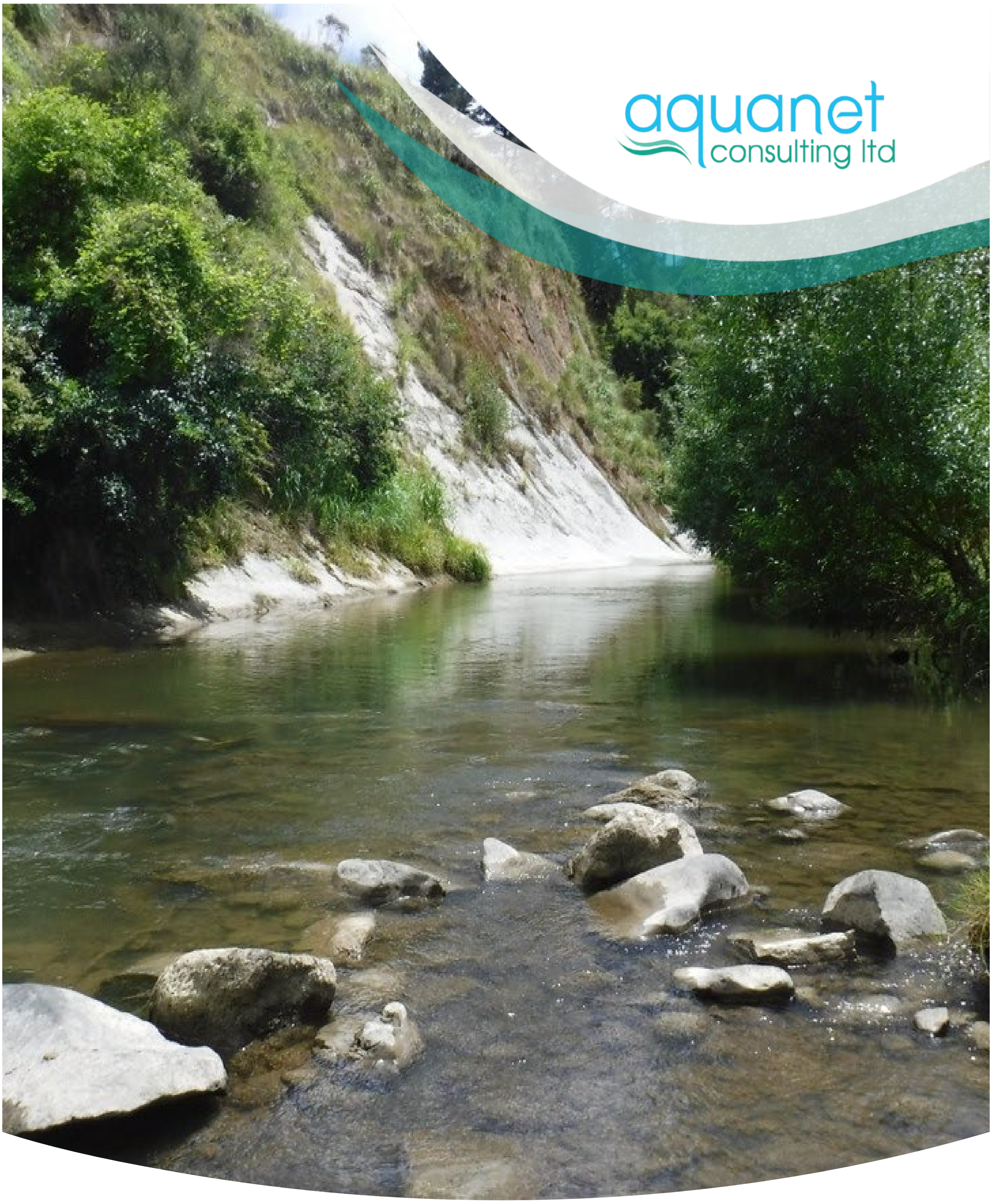

Freshwater Management Tool: Instream Monitoring Recommendations

April 2023

Report Prepared for

Healthy Waters, Auckland Council

FRESHWATER MANAGEMENT TOOL:

INSTREAM MONITORING RECOMMENDATIONS

6 April 2023

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EXECUTIVE SUMMARY

Background

The Freshwater Management Tool (FWMT) is a catchment model being developed by Auckland Council's Healthy Waters department to support operational decision making in relation to water quality management. The key features of the FWMT include the ability to predict baseline water quality and changes in water quality expected to occur from a range of potential management interventions. FWMT development is occurring in a staged approach, reflecting the relative novelty of continuous, process-based and intervention-optimisation modelling in Auckland Council, whilst enabling ongoing refinement of the tool from access to improved datasets. Stage 1 is targeted at describing baseline state (representative of 2013-2017) and evaluating management interventions (feasible actions, lifecycle costs and optimized strategies to improve baseline water quality).

Stage 1 of the FWMT ("Stage 1") simulates the generation and transport of water quality contaminants and provides high frequency in-stream predictions for every sub-catchment in the Auckland region. Stage 1 is intended to inform catchment planning, asset design and management, capital investments and operational programs for water quality outcomes.

Stage 1 was developed primarily using flow data from Auckland Council's hydrometric monitoring network and water quality data from the State of the Environment (SoE) river water quality monitoring network. The data from these two networks represented the best available flow and water quality information for Auckland's river network. However, SoE water quality monitoring network is intended to meet Resource Management Act 1991 monitoring obligations, rather than support the development of catchment models. Hence, the ability to assess the performance of the FWMT, and support its continuous development, is limited by the spatial and temporal coverage of the SoE water quality data.

Stage 1 has been the subject of a detailed peer-review by an independent panel. The peer-reviewers made several recommendations aimed at strengthening the model's existing and potential capabilities. Among other conclusions, the peer-review highlighted that the ability to configure the FWMT and to accurately determine model performance, is limited by existing water quality datasets.

In response to peer review recommendations, Healthy Waters engaged Puhoi Stour Limited and Aquanet Consulting Limited to investigate and advise on in-stream monitoring to support improved performance assessment of the FWMT. This report describes the approach we used to develop a series of monitoring recommendations that will enable Healthy Waters to prioritise the collection of instream water quality data to support the continuous improvement of the FWMT.

Through our reviews of FWMT documentation, existing monitoring datasets and discussion with the FWMT team, a clear high-level approach for future data collection emerged to "*acquire environmental data and information to improve performance assessment to support continual improvement of the FWMT*".

The approach was guided by two key **objectives**:

1. Improve FWMT baseline performance assessment (via improved observational data) to reduce uncertainty in Stage 1 baseline outputs and identify potential areas of improvement for model development.
2. Enhance FWMT baseline outputs by including recommendations for monitoring of key physicochemical measures governing contaminant process simulation and metal toxicity (e.g., temperature, DO, pH).

Objective 1 – improve performance assessment of FWMT

Time and Spatial Challenges

Two fundamental problems for assessing FWMT Stage 1 baseline performance using existing SoE water quality data were highlighted in Hamilton et al. (2021) and expressed in the workshops:

1. The time problem – the monthly frequency of SoE sampling does not match the high-resolution predictions (15-minute frequency) of the FWMT. At a simple level, the FWMT provides predictions for times that have no matching SoE data against which to assess performance. In addition, the large differences in the size of

the datasets have implications for some of the summary reporting metrics commonly used for water quality parameters (e.g., 95th percentiles, maximum).

2. The spatial problem – the number of SoE sampling locations does not match the region-wide coverage of the FWMT nor align with the diversity and mixes of land types (hydrological response units – HRU) in the FWMT. The FWMT offers water quality predictions for 5,465 sub-catchments in the region, whereas the SoE network provides water quality information only at monitored locations (36 locations at the time of Stage 1 development, but expanded to 48 locations from July 2022). Hence, there are currently 5,417 sub-catchments on the Auckland stream network with no SoE water quality information against which to assess FWMT performance.

Addressing both problems requires collecting of new FWMT-centric water quality data at currently un-monitored locations and times. It is clearly impossible to monitor at all sub-catchments, so data collection should be focused on locations of greatest value to the FWMT (e.g., stream types that are under-represented in existing datasets and locations with uniform HRU coverage). Similarly, increasing the temporal coverage of the available water quality information should be focused on the times that are under-represented in existing datasets and critical to modeling decision-making, although the ability to use continuous sensors means that for some parameters the frequency of monitoring can match that of the FWMT predictions. Our first recommendation and associated actions are intended to address these two problems. The desktop analyses (Actions 1 and 2) have been undertaken, with the results summarised below and reported in Section 4.

