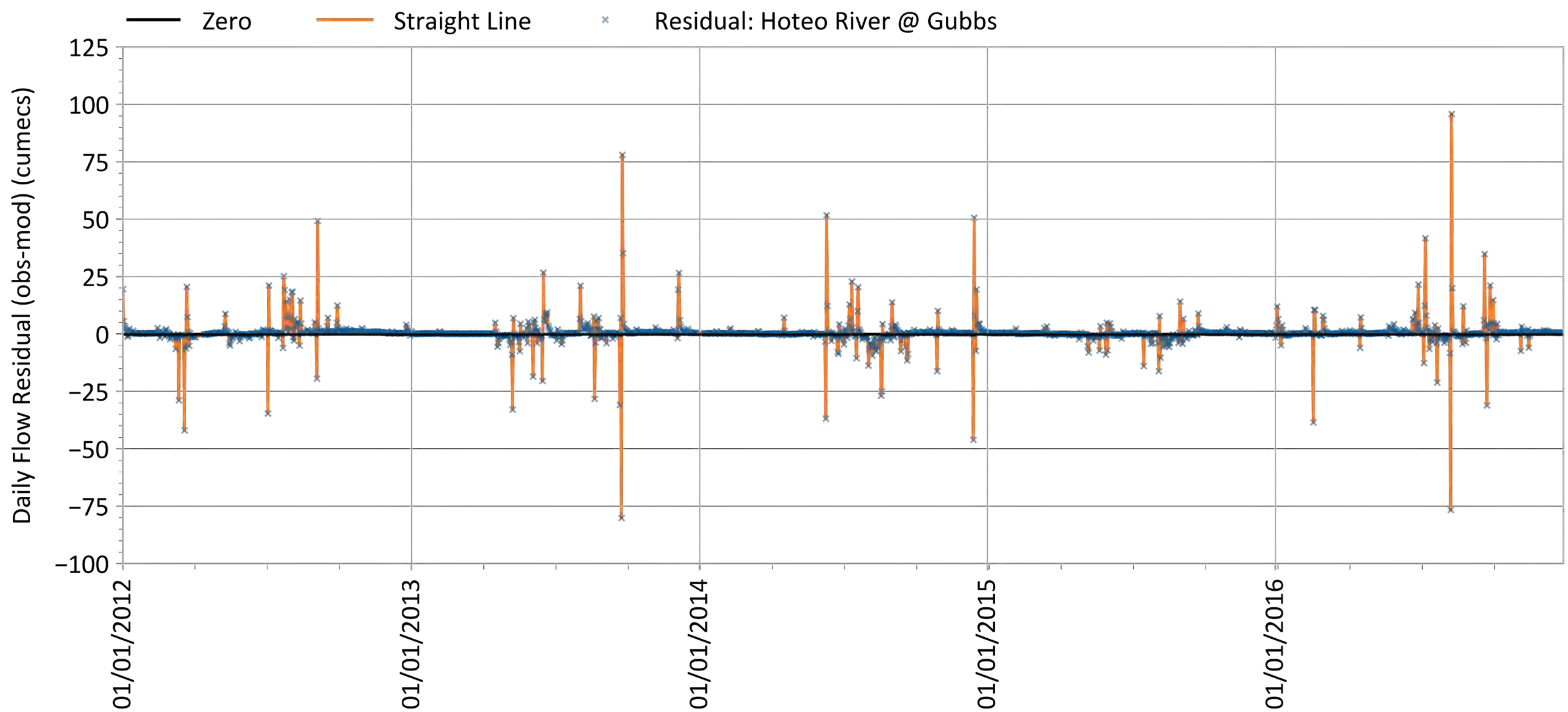


Figure 4-15. Example Panel from Hydrologic Validation: Hoteo River @ Gubbs (45703) – Hydrology calibration: Daily flow residual

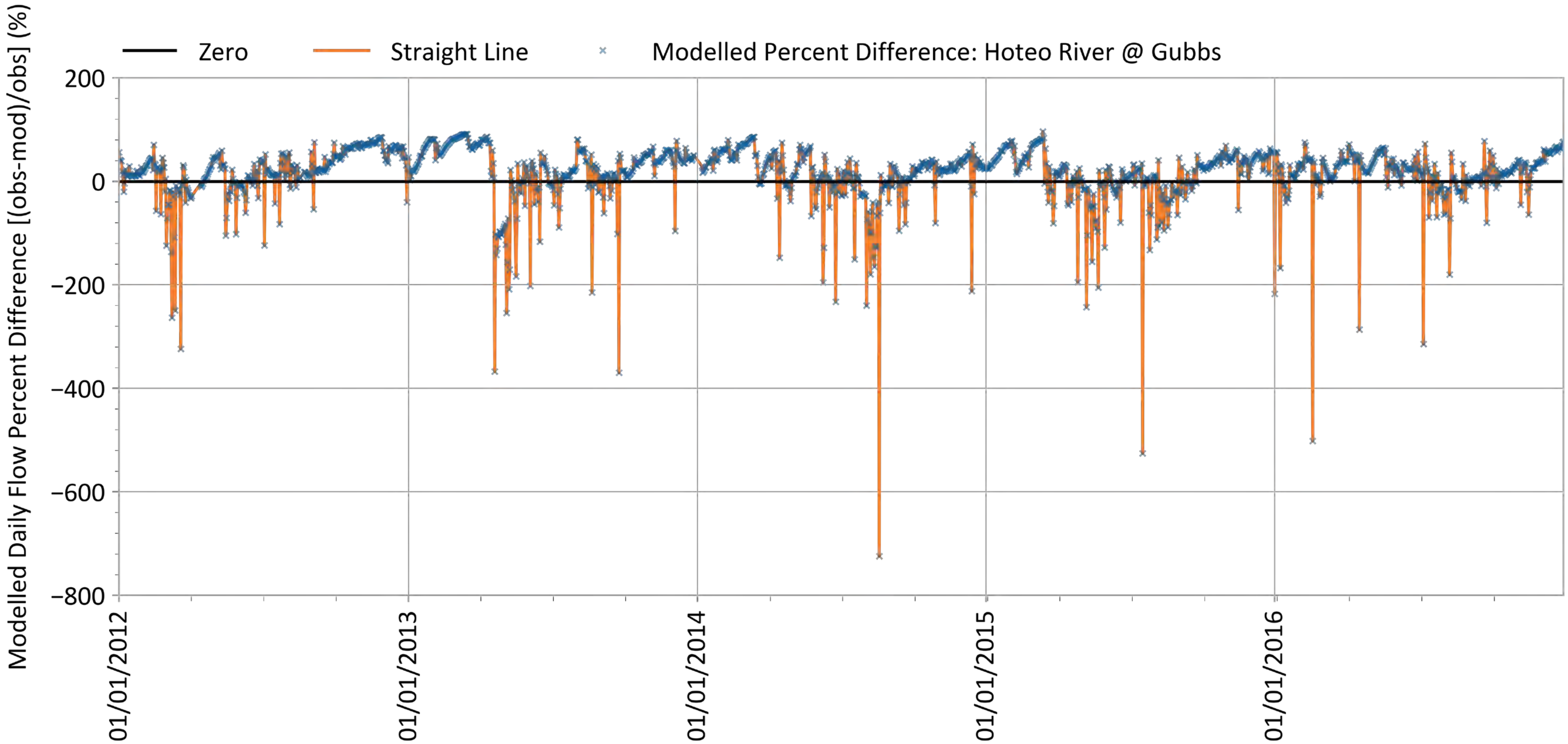


Figure 4-16. Example Panel from Hydrologic Validation: Hoteo River @ Gubbs (45703) – Hydrology calibration: Daily flow per cent difference

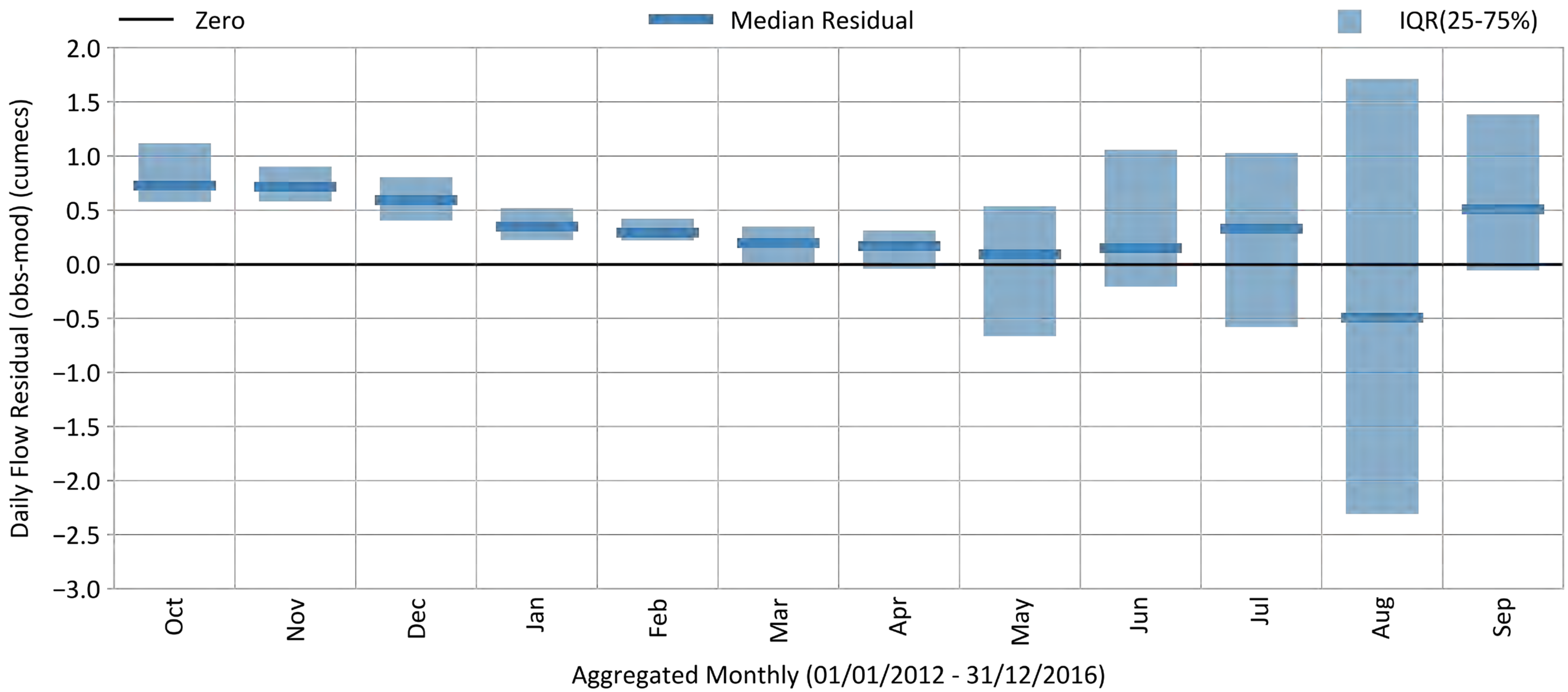


Figure 4-17. Example Panel from Hydrologic Validation: Hoteo River @ Gubbs (45703) – Hydrology calibration: Daily flow residual IQRs by month

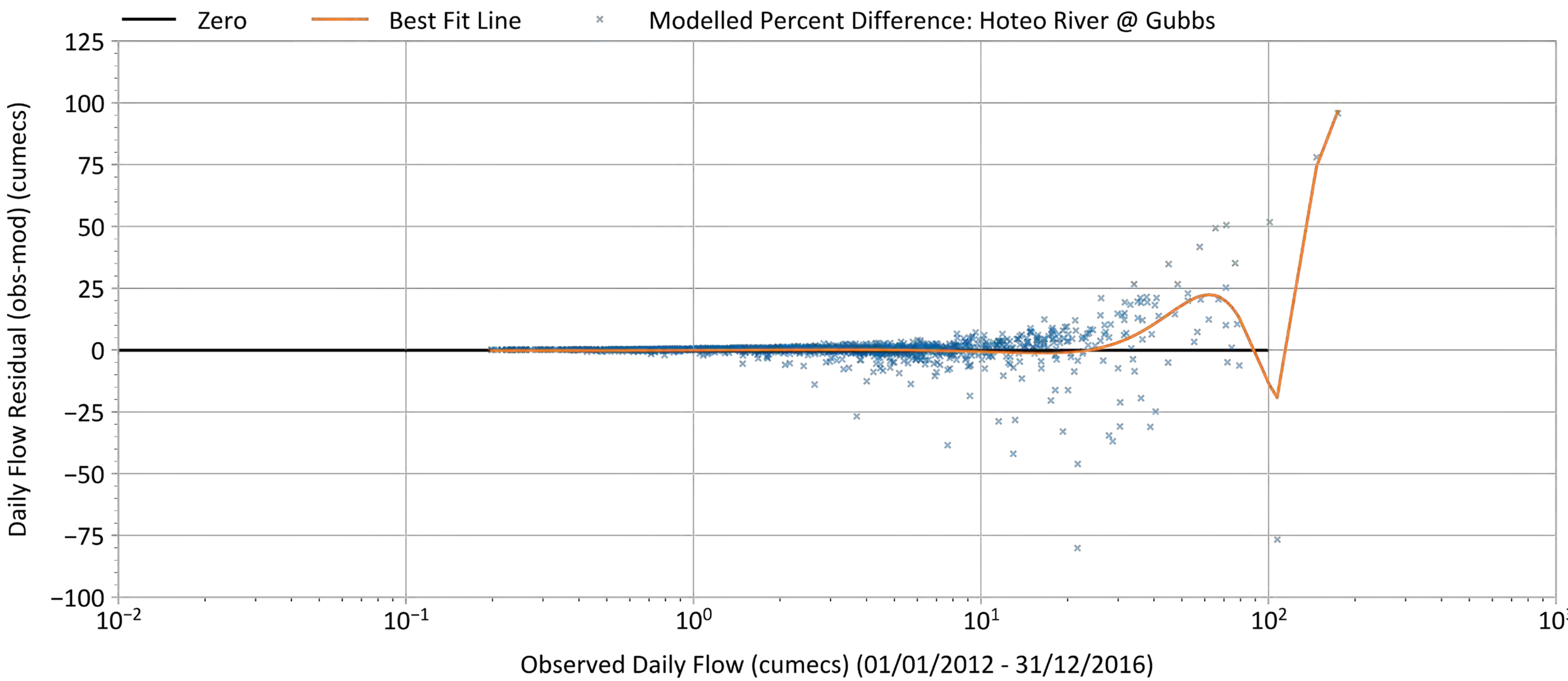


Figure 4-18. Example Panel from Hydrologic Validation: Hoteo River @ Gubbs (45703) – Hydrology calibration: Daily flow residual vs. observed flow magnitude

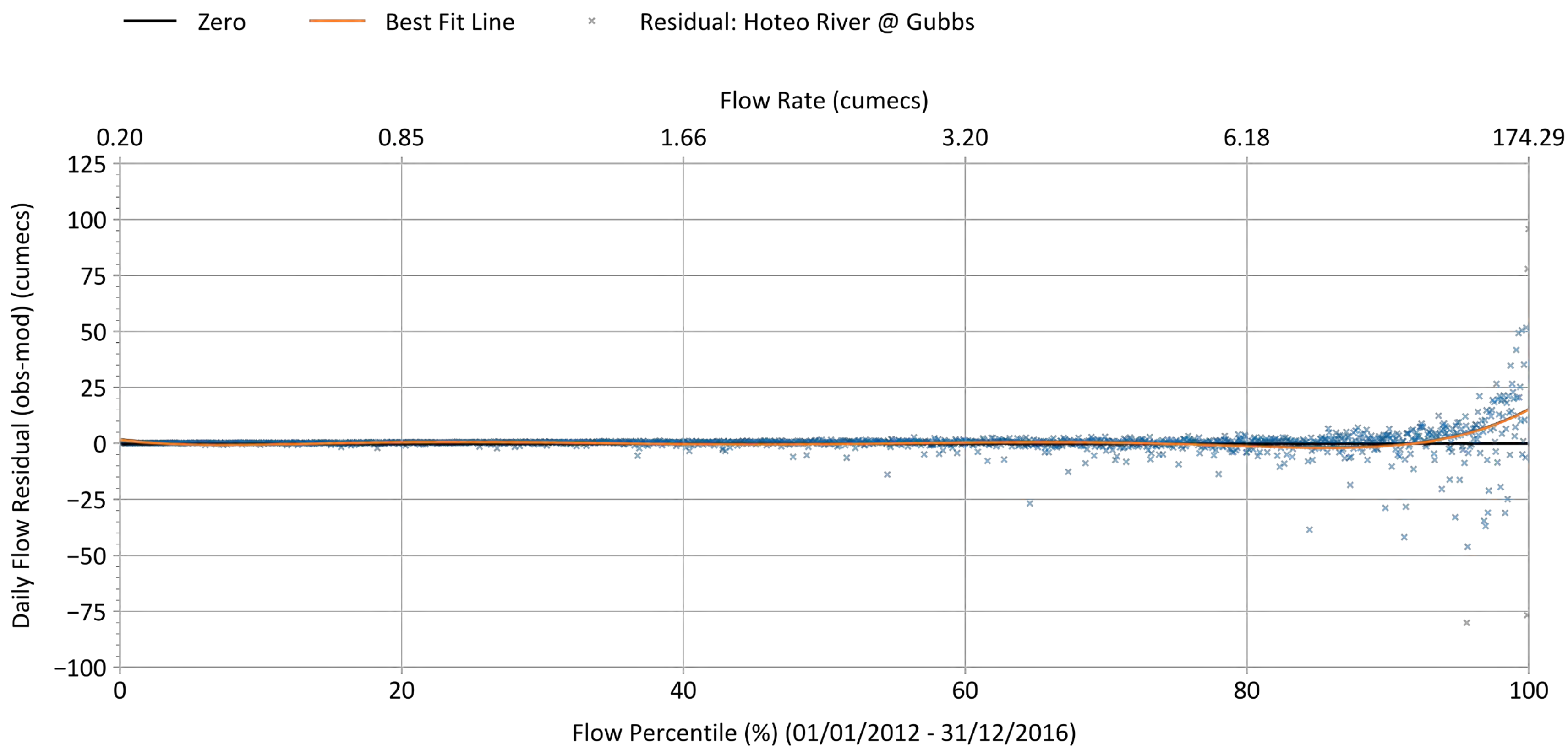


Figure 4-19. Example Panel from Hydrologic Validation: Hoteo River @ Gubbs (45703) – Hydrology calibration: Daily flow per cent difference vs. observed flow percentile

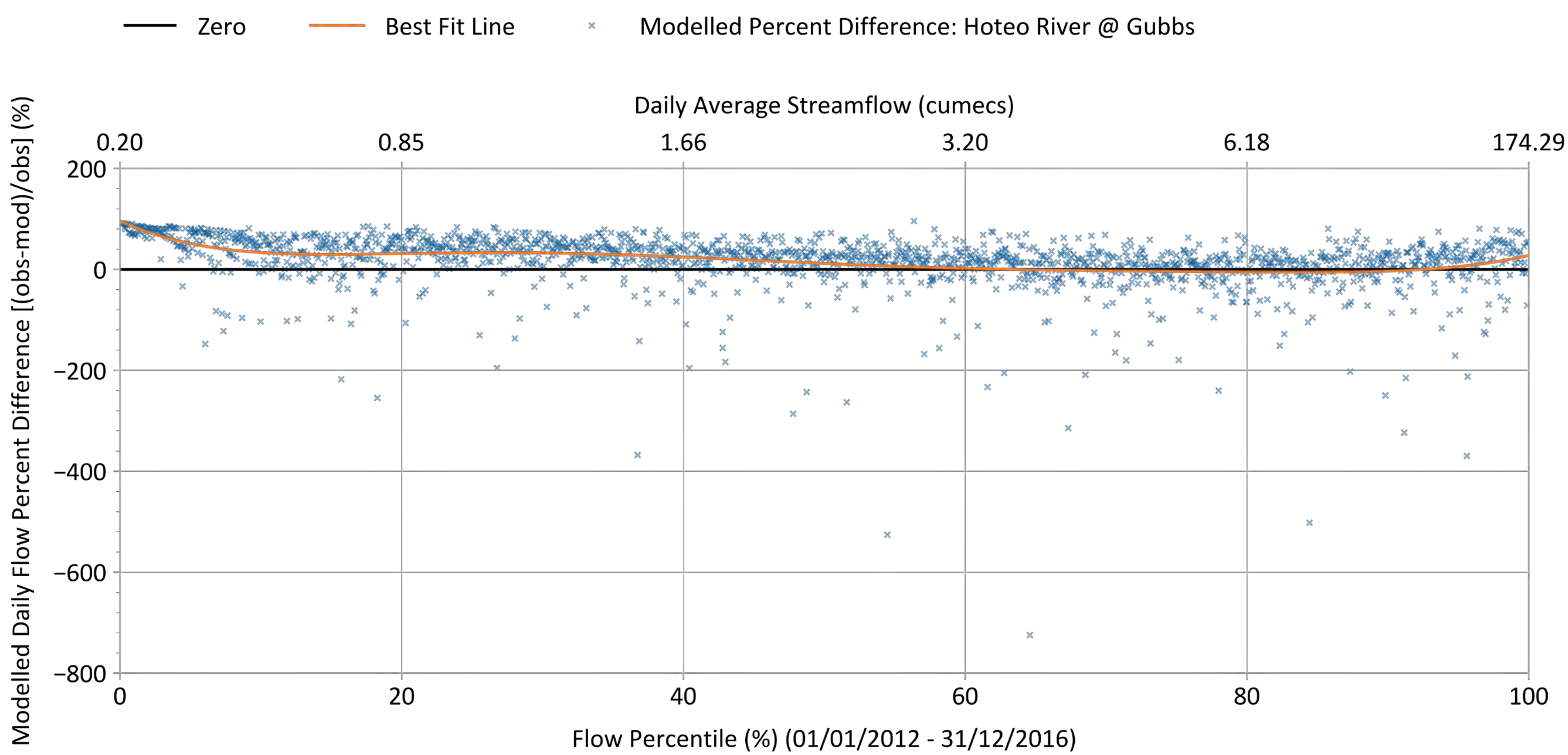


Figure 4-20. Hoteo River @ Gubbs (45703) – Hydrology calibration: Daily flow residual vs. observed flow percentile

Table 4-7. Example Panel from Hydrologic Validation: Hoteo River @ Gubbs (45703) – Hydrology calibration: Relative mean error statistical metric for modelled vs observed flow 01/01/2012-31/12/2016

Observed vs Simulated Calibration Performance for Runoff Volumes (Simulated vs Observed Total Volume for Condition-Season across Simulation)					
Calibration Metrics (01/01/2012 - 31/12/2016)	**Relative Mean Error (RME)**				
	All Seasons	**Winter**	**Spring**	**Summer**	**Fall**
Total Annual Volume	-9.5%	-5.5%	-29.0%	-9.5%	-4.8%
Highest 10% of Flows	-14.1%	-13.3%	-18.4%	-9.6%	-17.7%
Lowest 50% of Flows	-26.5%	-13.9%	-46.1%	-27.4%	3.2%
Storm Volume	-8.8%	-7.8%	-19.5%	-4.9%	-8.2%
Baseflow Volume	-10.3%	-2.8%	-34.7%	-15.2%	-1.4%
Baseflow Recession Rate	-1.3%	0.0%	-1.6%	-2.5%	-0.1%

Performance Metric	**Hydrological Condition**	**Comparison Type**	**Performance Threshold for Hydrology Simulation**				**Reference**
			Very Good	Good	Satisfactory	Unsatisfactory	
Relative Mean Error (RME)	Total Annual Volume	Compare Observed vs Simulated Total Volume across Simulation Period for Selected Season-Conditions	≤5%	5 - 10%	10 - 15%	>15%	Donigian et al. (1984), Lumb et al. (1984), and Donigian (2000)
	Highest 10% of Flows		≤10%	10 - 15%	15 - 25%	>25%	
	Lowest 50% of Flows		≤10%	10 - 15%	15 - 25%	>25%	
	Annual Storm Volume		≤10%	10 - 15%	15 - 25%	>25%	
	Seasonal Storm Volume		≤15%	15 - 30%	30 - 50%	>50%	
	Baseflow Volume		≤10%	10 - 15%	15 - 25%	>25%	
	Baseflow Recession Rate		≤3%	3 - 5%	5 - 10%	>10%	

Table 4-8. Example Panel from Hydrologic Validation: Hoteo River @ Gubbs (45703) – Hydrology calibration: Per cent bias statistical metric for modelled vs observed flow 01/01/2012-31/12/2016

Observed vs Simulated Calibration Performance for Flow Rates (Simulated vs Observed Flow Rates for Condition-Season across Simulation)					
Calibration Metrics (01/01/2012 - 31/12/2016)	Per cent Bias (PBIAS)				
	All Seasons	Winter	Spring	Summer	Fall
All Conditions	9.5%	5.5%	29.0%	9.5%	4.8%
Highest 10% of Daily Flow Rates	14.1%	13.3%	18.4%	9.6%	17.7%
Lowest 50% of Daily Flow Rates	26.5%	13.9%	46.1%	27.4%	-3.2%
Days Categorised as Storm Flow	6.5%	5.8%	26.8%	-0.0%	0.9%
Days Categorised as Baseflow	14.2%	5.0%	30.8%	22.0%	11.9%

Performance Metric	Hydrological Condition	Comparison Type	Performance Threshold for Hydrology Simulation				Reference
			Very Good	Good	Satisfactory	Unsatisfactory	
Per cent Bias (PBIAS)	All Conditions	Compare All Observed vs Simulated Daily Flow Rates that Occur During Selected Season-Conditions	<5%	5% - 10%	10% - 15%	>15%	Moriasi et al. (2015)
	Seasonal Flows Highest 10% of Daily Flow Rates Lowest 50% of Daily Flow Rates Days Categorised as Storm Flow Days Categorised as Baseflow		<10%	10% - 15%	15% - 25%	>25%	

Table 4-9. Example Panel from Hydrologic Validation: Hoteo River @ Gubbs (45703) – Hydrology calibration: r^2 statistical metric for modelled vs observed flow 01/01/2012-31/12/2016

Observed vs Simulated Calibration Performance for Flow Rates (Simulated vs Observed Flow Rates for Condition-Season across Simulation)					
Calibration Metrics (01/01/2012 - 31/12/2016)	**r-Squared (r^2)**				
	All Seasons	**Winter**	**Spring**	**Summer**	**Fall**
All Conditions	0.66	0.6	0.53	0.8	0.63
Highest 10% of Daily Flow Rates	0.42	0.41	0.01	0.75	0.26
Lowest 50% of Daily Flow Rates	0.44	0.44	0.6	0.7	0.42
Days Categorised as Storm Flow	0.62	0.55	0.42	0.78	0.6
Days Categorised as Baseflow	0.82	0.76	0.85	0.95	0.83

Performance Metric	**Hydrological Condition**	**Comparison Type**	**Performance Threshold for Hydrology Simulation**				**Reference**
			Very Good	Good	Satisfactory	Unsatisfactory	
r-Squared (r^2)	All Conditions	Compare All Observed vs Simulated Daily Flow Rates that Occur During Selected Season-Conditions	>0.85	0.75 - 0.85	0.60 - 0.75	≤0.60	Moriasi et al. (2015)
	Seasonal Flows		>0.75	0.60 - 0.75	0.50 - 0.60	≤0.50	
	Highest 10% of Daily Flow Rates						
	Lowest 50% of Daily Flow Rates						
	Days Categorised as Storm Flow						
	Days Categorised as Baseflow						

Table 4-10. Example Panel from Hydrologic Validation: Hoteo River @ Gubbs (45703) – Hydrology calibration: Nash-Sutcliffe efficiency statistical metric for modelled vs observed flow 01/01/2012-31/12/2016

Observed vs Simulated Calibration Performance for Flow Rates (Simulated vs Observed Flow Rates for Condition-Season across Simulation)					
Calibration Metrics (01/01/2012 - 31/12/2016)	Nash-Sutcliffe Efficiency (E)				
	All Seasons	Winter	Spring	Summer	Fall
All Conditions	0.65	0.58	0.47	0.78	0.62
Highest 10% of Daily Flow Rates	0.29	0.3	-0.96	0.7	0.06
Lowest 50% of Daily Flow Rates	-0.37	-1.61	-1.39	0.32	-1.45
Days Categorised as Storm Flow	0.59	0.52	0.33	0.73	0.58
Days Categorised as Baseflow	0.82	0.75	0.79	0.9	0.77

Performance Metric	Hydrological Condition	Comparison Type	Performance Threshold for Hydrology Simulation				Reference
			Very Good	Good	Satisfactory	Unsatisfactory	
Nash-Sutcliffe Efficiency (E)	All Conditions	Compare All Observed vs Simulated Daily Flow Rates that Occur During Selected Season-Conditions	>0.80	0.70 - 0.80	0.50 - 0.70	≤0.50	Moriasi et al. (2015)
	Seasonal Flows		>0.70	0.50 - 0.70	0.40 - 0.50	≤0.40	
	Highest 10% of Daily Flow Rates						
	Lowest 50% of Daily Flow Rates						
	Days Categorised as Storm Flow						
	Days Categorised as Baseflow						

Table 4-11. Example Panel from Hydrologic Validation: Hoteo River @ Gubbs (45703) – Hydrology calibration: Flow percentile metrics 01/01/2012-31/12/2016

Daily Streamflow Statistics				
Statistic	**Observed (cumecs)**	**Simulated (cumecs)**	**Difference (cumecs)**	**% Difference**
Average Flow	5.3617	4.8515	0.5102	9.52%
Minimum Flow	0.198	0.0173	0.1807	91.26%
5th Percentile Flow	0.393	0.1191	0.2739	69.69%
10th Percentile Flow	0.57	0.2533	0.3167	55.56%
25th Percentile Flow	1.0385	0.6062	0.4323	41.63%
Median Flow	2.287	1.8091	0.4779	20.9%
75th Percentile Flow	5.1725	5.085	0.0875	1.69%
90th Percentile Flow	11.717	11.27	0.447	3.81%
95th Percentile Flow	19.8843	16.7891	3.0952	15.57%
Maximum Flow	174.291	183.8653	-9.5743	-5.49%

Table 4-12. Example Panel from Hydrologic Validation: Hoteo River @ Gubbs (45703) – Hydrology calibration: Minimum 7-day averaged low-flow by year (7-day MALF) 01/01/2012-31/12/2016

Daily Streamflow Statistics					
Statistic and Year		Observed (cumecs)	Simulated (cumecs)	Residual (cumecs)	% Difference
7-day MALF	2012	0.6821	0.2407	0.4415	64.72%
	2013	0.2114	0.0194	0.1921	90.85%
	2014	0.3831	0.0985	0.2847	74.3%
	2015	0.51	0.0927	0.4173	81.82%
	2016	0.8686	0.2816	0.587	67.58%
	Average	0.5311	0.1466	0.3845	72.4%

Table 4-13. Example Panel from Hydrologic Validation: Hoteo River @ Gubbs (45703) – Hydrology calibration: Mean annual flood determined as the mean of annual maximum flows (MAF) 01/01/2012-31/12/2016

Daily Streamflow Statistics					
Statistic and Year		Observed (cumecs)	Simulated (cumecs)	Residual (cumecs)	% Difference
MAF	2012	79.225	85.4471	-6.2221	-7.85%
	2013	146.976	101.7532	45.2228	30.77%
	2014	100.94	73.4052	27.5348	27.28%
	2015	33.359	34.2431	-0.8841	-2.65%
	2016	174.291	183.8653	-9.5743	-5.49%
	Average	106.9582	95.7428	11.2154	10.49%

Table 4-14. Example Panel from Hydrologic Validation: Hoteo River @ Gubbs (45703) – Hydrology calibration: Number of events in excess of 3× median flow (FRE3) 01/01/2012-31/12/2016

Daily Streamflow Statistics					
Statistic and Year		Observed (No. of Events)	Simulated (No. of Events)	Residual (No. of Events)	% Difference
FRE3	2012-2016	8	6	2	25.0%

4.3 Contaminant Calibration and Validation

Water quality outputs from the FWMT are expected to inform policy decisions and management actions for protection of public health via recreation in freshwater and aquatic life via ecosystem health values. The FWMT simulates the build-up, wash off, and transport of nine contaminants that were subject to Stage 1 calibration and validation as follows:

- Sediment as total suspended solids (TSS),
- Nutrients:
    - Total nitrogen (TN)
    - Total oxidised nitrogen (TON)
    - Total ammoniacal nitrogen (TAM)
    - Total phosphorous (TP)
    - Dissolved reactive phosphorous (DRP)
- Metals:
    - Total copper (Cu),
    - Total zinc (Zn), and
- *Escherichia coli* (*E. coli*)

For each of these contaminants, the regional top-down and upstream-downstream calibration approach was used. Metrics based on both concentration and loading rate were generated. For water quality calibration, the upstream-downstream process also included ‘end-of-pipe’ data from ad-hoc studies that collected runoff samples prior to mixing with receiving waters. Diagrams illustrating the LSPC model processes for sediment and nutrients are presented in Section 2.3 along with detailed parameter tables. In the subsections below, the key model parameters adjusted during calibration are itemised.

4.3.1 Instream Monitoring Stations and Data

The water quality calibration effort leveraged from the Auckland Council’s State of the Environment (SoE) monitoring network. The SoE program collects water quality data across the Auckland region, including monthly grab sampling for an array of contaminants at 36 stations (see the red stars in Figure 4-21). The SoE stations were reviewed for length of record and proximity to a nearby flow gauge to select calibration and validation stations.

Shown in Table 4-15 is the list of stations used for FWMT water quality performance assessment, including the 17 calibration stations found to have relatively homogenous HRU composition upstream of the monitoring station. All 36 SoE stations were used, even though some stations do not have co-located flow monitoring (see the stations without a dot in both Flow columns in Table 4-15). The watershed areas upstream of the water quality calibration (shaded) and validation stations are shown in Figure 4-5. Note that Table 4-15 also reports the watershed area and HRU composition upstream of the water quality stations.

The approximately monthly grab samples collected at each water quality station are the primary dataset used for water quality calibration and validation. As shown in Table 4-16, for most stations and contaminants a total of 60 samples were available for the 2012-2016 calibration period.

Initial FWMT calibration exercises excluded the SoE stations that do not have a flow monitoring gauge proximal to the sampling location. (Note that observed daily loading here refers to the product of observed grab concentration and average daily observed flow on the sampling date, whereas simulated daily loads were generated from the cumulative sum of 15-minute concentration and flow estimates on the sampling date). However, for completeness the water quality calibration was expanded to include all SoE stations, and the *modelled* average daily flow rate for each day was substituted to both bin observed concentration samples by flow and to calculate comparative loading rates.

As discussed in Section 4.1, a daily timestep was used for water quality calibration. The SoE data are typically instantaneous grab samples. Therefore, the comparison between the simulated and observed time series has an intrinsic disconnect that is important to be acknowledged – the simulated time series presents the flow-weighted concentration from a uniformly mixed cross section across each day, while the grab samples represent the concentration at the sampling time for a single location in the cross-section. Variation in mixing (e.g., uniform rather than stratified flow), distribution of loading (e.g., the timestep rainfall and contaminants are simulated to reach a node) and water quality measurement error (described in Section 4.1.1), are all constraints on achieving perfect matches with simulated output in hydrologic and water quality calibration.

Table 4-15. HRU Distribution and Watershed Size for 36 SoE River Water Quality Calibration and Validation Stations

Monitoring Locations: Hydrology Calibration (predominant Land Use) and Model Validation (Water Quality)		Hydro Quality Tier	Available Data			Drainage Area (km^2)		Percent of Area														
								Land Use/Land Cover						Slope		Hydrologic Soil Group						
			Flow	WQ	Sed. Yield	Observed	Model	Developed	Forest	Horticulture	Open Space	Pasture	Other	High	Low	A+	A	B	C	D	Impervious	Water
Forest	Cascades Stream @ Confluence	-		●		-	11	0	97	0	0	0	3	96	4	0	0	10	87	0	0	3
	Opanuku Stream @ Candia Road Bridge	2	●	●	●	16	15	3	54	2	7	33	1	95	5	0	0	54	45	0	0	1
	Riverhead @ Ararimu Valley Road	-		●		-	4.6	1	70	0	24	5	0	91	9	0	0	6	93	0	0	0
	Vaughn Stream @ Lower Weir	4	●	●	●	2.3	2.4	6	45	0	49	0	0	92	8	0	0	14	85	0	1	0
	West Hoe @ Halls	2	●	●	●	0.5	0.5	0	63	0	1	35	0	99	1	0	0	73	27	0	0	0
Pasture	Kaukapakapa @ Taylors	3	●	●	●	62	62	1	8	1	15	75	1	68	32	0	0	20	16	64	0	1
	Papakura @ Alfriston/Ardmore Rd	-		●		-	23	1	20	1	16	61	1	78	22	0	0	19	80	1	0	0
	Wairoa Trib @ Caitchons Rd	-		●		-	2.2	0	1	0	0	99	0	100	0	0	0	100	0	0	0	0
Hort.	Ngakoroa Stream @ Mill Rd	2	●	●		4.7	4.8	2	2	24	12	59	1	50	50	90	0	7	1	0	1	1
	Oratia @ Parrs Cross Road	5	●	●	●	17	17	8	41	14	16	21	0	81	19	0	0	63	34	0	2	0
	Waitangi @ Waitangi Falls Bridge.	-		●		-	19	1	2	14	11	72	0	14	86	87	0	5	7	0	0	0
	Whangamaire @ Woodhouse Road	-		●		-	8.0	3	3	35	12	47	0	19	81	98	0	0	0	0	1	0
Developed	Lucas @ Gills Road	2	●	●		6.3	6.1	30	27	0	42	0	1	59	41	0	0	18	62	0	19	1
	Oakley Creek at Richardson Road	3	●	●		-	5.9	45	19	0	36	0	0	2	98	16	0	0	54	0	30	0
	Otara @ East Tamaki Rd	-		●		-	9.4	43	20	0	37	1	0	4	96	0	0	10	62	0	28	0
	Oteha River @ Days Bridge	2	●	●		12	12	41	21	0	34	0	4	34	66	0	0	21	44	0	30	4
	Puhinui @ Drop Structure	3	●	●		12	13	34	19	0	40	6	1	36	64	0	0	6	70	0	23	0
Other Monitoring Locations (Water Quality Validation)	Avondale Stream @ Shadbolt Park	-		●		-	3.0	29	46	0	24	0	0	41	59	0	0	0	84	0	16	0
	Cascades @ Whakanewha	-		●		-	0.6	0	49	1	41	8	1	99	1	0	0	52	48	0	0	0
	Kumeu @ Maddrens Weir	5	●	●		-	45	3	10	6	14	67	1	53	47	0	0	34	65	0	1	0
	Mahurangi Argonaut @ College	2	●	●		47	50	2	35	2	18	43	1	78	22	0	0	41	54	4	1	1
	Makarau at Coles	5	●	●		54	49	0	23	0	17	58	1	90	10	0	0	20	50	30	0	0
	Matakana @ Wenzlicks Farm	-		●		-	13	0	31	1	24	44	0	90	10	0	0	33	67	0	0	0
	Nukumea @ Upper Site	-		●		-	1.0	0	75	0	19	6	0	99	1	0	0	100	0	0	0	0
	Oakley Creek @ Carrington.	-		●		-	12	44	22	0	34	0	0	3	97	28	0	0	42	0	30	0
	Okura Creek @ Awanohi Rd	5	●	●	●	-	5.8	2	25	5	24	43	1	94	6	0	0	48	15	37	1	0
	Omaru @ Maybury Street	-		●		-	3.5	49	19	0	32	0	0	11	89	9	0	0	54	0	37	0
	Onetangi @ Waiheke Rd	-		●		-	0.7	4	86	0	5	4	0	99	1	0	0	70	29	0	1	0
	Otaki @ Middlemore Crescent	-		●		-	1.0	45	25	0	30	0	1	0	100	0	0	0	72	0	27	1
	Otara Stream @ Kennel Hill	-		●		-	18	17	14	0	58	11	1	41	59	1	0	21	68	0	9	1
	Pakuranga @ Botany Rd	-		●		-	6.6	53	21	0	24	2	0	2	98	0	0	18	45	0	37	0
	Pakuranga @ Greenmount Drive	-		●		-	2.4	47	15	0	35	3	0	20	80	18	0	16	34	0	31	0
	Papakura Stream @ Porchester Road Bridge	-		●		-	45	4	12	5	18	61	1	46	54	0	0	29	69	0	1	0
	Rangitopuni River @ Walkers	3	●	●		82	82	1	19	2	18	58	1	62	38	0	0	21	29	49	0	1
	Wairoa River @ Tourist Road	1	●	●	●	161	149	0	23	0	11	63	2	83	17	1	0	74	23	0	0	2
	Waiwera Stream @ Upper Waiwera Road	-		●		-	30	0	16	1	21	61	1	92	8	0	0	15	68	16	0	1

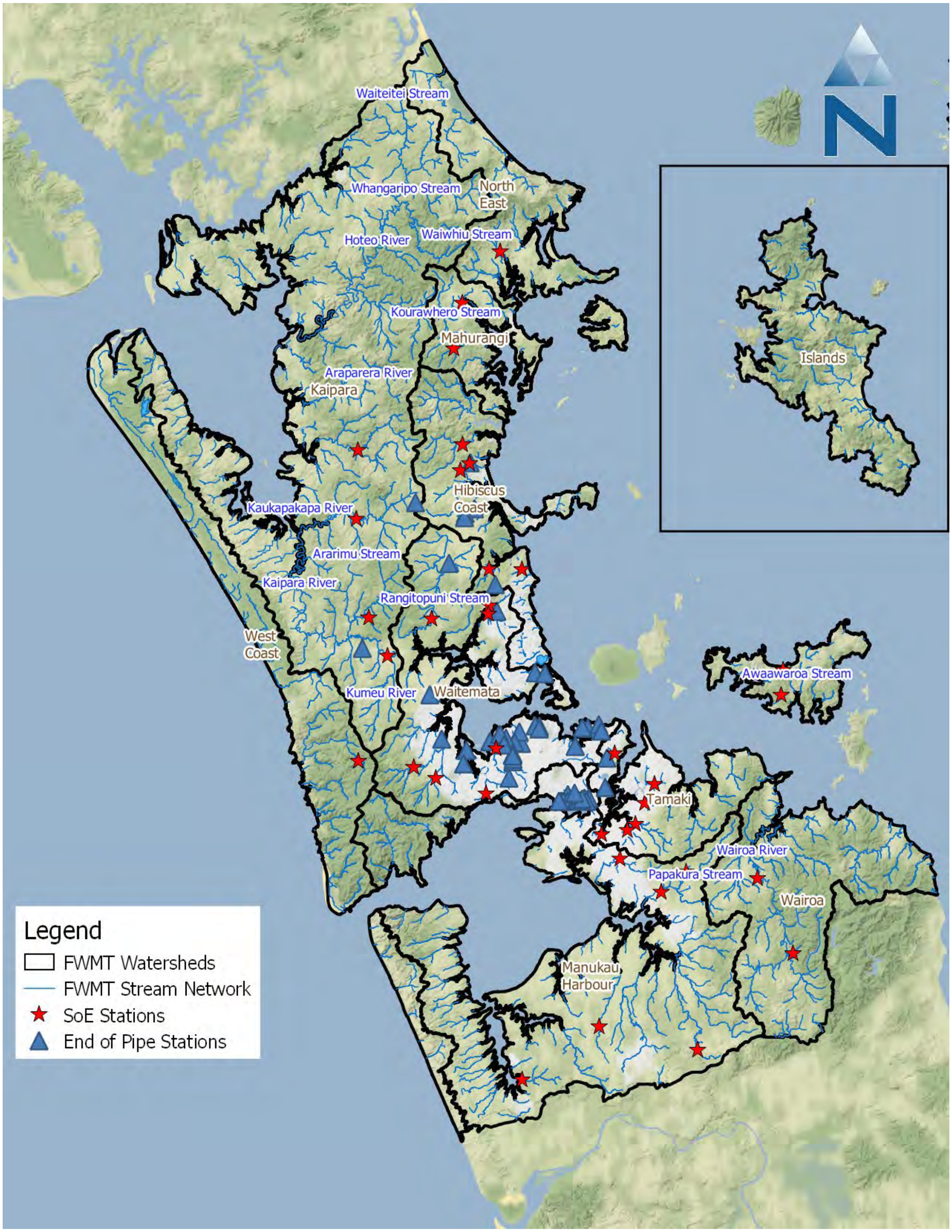


Figure 4-21. Instream and end-of-pipe river water quality sampling stations used for model calibration

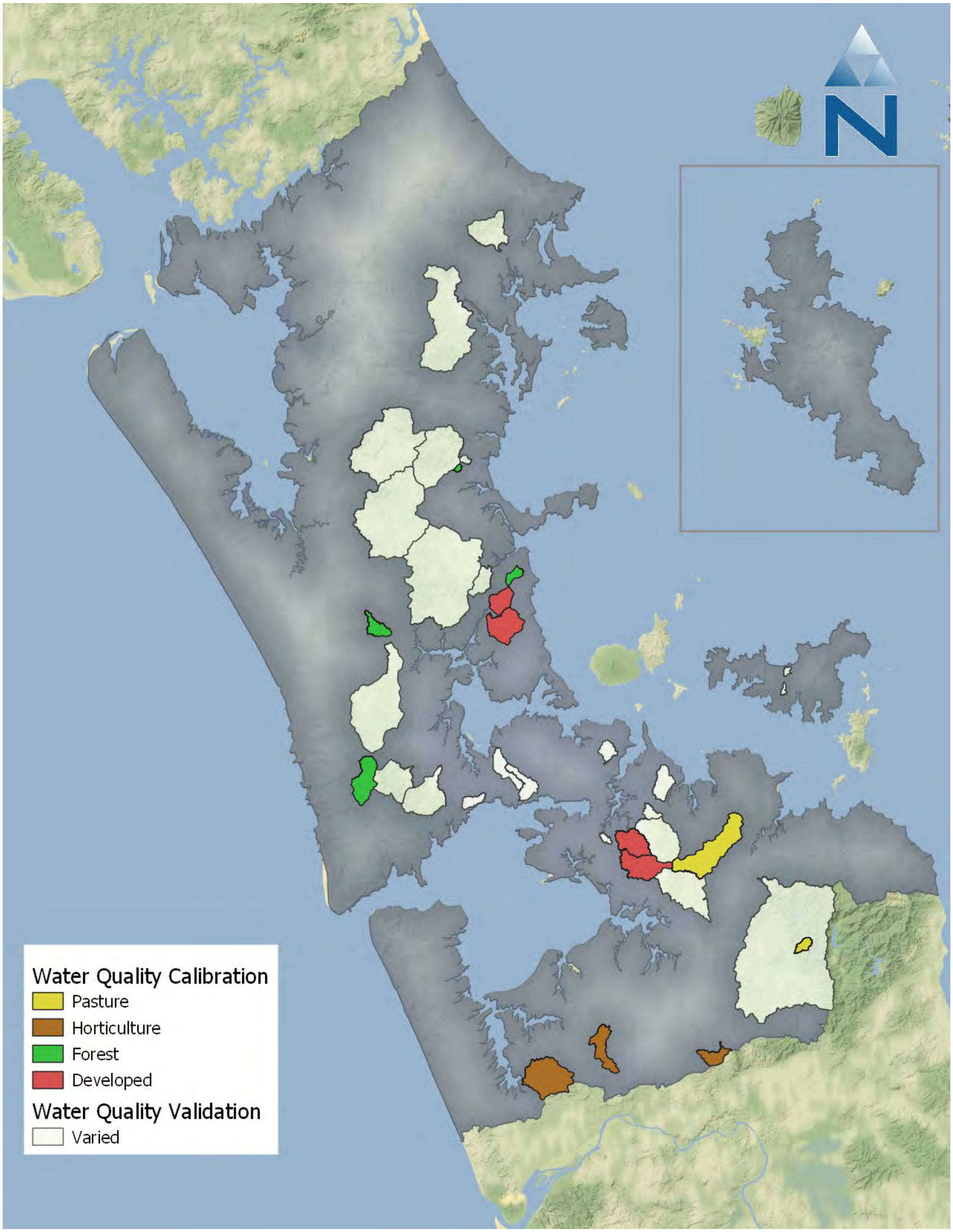


Figure 4-22. Watersheds Upstream of Water Quality Calibration and Validation Stations

Table 4-16. Sample Counts for Water Quality Calibration and Validation Stations

Watershed	Name	Station ID	Count of Grab Samples between 1/1/2012 and 31/12/2016								
			TSS	DRP	TN	TP	TON	*E. COLI*	TAM	Zn	Cu
Hibiscus Coast	West Hoe @ Halls	7206	58	55	52	55	38	46	32	0	0
	Nukumea @ Upper Site	7171	59	54	60	55	39	44	21	47	48
	Vaughn Stream @ Lower	7506	53	51	53	53	37	41	38	41	41
	Waiwera Stream @ Upper	7104	59	58	60	60	41	48	36	45	48
	Okura Creek @ Awanohi Rd	7502	19	18	19	19	6	7	6	7	7
Hauraki Gulf Islands	Onetangi @ Waiheke Rd	74401	45	46	46	46	46	42	41	0	0
	Cascades @ Whakanewha	74701	45	46	46	45	46	43	38	0	0
Kaipara Harbour	Kumeu River @ Weza Lane	45313	60	59	60	60	48	48	45	48	48
	Kaukapakapa @ Taylors	45415	60	60	60	60	46	48	44	0	0
	Makarau @ Railway	45505	57	59	60	60	38	48	32	38	48
	Riverhead @ Ararimu	45373	60	57	60	57	48	45	42	48	48
Mahurangi Estuary	Mahurangi @ Warkworth	6804	58	59	60	60	44	48	38	46	48
Manukau Harbour	Papakura Stream @	43856	59	60	60	60	47	48	48	48	48
	Waitangi @ Waitangi Falls	43601	49	57	60	59	48	48	28	0	0
	Papakura @ Alfriston	1043837	60	60	60	60	48	48	48	47	47
	Puhinui @ Drop Structure	43807	59	60	60	60	43	48	44	48	48
	Whangamaire	438100	57	57	60	59	48	48	42	0	0
	Ngakoroa Stream @ Mill Rd	43829	55	56	60	60	48	48	40	0	0
North East Coast	Matakana @ Wenzlicks	6604	56	59	60	60	43	48	37	35	47
Tamaki Estuary	Pakuranga @ Greenmount	8215	60	60	60	60	48	48	48	48	48
	Pakuranga @ Botany Rd	8217	60	60	60	60	48	47	48	48	48
	Otaki @ Middlemore	8219	59	57	59	59	47	47	47	47	47
	Otara Stream @ Kennel Hill	8205	60	60	60	60	48	48	48	48	48
	Otara @ East Tamaki Rd	8214	58	59	60	60	47	48	46	48	48
	Omaru @ Maybury Street	8249	60	60	60	60	47	48	47	48	48
Wairoa Coast	Wairoa River @ Tourist	8516	58	60	60	60	42	48	35	47	48
	Wairoa Trib @ Caitchons Rd	8568	57	60	60	60	41	46	20	0	0
Waitematā Harbour	Oakley Creek @ Richardson	8128	10	10	10	10	10	10	10	10	10
	Oakley Creek @ Carrington.	8110	56	60	60	60	48	48	42	47	47
	Lucas @ Gills Road	7830	60	58	60	60	45	48	44	48	48
	Opanuku Stream @ Candia	7904	54	56	57	57	44	45	35	0	0
	Avondale Stream @	8019	60	59	60	60	48	48	47	48	48
	Rangitopuni River @	7805	6	46	46	46	39	45	46	0	0
	Oteha River @ Days Bridge	7811	60	59	60	60	48	47	46	48	48
	Oratia @ Parrs Cross Road	7955	12	12	12	12	12	12	12	12	12
West Coast	Cascades Stream @	44603	49	60	51	60	43	43	14	0	0

4.3.2 End-of-Pipe Parameterisation

Data collected prior to mixing with receiving water, or end-of-pipe, provide an important checkpoint for contaminant concentrations in stormwater runoff. Readily available end-of-pipe data were compiled and used as a comparison point to the HRU-based yields and concentrations. The end-of-pipe data augment the calibration stations by representing the levels of contaminants at the edge-of-field before mixing with the receiving water. The end-of-pipe data are not subject to their own performance evaluation, but instead guide the relative parameterisation of different HRUs in LSPC. The end-of-pipe data, summarised in Table 4-17 were pulled from three key sources:

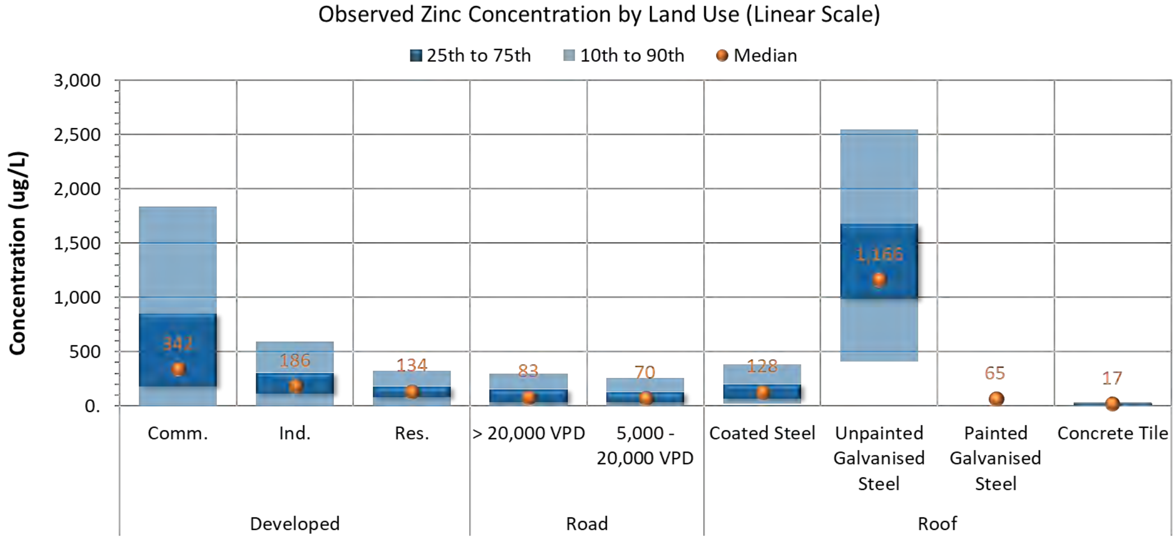
- URQIS database, queried for ‘untreated stormwater samples’ in Auckland region.
- Additional ad-hoc studies performed in the Auckland region.
- Data collected during field studies to evaluate the yields of zinc from roof types.

The end-of-pipe sampling locations in the compiled datasets are shown in Figure 4-21. The complete set of summarised end-of-pipe concentrations are summarised as box plots in Appendix C.

An important dataset within the end-of-pipe data is the concentrations of zinc in roof runoff. High impact, or zinc rooves, are one of the three FWMT Stage 1 HRUs for roof surface types in Auckland. The data from field studies were used to parameterise the concentrations from rooves across the impact factors: iron rooves, tile rooves and other rooves. Each roof types was recorded for extent in the land cover GIS dataset governing the HRU raster. The concentrations of total zinc in end-of-pipe datasets, including rooves, are shown in Figure 4-23 along with total copper for comparison.

End-of-pipe data were rarely collected from outfalls draining homogenous land uses, and a limitation when compiling the end-of-pipe datasets was the ability to delineate upstream drainage areas to corresponding mix of HRU. The land use types assigned to end-of-pipe stations are suitably coarse here. Whereas in reality HRUs represent components of a single parcel of land under equivalent use. For example, separate HRUs exist for the rooftop, imperious area and urban impervious area of a single parcel of urban land. So, even if an end-of-pipe dataset was collected from homogenous land use (e.g., shopping mall), it would represent multiple HRUs.

The constraints associated with end-of-pipe data precluded site-specific calibration for the locations where the data was sampled. However, generalising the data to the dominant land use of the sites Figure 4-23 allowed for comparison of concentration trends and ranges. Therefore, model initialisation involved parameterising urban HRUs to reasonably reflect the observed end-of-pipe water quality trends and ranges, these parameters were then further adjusted as needed during calibration to in-stream data.