Recommendation #1: Undertake in-stream water quality data collection for existing Stage 1 parameters to provide data suitable for assessing performance of the FWMT.

The new data collection should prioritise the six Stage 1 parameters (various forms of TN, TP, TSS, TCu, TZn, *E. coli*), with the time and spatial considerations requiring two pieces of desktop analysis **(Actions 1 and 2)** to provide more detailed direction for data collection.

Action #1: Undertake a spatial review to determine coverage of HRUs and selected factors for existing SoE sites and identify sub-catchments with under-represented factors for potential targeted monitoring.

Action #2: Undertake a temporal analysis of SoE water quality samples to identify under-represented flow conditions for potential targeted monitoring.

Processes and Parameterisation

The FWMT is a process-based model, meaning the tool simulates the generation, transport and fate of water quality variables across the Auckland region. Stage 1 of the FWMT includes several processes related to sediment and nutrients including deposition, re-suspension, scour and benthic release of nutrients.

The underlying models within the FWMT include calibrated and default values for on-land (HRU) and instream processes, derived from research and model application in the USA. The diversity of process, HRU and stream types within the FWMT create potential for numerous alternative process parameter sets to yield equivalent instream outcomes ("equifinality"). It is uncertain how accurate the default and adjusted values used in Stage 1 are for Auckland streams and this uncertainty was recognised as a high priority issue by the FWMT team and peer review panel. Therefore, our second recommendation and associated action is intended to explore this issue. Action 3 is being led by Healthy Waters scientists and will be detailed in a subsequent report.

Recommendation #2: Adopt a two-stage approach for assessing and improving the representation of processes in the FWMT, by:

1. Undertaking a desktop review of the processes and their representation in the FWMT, focusing on assessing the basis for the default or adjusted values and whether the values used are likely to be realistic for Auckland streams based on published work from New Zealand.
2. Depending on the outcome of (1), the values might be considered appropriate and no further action will be required. In contrast, a second stage (of data gathering) might be required.

Action #3: Undertake a desktop review to determine process coefficients across HRUs and reach types, demonstrating which processes have greater sensitivity on contaminant generation and transformation, as well determining which HRUs and reach types share similar process sets.

Objective 2 – Diversify Freshwater Parameters in FWMT

Stage 1 of the FWMT has been configured to model six core water quality parameters (nitrogen, phosphorus, copper, zinc, sediment and *E. coli*). The selection of these parameters for Stage 1 exercise was logical as they are important water quality parameters for resource managers and existing data for calibration were available from the SoE programme.

As part of future data collection, we consider that three additional physico-chemical parameters should be included to support model assessment and development (Recommendation #3). These parameters are important for process-modelling with the FWMT (which affects the predictions of the six Stage 1 parameters) and for the interpretation and application of the FWMT predictions.

Furthermore, we note a parallel project relating to metal toxicity undertaken by NIWA will deliver recommendations that include undertaking measurements of dissolved organic carbon, hardness and pH as modifying factors to assist with the assessment of metal toxicity (Gadd & White, in prep). These recommendations should be considered in the design of any FWMT centric monitoring activities.

Recommendation #3: Include temperature, DO and pH in water quality data collection undertaken under recommendation 1. Given the diurnal fluctuation patterns for these three parameters, priority should be given to high-frequency data collection.

Outcomes of Actions #1 and #2: Spatial and Temporal Desktop Analyses

Spatial HRU coverage

The functions of the FWMT include describing water quality information under a range of land use, management and climate boundary conditions, and deriving optimised action plans to improve water quality. Consequently, FWMT outputs are process-based, continuous and spatially-contiguous to identify "critical conditions" within thousands of sub-catchments. Critical conditions are those locations and periods when a contaminant regime is unacceptable, and management is required to improve water quality outcome(s).

To enable these functions, the FWMT simulates the generation and transport of contaminants to waterways via continuous responses of land units (called HRUs) to variation in intensity, duration and antecedent rainfall conditions. Each HRU can be parameterised uniquely for a suite of processes governing hydrology and contaminant generation, transport and transformation. Therefore, HRU parameterisation is critical aspect of FWMT configuration and performance and needs to be underpinned by representative observed datasets that span modelled gradients and capture critical conditions.

The purpose of this analysis is to assess the representativeness of the SoE monitoring sites in relation to the regional coverage of HRU types, to identify HRU types that are under-represented in the existing SoE dataset, thus informing priority HRU types for future monitoring. HRUs are the core modelling unit within the FWMT and there are 106 types in the Auckland region. The spatial extent of HRUs ranges from 0.17 hectares (or 0.00004% of the region) to 58,551 hectares (12% of the region), with 24 HRUs covering more than 1% of the region.

Most HRUs (95) are represented within the catchment of an SoE site, but 66 of those are present at a maximum coverage of less than 10%. Only four HRU types are present in the catchment of an SoE site at greater than 50% coverage (three in Forest and one in Developed Pervious land cover). In contrast, 62 HRU types are present in a FWMT sub-catchment at greater than 50% coverage (2,360 sub-catchments have an HRU present at greater than 50% cover). These 62 HRUs represent most (95%) of the region, covering 454,206 hectares.

Overall, the SoE sites do not provide a good coverage of the HRUs used in the FWMT, with only eight SoE sites having greater than 50% coverage of a single HRU in the catchment. This finding is not unexpected as the SoE programme pre-dates the establishment of HRUs for the FWMT, and the SoE sites were selected using several criteria related to RMA environmental management functions (Ingley & Groom, 2022), rather than the functions of the FWMT. Therefore, we consider that the SoE monitoring sites are not well suited to supporting the development of the FWMT.

Through the workshop discussions, it was agreed that monitoring data from sub-catchments with sufficiently uniform HRU composition would be of greatest value in assessing the performance of the FWMT. Both for improving knowledge of variation between HRU responses, and for variation within HRU type along meteorological gradients. This analysis has identified that there are 2,360 FWMT sub-catchments that offer the potential to collect data where the upstream catchment is dominated by a single HRU (i.e., > 50%) for 62 HRU types. We consider that prioritising data collection within this 'population' of sub-catchments should be an iterative process led by the FWMT modelling team, because they have the best understanding of which of the HRU types exert strongest influence on FWMT outputs and applications of the modelling to decision-making (i.e., reducing modelling uncertainty, improving model performance assessment and driving ongoing versioning of the FWMT for all users).

Temporal hydrograph coverage

Instream flow variation can cause changes in contaminant concentration independent of contribution. However, the precise part of the flow-hydrograph, whether rising or falling, and stormflow or baseflow, is also well known to be associated with differences in contaminant concentrations instream (e.g., from build-up/wash-off effects).

Therefore, the purpose of this analysis was to assess the hydrological conditions associated with SoE water quality data to identify representativeness of the data and opportunities for supplementary data collection to address under-represented parts of the flow regime.

For each SoE site, sample events were assigned a flow and an equivalent annual exceedance probability. In general, sampling occurred relatively evenly across the flow exceedance percentiles, although there was a slight bias toward sampling of flows below median (50th percentile) in some watersheds.

However, at all sites there was a strong bias towards sampling during stable flow conditions. Approximately eight percent of samples were taken during stormflow conditions (about 4% during rising stormflow and about 4% during stormflow recessions). In comparison, the streams were in stormflow conditions for 12% of the time (mean across all sites).

The dominance of sampling under stable flows has the potential to be problematic in assessing the performance of a build-up/wash-off model such as used in the FWMT (LSPC simulates HRU responses for the FWMT). In particular, when assessing FWMT performance at predicting infrequent, but higher concentrations and event loads occurring under stormflow conditions, as these conditions are proportionately less frequently sampled with disproportionately higher and more variable spread in absolute contaminant concentrations.

Both baseline states and critical conditions reported by the FWMT are governed by 95th percentile concentrations in nutrient, metal and faecal contaminants. Hence, the flow status bias observed in the SoE sampling data is problematic for assessing key measures of model performance, which underpin both baseline and intervention-optimisation modelling in the FWMT Stage 1. The potential implications for assessing the performance of the FWMT were further investigated by examining the relationship between water quality measures and flow characteristics at selected sites. For five of the FWMT Stage 1 parameters, higher concentrations tend to occur at higher flows and in the rising and receding stormflow categories.

In order to improve the 'hydrological representativeness' of water quality data used for performance assessment of the FWMT, it is recommended that future sampling targets stream flow above median during summer and autumn and stormflow conditions.

In summary, we note the SoE monitoring programme has been designed to meet RMA related functions, which include the principle of randomised sampling, purposely to ensure the validity of several important statistical analytical functions (e.g., trend analysis, generalised state analysis). However, to improve performance assessment of the FWMT and to reduce uncertainty in outputs (baseline, optimisation-intervention) it is apparent that more targeted sampling is needed, especially relating to critical conditions and HRU-dominated sub-catchments.

Our recommendation is to ensure a clear distinction of monitoring for FWMT model assessment and improvement purposes, compared with SoE monitoring. FWMT centric monitoring should be targeted at specific conditions and HRUs, and may be short-term in nature (i.e., time limited measurement campaigns). This contrasts to SoE monitoring, which is long-term and is required to meet statistical considerations for state and trend analysis. Such FWMT centric monitoring should be specified and managed the by the FWMT team, with specific input from the modellers, to ensure the data is of greatest value to the programme.

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1 Introduction

The Freshwater Management Tool (FWMT) is a catchment model developed by the Auckland Council Healthy Waters Department. The purpose of the FWMT is to support the Healthy Waters Department's decision making with regards to its catchment planning, asset design and management, capital investment and operational programmes for water quality outcomes.

The FWMT is described extensively elsewhere (Auckland Council 2021a-c), but key features include the ability to predict water quality (including near-continuous variation in concentration, load and source) and changes in water quality expected to occur from a range of potential management interventions under "critical conditions". Critical conditions are defined from the continuous instream time-series provided by the FWMT and include periods during which concentration or loading is excessive, for instance breaching a numeric attribute state target. The second feature is beyond the scope of other water quality modelling tools used in New Zealand and allows optimisation of action planning and development of least cost strategies for achieving water quality objectives.

The FWMT is New Zealand's first region-wide, continuous, process-based model for water quality:

- Region-wide means the tool includes the full Auckland region within its spatial scope

  Continuous means the tool provides high-frequency predictions of water quality (at 15-minute intervals)
- Process-based means the tool simulates the generation, transport, and fate of water quality parameters.
- Water quality means the tool assesses sources, concentrations and loads of six key water quality parameters (zinc, copper, sediment, phosphorus, nitrogen and *E. coli*) and environmental flows within catchments.

Whilst the FWMT is intended to be an operational tool, in the future, when it is fully operational the FWMT may also contribute to meeting some monitoring and reporting requirements set by the National Policy Statement for Freshwater Management 2020 (NPSFM), including freshwater accounting and reporting.

A 10-year programme is envisaged for the full development of the FWMT. This will enable the tool to become more comprehensive, reduce uncertainties and expand capabilities in response to advances in science and changes to planning and operational needs. At the time of writing, the first iteration of Stage 1 of the FWMT baseline development has been completed (action-planning and optimisation capability is in development). Stage 1 is intended primarily to inform on freshwater attribute states ("grading") and grading-based decisions. Therefore, the objective of Stage 1 was to develop the tool's capability for predicting current state of hydrological and contaminant distributions across catchments. Hence, the tool's performance has been assessed by the accuracy of the predicted concentrations, grading and loads (Auckland Council, 2021c).

FWMT Stage 1 baseline modelling has been the subject of a detailed peer-review by an independent panel. The purpose of the review was to provide an independent assessment of whether the baseline state assessment provides robust evidence to support the wider purpose and objectives of the FWMT. The peer-reviewers made a number of recommendations aimed at strengthening the model's existing and potential capabilities (Hamilton et al. 2021).

Among other conclusions, the peer-review highlighted that the ability to configure the FWMT for wide-ranging (continuous, sub-catchment-based) water quality conditions and to accurately determine modelled performance, is limited by existing water quality datasets (see Recommendations 6, 7, 8, 10, 14,, 16, 17, 21 in Hamilton et al 2021). Consequently, Healthy Waters engaged Puhoi Stour Limited and Aquanet Consulting Limited to investigate and advise on additional in-stream monitoring[1] that would assist in assessing the performance of the FWMT.

1.1 Aim and Scope

As with any model, the coverage and quality of data used in development and testing is critical as it influences the model's performance, which in turn determines how the model should be used, and how much confidence we can have in its predictions. The FWMT has been developed and tested using primarily continuous flow data from Auckland

[1] In this document we use the broad dictionary definition of monitoring, which encompasses a wide range of data collection approaches (for example, event-based sampling, targeted sampling, high-frequency monitoring), rather than solely monthly sampling undertaken by most councils in New Zealand

Council's hydrometric monitoring network and discrete (monthly) water quality data from the State of the Environment (SoE) river water quality monitoring network.

The data from these two networks represent the best available flow and water quality information for Auckland's river network, which is why it was used to support the development of the FWMT Stage 1. However, the SoE water quality network is not designed to support the development of catchment models, rather it is intended to meet Auckland Council's obligations associated with section 35 of the Resource Management Act 1991 (Ingley & Groom, 2022). The monthly frequency of water quality sampling, adopted by Auckland Council and most SoE water quality programmes, has its origins in design of New Zealand's National River Water Quality Monitoring Network (NRWQN). The monthly frequency was a statistical design reasoning and considered the optimum frequency for identification of long-term trends (Smith & McBride, 1990), with sampling timing also designed to reduce the influence of diurnal variability (Smith et al, 1996).

That the SoE water quality data was the best available information for the development of FWMT Stage 1 was recognised in the external peer review of the FWMT, but the reviewers also identified that the temporal and spatial coverage of the existing datasets limits the ability to assess the performance of the FWMT and support its continuous improvement.

This report describes the approach we used to develop a series of monitoring recommendations that will enable Healthy Waters to prioritise the collection of instream water quality data to support the development of the FWMT. The scope of this project was limited to instream data, focussing on water quality and process data from the rivers and streams in the Auckland region. The FWMT also makes use of terrestrial data (e.g., land use, soil, climate) that is beyond the scope of this project. The recommendations for additional FWMT monitoring are based on the best available water quality science and discussions with the FWMT team, including the model developers and the independent peer reviewers.

1.2 Our approach

Our approach involved a series of sequential steps that allowed us to develop an understanding of how existing monitoring information has been used in the FWMT and the type of monitoring data that would be valuable for future development of the FWMT. These steps included:

1. Undertaking reviews of:
   - statutory monitoring requirements associated with the RMA and NPS-FM
   - FWMT Stage 1 model reports
   - existing monitoring programmes and investigations in the Auckland region
2. Facilitating a series of workshops with the FWMT team to gain insight into the purpose and planned development of the FWMT, with a focus on how water quality data interacts with the FWMT. This included separate workshops with:
   - The internal Auckland Council FWMT project team
   - The independent peer review panel
   - The lead modeller
3. Identifying the overall monitoring purpose and objectives for future data collection
4. Developing high-level principles for FWMT-centric monitoring activities
5. Identifying, undertaking and reporting on analysis to guide the application of high-level principles:
   - Assess spatial representativeness and gaps - spatial analysis
   - Assess temporal representativeness and gaps - water quality/hydrograph analysis
6. Develop detailed recommendations for future monitoring.

2 Background

2.1 Statutory monitoring requirements

2.1.1 Resource Management Act 1991 (RMA 1991)

The Resource Management Act 1991 (RMA) defines the roles and responsibilities of regional councils. These are charged with the integrated management of the natural and physical resources of a region, which includes monitoring of these resources. In particular, Section 35 ("Duty to gather information, monitor and keep records") sets monitoring and reporting requirements in relation to a range of monitoring purposes, including:

- Monitoring the state of the whole or any part of the environment, to the extent that is appropriate to enable the council to effectively carry out its functions. Monitoring of the state of the environment must include indicators or other matters prescribed by regulations made under the Act
- Policy and plan effectiveness and efficiency monitoring
- Monitoring of activities subject to resource consents and their effects.

We note that the RMA is under reform, and the Government plans to repeal the RMA and replace it with three new pieces of legislation. However, it is expected that there will be little substantive change to monitoring requirements, so this statutory imperative and role of councils will persist in the Natural and Built Environments Act (NBA).

2.1.2 2020 "Essential Freshwater" package

The 2020 "Essential Freshwater" package refers to a suite of rules and regulations released by the New Zealand government in September 2020. The package introduces new rules and regulations to:

- stop further degradation of New Zealand's freshwater resources and improve water quality within five years
- reverse past damage and bring New Zealand's freshwater resources, waterways and ecosystems to a healthy state within a generation.