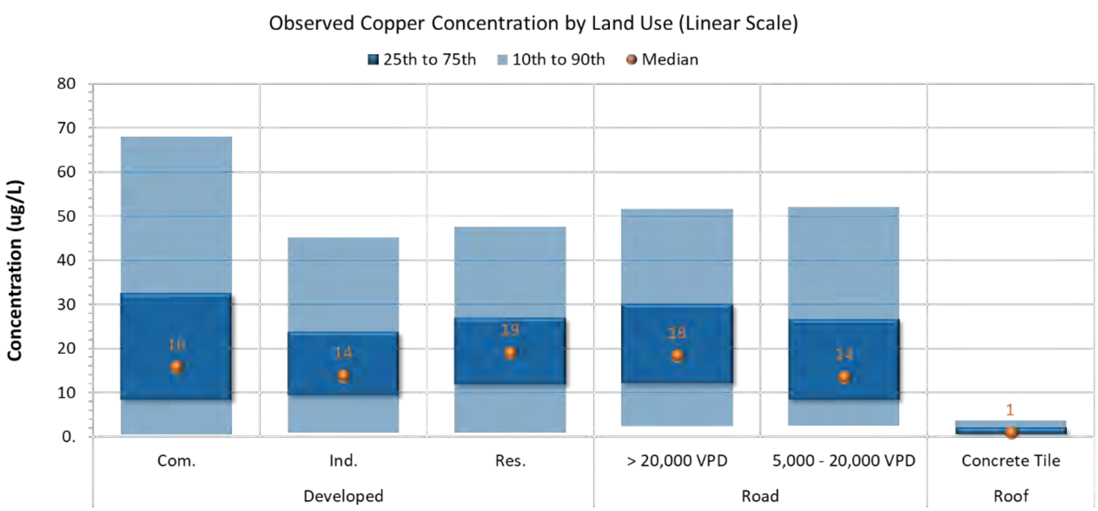


Figure 4-23. Observed end-of-pipe concentrations for Total Zinc (top) and Total Copper (bottom) assigned coarsely to HRU land use factor across all EOP events simulated for baseline by FWMT Stage 1 (2013-2017)

Table 4-17. Inventory of end-of-pipe stations used to support water quality calibration

	Study Name	# Sites	Start Date	End Date	Primary Constituents						Secondary Constituents												
					E.coli	TSS	Total Copper	Total Zinc	TN	TP	Ammonia	Ammonia + Ammonium	BOD	DO	Enterococci	Nitrate	Nitrate + Nitrite	Nitrite	Organic N	Total Phosphate	Reactive Phosphorus	Temp	TKN
URQIS	Gadd et. al. (2009)	1	5/17/2009	8/14/2009	30	36	36	30		30					30	24		30					
	Moores et. al. (2012)	3	9/6/2010	3/18/2012		108	108	108															
	Moores, Pattinson, Hyde (2010)	4	2/23/2008	6/9/2009		305	305	305															
	Moores & Pattinson (2008)	1	3/29/2007	12/19/2007		41																	
	Moores, Pattinson, Hyde (2008)	1	11/23/2007	7/20/2008		174	174	174															
	Moores et. al. (2008)	4	5/9/2006	7/29/2007		65	9	9															
	Reed & Timperley (2004) a	2	5/31/2001	4/6/2003	24	291	273	273							255	269							
	Semadeni-Davies & Pattinson (2008)	1	9/30/2007	6/7/2008		134																	
	Timperley et. al. (2004)	3	1/31/2001	3/14/2002		610	484	484							291	487							
	Timperley, Webster, Bailey (2004)	3	2/21/2001	8/8/2002		668	514	514							455	460							
	URQIS Database (no study name attached)	13	10/9/2003	5/9/2013		230	231	232															
Other Special Studies	East West Link Event Based Monitoring	1	6/9/2016	7/19/2016	16	62	62	62															
	East West Link Grab Sampling	21	3/15/2016	7/13/2016	13	46	47	47	15		46			3			18		15	9	12	29	15
	Industrial Monitoring (Whau)	2	6/8/2017	10/19/2017										169,027								150,201	
	Meola Catchment 2011 Environmental Monitoring	9	11/29/2010	4/16/2011	76	75	75	75				75	75								75		75
	Separated Catchment Sampling 2017	11	3/3/2017	3/16/2017	21	21	42	42	21						21		21			21			21
Total Number of Samples					**180**	**2,866**	**2,360**	**2,355**	**36**	**30**	**46**	**75**	**75**	**169,030**	**1,052**	**1,240**	**39**	**30**	**15**	**30**	**87**	**150,230**	**111**

4.3.3 Hydrological-Contaminant Pattern Analysis

It is important to review and understand patterns of contaminant behaviour with hydrology to configure and calibrate water quality models. Before FWMT model calibration began, the observed sediment, nutrient, and metal data at Auckland Council SoE calibration stations within each watershed were paired with streamflow from-co-located stations and rainfall data for associated sub-catchments and sorted into seasonal, wet- and dry-weather, and antecedent moisture conditions.

An objective for FWMT development is to parameterise the model in such a way as to replicate the patterns inherent in the observed data (i.e., wet and dry streamflow conditions and rainfall magnitude). Thereby ensuring the FWMT is more representative of watershed and climatic conditions in Auckland, and ensuring sufficient sensitivity to both changes in management that are hydrologically based and changes in boundary conditions that influence hydrology (e.g., altered boundary conditions of climate and HRU in scenario testing).

To review contaminant behaviour across the region, 'hydrologic patterns' panels were created for each of the 10 watersheds. The full set of 127 hydrologic patterns panels are presented in Appendix D. Example panels are shown of the following:

- Figure 4-24: TSS in Kaipara Harbour watershed stations
- Figure 4-25: Total zinc in Tamaki Estuary watershed stations
- Figure 4-26: Total nitrogen in Manukau Harbour watershed stations

Each of the evaluation panels has six graphs that highlight variability in median observed concentration for the following conditions:

- Upper Left (Annualised): Concentration changes over time
- Upper Right (Monthly): Seasonal variability in concentration over all the years
- Middle Left (Rainfall Depth): Variability in concentration with increasing rainfall
- Middle Right (Streamflow): Variability in concentration with increasing streamflow
- Lower Left (Wet Weather by Antecedent Dry Days): Assessment of concentration during wet weather for varying duration of prior dry days
- Lower Right (Dry Weather by Dry Days): Assessment of concentration during dry weather for varying duration of prior dry days

Hydrological-pattern analysis is helpful to model parameterisation, illustrating any underlying hydrological driver-relationships to contaminants (e.g., positive or negative relationships to increasing antecedent dry period, rainfall, streamflow, season). Typical patterns observed include:

- Both sediment and metals exhibit similar seasonal, wet-weather, and dry-weather patterns with hydrology and climate, confirming an association between the two contaminants (i.e., co-variation in sediment and metal concentration). While Appendix E shows that rural roads had a relatively high metal yield compared to other HRUs, rural roads represented a very small part of the overall loading and did not undergo a robust calibration. The distribution of metals concentrations and loadings (appendix E) from urban roads is a function of increased sediment erosion as well as the potency factors for metals. Based on these hydrological patterns, metals were modelled as sediment-associated process for simulating sediment and associated metals from developed HRUs.
- Sediment exhibits a non-linear increase in median concentration with increasing streamflow (middle-right panels), suggesting that sediment scour is likely occurring across pervious HRUs (i.e. at ~70th% instream flow).
- Nitrogen concentrations near horticulture areas are typically highest at lowest flow conditions (bottom left panel), suggesting that groundwater is enriched in TN and an important source of TN at baseflow. This further underscored the need for an active groundwater pathway for nitrate from horticultural HRUs to instream. However, the highest levels occurred 0 to 2 days after a rainfall event (bottom two panels) suggesting that flushing of nitrate from groundwater to streams is most pronounced in the days *immediately following* a rainfall event. Such behaviour has been observed more broadly from diffuse sources of TON in other regions of New Zealand and highlights the importance of understanding vadose zone denitrification processes particularly for intensively farmed or N-enriched sub-catchments (e.g., Stenger et al., 2014; Singh et al., 2014, 2017; Horne et al., 2017).
- Nitrogen concentrations possess strong seasonal variation (top right panel), with higher levels occurring in the autumn and winter months. This suggests a diffuse contribution from land with varying effects of nutrient uptake and denitrification (i.e., lesser residence time, denitrification and uptake likely in colder seasons). Alternatively, phosphorus concentrations were generally lowest in late autumn and early winter (Appendix D). Therefore, seasonal nutrient parameters are activated for groundwater and interflow to improve model calibration (see 3.10 for discussion of groundwater-N and groundwater-P parameterisation).
- Metals exhibit a likely first-flush behaviour in wet-weather: greater median concentrations of Cu and Zn accompany longer (5-13 days) antecedent dry period prior to wet weather (bottom-left panels); and dry weather concentrations decrease with increasing dry-weather antecedent period (bottom-right panels). These patterns suggests that a build-up/wash off approach is suitable for the FWMT purposes.

These findings from hydrologic pattern analysis guided the parameterisation and calibration approach within the LSPC build for the FWMT Stage 1.

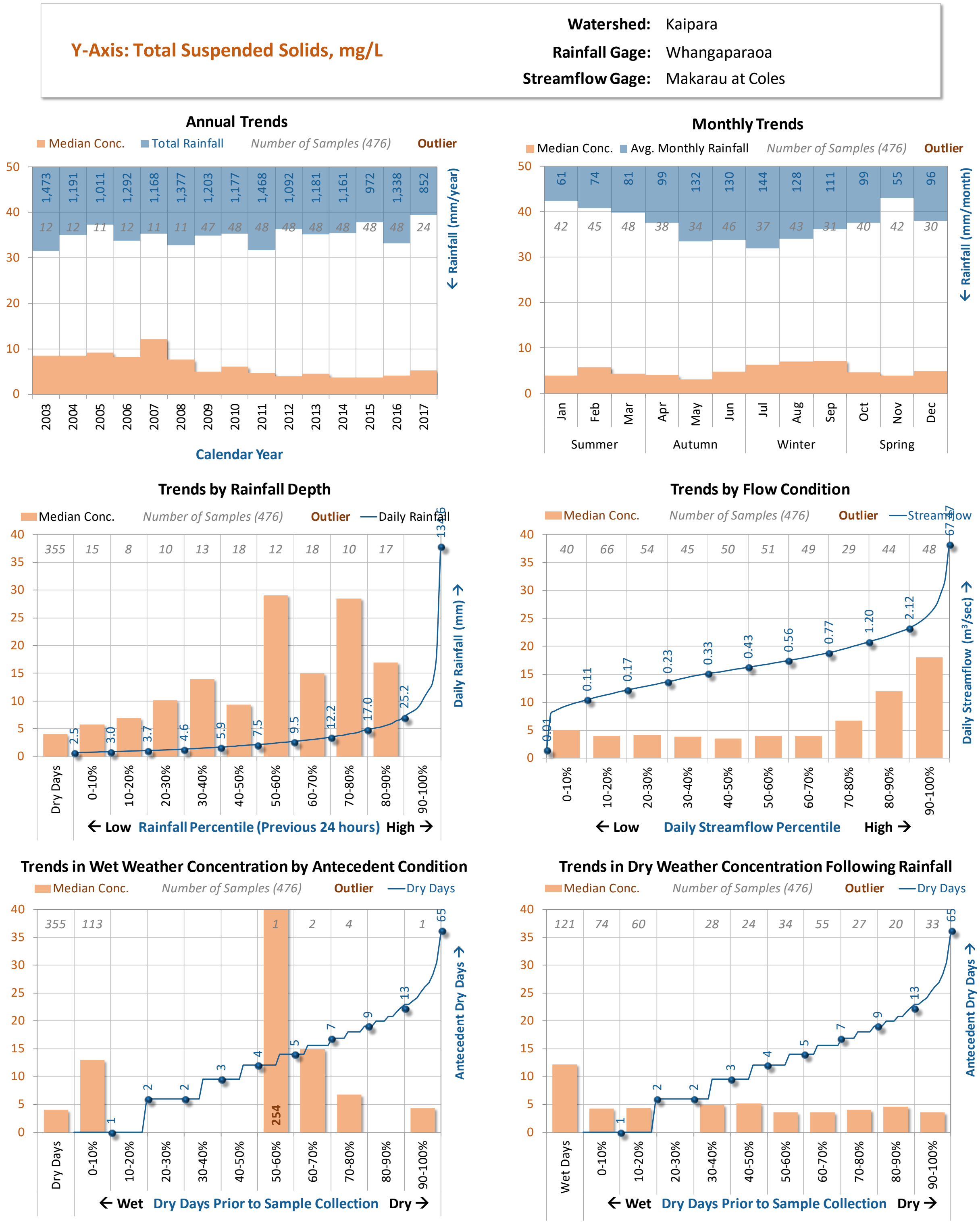


Figure 4-24. Hydrologic trends analysis for stations in Kaipara Harbour watershed: Total Suspended Solids mg/L

Figure 4-25. Hydrologic trends analysis for stations in Tamaki Estuary watershed: Zinc (total), mg/L

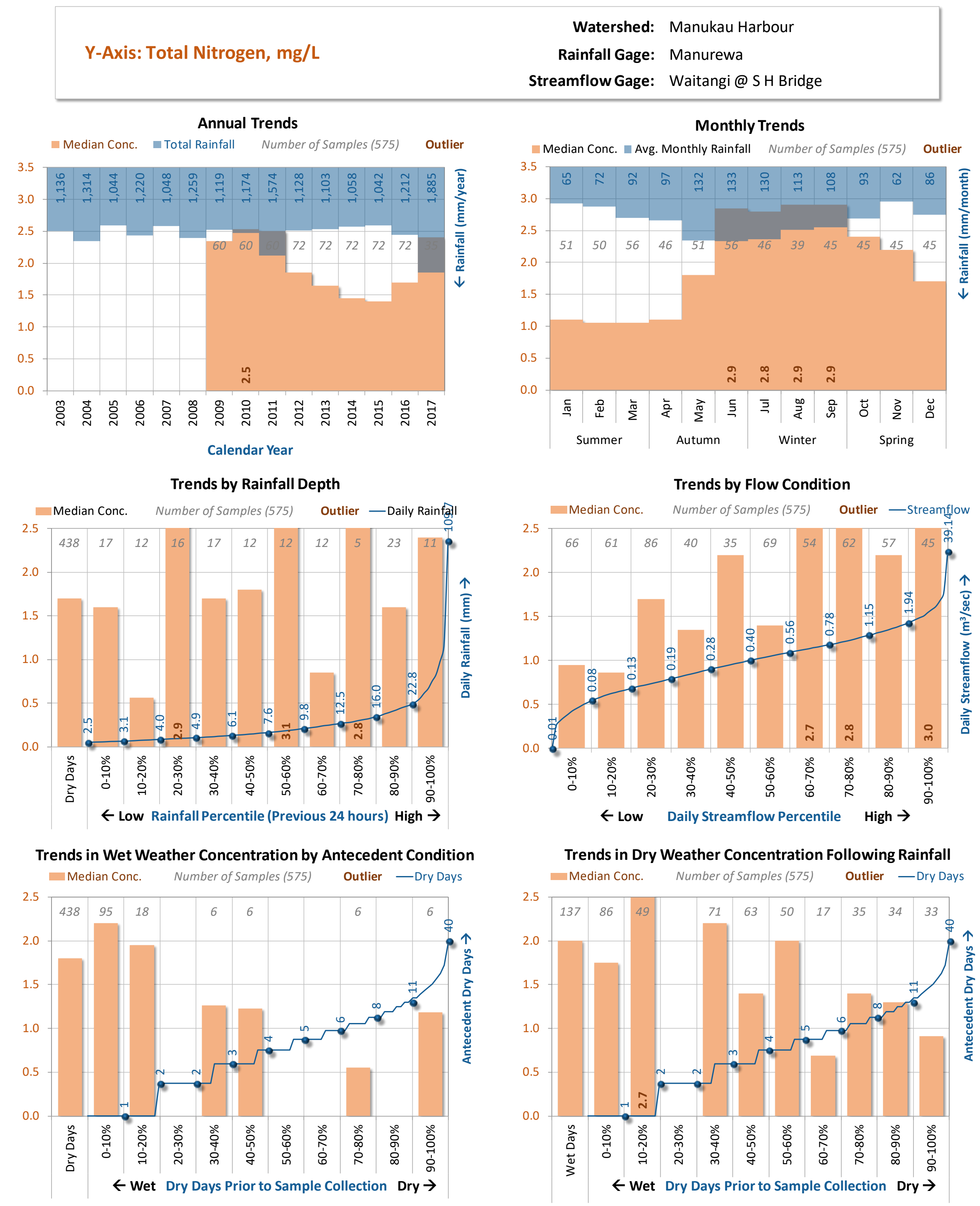


Figure 4-26. Hydrologic trends analysis for stations in Manukau Harbour watershed: total nitrogen, mg/L

4.3.4 Calibration Outcomes and Performance

The receiving water component of the water quality calibration was based on the upstream-downstream approach and leveraged the five years of monthly grab samples (2012-2016) from 17 calibration stations to develop model parameters for pastoral, horticultural, forested and urban land cover HRUs. The results of the parameterisation were analysed at an additional 19 validation stations which tend to be larger, mixed HRU stations. Table 4-15 and Figure 4-22 provides details on the water quality stations, upstream watersheds and HRU composition.

The observed vs simulated time series were analysed to generate performance metrics across seasonal and flow conditions, with an extensive series of water quality panels created for each station. Performance metrics were generated for both concentration and loading. The complete set of calibration outputs are presented as Appendix F: Water Quality Calibration Panels.

An example series of panels for the Ngakaroa validation station is presented as the following for observed vs simulated time series:

- Figure 4-27 and Figure 4-28: raw time series comparison for daily and monthly average concentrations vs grab sample concentrations
- Figure 4-29 and Figure 4-31: flow conditions on grab sampling dates and concentrations by flow percentile
- Figure 4-32 to Figure 4-35: simulated vs observed concentrations and loading rates as one-to-one plots and binned by season and month
- Figure 4-36 to Figure 4-44: residuals and per cent differences for both concentrations and loading rates across time, months and flow conditions (temporal and flow bias plots)
- Figure 4-45 and Figure 4-46: regression of flow-based relationships for concentration and loading rates
- Table 4-18 to Table 4-25: detailed reporting of performance metrics for r^2, NSE and PBIAS across seasons and flow bins, for both concentration and loading rate

Combined, the water quality performance panels total over 9,000 pages of detailed information regarding model performance and streamflow statistics at the 46 calibration and validation stations used to develop FWMT Stage 1.

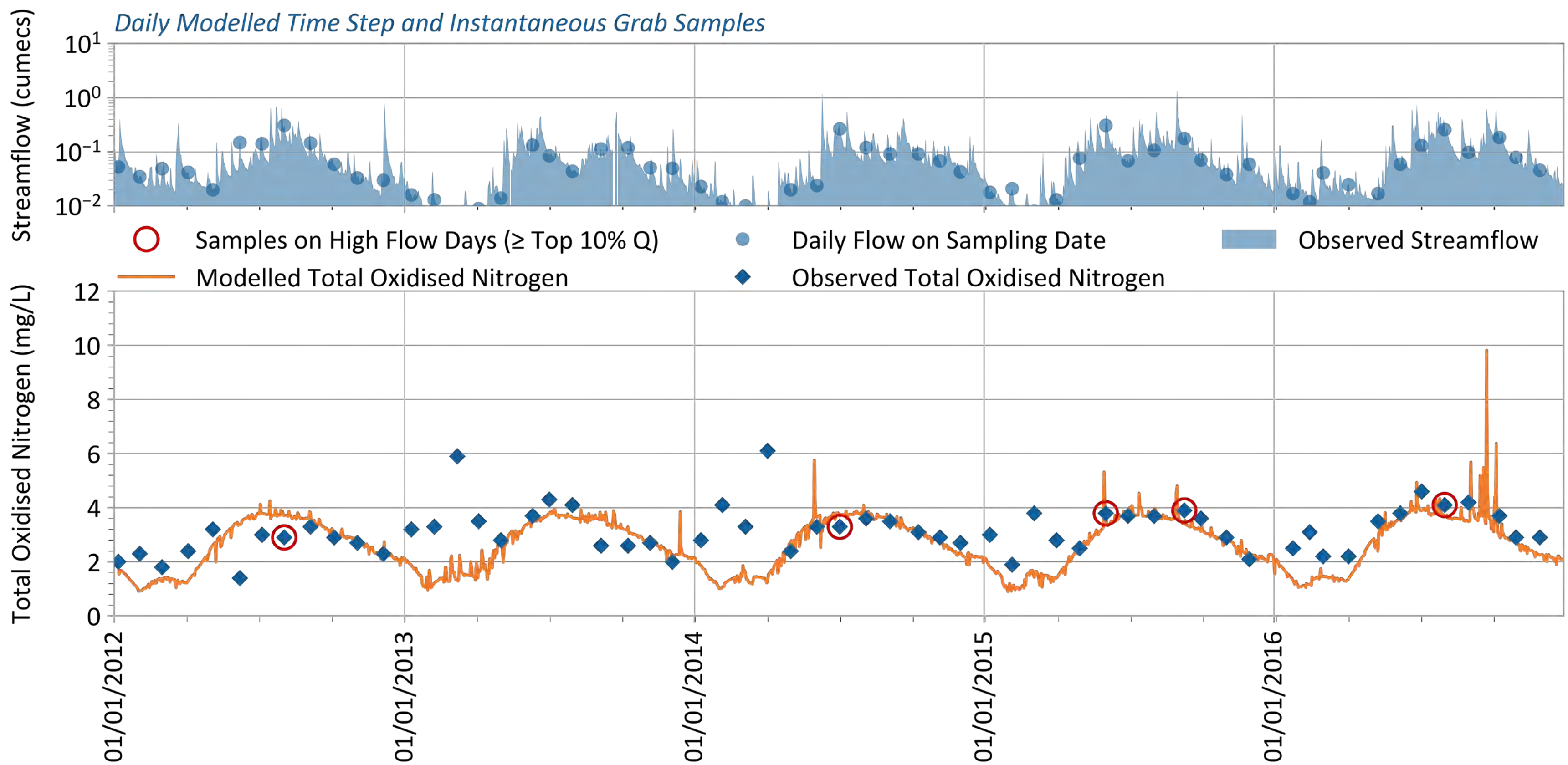


Figure 4-27. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Simulated daily modelled time series vs observed grab sample concentrations

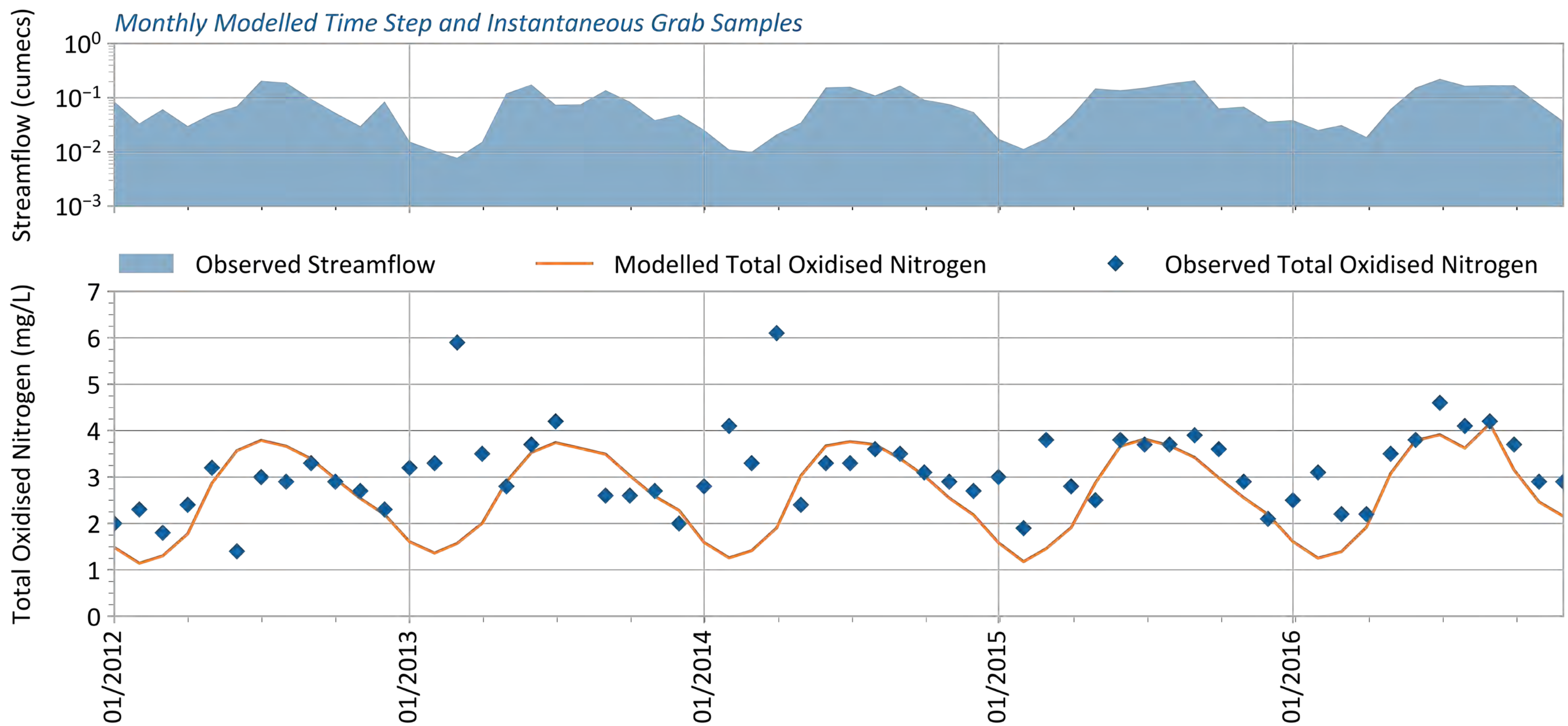


Figure 4-28. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Simulated monthly modelled time series vs observed grab sample concentrations

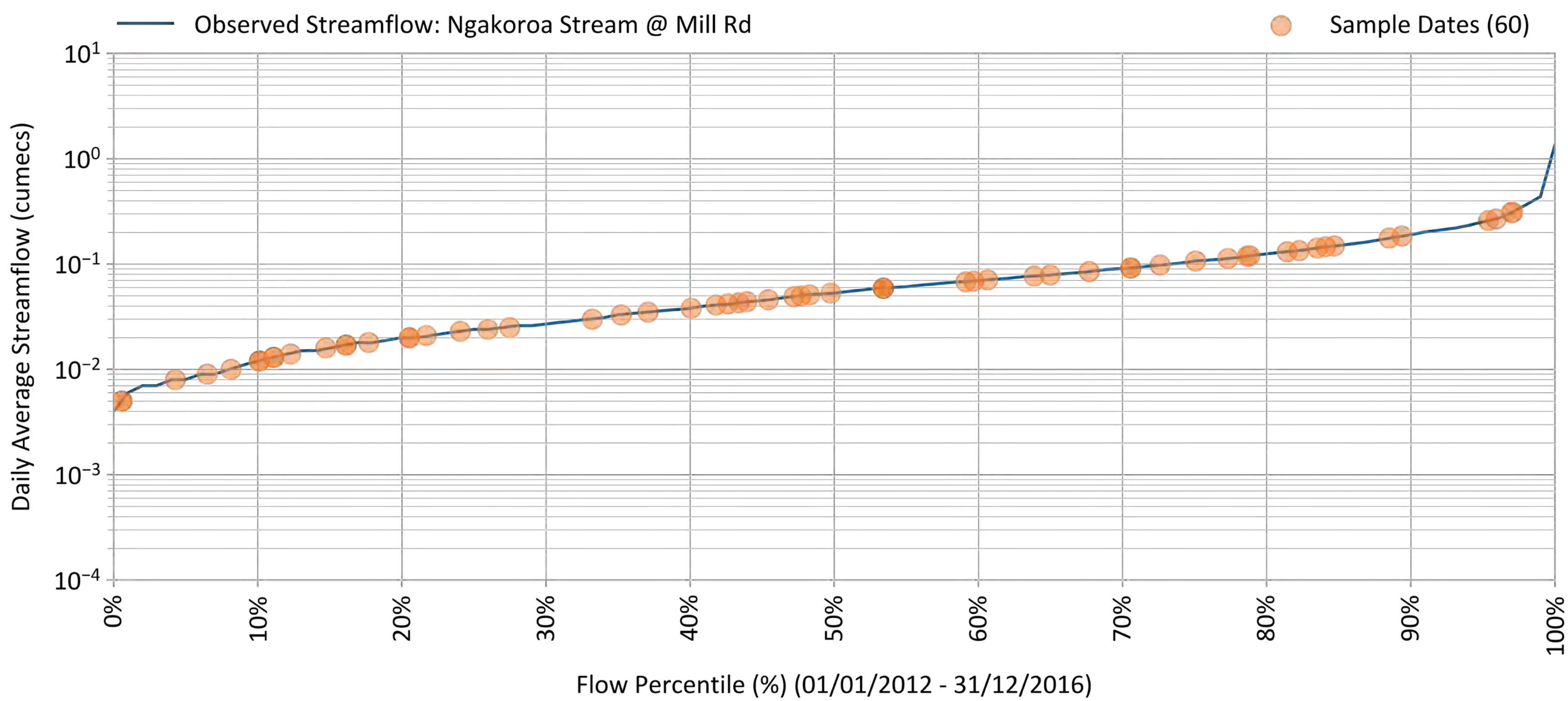


Figure 4-29. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Flow conditions on observed grab sampling dates

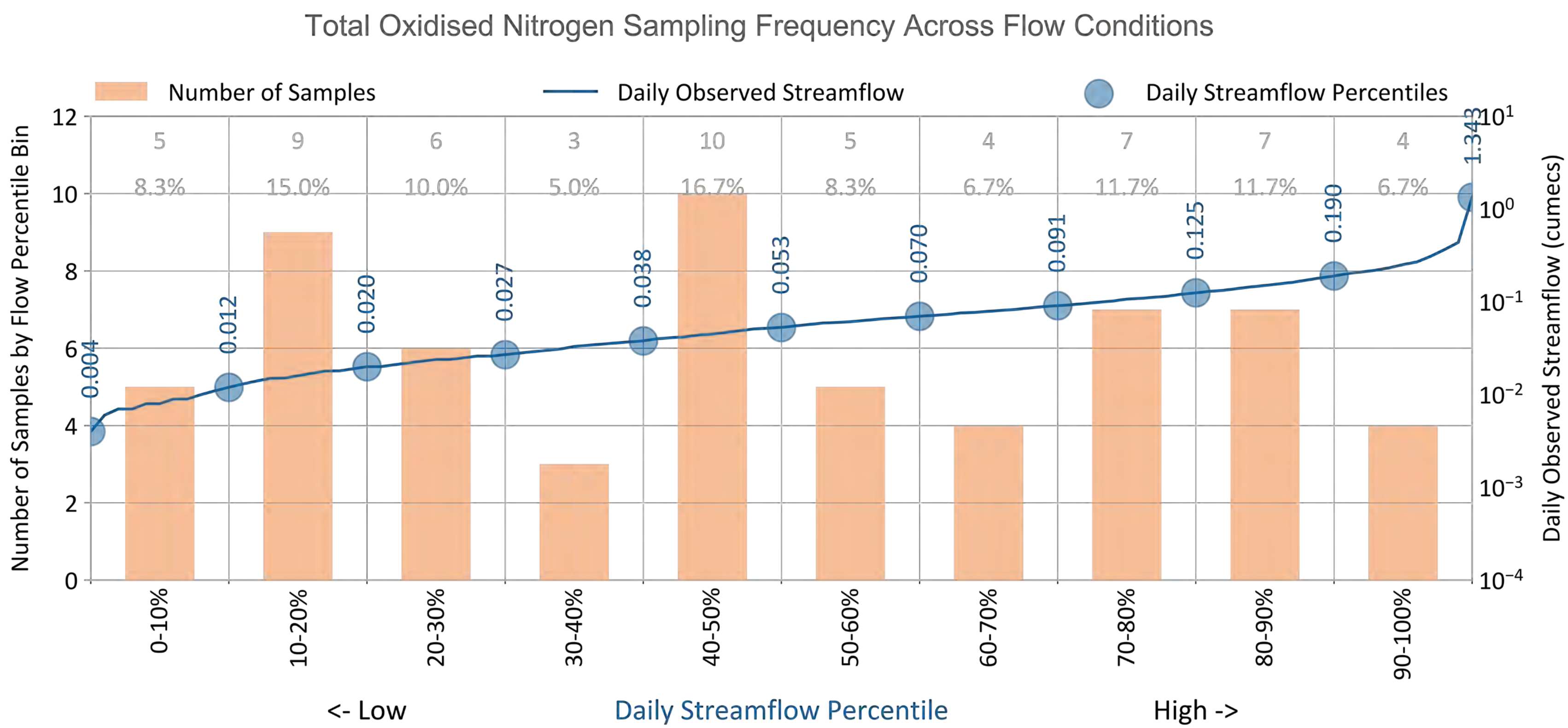


Figure 4-30. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: observed grab sampling frequency by flow percentile

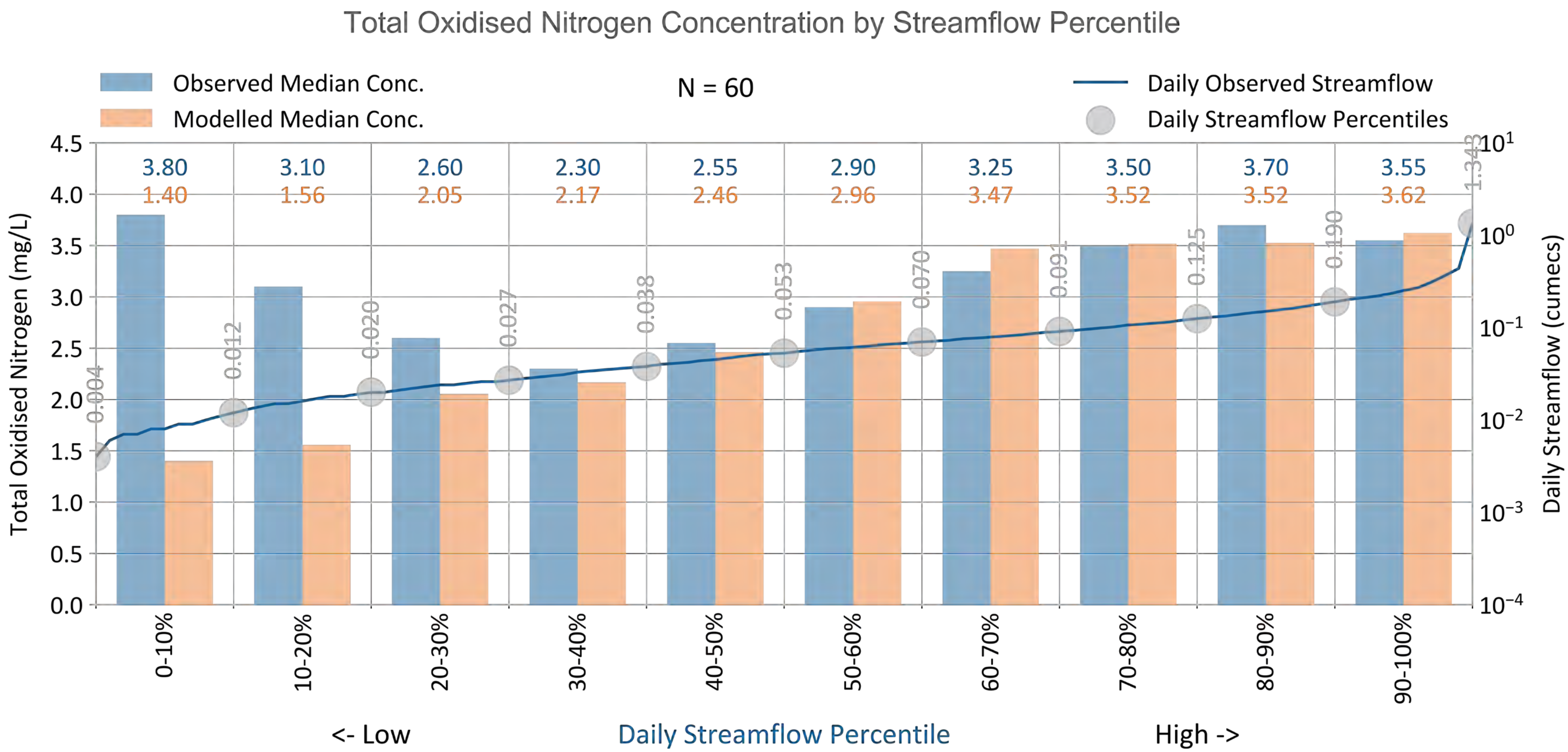


Figure 4-31. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Daily modelled (flow-weighted average) and observed grab sample median concentration by flow percentile

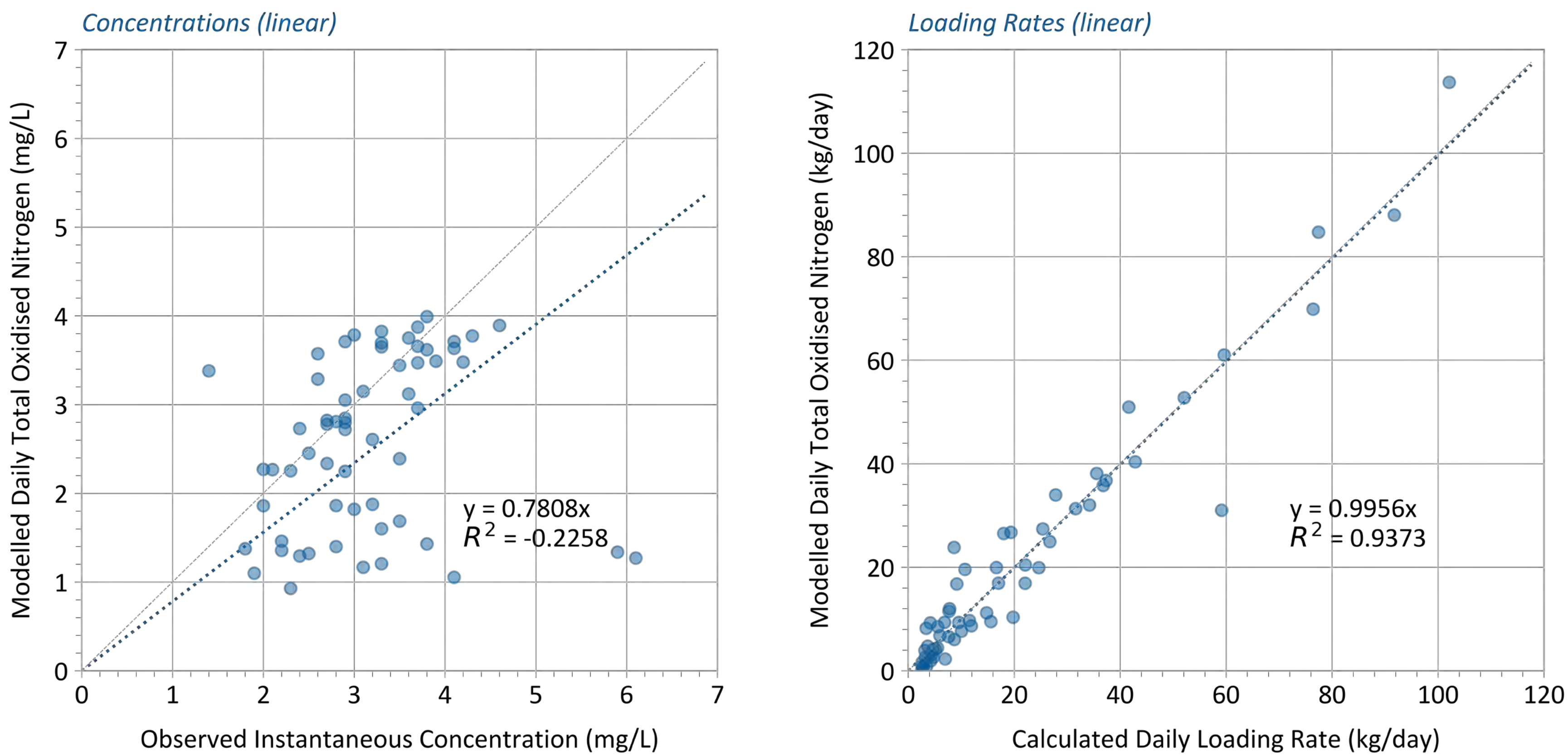


Figure 4-32. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Daily modelled (flow-weighted average) vs observed concentrations (left) and calculated daily loading rates (right) with linear scale.
Note: the R^2 values here are not relevant to calibration performance

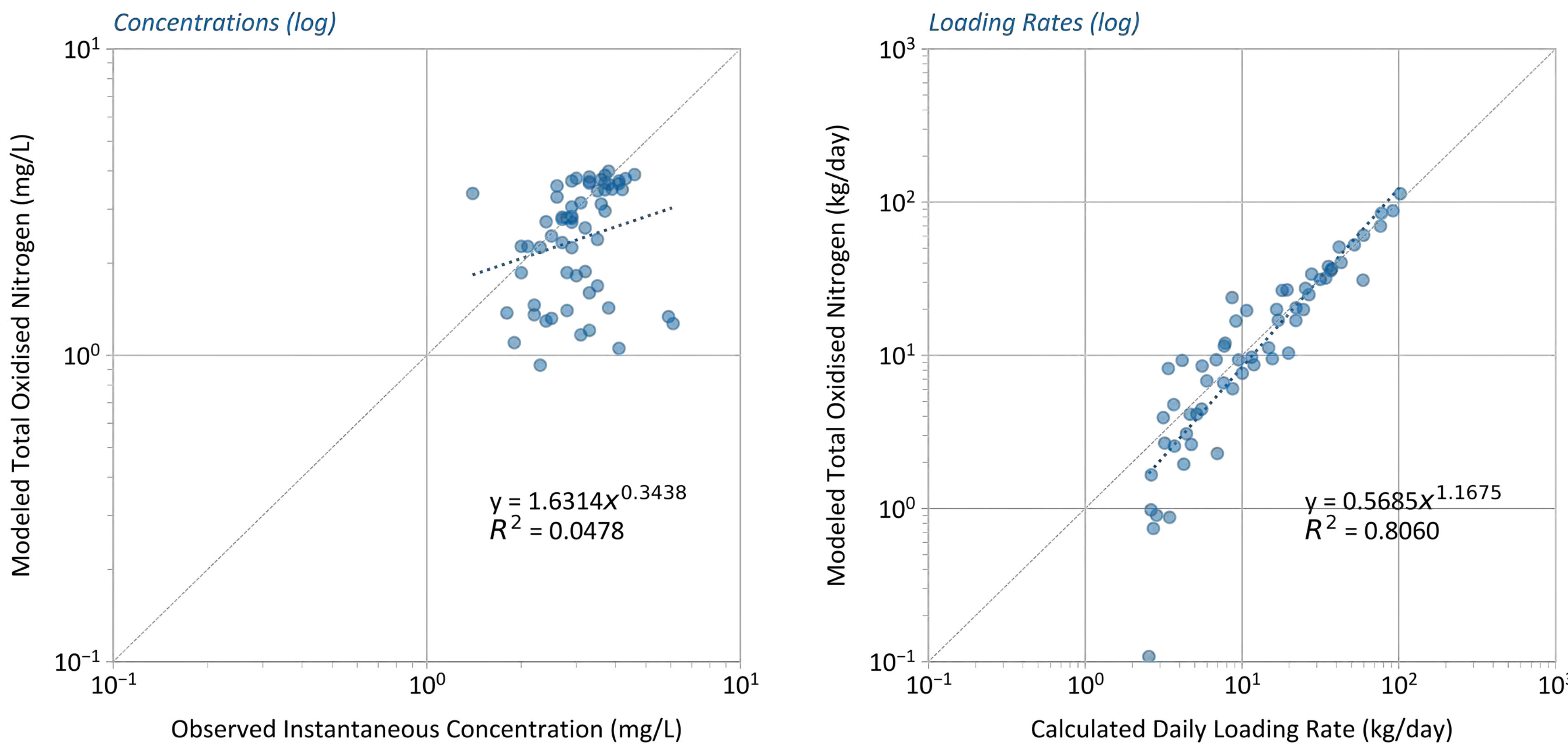


Figure 4-33. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Daily modelled (flow-weighted average) vs observed concentrations (left) and calculated daily loading rates (right) with log scale. Note: the r^2 values here are not relevant to calibration performance

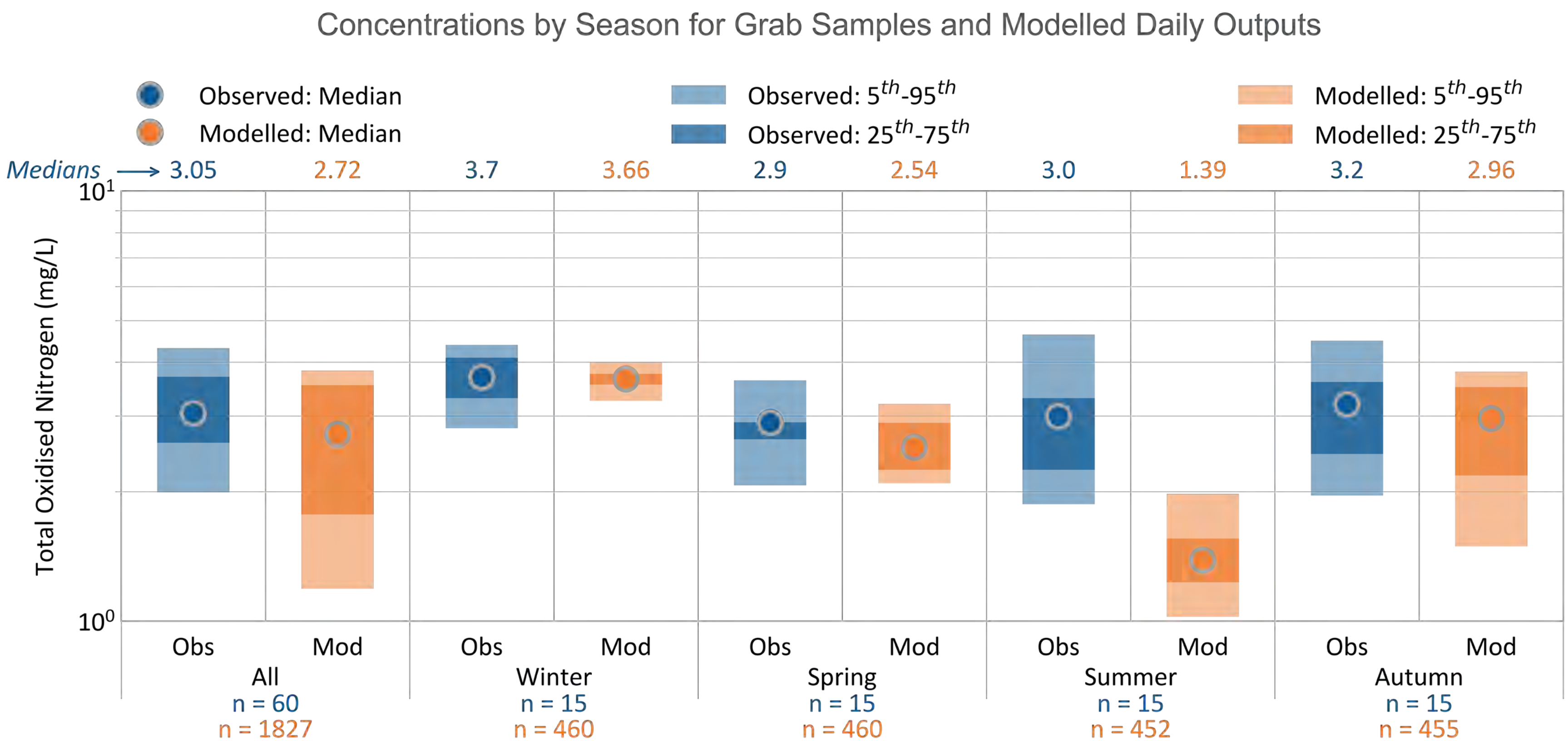


Figure 4-34. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Modelled daily (flow-weighted average) vs observed grab concentrations by season

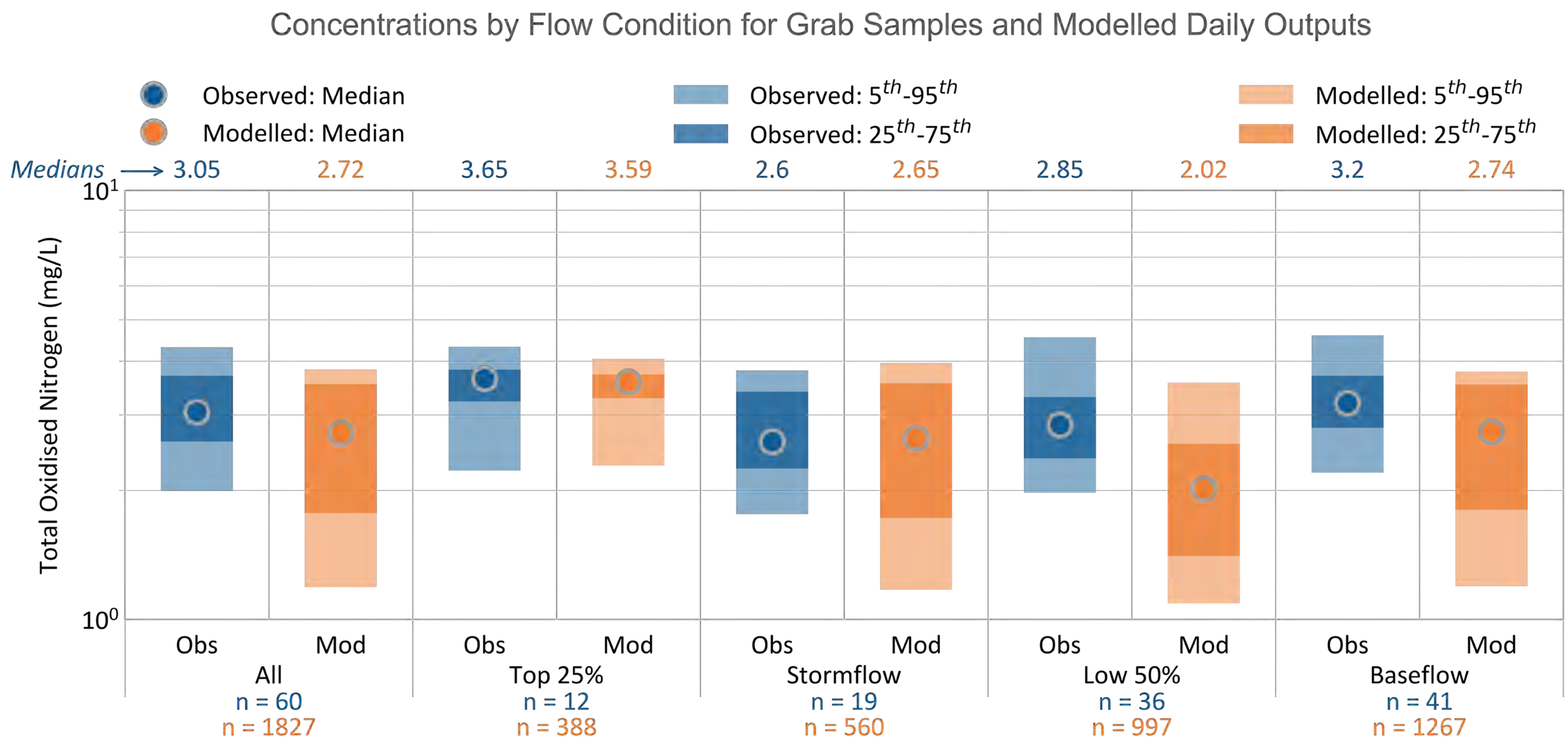


Figure 4-35. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Modelled daily (flow-weighted average) vs observed grab concentrations by flow condition

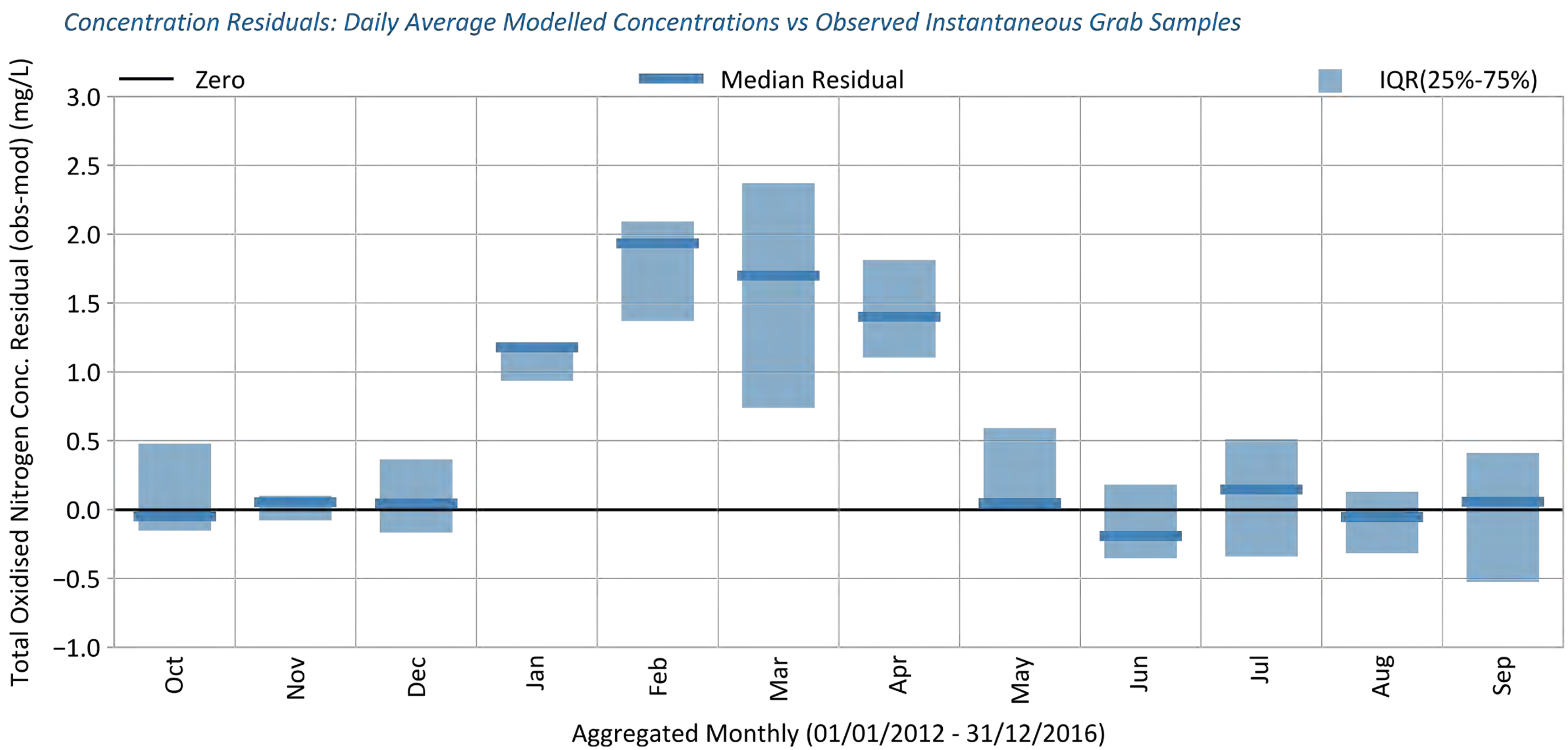


Figure 4-36. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Modelled daily (flow-weighted average) vs observed grab sample concentration residual by calendar month

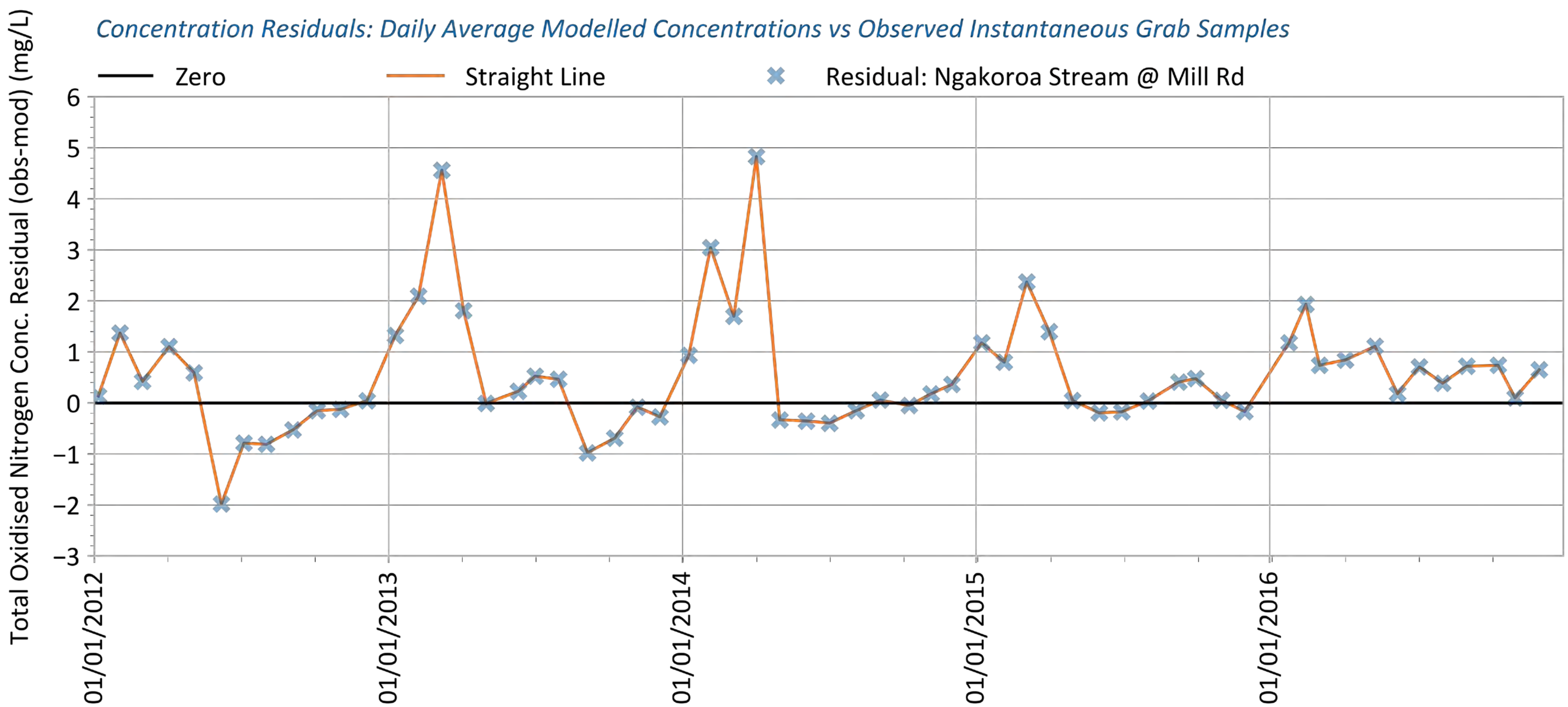


Figure 4-37. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Modelled daily (flow-weighted average) vs observed grab sample concentration residual across simulation period

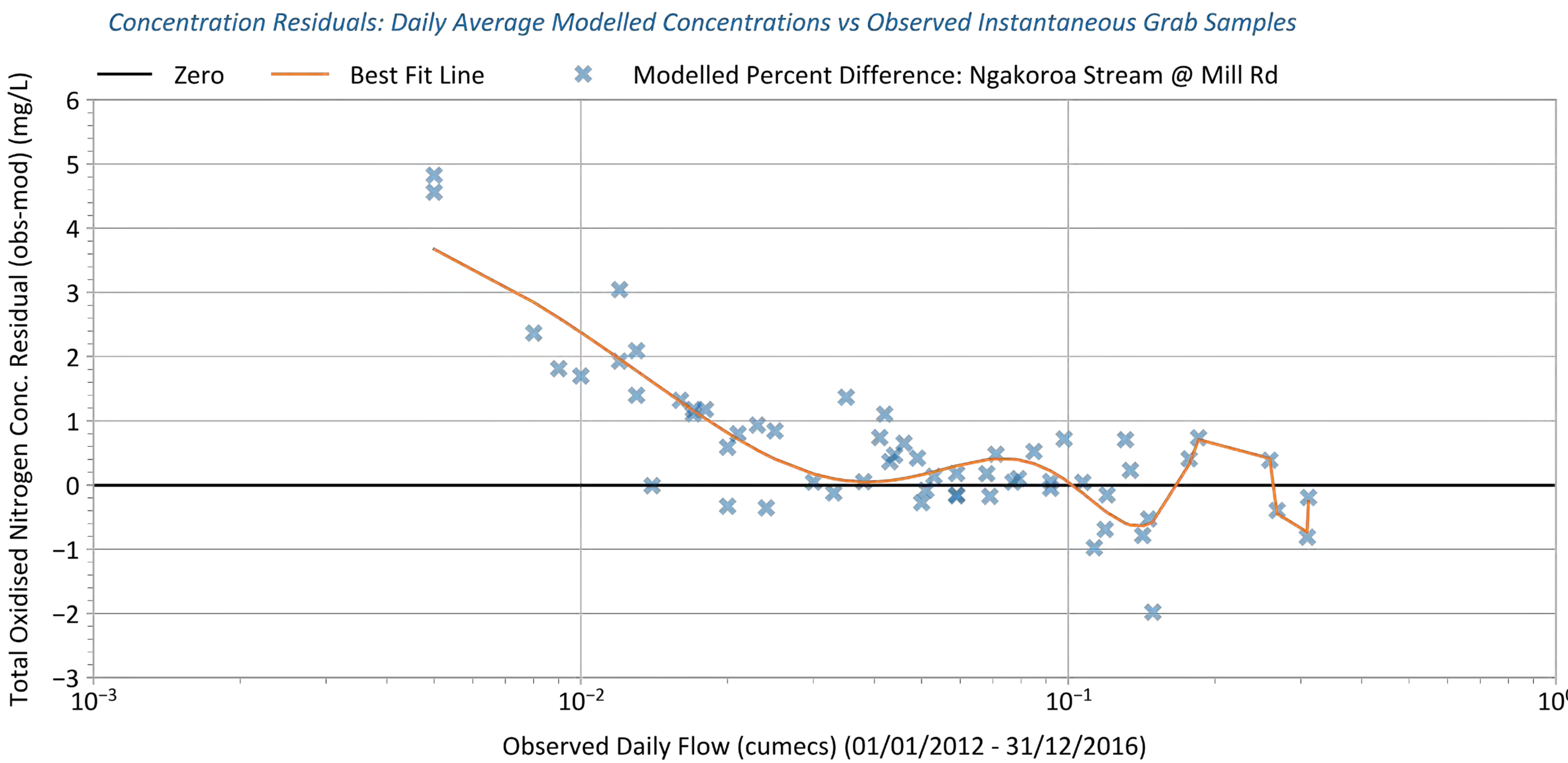


Figure 4-38. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Modelled daily (flow-weighted average) vs observed grab sample concentration residual by observed daily average streamflow on sampling dates

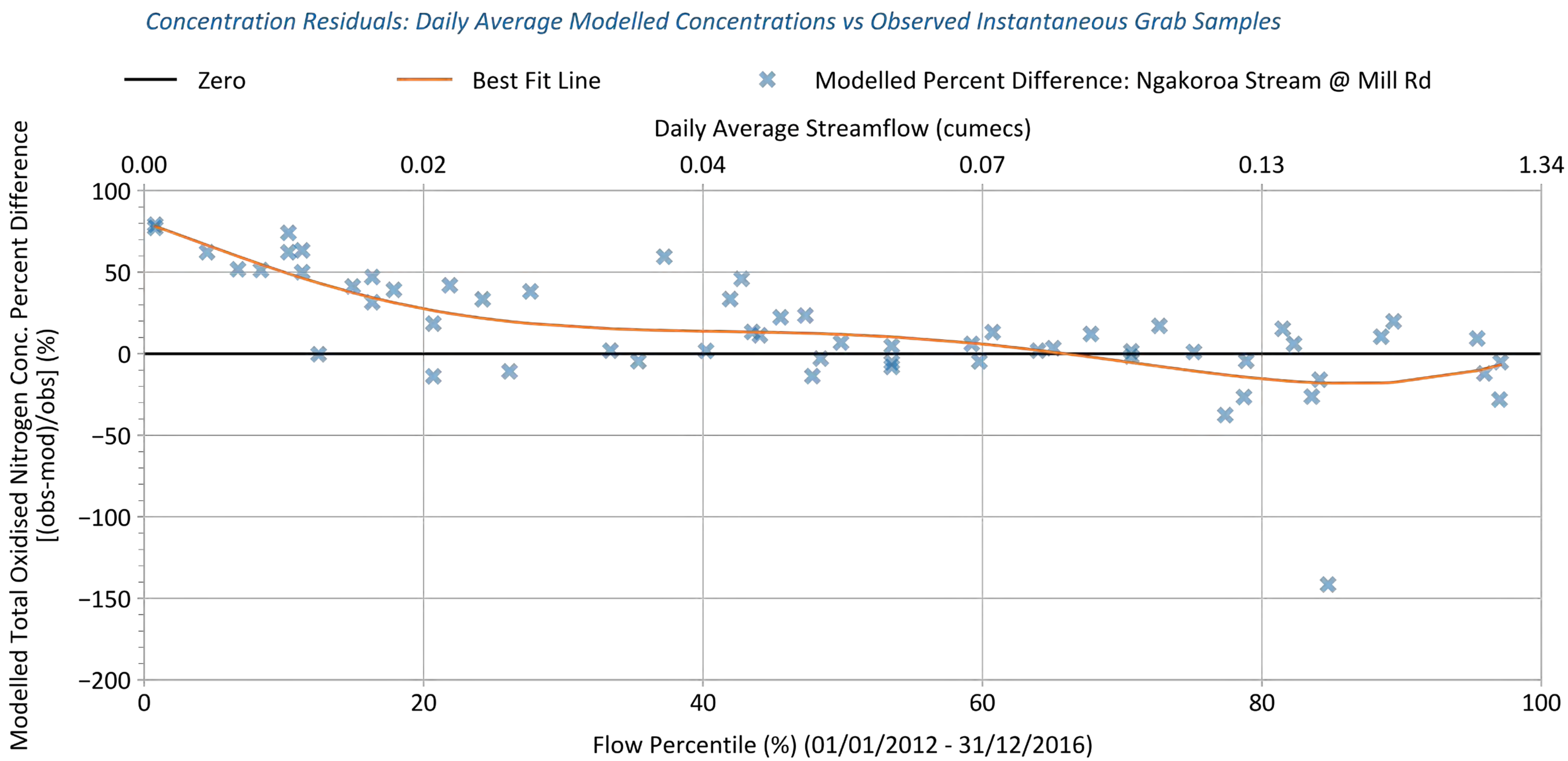


Figure 4-39. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Modelled daily (flow-weighted average) vs observed grab sample concentration per cent difference by observed daily average streamflow percentile

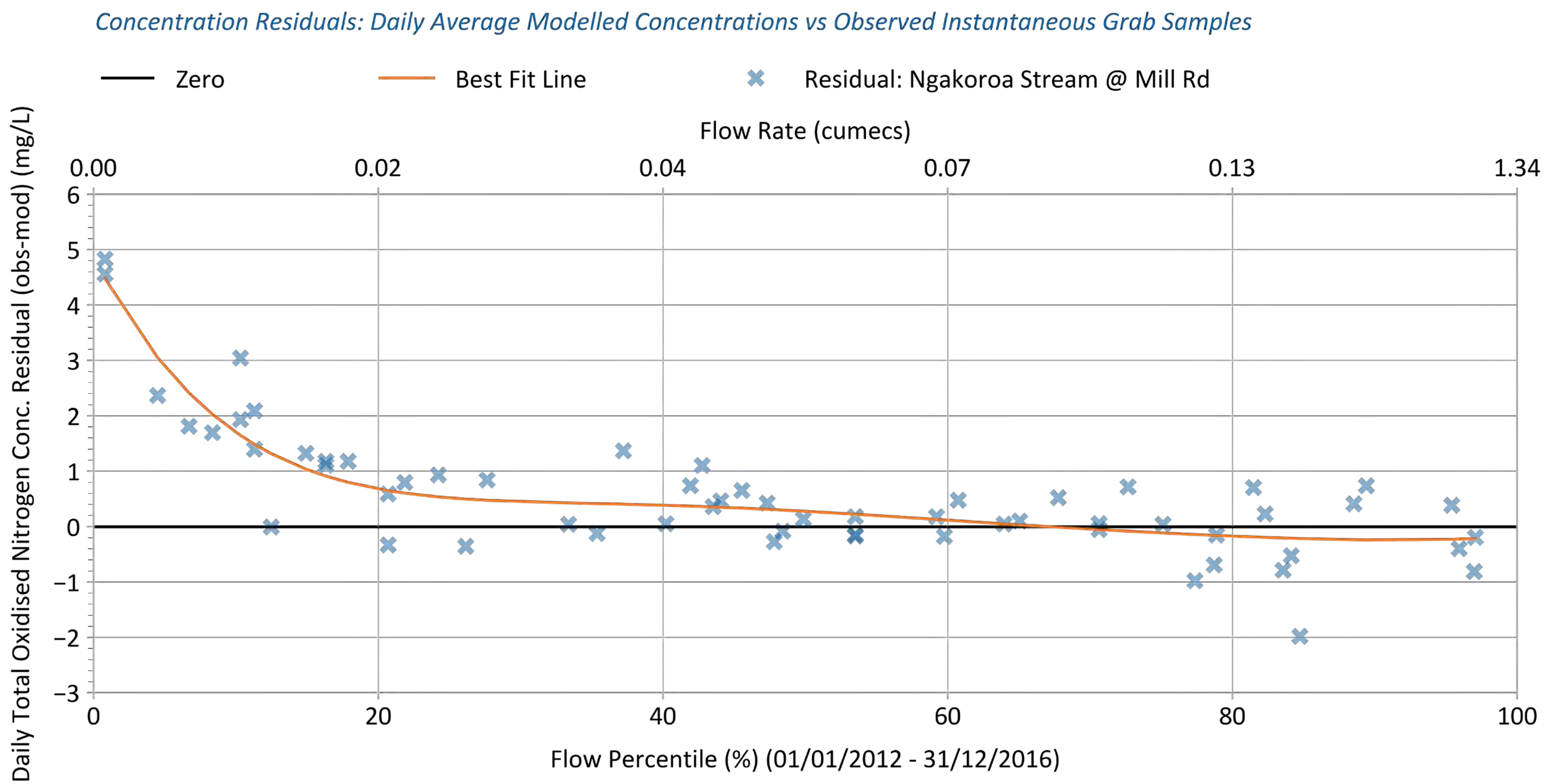


Figure 4-40. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Modelled daily (flow-weighted average) vs observed grab sample concentration residual by observed daily average streamflow percentile

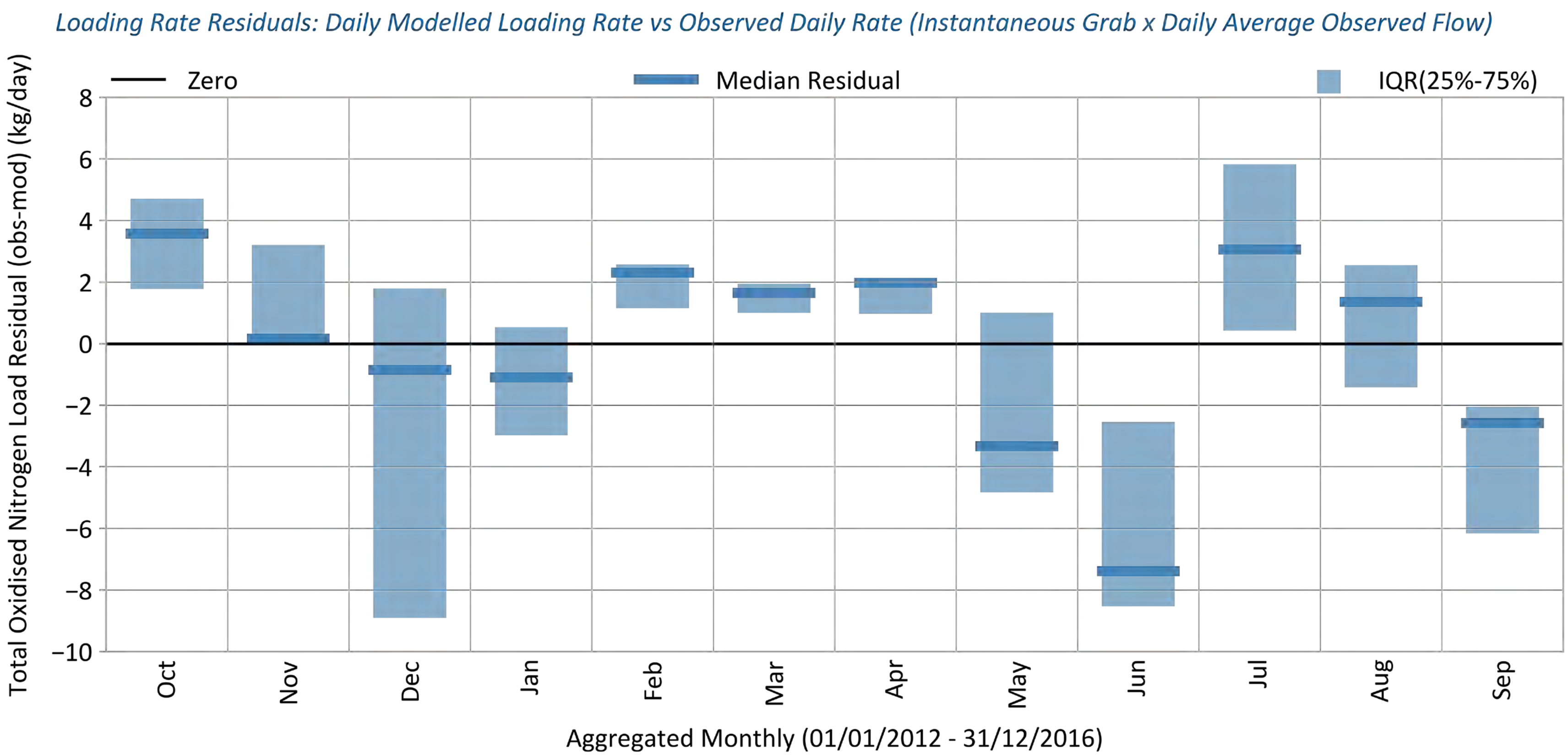


Figure 4-41. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Modelled daily (flow-weighted average) vs calculated grab sample loading rate residual by calendar month

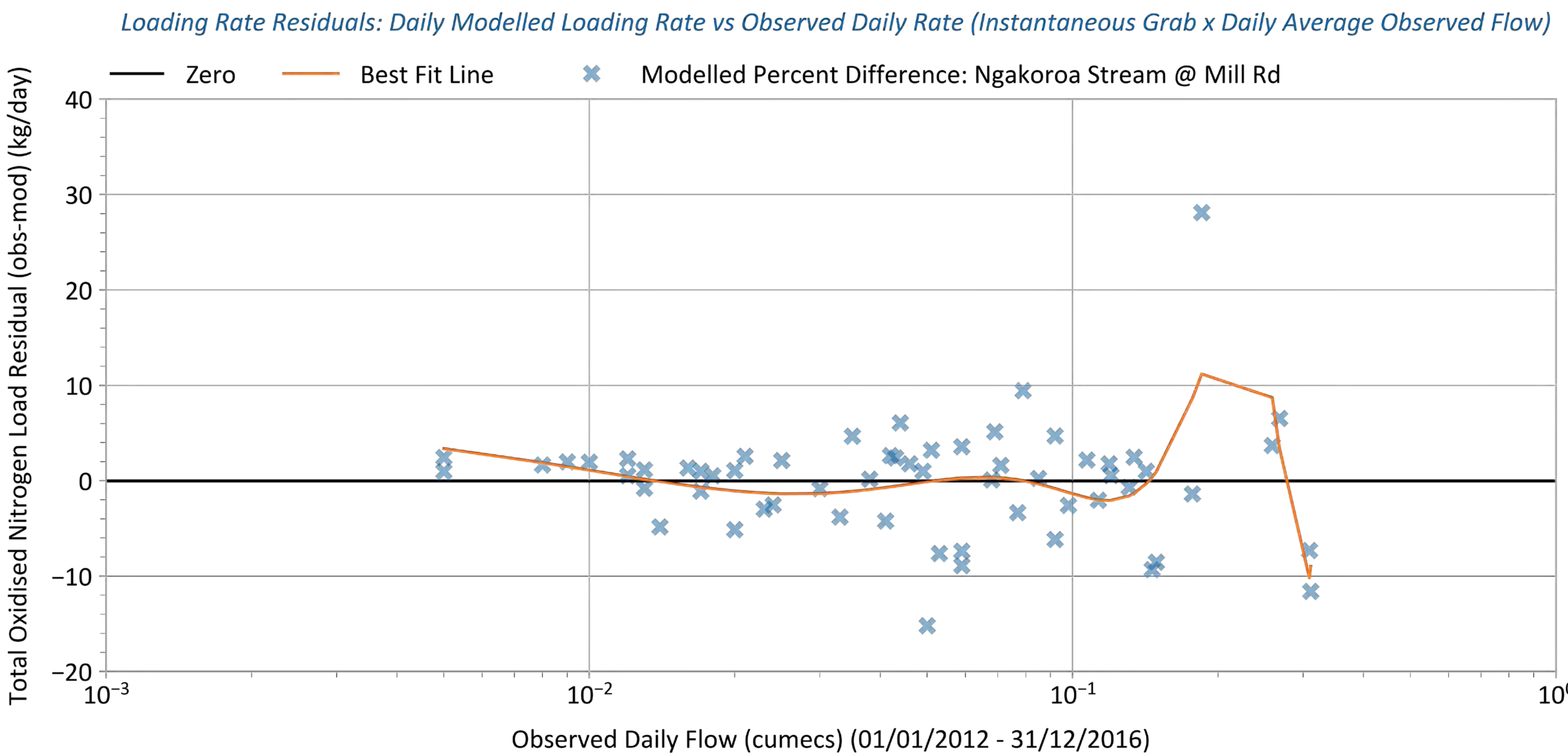


Figure 4-42. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Modelled daily (flow-weighted average) vs calculated grab sample loading rate residual by observed daily average streamflow on sampling dates

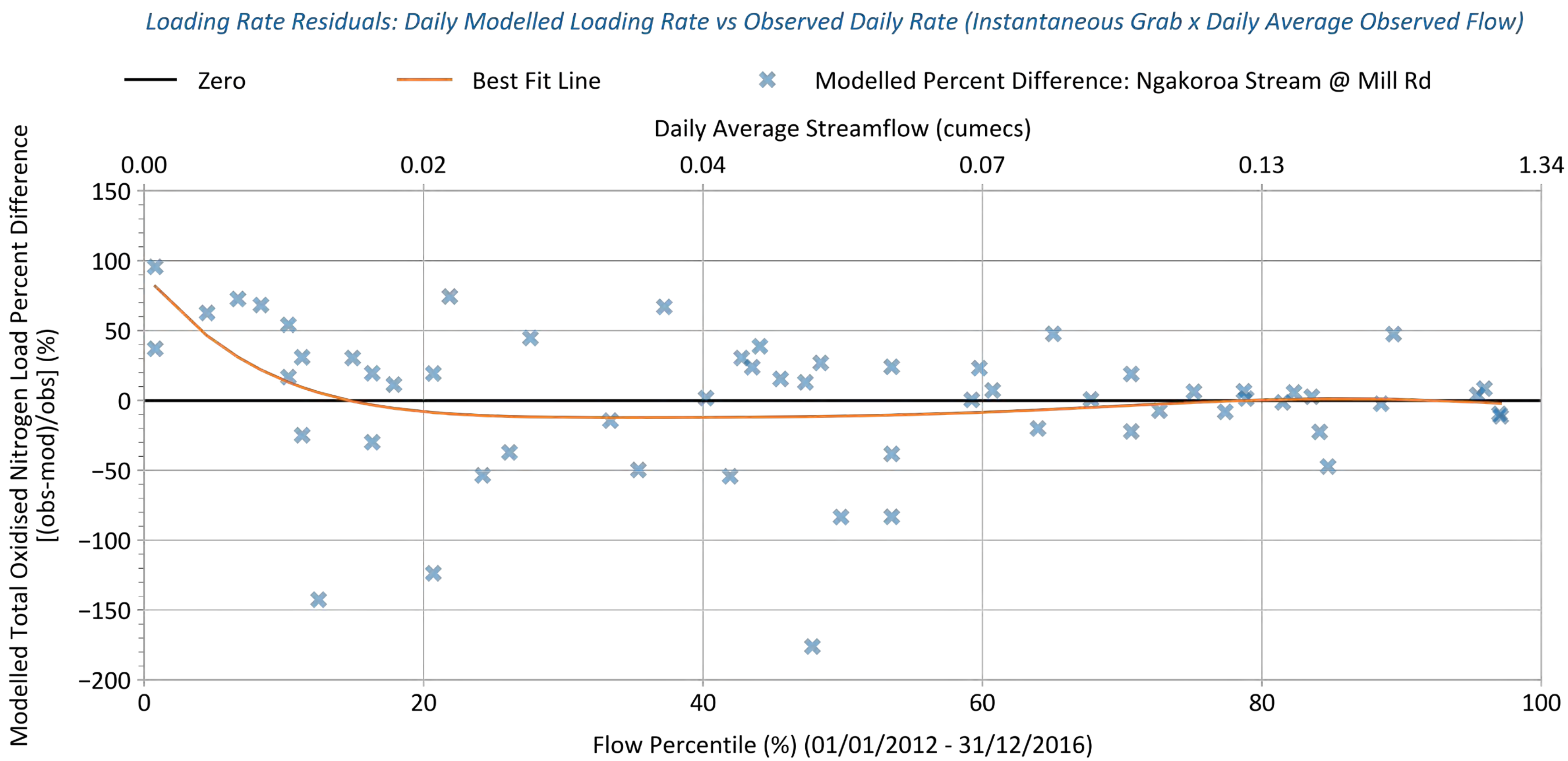


Figure 4-43. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Modelled daily (flow-weighted average) vs calculated grab sample loading rate per cent difference by observed daily average streamflow percentile

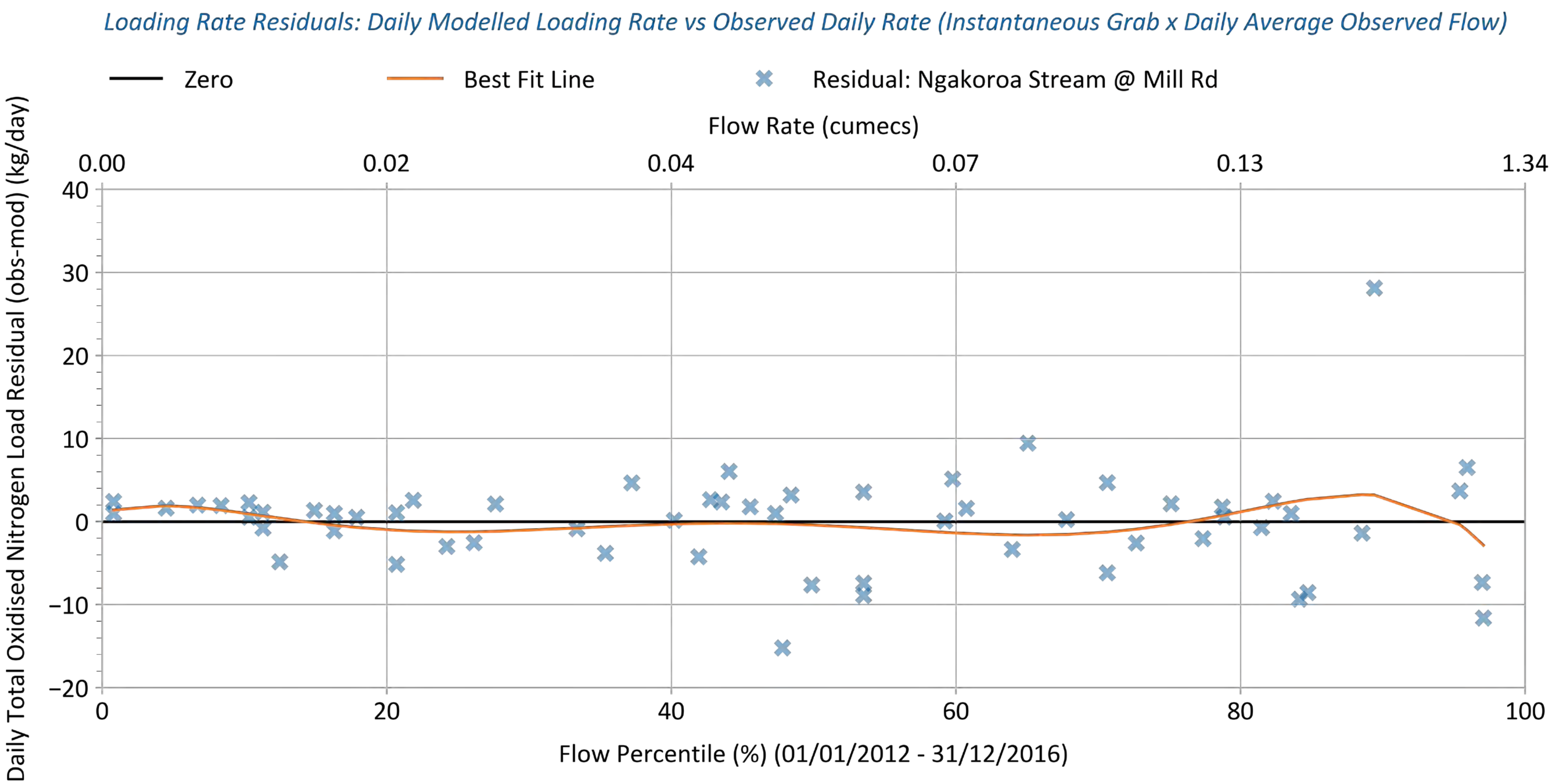


Figure 4-44. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Modelled daily (flow-weighted average) vs calculated grab sample loading rate residual by observed daily average streamflow percentile

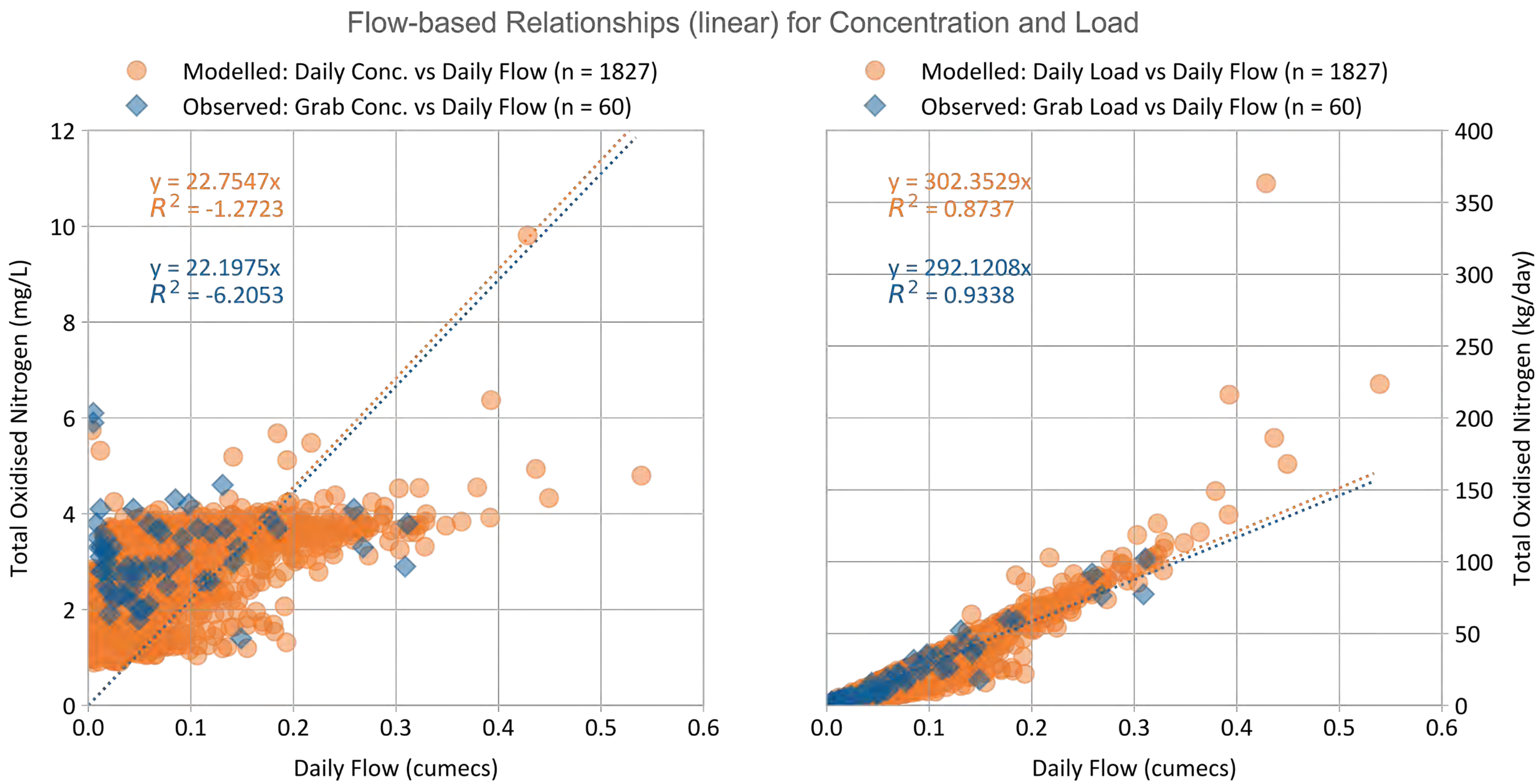


Figure 4-45. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Flow-based relationships for modelled daily (flow-weighted average) vs observed grab concentrations (left) and calculated grab sample loading rates (right) with linear scale. Note: the r² values here are not relevant to calibration performance

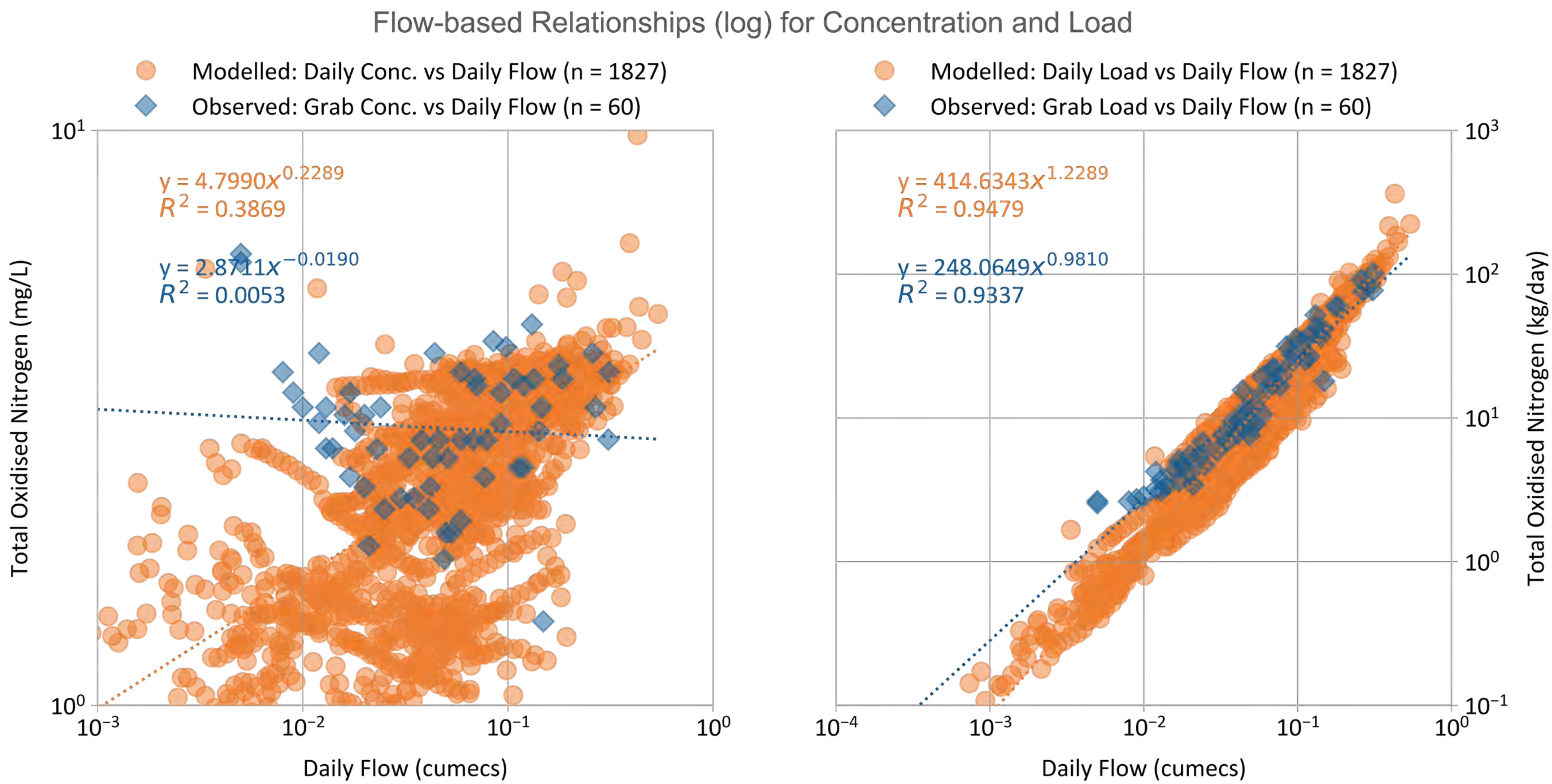


Figure 4-46. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Flow-based relationships for modelled daily vs observed grab concentrations (left) and calculated grab sample loading rates (right) with log scale. Note: R^2 values here are not relevant to calibration performance

Table 4-18. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Per cent bias statistical performance metric for simulated concentrations at Ngakoroa Stream @ Mill Rd 01/01/2012-31/12/2016

Metrics based on Concentrations	**Observed vs Simulated Calibration Performance for Total Oxidised Nitrogen Average Concentration** (Observed Instantaneous Grab Sample Concentration vs Daily Average Simulated Concentration)									
Condition during Sample Collection *(01/01/2012 - 31/12/2016)*	**Per cent Bias (PBIAS)**									
	All Seasons	**n =**	**Winter**	**n =**	**Spring**	**n =**	**Summer**	**n =**	**Fall**	**n =**
All Conditions	17.8%	60	-0.9%	15	2.6%	15	52.6%	15	19.6%	15
Samples on Days with Highest 25% of Flows	-5.7%	12	-4.0%	8	N/A	1	N/A	0	N/A	3
Samples on Days with Lowest 50% of Flows	33.0%	36	N/A	1	1.4%	9	52.6%	15	31.1%	11
Samples on Storm Volume Days	14.2%	19	N/A	3	-7.2%	5	50.3%	6	11.1%	5
Samples on Baseflow Volume Days	19.1%	41	1.3%	12	6.7%	10	53.9%	9	23.3%	10

*N/A: Metric not calculated for n < 5

Per cent Bias (PBIAS)	**Performance Threshold for WQ Simulation**				**Reference**
	Very Good	Good	Satisfactory	Unsatisfactory	
All Conditions (Combined)	<15%	15% - 20%	20% - 30%	>30%	Moriasi et al. (2015)
Seasonal and High/Low Flows	<20%	20% - 30%	30% - 40%	>40%	

Table 4-19. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: r-Squared statistical performance metric for simulated concentrations at Ngakoroa Stream @ Mill Rd 01/01/2012-31/12/2016

Metrics based on Concentrations	**Observed vs Simulated Calibration Performance for Total Oxidised Nitrogen Average Concentration** (Observed Instantaneous Grab Sample Concentration vs Daily Average Simulated Concentration)									
Condition during Sample Collection *(01/01/2012 - 31/12/2016)*	**r-Squared (r^2)**									
	All Seasons	**n =**	**Winter**	**n =**	**Spring**	**n =**	**Summer**	**n =**	**Fall**	**n =**
All Conditions	0.05	60	0.01	15	0.43	15	0.0	15	0.0	15
Samples on Days with Highest 25% of Flows	0.06	12	0.0	8	N/A	1	N/A	0	N/A	3
Samples on Days with Lowest 50% of Flows	0.0	36	N/A	1	0.39	9	0.0	15	0.0	11
Samples on Storm Volume Days	0.07	19	N/A	3	0.53	5	0.27	6	0.0	5
Samples on Baseflow Volume Days	0.01	41	0.0	12	0.46	10	0.24	9	0.01	10

*N/A: Metric not calculated for n < 5

r-Squared (r^2)	**Performance Threshold for WQ Simulation**				**Reference**
	Very Good	Good	Satisfactory	Unsatisfactory	
All Conditions (Combined)	>0.70	0.6 - 0.70	0.30 - 0.60	<0.30	Moriasi et al. (2015)
Seasonal and High/Low Flows	> 0.60	0.30 - 0.60	0.20 - 0.30	<0.20	

Table 4-20. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Relative mean error statistical performance metric for simulated concentrations at Ngakoroa Stream @ Mill Rd 01/01/2012-31/12/2016

Metrics based on Concentrations	**Observed vs Simulated Calibration Performance for Total Oxidised Nitrogen Average Concentration** (Observed Instantaneous Grab Sample Concentration vs Daily Average Simulated Concentration)									
Condition during Sample Collection *(01/01/2012 - 31/12/2016)*	**Nash-Sutcliffe Efficiency (E)**									
	All Seasons	**n =**	**Winter**	**n =**	**Spring**	**n =**	**Summer**	**n =**	**Fall**	**n =**
All Conditions	-2.58	60	-0.04	15	0.39	15	-5.91	15	-2.3	15
Samples on Days with Highest 25% of Flows	-0.04	12	-0.14	8	N/A	1	N/A	0	N/A	3
Samples on Days with Lowest 50% of Flows	-4.24	36	N/A	1	0.32	9	-5.91	15	-4.37	11
Samples on Storm Volume Days	-2.33	19	N/A	3	0.14	5	-5.95	6	-1.33	5
Samples on Baseflow Volume Days	-3.55	41	-0.04	12	0.24	10	-7.42	9	-3.66	10

*N/A: Metric not calculated for n < 5

Nash-Sutcliffe Efficiency (E)	**Performance Threshold for WQ Simulation**				**Reference**
	Very Good	Good	Satisfactory	Unsatisfactory	
All Conditions (Combined)	>0.65	0.50 - 0.65	0.35 - 0.50	<0.35	Moriasi et al. (2015)
Seasonal and High/Low Flows	>0.50	0.35 - 0.50	0.25 - 0.35	<0.25	

Table 4-21. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Per cent bias statistical performance metric for simulated loading rates at Ngakoroa Stream @ Mill Rd 01/01/2012-31/12/2016

Metrics based on Loading Rates	**Observed vs Simulated Calibration Performance for Total Oxidised Nitrogen Load** (Observed Daily Average Load vs Simulated Daily Average Load)									
Condition during Sample Collection *(01/01/2012 - 31/12/2016)*	**Per cent Bias (PBIAS)**									
	All Seasons	**n =**	**Winter**	**n =**	**Spring**	**n =**	**Summer**	**n =**	**Fall**	**n =**
All Conditions	-0.3%	60	-0.6%	15	10.8%	15	5.8%	15	-12.9%	15
Samples on Days with Highest 25% of Flows	0.5%	12	-1.5%	8	N/A	1	N/A	0	N/A	3
Samples on Days with Lowest 50% of Flows	-7.4%	36	N/A	1	-19.5%	9	5.8%	15	-16.4%	11
Samples on Storm Volume Days	-5.2%	19	N/A	3	-2.2%	5	39.5%	6	-11.3%	5
Samples on Baseflow Volume Days	1.7%	41	1.6%	12	15.9%	10	-14.4%	9	-14.9%	10

*N/A: Metric not calculated for n < 5

Per cent Bias (PBIAS)	**Performance Threshold for WQ Simulation**				**Reference**
	Very Good	Good	Satisfactory	Unsatisfactory	
All Conditions (Combined)	<15%	15% - 20%	20% - 30%	>30%	Moriasi et al. (2015)
Seasonal and High/Low Flows	<20%	20% - 30%	30% - 40%	>40%	

Table 4-22. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: r-Squared statistical performance metric for simulated loading rates at Ngakoroa Stream @ Mill Rd 01/01/2012-31/12/2016

Metrics based on Loading Rates	**Observed vs Simulated Calibration Performance for Total Oxidised Nitrogen Load** (Observed Daily Average Load vs Simulated Daily Average Load)									
Condition during Sample Collection *(01/01/2012 - 31/12/2016)*	**r-Squared (r^2)**									
	All Seasons	**n =**	**Winter**	**n =**	**Spring**	**n =**	**Summer**	**n =**	**Fall**	**n =**
All Conditions	0.81	60	0.93	15	0.46	15	0.64	15	0.83	15
Samples on Days with Highest 25% of Flows	0.75	12	0.94	8	N/A	1	N/A	0	N/A	3
Samples on Days with Lowest 50% of Flows	0.6	36	N/A	1	0.02	9	0.64	15	0.57	11
Samples on Storm Volume Days	0.87	19	N/A	3	0.21	5	0.52	6	0.95	5
Samples on Baseflow Volume Days	0.77	41	0.94	12	0.66	10	0.77	9	0.78	10

*N/A: Metric not calculated for n < 5

r-Squared (r^2)	**Performance Threshold for WQ Simulation**				**Reference**
	Very Good	Good	Satisfactory	Unsatisfactory	
All Conditions (Combined)	>0.70	0.6 - 0.70	0.30 - 0.60	<0.30	Moriasi et al. (2015)
Seasonal and High/Low Flows	> 0.60	0.30 - 0.60	0.20 - 0.30	<0.20	

Table 4-23. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Relative mean error statistical performance metric for simulated loading rates at Ngakoroa Stream @ Mill Rd 01/01/2012-31/12/2016

Metrics based on Loading Rates	**Observed vs Simulated Calibration Performance for Total Oxidised Nitrogen Load** (Observed Daily Average Load vs Simulated Daily Average Load)									
Condition during Sample Collection *(01/01/2012 - 31/12/2016)*	**Nash-Sutcliffe Efficiency (E)**									
	All Seasons	**n =**	**Winter**	**n =**	**Spring**	**n =**	**Summer**	**n =**	**Fall**	**n =**
All Conditions	0.62	60	0.88	15	0.44	15	-6.12	15	0.73	15
Samples on Days with Highest 25% of Flows	0.75	12	0.93	8	N/A	1	N/A	0	N/A	3
Samples on Days with Lowest 50% of Flows	-1.1	36	N/A	1	-2.29	9	-6.12	15	-0.21	11
Samples on Storm Volume Days	0.57	19	N/A	3	-0.07	5	-4.29	6	0.73	5
Samples on Baseflow Volume Days	0.64	41	0.88	12	0.64	10	-7.85	9	0.72	10

*N/A: Metric not calculated for n < 5

Nash-Sutcliffe Efficiency (E)	**Performance Threshold for WQ Simulation**				**Reference**
	Very Good	Good	Satisfactory	Unsatisfactory	
All Conditions (Combined)	>0.65	0.50 - 0.65	0.35 - 0.50	<0.35	Moriasi et al. (2015)
Seasonal and High/Low Flows	>0.50	0.35 - 0.50	0.25 - 0.35	<0.25	

Table 4-24. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Total oxidised nitrogen concentration percentiles 01/01/2012-31/12/2016

Total Oxidised Nitrogen Concentration Statistics				
Statistic	**Observed (mg/L)**	**Simulated (mg/L)**	**Difference (mg/L)**	**% Difference**
Average	3.16	2.63	0.52	16.6%
Minimum	1.4	0.90	0.50	36.0%
5th Percentile	1.99	1.19	0.80	40.3%
10th Percentile	2.19	1.33	0.86	39.4%
25th Percentile	2.6	1.77	0.83	31.9%
Median	3.05	2.72	0.33	10.7%
75th Percentile	3.7	3.54	0.16	4.3%
90th Percentile	4.1	3.74	0.36	8.9%
95th Percentile	4.32	3.82	0.49	11.4%
Maximum	6.1	9.81	-3.71	-60.9%

Table 4-25. Example Panel from Water Quality Calibration: Ngakoroa Stream @ Mill Rd (43829) – Total oxidised nitrogen calibration: Total oxidised nitrogen loading rate percentiles 01/01/2012-31/12/2016

Total Oxidised Nitrogen Loading Rates Statistics				
Statistic	**Observed (kg/day)**	**Simulated (kg/day)**	**Difference (kg/day)**	**% Difference**
Average	20732	21957	-1225	-5.9%
Minimum	2549	12	2537	99.5%
5th Percentile	2717	760	1958	72.0%
10th Percentile	3207	1635	1572	49.0%
25th Percentile	4730	5101	-371	-7.8%
Median	10368	13354	-2986	-28.8%
75th Percentile	27004	31075	-4070	-15.1%
90th Percentile	52772	53673	-901	-1.7%
95th Percentile	76463	67110	9353	12.2%
Maximum	102108	363215	-261107	-255.7%

In addition to the time series comparisons presented for calibration, HRU summary outputs are an important outcome of the LSPC build. HRU summaries, which represent ‘edge-of-stream’ contributions, provide transparency in how the various downstream time series were generated (e.g., are the contributing sources prior to instream processes). HRU edge-of-stream outputs are summarised for the 717 sub-catchments upstream of the 46 SoE stations, in Appendix E (i.e., not inclusive of all sub-catchments throughout the Auckland region). An example set of HRU outputs, for TSS, is shown in Figure 4-47 to Figure 4-50. The HRU outputs are expressed as both yields and concentrations as follows:

- Simulated yields are presented using all the HRU-rain gage combinations upstream of the calibration stations. The variation in unit-area annual average yields of each contaminant for each HRU is based on the 5-year simulation (2012-2016) and represents the spatial variation over 717 sub-catchments (drainage area to 36 SoE stations) and 57 rainfall gages. The examples for TSS are shown in Figure 4-47 (only surface runoff) and Figure 4-48 (all flow including interflow and groundwater flow). The fact that FWMT outputs a *range* of yields, due to spatial variation in slope and weather, illustrates the difference in FWMT and empirical annualised models which often output a single yield per land use. Note that FWMT outputs could be processed for each year, as well, to compare yields among years. Finally, the fact that surface runoff, interflow and groundwater flow can each be configured and post-processed demonstrates flexibility to simulate a variety of edge-of-stream contaminant time series within the FWMT Stage 1 (e.g., by flow path).
- Idealised concentrations are presented for all 106 HRU combinations across the Auckland region, using final calibrated parameterisation but for a consistent climatic boundary condition (i.e., using the climate time series for ACC West, Gauge 6 central Auckland). The HRU slope was set as the average slope across Auckland region for each HRU class. For the concentration outputs, a single weather boundary condition is used to more readily allow for comparison among HRUs and their differential impacts and downstream water quality. If the concentration outputs were generated with all the gages across Auckland, then variations among HRUs would include differences in weather time series and slope, which can cloud HRU-to-HRU comparisons. The examples for zinc are shown in Figure 4-49 (only surface runoff) and Figure 4-50 (all flow including interflow and groundwater flow). Table 4-26 summarises the predictive performance of calibration and validation sites, load was assessed for sites with observed flow and water quality.

The following sections describe the calibration performance evaluation for each of the seven simulated contaminants, along with details on which parameter adjustments were relied upon most heavily during the calibration exercise. Discussion of the hydrologic calibration outcomes is provided in Section 4-4**.**

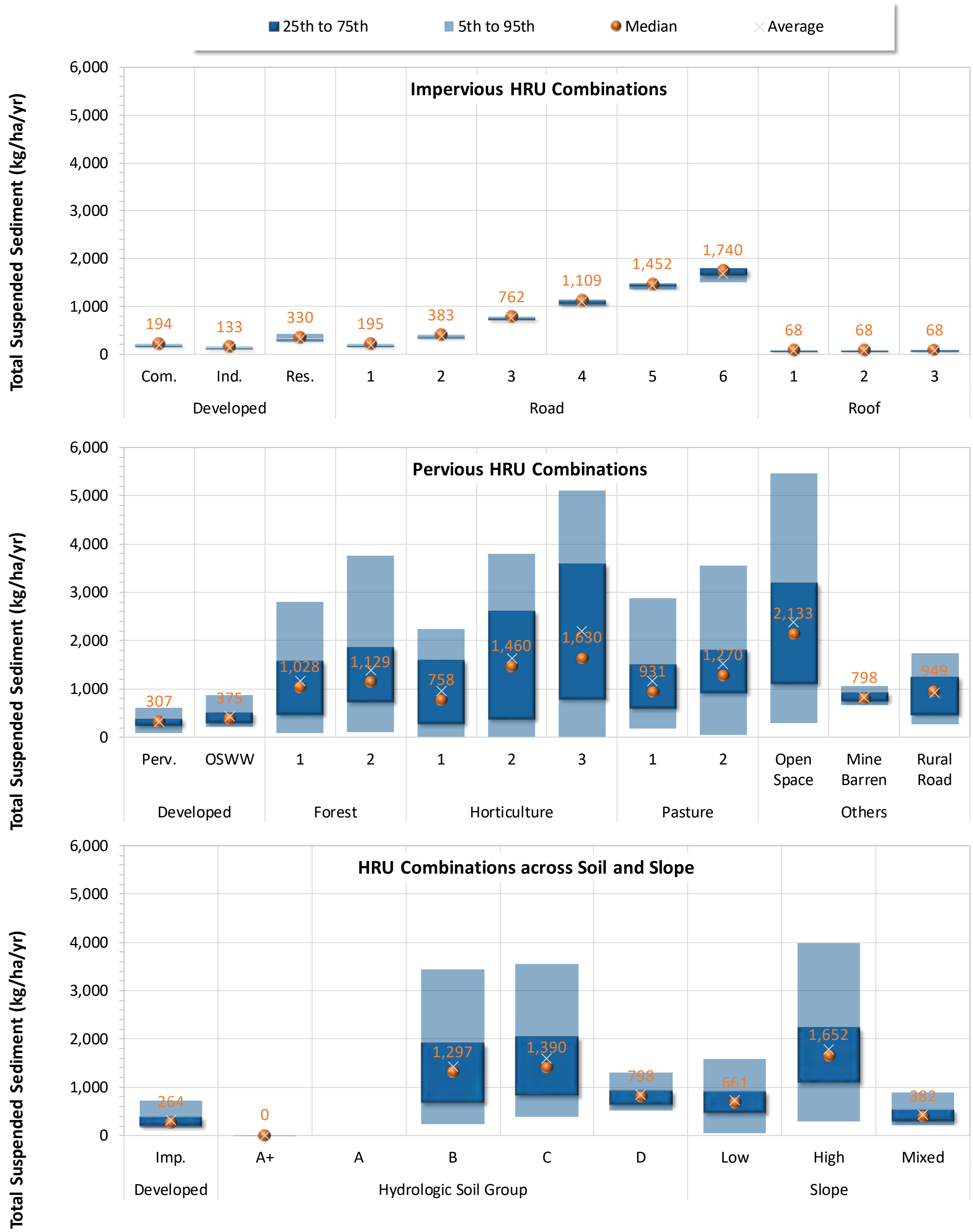


Figure 4-47. HRU edge-of-stream annual average yield (based on surface runoff): Total Suspended Sediment (kg/ha/yr)

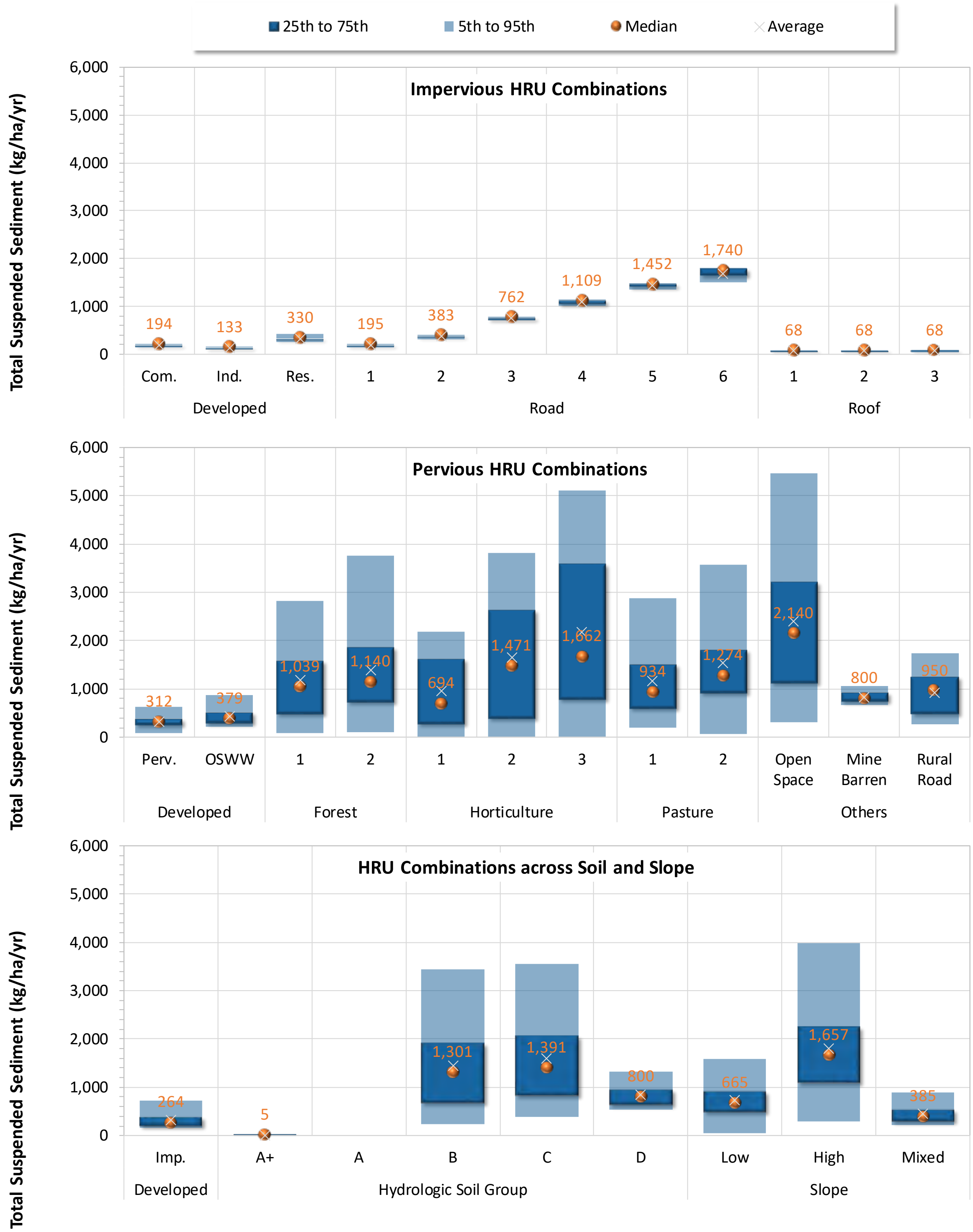


Figure 4-48. HRU edge-of-stream annual average yield (based on total water yield): Total Suspended Sediment (kg/ha/yr)