Central to the Essential Freshwater package, the National Policy Statement for Freshwater Management (NPS-FM) sets Te Mana o Te Wai as guiding principle and establishes a hierarchy of obligations within its framework: to waterbodies first, then to the essential needs of people, and finally for other uses. The NPS-FM sets a **National Objectives Framework (NOF)**, which specifies a series of parameters and thresholds for identified 'attributes' of water quality. These parameters and thresholds provide a nationally consistent framework for measurement and management to standardise regulatory planning and management, ensuring that the health and well-being of degraded water bodies and freshwater ecosystems is improved, and the health and well-being of all other water bodies and freshwater ecosystems is maintained and (if communities choose) improved.

The NPS-FM sets out a range of requirements that directly relate to this project:

- The NPS-FM covers all freshwater systems, including rivers, lakes, wetlands and groundwater aquifers. It promotes the integrated management of the catchment, freshwater resource and receiving environment, such as estuaries and coastal ecosystems;
- The NOF and associated appendices, as well as specific clauses of the NPS-FM define a wide range of freshwater Attributes applicable to rivers, lakes and (to a more limited extent) groundwater and how they relate to freshwater Values.
- Regional Councils must develop and maintain freshwater quality and quantity accounting systems. These systems must be able to inform the setting of target freshwater attribute states and limits, and thus must be developed in the early stages of the NPS-FM implementation process. They also need to be able to assess and track over time the sources and loads of contaminants, as well as the allocation status of each FMU with regards to each contaminant.

- Clauses 3.18, 3.19, 3.20, 3.29 and 3.30 (detailed in Appendix A) set freshwater monitoring and reporting requirements and are of particular relevance to this project. Together, they require the development of monitoring and action plans, to characterise the state of the freshwater resource and respond to degraded or degrading freshwater, with a common requirement to monitor and evaluate the effectiveness of policies, rules and methods (including action plans) and progress towards environmental outcomes.

When fully developed, the FWMT may be used as a freshwater quality accounting system, as well as a tool to assess and report on the state of freshwater attributes, quantify sources of contaminants and optimise mitigation measures at the regional scale. It may also be used as a tool to track progress towards meeting target freshwater attributes in the future. The above requirements of the NPS-FM are thus important considerations for the future development of the FWMT.

2.2 Summary of regular water quantity and quality monitoring

The FWMT Stage 1 baseline has been developed and tested primarily using data from Auckland Council's hydrometric flow and SoE river water quality monitoring programmes. The SoE monitoring programme is designed to meet the council's obligation to monitor and report the environment under Section 35(2)(a) of the Resource Management Act (RMA).

Over the 2013-2017 baseline period, the hydrometric network monitors river flow continuously at 46 stations across the river network (i.e., every 15 minutes). In contrast, consistent with nationally specified monitoring requirements, the SoE river water quality programme collected monthly grab samples at 36[2] locations on Auckland's rivers (Ingley & Green, 2021). The SoE programme provides baseline observed data and helps to identify trends in water quality in the Auckland region. The SoE observations offer a source of evidence on how the council is maintaining and enhancing Auckland's rivers by evaluating water quality data against the National Objectives Framework (NOF) river attributes set out in the National Policy for Freshwater Management (NPS-FM 2020).

Table 1 shows a comparison of the attributes monitored on a regular basis by Auckland Council against the list of attributes required for evaluation against the NPS-FM 2020 and attributes currently modelled in the FWMT. A complete list of the existing State of the Environment monitoring sites and programmes routinely carried out by the Auckland Council is presented in Appendix A.

Stage 1 of the development of the FWMT was configured using the best available data at the time (2017) to cover water quality conditions in the Auckland region over a calibration and validation period of 2012-2016, a baseline reporting period of 2013-2017 and a longer model simulation period of 2003-2017. Stage 1 of the FWMT used water quality data from the SoE programme for 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*). Data used for configuration of the tool also included high resolution meteorology, soils, land cover and use, topography, wastewater and stormwater networks, consented water takes and discharges.

It is important to note that, over time, Auckland Council have augmented their SoE water quality monitoring programme at a number of sites to include measures of river ecosystem metabolism (continuous dissolved oxygen and temperature, see Doehring & Young, 2010; Clapcott et al., 2016) and event-based sediment yield monitoring (continuous automated sampling of suspended sediment during storm events, see Hicks et al., 2021). Some of the sediment yield data has since been used to compare the model's performance to the sampling results (Auckland Council 2021c) although the majority of contaminant calibration-validation has been conducted with discrete SoE data.

[2] The SoE data used in the FWMT development was from the 36-site network operated up to 2022. From July 2022, the network was expanded to cover 48 sites (Auckland Council, 2023)

Table 1: List of attributes currently covered by the Auckland Council for State of the Environment (SoE) monitoring programme, attributes requiring assessment in the 2020 New Zealand Policy Statement for Freshwater Management (NPS-FM) and attributes modelled in the Auckland Council Freshwater Management Tool (FWMT).

Attribute	AC SoE	NPS-FM 2020	FWMT
Ammoniacal nitrogen	*	*	*
Nitrate	*	*	
Nitrite	*		
Total Nitrogen	*		*
Total Oxidised Nitrogen	*		
Dissolved Inorganic Nitrogen	*		*
Total Phosphorus	*		*
Dissolved reactive phosphorus	*	*	*
Total Suspended Solids	*		*
Turbidity	*		
Visual clarity		*	
Deposited fine sediment		*	
E. coli	*	*	*
Water temperature	*		
pH	*		
Conductivity	*		
Salinity	*		
Dissolved Oxygen	*	*	
Oxidation reduction potential	*		
Total Copper	*		*
Dissolved Copper	*		
Total Zinc	*		*
Dissolved Zinc	*		
Dissolved organic carbon	*		
Total hardness	*		
Chlorophyll-a (planktonic)	*	*	
SEV score	*		
Taxa richness	*		
% EPT richness	*		
MCI	*	*	
QMCI		*	
ASPM		*	
Fish Index of Biotic Integrity		*	
Ecosystem metabolism	*	*	

2.3 Workshop Key Findings

A series of workshops were convened at the start of this project with members of the FWMT team and the discussions within these sessions were wide-ranging. We have captured some of the key aspects of the workshop discussions below, focussing on the content that was specifically related to this project (i.e., the below does represent a full record of the workshops).

2.3.1 Workshop 1: The Auckland Council FWMT team

A kick-off workshop carried out on the 11th of August 2021 involving the Healthy Waters FWMT project team, Puhoi Stour and Aquanet Ltd.

The FWMT team explained the background and proposed development trajectory of the FWMT, stressing that Stage 1 is the first stage in a potential 10-year development programme (Figure 1). Stage 1 is intended to provide current state information on water quality, specifically focussed on "operationally relevant" contaminants, those most strongly linked to discharges or the effects of urban and rural resource use, generally with greater observational records and with strong links to key measures of overall ecosystem health and human health values (e.g., measures of nutrient, heavy metal, sediment and faecal contaminants).

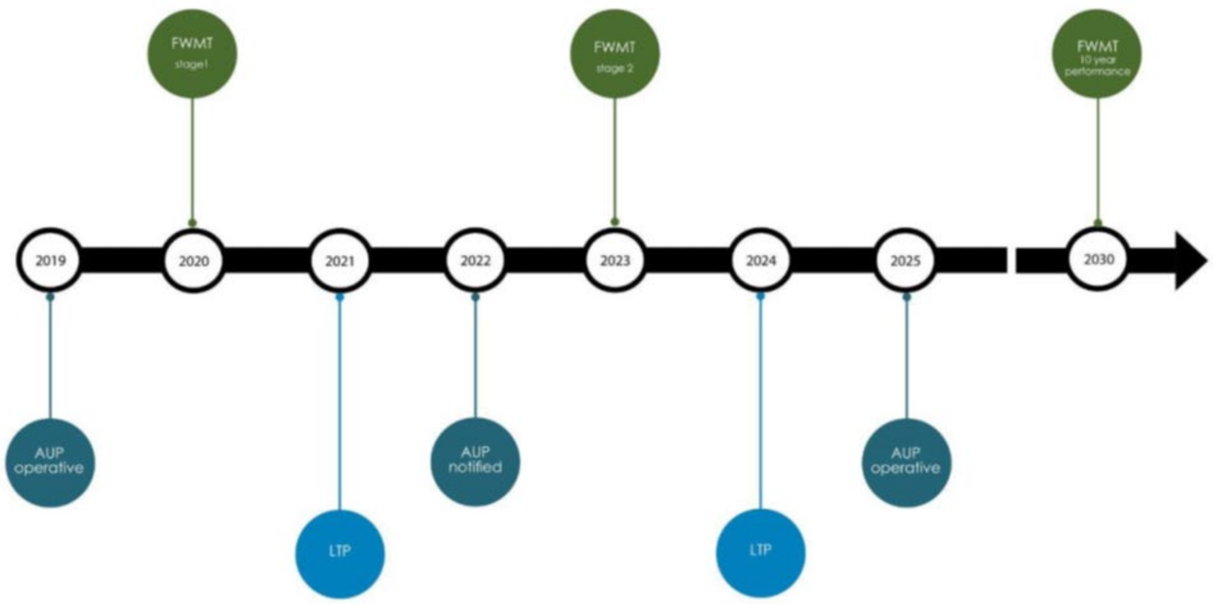

Figure 1: FWMT development trajectory as at 2020 (Source Stephens et al., 2020). Note imagery indicative, programme timings under continual review.

The FWMT team indicated that their priority is to address uncertainties in the input data and improve the performance assessment of the FWMT Stage 1 for the six existing parameters. While improving the assessment of the FWMT's performance will not explicitly improve FWMT predictions in the short term, in the longer-term improving performance assessment can better guide and support continuous improvement in FWMT predictions.

Importantly, state outputs based on FWMT predictions underpin the tools' action-planning functionality; intervention modelling and optimisation of actions for achieving objectives. Therefore, improving performance assessment with a wider range of observational datasets is integral to improvement in all FWMT functions and outputs.

The workshop clarified the purpose of this project, which was to provide recommendations for the collection of water quality observation data to support a more robust assessment of the FWMT's predictions. Improved performance assessments in turn leads to improving knowledge of uncertainty, modelling limitations and continuous improvement of model predictions.

2.3.2 Workshop 2: Peer Reviewers

A workshop was carried out with the authors of the FWMT Stage 1 baseline peer review report (David Hamilton, Kit Rutherford and Nic Conland) and the FWMT team on the 8th of November 2021 to discuss how, in their view, additional monitoring could help refine the capabilities of the FWMT. The main conclusions arising from this workshop are summarised as follows:

- The peer reviewers reiterated Recommendation 6 of the peer review report (copied below), which described their recommendation to re-examine calibration and validation of Stage 1 of the FWMT.

> *Recommendation 6: Further analysis is required to set out the strengths and weaknesses of FWMT Stage 1. This work includes: (1) clear delineation of calibration and validation processes, possibly scaled to 1-2 sub catchments so that computational times do not become too cumbersome, (2) uncertainty analysis to understand the relative effects of input data, model conceptualization and parameter calibration and (3) examining in detail the processes of contaminant generation, delivery and attenuation which will help to better inform the possible mitigation actions.*

- It was recognised that calibration and validation processes to date are affected by existing water quality data being focussed to the city (i.e., urban areas) and the predominance of observations being at periods of low flow (or conversely an absence of event-based water quality information).
- The importance of taking a Source-to-Sea approach was highlighted. The FWMT provides predictions for in-stream concentrations at sub-catchment nodes longitudinally along a watercourse and there is currently an absence of water quality data to assess changes in concentration along watercourses. Understanding how observed and predicted concentrations compare along a longitudinal gradient is important for FWMT performance assessment, but may also indicate how effectively in-stream processes, such as generation, transport, mixing, dilution, attenuation, are represented with the tool.
- Related to the longitudinal aspect, the peer reviewers considered that the FWMT should consider intensive, but shorter term 'measurement campaigns' (i.e., weeks or months) rather than focussing solely on long-term SoE type monitoring programmes (i.e., years). This approach could be designed to investigate the tool's capability to capture the processes of contaminant transport and transformation as it travels through a catchment. Thus, consideration should be given to investing some monitoring effort on selected sub-catchments, and potentially apply the findings more generally.
- A key element of the discussion was whether focusing the monitoring recommendations to a limited number of sub catchments and taking a case study type of approach would help address uncertainties in the input data. This may involve the development of sub-regional models for each of the smaller "case-study catchments". The AC FWMT team indicated that they would be open to considering this approach in the future to increase the rigour of the model in catchments with particular management issues. However, there was an immediate need for the FWMT to operate at a regional scale to enable a high level assessment of management issues, potential interventions and associated costs. Sub-regional models are likely to be a longer-term requirement as interventions are 'stepped down' to catchment scales.

2.3.3 Workshop 3: Modelers

A workshop was carried out with Dustin Bambic (FWMT lead modeller and director of Paradigm Environmental) and the FWMT team on the 25th of January 2022 to discuss how additional monitoring could inform the next stages in the model's development. The main conclusions from this workshop are summarised as follows:

- Catchment specific configuration has not been carried out for the first stage of the FWMT, which is designed as a regionalised tool (i.e., process coefficients are selected across all monitoring sites to assure better performance at all rather than one specific location). However, monitoring is expensive and time consuming and should be focused on collecting data of broad, regional relevance, rather than single watersheds. There will always be a demand for a regionalised tool (even if some effort is centred on specific catchments). There are large areas in the region that are unmonitored, however one cannot monitor everything everywhere. Thus, a pilot area approach based on intervention or land use priorities could be considered. Over time the model may potentially become a hybrid (regionalised, but with catchment specific applications).
- Hydrological Response Units (HRUs) are the foundational building blocks of the FWMT, hence there will always be a need for water quality monitoring data that are specific to HRU types. The first stage of the calibration process was to identify monitoring data that are representative of the dominant HRUs in the region. Then the data were used to represent how an HRU behaves and to upscale the findings for the entire region.
- The existing SoE monitoring programme has limited resolution in terms of HRUs. Thus, the monitoring recommendations should consider the balance between "lighter" monitoring at many sites for a sustained period such as the SoE programme vs. "heavier" monitoring at few sites with intensive and targeted HRU monitoring where data are lacking.
- The objective of the first stage of the model was to simulate the stream's response based on land characteristics and rainfall. Contaminant generation in the FWMT is based on a "build-up/wash-off" approach, thus end-of-pipe, and edge-of-field data are important (i.e., represent HRU time-series prior to instream process modification). End-of-pipe and edge-of-field data are influenced by contaminant build-up and the magnitude of any given storm event, which means contaminant generation can be highly variable. This variability can be investigated in two broad ways:
  - The Paradigm and the FWMT teams acknowledged that there are existing end of pipe datasets that have not been utilised in Stage 1. A review of existing datasets to identify those that could be helpful in an improved performance assessment should be undertaken.
  - Investing some monitoring effort in small headwater catchments (i.e., those without modelled reaches), where the absence of in-stream processes means the data could serve as a surrogate for edge-of-field data in catchments.
- The inability to assess in-stream processes based on existing SoE data was highlighted. To better understand what drives the fractionation of N and P as it moves through the stream is considered a priority. Process parameters in the model were based on default values from the USA that were calibrated using best fit, but there is no observational data to check that the model process parameters were set at realistic values.
- The difference between (near) continuous hydrology data and monthly water quality sampling was discussed and is likely to have contributed to any lack-of-fit in the model's water quality predictions. Furthermore, base-flow conditions appear to dominate the water quality observational records, and more data associated with various stages of flow events (rising and falling limb) is necessary to improve performance assessment. Some monitoring effort should therefore aim to capture how contaminant concentrations rise and fall over time (rising/falling limbs and peak flow concentrations).

2.3.4 Summary of findings

Overall, there was a clear message that additional FWMT centric water quality data was required to support improved performance assessment of the FWMT, which would be fundamentally different to regular SoE monitoring. This included water quality data explicitly targeted to specific flow conditions and locations most representative of HRU pressure-responses along a large gradient of regional responses to meteorological variation. This data collection approach is likely to focus on defined 'measurement campaigns' rather then open ended, long-term SoE type monitoring as the FWMT does not have a trend analysis function.

At first, there seemed to be a disconnect amongst the workshops in terms of the spatial extent at which the FWMT should be developed and applied, but we consider this primarily a timing issue rather than discord about how the tool should be applied. For example, it was articulated that there is a clear need for a region-wide tool that can be used to inform management strategies and funding decisions at that scale. Subsequent to this regional exercise, it is likely that sub-regional applications of the FWMT may be appropriate to ensure catchment scale management is effectively designed and implemented.