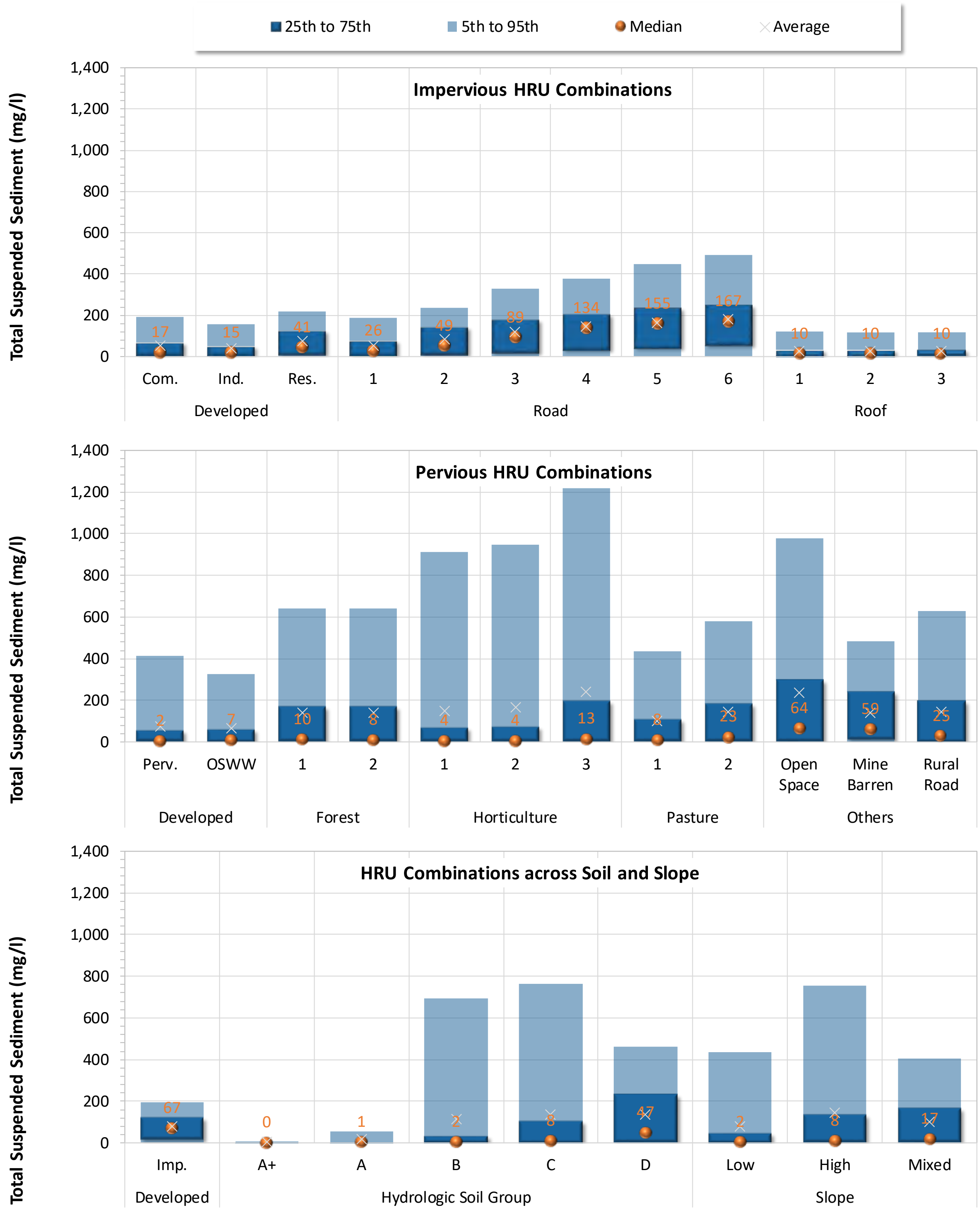


Figure 4-49. HRU edge-of-stream daily average concentration (based on surface runoff): Total Suspended Sediment (mg/l)

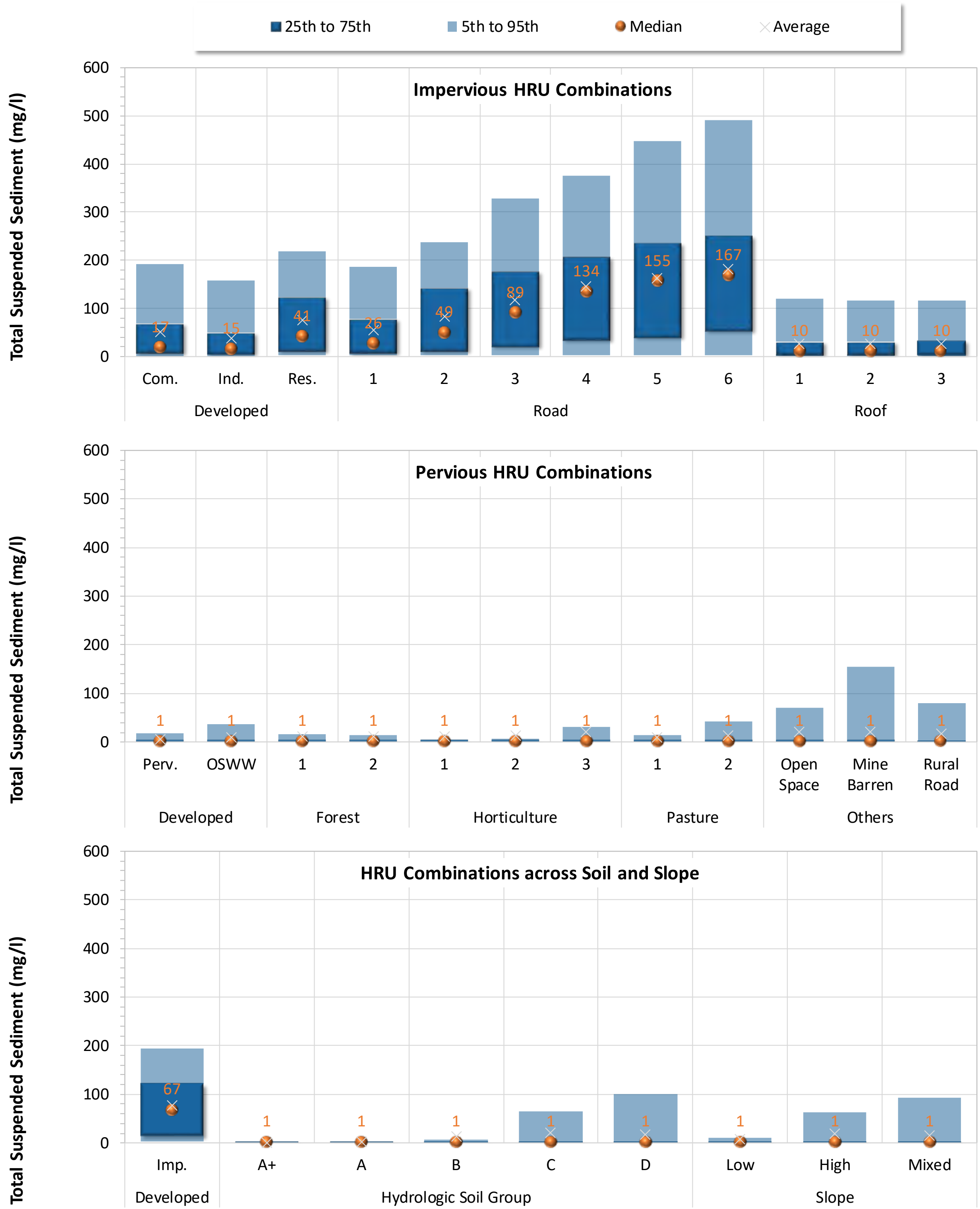


Figure 4-50. HRU edge-of-stream daily average concentration (based on total water yield): Total Suspended Sediment (mg/l)

Table 4-26. Summary of per cent of calibration and validation sites achieving satisfactory or better performance metric values for predicting contaminant concentration (Conc) and Load

Station	Metric	TSS		TN		TON		TAM		TP		DRP		TCu		TZn		*E. coli*	
		Conc	Load	Conc	Load	Conc	Load	Conc	Load	Conc	Load	Conc	Load	Conc	Load	Conc	Load	Conc	Load
Forest	PBIAS	0% (0/5)	0% (0/3)	40% (2/5)	33% (1/3)	40% (2/5)	33% (1/3)	0% (0/5)	33% (1/3)	40% (2/5)	33% (1/3)	60% (3/5)	67% (2/3)	50% (1/2)	0% (0/1)	50% (1/2)	100% (1/1)	40% (2/5)	67% (2/3)
	r2	0% (0/5)	100% (3/3)	0% (0/5)	100% (3/3)	0% (0/5)	67% (2/3)	0% (0/4)	100% (2/2)	0% (0/5)	100% (3/3)	0% (0/5)	100% (3/3)	0% (0/2)	100% (1/1)	0% (0/2)	100% (1/1)	0% (0/5)	67% (2/3)
	NSE	0% (0/5)	0% (0/3)	0% (0/5)	33% (1/3)	0% (0/5)	33% (1/3)	0% (0/4)	0% (0/2)	0% (0/5)	33% (1/3)	0% (0/5)	33% (1/3)	0% (0/2)	0% (0/1)	0% (0/2)	100% (1/1)	0% (0/5)	33% (1/3)
Pasture	PBIAS	33% (1/3)	0% (0/1)	100% (3/3)	0% (0/1)	67% (2/3)	0% (0/1)	67% (2/3)	0% (0/1)	100% (3/3)	0% (0/1)	33% (1/3)	0% (0/1)	0% (0/1)	NA	100% (1/1)	NA	67% (2/3)	0% (0/1)
	r2	33% (1/3)	100% (1/1)	33% (1/3)	100% (1/1)	33% (1/3)	100% (1/1)	0% (0/3)	100% (1/1)	33% (1/3)	100% (1/1)	0% (0/3)	100% (1/1)	0% (0/1)	NA	0% (0/1)	NA	0% (0/3)	100% (1/1)
	NSE	0% (0/3)	100% (1/1)	0% (0/3)	100% (1/1)	0% (0/3)	100% (1/1)	0% (0/3)	100% (1/1)	0% (0/3)	100% (1/1)	0% (0/3)	100% (1/1)	0% (0/1)	NA	0% (0/1)	NA	0% (0/3)	100% (1/1)
Horticulture	PBIAS	25% (1/4)	0% (0/2)	75% (3/4)	50% (1/2)	75% (3/4)	50% (1/2)	50% (2/4)	0% (0/2)	0% (0/4)	0% (0/2)	25% (1/4)	0% (0/2)	0% (0/1)	0% (0/1)	0% (0/1)	0% (0/1)	25% (1/4)	0% (0/2)
	r2	25% (1/4)	100% (2/2)	50% (2/4)	100% (2/2)	50% (2/4)	100% (2/2)	0% (0/2)	NA	25% (1/4)	100% (2/2)	0% (0/4)	100% (2/2)	0% (0/1)	100% (1/1)	0% (0/1)	100% (1/1)	33% (1/3)	100% (2/2)
	NSE	0% (0/4)	100% (2/2)	25% (1/4)	100% (2/2)	0% (0/4)	50% (1/2)	0% (0/2)	NA	0% (0/4)	50% (1/2)	0% (0/4)	0% (0/2)	0% (0/1)	0% (0/1)	0% (0/1)	100% (1/1)	0% (0/3)	0% (0/2)
Developed	PBIAS	0% (0/5)	25% (1/4)	20% (1/5)	50% (2/4)	20% (1/5)	50% (2/4)	0% (0/5)	25% (1/4)	60% (3/5)	0% (0/4)	40% (2/5)	0% (0/4)	60% (3/5)	50% (2/4)	60% (3/5)	25% (1/4)	40% (2/5)	25% (1/4)
	r2	0% (0/5)	100% (4/4)	0% (0/5)	75% (3/4)	0% (0/5)	25% (1/4)	0% (0/2)	100% (1/1)	0% (0/5)	100% (4/4)	0% (0/5)	100% (4/4)	0% (0/5)	100% (4/4)	0% (0/5)	100% (4/4)	25% (1/4)	33% (1/3)
	NSE	0% (0/5)	0% (0/4)	0% (0/5)	0% (0/4)	0% (0/5)	0% (0/4)	0% (0/2)	0% (0/1)	0% (0/5)	25% (1/4)	0% (0/5)	0% (0/4)	0% (0/5)	0% (0/4)	0% (0/5)	0% (0/4)	0% (0/4)	0% (0/3)
Validation	PBIAS	11% (2/19)	17% (1/6)	42% (8/19)	0% (0/6)	26% (5/19)	17% (1/6)	5% (1/19)	0% (0/6)	21% (4/19)	17% (1/6)	26% (5/19)	0% (0/6)	31% (5/16)	20% (1/5)	44% (7/16)	20% (1/5)	26% (5/19)	33% (2/6)
	r2	32% (6/19)	100% (6/6)	11% (2/18)	100% (5/5)	11% (2/19)	100% (6/6)	0% (0/13)	100% (5/5)	17% (3/18)	100% (5/5)	0% (0/19)	100% (6/6)	12% (2/16)	100% (5/5)	12% (2/16)	100% (5/5)	6% (1/18)	100% (6/6)
	NSE	0% (0/19)	100% (6/6)	0% (0/18)	100% (5/5)	5% (1/19)	100% (6/6)	0% (0/13)	100% (5/5)	0% (0/18)	80% (4/5)	0% (0/19)	67% (4/6)	0% (0/16)	0% (0/5)	0% (0/16)	100% (5/5)	6% (1/18)	100% (6/6)

4.3.4.1 Total Suspended Solids (TSS)

Sediment was calibrated first within the top-down calibration process for the FWMT Stage 1 because sediment delivery is an important driver of other contaminants (copper, zinc, and phosphorous – nitrogen and *E. coli* are not sediment associated in the FWMT model build).

Sediment sources and mobilisation processes vary with land cover (pervious/impervious) and soil type. Sediment is lost via several pathways including wash off, gullies (scour outside of simulated channels), and streams (hydraulic scour in simulated channels). A unique component of the sediment calibration was activation of the bank erosion module in LSPC (Section 3.9.3), which was parameterised along with HRUs to generate outputs that reasonably represent observed concentrations and yields. The parameter adjustments relied upon most heavily during the sediment calibration are listed in Table 4-27.

For sediment, an additional tier of monitoring outputs was leveraged for the calibration – estimates of sediment yield developed by Auckland Council (Holwerda, N., pers. comm. 2019) based on regression approaches, as described in the next subsection.

Table 4-27. Primary LSPC parameters leveraged during sediment calibration

Parameter Name	Description	Units
KRER	Coefficient in the soil detachment equation	unitless
JRER	Exponent in the soil detachment equation	unitless
KBER *	Coefficient for scour of the stream bank matrix soil	unitless
JBER *	Exponent for scour of the bank matrix soil	unitless
COVER	Fraction of land surface shielded from rainfall erosion	unitless
KSER	Coefficient in the detached sediment wash-off equation	unitless
JSER	Exponent in the detached sediment wash-off equation	unitless
KGER	Coefficient in the gully erosion equation	unitless
JGER	Exponent in the gully erosion equation	unitless
ACCSDP	Rate at which solids accumulate on the land surface	kg/ha/day

* Instream parameter set at model reaches

4.3.4.1.1 Comparison to Sediment Yields based on Regression

Estimates of sediment yield at stations around the Auckland region were available from Auckland Council (Holwerda, N., pers. comm. 2019and used to help parameterise sediment in the FWMT. The list of stations used for this effort are shown with the 'Sed Yield' dots in Table 4-15. The AC estimates are based on site-specific regressions equations that based upon TSS-flow rate relationships at each station (Curran-Cournane et al., 2013). The Auckland Council Research and Evaluation Unit provided an estimate for each year based on the flows during the year (Holwerda, N., pers. comm. 2019), and those estimates were combined for comparison to FWMT output. The years and number of years for which AC estimates were available for each station varied. Shown in Table 4-28 is a comparison of FWMT outputs to the AC estimates. The FWMT outputs were binned into two periods, with and without 2017, noting 2017 possessed unusually frequent high flow events. For some stations (Wairoa River, Kaipara River and Mangemangeroa), the FWMT-estimated sediment yield in 2017 was 5 to 10 times the annualised average of the 2012-2016 period. Blue and red shading in Table 4-28 indicates relative underprediction and overprediction, respectively compared to AC yield data for each station – for five stations the 2012-2016 FWMT average was less than the averaged AC estimate, while seven stations were greater – which indicates no systematic bias of the FWMT for estimating sediment yields.

For these comparisons, estimates from other sediment models in New Zealand were also available for CLUES, Loadest, WANSY and SedNetNZ (Haddadchi and Hicks, 2016). These are empirical annualised models that estimate annual averages sediment yield for a river outlet from a range of stationary predictors (e.g., simplified on LSPC). See Haddadchi and Hicks (2016) for more information and discussion of these models.

As shown in Figure 4-51 to Figure 4-62, to allow for comparison to empirical models and AC observed estimates, the output from FWMT was averaged across the calibration period. Review of Figure 4-51 to Figure 4-62 indicates limited likelihood of systematic bias of the FWMT for estimating sediment yields.

For the same stations linked to AC estimates and empirical models reported in Haddadchi and Hicks (2016), the relative contribution of wash off, gully erosion and streambank scour are reported in

Table 4-29. For FWMT, the gully erosion (simulated via HRUs) and explicit mainstem bank erosion (simulated via bank erosion module of the single modelled reach per sub-catchment) are combined into total bank erosion estimates. The remainder of sediment loading is simulated as originating from land via wash off in the FWMT Stage 1.

Table 4-28. Comparison of FWMT Sediment Yield and AC Regression Estimates

					Annual Average FWMT Specific Yield ($t/km^2/yr$)							
ID	Station	Drainage Area (km^2)	AC yield*	AC Yield Years	2012-2016	2012-2017	2012	2013	2014	2015	2016	2017
7505	Okura @ Weiti Forest	1.7	201	2012-2013	59	73	53	31	73	19	55	[illegible]
7506	Vaughn Stream @ Lower Weir	2.4	57	2012-2017	70	99	48	73	92	49	89	241
8304	Mangemangeroa	4.3	115	2012-2015	78	153	69	90	31	139	63	338
7502	Okura Creek @ Awanohi Rd	5.8	49	2012-2013	93	124	54	193	85	28	103	279
45702	Waiwhiu Stream @ Dome Shadow	8.8	70	2014	150	178	91	315	72	22	251	307
7202	Orewa @ Kowhai Ave	9.7	76	2012-2014	37	51	41	68	29	11	33	124
7955	Oratia @ Parrs Cross Road	17.1	80	2016	123	153	97	125	144	132	115	304
7907	Swanson Stream @ Woodside Reserve	23.4	82	2016	62	108	78	77	18	54	83	343
45415	Kaukapakapa @ Taylors	62.2	46	2012-2014	75	108	81	109	89	33	63	273
8516	Wairoa River @ Tourist Road	146.9	42	2012-2014	37	108	28	32	34	47	46	463
45311	Kaipara River @ Waimauku	155.6	23	2012-2014	54	95	44	86	50	43	48	300
45703	Hoteo River @ Gubbs	269.7	74	2012-2014, 2017	87	124	80	137	55	16	145	312

* Reported by AC, based on regression methods that leverage observed TSS concentrations and flow rates. Available for subset of years, often 2012-2014

Table 4-29. Relative Contribution of Sediment Sources at Select Stations based on FWMT Simulations 2012-2016

Station	Wash off sediment (%)	Gully Erosion (%)	Mainstem Bank Erosion (%)	Total Bank Erosion (%)
Okura @ Weiti Forest	57%	31%	12%	43%
Vaughn Stream @ Lower Weir	61%	39%	0%	39%
Mangemangeroa	58%	37%	5%	42%
Okura Creek @ Awanohi Rd	54%	40%	6%	46%
Waiwhiu Stream @ Dome Shadow	66%	30%	4%	34%
Orewa @ Kowhai Ave	50%	48%	2%	50%
Oratia @ Parrs Cross Road	46%	43%	11%	54%
Swanson Stream @ Woodside	51%	40%	8%	49%
Kaukapakapa @ Taylors	46%	41%	13%	54%
Wairoa River @ Tourist Road	50%	40%	10%	50%
Kaipara River @ Waimauku	46%	44%	10%	54%
Hoteo River @ Gubbs	48%	37%	15%	52%

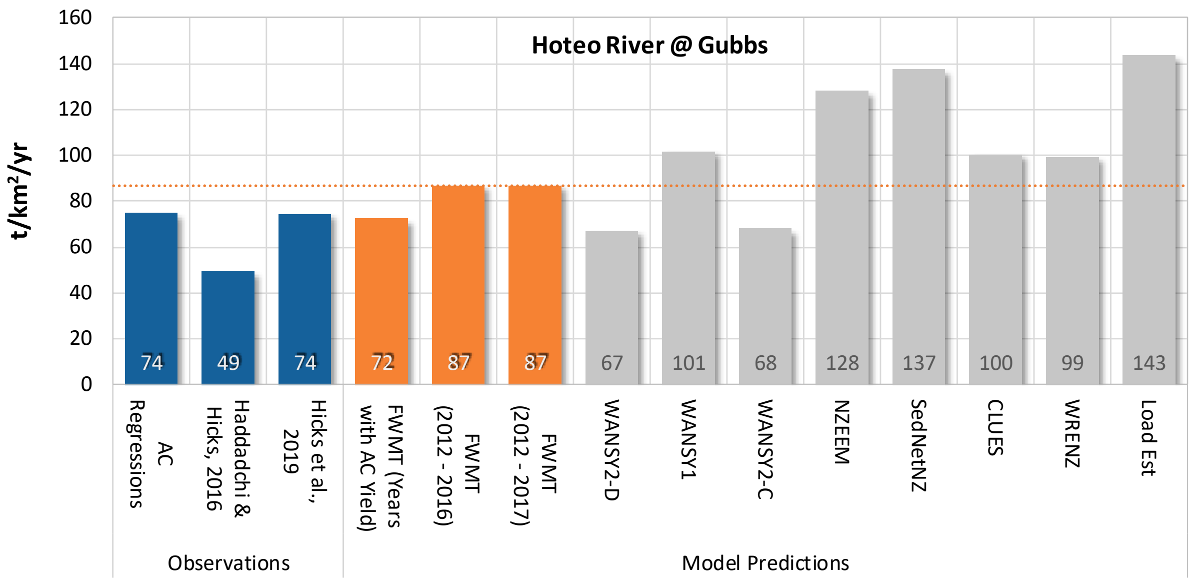


Figure 4-51. Sediment yield comparisons at Hoteo River @ Gubbs. Dashed line shows FWMT (2012-2016) yield

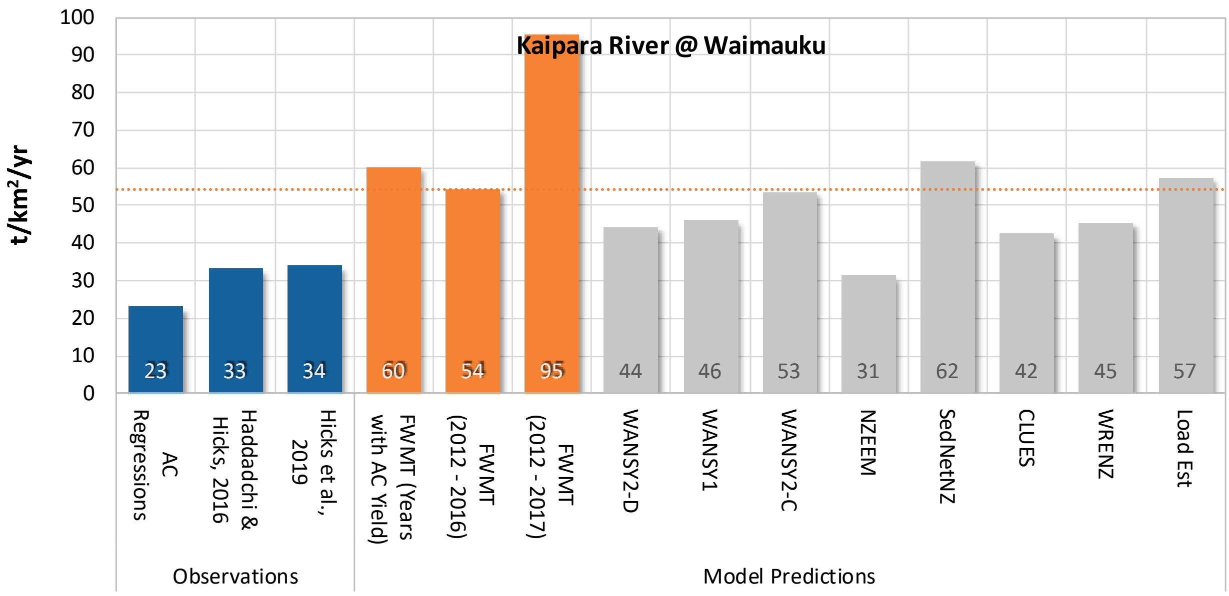


Figure 4-52. Sediment yield comparisons at Kaipara River @ Waimauku. Dashed line shows FWMT (2012-2016) yield

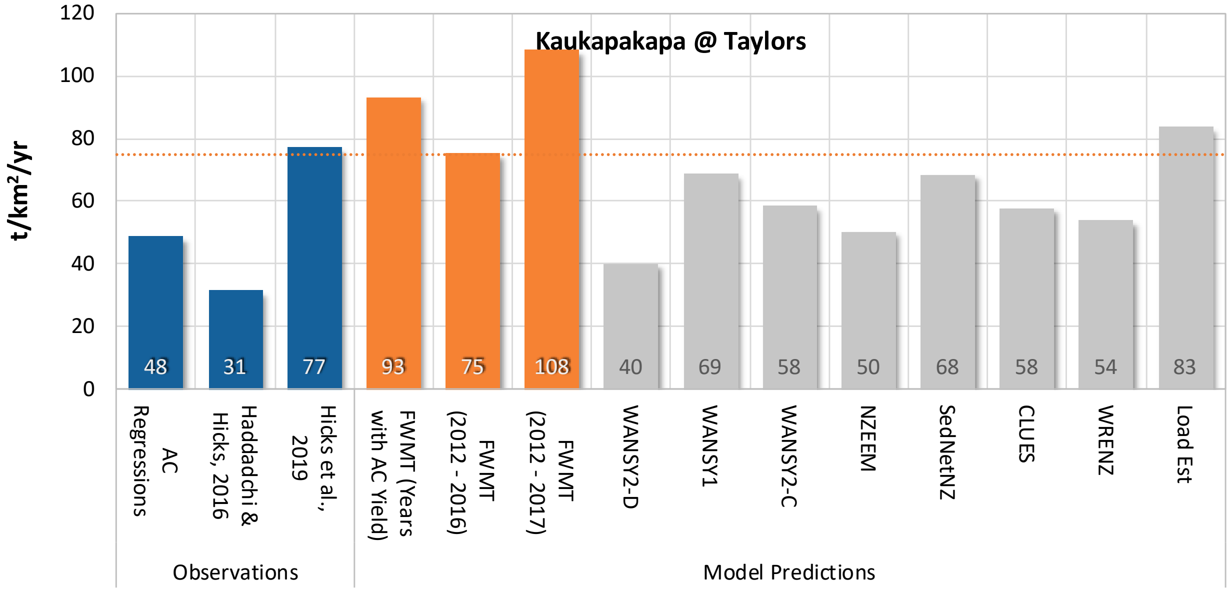


Figure 4-53. Sediment yield comparisons at Kaukapakapa @ Taylors. Dashed line shows FWMT (2012-2016) yield

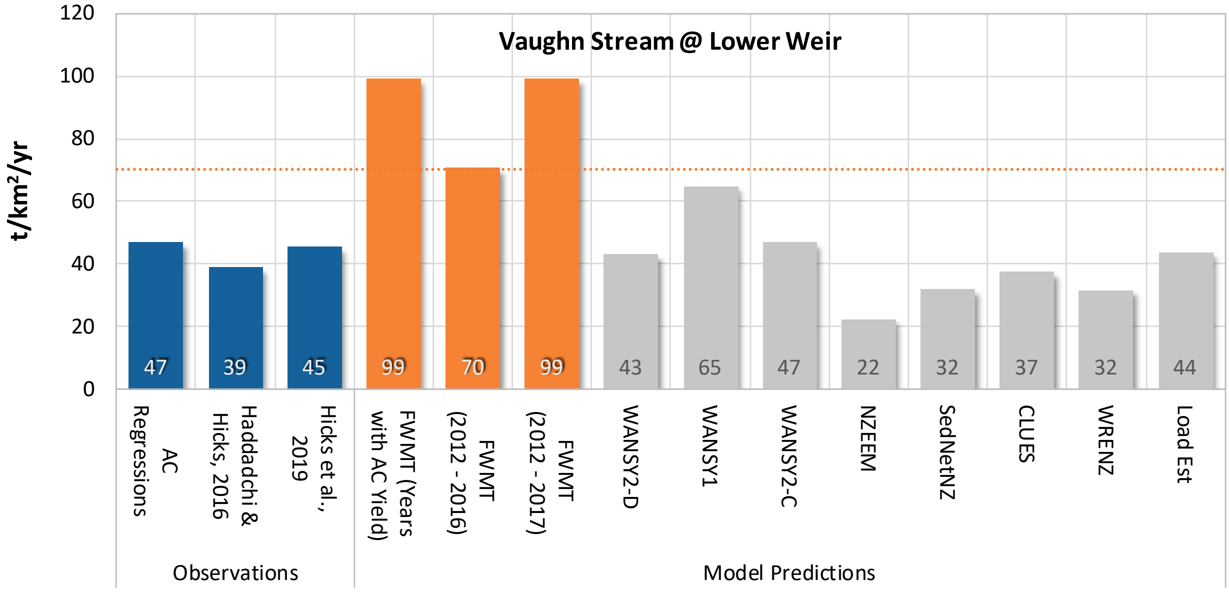


Figure 4-54. Sediment yield comparisons at Vaughn Stream @ Lower Weir. Dashed line shows FWMT (2012-2016) yield

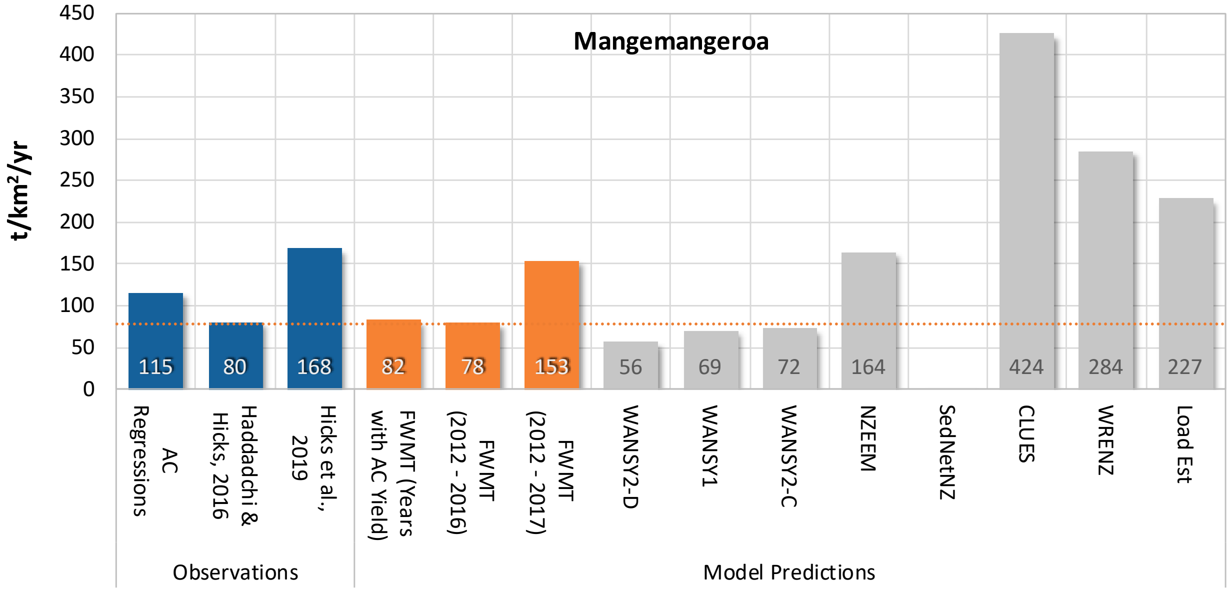


Figure 4-55. Sediment yield comparisons at Mangemangeroa. Dashed line shows FWMT (2012-2016) yield

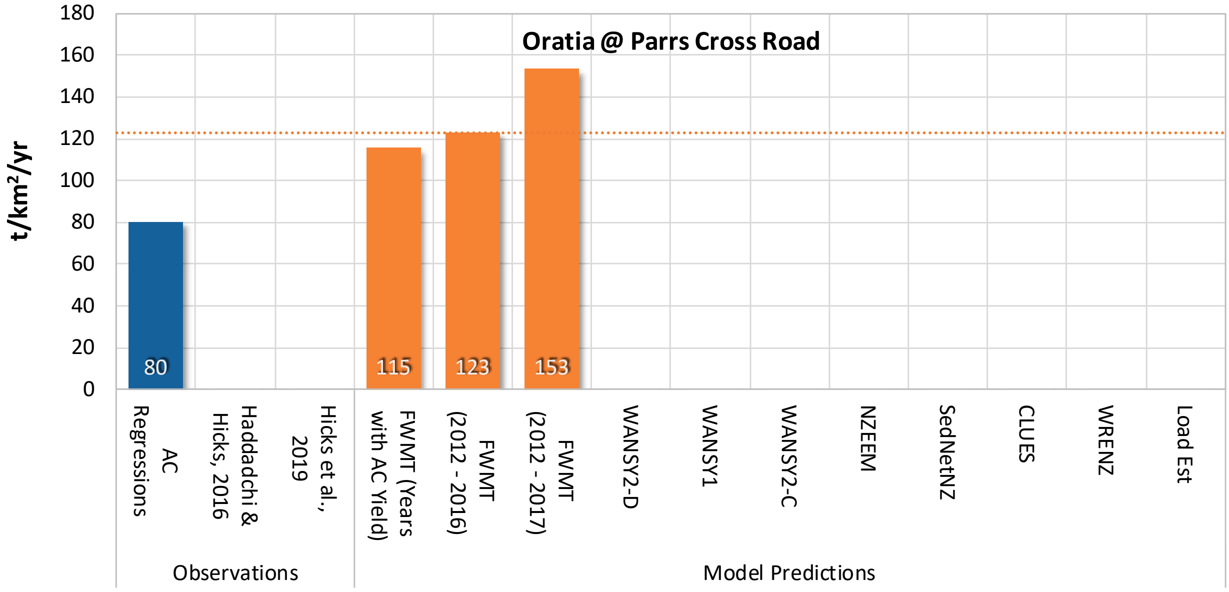


Figure 4-56. Sediment yield comparisons at Oratia @ Parrs Cross Road. Dashed line shows FWMT (2012-2016) yield

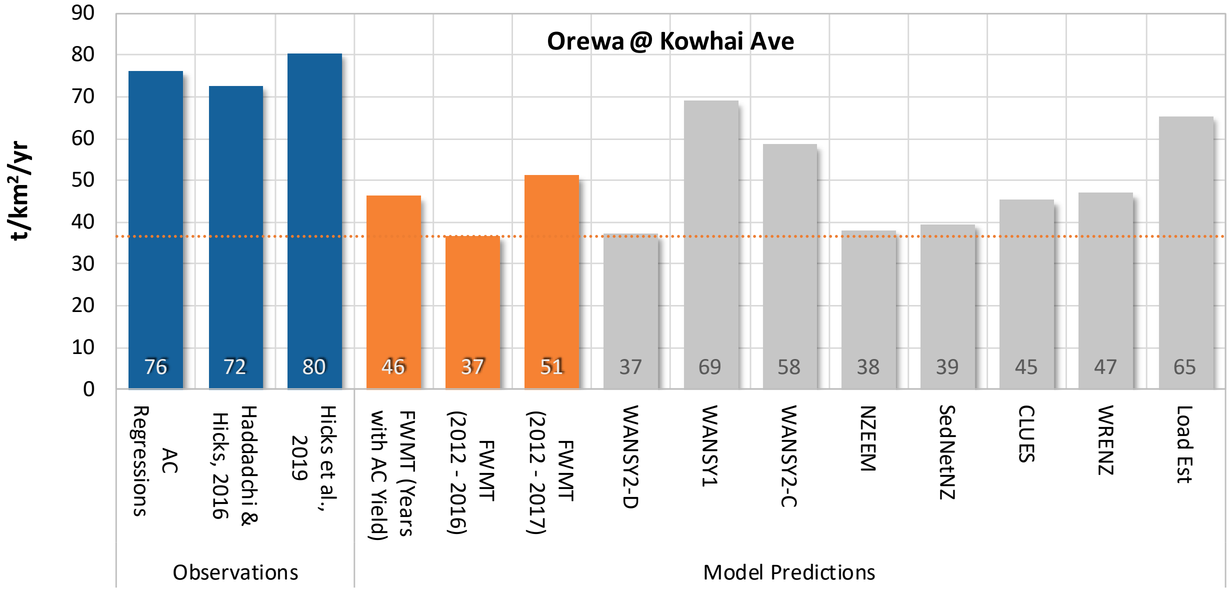


Figure 4-57. Sediment yield comparisons at Orewa @ Kowhai Ave. Dashed line shows FWMT (2012-2016) yield

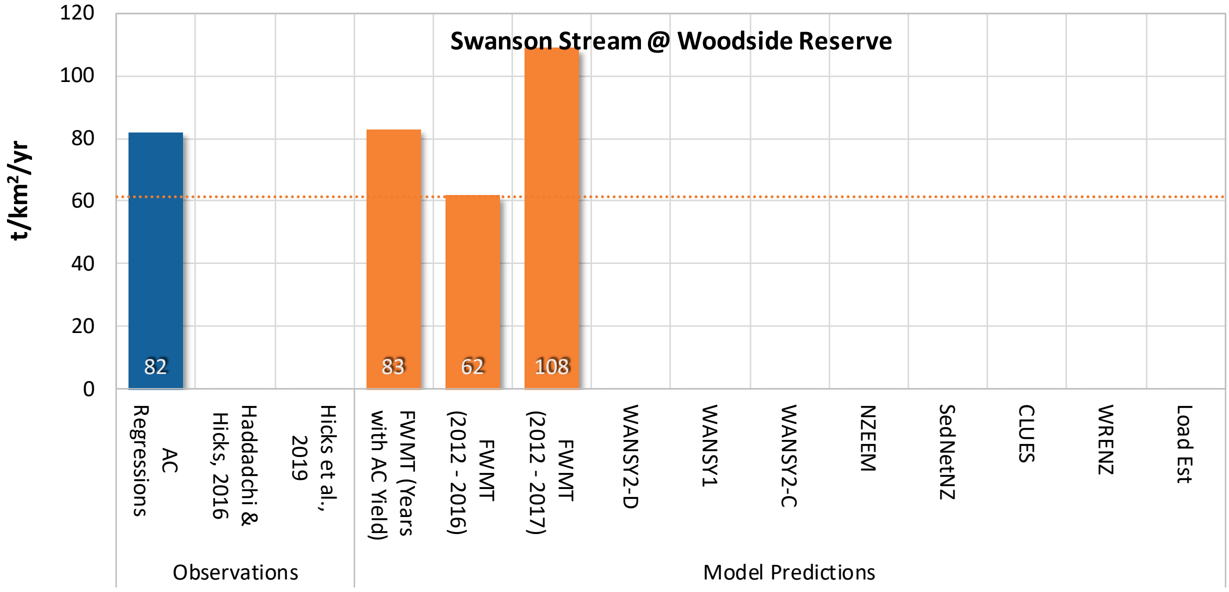


Figure 4-58. Sediment yield comparisons at Swanson Stream @ Woodside Reserve. Dashed line shows FWMT (2012-2016) yield

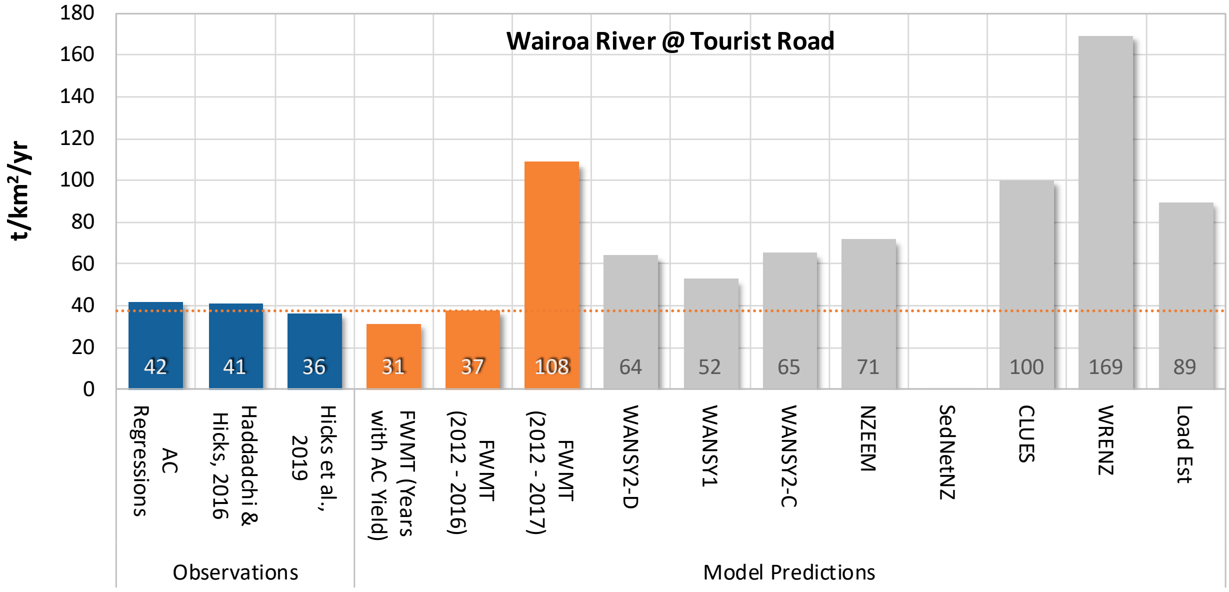


Figure 4-59. Sediment yield comparisons at Wairoa River @ Tourist Road. Dashed line shows FWMT (2012-2016) yield

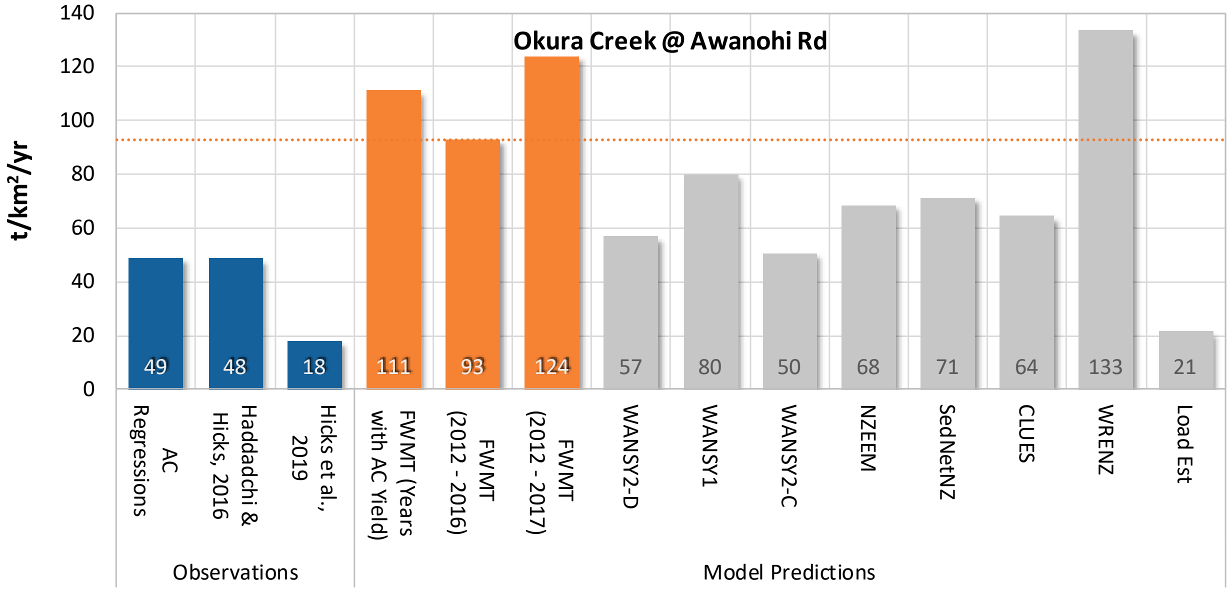


Figure 4-60. Sediment yield comparisons at Okura Creek @ Awanohi Rd. Dashed line shows FWMT (2012-2016) yield

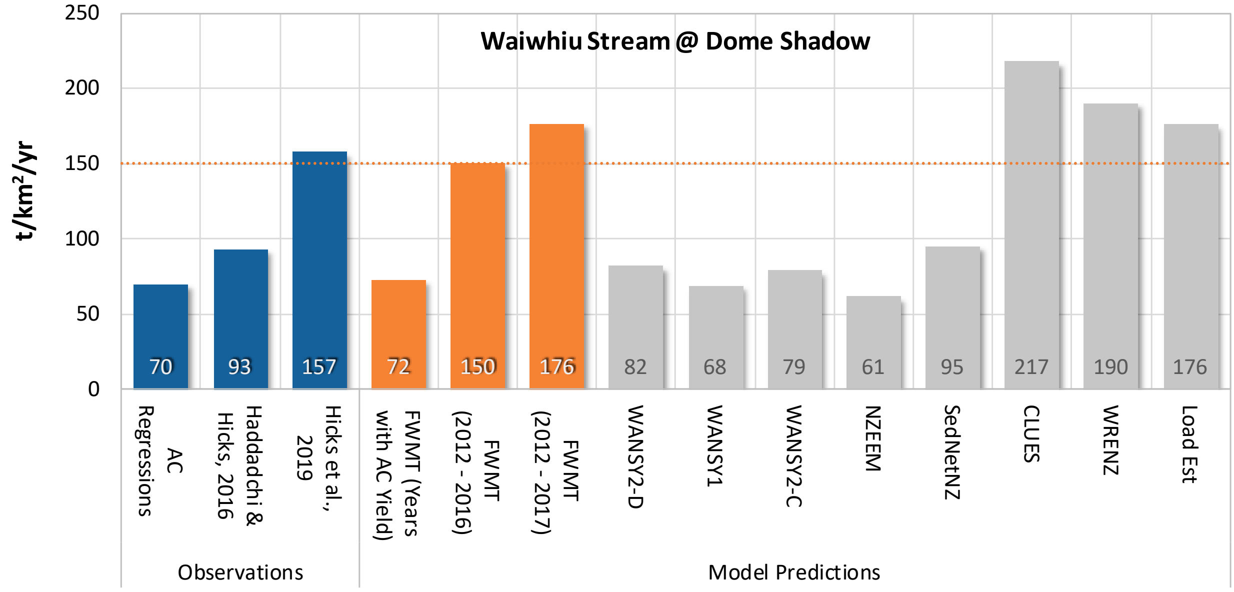


Figure 4-61. Sediment yield comparisons at Waiwhiu Stream @ Dome Shadow. Dashed line shows FWMT (2012-2016) yield

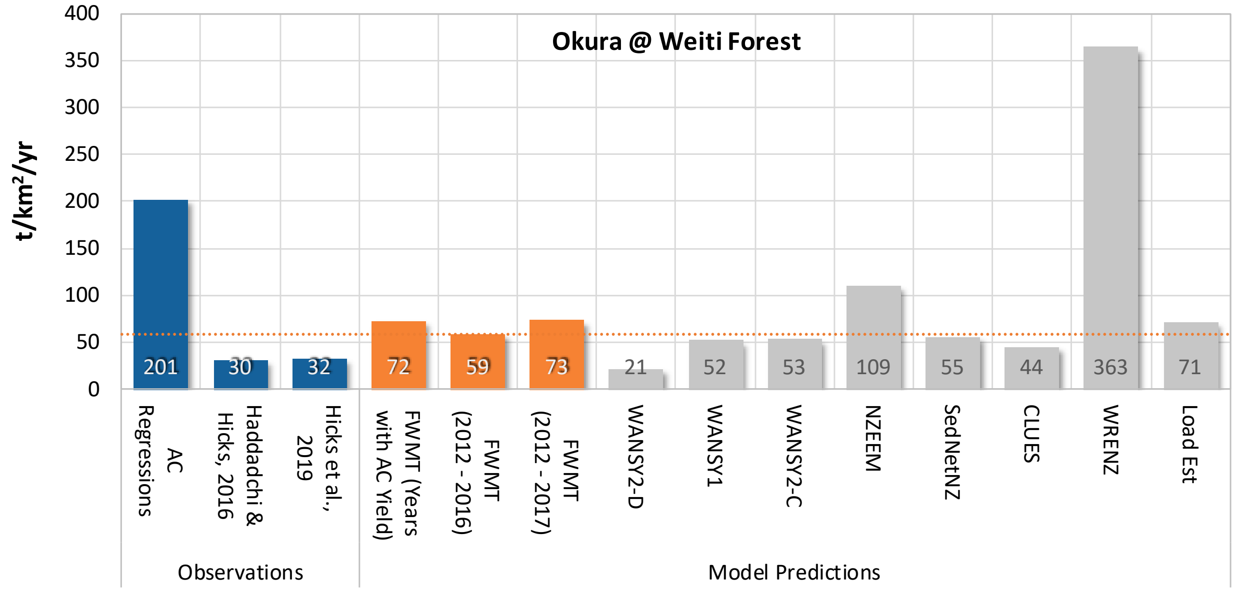


Figure 4-62. Sediment yield comparisons at Okura @ Weiti Forest. Dashed line shows FWMT (2012-2016) yield

4.3.4.1.2 Performance Evaluation based on Instream Metrics

The following subsections present the results of water quality calibration for performance metrics and flow or seasonal bins. For each simulated contaminant, the regionwide summary is presented as per the hydrologic performance assessment (e.g., station-by-station performance table and regional summary). For water quality, performance assessment is presented for both daily flow-weighted average concentrations and daily loading rates.

For sediment, the performance of the FWMT as an accounting system is presented in:

- Table 4-30: reports the station-by-station accuracy based on flow-weighted daily average concentration for different seasons (left performance columns) and flow conditions (right performance columns) for r^2, PBIAS and NSE. White cells indicate insufficient samples in the bin to evaluate the metric (n<5 samples). Stations labelled N/A for Tier do not have a co-located flow gauge.
- Table 4-31: reports the station-by-station performance assessment based on daily loading rate (cumulative sum of 15-min flow weighted concentrations for daily period) for different seasons (left performance columns) and flow conditions (right performance columns) for r^2, PBIAS and NSE.
- Figure 4-63: summarises the per cent of stations achieving different performance categories for flow-weighted daily average concentration across seasonal and flow-based conditions for r^2, PBIAS and NSE.
- Figure 4-64: summarises the per cent of stations achieving different performance categories for daily loading rate (cumulative sum of 15-min concentration by flow for daily period) across seasonal and flow-based conditions for r^2, PBIAS and NSE.
- Figure 4-65: presents the range and median of performance criteria results for calibration stations associated with a specific, dominant land use, as well as validation stations. The figure presents results for both concentrations and loads. Only stations with both observed water quality and flow data are presented for loading rate results.

The sediment performance panels are presented for each of the 36 AC SoE stations in Appendix F1. The stations are ordered in the appendices identical to Table 4-30.

Table 4-30. TSS (concentration) FWMT Prediction Performance at AC SoE Stations

Tier	Water Quality Monitoring Locations	Drainage Area(km2)	Performance Metrics (Seasonal)															Performance Metrics (Flow Regime)														
			PBIAS					r-Squared					Nash-Sutcliffe E					PBIAS					r-Squared					Nash-Sutcliffe E				
			All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow
Tier 1	Wairoa River @ Tourist Road	149	+	+	+	-	-											+	+	+	+	+										
Tier 2	Opanuku Stream @ Candia Road Bridge	15.3	-	-	-	-	-											-	-	-	-	-										
	Oteha River @ Days Bridge	12.2	-	+	-	-	-											-	-	-	-	+										
	Lucas @ Gills Road	6.1	-	-	-	-	-											-	-	-	-	-										
	Ngakoroa Stream @ Mill Rd	4.8	-	+	+	+	-											-	-	-	+	+										
	West Hoe @ Halls	0.5	+	+	+	+	+											+	+	+	+	+										
Tier 3	Rangitopuni River @ Walkers	81.7	+															+														
	Kaukapakapa @ Taylors	62.2	-	-	+	+	+											-	-	-	+	-										
	Puhinui @ Drop Structure	12.6	-	-	-	-	-											-	-	-	-	-										
	Oakley Creek at Richardson Road	5.9	-															-			-	-										
Tier 4	Vaughn Stream @ Lower Weir	2.4	-	-	-	+	+											-	-	-	+	+										
Tier 5	Oratia @ Parrs Cross Road	17.1	+															+			+	-										
	Okura Creek @ Awanohi Rd	5.8	+	+		+	+											+	+	+	+	+										
N/A	Mahurangi @ Warkworth Water Treatment Plant	50.1	-	-	+	-	-											-	-	-	+	+										
	Makarau @ Railway	49.1	-	-	+	+	-											-	-	-	+	+										
	Papakura Stream @ Porchester Road Bridge	45.1	-	+	-	-	-											-	-	-	-	+										
	Kumeu River At Weza Lane	44.9	-	-	+	-	+											-	-	-	+	+										
	Waiwera Stream @ Upper Waiwera Road	30.2	-	-	+	+	+											-	-	-	+	-										
	Papakura @ Alfriston/Ardmore Rd	23.3	-	+	+	+	-											-	-	-	-	+										
	Waitangi @ Waitangi Falls Bridge.	19.3	-	-	-	-	-											-	-	-	-	-										
	Otara Stream @ Kennel Hill	18.3	-	-	+	-	-											-	-	-	+	-										
	Matakana @ Wenzlicks Farm	13.4	-	+	-	-	+											-	-	-	-	+										
	Oakley Creek @ Carrington.	11.9	-	-	-	-	-											-	-	-	-	-										
	Cascades Stream @ Confluence	10.8	-	-	-	+	-											-	-	-	+	-										
	Otara @ East Tamaki Rd	9.4	-	-	-	-	+											-	-	-	-	-										
	Whangamaire @ Woodhouse Road	8	+	+	+	+	+											+	+	+	+	+										
	Pakuranga @ Botany Rd	6.6	-	-	-	-	-											-	-	-	+	-										
	Riverhead @ Ararimu Valley Road	4.6	-	-	-	+	-											-	-	-	+	+										
	Omaru @ Maybury Street	3.5	-	-	-	-	-											-	-	-	+	-										
	Avondale Stream @ Shadbolt Park	3	-	-	+	-	-											-	-	-	-	-										
	Pakuranga @ Greenmount Drive	2.4	-	-	-	-	-											-	-	-	+	-										
	Wairoa Trib @ Caitchons Rd	2.2	+	+	+	+	-											+	-	-	+	+										
	Otaki @ Middlemore Crescent	1	-	-	-	-	-											-	-	-	-	+										
	Nukumea @ Upper Site	1	+	+	+	+	+											+	+	+	+	+										
	Onetangi @ Waiheke Rd	0.7	+	+	+	-	+											+	+	-	+	+										
	Cascades @ Whakanewha	0.6	+	+	+	+	+											+	-	-	+	+										

Grey shaded stations used modeled flow data for load calculations

Very Good | Good | Satisfactory | Unsatisfactory

\+ Overpredicts | - Underpredicts

Note: Tier refers to hydrologic data quality tier

Table 4-31. TSS (load) FWMT Prediction Performance at AC SoE Stations

	Water Quality Monitoring Locations		Performance Metrics (Seasonal)															Performance Metrics (Flow Regime)														
			PBIAS					r-Squared					Nash-Sutcliffe E					PBIAS					r-Squared					Nash-Sutcliffe E				
			All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow
Tier 1	Wairoa River @ Tourist Road	149	+	+	+	-	-											+	+	-	+	+										
Tier 2	Opanuku Stream @ Candia Road Bridge	15.3	-	-	-	+	-											-	-	-	-	-										
	Oteha River @ Days Bridge	12.2	-	+	-	-	-											-	-	-	-	+										
	Lucas @ Gills Road	6.1	-	-	-	-	-											-	-	-	-	-										
	Ngakoroa Stream @ Mill Rd	4.8	-	+	-	-	-											-	-	-	-	+										
	West Hoe @ Halls	0.5	+	+	+	+	+											+	+	+	+	+										
Tier 3	Rangitopuni River @ Walkers	81.7	+															+														
	Kaukapakapa @ Taylors	62.2	-	-	+	+	-											-	-	-	+	-										
	Puhinui @ Drop Structure	12.6	-	-	-	-	-											-	-	-	-	-										
	Oakley Creek at Richardson Road	5.9	-															-			-	-										
Tier 4	Vaughn Stream @ Lower Weir	2.4	-	-	-	+	-											-	-	-	+	+										
Tier 5	Oratia @ Parrs Cross Road	17.1	+															+			+	-										
	Okura Creek @ Awanohi Rd	5.8	+	+		+	+											+	+	+	-	+										
N/A	Mahurangi @ Warkworth Water Treatment Plan	50.1	-	-	+	+	-											-	-	-	+	-										
	Makarau @ Railway	49.1	-	-	+	+	-											-	-	-	+	-										
	Papakura Stream @ Porchester Road Bridge	45.1	-	+	+	+	-											-	-	-	-	-										
	Kumeu River At Weza Lane	44.9	-	-	+	-	+											-	-	-	+	+										
	Waiwera Stream @ Upper Waiwera Road	30.2	-	-	+	+	-											-	-	-	+	-										
	Papakura @ Alfriston/Ardmore Rd	23.3	-	+	+	+	-											-	-	-	+	-										
	Waitangi @ Waitangi Falls Bridge.	19.3	-	-	-	-	-											-	-	-	+	-										
	Otara Stream @ Kennel Hill	18.3	-	-	+	-	-											-	-	-	-	-										
	Matakana @ Wenzlicks Farm	13.4	-	-	-	+	+											-	-	-	+	+										
	Oakley Creek @ Carrington.	11.9	-	-	-	-	-											-	-	-	-	-										
	Cascades Stream @ Confluence	10.8	-	-	-	+	-											-	-	-	+	-										
	Otara @ East Tamaki Rd	9.4	-	-	-	-	+											-	-	-	-	-										
	Whangamaire @ Woodhouse Road	8	+	+	+	+	+											+	+	+	+	+										
	Pakuranga @ Botany Rd	6.6	-	-	-	-	-											-	-	-	-	-										
	Riverhead @ Ararimu Valley Road	4.6	-	-	-	+	-											-	-	-	+	-										
	Omaru @ Maybury Street	3.5	-	-	-	-	-											-	-	-	-	-										
	Avondale Stream @ Shadbolt Park	3	-	-	+	-	-											-	-	-	-	-										
	Pakuranga @ Greenmount Drive	2.4	-	-	-	-	-											-	-	-	-	+										
	Wairoa Trib @ Caitchons Rd	2.2	-	+	+	+	-											-	-	-	+	-										
	Otaki @ Middlemore Crescent	1	+	-	-	+	+											+	+	-	-	+										
	Nukumea @ Upper Site	1	+	+	+	+	+											+	+	+	+	+										
	Onetangi @ Waiheke Rd	0.7	+	+	+	+	+											+	+	+	+	+										
	Cascades @ Whakanewha	0.6	-	+	+	+	-											-	-	-	+	+										

Grey shaded stations used modeled flow data for load calculations

Very Good | Good | Satisfactory | Unsatisfactory

+ Overpredicts | - Underpredicts

Note: Tier refers to hydrologic data quality tier

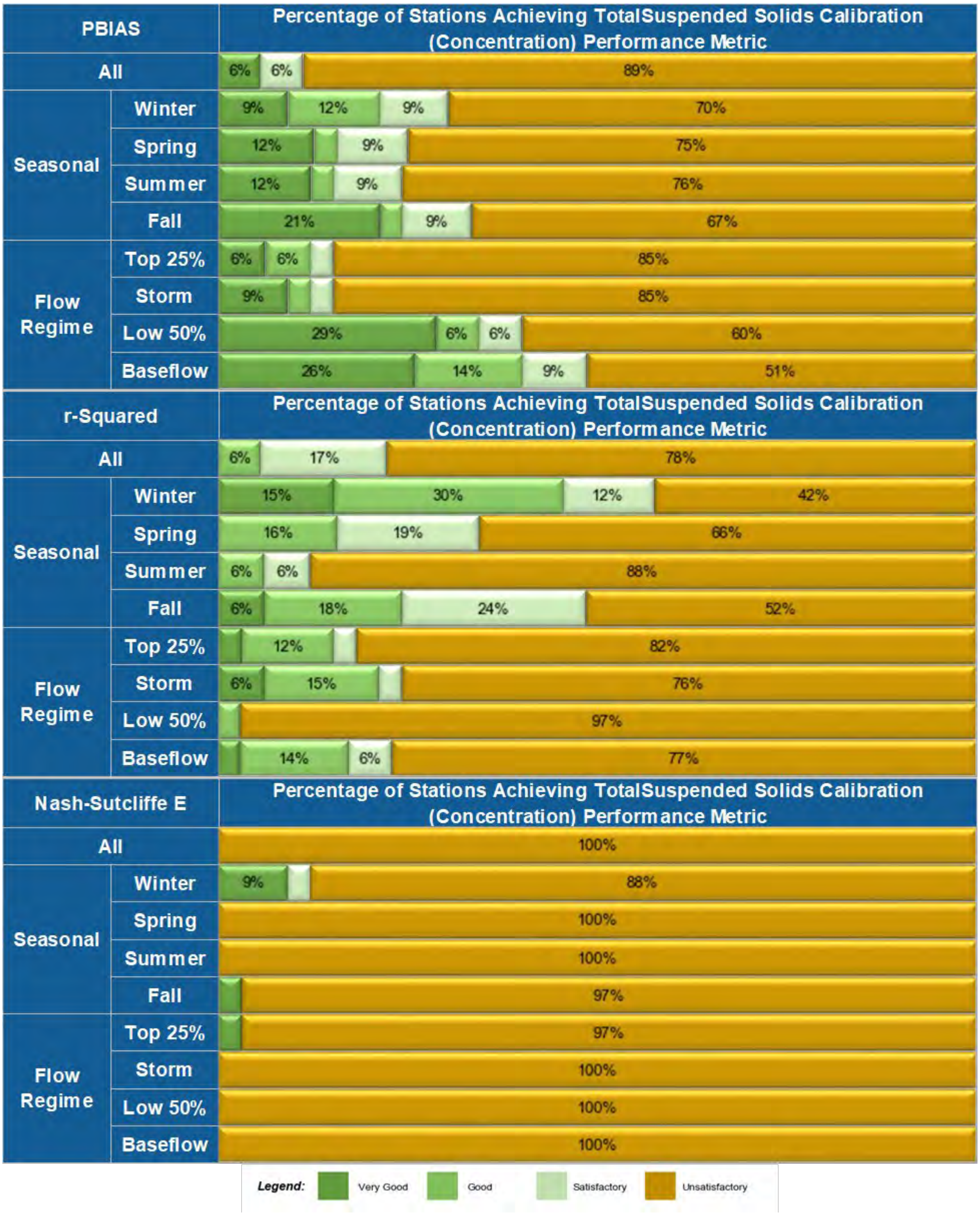


Figure 4-63. Total suspended solids (concentration) performance metrics for 36 Calibration and Validation SoE Stations (including 10 stations with co-located flow records)

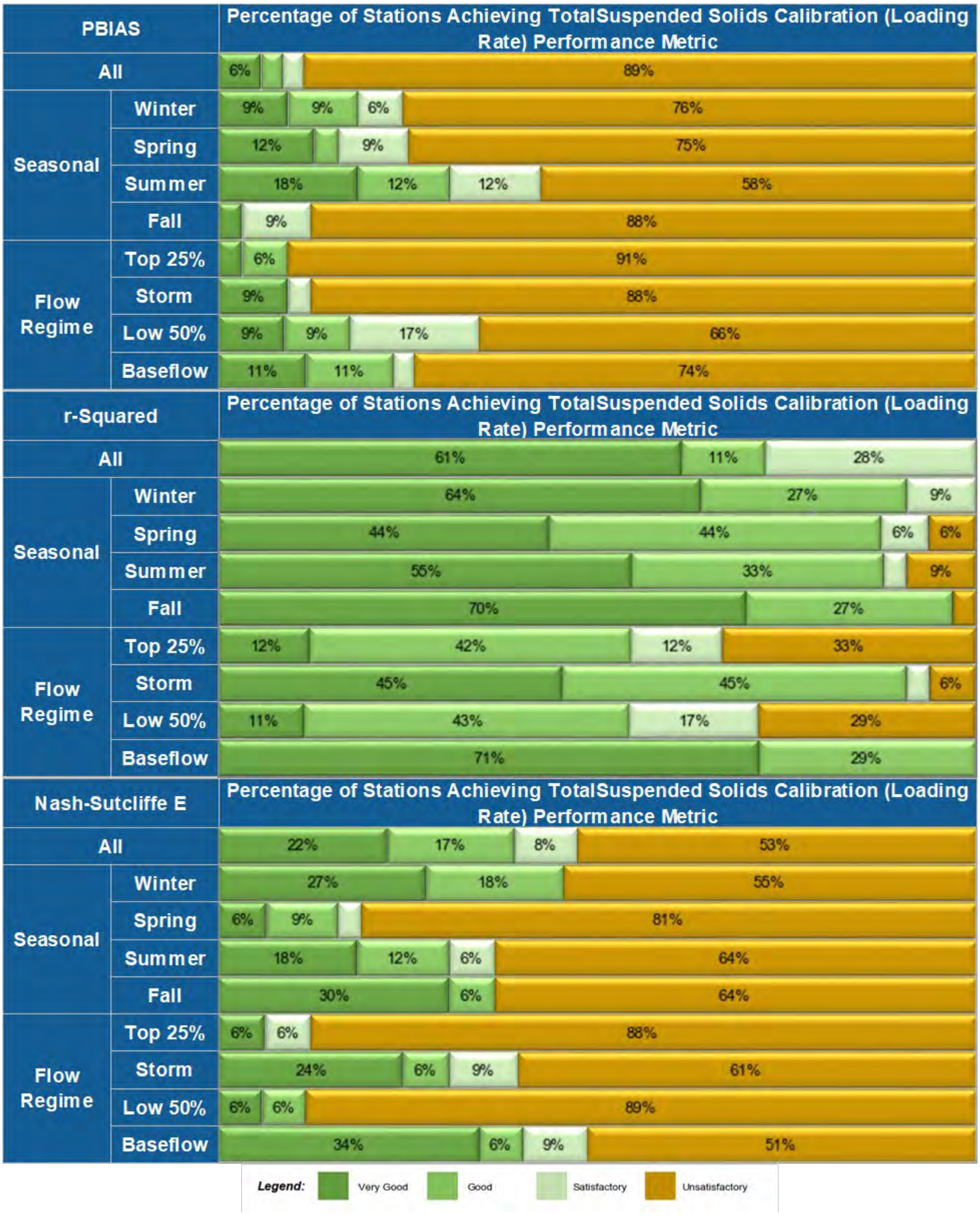
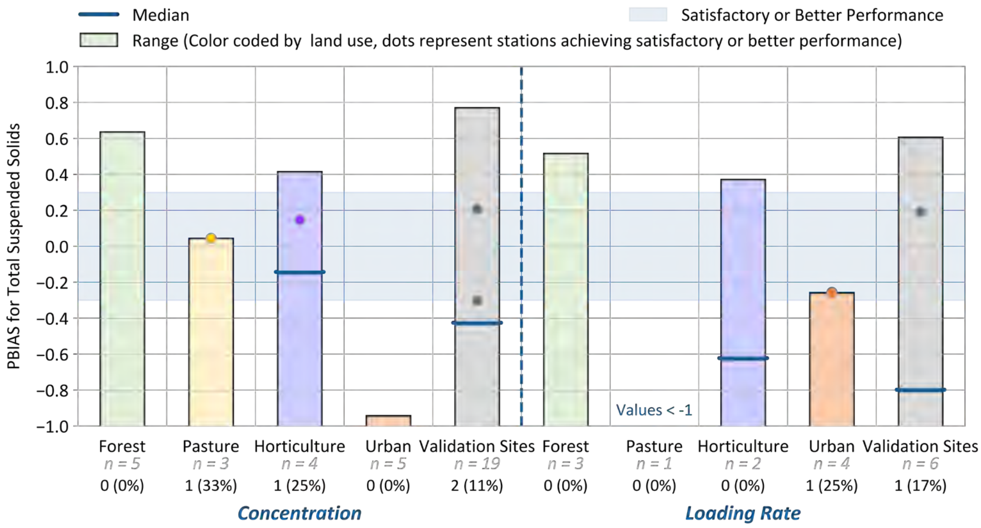
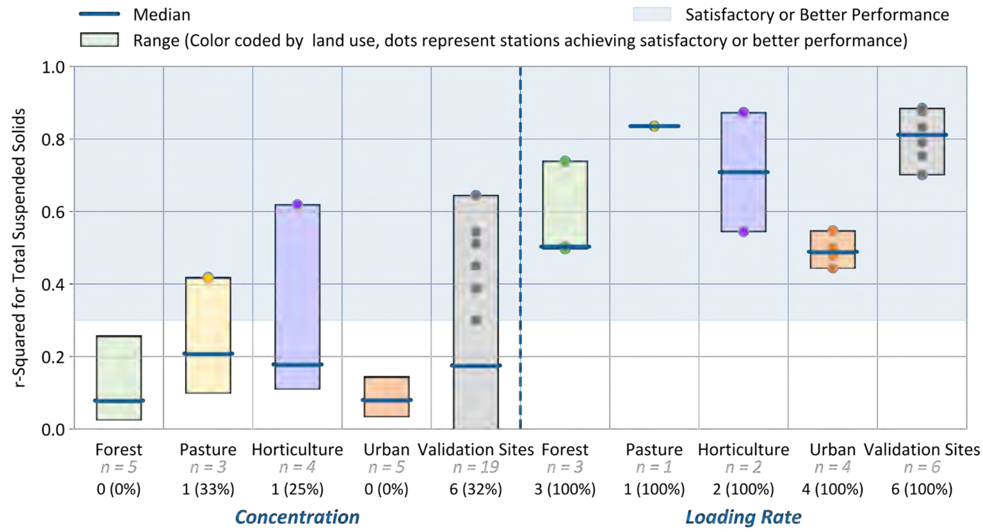


Figure 4-64. Total suspended solids (load) performance metrics for 36 Calibration and Validation SoE Stations (including 10 stations with co-located flow records)





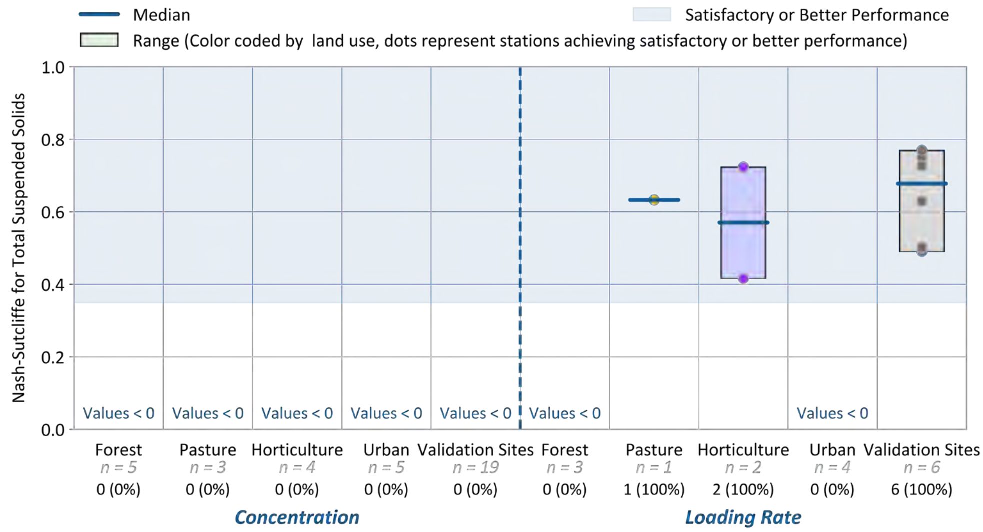


Figure 4-65. Concentrations and load performance metrics for TSS by land use for the entire calibration period (2012-2016)

4.3.4.2 Total Nitrogen

This subsection presents the total nitrogen calibration outcomes. Nitrogen was simulated with GQUAL and RQUAL modules to allow for prediction of total oxidised and ammoniacal nitrogen inclusive of instream transformations. The parameters relied upon most for total nitrogen calibration (in GQUAL) are presented in Table 4-32.

The total nitrogen prediction performance of the FWMT is presented as the following:

- Table 4-33: reports the station-by-station performance assessment based on flow-weighted average daily concentration for different seasons (left performance columns) and flow conditions (right performance columns) for r^2, PBIAS and NSE. White cells indicate insufficient samples in the bin to evaluate the metric (n<5 samples). Stations labelled N/A for Tier do not have a co-located flow gauge.
- Table 4-34: reports the station-by-station performance assessment based on daily loading rate (cumulative sum of 15-min concentration by flow for daily period) for different seasons (left performance columns) and flow conditions (right performance columns) for r^2, PBIAS and NSE.
- Figure 4-66: summarises the per cent of stations achieving different performance categories for flow-weighted average daily concentration across seasonal and flow-based conditions for r^2, PBIAS and NSE.
- Figure 4-67: summarises the per cent of stations achieving different performance categories for daily loading rate (cumulative sum of 15-min concentration by flow for daily period) across seasonal and flow-based conditions for r^2, PBIAS and NSE.
- Figure 4-69: presents the range and median of performance criteria results for calibration stations associated with a specific, dominant land use, as well as validation stations. The figure presents results for both concentrations and loads. Only stations with both observed water quality and flow data are presented for loading rate results.

The total nitrogen performance panels are presented for each of the 36 stations in Appendix F2. The stations are ordered in the appendices identical to Table 4-33.

Table 4-32. Primary parameters leveraged during total nitrogen calibration

Parameter Name	Description	Units
ACQOP (TN)	Rate at which nitrogen accumulates on the land surface	kg/ha/day
SQOLIM (TN)	Maximum storage of nitrogen on surface	kg/ha
IOQC(TN)	Interflow concentration of TN	mg/l
AOQC(TN)	Active groundwater concentration of TN	mg/l

Table 4-33. Total nitrogen (concentration) FWMT Prediction Performance at AC SoE Stations

Tier	Water Quality Monitoring Locations	Drainage Area(km2)	Performance Metrics (Seasonal)															Performance Metrics (Flow Regime)														
			PBIAS					r-Squared					Nash-Sutcliffe E					PBIAS					r-Squared					Nash-Sutcliffe E				
			All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow
Tier 1	Wairoa River @ Tourist Road	149	+	+	+	+	-											+	-	-	+	+										
Tier 2	Opanuku Stream @ Candia Road Bridge	15.3	-	-	-	+	-											-	-	-	-	-										
	Oteha River @ Days Bridge	12.2	-	+	-	-	-											-	-	-	+	+										
	Lucas @ Gills Road	6.1	-	+	-	-	-											-	-	-	-	+										
	Ngakoroa Stream @ Mill Rd	4.8	+	+	+	+	+											+	-	+	+	+										
	West Hoe @ Halls	0.5	+	-	+	+	-											+	+	-	-	+										
Tier 3	Rangitopuni River @ Walkers	81.7	+	+	+	+	-											+	-	-	+	+										
	Kaukapakapa @ Taylors	62.2	-	-	+	+	-											-	-	-	+	+										
	Puhinui @ Drop Structure	12.6	-	+	-	-	-											-	+	-	-	+										
	Oakley Creek at Richardson Road	5.9	+															+			-	+										
Tier 4	Vaughn Stream @ Lower Weir	2.4	+	+	+	-	+											+	+	-	+	+										
Tier 5	Oratia @ Parrs Cross Road	17.1	-															-			-	-										
	Okura Creek @ Awanohi Rd	5.8	+	+		+	+											+	+	+	+	+										
N/A	Mahurangi @ Warkworth Water Treatment Plant	50.1	-	-	+	+	-											-	-	-	+	+										
	Makarau @ Railway	49.1	-	-	+	+	-											-	-	-	+	+										
	Papakura Stream @ Porchester Road Bridge	45.1	-	+	-	+	-											-	-	-	+	+										
	Kumeu River At Weza Lane	44.9	-	-	+	-	-											-	-	-	+	+										
	Waiwera Stream @ Upper Waiwera Road	30.2	+	-	+	+	+											+	-	-	+	+										
	Papakura @ Alfriston/Ardmore Rd	23.3	+	+	+	+	-											+	-	-	+	+										
	Waitangi @ Waitangi Falls Bridge.	19.3	+	+	+	+	-											+	+	-	+	+										
	Otara Stream @ Kennel Hill	18.3	+	+	+	-	+											+	+	-	-	+										
	Matakana @ Wenzlicks Farm	13.4	-	-	-	+	-											-	-	-	-	+										
	Oakley Creek @ Carrington.	11.9	+	+	+	-	-											+	+	-	+	+										
	Cascades Stream @ Confluence	10.8	+	-	+	+	+											+	-	-	+	+										
	Otara @ East Tamaki Rd	9.4	+	+	+	+	+											+	+	+	+	+										
	Whangamaire @ Woodhouse Road	8	+	-	+	+	+											+	-	+	+	+										
	Pakuranga @ Botany Rd	6.6	+	+	+	+	+											+	+	+	+	+										
	Riverhead @ Ararimu Valley Road	4.6	+	-	+	+	+											+	-	-	+	+										
	Omaru @ Maybury Street	3.5	+	+	+	+	+											+	-	-	+	+										
	Avondale Stream @ Shadbolt Park	3	+	+	+	-	+											+	+	-	+	+										
	Pakuranga @ Greenmount Drive	2.4	+	+	+	+	+											+	+	+	+	+										
	Wairoa Trib @ Caitchons Rd	2.2	-	-	-	+	-											-	-	-	+	+										
	Otaki @ Middlemore Crescent	1	+	+	+	+	+											+	+	+	+	+										
	Nukumea @ Upper Site	1	-	-	-	-	-											-	-	-	-	-										
	Onetangi @ Waiheke Rd	0.7	+	+	+	-	+											+	+	-	+	+										
	Cascades @ Whakanewha	0.6	+	+	+	+	+											+	+	+	+	+										

Grey shaded stations used modeled flow data for load calculations

Very Good | Good | Satisfactory | Unsatisfactory

\+ Overpredicts | - Underpredicts

Note: Tier refers to hydrologic data quality tier

Table 4-34. Total nitrogen (load) FWMT Prediction Performance at AC SoE Stations

	Water Quality Monitoring Locations		Performance Metrics (Seasonal)															Performance Metrics (Flow Regime)														
			PBIAS					r-Squared					Nash-Sutcliffe					PBIAS					r-Squared					Nash-Sutcliffe				
			All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow
Tier 1	Wairoa River @ Tourist Road	149	-	-	+	-	-											-	-	-	-	+										
Tier 2	Opanuku Stream @ Candia Road Bridge	15.3	-	-	-	+	-											-	-	-	-	-										
	Oteha River @ Days Bridge	12.2	-	+	-	-	-											-	-	-	-	+										
	Lucas @ Gills Road	6.1	+	+	+	-	-											+	+	-	-	+										
	Ngakoroa Stream @ Mill Rd	4.8	-	+	+	+	-											-	-	-	-	+										
	West Hoe @ Halls	0.5	+	+	+	+	+											+	+	+	+	+										
Tier 3	Rangitopuni River @ Walkers	81.7	-	+	-	+	-											-	-	-	+	-										
	Kaukapakapa @ Taylors	62.2	-	-	-	+	-											-	-	-	-	-										
	Puhinui @ Drop Structure	12.6	-	+	-	-	-											-	-	-	-	+										
	Oakley Creek at Richardson Road	5.9	+															+			-	+										
Tier 4	Vaughn Stream @ Lower Weir	2.4	+	+	-	+	+											+	+	+	+	+										
Tier 5	Oratia @ Parrs Cross Road	17.1	-															-			-	-										
	Okura Creek @ Awanohi Rd	5.8	+	+		+	+											+	+	+	-	+										
N/A	Mahurangi @ Warkworth Water Treatment Plan	50.1	-	-	+	+	-											-	-	-	+	-										
	Makarau @ Railway	49.1	-	-	-	+	-											-	-	-	+	+										
	Papakura Stream @ Porchester Road Bridge	45.1	-	+	-	+	-											-	-	-	+	+										
	Kumeu River At Weza Lane	44.9	-	-	+	-	-											-	-	-	+	+										
	Waiwera Stream @ Upper Waiwera Road	30.2	-	-	+	+	+											-	-	-	+	+										
	Papakura @ Alfriston/Ardmore Rd	23.3	-	+	+	+	-											-	-	-	+	+										
	Waitangi @ Waitangi Falls Bridge.	19.3	+	+	+	+	-											+	+	-	+	+										
	Otara Stream @ Kennel Hill	18.3	+	+	+	-	+											+	+	-	-	+										
	Matakana @ Wenzlicks Farm	13.4	-	-	-	+	-											-	-	-	-	+										
	Oakley Creek @ Carrington.	11.9	+	+	-	-	-											+	+	-	-	+										
	Cascades Stream @ Confluence	10.8	-	-	+	+	+											-	-	-	+	-										
	Otara @ East Tamaki Rd	9.4	+	+	+	+	+											+	+	+	+	+										
	Whangamaire @ Woodhouse Road	8	-	-	-	-	-											-	-	-	+	-										
	Pakuranga @ Botany Rd	6.6	+	+	+	+	+											+	+	+	+	+										
	Riverhead @ Ararimu Valley Road	4.6	-	-	+	+	+											-	-	-	+	+										
	Omaru @ Maybury Street	3.5	-	+	+	-	-											-	-	-	+	+										
	Avondale Stream @ Shadbolt Park	3	+	+	+	-	+											+	+	+	+	+										
	Pakuranga @ Greenmount Drive	2.4	+	+	+	+	+											+	+	+	+	+										
	Wairoa Trib @ Caitchons Rd	2.2	-	-	-	+	-											-	-	-	-	-										
	Otaki @ Middlemore Crescent	1	+	+	+	+	+											+	+	+	+	+										
	Nukumea @ Upper Site	1	-	-	-	-	-											-	-	-	-	-										
	Onetangi @ Waiheke Rd	0.7	+	+	+	+	+											+	+	+	+	+										
	Cascades @ Whakanewha	0.6	+	+	+	+	+											+	+	+	+	+										

Grey shaded stations used modeled flow data for load calculations

Very Good | Good | Satisfactory | Unsatisfactory

+ Overpredicts | - Underpredicts

Note: Tier refers to hydrologic data quality tier

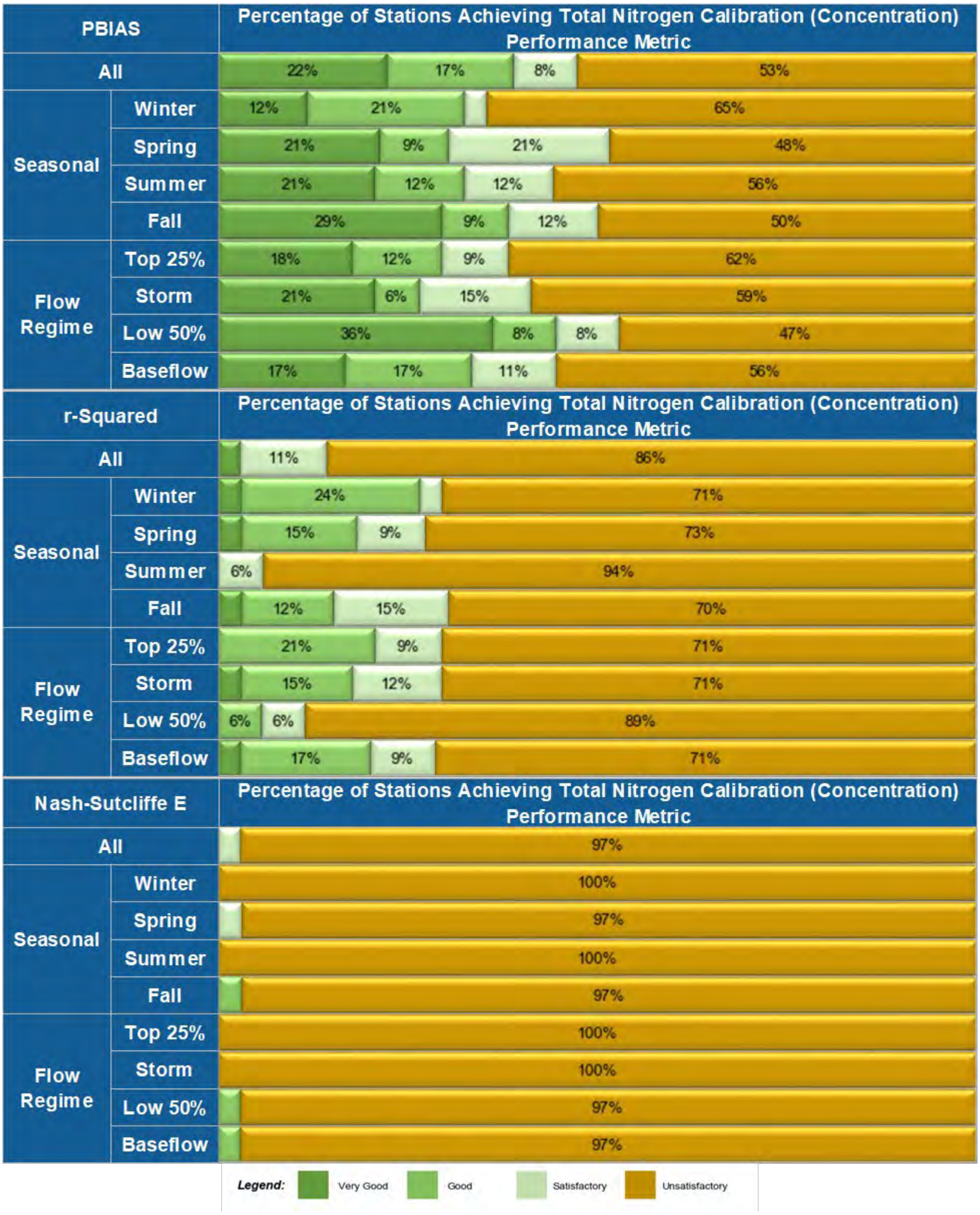


Figure 4-66. Total nitrogen (concentration) Performance Metrics for Calibration and Validation AC SoE Stations

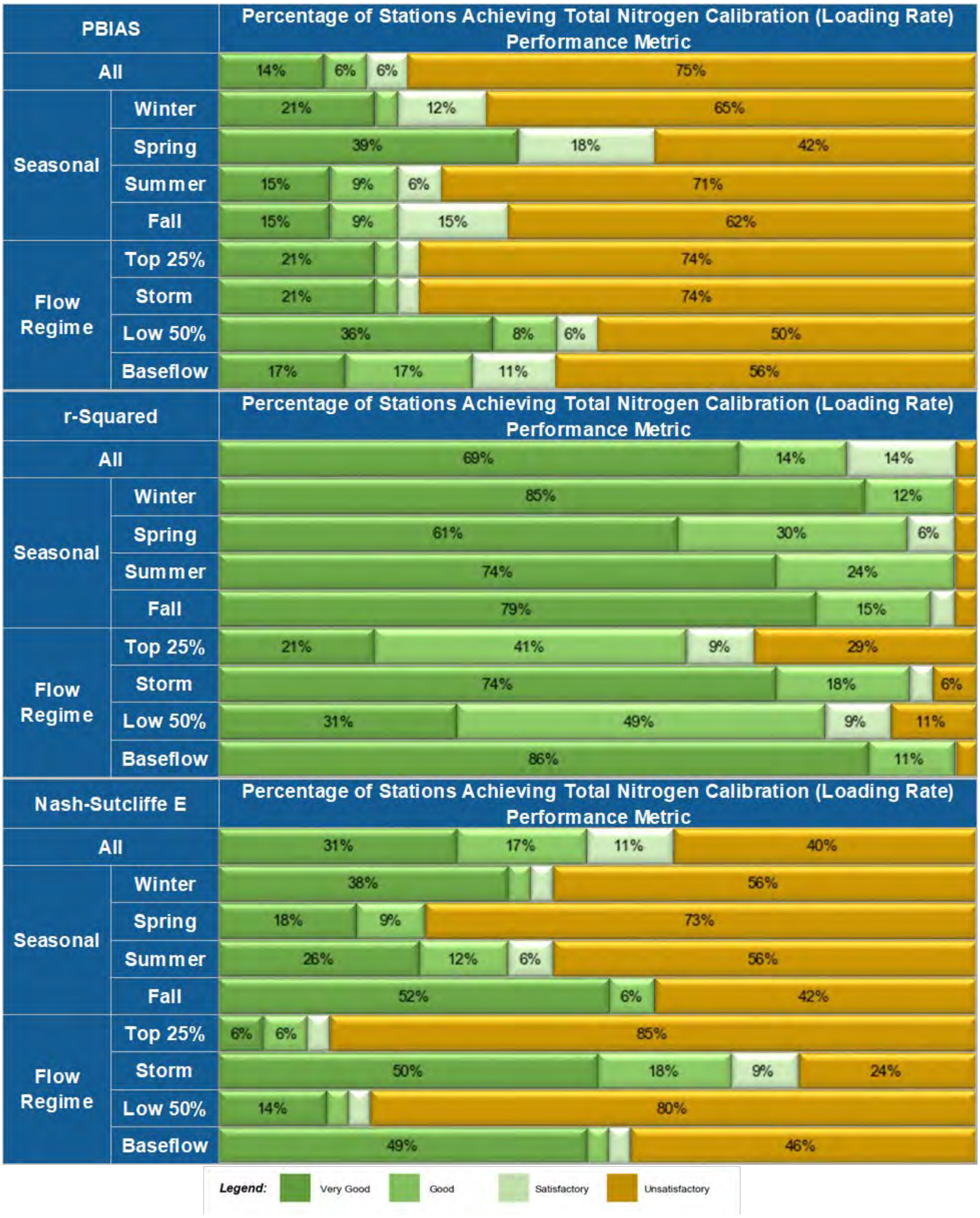


Figure 4-67. Total nitrogen (load) performance metrics for 36 Calibration and Validation AC SoE Stations

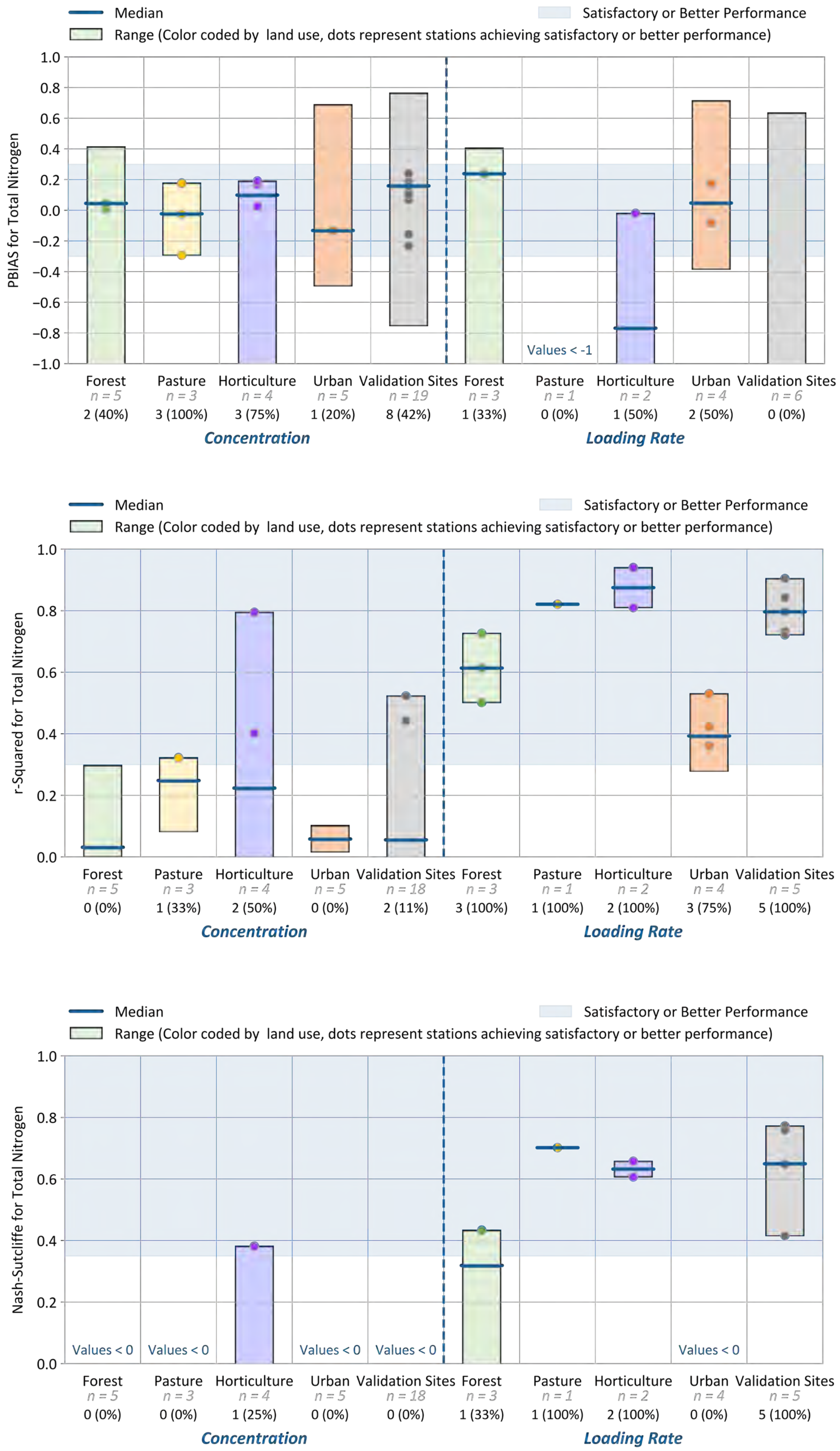


Figure 4-68. Concentrations and load performance metrics for TN by land use for the entire calibration period (2012-2016)

4.3.4.3 Total Oxidised Nitrogen

This subsection presents the TON calibration outcomes. TON was simulated with the RQUAL module to allow for prediction of instream transformations. HRUs represent the TN generation from land before RQUAL fractionates TN into nutrient species for instream simulations (e.g., TON, TAM). The parameters relied upon most-heavily for TON calibration are presented in . Recall that several sub-catchments in Franklin region were assigned a unique default parameter group to affect groundwater outflow TON concentrations (Section 3.10).

The TON predictive performance of the FWMT is presented as the following:

- Table 4-36: reports the station-by-station performance assessment based on flow-weighted average daily concentration for different seasons (left performance columns) and flow conditions (right performance columns) for r^2, PBIAS and NSE. White cells indicate insufficient samples in the bin to evaluate the metric (n<5 samples). Stations labelled N/A for Tier do not have a co-located flow gauge.
- Table 4-37: reports the station-by-station performance assessment based on daily loading rate (cumulative sum of 15-min concentration by flow for daily period) for different seasons (left performance columns) and flow conditions (right performance columns) for r^2, PBIAS and NSE.
- Figure 4-69: summarises the per cent of stations achieving different performance categories for flow-weighted average daily concentration across seasonal and flow-based conditions for r^2, PBIAS and NSE.
- Figure 4-70: summarises the per cent of stations achieving different performance categories for daily loading rate (cumulative sum of 15-min concentration by flow for daily period) across seasonal and flow-based conditions for r^2, PBIAS and NSE.
- Figure 4-71: presents the range and median of performance criteria results for calibration stations associated with a specific, dominant land use, as well as validation stations. The figure presents results for both concentrations and loads. Only stations with both observed water quality and flow data are presented for loading rate results.

The TON performance panels are presented for each of the 36 AC SoE stations in Appendix F3. The stations are ordered in the appendices identical to Table 4-36.

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Table 4-35. Primary parameters configured during total oxidised nitrogen calibration

Parameter Name	Description	Units
KNO320 *	Denitrification rate of NO3-N	1/hr
NOX	Nitrate fraction of TN loading from land entering stream	unitless
IOQC(TN)	Interflow concentration of TN	mg/l
AOQC(TN)	Active groundwater concentration of TN	mg/l

* Instream parameter set at model reaches

Table 4-36. Total oxidised nitrogen (concentration) FWMT Prediction Performance at AC SoE Stations

Tier	Water Quality Monitoring Locations	Drainage Area(km2)	Performance Metrics (Seasonal)															Performance Metrics (Flow Regime)														
			PBIAS					r-Squared					Nash-Sutcliffe E					PBIAS					r-Squared					Nash-Sutcliffe E				
			All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow
Tier 1	Wairoa River @ Tourist Road	149	+	+	+	+	+											+	+	+	+	+										
Tier 2	Opanuku Stream @ Candia Road Bridge	15.3	-	-	-	-	-											-	-	-	-	-										
	Oteha River @ Days Bridge	12.2	-	+	-	-	-											-	-	-	-	+										
	Lucas @ Gills Road	6.1	-	+	-	-	-											-	-	-	-	+										
	Ngakoroa Stream @ Mill Rd	4.8	+	-	+	+	+											+	-	+	+	+										
	West Hoe @ Halls	0.5	-	-	-	+	-											-	-	-	-	-										
Tier 3	Rangitopuni River @ Walkers	81.7	-	-	-	-	-											-	-	-	-	-										
	Kaukapakapa @ Taylors	62.2	-	-	+	+	-											-	-	-	+	-										
	Puhinui @ Drop Structure	12.6	+	+	-	-	-											+	+	-	-	+										
	Oakley Creek at Richardson Road	5.9	+															+			-	+										
Tier 4	Vaughn Stream @ Lower Weir	2.4	-	+	-	-	+											-	+	-	-	+										
Tier 5	Oratia @ Parrs Cross Road	17.1	-															-			-	-										
	Okura Creek @ Awanohi Rd	5.8	+	+			+											+	+	+	+	+										
N/A	Mahurangi @ Warkworth Water Treatment Plant	50.1	-	-	+	+	-											-	-	-	-	+										
	Makarau @ Railway	49.1	+	-	+	-	-											+	-	-	+	+										
	Papakura Stream @ Porchester Road Bridge	45.1	-	+	-	-	-											-	-	-	-	+										
	Kumeu River At Weza Lane	44.9	-	-	+	-	-											-	-	-	+	+										
	Waiwera Stream @ Upper Waiwera Road	30.2	+	+	+	+	+											+	-	-	+	+										
	Papakura @ Alfriston/Ardmore Rd	23.3	+	+	+	-	+											+	+	-	+	+										
	Waitangi @ Waitangi Falls Bridge.	19.3	+	+	+	+	+											+	+	+	+	+										
	Otara Stream @ Kennel Hill	18.3	+	+	-	-	+											+	+	-	-	+										
	Matakana @ Wenzlicks Farm	13.4	-	-	-	-	-											-	-	-	-	-										
	Oakley Creek @ Carrington.	11.9	+	+	+	+	+											+	+	-	+	+										
	Cascades Stream @ Confluence	10.8	+	-	+	+	+											+	-	-	+	+										
	Otara @ East Tamaki Rd	9.4	+	+	+	+	+											+	+	+	+	+										
	Whangamaire @ Woodhouse Road	8	-	-	-	+	-											-	-	+	+	-										
	Pakuranga @ Botany Rd	6.6	+	+	+	+	+											+	+	+	+	+										
	Riverhead @ Ararimu Valley Road	4.6	-	-	-	-	-											-	-	-	-	+										
	Omaru @ Maybury Street	3.5	+	+	+	-	+											+	+	-	+	+										
	Avondale Stream @ Shadbolt Park	3	+	+	+	-	+											+	+	-	+	+										
	Pakuranga @ Greenmount Drive	2.4	+	+	+	+	+											+	+	+	+	+										
	Wairoa Trib @ Caitchons Rd	2.2	+	-	+	+	-											+	-	-	+	+										
	Otaki @ Middlemore Crescent	1	+	+	+	+	+											+	+	+	+	+										
	Nukumea @ Upper Site	1	-	-	-	-	-											-	-	-	-	-										
	Onetangi @ Waiheke Rd	0.7	+	+	+	-	+											+	+	-	-	+										
	Cascades @ Whakanewha	0.6	+	+	+	+	+											+	+	+	+	+										

Grey shaded stations used modeled flow data for load calculations

Very Good | Good | Satisfactory | Unsatisfactory
+ Overpredicts | - Underpredicts

Note: Tier refers to hydrologic data quality tier

Table 4-37. Total oxidised nitrogen (load) FWMT Prediction Performance at AC SoE Stations

	Water Quality Monitoring Locations		Performance Metrics (Seasonal)															Performance Metrics (Flow Regime)														
			PBIAS					r-Squared					Nash-Sutcliffe E					PBIAS					r-Squared					Nash-Sutcliffe E				
			All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow
Tier 1	Wairoa River @ Tourist Road	149	+	+	+	+	-											+	+	+	+	+										
Tier 2	Opanuku Stream @ Candia Road Bridge	15.3	-	-	-	+	-											-	-	-	-	-										
	Oteha River @ Days Bridge	12.2	-	+	-	-	-											-	-	-	-	+										
	Lucas @ Gills Road	6.1	+	+	+	-	-											+	+	-	-	+										
	Ngakoroa Stream @ Mill Rd	4.8	-	-	+	+	-											-	+	-	-	+										
	West Hoe @ Halls	0.5	-	-	-	+	-											-	-	-	-	-										
Tier 3	Rangitopuni River @ Walkers	81.7	-	-	-	-	-											-	-	-	-	-										
	Kaukapakapa @ Taylors	62.2	-	-	-	+	-											-	-	-	-	-										
	Puhinui @ Drop Structure	12.6	-	+	-	-	-											-	+	-	-	+										
	Oakley Creek at Richardson Road	5.9	+															+			-	+										
Tier 4	Vaughn Stream @ Lower Weir	2.4	-	+	-	-	+											-	-	-	-	+										
Tier 5	Oratia @ Parrs Cross Road	17.1	-															-			-	-										
	Okura Creek @ Awanohi Rd	5.8	+	+			+											+	+	+	-	+										
N/A	Mahurangi @ Warkworth Water Treatment Plan	50.1	-	-	+	+	-											-	-	-	-	-										
	Makarau @ Railway	49.1	-	-	+	+	-											-	-	-	+	+										
	Papakura Stream @ Porchester Road Bridge	45.1	-	+	-	-	-											-	-	-	-	+										
	Kumeu River At Weza Lane	44.9	-	-	+	-	-											-	-	-	+	+										
	Waiwera Stream @ Upper Waiwera Road	30.2	-	-	-	+	+											-	-	-	+	+										
	Papakura @ Alfriston/Ardmore Rd	23.3	+	+	+	+	-											+	+	-	+	+										
	Waitangi @ Waitangi Falls Bridge.	19.3	+	+	+	+	+											+	+	-	+	+										
	Otara Stream @ Kennel Hill	18.3	+	+	-	-	+											+	+	+	-	+										
	Matakana @ Wenzlicks Farm	13.4	-	-	-	+	-											-	-	-	-	-										
	Oakley Creek @ Carrington.	11.9	+	+	+	+	+											+	+	+	+	+										
	Cascades Stream @ Confluence	10.8	-	-	+	+	-											-	-	-	+	-										
	Otara @ East Tamaki Rd	9.4	+	+	+	+	+											+	+	+	+	+										
	Whangamaire @ Woodhouse Road	8	-	-	-	-	-											-	-	-	-	-										
	Pakuranga @ Botany Rd	6.6	+	+	+	+	+											+	+	+	+	+										
	Riverhead @ Ararimu Valley Road	4.6	-	-	-	+	-											-	-	-	-	+										
	Omaru @ Maybury Street	3.5	+	+	+	+	-											+	+	-	+	+										
	Avondale Stream @ Shadbolt Park	3	+	+	+	-	+											+	+	+	+	+										
	Pakuranga @ Greenmount Drive	2.4	+	+	+	+	+											+	+	+	+	+										
	Wairoa Trib @ Caitchons Rd	2.2	-	-	+	+	-											-	-	-	+	-										
	Otaki @ Middlemore Crescent	1	+	+	+	+	+											+	+	+	+	+										
	Nukumea @ Upper Site	1	-	-	-	-	-											-	-	-	-	-										
	Onetangi @ Waiheke Rd	0.7	+	+	+	-	+											+	+	-	+	+										
	Cascades @ Whakanewha	0.6	+	+	+	+	+											+	+	+	+	+										

Grey shaded stations used modeled flow data for load calculations

Very Good | Good | Satisfactory | Unsatisfactory

\+ Overpredicts | - Underpredicts

Note: Tier refers to hydrologic data quality tier

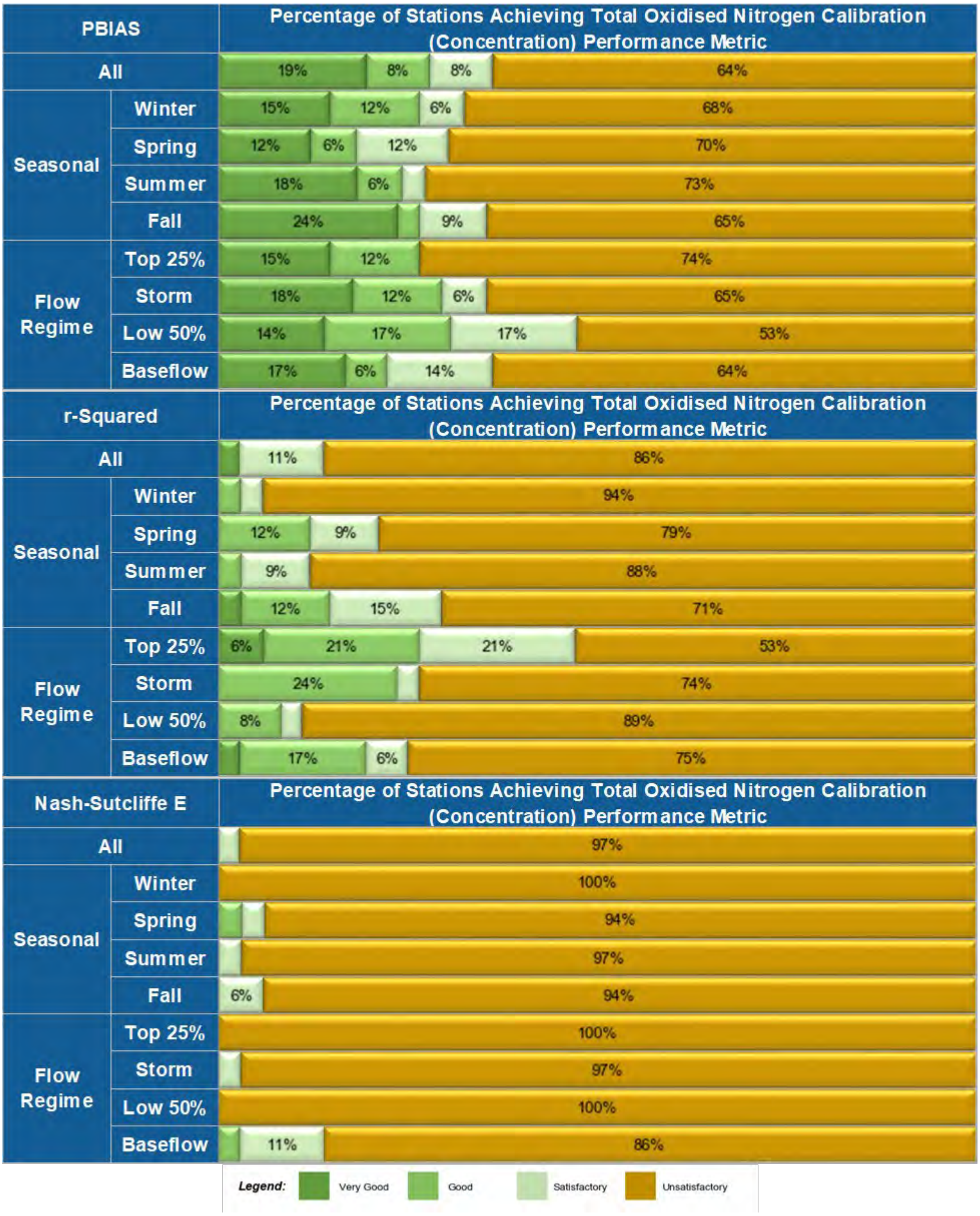


Figure 4-69. Total oxidised nitrogen (concentration) performance metrics for 36 Calibration and Validation AC SoE Stations

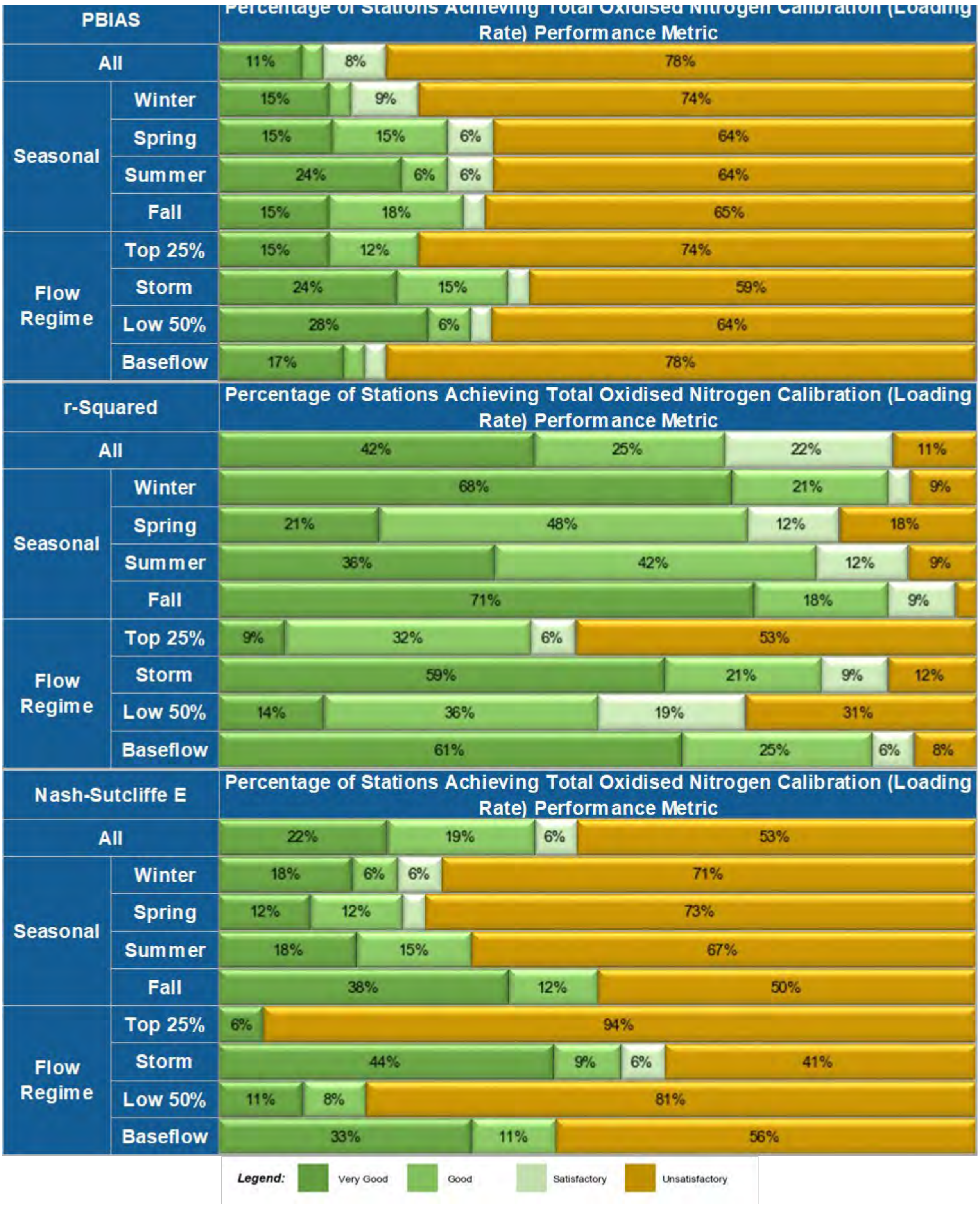


Figure 4-70. Total oxidised nitrogen (load) performance metrics for 36 Calibration and Validation AC SoE Stations

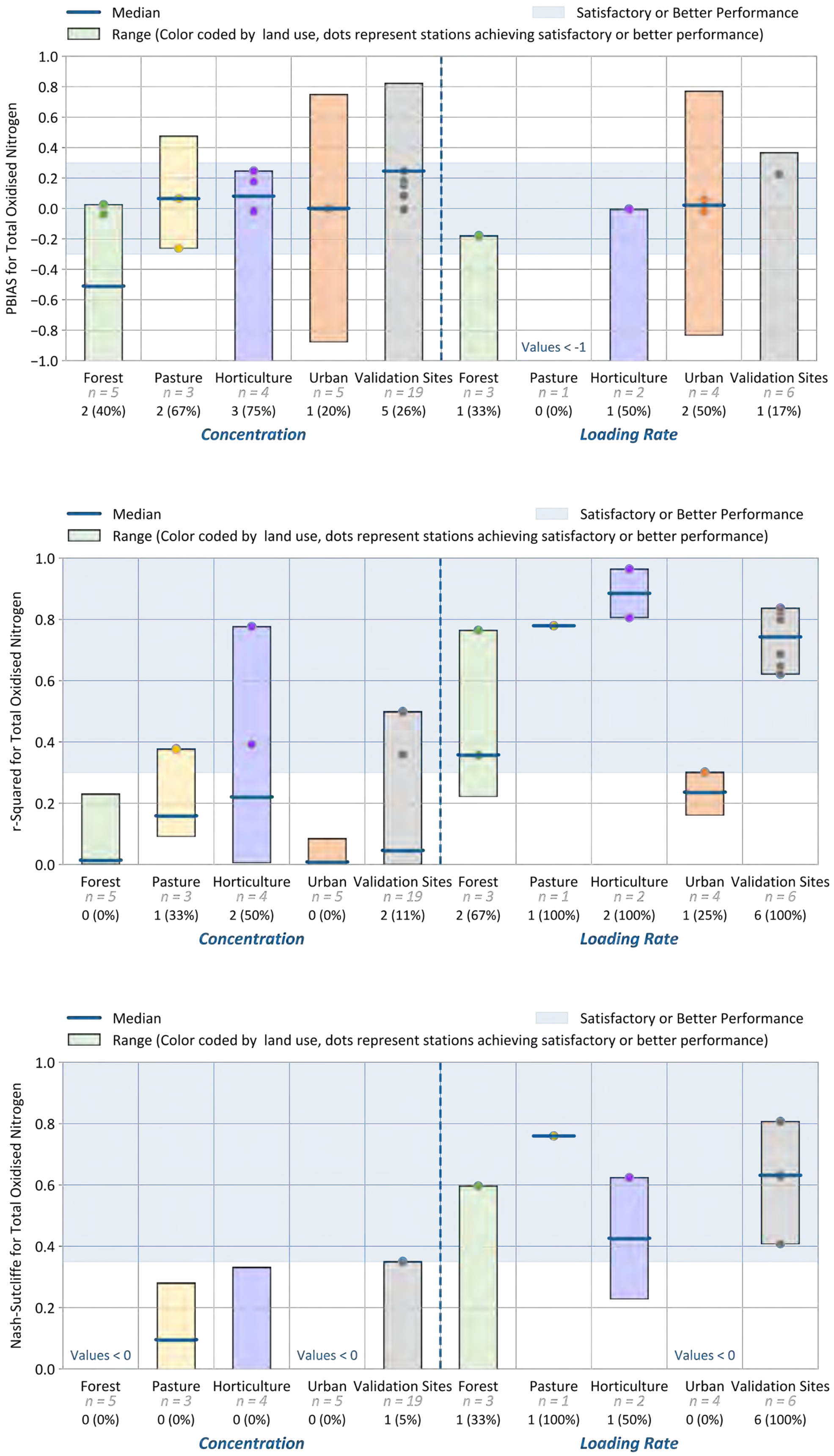


Figure 4-71. Concentrations and load performance metrics for TON by land use for the entire calibration period (2012-2016)

4.3.4.4 Total Ammoniacal Nitrogen

This subsection presents the TAM calibration outcomes. TAM was simulated with the RQUAL module to allow for prediction of instream transformations. HRUs represent the TN generation from the land before RQUAL fractionates this into nutrient species for instream simulations. The parameters relied upon most for total ammoniacal nitrogen calibration are presented in Table 4-38.