A visual summary of the key workshop outcomes is presented in Figure 2.

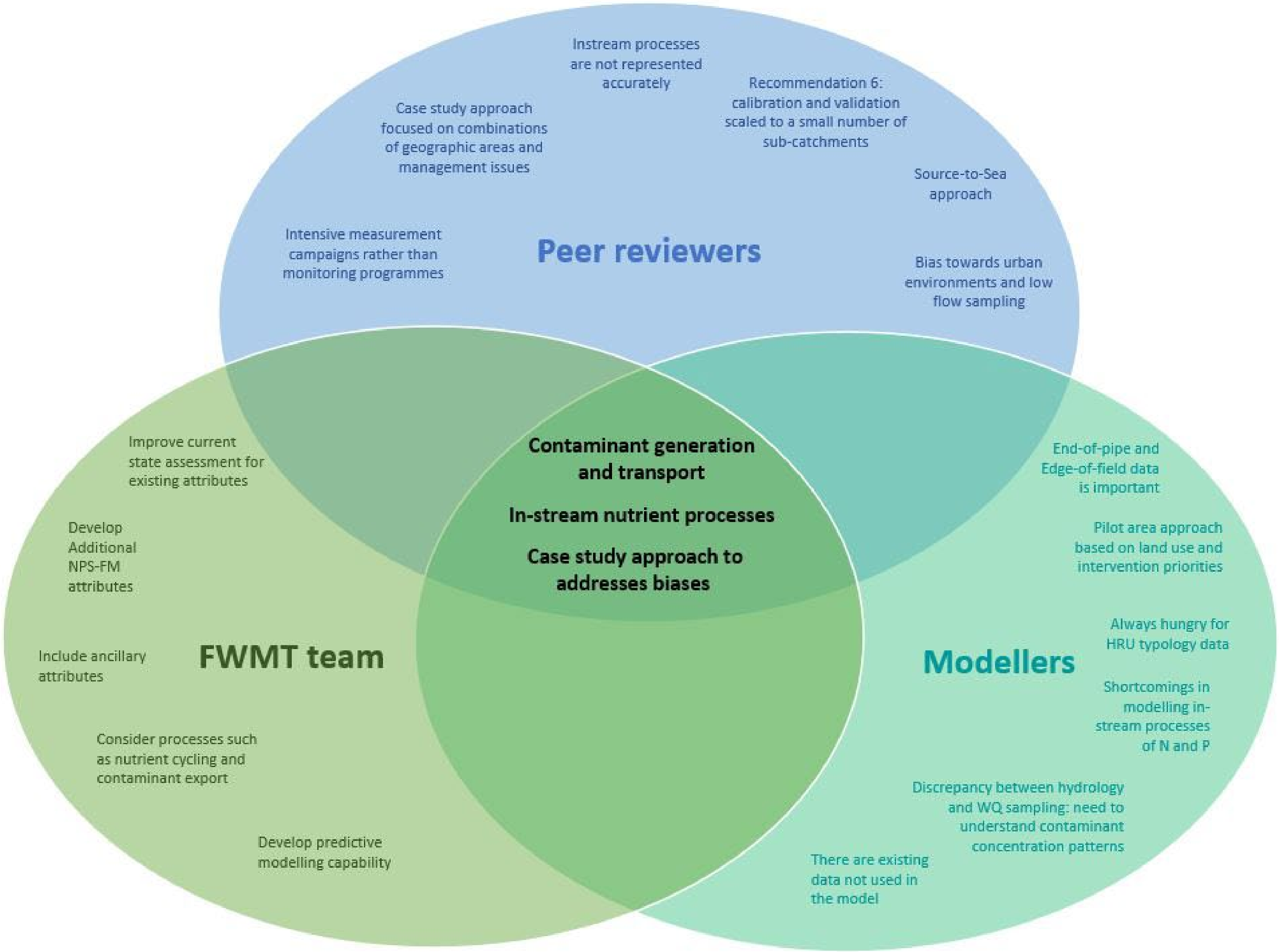

Figure 2: Venn diagram showing a summary of outcomes from workshops carried out with the FWMT team, the peer reviewers, and the modellers. The overlapping area shows topics highlighted by all groups.

3 Monitoring Objectives, Recommendations & Actions

A key consideration when undertaking any environmental data collection activity is that design of the data collection is fit for purpose; that is the design should be appropriate to provide the information that satisfies the purpose of the data collection. Therefore, it is a critical step in developing monitoring recommendations that the monitoring purpose and objectives are clearly defined. The design of the data collection and the analytical approaches (i.e., the "what, where, when and how" that define a monitoring programme) should be derived from the purpose and objectives.

Through our discussion with the FWMT team, modelers and peer reviewers, a clear high-level FWMT centric purpose for future data collection became apparent, which was to '*acquire environmental data and information to improve performance assessment of the FWMT*'.

The monitoring purpose is explicitly focused on improving the 'assessment of performance', rather than improving performance of the FWMT, as simply collecting more data will not lead to change in the performance of the tool. Nevertheless, we note that water quality data collected purposely for assessing the performance FWMT will likely cover a wider range of flow conditions and catchments with high HRU coverage. This data should enable the limitations of Stage 1 to be better understood, and in the longer term the data may be used in the configuration of future iterations of the FWMT. Improving performance assessment is also essential to continuous improvement of the FWMT and critical to ensuring model uncertainty is correctly understood and communicated to users of the FWMT.

Within this FWMT centric purpose, two objectives for the data collection emerged from the discussions and our subsequent analysis:

1. Improve FWMT baseline performance assessment (via improved observational data) to reduce uncertainty in Stage 1 baseline outputs and identify areas of improvement for model development
2. Enhance FWMT baseline outputs by to include recommendations for monitoring of key physicochemical parameters governing contaminant process simulation and metal toxicity (e.g., temperature, DO, pH).

The scope of our monitoring recommendations is limited to Stage 1 baseline of the FWMT. However, several issues relevant to the intervention modelling and optimisation capability of the FWMT were discussed or identified during the project. We have captured these discussions here to ensure they are not lost, and therefore provide high-level commentary on a supplementary objective:

3. Improve management (intervention) process-modelling in FWMT (devices, source controls)

3.1 Objective 1 – Improve Performance Assessment of FWMT

The first objective addresses two fundamental problems faced in assessing FWMT Stage 1 baseline performance using existing SoE water quality data, which were highlighted in Hamilton et al. (2021) and expressed in the workshops during this project:

- *Time-problem.* The monthly frequency of SoE sampling is unsuitable for assessing high-resolution model predictions, particularly non-central statistics. In simple terms, the SoE data does not provide for a reliable assessment of 95th percentiles, or other non-central numeric measures of contaminant concentration, nor loads calculated from them. As such, it remains difficult to assess FWMT performance at predicting 95th percentile concentrations because of the difference in sample size of 95th percentile events between FWMT and SoE data (e.g., statistical artefacts are likely to bias the comparison). We note this problem is less notable and unlikely to affect central statistics like median-based numeric states.
- *Spatial-problem.* The limited coverage of SoE sampling locations is unsuitable for assessing regionwide model predictions. In simple terms, the SoE sampling locations have limited coverage of the rivers in the region, as well as the mix of climate, soil, slope and land cover combinations used by the FWMT. As a process-based model, the FWMT is able to provide water quality information away from monitored locations, and represent diverse types and sizes of catchments, however the absence of water quality data precludes assessment of performance. Therefore, it remains challenging to assess FWMT performance away from SoE sites due to absence of water quality data from other parts of the river network.

A third issue is inherently linked to FWMT water quality predictions – their process basis and a lack of corresponding detailed observational records of process-variation (e.g., of changes in key parameters driving or responding to contaminant processes in LSPC such as speciation of nutrients under varying oxygenation).

Part 1 – Time and Spatial Challenges

The FWMT has been developed using data from the existing SoE water quality monitoring network operated by Auckland Council over the baseline period (2013-2017). As previously discussed, this monitoring involved the collection of water quality samples taken monthly from up to 36 locations on the Auckland stream network. The limited, if representative, spatial and temporal coverage (i.e., monthly samples) of SoE data is one of the key reasons for developing the FWMT.

The FWMT offers a prediction of water quality throughout all 5,465 sub-catchments in the region at a high temporal-resolution (15-minute simulation timestep) to provide greater spatial and temporal coverage of information about in-stream water quality (and supporting information on the key sources of contaminants at all locations and times via continuous, process-based modelling). However, the reason for developing the FWMT is also a reason for uncertainty in predictions; the lack of water quality data away from SoE locations and times provides the challenge of how to verify FWMT outputs.

The difference in spatial information on water quality between the SoE network and the FWMT predictions is simple to understand. The FWMT offers water quality predictions for each of the 5,465 sub-catchments in the region, whereas the SoE network provided water quality information for the 36 monitored locations over the baseline period (2013-2017). There are therefore 5,429 sub-catchments on the Auckland stream network where the FWMT provides water quality information that were not regularly monitored.

To improve baseline performance assessment, and reduce modelling uncertainty, the generation of new water quality data is required at un-monitored locations. It is clearly impossible to monitor at all 5,429 sub-catchments outside of SoE coverage, so further monitoring should be focused at locations of greatest value to the FWMT (e.g., in sub-catchments that are under-represented in existing datasets and have uniform upstream HRU coverage).

The difference in temporal information on water quality between the SoE network and the FWMT is similar to the spatial differences, but perhaps the implications for assessing and improving performance of the FWMT are not as obvious. Stage 1 of the FWMT provides water quality predictions every 15 minutes (then aggregated to daily averages), for the 2013 to 2017 period, whereas over the same 5-year period the SoE monitoring was carried out monthly. Therefore, over the 5-year period there are 1,826 days (and ~175,000 15-minute estimates) with water quality information provided by the FWMT and 60 days with water quality information provided by SoE monitoring. These differences in temporal frequency affect the ability to assess and refine the FWMT in two ways.

First, for each SoE monitoring location, during the 5-year period there are 1,766 days with water quality information available from the FWMT, without directly comparable SoE monitoring information on which to assess performance.

Second, the large differences in the size of the two datasets has implications for some of the summary reporting metrics commonly used for water quality parameters. While median values may not be substantially affected by the differing dataset sizes, some of the metrics commonly used for water quality reporting, and specified in the NPSFM, are more sensitive to the size of the dataset (e.g., 95th percentile, maximum). For example, 60 samples over a 5-year period are unlikely to capture the full range of variability in water quality parameters over that period. As a result, descriptive statistics calculated from this dataset, such as medians, 95th percentiles and maxima, may not be fully representative of the water quality during the 5-year period.

By providing water quality information for every day during the 5-year period, the FWMT will likely capture more variation in water quality parameters, in particular resolving more variation in lower and higher percentiles. This will mean the metrics that describe the extremes of the distribution of data (e.g., 95th percentile, maximum) are likely to be higher based on the FWMT dataset than the SoE dataset. Hence, it is entirely plausible, if not likely that the FWMT outputs for 95th percentiles should be higher than those observed from the SoE monthly sampling regime, and that such a finding should not be used to infer the FWMT predictions to be inaccurate.

Increasing the temporal coverage of the available water quality information is perhaps the biggest opportunity to provide insight into the performance of the FWMT. This is because it would permit analysis to distinguish the reason for any disagreement between modelled and observed conditions, disentangling the ‘dataset size and shape’ issue from other aspects of model performance.

This issue was identified during the development of water quality models for Safeswim and can be explored by sub-sampling the larger dataset (Tuckey & Chakravarthy, 2018). However, we consider that the optimal approach for resolving this issue is to generate new water quality data that is a closer match to the frequency of predictions from the FWMT. Whilst sub-sampling of the data can be insightful, as previously discussed the lower frequency of observed data is unlikely to capture the full range of potential observations. Therefore, data collection will need to happen at greater frequencies than monthly or at specified times (e.g., event based) to capture a broader range of flow conditions, to improve confidence that the observed dataset is representative of true conditions at a site.

This could involve additional data collection to supplement the monthly data from some of the existing SoE sites if the HRU composition is useful for performance assessment, as well as collecting higher frequency data at any new sites established (reflecting the spatial problem distinction). It is our understanding that monitoring at the existing SoE sites will continue for the foreseeable future and therefore this investment in data collection by Auckland Council can be leveraged to support the FWMT.

Recommendation #1 (Objective 1) – to undertake in-stream water quality data collection for existing Stage 1 parameters to provide data suitable for assessing performance of the FWMT.

Several factors should be considered in implementing recommendation #1:

1. What
    - Prioritise the existing six Stage 1 parameters (various forms of TN, TP, TSS, TCu, TZn, *E. coli*) to ensure the time and space challenges in assessing performance are addressed for the key FWMT outputs, noting later recommendations to ensure additional physicochemical measures that underpin the process-based outputs are included in data collection. All data collection should be supported by flow information (measured or modelled).
2. Where
    - Consider some **existing** SoE sites – undertake greater frequency data collection at some existing sites to fill temporal gaps, particularly where SoE sites have relatively homogenous HRU composition (e.g., a subset of the 17 SoE locations used for calibration (see Table 4-15 in Auckland Council (2021c)). The SoE network is a significant investment by Auckland Council and utilising the existing network offers efficiencies for data collection, including potential sampling infrastructure for continuous sensors.
    - Prioritise entirely **new** sites to capture HRU types that are not well represented by the current SoE sites – recognising representativity is preferred for key HRU factors (soil, slope, land cover and impact types).
        - Site selected for performance assessment should follow a two-step process:
            - Step 1 – select sites with homogenous HRU composition to assess the FWMT's prediction in relatively 'simple' catchments.
            - Step 2 – select sites with heterogenous HRU composition to assess FWMT's predictions in more 'complex' catchments.
        - We recognise that catchment size will likely be a co-variable in the selection of new sites, with sites with smaller catchments more likely to have homogenous HRU composition, but larger catchments are less subject to "noise" (random variation) affecting their instream variation in water quality. Therefore, we consider that a robust performance assessment would capture a range of sub-catchments of different size.
        - For selecting both existing and new sites, the water quality predictions of the FWMT could be used to further guide decision making. For example:
            - For existing sites, where model predictions and observed data are known to differ, additional data collection could provide insight into the reason for differences.
            - For both existing and new sites, collecting water quality information for HRU types where model predictions have high variability may provide insight into the reasons for high variability, and provide information to support more precise predictions in future iterations of the FWMT.

3. When

   - At existing SoE sites, data collection should be designed to improve the 'data shape' to better represent the range of concentrations that might be observed in response to flow events. This may involve targeting sampling to collect data at under-represented parts of the hydrograph (e.g., rain events, low flows) and/or the collection of data at higher frequencies (e.g., deployment of "continuous" monitoring probes)
   - At new sites, data collection should consider how the sampling regime can best represent the true distribution of data.
   - The methods used to increase the temporal coverage of water quality data will vary depending on the parameter(s) of interest.
     - Some parameters are able to be monitored at high frequency using deployed sensors (e.g., temperature, DO, nitrate). Where feasible, from a logistical and cost basis, we consider this to be the optimal approach.
     - Some parameters are not currently able to be monitored using deployed sensors (e.g., TP, *E. coli*). Increasing the temporal coverage of data for these parameters will require a greater frequency of discrete samples being collected (e.g., weekly, daily, sub-daily). Autosamplers may be useful for these parameters as they can be triggered to sample based on flow conditions or remotely at desired times.
   - Stream flow data should be acquired for each new site, either by direct measurement or by modelling or correlation with existing flow monitoring sites
   - The duration of this data collection programme should be sufficient to allow the variability in water quality to be adequately captured – seasonal and inter-annual (wet v dry years) and should consider the "simulation period" used for the next stage(s) of FWMT development. The duration of data collection should not be determined by the need for trend identification, rather to capture the variation in water quality across flow status.

Recommendation #1 and the considerations within it, require two pieces of desktop analysis to provide more detailed direction for data collection.

Action #1 (**Objective 1) –** Undertake a spatial review to determine coverage of HRUs and selected factors for existing SoE and identify sub-catchments with under-represented factors for potential targeted monitoring.

Action #2 (Objective 1) - Undertake a temporal analysis to determine coverage of SoE samples across the observed hydrograph at selected SoE sites to identify under-represented flow conditions for potential targeted monitoring.

These desktop analyses have been undertaken and are reported in Section 4.