The total ammoniacal nitrogen prediction performance of the FWMT is presented as the following:

- Table 4-39: reports the station-by-station performance assessment based on flow-weighted average daily concentration for different seasons (left performance columns) and flow conditions (right performance columns) for r^2, PBIAS and NSE. White cells indicate insufficient samples in the bin to evaluate the metric (n<5 samples). Stations labelled N/A for Tier do not have a co-located flow gauge.
- Table 4-40: reports the station-by-station performance assessment based on daily loading rate (cumulative sum of 15-min concentration by flow for daily period) for different seasons (left performance columns) and flow conditions (right performance columns) for r^2, PBIAS and NSE.
- Figure 4-72: summarises the per cent of stations achieving different performance categories for flow-weighted average daily concentration across seasonal and flow-based conditions for r^2, PBIAS and NSE.
- Figure 4-73: summarises the per cent of stations achieving different performance categories for daily loading rate (cumulative sum of 15-min concentration by flow for daily period) across seasonal and flow-based conditions for r^2, PBIAS and NSE.
- Figure 4-74: presents the range and median of performance criteria results for calibration stations associated with a specific, dominant land use, as well as validation stations. The figure presents results for both concentrations and loads. Only stations with both observed water quality and flow data are presented for loading rate results.

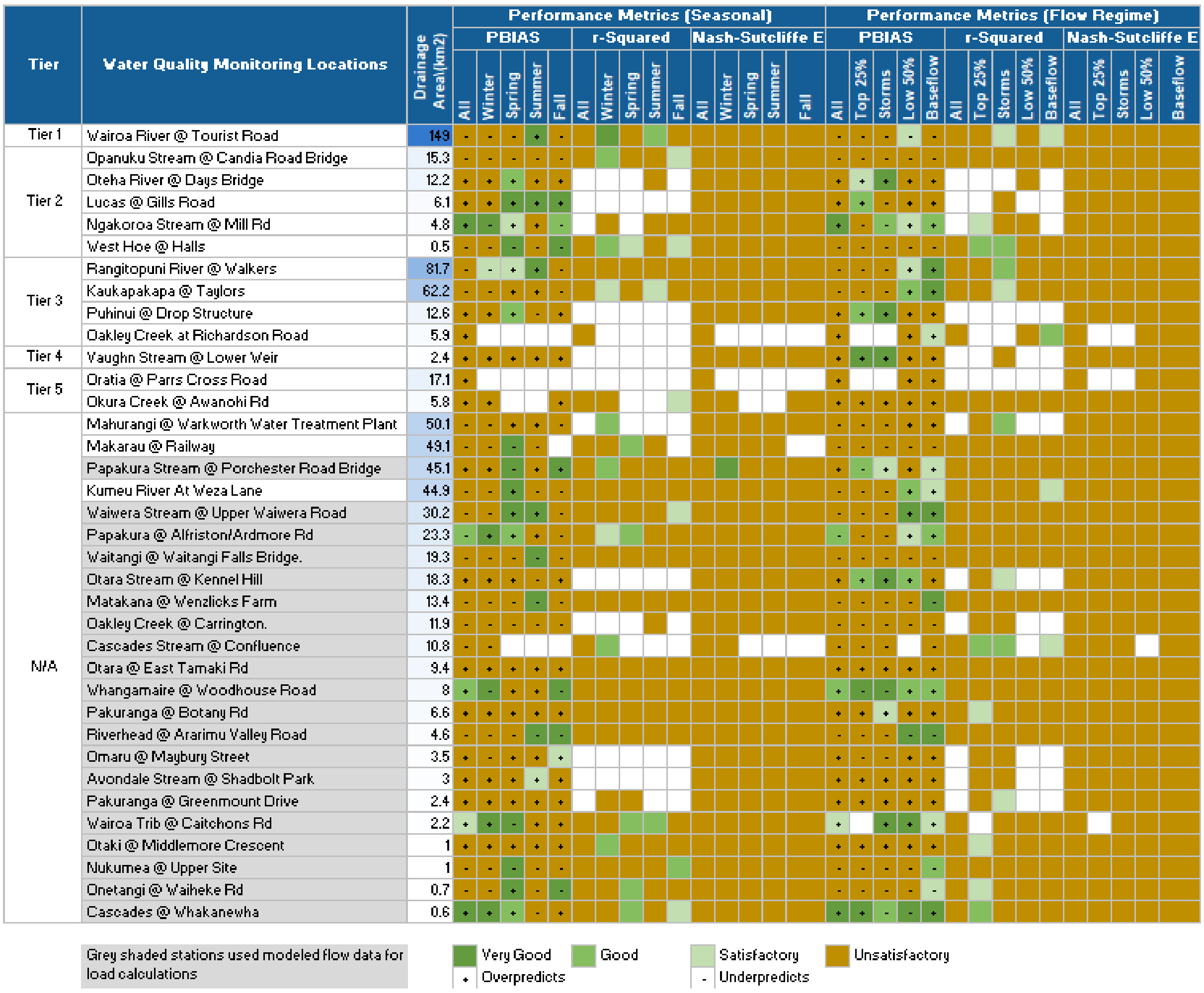
The total ammoniacal nitrogen performance panels are presented for each of the 36 AC SoE stations in Appendix F4. The stations are ordered in appendices identical to Table 4-39.

Table 4-38. Primary parameters leveraged for total ammoniacal nitrogen calibration

Parameter Name	Description	Units
KTAM20 *	Nitrification rate of NH4-N	1/hr
TAM	Total ammonia fraction of TN loading from land entering stream	unitless
ORN	Organic nitrogen fraction of TN loading from land entering stream	unitless
ADNHPM *	adsorption coefficients for ammonia-N adsorbed to sand, silt, and clay in reach	cm3/g

* Instream parameter set at model reaches

Table 4-39. Total ammoniacal nitrogen (concentration) FWMT Prediction Performance at AC SoE Stations



Note: Tier refers to hydrologic data quality tier

Table 4-40. Total ammoniacal nitrogen (load) FWMT Prediction Performance at AC SoE Stations

	Water Quality Monitoring Locations		Performance Metrics (Seasonal) PBIAS					Performance Metrics (Flow Regime) PBIAS				
			All	Winter	Spring	Summer	Fall	All	Top 25%	Storms	Low 50%	Baseflow
Tier 1	Wairoa River @ Tourist Road	149	-	-	-	-	-	-	-	-	-	-
Tier 2	Opanuku Stream @ Candia Road Bridge	15.3	-	-	-	-	-	-	-	-	-	-
	Oteha River @ Days Bridge	12.2	+	+	+	+	+	+	+	+	+	+
	Lucas @ Gills Road	6.1	+	+	+	-	+	+	+	+	+	+
	Ngakoroa Stream @ Mill Rd	4.8	-	-	+	+	-	-	-	-	+	+
	West Hoe @ Halls	0.5	+	+	-	+	+	+	+	+	+	-
Tier 3	Rangitopuni River @ Walkers	81.7	-	-	-	-	-	-	-	-	+	-
	Kaukapakapa @ Taylors	62.2	-	-	-	+	-	-	-	-	-	-
	Puhinui @ Drop Structure	12.6	+	+	-	+	-	+	-	-	+	+
	Oakley Creek at Richardson Road	5.9	+					+			+	+
Tier 4	Vaughn Stream @ Lower Weir	2.4	-	-	-	+	+	-	-	-	+	+
Tier 5	Oratia @ Parrs Cross Road	17.1	+					+			+	+
	Okura Creek @ Awanohi Rd	5.8	+	+			+	+	+	+	-	+
N/A	Mahurangi @ Warkworth Water Treatment Plan	50.1	-	-	+	+	-	-	-	-	+	-
	Makarau @ Railway	49.1	-	-	-	-		-	-	-	-	-
	Papakura Stream @ Porchester Road Bridge	45.1	-	+	-	+	-	-	-	-	+	-
	Kumeu River At Weza Lane	44.9	-	-	+	-	-	-	-	-	+	+
	Waiwera Stream @ Upper Waiwera Road	30.2	-	-	-	+	-	-	-	-	-	-
	Papakura @ Alfriston/Ardmore Rd	23.3	-	-	+	+	-	-	-	-	+	-
	Waitangi @ Waitangi Falls Bridge.	19.3	-	-	-	+	-	-	-	-	-	-
	Otara Stream @ Kennel Hill	18.3	+	+	+	+	+	+	+	-	+	+
	Matakana @ Wenzlicks Farm	13.4	-	-	-	+	-	-	-	-	-	-
	Oakley Creek @ Carrington.	11.9	-	-	-	-	-	-	-	-	-	-
	Cascades Stream @ Confluence	10.8	-	-				-	-	-		-
	Otara @ East Tamaki Rd	9.4	+	+	+	+	+	+	+	+	+	+
	Whangamaire @ Woodhouse Road	8	+	-	+	+	-	+	-	-	+	+
	Pakuranga @ Botany Rd	6.6	+	+	+	+	+	+	+	+	+	+
	Riverhead @ Ararimu Valley Road	4.6	-	-	-	-	-	-	-	-	-	-
	Omaru @ Maybury Street	3.5	-	-	+	-	-	-	-	-	+	-
	Avondale Stream @ Shadbolt Park	3	+	+	+	+	+	+	+	+	+	+
	Pakuranga @ Greenmount Drive	2.4	+	+	+	+	+	+	+	+	+	+
	Wairoa Trib @ Caitchons Rd	2.2	-	-	-	+	+	-		+	-	-
	Otaki @ Middlemore Crescent	1	+	+	+	+	+	+	+	+	+	+
	Nukumea @ Upper Site	1	-	-	-	-	-	-	-	-	-	-
	Onetangi @ Waiheke Rd	0.7	-	-	-	-	-	-	-	-	-	-
	Cascades @ Whakanewha	0.6	+	+	+	-	+	+	+	-	+	+

Grey shaded stations used modeled flow data for load calculations

Very Good | Good | Satisfactory | Unsatisfactory

+ Overpredicts | - Underpredicts

Note: Tier refers to hydrologic data quality tier

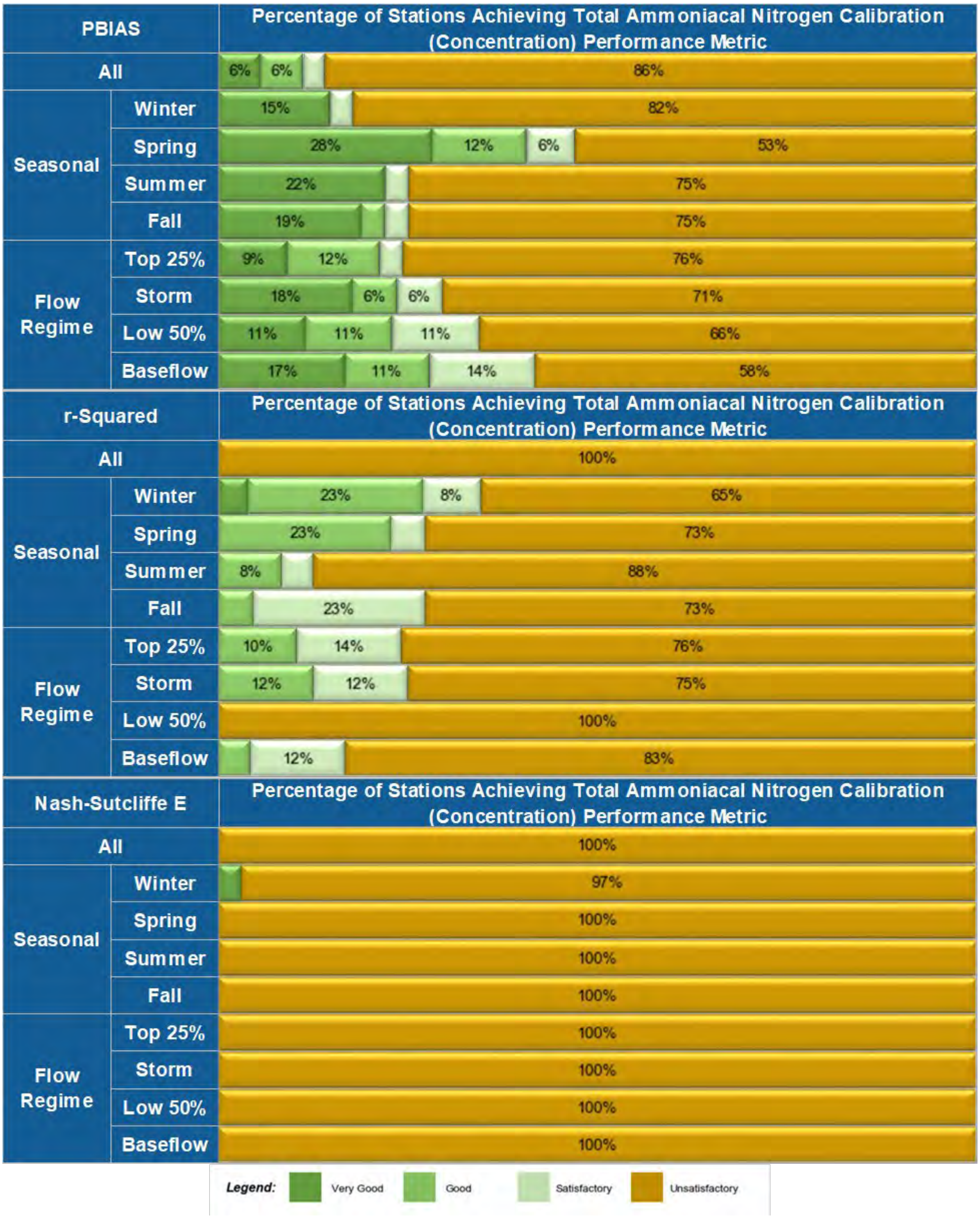


Figure 4-72. Total ammoniacal nitrogen (concentration) performance metrics for 36 Calibration and Validation AC SoE Stations

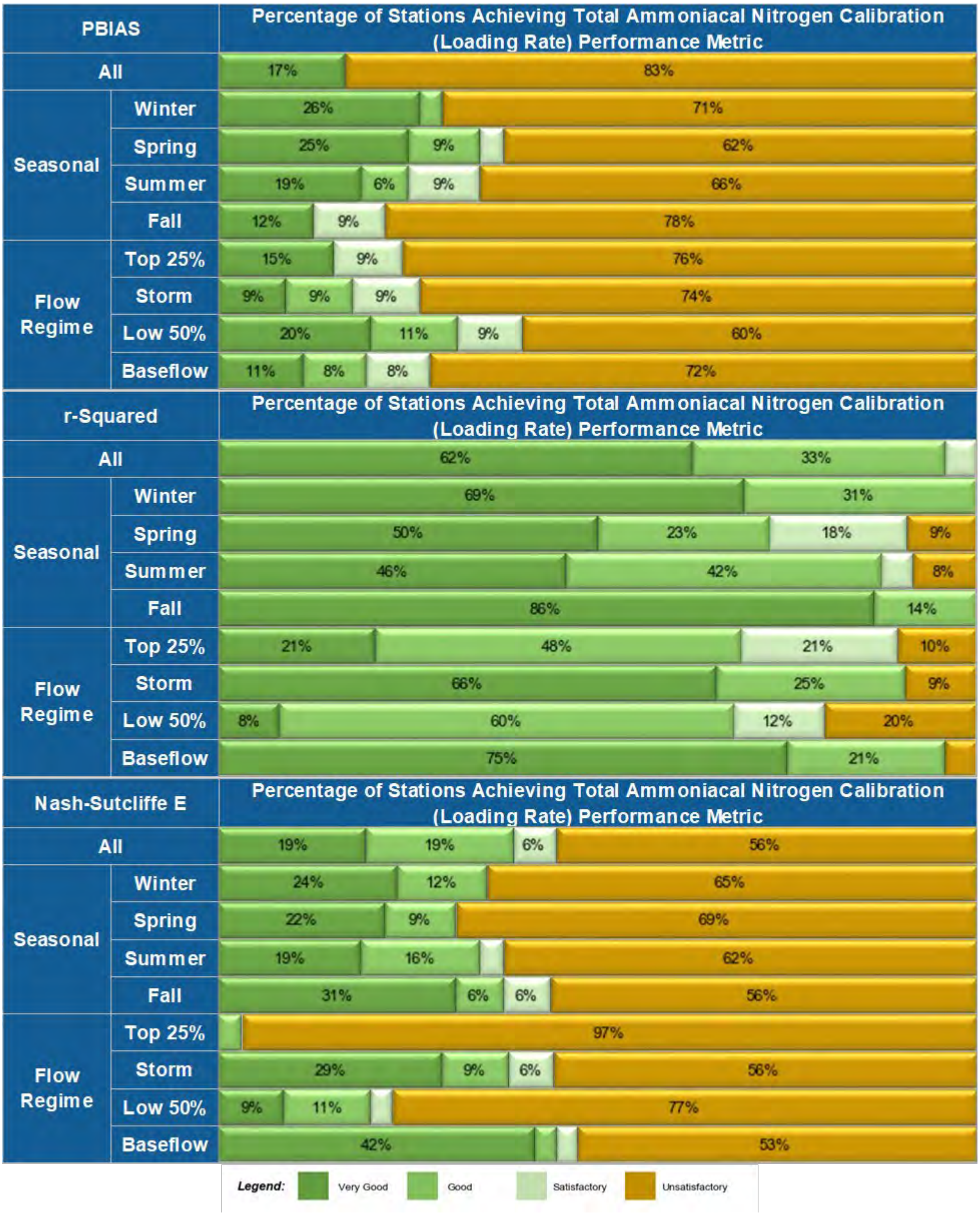


Figure 4-73. Total ammoniacal nitrogen (load) performance metrics for 36 Calibration and Validation AC SoE Stations

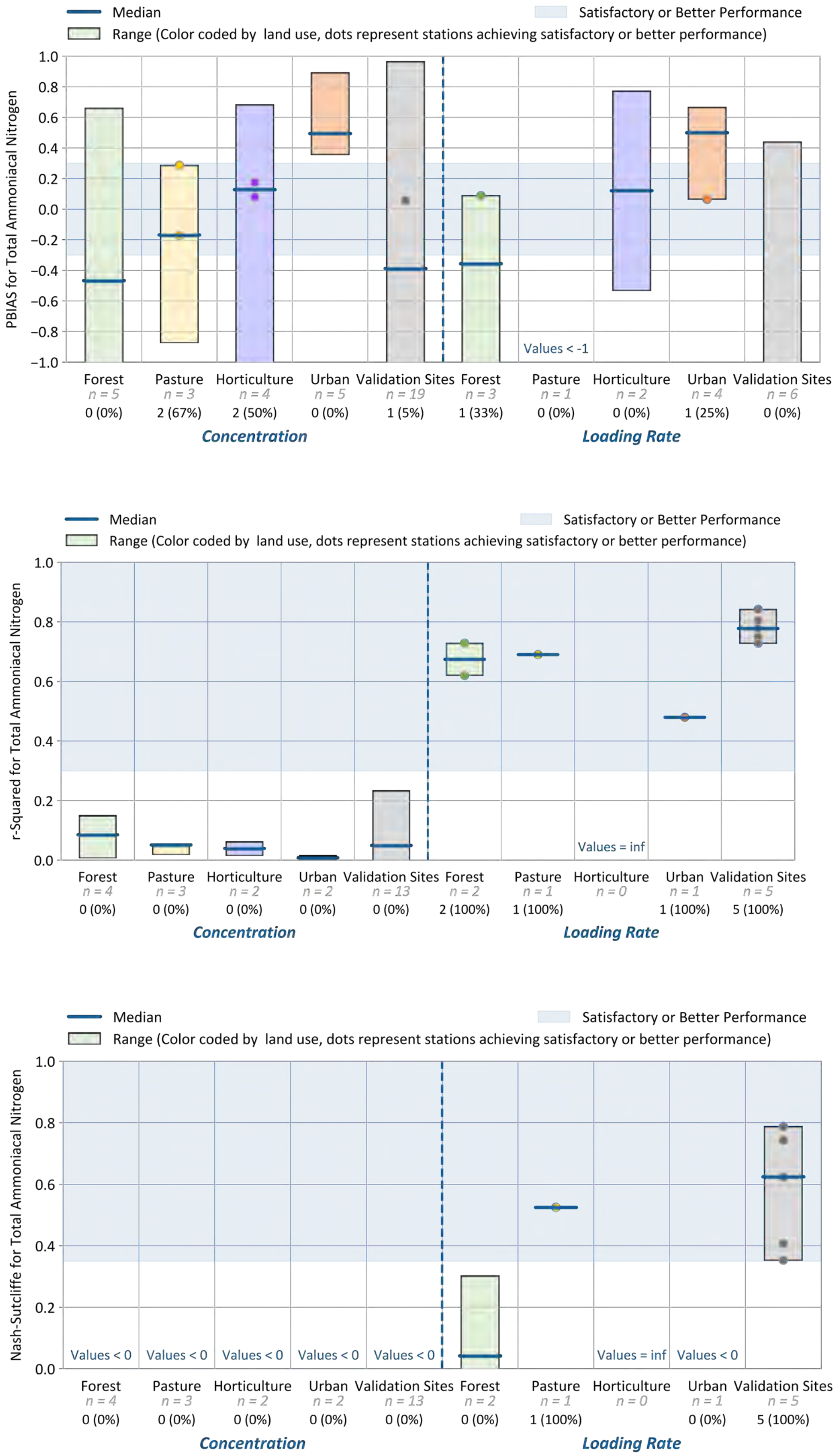


Figure 4-74. Concentrations and load performance metrics for TAM by land use for the entire calibration period (2012-2016)

4.3.4.5 Total Phosphorus

This subsection presents the TP calibration outcomes. Phosphorous was simulated with GQUAL and RQUAL modules to allow for prediction of oxidised and ammoniacal phosphorous inclusive of instream transformations. TP, which was simulated with GQUAL, represents the total mass of phosphorous and is the basis of simulated DRP concentrations. Unlike nitrogen, phosphorous is represented as sediment-associated in the FWMT. The three sources of TP in the FWMT Stage 1 were sediment eroded from pervious surfaces, sediment eroded from stream banks, sediment washed off of impervious surfaces, and background concentrations in groundwater/interflow. Therefore, sources such as fertilizer are not directly simulated. However, future updates can include monthly adjusted TP potency factors or simulating monthly build-up and wash off of TP on agricultural HRUs to represent fertilizer application. The parameters relied upon most for total phosphorous calibration are presented in Table 4-41.

The TP predictive performance of the FWMT is presented as the following:

- Table 4-42: reports the station-by-station performance assessment based on flow-weighted average daily concentration for different seasons (left performance columns) and flow conditions (right performance columns) for r^2, PBIAS and NSE. White cells indicate insufficient samples in the bin to evaluate the metric (n<5 samples). Stations labelled N/A for Tier do not have a co-located flow gauge.
- Table 4-43: reports the station-by-station performance assessment based on daily loading rate (cumulative sum of 15-min concentration by flow for daily period) for different seasons (left performance columns) and flow conditions (right performance columns) for r^2, PBIAS and NSE.
- Figure 4-75: summarises the per cent of stations achieving different performance categories for flow-weighted average daily concentration across seasonal and flow-based conditions for r^2, PBIAS and NSE.
- Figure 4-76: summarises the per cent of stations achieving different performance categories for daily loading rate (cumulative sum of 15-min concentration by flow for daily period) across seasonal and flow-based conditions for r^2, PBIAS and NSE.
- Figure 4-77: presents the range and median of performance criteria results for calibration stations associated with a specific, dominant land use, as well as validation stations. The figure presents results for both concentrations and loads. Only stations with both observed water quality and flow data are presented for loading rate results.

The TP performance panels are presented for each of the 36 AC SoE stations in Appendix F5. The stations are ordered in the appendices identical to Table 4-42.

Table 4-41. Primary parameters leveraged during total phosphorous calibration

Parameter Name	Description	Units
POTFW (TP)	Potency factor of TP in sediment washed off from surfaces	kg TP / ton sediment
POTFS (TP)	Potency factor of TP in sediment scoured from streambanks	kg TP / ton sediment
PO4	Orthophosphate fraction of TP loading from land entering stream	unitless
ORP	Organic phosphorus fraction of TP loading from land entering stream	unitless
SPO4	Orthophosphate sediment bound fraction of TP loading from land entering stream	Unitless
IOQC (TP)	Interflow concentration of TP	mg/l
AOQC (TP)	Active groundwater concentration of TP	mg/l

* Instream parameter set at model reaches

Table 4-42. Total phosphorus (concentration) FWMT Prediction Performance at AC SoE Stations

Tier	Water Quality Monitoring Locations	Drainage Area(km2)	Performance Metrics (Seasonal)															Performance Metrics (Flow Regime)														
			PBIAS					r-Squared					Nash-Sutcliffe					PBIAS					r-Squared					Nash-Sutcliffe				
			All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow
Tier 1	Wairoa River @ Tourist Road	149	-	-	+	-	-											-	-	-	-	-										
Tier 2	Opanuku Stream @ Candia Road Bridge	15.3	-	-	-	-	-											-	-	-	-	-										
	Oteha River @ Days Bridge	12.2	+	+	-	+	+											+	+	-	+	+										
	Lucas @ Gills Road	6.1	-	+	-	+	-											-	-	-	-	+										
	Ngakoroa Stream @ Mill Rd	4.8	-	+	-	-	-											-	-	-	-	+										
	West Hoe @ Halls	0.5	-	-	+	-	-											-	-	+	+	-										
Tier 3	Rangitopuni River @ Walkers	81.7	+	+	+	+	-											+	-	-	+	+										
	Kaukapakapa @ Taylors	62.2	-	-	+	+	+											-	-	-	+	+										
	Puhinui @ Drop Structure	12.6	+	+	+	+	-											+	-	-	+	+										
	Oakley Creek at Richardson Road	5.9	+															+			+	+										
Tier 4	Vaughn Stream @ Lower Weir	2.4	+	+	+	+	+											+	+	+	+	+										
Tier 5	Oratia @ Parrs Cross Road	17.1	+															+			+	+										
	Okura Creek @ Awanohi Rd	5.8	+	+		+	+											+	+	+	+	+										
N/A	Mahurangi @ Warkworth Water Treatment Plan	50.1	-	-	+	+	-											-	-	-	+	+										
	Makarau @ Railway	49.1	-	-	-	-	-											-	-	-	+	-										
	Papakura Stream @ Porchester Road Bridge	45.1	+	+	+	+	-											+	-	-	+	+										
	Kumeu River At Weza Lane	44.9	-	-	+	-	-											-	-	-	+	+										
	Waiwera Stream @ Upper Waiwera Road	30.2	-	-	+	+	+											-	-	-	+	+										
	Papakura @ Alfriston/Ardmore Rd	23.3	+	+	+	+	-											+	-	-	+	+										
	Waitangi @ Waitangi Falls Bridge.	19.3	-	-	-	-	-											-	-	-	-	-										
	Otara Stream @ Kennel Hill	18.3	+	-	+	-	+											+	-	-	+	+										
	Matakana @ Wenzlicks Farm	13.4	+	+	-	+	+											+	-	-	+	+										
	Oakley Creek @ Carrington.	11.9	-	-	-	-	-											-	-	-	-	-										
	Cascades Stream @ Confluence	10.8	+	-	+	+	+											+	-	+	+	+										
	Otara @ East Tamaki Rd	9.4	+	+	+	+	+											+	+	+	+	+										
	Whangamaire @ Woodhouse Road	8	+	+	+	-	+											+	+	+	+	+										
	Pakuranga @ Botany Rd	6.6	+	+	+	+	+											+	+	-	+	+										
	Riverhead @ Ararimu Valley Road	4.6	+	-	+	+	+											+	-	-	+	+										
	Omaru @ Maybury Street	3.5	-	-	+	+	-											-	-	-	+	+										
	Avondale Stream @ Shadbolt Park	3	+	+	+	+	+											+	+	+	+	+										
	Pakuranga @ Greenmount Drive	2.4	+	+	+	+	+											+	+	+	+	+										
	Wairoa Trib @ Caitchons Rd	2.2	+	+	+	+	+											+	-	+	+	+										
	Otaki @ Middlemore Crescent	1	+	+	+	+	+											+	+	+	+	+										
	Nukumea @ Upper Site	1	+	+	+	+	+											+	+	+	+	+										
	Onetangi @ Waiheke Rd	0.7	+	+	+	+	+											+	+	+	+	+										
	Cascades @ Whakanewha	0.6	+	+	+	+	+											+	+	+	+	+										

Grey shaded stations used modeled flow data for load calculations

Very Good | Good | Satisfactory | Unsatisfactory

+ Overpredicts | - Underpredicts

Table 4-43. Total phosphorus (load) FWMT Prediction Performance at AC SoE Stations

	Water Quality Monitoring Locations		Performance Metrics (Seasonal)															Performance Metrics (Flow Regime)														
			PBIAS					r-Squared					Nash-Sutcliffe E					PBIAS					r-Squared					Nash-Sutcliffe E				
			All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow
Tier 1	Wairoa River @ Tourist Road	149	-	-	+	-	-											-	-	-	-	-										
Tier 2	Opanuku Stream @ Candia Road Bridge	15.3	-	-	-	+	-											-	-	-	-	-										
	Oteha River @ Days Bridge	12.2	+	+	+	-	+											+	+	+	-	+										
	Lucas @ Gills Road	6.1	+	+	+	-	-											+	+	+	-	+										
	Ngakoroa Stream @ Mill Rd	4.8	-	+	-	-	-											-	-	-	-	+										
	West Hoe @ Halls	0.5	+	-	+	+	-											+	-	+	+	-										
Tier 3	Rangitopuni River @ Walkers	81.7	-	+	-	+	-											-	-	-	+	-										
	Kaukapakapa @ Taylors	62.2	-	-	+	+	-											-	-	-	+	-										
	Puhinui @ Drop Structure	12.6	-	-	+	+	-											-	-	-	+	+										
	Oakley Creek at Richardson Road	5.9	+															+			+	+										
Tier 4	Vaughn Stream @ Lower Weir	2.4	+	+	+	+	+											+	+	+	+	+										
Tier 5	Oratia @ Parrs Cross Road	17.1	+															+			+	+										
	Okura Creek @ Awanohi Rd	5.8	+	+		+	+											+	+	+	+	+										
N/A	Mahurangi @ Warkworth Water Treatment Plant	50.1	-	-	+	+	-											-	-	-	+	+										
	Makarau @ Railway	49.1	-	-	-	-	-											-	-	-	+	-										
	Papakura Stream @ Porchester Road Bridge	45.1	-	+	+	+	-											-	-	-	+	+										
	Kumeu River At Weza Lane	44.9	-	-	+	-	-											-	-	-	+	+										
	Waiwera Stream @ Upper Waiwera Road	30.2	-	-	+	+	+											-	-	-	+	-										
	Papakura @ Alfriston/Ardmore Rd	23.3	-	+	+	+	-											-	-	-	+	+										
	Waitangi @ Waitangi Falls Bridge.	19.3	-	+	-	-	-											-	-	-	-	-										
	Otara Stream @ Kennel Hill	18.3	-	-	+	-	+											-	-	-	+	-										
	Matakana @ Wenzlicks Farm	13.4	-	-	-	+	+											-	-	-	+	+										
	Oakley Creek @ Carrington.	11.9	-	-	-	-	-											-	-	-	-	-										
	Cascades Stream @ Confluence	10.8	-	-	+	+	-											-	-	-	+	-										
	Otara @ East Tamaki Rd	9.4	+	+	+	+	+											+	+	+	+	+										
	Whangamaire @ Woodhouse Road	8	+	+	+	+	+											+	+	+	+	+										
	Pakuranga @ Botany Rd	6.6	-	-	+	+	+											-	-	-	+	+										
	Riverhead @ Ararimu Valley Road	4.6	-	-	+	+	+											-	-	-	+	+										
	Omaru @ Maybury Street	3.5	-	-	+	-	-											-	-	-	+	-										
	Avondale Stream @ Shadbolt Park	3	+	+	+	+	+											+	+	+	+	+										
	Pakuranga @ Greenmount Drive	2.4	+	+	+	+	+											+	+	+	+	+										
	Wairoa Trib @ Caitchons Rd	2.2	-	+	+	+	-											-	-	-	+	+										
	Otaki @ Middlemore Crescent	1	+	+	+	+	+											+	+	+	+	+										
	Nukumea @ Upper Site	1	+	+	+	+	-											+	+	+	+	+										
	Onetangi @ Waiheke Rd	0.7	+	+	+	+	+											+	+	+	+	+										
	Cascades @ Whakanewha	0.6	+	+	+	+	+											+	+	+	+	+										

Grey shaded stations used modeled flow data for load calculations

Very Good | Good | Satisfactory | Unsatisfactory
+ Overpredicts | - Underpredicts

Note: Tier refers to hydrologic data quality tier

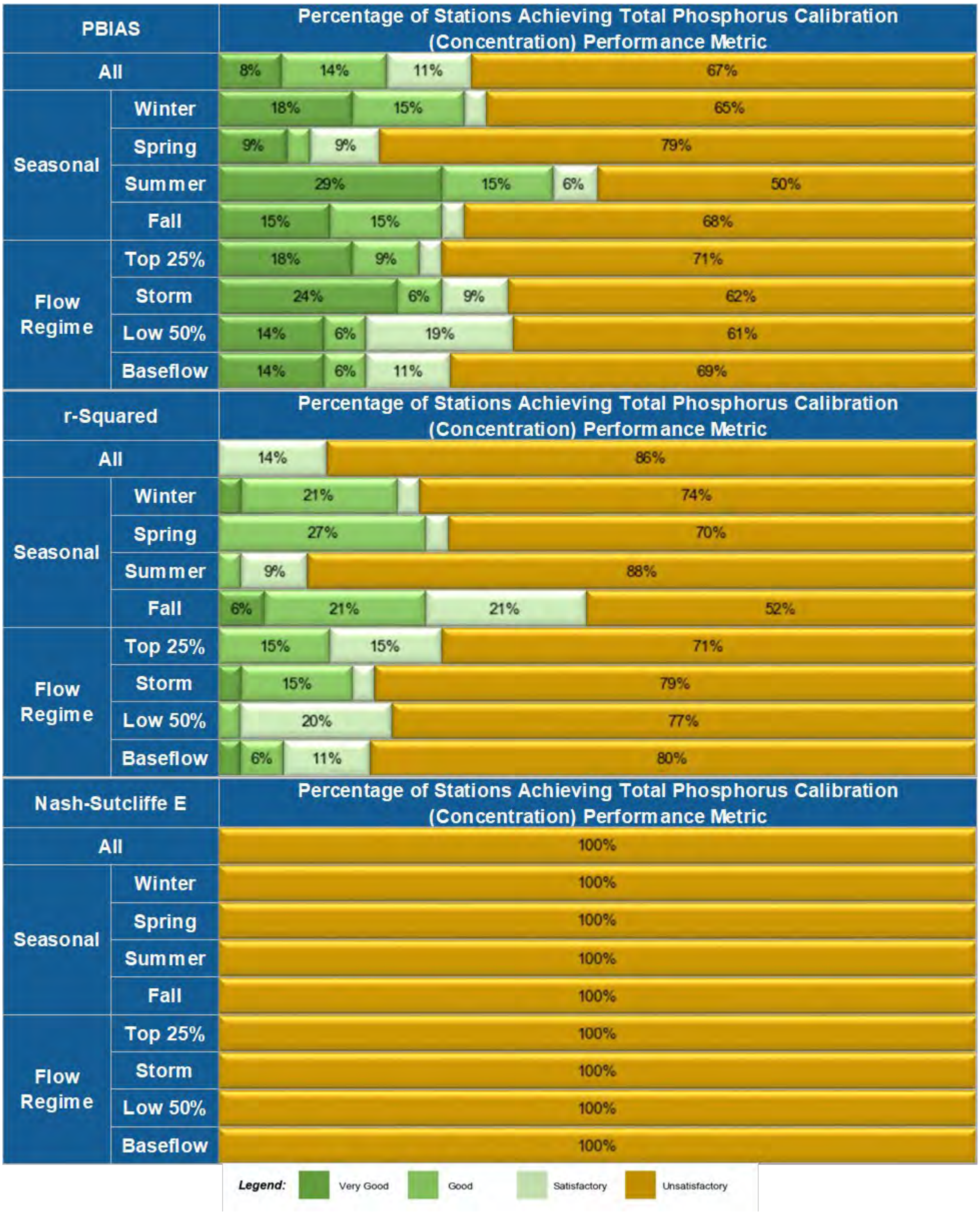


Figure 4-75. Total phosphorus (concentration) performance metrics for 36 Calibration and Validation AC SoE Stations

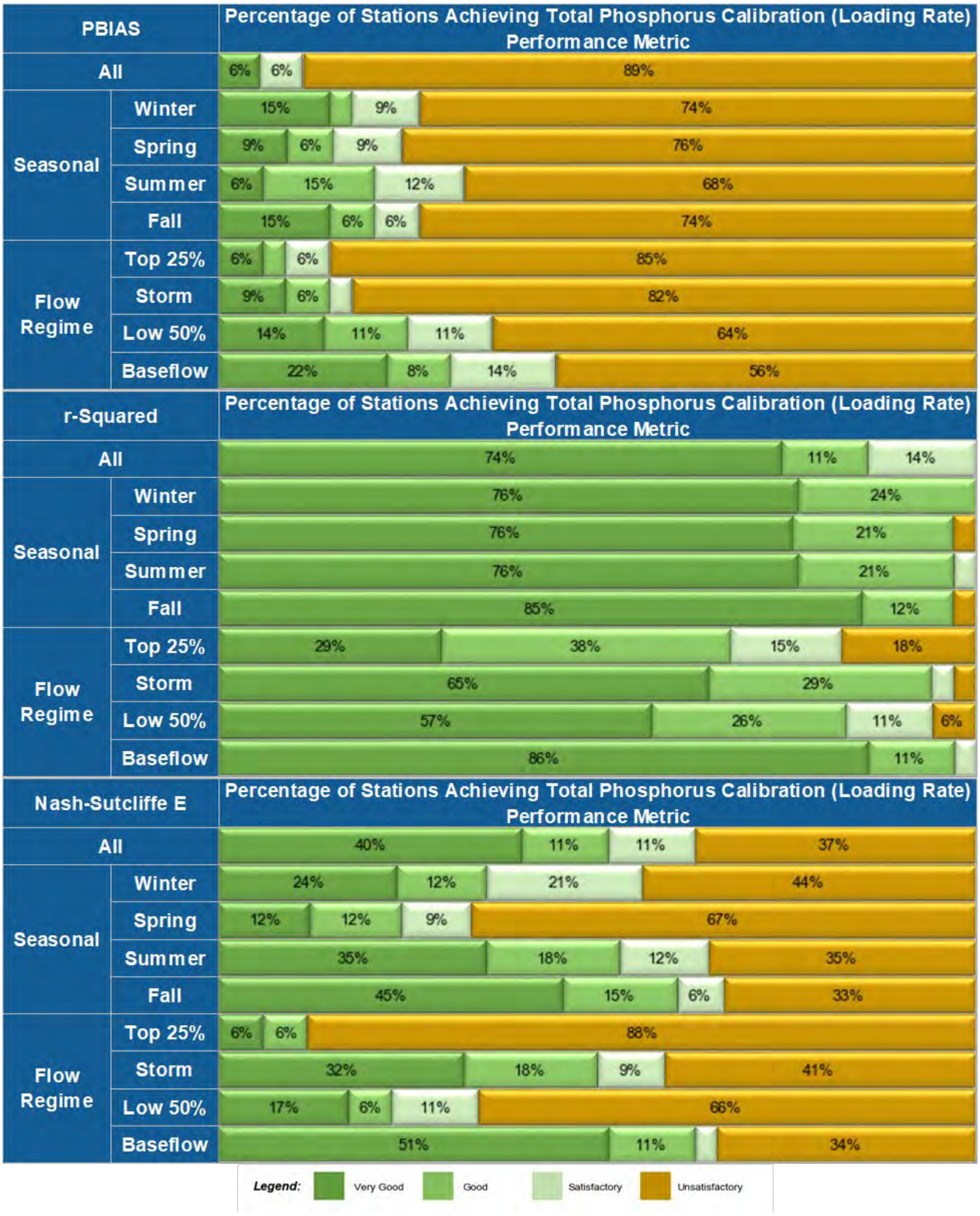


Figure 4-76. Total phosphorus (load) performance metrics for 36 Calibration and Validation AC SoE Stations

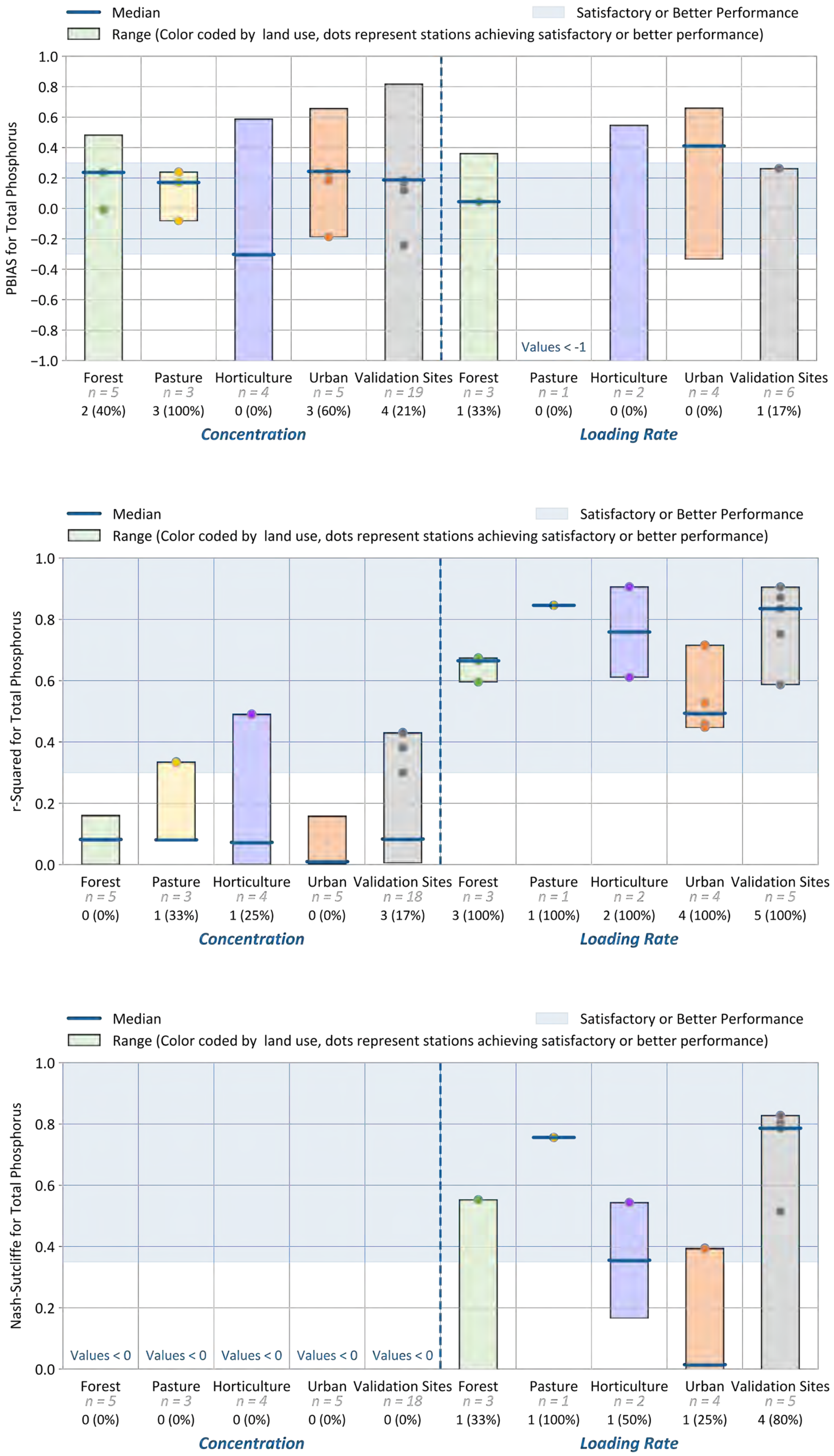


Figure 4-77. Concentrations and load performance metrics for TP by land use for the entire calibration period (2012-2016)

4.3.4.6 Dissolved Reactive Phosphorus

This subsection presents the DRP calibration outcomes. DRP was simulated with the RQUAL module to allow for prediction of instream transformations. HRUs represent the TP generation from the land before RQUAL fractionates this into phosphorous species for instream simulations (in LSPC, DRP is labelled orthophosphate). The parameters relied upon most for dissolved reactive phosphorous calibration are presented in Table 4-44.

The DRP prediction performance of the FWMT is presented as the following:

- Table 4-45: reports the station-by-station performance assessment based on flow-weighted average daily concentration for different seasons (left performance columns) and flow conditions (right performance columns) for r^2, PBIAS and NSE. White cells indicate insufficient samples in the bin to evaluate the metric (n<5 samples). Stations labelled N/A for Tier do not have a co-located flow gauge.
- Table 4-46: reports the station-by-station performance assessment based on daily loading rate (cumulative sum of 15-min concentration by flow for daily period) for different seasons (left performance columns) and flow conditions (right performance columns) for r^2, PBIAS and NSE.
- Figure 4-78: summarises the per cent of stations achieving different performance categories for flow-weighted average daily concentration across seasonal and flow-based conditions for r^2, PBIAS and NSE.
- Figure 4-79: summarises the per cent of stations achieving different performance categories for daily loading rate (cumulative sum of 15-min concentration by flow for daily period) across seasonal and flow-based conditions for r^2, PBIAS and NSE.
- Figure 4-80: presents the range and median of performance criteria results for calibration stations associated with a specific, dominant land use, as well as validation stations. The figure presents results for both concentrations and loads. Only stations with both observed water quality and flow data are presented for loading rate results.

The DRP performance panels are presented for each of the 36 stations in Appendix F6. The stations are ordered in the appendices identical to Table 4-45.

Table 4-44. Primary parameters leveraged during dissolved phosphorous calibration

Parameter Name	Description	Units
PO4	Orthophosphate fraction of TP loading from land entering stream	unitless
SPO4	Orthophosphate sediment bound fraction of TP loading from land entering stream	Unitless
ADPOPM *	adsorption coefficients for ortho-phosphorus-P adsorbed to sand, silt, and clay in reach	cm3/g

* Instream parameter set at model reaches

Table 4-45. Dissolved reactive phosphorus (concentration) FWMT Prediction Performance at AC SoE Stations

Tier	Water Quality Monitoring Locations	Drainage Area(km2)	Performance Metrics (Seasonal) PBIAS					Performance Metrics (Flow Regime) PBIAS				
			All	Winter	Spring	Summer	Fall	All	Top 25%	Storms	Low 50%	Baseflow
Tier 1	Wairoa River @ Tourist Road	149	-	-	+	-	-	-	-	-	-	-
Tier 2	Opanuku Stream @ Candia Road Bridge	15.3	-	-	-	-	-	-	-	-	-	-
	Oteha River @ Days Bridge	12.2	-	-	-	-	-	-	-	-	-	+
	Lucas @ Gills Road	6.1	-	-	-	-	-	-	-	-	-	-
	Ngakoroa Stream @ Mill Rd	4.8	-	-	-	-	-	-	-	-	-	-
	West Hoe @ Halls	0.5	-	-	+	-	-	-	-	-	-	-
Tier 3	Rangitopuni River @ Walkers	81.7	-	-	+	-	-	-	-	-	+	-
	Kaukapakapa @ Taylors	62.2	-	-	+	+	-	-	-	-	+	+
	Puhinui @ Drop Structure	12.6	-	-	-	+	-	-	-	-	-	+
	Oakley Creek at Richardson Road	5.9	+					+			+	+
Tier 4	Vaughn Stream @ Lower Weir	2.4	+	+	+	+	+	+	+	-	+	+
Tier 5	Oratia @ Parrs Cross Road	17.1	+					+			+	+
	Okura Creek @ Awanohi Rd	5.8	+	-		+	+	+	-	-	+	+
N/A	Mahurangi @ Warkworth Water Treatment Plant	50.1	-	-	+	+	-	-	-	-	+	+
	Makarau @ Railway	49.1	-	-	-	-	-	-	-	-	-	-
	Papakura Stream @ Porchester Road Bridge	45.1	+	+	+	+	-	+	-	-	+	+
	Kumeu River At Weza Lane	44.9	-	-	+	-	-	-	-	-	+	+
	Waiwera Stream @ Upper Waiwera Road	30.2	-	-	+	-	-	-	-	-	+	-
	Papakura @ Alfriston/Ardmore Rd	23.3	-	+	+	+	-	-	-	-	+	+
	Waitangi @ Waitangi Falls Bridge.	19.3	-	-	-	-	-	-	-	-	-	-
	Otara Stream @ Kennel Hill	18.3	-	-	+	-	+	-	-	-	+	+
	Matakana @ Wenzlicks Farm	13.4	-	-	-	+	+	-	-	-	+	+
	Oakley Creek @ Carrington.	11.9	-	-	-	-	-	-	-	-	-	+
	Cascades Stream @ Confluence	10.8	+	-	+	+	+	+	-	+	+	+
	Otara @ East Tamaki Rd	9.4	+	+	+	+	-	+	-	-	+	+
	Whangamaire @ Woodhouse Road	8	-	-	+	-	-	-	-	-	-	-
	Pakuranga @ Botany Rd	6.6	-	-	-	-	-	-	-	-	+	-
	Riverhead @ Ararimu Valley Road	4.6	+	-	+	+	+	+	-	-	+	+
	Omaru @ Maybury Street	3.5	-	-	+	-	-	-	-	-	+	+
	Avondale Stream @ Shadbolt Park	3	-	+	+	-	-	-	-	-	-	+
	Pakuranga @ Greenmount Drive	2.4	+	+	+	+	+	+	+	+	+	+
	Wairoa Trib @ Caitchons Rd	2.2	+	+	+	+	+	+	-	+	+	+
	Otaki @ Middlemore Crescent	1	+	+	+	+	+	+	+	+	+	+
	Nukumea @ Upper Site	1	+	+	+	+	+	+	+	+	+	+
	Onetangi @ Waiheke Rd	0.7	+	+	+	+	+	+	+	+	+	+
	Cascades @ Whakanewha	0.6	+	+	+	+	+	+	+	+	+	+

Performance Metrics (Seasonal): PBIAS, r-Squared, Nash-Sutcliffe E (All, Winter, Spring, Summer, Fall). Performance Metrics (Flow Regime): PBIAS, r-Squared, Nash-Sutcliffe E (All, Top 25%, Storms, Low 50%, Baseflow).

Grey shaded stations used modeled flow data for load calculations

Very Good | Good | Satisfactory | Unsatisfactory | + Overpredicts | - Underpredicts

Note: Tier refers to hydrologic data quality tier

Table 4-46. Dissolved reactive phosphorus (load) FWMT Prediction Performance at AC SoE Stations

	Water Quality Monitoring Locations		Performance Metrics (Seasonal)															Performance Metrics (Flow Regime)														
			PBIAS					r-Squared					Nash-Sutcliffe E					PBIAS					r-Squared					Nash-Sutcliffe E				
			All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow
Tier 1	Wairoa River @ Tourist Road	149	-	-	+	-	-											-	-	-	-	-										
Tier 2	Opanuku Stream @ Candia Road Bridge	15.3	-	-	-	+	-											-	-	-	-	-										
	Oteha River @ Days Bridge	12.2	-	+	-	-	-											-	-	-	-	+										
	Lucas @ Gills Road	6.1	-	-	-	-	-											-	-	-	-	+										
	Ngakoroa Stream @ Mill Rd	4.8	-	-	-	-	-											-	-	-	-	-										
	West Hoe @ Halls	0.5	-	-	+	+	-											-	-	-	+	-										
Tier 3	Rangitopuni River @ Walkers	81.7	-	+	-	-	-											-	-	-	-	-										
	Kaukapakapa @ Taylors	62.2	-	-	-	+	-											-	-	-	+	-										
	Puhinui @ Drop Structure	12.6	-	-	-	+	-											-	-	-	-	+										
	Oakley Creek at Richardson Road	5.9	+															+			+	+										
Tier 4	Vaughn Stream @ Lower Weir	2.4	-	-	-	+	-											-	-	-	-	+										
Tier 5	Oratia @ Parrs Cross Road	17.1	+															+			+	+										
	Okura Creek @ Awanohi Rd	5.8	-	-		-	-											-	-	-	-	+										
N/A	Mahurangi @ Warkworth Water Treatment Plant	50.1	-	-	+	+	-											-	-	-	+	-										
	Makarau @ Railway	49.1	-	-	-	-	-											-	-	-	-	-										
	Papakura Stream @ Porchester Road Bridge	45.1	-	+	+	+	-											-	-	-	+	+										
	Kumeu River At Weza Lane	44.9	-	-	+	-	-											-	-	-	+	-										
	Waiwera Stream @ Upper Waiwera Road	30.2	-	-	-	-	-											-	-	-	+	-										
	Papakura @ Alfriston/Ardmore Rd	23.3	-	-	+	+	-											-	-	-	+	+										
	Waitangi @ Waitangi Falls Bridge.	19.3	-	-	-	-	-											-	-	-	-	-										
	Otara Stream @ Kennel Hill	18.3	-	-	+	-	+											-	-	-	+	-										
	Matakana @ Wenzlicks Farm	13.4	-	-	-	+	+											-	-	-	+	+										
	Oakley Creek @ Carrington.	11.9	-	-	-	-	-											-	-	-	-	-										
	Cascades Stream @ Confluence	10.8	-	-	+	+	+											-	-	-	+	-										
	Otara @ East Tamaki Rd	9.4	-	-	+	+	-											-	-	-	+	+										
	Whangamaire @ Woodhouse Road	8	-	-	+	-	-											-	-	-	+	-										
	Pakuranga @ Botany Rd	6.6	-	-	-	-	+											-	-	-	-	-										
	Riverhead @ Ararimu Valley Road	4.6	-	-	-	+	-											-	-	-	+	-										
	Omaru @ Maybury Street	3.5	-	-	+	-	-											-	-	-	+	-										
	Avondale Stream @ Shadbolt Park	3	-	-	-	-	-											-	-	-	-	-										
	Pakuranga @ Greenmount Drive	2.4	+	-	+	+	+											+	+	-	+	+										
	Wairoa Trib @ Caitchons Rd	2.2	-	-	+	+	-											-	-	-	+	+										
	Otaki @ Middlemore Crescent	1	+	+	+	+	+											+	+	+	+	+										
	Nukumea @ Upper Site	1	+	-	+	+	+											+	+	-	+	+										
	Onetangi @ Waiheke Rd	0.7	+	+	+	+	+											+	+	+	+	+										
	Cascades @ Whakanewha	0.6	+	+	+	+	+											+	+	+	+	+										

Grey shaded stations used modeled flow data for load calculations

Very Good | Good | Satisfactory | Unsatisfactory
+ Overpredicts | - Underpredicts

Note: Tier refers to hydrologic data quality tier

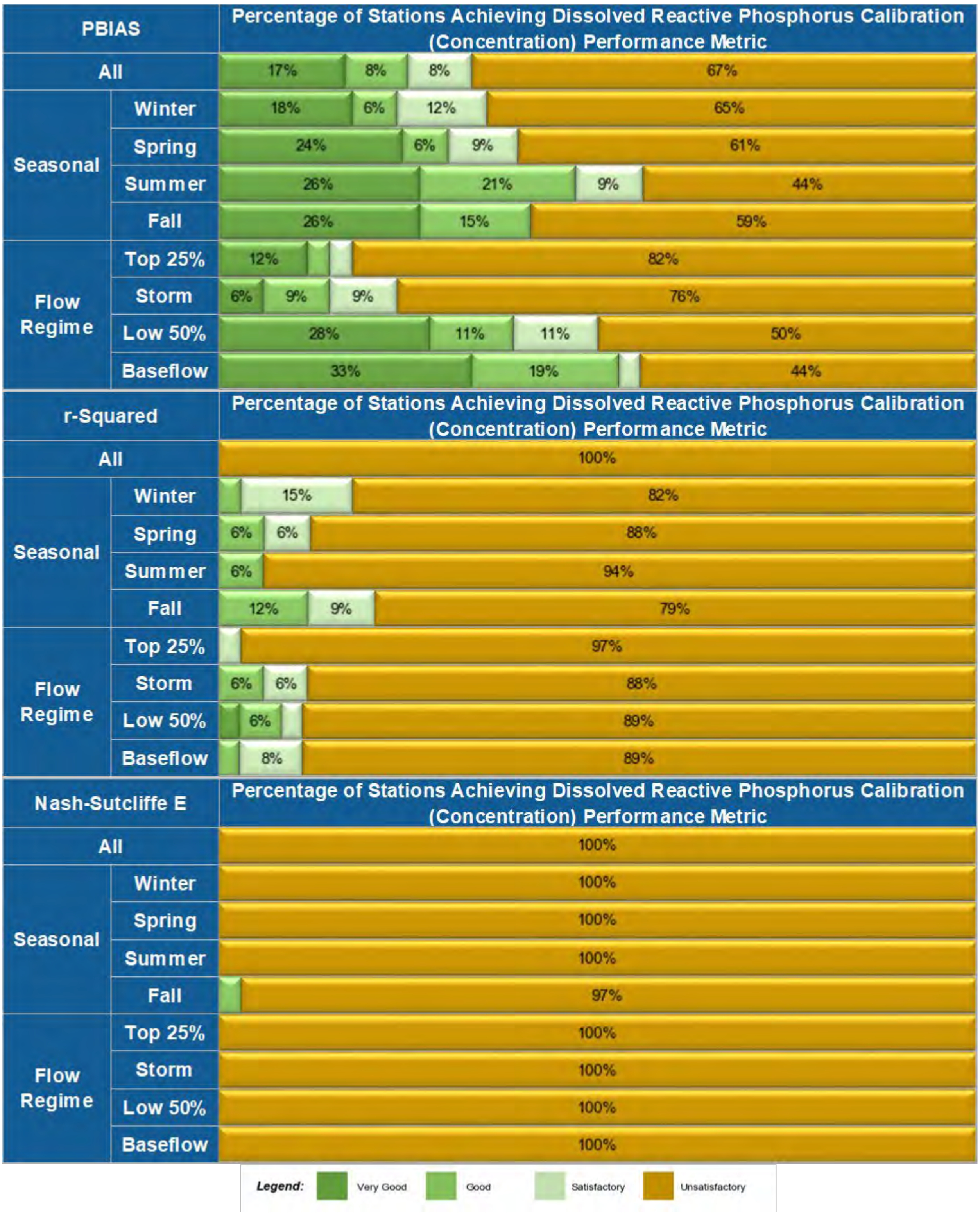


Figure 4-78. Dissolved reactive phosphorus (concentration) performance metrics for 36 Calibration and Validation AC SoE Stations

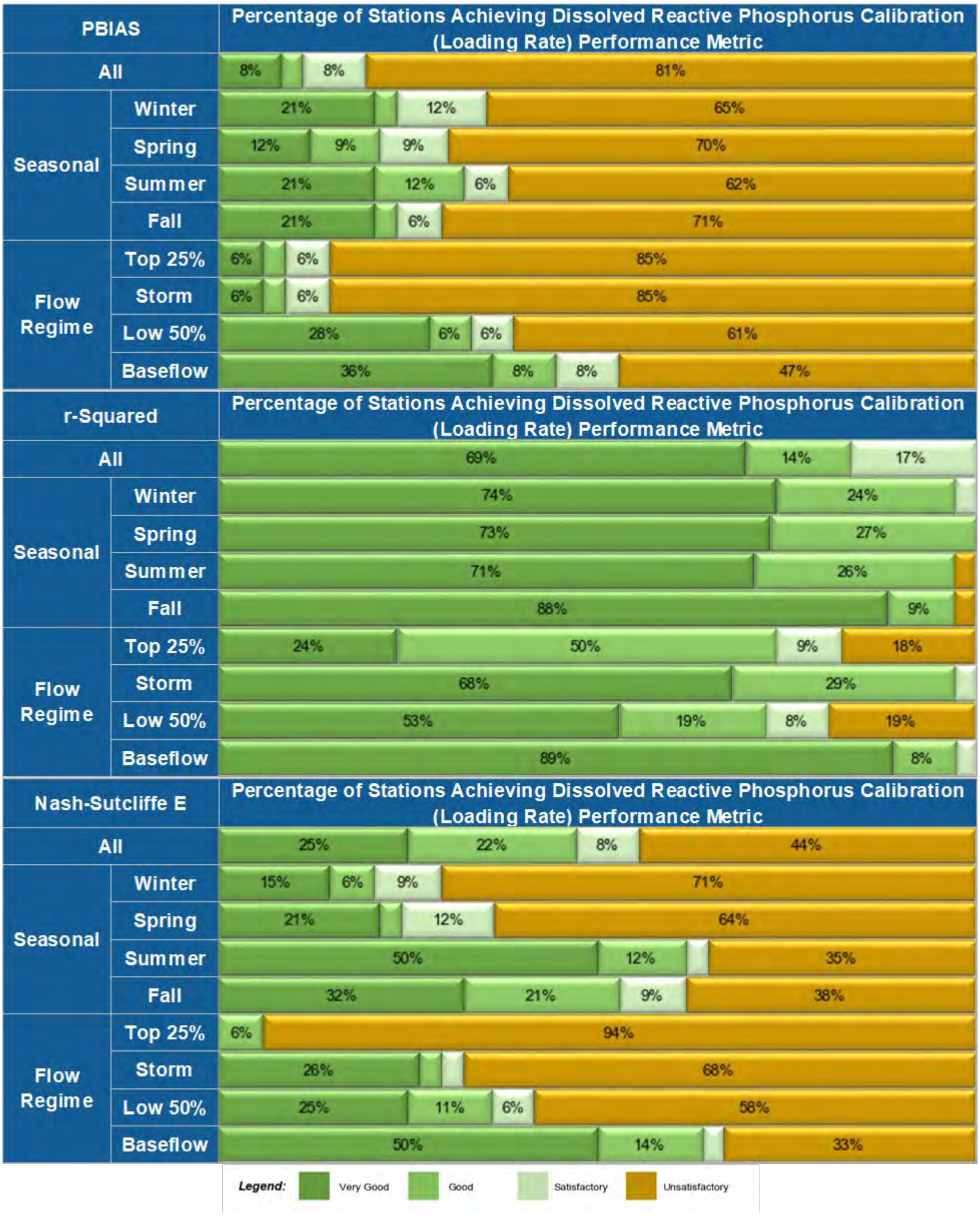


Figure 4-79. Dissolved reactive phosphorus (load) performance metrics for 36 Calibration and Validation AC SoE Stations

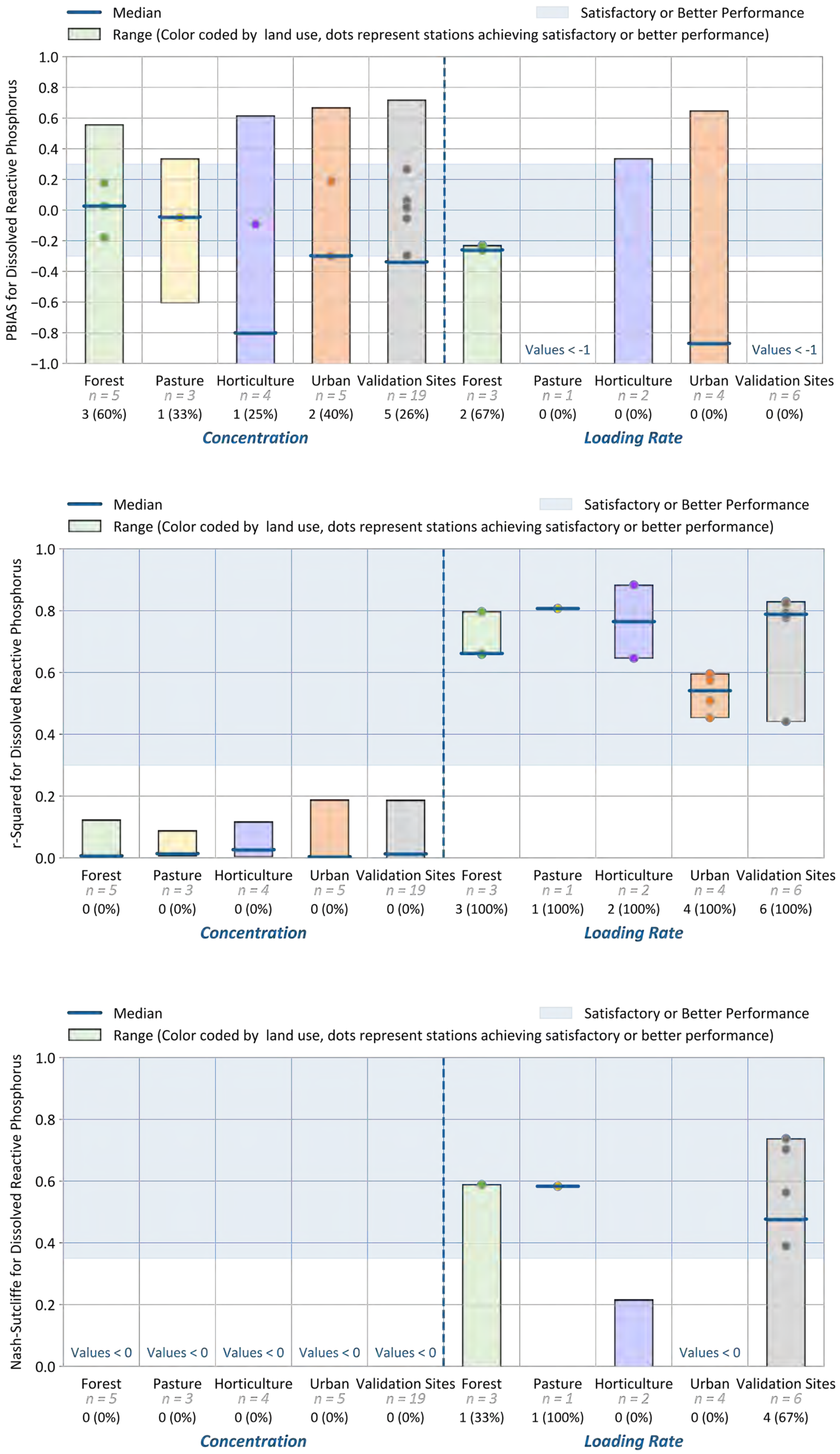


Figure 4-80. Concentrations and load performance metrics for DRP by land use for the entire calibration period (2012-2016)

4.3.4.7 Total Copper

This subsection presents the TCu calibration outcomes. TCu was simulated with GQUAL and is represented as sediment-associated by the FWMT. The parameters relied upon most for total copper calibration are presented in Table 4-47.

The TCu predictive performance of the FWMT is presented as the following:

- Table 4-48: reports the station-by-station performance assessment based on flow-weighted average daily concentration for different seasons (left performance columns) and flow conditions (right performance columns) for r^2, PBIAS and NSE. White cells indicate insufficient samples in the bin to evaluate the metric (n<5 samples). Stations labelled N/A for Tier do not have a co-located flow gauge.
- Table 4-49: reports the station-by-station performance assessment based on daily loading rate (cumulative sum of 15-min concentration by flow for daily period) for different seasons (left performance columns) and flow conditions (right performance columns) for r^2, PBIAS and NSE.
- Figure 4-81: summarises the per cent of stations achieving different performance categories for flow-weighted average daily concentration across seasonal and flow-based conditions for r^2, PBIAS and NSE.
- Figure 4-82: summarises the per cent of stations achieving different performance categories for daily loading rate (cumulative sum of 15-min concentration by flow for daily period) across seasonal and flow-based conditions for r^2, PBIAS and NSE.
- Figure 4-83: presents the range and median of performance criteria results for calibration stations associated with a specific, dominant land use, as well as validation stations. The figure presents results for both concentrations and loads. Only stations with both observed water quality and flow data are presented for loading rate results.

The TCu performance panels are presented for each of 25 AC SoE stations in Appendix F7. The stations are ordered in the appendices identical to Table 4-48.

Table 4-47. Primary parameters leveraged during total copper calibration

Parameter Name	Description	Units
POTFW (Copper)	Potency factor of Copper in sediment washed off from surfaces	kg TCu / ton sediment
POTFS (Copper)	Potency factor of Copper in sediment scoured from streambanks	kg TCu / ton sediment
IOQC(Copper)	Interflow concentration of Copper	mg/l
AOQC(Copper)	Active groundwater concentration of Copper	mg/l

Table 4-48. Total copper (concentration) FWMT Performance at 25 Calibration and Validation AC SoE Stations

Tier	Water Quality Monitoring Locations	Drainage Area\(km2)	Performance Metrics (Seasonal)															Performance Metrics (Flow Regime)														
			PBIAS					r-Squared					Nash-Sutcliffe E					PBIAS					r-Squared					Nash-Sutcliffe E				
			All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow
Tier 1	Wairoa River @ Tourist Road	148.9	+	+	+	+	+											+	+	+	+	+										
Tier 2	Oteha River @ Days Bridge	12.2	-	+	-	-	-											-	+	-	-	+										
	Lucas @ Gills Road	6.1	-	+	-	-	-											-	-	-	-	+										
Tier 3	Puhinui @ Drop Structure	12.6	-	+	-	-	-											-	+	-	-	+										
	Oakley Creek at Richardson Road	5.9	+															+			+	+										
Tier 4	Vaughn Stream @ Lower Weir	2.4	-	+	-	-	+											-	-	-	-	+										
Tier 5	Oratia @ Parrs Cross Road	17.1	+															+			+	+										
	Okura Creek @ Awanohi Rd	5.8	+	+		+	+											+	+	+	+	+										
N/A	Mahurangi @ Warkworth Water Treatment Plant	50.1	+	-	+	+	+											+	+	-	+	+										
	Makarau @ Railway	49.1	+	-	+	+	+											+	+	+	+	+										
	Papakura Stream @ Porchester Road Bridge	45.1	+	+	+	+	-											+	+	-	-	+										
	Kumeu River At Weza Lane	44.9	+	+	+	+	+											+	+	+	+	+										
	Waiwera Stream @ Upper Waiwera Road	30.2	-	-	+	+	+											-	-	-	+	+										
	Papakura @ Alfriston/Ardmore Rd	23.3	+	+	+	+	-											+	-	-	+	+										
	Otara Stream @ Kennel Hill	18.3	+	-	+	-	+											+	+	-	-	+										
	Matakana @ Wenzlicks Farm	13.4	+	+	+	+	+											+	+	+	+	+										
	Oakley Creek @ Carrington.	11.9	-	+	-	-	-											-	+	-	-	-										
	Otara @ East Tamaki Rd	9.4	+	+	+	-	+											+	+	-	-	+										
	Pakuranga @ Botany Rd	6.6	+	+	+	+	+											+	+	+	+	+										
	Riverhead @ Ararimu Valley Road	4.6	-	-	+	+	-											-	-	-	+	+										
	Omaru @ Maybury Street	3.5	+	+	+	+	+											+	+	-	+	+										
	Avondale Stream @ Shadbolt Park	3	+	+	+	-	+											+	+	-	-	+										
	Pakuranga @ Greenmount Drive	2.4	+	+	+	+	+											+	+	-	+	+										
	Otaki @ Middlemore Crescent	1	+	+	+	+	+											+	+	+	+	+										
	Nukumea @ Upper Site	1	+	+	+	+	+											+	+	+	+	+										

Grey shaded stations used modeled flow data for load calculations

Very Good | Good | Satisfactory | Unsatisfactory
+ Overpredicts | - Underpredicts

Note: Tier refers to hydrologic data quality tier

Table 4-49. Total copper (load) FWMT Prediction Performance at 25 Calibration and Validation AC SoE Stations

Tier	Water Quality Monitoring Locations		Seasonal PBIAS All	Seasonal PBIAS Winter	Seasonal PBIAS Spring	Seasonal PBIAS Summer	Seasonal PBIAS Fall	Seasonal r-Squared All	Seasonal r-Squared Winter	Seasonal r-Squared Spring	Seasonal r-Squared Summer	Seasonal r-Squared Fall	Seasonal Nash-Sutcliffe E All	Seasonal Nash-Sutcliffe E Winter	Seasonal Nash-Sutcliffe E Spring	Seasonal Nash-Sutcliffe E Summer	Seasonal Nash-Sutcliffe E Fall	Flow Regime PBIAS All	Flow Regime PBIAS Top 25%	Flow Regime PBIAS Storms	Flow Regime PBIAS Low 50%	Flow Regime PBIAS Baseflow	Flow Regime r-Squared All	Flow Regime r-Squared Top 25%	Flow Regime r-Squared Storms	Flow Regime r-Squared Low 50%	Flow Regime r-Squared Baseflow	Flow Regime Nash-Sutcliffe E All	Flow Regime Nash-Sutcliffe E Top 25%	Flow Regime Nash-Sutcliffe E Storms	Flow Regime Nash-Sutcliffe E Low 50%	Flow Regime Nash-Sutcliffe E Baseflow
Tier 1	Wairoa River @ Tourist Road	148.9	+	+	+	+	+											+	+	+	+	+										
Tier 2	Oteha River @ Days Bridge	12.2	+	+	+	-	-											+	+	+	-	+										
	Lucas @ Gills Road	6.1	+	+	+	-	-											+	+	-	-	+										
Tier 3	Puhinui @ Drop Structure	12.6	-	+	-	-	-											-	-	-	-	+										
	Oakley Creek at Richardson Road	5.9	+															+			-	+										
Tier 4	Vaughn Stream @ Lower Weir	2.4	-	-	-	-	+											-	-	-	-	+										
Tier 5	Oratia @ Parrs Cross Road	17.1	+															+			+	+										
	Okura Creek @ Awanohi Rd	5.8	+	+		+	+											+	+	+	+	+										
N/A	Mahurangi @ Warkworth Water Treatment Plant	50.1	-	-	+	+	+											-	-	-	+	+										
	Makarau @ Railway	49.1	-	-	+	+	+											-	-	-	+	+										
	Papakura Stream @ Porchester Road Bridge	45.1	+	+	+	+	-											+	+	-	+	+										
	Kumeu River At Weza Lane	44.9	+	-	+	+	+											+	+	-	+	+										
	Waiwera Stream @ Upper Waiwera Road	30.2	-	-	+	+	+											-	-	-	+	+										
	Papakura @ Alfriston/Ardmore Rd	23.3	-	+	+	+	-											-	-	-	+	+										
	Otara Stream @ Kennel Hill	18.3	-	-	+	+	+											-	-	-	-	+										
	Matakana @ Wenzlicks Farm	13.4	+	+	-	+	+											+	+	+	+	+										
	Oakley Creek @ Carrington.	11.9	+	+	-	+	-											+	+	+	-	-										
	Otara @ East Tamaki Rd	9.4	-	-	+	+	+											-	-	-	-	+										
	Pakuranga @ Botany Rd	6.6	+	-	+	+	+											+	+	-	+	+										
	Riverhead @ Ararimu Valley Road	4.6	-	-	+	+	-											-	-	-	+	+										
	Omaru @ Maybury Street	3.5	+	+	+	+	+											+	+	-	+	+										
	Avondale Stream @ Shadbolt Park	3	+	+	+	+	+											+	+	+	-	+										
	Pakuranga @ Greenmount Drive	2.4	-	-	+	+	+											-	-	-	+	+										
	Otaki @ Middlemore Crescent	1	+	+	-	+	+											+	+	+	+	+										
	Nukumea @ Upper Site	1	+	+	+	+	+											+	+	+	+	+										

Grey shaded stations used modeled flow data for load calculations

Very Good · Good · Satisfactory · Unsatisfactory

\+ Overpredicts · - Underpredicts

Note: Tier refers to hydrologic data quality tier

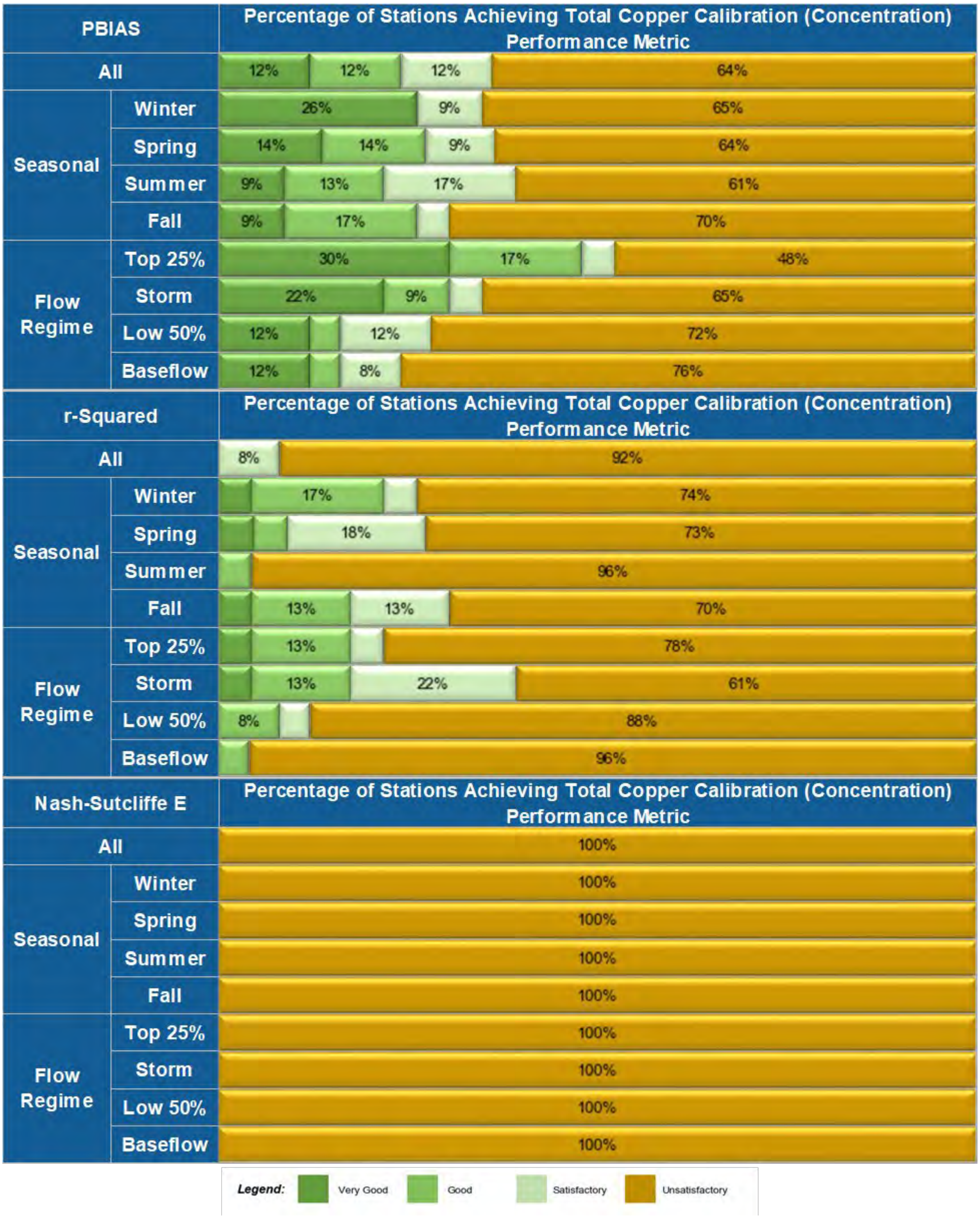


Figure 4-81. Total copper (concentration) Performance at 25 Calibration and Validation AC SoE Stations

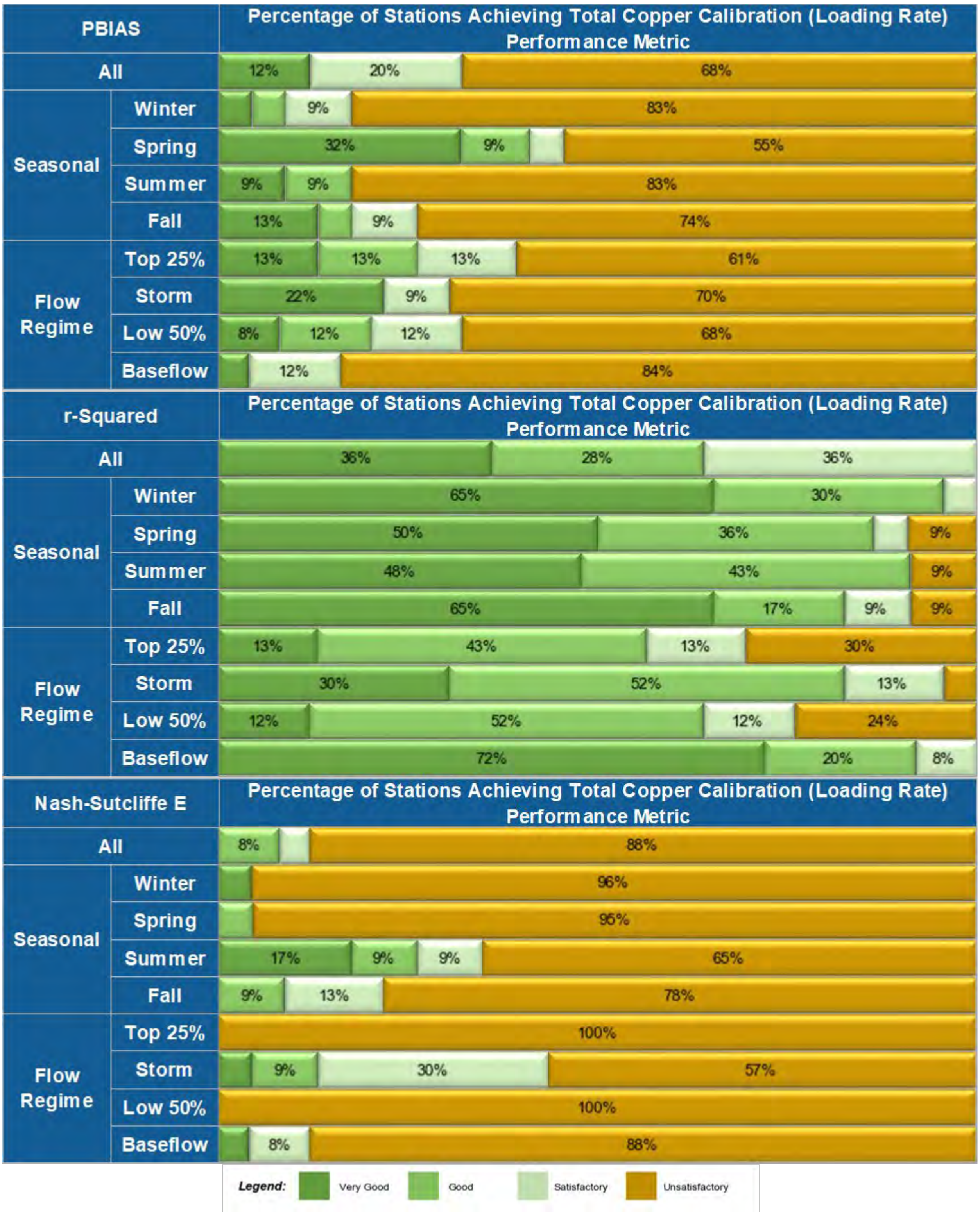
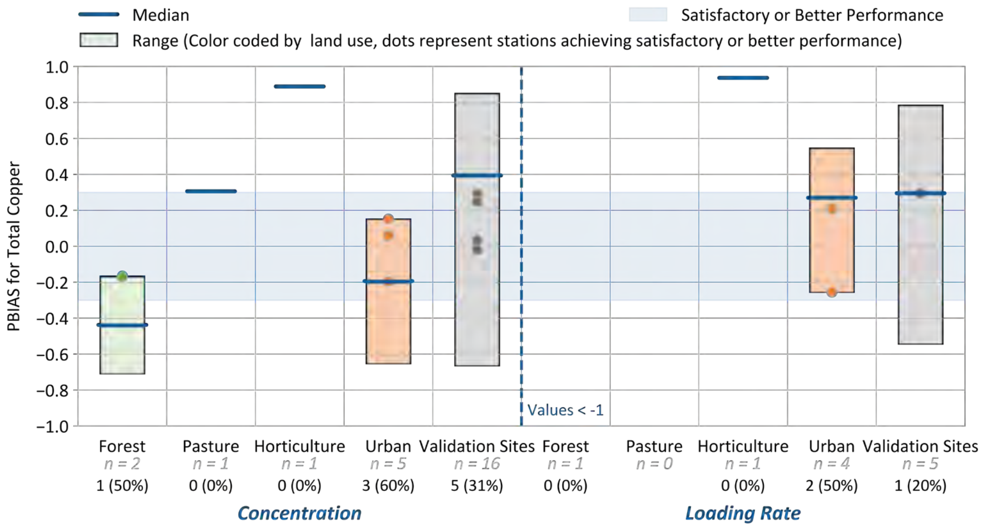
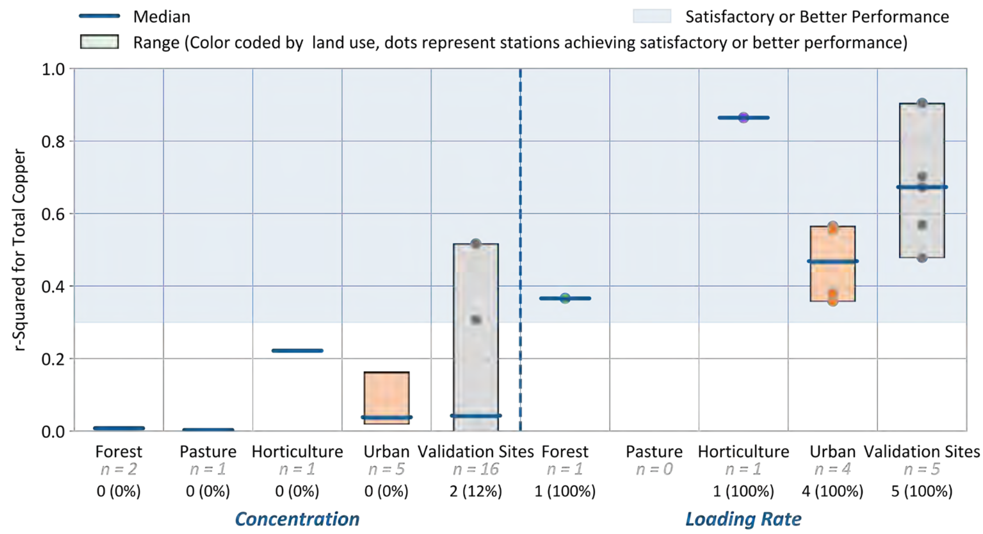


Figure 4-82. Total copper (load) Performance at 25 Calibration and Validation AC SoE Stations





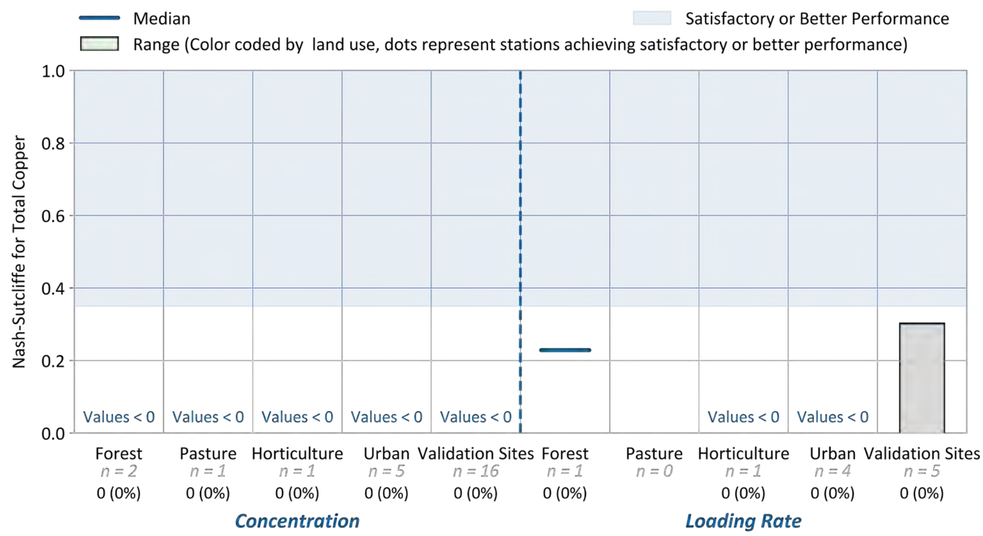


Figure 4-83. Concentrations and load performance metrics for TCu by land use for the entire calibration period (2012-2016)

4.3.4.8 Total Zinc

This subsection presents the TZn calibration outcomes. TZn was simulated with GQUAL and is represented as sediment-associated by the FWMT. The parameters relied upon most for TZn calibration are presented in Table 4-50.

The TZn predictive performance of the FWMT is presented as the following:

- Table 4-51: reports the station-by-station performance assessment based on flow-weighted average daily concentration for different seasons (left performance columns) and flow conditions (right performance columns) for r^2, PBIAS and NSE. White cells indicate insufficient samples in the bin to evaluate the metric (n<5 samples). Stations labelled N/A for Tier do not have a co-located flow gauge.
- Table 4-52: reports the station-by-station performance assessment based on daily loading rate (cumulative sum of 15-min concentration by flow for daily period) for different seasons (left performance columns) and flow conditions (right performance columns) for r^2, PBIAS and NSE.
- Figure 4-84: summarises the per cent of stations achieving different performance categories for flow-weighted average daily concentration across seasonal and flow-based conditions for r^2, PBIAS and NSE.
- Figure 4-85: summarises the per cent of stations achieving different performance categories for daily loading rate (cumulative sum of 15-min concentration by flow for daily period) across seasonal and flow-based conditions for r^2, PBIAS and NSE.
- Figure 4-86: presents the range and median of performance criteria results for calibration stations associated with a specific, dominant land use, as well as validation stations. The figure presents results for both concentrations and loads. Only stations with both observed water quality and flow data are presented for loading rate results.

The TZn performance panels are presented for each of the 25 AC SoE stations in Appendix F7. The stations are ordered in the appendices identical to Table 4-51.

Table 4-50. Primary parameters leveraged during total zinc calibration

Parameter Name	Description	Units
POTFW (Copper)	Potency factor of Copper in sediment washed off from surfaces	kg TCu / ton sediment
POTFS (Copper)	Potency factor of Copper in sediment scoured from streambanks	kg TCu / ton sediment
IOQC(Copper)	Interflow concentration of Copper	mg/l
AOQC(Copper)	Active groundwater concentration of Copper	mg/l

Table 4-51. Total zinc (concentration) FWMT Performance at 25 Calibration and Validation AC SoE Stations

Tier	Water Quality Monitoring Locations	Drainage Area\(km2)	Performance Metrics (Seasonal)															Performance Metrics (Flow Regime)														
			PBIAS					r-Squared					Nash-Sutcliffe E					PBIAS					r-Squared					Nash-Sutcliffe E				
			All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow
Tier 1	Wairoa River @ Tourist Road	148.9	+	+	+	-	+											+	+	+	-	+										
Tier 2	Oteha River @ Days Bridge	12.2	+	+	-	-	+											+	+	-	+	+										
	Lucas @ Gills Road	6.1	-	+	-	-	-											-	-	-	-	-										
Tier 3	Puhinui @ Drop Structure	12.6	+	+	+	-	+											+	+	+	-	+										
	Oakley Creek at Richardson Road	5.9	-															-			-	-										
Tier 4	Vaughn Stream @ Lower Weir	2.4	+	+	-	-	+											+	+	-	-	+										
Tier 5	Oratia @ Parrs Cross Road	17.1	+															+			+	+										
	Okura Creek @ Awanohi Rd	5.8	+	+		+	+											+	+	+	-	+										
N/A	Mahurangi @ Warkworth Water Treatment Plant	50.1	-	+	-	-	+											-	+	+	-	-										
	Makarau @ Railway	49.1	+	-	+	+	+											+	-	-	+	+										
	Papakura Stream @ Porchester Road Bridge	45.1	+	+	-	-	-											+	+	-	-	+										
	Kumeu River At Weza Lane	44.9	+	+	+	+	+											+	+	+	+	+										
	Waiwera Stream @ Upper Waiwera Road	30.2	-	-	-	-	-											-	-	-	-	-										
	Papakura @ Alfriston/Ardmore Rd	23.3	+	+	+	+	-											+	+	-	+	+										
	Otara Stream @ Kennel Hill	18.3	+	+	+	-	+											+	+	+	-	+										
	Matakana @ Wenzlicks Farm	13.4	+	+	-	-	+											+	+	+	-	+										
	Oakley Creek @ Carrington.	11.9	-	+	-	-	-											-	+	-	-	-										
	Otara @ East Tamaki Rd	9.4	+	+	+	-	+											+	+	+	+	+										
	Pakuranga @ Botany Rd	6.6	+	+	+	+	+											+	+	+	+	+										
	Riverhead @ Ararimu Valley Road	4.6	+	+	+	+	+											+	+	+	+	+										
	Omaru @ Maybury Street	3.5	+	+	+	+	+											+	+	+	+	+										
	Avondale Stream @ Shadbolt Park	3	+	+	+	-	+											+	+	+	-	+										
	Pakuranga @ Greenmount Drive	2.4	+	+	+	+	+											+	+	+	+	+										
	Otaki @ Middlemore Crescent	1	+	+	+	+	+											+	+	+	+	+										
	Nukumea @ Upper Site	1	+	+	+	+	+											+	+	+	+	+										

Grey shaded stations used modeled flow data for load calculations

Very Good | Good | Satisfactory | Unsatisfactory

+ Overpredicts | - Underpredicts

Note: Tier refers to hydrologic data quality tier

Table 4-52. Total zinc (load) Performance at 25 Calibration and Validation AC SoE Stations

	Water Quality Monitoring Locations		Performance Metrics (Seasonal)															Performance Metrics (Flow Regime)														
			PBIAS					r-Squared					Nash-Sutcliffe E					PBIAS					r-Squared					Nash-Sutcliffe E				
			All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Winter	Spring	Summer	Fall	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow	All	Top 25%	Storms	Low 50%	Baseflow
Tier 1	Wairoa River @ Tourist Road	148.9	+	+	+	-	+											+	+	+	-	+										
Tier 2	Oteha River @ Days Bridge	12.2	+	+	+	-	+											+	+	+	-	+										
	Lucas @ Gills Road	6.1	-	+	-	-	-											-	+	-	-	+										
Tier 3	Puhinui @ Drop Structure	12.6	+	+	+	+	+											+	+	+	+	+										
	Oakley Creek at Richardson Road	5.9	+															+			-	-										
Tier 4	Vaughn Stream @ Lower Weir	2.4	-	-	-	-	+											-	-	-	-	+										
Tier 5	Oratia @ Parrs Cross Road	17.1	+															+			+	+										
	Okura Creek @ Awanohi Rd	5.8	+	+		+	+											+	+	+	-	+										
N/A	Mahurangi @ Warkworth Water Treatment Plant	50.1	+	-	+	+	+											+	+	-	-	+										
	Makarau @ Railway	49.1	-	-	+	+	+											-	-	-	+	+										
	Papakura Stream @ Porchester Road Bridge	45.1	+	+	+	+	-											+	+	+	-	+										
	Kumeu River At Weza Lane	44.9	+	+	+	+	+											+	+	+	+	+										
	Waiwera Stream @ Upper Waiwera Road	30.2	-	-	+	-	+											-	-	-	-	+										
	Papakura @ Alfriston/Ardmore Rd	23.3	-	+	+	+	-											-	-	-	+	+										
	Otara Stream @ Kennel Hill	18.3	+	+	-	+	+											+	+	+	-	+										
	Matakana @ Wenzlicks Farm	13.4	+	+	-	+	+											+	+	+	-	+										
	Oakley Creek @ Carrington.	11.9	+	+	-	-	-											+	+	+	-	+										
	Otara @ East Tamaki Rd	9.4	+	+	+	+	+											+	+	+	+	+										
	Pakuranga @ Botany Rd	6.6	+	+	+	+	+											+	+	+	+	+										
	Riverhead @ Ararimu Valley Road	4.6	+	+	+	+	+											+	+	-	+	+										
	Omaru @ Maybury Street	3.5	+	+	+	+	+											+	+	+	+	+										
	Avondale Stream @ Shadbolt Park	3	+	+	+	+	+											+	+	+	-	+										
	Pakuranga @ Greenmount Drive	2.4	+	+	+	+	+											+	+	+	+	+										
	Otaki @ Middlemore Crescent	1	+	+	+	+	+											+	+	+	+	+										
	Nukumea @ Upper Site	1	+	+	+	+	+											+	+	+	+	+										

Grey shaded stations used modeled flow data for load calculations

Very Good | Good | Satisfactory | Unsatisfactory

\+ Overpredicts | - Underpredicts

Note: Tier refers to hydrologic data quality tier

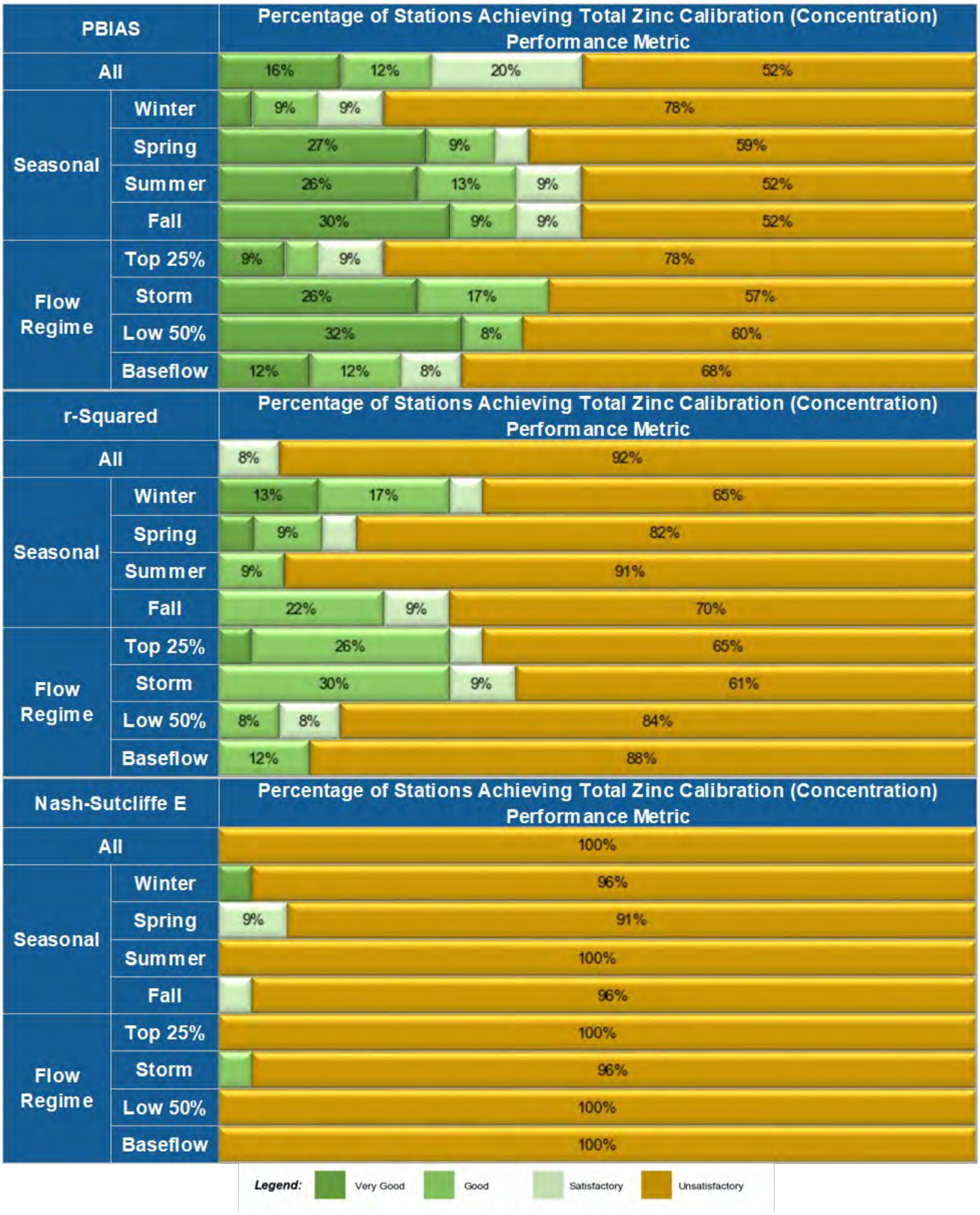


Figure 4-84. Total zinc (concentration) Performance at 25 Calibration and Validation AC SoE Stations

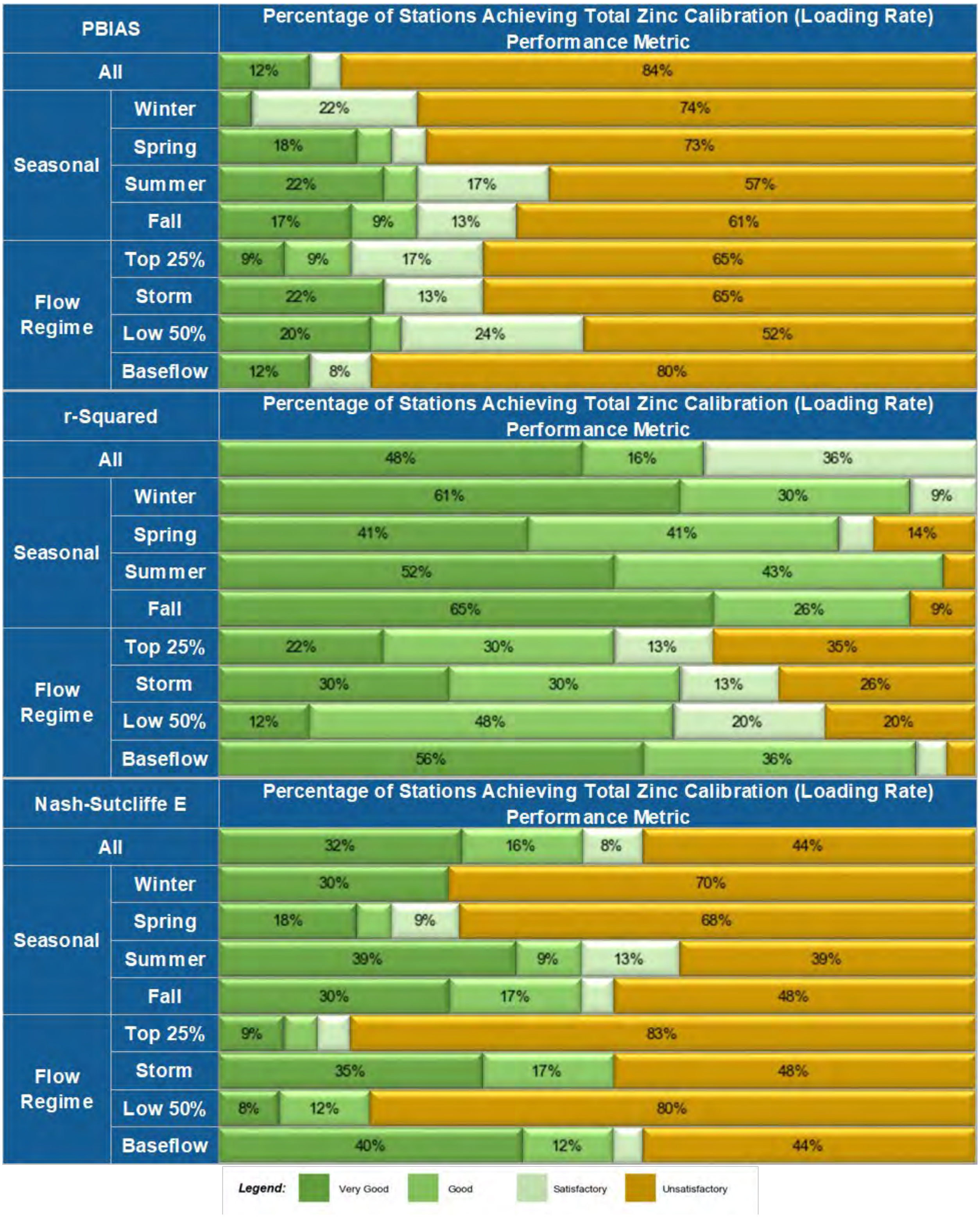


Figure 4-85. Total zinc (load) Performance at 25 Calibration and Validation AC SoE Stations

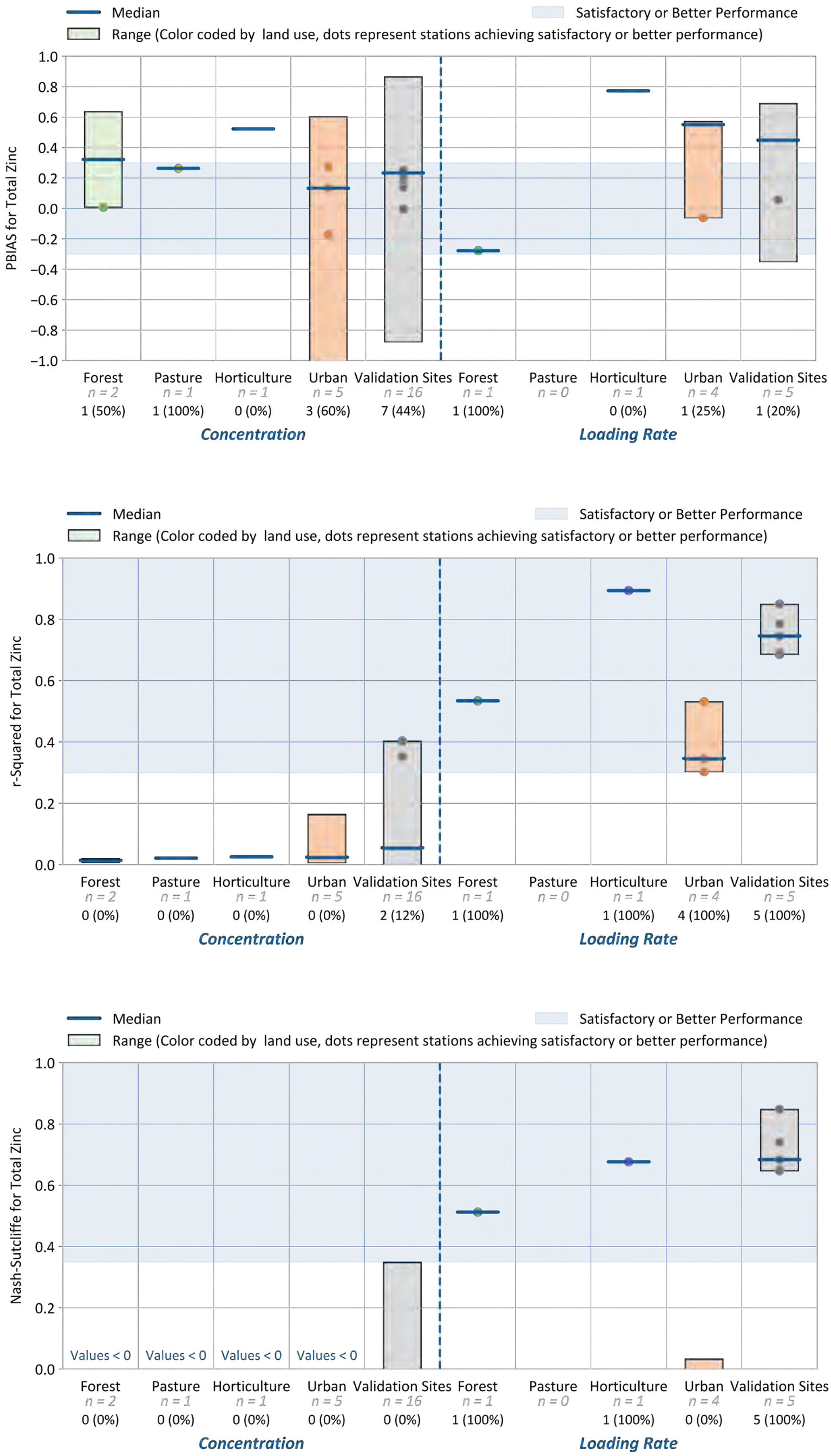


Figure 4-86. Concentrations and load performance metrics for TZn by land use for the entire calibration period (2012-2016)

4.3.4.9 *E. coli*

This subsection presents the *E. coli* calibration outcomes. *E. coli* was simulated with GQUAL and is represented as sediment-associated by the FWMT. The parameters relied upon most for *E. coli* calibration are presented in Table 4-53.

The *E. coli* prediction performance of the FWMT is presented as the following:

- Table 4-54: reports the station-by-station performance assessment based on flow-weighted average daily concentration for different seasons (left performance columns) and flow conditions (right performance columns) for r^2, PBIAS and NSE. White cells indicate insufficient samples in the bin to evaluate the metric (n<5 samples). Stations labelled N/A for Tier do not have a co-located flow gage.
- Table 4-55: reports the station-by-station performance assessment based on daily loading rate (cumulative sum of 15-min concentration by flow for daily period) for different seasons (left performance columns) and flow conditions (right performance columns) for r^2, PBIAS and NSE.
- Figure 4-87: summarises the per cent of stations achieving different performance categories for flow-weighted average daily concentration across seasonal and flow-based conditions for r^2, PBIAS and NSE.
- Figure 4-88: summarises the per cent of stations achieving different performance categories for daily loading rate (cumulative sum of 15-min concentration by flow for daily period) across seasonal and flow-based conditions for r^2, PBIAS and NSE.
- Figure 4-89: presents the range and median of performance criteria results for calibration stations associated with a specific, dominant land use, as well as validation stations. The figure presents results for both concentrations and loads. Only stations with both observed water quality and flow data are presented for loading rate results.

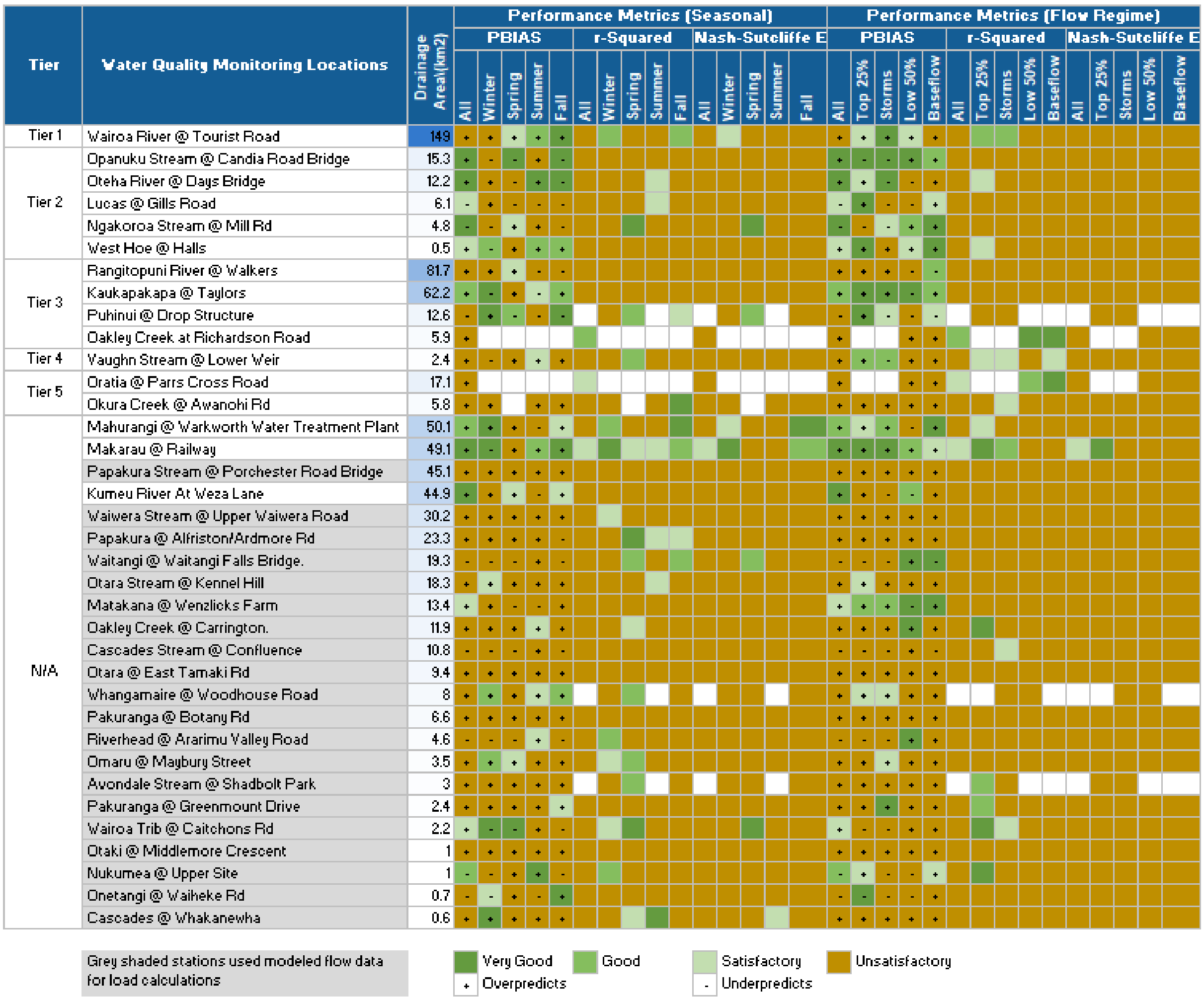
The *E. coli* performance panels are presented for each of the 36 AC SoE stations in Appendix F9. The stations are ordered in the appendices identical to Table 4-54.

Table 4-53. Primary parameters leveraged during *E. coli* calibration

Parameter Name	Description	Units
ACQOP (*E. coli*)	Rate at which *E. coli* accumulates on the land surface	#/ha/day
SQOLIM (*E. coli*)	Maximum storage of *E. coli* on surface	#/ha
IOQC	Interflow concentration of *E. coli*	#/100ml
AOQC	Active groundwater concentration of *E. coli*	#/100ml
DECAY *	general first-order instream loss rate of *E. coli*	1/day

* Instream parameter set at model reaches

Table 4-54. *E. coli* (concentration) FWMT Prediction Performance at AC SoE Stations



Note: Tier refers to hydrologic data quality tier

Table 4-55. *E. coli* (load) FWMT Prediction Performance at AC SoE Stations

Tier	Water Quality Monitoring Locations		Seasonal PBIAS All	Seasonal PBIAS Winter	Seasonal PBIAS Spring	Seasonal PBIAS Summer	Seasonal PBIAS Fall	Seasonal r-Squared All	Seasonal r-Squared Winter	Seasonal r-Squared Spring	Seasonal r-Squared Summer	Seasonal r-Squared Fall	Seasonal Nash-Sutcliffe E All	Seasonal Nash-Sutcliffe E Winter	Seasonal Nash-Sutcliffe E Spring	Seasonal Nash-Sutcliffe E Summer	Seasonal Nash-Sutcliffe E Fall	Flow Regime PBIAS All	Flow Regime PBIAS Top 25%	Flow Regime PBIAS Storms	Flow Regime PBIAS Low 50%	Flow Regime PBIAS Baseflow	Flow Regime r-Squared All	Flow Regime r-Squared Top 25%	Flow Regime r-Squared Storms	Flow Regime r-Squared Low 50%	Flow Regime r-Squared Baseflow	Flow Regime Nash-Sutcliffe E All	Flow Regime Nash-Sutcliffe E Top 25%	Flow Regime Nash-Sutcliffe E Storms	Flow Regime Nash-Sutcliffe E Low 50%	Flow Regime Nash-Sutcliffe E Baseflow
Tier 1	Wairoa River @ Tourist Road	149	+	+	+	-	+											+	+	+	+	+										
Tier 2	Opanuku Stream @ Candia Road Bridge	15.3	-	-	+	+	-											-	-	-	+	-										
	Oteha River @ Days Bridge	12.2	+	+	+	-	+											+	+	+	-	+										
	Lucas @ Gills Road	6.1	+	+	+	-	-											+	+	+	-	+										
	Ngakoroa Stream @ Mill Rd	4.8	-	-	+	+	-											-	-	-	-	-										
	West Hoe @ Halls	0.5	+	-	+	+	+											+	+	+	+	+										
Tier 3	Rangitopuni River @ Walkers	81.7	+	+	+	-	-											+	+	+	-	+										
	Kaukapakapa @ Taylors	62.2	-	-	+	-	+											-	-	-	-	-										
	Puhinui @ Drop Structure	12.6	-	+	+	-	-											-	+	-	-	+										
	Oakley Creek at Richardson Road	5.9	+															+			+	+										
Tier 4	Vaughn Stream @ Lower Weir	2.4	-	-	+	+	+											-	-	-	+	+										
Tier 5	Oratia @ Parrs Cross Road	17.1	+															+			+	+										
	Okura Creek @ Awanohi Rd	5.8	+	+		+	+											+	+	+	+	+										
N/A	Mahurangi @ Warkworth Water Treatment Plant	50.1	+	+	+	+	+											+	+	+	-	+										
	Makarau @ Railway	49.1	+	-	+	+	+											+	+	+	+	+										
	Papakura Stream @ Porchester Road Bridge	45.1	+	+	+	+	-											+	+	+	+	+										
	Kumeu River At Weza Lane	44.9	+	+	+	-	+											+	+	-	-	+										
	Waiwera Stream @ Upper Waiwera Road	30.2	+	+	+	+	+											+	+	+	+	+										
	Papakura @ Alfriston/Ardmore Rd	23.3	-	+	+	+	-											-	-	-	+	+										
	Waitangi @ Waitangi Falls Bridge.	19.3	-	-	-	+	-											-	-	-	+	-										
	Otara Stream @ Kennel Hill	18.3	+	-	+	+	+											+	+	-	+	+										
	Matakana @ Wenzlicks Farm	13.4	+	+	-	+	+											+	+	+	+	+										
	Oakley Creek @ Carrington.	11.9	+	+	+	+	+											+	+	+	+	+										
	Cascades Stream @ Confluence	10.8	-	-	+	+	-											-	-	-	-	-										
	Otara @ East Tamaki Rd	9.4	+	+	+	+	+											+	+	+	+	+										
	Whangamaire @ Woodhouse Road	8	+	+	+	+	+											+	+	+	+	+										
	Pakuranga @ Botany Rd	6.6	+	+	+	+	+											+	+	+	+	+										
	Riverhead @ Ararimu Valley Road	4.6	-	-	-	+	-											-	-	-	-	-										
	Omaru @ Maybury Street	3.5	+	+	+	+	+											+	+	+	+	+										
	Avondale Stream @ Shadbolt Park	3	+	+	+	+	+											+	+	+	+	+										
	Pakuranga @ Greenmount Drive	2.4	+	-	+	+	+											+	+	-	+	+										
	Wairoa Trib @ Caitchons Rd	2.2	-	-	-	+	-											-	-	-	+	+										
	Otaki @ Middlemore Crescent	1	+	+	+	+	+											+	+	+	+	+										
	Nukumea @ Upper Site	1	+	-	+	+	-											+	+	+	-	-										
	Onetangi @ Waiheke Rd	0.7	+	-	+	+	-											+	-	-	-	+										
	Cascades @ Whakanewha	0.6	+	+	+	+	+											+	+	+	+	+										

Grey shaded stations used modeled flow data for load calculations

Very Good | Good | Satisfactory | Unsatisfactory

+ Overpredicts | - Underpredicts

Note: Tier refers to hydrologic data quality tier

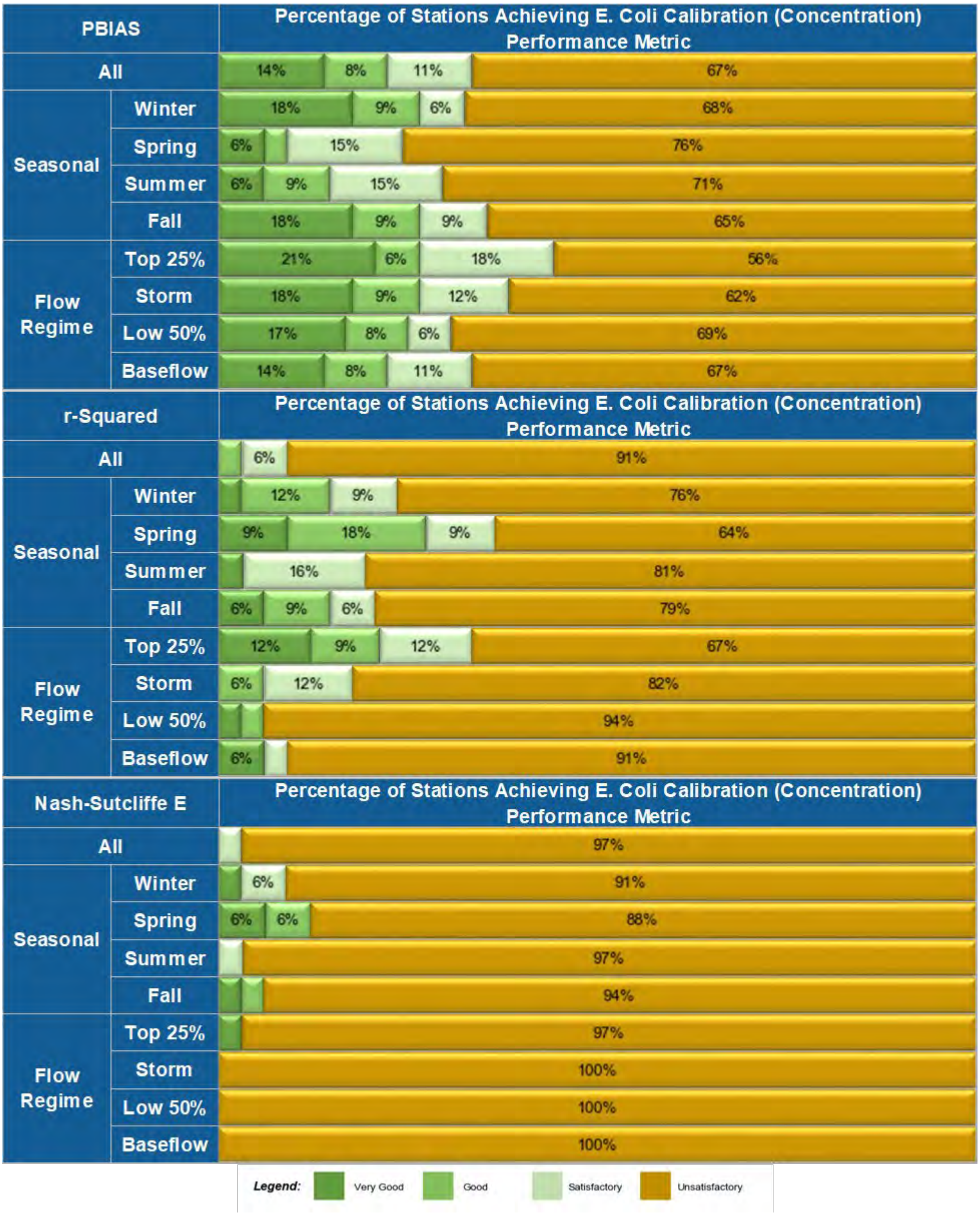


Figure 4-87. ***E. coli*** **(concentration) performance metrics for 36 Calibration and Validation AC SoE Stations**

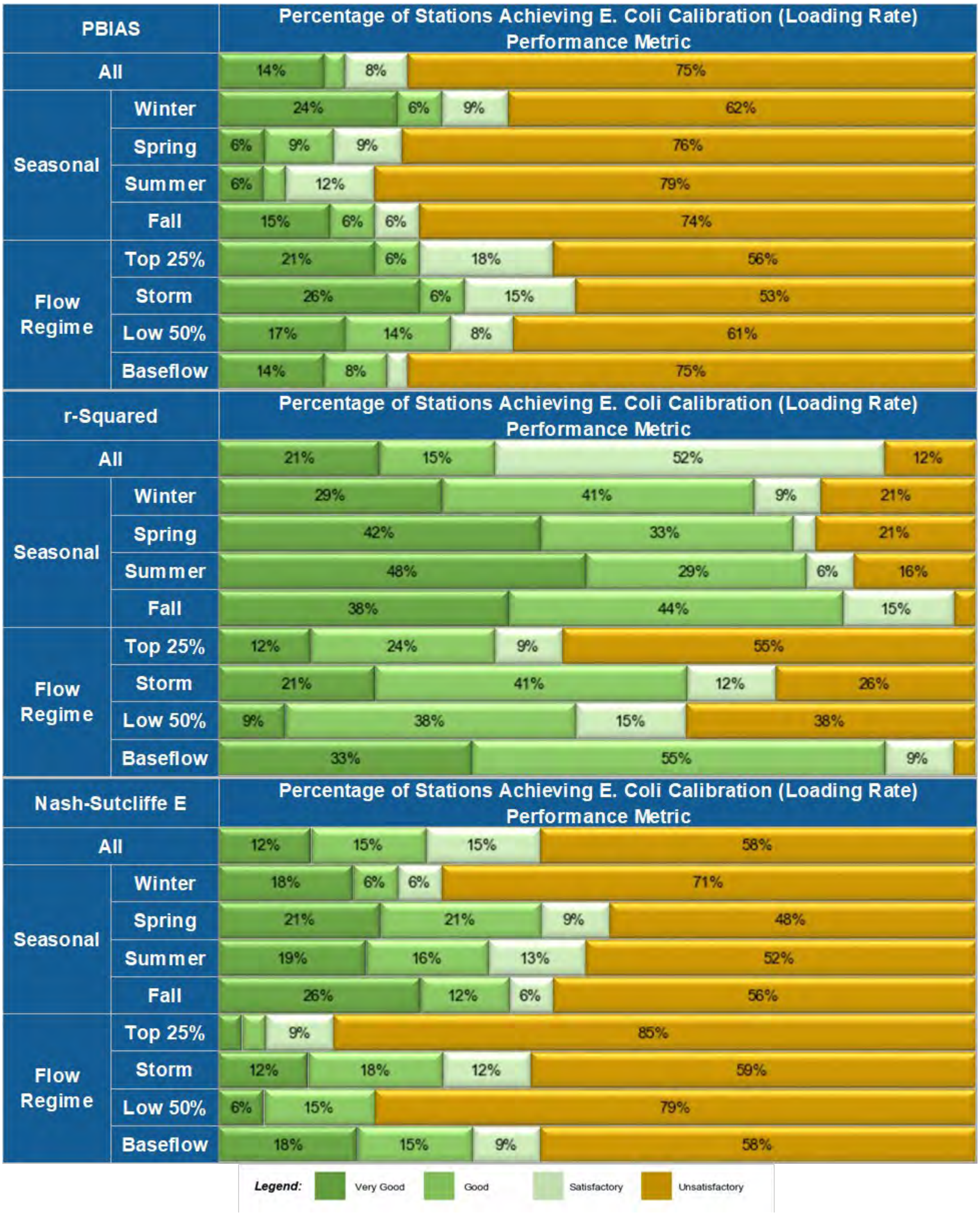


Figure 4-88. ***E. coli*** **(load) performance metrics for 36 Calibration and Validation AC SoE Stations**

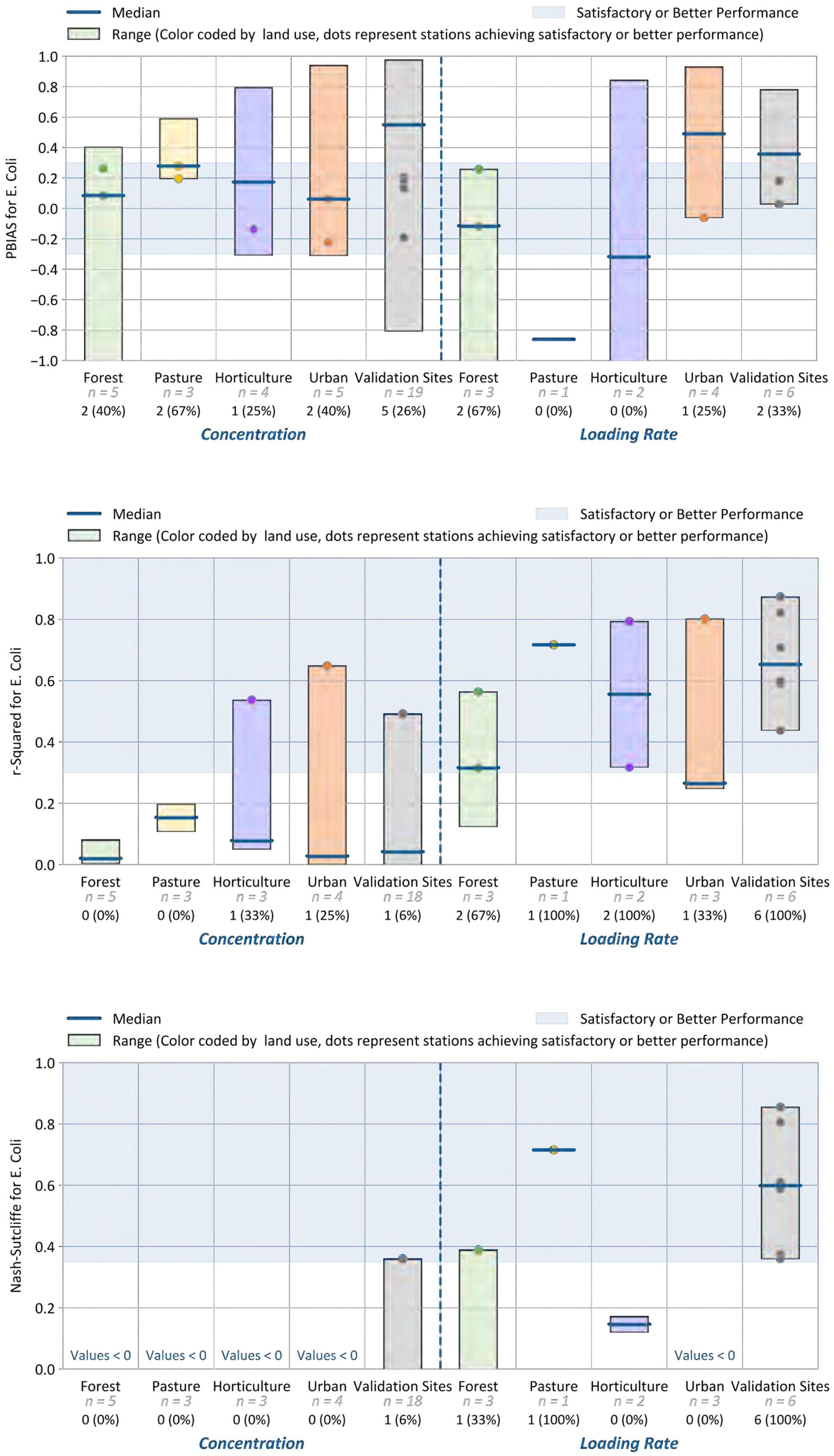


Figure 4-89. Concentrations and load performance metrics for *E. coli* by land use for the entire calibration period (2012-2016)

4.3.5 Performance Summary

This section provides a summary overview including subsections for each contaminant (Table 4-56). Inferring an overall narrative about performance of the FWMT Stage 1 is challenging. For instance, Auckland Council's planning response to the NPS-FM is in development (e.g., Freshwater Management Units, regional priority contaminants and conditions defining water quality objectives remain undefined). Also, (1) the applied metrics used for performance assessment are highly stringent and do not reflect FWMT purposes but rather a wider suite of model type and purpose; (2) do not consider the grading-based outcomes informing NOF and regional objective decision-making (i.e., Section 4 reports on "accuracy" or the ability to predict any concentration or load along a full gradient, not specificity or sensitivity to predict envelopes of concentrations or grades well; both of which are particularly important to using models for grading-based purposes [Nevers and Whitman, 2011; Theo et al., 2014]); (3) the comparison of grab samples to daily average concentrations is intrinsically challenging (i.e., lacks information on how representative grab samples are of diel or cross-sectional variation, but compares to uniformly-mixed continuous output); (4) the temporal coverage of the monthly water quality dataset is much more limited than the hydrologic dataset (i.e., observations are lacking between monthly sampling – less a performance problem and more a representation challenge for modelled output then disagreeing with observed in later assessments of baseline state); and (5) water quality measurements are subject to much more error than flow rate measurements (e.g., field, laboratory and database – with limited ability to account for these in performance assessments except by tiering stations).

Importantly, the continuous measures of performance assessed here (r2, PBias, NSE) and guidance (Moriasi et al., 2015) have purposely been chosen to deliver conservative findings; to support ongoing and continuous improvement without shifting performance thresholds in continuous measures over the full decadal FWMT development programme.

Collectively, contaminant loading is considerably better simulated than concentration reflecting generally "good" or better ability to continuously simulate hydrology in the FWMT Stage 1.

Overall, across "all" flows for the five-year period 2012-2016 and across the three performance metrics, the number of SoE stations continuously modelled with "satisfactory" or better performance varied[8]:

[8] Noting concentration performance is estimated at varying numbers of the 36 SoE stations (depending on metric and varying from 9-17 stations for calibration through to 5-19 stations for validation). Satisfactory or better defined by modification of Moriasi et al. (2015).

- TSS concentration 0-12% for calibration (0-32% validation) and TSS load 0-65% for calibration (10-100% validation);
- TN concentration 6-53% for calibration (0-42% validation) and TN load 40-90% for calibration (0-100% validation);
- TON concentration 0-47% for calibration (5-26% validation) and TON load 30-60% for calibration (17-100% validation);
- TAM concentration 0-24% for calibration (0-5% validation) and TAM load 25-100% for calibration (0-100% validation);
- TP concentration 0-47% for calibration (0-21% validation) and TP load 10-100% for calibration (17-100% validation);
- DRP concentration 0-42% for calibration (0-26% validation) and DRP load 20-100% for calibration (0-100% validation)
- TCu concentration 0-44% for calibration (0-31% validation) and TCu load 0-67% for calibration (0-100% validation)
- TZn concentration 0-56% for calibration (0-44% validation) and TZn load 33-100% for calibration (20-100% validation)
- *E. coli* concentration 0-42% for calibration (6-26% validation) and *E. coli* load 22-67% for calibration (33-100% validation)

Limitations need to be carefully considered, not simply in the quality and representativity of existing contaminant sampling (e.g., upstream composition and sizes of SoE catchments) but in the value of *continuous* performance assessment (e.g., r2, PBias, NSE). The FWMT Stage 1 is intended primarily for use in reporting on grading and optimisation of management to grading-based outcomes. LSPC is naturally likely to be limited by inherent complexity in any assessment of NSE, whilst continuous performance is not alike to grading-based performance (correctly grading sites) and not preferential to enriched (degraded) sites when otherwise regional planning must prioritise degraded sites for managed improvement (i.e., that lower accuracy in A-graded sites is less concerning than lower accuracy in D-graded sites, for FWMT purposes).

4.3.5.1 Total Suspended Solids

For TSS concentration, 4 stations achieved satisfactory or better performance for PBIAS (Figure 4-65). Both concentration and loading appear to generally overpredicted based on prevalence of negative PBIAS values. Agreement substantially improved based on r^2 with all sited achieving satisfactory or better results for loading. While no sites had satisfactory concentration prediction based on

NSE, all horticulture and validation sites, as well as the pasture site had satisfactory or better predictions for loading.

4.3.5.2 Total Nitrogen

For TN concentration, 47% of stations achieved satisfactory or better performance based on PBIAS (Figure 4-68). The majority (93%) of both calibration and validation sites obtained satisfactory performance for TN loading based on r^2. A satisfactory NSE for concentration was achieved for a horticultural site. Overall, horticultural sites had the highest percentage of sites achieving a satisfactory performance across metrics.

4.3.5.3 Total Oxidised Nitrogen

For TON concentration predictions, 36% of calibration stations achieved satisfactory PBIAS performance, with 3 of the 4 horticultural calibration stations achieving satisfactory or better performance (Figure 4-71). A smaller percentage of stations achieved satisfactory or better PBIAS performance for load predictions. Alternatively, loading predictions improved based on r^2 with all horticultural and validation sites as well as the pasture site achieving satisfactory or better performance. All six validation sites achieved satisfactory or better NSE performance for loading.

4.3.5.4 Total Ammoniacal Nitrogen

For TAM, more calibration and validation sites achieved satisfactory or better PBIAS values for concentration compared to load (Figure 4-74). While no sites achieved satisfactory r^2 values for concentration, all achieved satisfactory or better values for loading. The horticultural site could not be assessed for the r^2 load metric. The pasture site and all assessed validation sites achieved satisfactory or better NSE values for TAM loading while no stations achieved satisfactory NSE values for concentrations.

4.3.5.5 Total Phosphorus

For TP, several sites achieved satisfactory PBIAS results for concentration, including all 3 pasture sites and 3 of the 5 urban sites (Figure 4-77). All assessed sites achieved satisfactory or better r^2 values for loading. A majority of validation sites (80%) as well as one of each land use calibration site achieved satisfactory or better NSE scores for loading while no site had a satisfactory NSE score for concentration.

4.3.5.6 Dissolved Reactive Phosphorus

Several stations calibration and validation stations achieved satisfactory or better PBIAS scores for DRP concentrations, however, only two forest sites achieved such scores flow loading (Figure 4-80). While no sites achieved satisfactory r^2 values for concentrations, all sites achieved satisfactory or better r^2 values for loading. Loading was also better predicted based on NSE values, with several validation sites as well as a forest and pasture site achieving satisfactory or better performance while no sites achieved satisfactory performance based on concentration.

4.3.5.7 Total Copper

For TCu, 25% of sites achieved satisfactory or better scores for concentrations based on PBIAS scores (Figure 4-83). Scores for both the pasture and horticulture calibration sites were positive, suggesting underestimation. Developed sites had generally good agreement for both concentration and loading. All assessed sites achieved satisfactory or better r^2 values for loading, although no statistic could be calculated for loading from the pasture site. No sites achieved satisfactory values for NSE for either concentration or loading.

4.3.5.8 Total Zinc

Zinc had similar performance to TCu, with 33% of sites achieved satisfactory or better scores for concentrations based on PBIAS scores (Figure 4-86). While the pasture site achieved a satisfactory score and the horticultural site did not, both were positive, indicating underprediction. All assessed sites achieved satisfactory or better r^2 values for loading, although no statistic could be calculated for loading from the pasture site. Unlike TCu, several sites, including all validation sites as well as the horticulture and forest sites achieved satisfactory NSE score for loading.

4.3.5.9 *E. coli*

For *E. coli*, 33% of sties achieved satisfactory or better PBIAS performance for predicting concentration and loading (Figure 4-89). Loading predictions tended toward over prediction in forest, pasture, and horticulture sites, while developed and validation sites tended toward underprediction. Performance was higher for loading predictions compared to concentration based on r^2. Only one validation site achieved satisfactory performance for concentration prediction based on NSE. Alternatively, all validation sites as well as the pasture site and forest site achieved satisfactory performance for load predictions based on NSE.

Table 4-56. Summary of per cent of SoE stations calibrated or validated with satisfactory or better performance, for each of three metrics by concentration (Conc) and Load (for period 2012-2016)

Station	Metric	TSS		TN		TON		TAM		TP		DRP		TCu		TZn		*E. coli*	
		Conc	Load	Conc	Load	Conc	Load	Conc	Load	Conc	Load	Conc	Load	Conc	Load	Conc	Load	Conc	Load
Forest	PBIAS	0% (0/5)	0% (0/3)	40% (2/5)	33% (1/3)	40% (2/5)	33% (1/3)	0% (0/5)	33% (1/3)	40% (2/5)	33% (1/3)	60% (3/5)	67% (2/3)	50% (1/2)	0% (0/1)	50% (1/2)	100% (1/1)	40% (2/5)	67% (2/3)
	r2	0% (0/5)	100% (3/3)	0% (0/5)	100% (3/3)	0% (0/5)	67% (2/3)	0% (0/4)	100% (2/2)	0% (0/5)	100% (3/3)	0% (0/5)	100% (3/3)	0% (0/2)	100% (1/1)	0% (0/2)	100% (1/1)	0% (0/5)	67% (2/3)
	NSE	0% (0/5)	0% (0/3)	0% (0/5)	33% (1/3)	0% (0/5)	33% (1/3)	0% (0/4)	0% (0/2)	0% (0/5)	33% (1/3)	0% (0/5)	33% (1/3)	0% (0/2)	0% (0/1)	0% (0/2)	100% (1/1)	0% (0/5)	33% (1/3)
Pasture	PBIAS	33% (1/3)	0% (0/1)	100% (3/3)	0% (0/1)	67% (2/3)	0% (0/1)	67% (2/3)	0% (0/1)	100% (3/3)	0% (0/1)	33% (1/3)	0% (0/1)	0% (0/1)	NA	100% (1/1)	NA	67% (2/3)	0% (0/1)
	r2	33% (1/3)	100% (1/1)	33% (1/3)	100% (1/1)	33% (1/3)	100% (1/1)	0% (0/3)	100% (1/1)	33% (1/3)	100% (1/1)	0% (0/3)	100% (1/1)	0% (0/1)	NA	0% (0/1)	NA	0% (0/3)	100% (1/1)
	NSE	0% (0/3)	100% (1/1)	0% (0/3)	100% (1/1)	0% (0/3)	100% (1/1)	0% (0/3)	100% (1/1)	0% (0/3)	100% (1/1)	0% (0/3)	100% (1/1)	0% (0/1)	NA	0% (0/1)	NA	0% (0/3)	100% (1/1)
Horticulture	PBIAS	25% (1/4)	0% (0/2)	75% (3/4)	50% (1/2)	75% (3/4)	50% (1/2)	50% (2/4)	0% (0/2)	0% (0/4)	0% (0/2)	25% (1/4)	0% (0/2)	0% (0/1)	0% (0/1)	0% (0/1)	0% (0/1)	25% (1/4)	0% (0/2)
	r2	25% (1/4)	100% (2/2)	50% (2/4)	100% (2/2)	50% (2/4)	100% (2/2)	0% (0/2)	NA	25% (1/4)	100% (2/2)	0% (0/4)	100% (2/2)	0% (0/1)	100% (1/1)	0% (0/1)	100% (1/1)	33% (1/3)	100% (2/2)
	NSE	0% (0/4)	100% (2/2)	25% (1/4)	100% (2/2)	0% (0/4)	50% (1/2)	0% (0/2)	NA	0% (0/4)	50% (1/2)	0% (0/4)	0% (0/2)	0% (0/1)	0% (0/1)	0% (0/1)	100% (1/1)	0% (0/3)	0% (0/2)
Developed	PBIAS	0% (0/5)	25% (1/4)	20% (1/5)	50% (2/4)	20% (1/5)	50% (2/4)	0% (0/5)	25% (1/4)	60% (3/5)	0% (0/4)	40% (2/5)	0% (0/4)	60% (3/5)	50% (2/4)	60% (3/5)	25% (1/4)	40% (2/5)	25% (1/4)
	r2	0% (0/5)	100% (4/4)	0% (0/5)	75% (3/4)	0% (0/5)	25% (1/4)	0% (0/2)	100% (1/1)	0% (0/5)	100% (4/4)	0% (0/5)	100% (4/4)	0% (0/5)	100% (4/4)	0% (0/5)	100% (4/4)	25% (1/4)	33% (1/3)
	NSE	0% (0/5)	0% (0/4)	0% (0/5)	0% (0/4)	0% (0/5)	0% (0/4)	0% (0/2)	0% (0/1)	0% (0/5)	25% (1/4)	0% (0/5)	0% (0/4)	0% (0/5)	0% (0/4)	0% (0/5)	0% (0/4)	0% (0/4)	0% (0/3)
Validation	PBIAS	11% (2/19)	17% (1/6)	42% (8/19)	0% (0/6)	26% (5/19)	17% (1/6)	5% (1/19)	0% (0/6)	21% (4/19)	17% (1/6)	26% (5/19)	0% (0/6)	31% (5/16)	20% (1/5)	44% (7/16)	20% (1/5)	26% (5/19)	33% (2/6)
	r2	32% (6/19)	100% (6/6)	11% (2/18)	100% (5/5)	11% (2/19)	100% (6/6)	0% (0/13)	100% (5/5)	17% (3/18)	100% (5/5)	0% (0/19)	100% (6/6)	12% (2/16)	100% (5/5)	12% (2/16)	100% (5/5)	6% (1/18)	100% (6/6)
	NSE	0% (0/19)	100% (6/6)	0% (0/18)	100% (5/5)	5% (1/19)	100% (6/6)	0% (0/13)	100% (5/5)	0% (0/18)	80% (4/5)	0% (0/19)	67% (4/6)	0% (0/16)	0% (0/5)	0% (0/16)	100% (5/5)	6% (1/18)	100% (6/6)

4.4 Discussion

The FWMT is being designed to provide reasonable assurance that implementation planning and policies for the NPS-FM in Auckland Council, are robust and based upon the best available evidence (i.e., required under Clause 1.6 of NPS-FM 2020). Other NPS-FM (2020) clauses are also relevant to discussion of FWMT Stage 1 design for purpose. Notably:

- Clause 3.2 – Implementation of Te Mana o te Wai with an integrated approach (“ki uta ki tai”);
- Clause 3. 4 – Tangata whenua involvement and active participation in decision-making (e.g., development of necessary support tools/systems);
- Clause 3.5 – Integrated management of freshwater to avoid, remedy or mitigate adverse effects (cumulative) and pre-emptive management of over-allocation;
- Clause 3.6 – Transparent decision-making through publication of decisions and relevant or supporting matters (e.g., decision support tools/systems).

For context, water quality implementation plans (called Reasonable Assurance Analyses [RAAs]; many of which used LPSC and SUSTAIN), in Los Angeles County California were recently challenged to the State Water Resources Control Board (link), which issued an order with the following discussion:

> “The RAA, particularly in its early iterations, is not and cannot be expected to be precise. Permittees are working with incomplete data and models that, while advanced, are imperfect. While we expect the RAAs to be developed through a rigorous process, we recognise that their initial iterations will necessarily be imprecise. “[T]he very purpose of a model is to aid in evaluating conditions and outcomes over space and time when limited data are available. As data continue to be collected, model results are validated and model inputs and assumptions can be adjusted if necessary.”

Water quality performance metrics spanned thresholds for “very good” to “unsatisfactory”, developed from Moriasi et al. (2015). Model performance was markedly better for contaminant loading than concentration. Some error is attributable to comparing continuously simulated model output to monthly grab sample results. Extremes in continuous daily loads may be represented in the simulation but more poorly represented by monthly grab sampling. While the model output is summarised as a flow weighted average concentration for comparison to observations, a preferable alternative would be for targeted, more frequent validation monitoring. These findings do not mean that FWMT cannot be used to simulate contaminant concentrations. The NPS-FM (2020) indeed, obliges use of best available information used in decision-making and reporting, including from modelling (e.g., sub-clauses 1.6, 3.10, 3.11, 3.14, 3.16).

Through continuous improvement during a decadal development programme, the FWMT offers valuable information on water quality (e.g., daily average concentrations based on long-term, processed-based continuous simulation; information on long-term and event-based contaminant sources; information on acute and chronic risks to target with management; integration of land use for freshwater streams and coastal receiving environments regionwide from mountains to sea). The FWMT also has clear benefit for understanding and managing pollutant loadings. In the United States, TMDLs often focus on daily loads rather than daily concentrations and the FWMT may support mass-based and/or concentration-based limits and management objectives that may be deemed appropriate under varying circumstances.

Recommendations for improved contaminant concentration and load simulation performance in the FWMT, include: (1) temporal-compositing during storm events (e.g., high-resolution event-based sampling); (2) monitoring locations distributed at end-of-pipe and prior to mixing with receiving water as well as instream; (3) instream stations distributed downstream of moderate or larger, fairly homogeneous HRUs (i.e., large enough and homogenous enough to capture regionalised HRU responses); (4) improved records of HRUs to enable dynamic configuration (e.g., extent and over time); and (5) data regarding the potency of sediment for phosphorous, copper and zinc as LSPC processing is relatively sensitive to TSS (i.e., whether a distinct process akin to groundwater contributions of TON should be incorporated for some contaminants and able to simulate non-sedimentary sources like fertilizer usage).

In the FWMT Stage 1 “Baseline State – Rivers” report, evaluation of the LSPC outputs and performance incorporates principles that might be more relevant (than performance metrics) for evaluating LSPC’s ability to predict water quality in Auckland’s streams. The approach evaluates the performance of Stage 1 LSPC for predicting the water quality *grading* of stream segments; that is, considering performance with ‘bands’ of concentrations instead of only relying on metrics like PBIAS. This alternative approach addresses limitations of PBIAS-type metrics which do not account for the absolute magnitude of the concentration. For example, at very low levels of a contaminant (e.g., 1 mg/L of TSS), a 50% or 100% difference in simulated vs observed concentration is likely inconsequential to water quality planning. The same applies to very high levels of contaminant – for example, eutrophication effects may be identical at 2 mg/L vs 10 mg/L of nitrate. Such grading-based foci are shared by recreational public health modelling in Auckland Council (e.g., Safeswim prediction of recreational risk grading – that the absolute value of the prediction is less important than whether beach conditions are safe vs unsafe). However, accuracy and the ability to predict continuously along a gradient of contaminant outcomes is particularly important to optimisation that aims to achieve a discrete concentration or load-based outcome. Hence, the FWMT Stage 1 will require careful application in future state or scenario modelling to ensure the sensitivity of intervention strategies to optimisation is well understood.

Under its iterative development approach, the FWMT will evolve over time to improve and meet the needs of Auckland's water quality programmes – whether accuracy, sensitivity or specificity-based. For Stage 1 and as outlined in Section 1, the major next steps for reporting of boundary conditions include the reports in Table 4-57.

In the long-term as described in Section 1, the FWMT will enable delivery of adaptive planning for stormwater management under the Healthy Waters Network Discharge Consent. It will support decision-making and communication, facilitating the development of water quality investment strategies through the Long-term Plan (LTP), including for the prioritised allocation of funding sources such as the Water Quality Targeted Rate (WQTR). The configuration and calibration of the LSPC component of the FWMT demonstrates its adherence to the principles of freshwater accounting (MfE, 2015). The FWMT is therefore seen as an important part of the development of Auckland's Water Strategy, as described in the "Our Water Future – Tō tātou wai ahu ake nei" discussion document. By simulating future scenarios supported on integrated water management principles, the FWMT can provide a fast track towards implementing innovative solutions, such as multifunctional or green infrastructure, and evaluate contributions to wellbeing in the environmental, cultural, social, and economic facets of our society.

Table 4-57. Reports linked to the FWMT Stage 1 Baseline Configuration and Calibration report.

Baseline Report (Stage 1 FWMT)	Purpose
Baseline Inputs	Describes inputs of boundary conditions and HRU typology utilised to represent baseline (2013-17) conditions in the FWMT. Incorporates all datasets whether pre-existing or generated purposely for the FWMT that have subsequently configured or driven LSPC.
Baseline State (Rivers)	Describes output of baseline accounting. Assesses spread of predicted hydrology, distribution of yields and instream loads – describing that by watershed, source and pathway, for 5-year baseline state interval (2013-17). Assesses instream gradings by contaminant over full 5-year interval (2013-17) and subsets of (wet vs. dry years; storm vs. base flow) – linking back to calibration findings on robustness of such output for FWMT purposes and objectives.
Baseline State (Lakes)	Describes output of LSPC and post process assessment on baseline lake conditions utilising optimised Vollenweider equations for predicting steady-state in-lake TN, TP, Chl-a and SD from continuous external TN and TP inputs.

5.0 References

APWA (American Public Works Association), 1969. Water Pollution.

Aspects of Urban Runoff. U.S. Department of the Interior, Federal Water Pollution Control Administration.

ARC (Auckland Regional Council). 1999. Guidelines for Stormwater Runoff Modelling in the Auckland Region. Technical publication. TP108

ARC (Auckland Regional Council). 2000. Low Impact Design Manual for the Auckland Region. Technical publication, TP124.

ARC (Auckland Regional Council). 2003. Stormwater management devices: Design guidelines manual. Second Edition. http://www.aucklandcity.govt.nz/council/documents/technicalpublications/TP10%20Stormwater%20management%20devices%20design%20guideline%20manual%202003.pdf

ARC (Auckland Regional Council). 2010a. Contaminant Load Model User's Manual. Auckland Regional Council technical report, TR2010/003.

ARC (Auckland Regional Council). 2010b. Development of the Contaminant Load Model. Auckland Regional Council technical report, TR2010/004.

ARC (Auckland Regional Council). 2012. Digital Elevation Model 2006-2010.

ARC (Auckland Regional Council). 2013. Auckland Unitary Plan stormwater management provisions: Technical basis of contaminant and volume management requirements, Prepared by Auckland Council. Auckland Council technical report, TR2013/035

ARC (Auckland Regional Council). 2016b. Watercourse Assessment Methodology: Infrastructure and Ecology (Version 2.0). Technical report, TR2016/002.

Baillie, B.R., Neary, D.G. 2015. Water quality in New Zealand's planted forests: a review. *New Zealand Journal of Forestry Science*.

Beef and Lamb New Zealand. 2019. https://beeflambnz.com/data-tools/benchmarking-tool Accessed 12/9/2019.

Benham, B.L., C. Baffaut, R.W. Zeckoski, K.R. Mankin, Y.A. Pachepsky, A.M. Sadeghi, K.M. Brannan, M.L. Soupir, and M.J. Habersack. 2006. Modeling bacteria fate and transport in watershed models to support TMDLs. Trans. ASABE 49(4): 987-1002.

Bicknell, B. R., J. C. Imhoff, A. S. Donigian, R. C. Johanson. 1997. Hydrological Simulation Program – FORTRAN (HSPF), User's Manual For Release 11. EPA – 600/R-97/080. U.S. Environmental Protection Agency, Athens, GA.

Booker DJ. 2013. Spatial and temporal patterns in the frequency of events exceeding three times the median flow (FRE3) across *New Zealand. Journal of Hydrology* (NZ) 52: 15-40.

Buckthought, L. 2019. State of the Environment Monitoring: River Water Quality Annual Report 2017. Auckland Council technical report, TR2019/010. www.knowledgeauckland.org.nz/media/1073/tr2019-010-river-water-quality-annual-report-2017.pdf

CSWRCB (California State Water Resources Control Board. 2018. Draft Shasta River Watershed Characterization and Model Study Plan. Prepared by Paradigm Environmental. https://www.waterboards.ca.gov/waterrights/water_issues/programs/instream_flows/cwap_enhancing/docs/shasta_river/shasta_draft_model_plan.pdf

Crawford, H.H. and Linsley, R.K. 1966. Digital Simulation in Hydrology: Stanford Watershed Model IV. Technical report No. 39, Department of Civil and Environmental Engineering, Stanford University, Stanford.

Chen, Z. Roberts, G.S. 2018. On-site Wastewater Management in the Auckland Region. Auckland Council guideline document, GD2018/006.

Chow, V.T., Maidment, D.R., Mays, L.W. 1988. Applied Hydrology. McGraw-Hill.

Clothier, B., Mackay, A., Carran, A., Gray, R., Parfitt, R., Francis, G., Manning, M., Duerer, M., Green S. 2007. Farm Strategies for Contaminant Management. A report by SLURI, the Sustainable Land Use Research Initiative, for Horizons Regional Council. Report prepared for Horizons Regional Council Farm Strategies for Contaminant Management.

Clausen, B., Biggs, B.J.F. 1997. Relationships between benthic biota and hydrological indices in New Zealand streams. *Freshwater Biology*, 38: 327 - 342.

Clausen, B., Biggs, B.J.F. 2000. Flow variables for ecological studies in temperate streams: Grouping based on covariance. *Journal of Hydrology*. 237(2-4).

Crawford, N.H. and R.K. Linsley, 1966. Digital Simulation in Hydrology: Stanford Watershed Model IV. Technical report No. 39, Department of Civil Engineering, Stanford University, p. 210

Donigian, A.S. Jr. 2000. HSPF Training Workshop Handbook. Lecture #15. Watershed Model Calibration and Verification: Issues and Procedures. Prepared for U.S. Environmental Protection Agency, Office of Water, Office of Science and Technology, Washington, DC.

Donigian, A.S. and Crawford, N.H. 1976. Modelling Nonpoint Pollution from the Land Surface. EPA/600/3-76-083, Environmental Research Laboratory, Athens. GA, USA

Donigian, A.S. Jr., J.C. Imhoff, B.R. Bicknell and J.L. Kittle. 1984. Application Guide for Hydrological Simulation Program – Fortran (HSPF). Prepared for U.S. EPA, EPA-600/3-84-065, Environmental Research Laboratory, Athens, GA.

Fassman-Beck, E A, Voyde, E A, Liao, M. 2013. Defining hydrologic mitigation targets for stormwater design in Auckland. Prepared by Auckland UniServices for Auckland Council. Auckland Council technical report, TR2013/024

Fish and game, 2019. Colmar Brunton annual survey. https://fishandgame.org.nz/news/water-pollution-is-now-new-zealanders-number-one-concern

Gadd, J., R B Williamson, G N Mills, C W Hickey, M Cameron, N Vigar, L Buckthought and J Milne. 2019. Developing Auckland-specific ecosystem health attributes for copper and zinc: summary of work to date and identification of future tasks. Prepared by the National Institute of Water and Atmospheric Research, NIWA and Diffuse Sources Ltd for Auckland Council. Auckland Council discussion paper, DP2019/004

Gentile, R., Green, S., Mason, K., van den Dijssel, C., Johnstone, P., Clothier, B. 2014. Land Management Practices and Nutrient Losses from Farms on the Poverty Bay Flats. Report for Gisborne District Council. New Zealand Plant and Food Research.

Hewitt, A. E. 1993. Methods and rationale of the New Zealand Soil Classification. Landcare Research Science Series 2, Lincoln, New Zealand, Manaaki Whenua Press. 71p.

Graham, E., Stephens, T., Wright-Stow, A., Matthews, A., Brown, L., Patterson, M., and Patterson, M. 2019. Drivers of macroinvertebrate communities in the Horizons region. NIWA client report for HRC and DNZ 2019136HN.

Green 2008a. Central Waitemata Harbour Contaminant Study. USC-3 Model Description, Implementation and Calibration. Prepared by NIWA Ltd for Auckland Regional Council. Auckland Regional Council technical report, TR2008/042.

Green 2008b. Central Waitemata Harbour Contaminant Study. Predictions of Sediment, Zinc and Copper Accumulation under Future Development Scenario 1. Prepared by NIWA Ltd for Auckland Regional Council. Auckland Regional Council technical report, TR2008/043.

Haddadchi, A and Hicks, M. 2016. Models for estimating sediment yields in the Waikato-Auckland-Northland region. A comparison. Prepared for Auckland Council by the National Institute of Water and Atmospheric Research, NIWA. Auckland Council technical report, TR2016/036

Harmel, R. and Cooper, R. and Slade, Raymond and Haney, R. and A. Jeff. 2006. Cumulative Uncertainty in Measured Streamflow and Water Quality Data for Small Watersheds. *Transactions of the ASABE*. 49. 10.13031/2013.20488.

Hewitt, J.E., Ellis, J. 2010. Assessment of the benthic health model. Prepared by NIWA for Auckland Regional Council. Auckland Regional Council technical report, TR2010/034.

Hicks, M., A, Semadeni-Davies, A. Haddachi, U. Shankar, and D. Plew. 2019. Updated sediment load estimator of New Zealand. Prepared for the Ministry for the Environment. NIWA Client Report No: 2018341CH

Horne, D., Elwan, A., Singh, R., Manderson, A., Patterson, M., Roygard, J., 2017. Predicting land based nitrogen loads and attenuation in the Rangitikei River catchment – the implications for landuse. In: Science and policy: nutrient management challenges for the next generation. (Eds L. D. Currie and M. J. Hedley). http://flrc.massey.ac.nz/publications.html Occasional Report No. 30. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand.

Hughey, K.F.D., Kerr, G.N., and Cullen, R. (2016). Public perceptions of New Zealand's environment: 2016. Lincoln University, Christchurch, NZ. https://www.nzae.org.nz/wp-content/uploads/2011/08/Hughey_et_al__A_Decade_of_Public_Perceptions.pdf

HydroQual. 2006. Leipsic River Watershed Proposed TMDLs. Delaware Department of Natural Resources and Environmental Control. http://www.dnrec.delaware.gov/swc/wa/Documents/TMDL_TechnicalAnalysisDocuments/7_LeipsicTMDLAnalysis.pdf

Jacobs New Zealand Limited, 2019a. Porirua Whaitua Collaborative Modelling Project. Baseline Modelling Technical Report.

Jacobs New Zealand Limited, 2019b. Porirua Whaitua Collaborative Modelling Project. Scenario Modelling Technical Report.

Jawitz J W and Mitchell J 2011 Temporal inequality in catchment discharge and solute export: temporal inequality in catchment discharge and solute export. *Water Resource Research*, 47 W00J14

Julian, J., de Beurs, K., Owsley, B., Davies-Colley, R. and Ausseil, A. 2017. River water quality changes in New Zealand over 26 years: response to land use intensity. *Hydrological, Earth Systems Science*, 21: 1149-1171.

Katz, H.A., Daniels, J.M., Ryan, S. 2013. Slope-area thresholds of road-induced gully erosion and consequent hillslope-channel interactions. *Earth Surface Processes and Landforms*, 39:285-295.

Kilroy, C., Greenwood, M., Wech, J.A., Stephens, T., Brown, L., Matthews, M., Patterson, Maree, Patterson, Mike. 2018. Periphyton – environment relationships in the Horizons region: Analysis of a seven-year dataset. NIWA Client Report No: 2018123CH. For: Dairy NZ / Horizons Regional Council. 188 p.

Kingett Mitchell Ltd. 2003. A study of roof runoff quality in Auckland New Zealand implications for stormwater management. Prepared on behalf of Auckland Regional Council by Kingett Mitchell and Diffuse Sources Ltd. Auckland Regional Council technical publication, TP213. 133 pp.

Land Information New Zealand (LINZ). 2016. NZ Property Titles. Website: https://data.linz.govt.nz/layer/50804-nz-property-titles

LARWQCB (Los Angeles Regional Water Quality Control Board). 2014. Guidelines for Conducting Reasonable Assurance Analysis in a Watershed Management Program, Including an Enhanced Watershed Management Program. LARWQCB, Los Angeles, CA. https://www.waterboards.ca.gov/losangeles/water_issues/programs/stormwater/municipal/watershed_management/tac/doc/RevisedRAAModelingCriteria1-22-14.pdf

Larned, S., Snelder, T., Unwin, M., and McBride, G. 2016. Water quality in New Zealand rivers: current state and trends. *New Zealand Journal of Marine and Freshwater Research*, 50: 389-417

Larned ST, Scarsbrook MR, Snelder TH, Norton NJ, Biggs BJF. 2004. Water quality in low-elevation streams and rivers of New Zealand: recent state and trends in contrasting land-cover classes*. New Zealand Journal of Marine and Freshwater Research*, 38:347-366.

Leathwick, J.R., West D., Chadderton, L., Gerbeaux, P., Kelly, D., Robertson, H., and D. Brown. 2010. Freshwater Ecosystems of New Zealand (FENZ) Geodatabase. New Zealand Department of Conservation.

Lowe, M., Ingley, R and Young, D (2016). Watercourse assessment methodology: infrastructure and ecology version 2.0. Prepared by Morphum Environmental for Auckland Council. Auckland Council technical report, TR2016/002.

McDowell, R.W., Larned, S.T., Houlbrooke, D.J. 2009. Nitrogen and phosphorus in New Zealand streams and rivers: control and impact of eutrophication and the influence of land management. *New Zealand Journal of Marine and Freshwater Research*, 43(4): 985-995.

McDowell RW, Snelder TH, Cox N, Booker DJ Wilcock RJ. 2013. Establishment of reference or baseline conditions of chemical indicators in New Zealand streams and rivers relative to present conditions*. Journal of Marine and Freshwater Research*, 64:387-400.

Meals, D.W. and R.B. Hopkins. 2002. Phosphorus reductions following riparian restoration in two agricultural watersheds in Vermont, USA. Water Science and Technology. 45(9).

Meijer, K., Buckthought, L., Curran-Cournane, F., Martindale, M., Prebble, N and Long, L. 2016. Elevated nitrate concentrations in Franklin surface and groundwater: a review. Auckland Council technical report, TR2016/015.

Menneer, J.C., Ledgard, S.F., A.G. Gillingham. 2004. Land Use Impacts on Nitrogen and Phosphorus Loss and Management Options for Intervention. Prepared for Environment Bay of Plenty.

MfE (Ministry for the Environment). 2008. Proposed National Environmental Standard for On-site Wastewater Systems Discussion Document. Publication #: ME 890.

MfE (Ministry for the Environment). 2014. National Policy Statement for Freshwater Management (amended 2017). https://www.mfe.govt.nz/sites/default/files/media/Fresh%20water/nps-freshwater-ameneded-2017_0.pdf

MfE (Ministry for the Environment). 2015. A Guide to Freshwater Accounting under the National Policy Statement for Freshwater Management 2014. Wellington: Ministry for the Environment. (https://www.mfe.govt.nz/sites/default/files/media/Fresh%20water/guide-to-freshwater-accounting_0.pdf)

MfE (Ministry for the Environment). 2017. A Guide to the National Policy Statement for Freshwater Management 2014 (as amended 2017). Wellington: Ministry for the Environment.

Milne, J. 2019. Water Quality Part 2 – Sampling, Measuring, Processing and Archiving of Discrete River Water Quality Data. Ministry for the Environment. National Environmental Monitoring Standards. http://www.nems.org.nz/assets/Documents/NEMS-60/Water-Quality-Part-2-Sampling-Measuring-Processing-and-Archiving-of-Discrete-River-Water-Quality-Data.pdf

Mills, G. N. and Williamson, R. B., 2008. The Impacts of Urban Stormwater in Auckland's Aquatic Receiving Environment: A Review of Information 1995 to 2005. Diffuse Sources Ltd and Geosynthec Consultants.

Moriasi, D.N., Gitau, M.W., Pai, N. Daggaupati, P. 2015. Hydrologic and Water Quality Models: Performance Measures and Evaluation Criteria. *Transactions in American Society of Agricultural and Biological Engineers*, Volume 58(6): 1763-1785.

Morris, S.T. 2013. Sheep and Cattle Productions Systems. Ecosystem services of New Zealand – conditions and trends, ed. Dymond, J.R. Manaaki Whenua Press, Lincoln, New Zealand.

Negev, M. 1967. A Sediment Model on a Digital Computer. Department of Civil Engineering, Stanford University, Stanford, CA. Technical Report No. 76. P. 109.

Nevers, M.B., Whitman, R.L. 2011. Efficacy of monitoring and empirical predictive modelling at improving public health protection at Chicago beaches. Water Research 45 (4).

NRCS (Natural Resources Conservation Service). 1986. Urban Hydrology for Small Watersheds. Technical Release 55 (TR-55). United States Department of Agriculture Natural Resources Conservation Service, Conservation Engineering Division. June 1986.

NRCS (Natural Resources Conservation Service). 1997. National Engineering Handbook Part 630 Hydrology Chapter 7 Hydrological Soil Groups Issued September 1997 United States Department of Agriculture.

Omernik, J.M. 1976. The influence of land use on stream nutrient levels. Environmental Research Laboratory. Office of Research and Development. US Environmental Protection Agency, Corvalis Oregon. EPA-600/3-76-014.

Pennino, M.J., McDonald, R.I., Jaffe, P.R. 2016. Watershed-scale impacts of stormwater green infrastructure on hydrology, nutrient fluxes, and combined sewer overflows in the mid-Atlantic region. Science of The Total Environment (565).

PCE. 2013. Water quality in New Zealand: Land use and nutrient pollution. Report from the Parliamentary Commissioner for the Environment. Pp.82.

PCE. 2015. Update Report. Water quality in New Zealand: Land use and nutrient pollution. Report from the Parliamentary Commissioner for the Environment. Pp.29.

Pang, L., Close, M., Flintoft, M. 2004. Attenuation and Transport Characteristics of Cadmium, Zinc and Lead in Selected New Zealand Aquifer Systems. *Journal of Hydrology (New Zealand)* 43, no. 2: 95-110.

Prime Minister's Chief Science Advisor (PMCSA), 2017. New Zealand's fresh water: Values, state, trends and human impacts. https://www.pmcsa.org.nz/wp-content/uploads/PMCSA-Freshwater-Report.pdf

Sartor, J.D., G.B. Boyd, and F.J. Agardy, 1974. Water Pollution Aspects of Street Surface Contaminants. *Journal (Water Pollution Control Federation)* 46(3):458-467.

Semadeni-Davies, A and S. Wadhwa. 2014. C-CALM 2.0 User Manual Catchment Contaminant Annual Load Model. NIWA Report No: AKL2014-026. August 2014. Pp157.

Shen, J., A. Parker, J. Riverson, 2005. A new approach for a Windows-based watershed modelling system based on a database-supporting architecture. Environmental Modelling and Software 20:1127-1138

Shoemaker, L., Riverson, J., Alvi., K., Zhen, J.X., Paul, S., Rafi, T. 2009. SUSTAIN – A Framework for Placement of Best Management Practices in Urban Watersheds to Protect Water Quality. In support of EPA Contract No. GS-10F-0268K. National Risk Management Research Laboratory. Office of Research and Development. U.S. Environmental Protection Agency. Cincinnati, OH 45268.

Shoemaker, L., Dai, T., Koening, J. 2005. TMDL Model Evaluation and Research Needs. National Risk Management Research Laboratory. Office of Research and Development. Contract 68-C-04-007.

Singh, R., Rivas, A., Espanto, P., Elwan, A., Horne, D., Roygard, J., Matthews, A., Clothier, B., 2014. Assessment of transport and transformation of nitrogen in the subsurface environment of Manawatu River catchment – work in progress. In: Nutrient management for the farm, catchment and community. (Eds L.D. Currie and L. L. Burkitt). http://flrc.massey.ac.nz/publications.html Occasional Report No. 27. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand.

Singh, R., Elwan, A., and Horne, D., 2017. Nitrogen Accounting in the Rangitikei catchment. Massey FLRC Report to Horizons Regional Council.

Sloto, R.A., and Crouse, M.Y., 1996, HYSEP: A computer program for streamflow hydrograph separation and analysis: U.S. Geological Survey Water-Resources Investigations Report 96-4040, 46 p.

Snelder, T., Biggs, B., Weatherhead, M. 2004 New Zealand River Environment Classification User Guide. New Zealand Ministry for the Environment. Updated June 2010.

Stats NZ. 2019. Wellbeing statistics: 2019. https://www.stats.govt.nz/information-releases/wellbeing-statistics-2018

Stenger, R., Clague, J., Woodward, S., Moorhead, B., Wilson, S., Shokri, A., Wohling, T., Canard, H., 2014. Root zone losses are just the beginning. In: Nutrient management for the farm, catchment and community. (Eds L.D. Currie and C.L Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 27, Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand.

Storey, R.; Wadhwa, S. 2009. An Assessment of the Lengths of Permanent, Intermittent and Ephemeral Streams in the Auckland Region. Prepared by NIWA for Auckland Regional Council. Auckland Regional Council technical report, TR2009/028.

Sutherland, R. 2000. Methods for Estimating the Effective Impervious Area of Urban Watersheds. In: The Practice of Watershed Protection (Edited by T. R. Schueler and H. K. Holland). Technical Note #58. Center for Watershed Protection, Ellicott City, MD: 193-195.

Tetra Tech. 2010. Total Maximum Daily Load Document. Gills Creek Watershed. Prepared for: South Carolina Department of Health and Environmental Control. CSCDHEC Technical Document: 011N-17. https://www.scdhec.gov/sites/default/files/docs/HomeAndEnvironment/Docs/tmdl_gills_fc.pdf

Tetra Tech. 2014a. Modeling Hydrology, Sediment, and Nutrients in the Flathead Lake Watershed. Prepared for U.S.EPA. 10 West 15th St. Helene, MT 59601.

Tetra Tech 2014b. James River Watershed Modeling. Supporting Virginia DEQ's Chlorophyll Study.

Tonkin and Taylor. 2017. Memo: Regional On-site Wastewater (OSWW) GIS Risk Assessment Tool. Prepared by Sam Reed and Tim Fisher Job No: 30552.3081 v2.0

Taylor, A and J Irvine. 2019. Memorandum to Tom Stephens. Subject: Literature review to inform sediment modelling in the Freshwater Management Tool. WSP OPUS.

USEPA (U.S. Environmental Protection Agency). 2000. BASINS Technical Note 6: Estimating Hydrology and Hydraulic Parameters for HSPF. Office of Water 4305. EPA-823-R00-012. July 2000.

USEPA (U.S. Environmental Protection Agency). 2006. BASINS Technical Note 8: Sediment Parameter and Calibration Guidance for HSPF. Office of Water 4305. January 2006.

USEPA. 2008. Handbook for Developing Watershed Plans to Restore and Protect Our Waters. Office of Water, Nonpoint Source Control Branch. Washington DC. EPA 841-B-08-002.

USEPA. 2014, Guide for Estimating Infiltration and Inflow. Water Infrastructure Outreach.

USEPA. 2015a. TMDL Modeling Toolbox. https://www.epa.gov/sites/production/files/2015-10/documents/toolbox-overview.pdf

USEPA. 2015b. SWMM – Storm Water Management Model User's Manual Version 5.1. (Publication No. EPA/600/R-14/413b, Revised September 2015).

USEPA. 2017. Loading Simulation Program in C++ (LSPC) Version 5.0 – User's Manual. EP-R8-12-04.

Wischmeier, W.H., and Smith D.D. 1978. Predicting rainfall-erosion losses – a guide to conservation planning. USDA Agriculture Handbook. No. 537, 58 p.

Find out more: fwmt@aucklandcouncil.govt.nz