Part 2 – Processes and Parameterisation Challenges

The FWMT is a process-based model, meaning the tool simulates the generation, transport and fate of water quality variables across the Auckland region. Stage 1 of the FWMT includes several processes related to sediment and nutrients, including:

- Deposition
- Re-suspension
- Scour
- Desorption
- Nitrification
- Denitrification

- Benthic release of nutrients
- Nutrient adsorption to suspended sediment
- Algal growth and death rates

The underlying LSPC model includes default values for these processes based on research and model application in the USA. Some of these default values have been used in the FWMT, while others have been adjusted during calibration to improve the fit of predicted and observed data (e.g., deposition, re-suspension and source are calibrated to Auckland stream conditions). In addition, water temperature is a key controlling parameter for most of these processes in the FWMT; however, temperature is not explicitly calibrated-validated in the FWMT and is instead represented by "default" values.

Earlier recommendations relate to ensuring outputs from the FWMT are better able to be tested for their fit to a better surveyed reality (e. g., better assess performance). Here, we are discussing better targeting monitoring to ensure FWMT modelled outputs match reality in a logical, process-based manner. Specifically, that variation in process parameters reflect marked differences in variability of key instream processes by reach type (and over variation in physico-chemistry). Acquiring (or using existing) high-frequency temperature data is therefore seen as a high priority monitoring need to support the modelling of the processes in FWMT.

It is uncertain how well the default and adjusted values used in Stage 1 accord with rates of these processes in Auckland streams, including their classification into groups of similar or dissimilar coefficients by HRU and reach type (i.e., the FWMT includes several reach types for nutrient, sediment and broader temperature regimes). This was an issue that was stressed as high priority by both the peer reviews and the modelers in the respective workshops. The issue is both one of understanding what range in process responses are characteristic of New Zealand streams, and what diversity in those responses occurs (or alternatively, how to logically assign similar process coefficient values to combinations of HRU and/or reach type – which should share similar or dissimilar values).

Recommendation #2 (Objective 1) – adopt a two-stage approach for assessing and improving the representation of processes in the FWMT, by:

a) Undertaking a desktop review of the processes and their representation in the FWMT, focusing on assessing the basis for the default or adjusted values and whether the values used are likely to be a realistic for Auckland streams based on published work from New Zealand. This review should consider the key environmental factors that may affect variability in processes (e.g., seasonality, land use and impact gradients, stream order, position in catchment and stream substrate).
b) Depending on the availability of suitable data and how well it accords with the values used in the FWMT, the values might be considered appropriate, and no further action might be required. In contrast, if there is no data, the data has limited coverage of Auckland conditions, or the local data does not support the values used in the FWMT, a second stage (of data gathering) might be required. In such cases, local data on processes should be acquired to fill gaps or resolve inconsistencies. Detailed measurement or sampling campaigns will be designed depending on the process being considered, and may include in-stream measurements at existing monitoring sites, and longitudinal or high spatial density surveys in the catchments upstream of given monitoring sites or in the reach between two monitoring sites.

Action #3 (Objective 1) – undertake desktop review to determine process coefficients across HRU's and reach types, demonstrating which processes have greater sensitivity on contaminant generation and transformation, as well determining which HRU's and reach types share similar process sets. Contrasting HRU outputs with knowledge of surface/activity types to determine if similar process coefficients are logical for build-up and wash-off processes, and contracting reach outputs. This action will be undertaken Healthy Waters and is not covered further in this report.

3.2 Objective 2 – Enhance FWMT baseline outputs by including additional water quality parameters

Stage 1 of the FWMT has been configured to model six core water quality parameters (nitrogen, phosphorus, copper, zinc, sediment and *E. coli*). The selection of these parameters for Stage 1 exercise was logical as they are important water quality parameters for resource managers, which reflects the operational focus of the FWMT, and existing data for calibration were available from the SoE programme.

As the FWMT moves into the next stage of its development, additional parameters could be included to support model development and potential application. We consider that inclusion of additional parameters into the FWMT should arise because of two main reasons:

1. Some parameters are important for the process-modelling in the FWMT (e.g., affect the six core parameters)
2. Some parameters are important for management of freshwater (e.g., affect the wider management value of FWMT)

The FWMT utilises LSPC modules for sediment, temperature and water quality (RQUAL). Whilst temperature was part of the instream process modelling, temperature predictions have not been calibrated in Stage 1 development. It is stated that this is due to an absence of robust instream temperature data (Auckland Council, 2021b). Temperature dependency is present in nearly all LSPC processes affecting nutrient dynamics in streams. It is therefore essential that continuous temperature monitoring is included in any water quality data collection arising from Objective 1.

We consider the inclusion of dissolved oxygen and pH in any monitoring activity is of similar importance to temperature, based on their importance for resource managers (e.g., dissolved oxygen is an NPS-FM attribute), their value in assisting with the assessment of other parameters (e.g., pH adjustments as specified in the NPS-FM) and processes (e.g., de-nitrification).

In addition, consideration should be given to the potential for monitoring of metal toxicity modifying factors reported for the FWMT programme by NIWA (Gadd & White, in prep). This parallel project determined that identifying variation in hardness, dissolved organic carbon and pH is important in the assessment of metal toxicity.

Recommendation #3 and Action #3 (Objective 2) – include temperature, hardness, dissolved organic carbon, DO and pH in water quality data collection undertaken under recommendation 1. Given the diurnal fluctuation patterns for some of these parameters, priority should be given to high-frequency data collection for temperature, DO and pH. .

It is our understanding that in-stream primary production in the FWMT (LSPC) is represented by planktonic algae growth processes. Based on our knowledge of Auckland streams, planktonic algae growth is unlikely to be the dominant primary production process due to the short stream length and associated short residence time. Instead, primary production in Auckland streams is generally dominated by macrophytes and, to a lesser extent, periphyton (often epiphytic), growth. We suggest that further investigation of the role of primary production in nutrient uptake and decay in the FWMT is needed to confirm if macrophyte or periphyton monitoring would add value to the FWMT.

3.3 (Supplementary) Objective 3 – Improve representation of management interventions in FWMT

As stated, this report has a narrow scope to provide monitoring recommendations to improve performance assessment of water quality predictions from the FWMT Stage 1 (e.g., objectives 1 and 2). However, several issues relevant to the action-planning capability of the FWMT were identified during our discussions with the FWMT team. We have captured these discussions here to ensure they are not lost, and therefore provide commentary on a supplementary objective for any FWMT related monitoring, which was to improve the representation of management actions in the FWMT to support scenario modelling.

Both objectives 1 and 2 are fundamental to developing better intervention modelling and optimized intervention modelling with the FWMT Stage 1. Therefore, our recommendations made in relation to state (Section 3.1 part 1) and processes (Section 3.1, part 2) are highly relevant to the FWMT's action-planning capability.

One of the FWMT's key objectives is to support the development of interventions or mitigations to improve the health of freshwater and coastal environments. Ultimately, the FWMT will assist with optimising the nature (type, size, functioning), location and cost of interventions to achieve a range of quantified remediation objectives. An example could include meeting a national bottom line for an attribute or reducing the contaminant loads delivered from the freshwater catchment into a sensitive coastal environment.

Developing the FWMT's capability in this field will require a range of environmental data collection, including:

- The collection of more edge-of-field and end-of-pipe data – as interventions within FWMT model architecture alter HRU-contaminant generation and transport processes rather than instream time-series (e.g., affect the generation and loss of contaminant from surfaces and land activities).
- Monitoring to measure the effectiveness of individual interventions (devices, source controls; urban, rural). In this context, consideration should be given to Before/After/Control/impact (BACI) monitoring design as well as the underlying build/management/age of an intervention (e.g., capture variation in effect for factors other than "type" or "size" of intervention). This may include targeting areas of new (greenfield) development, adoption of farming/growing good practices or where edge-of-field and stormwater devices are retrofitted.

Our review is restricted to in-stream monitoring, meaning that most of the above considerations fall outside its scope. However, where possible additional monitoring design should consider device and source control monitoring requirements. For example, data collection in headwater/first order streams may be useful as a surrogate for "edge of field / end of pipe" data.

4 Spatial and Temporal Desktop Analyses

Section 3 identified three objectives for FWMT-centric, targeted monitoring to underpin continuous improvement in modelling and FWMT-supported decision-making. The objectives of FWMT baseline targeted monitoring are:

1. Improve performance assessment of FWMT.
2. Enhance FWMT baseline outputs by including additional water quality parameters.
3. Improve representation of interventions in FWMT (e.g., devices, source controls)

Of these, the first objective is associated with three actions requiring desktop review. This section of the report contains the output of those actions:

- **Action #1 –** undertake a spatial review to determine coverage of HRUs and selected factors for existing SoE and identify sub-catchments with under-represented factors for potential targeted monitoring.
- **Action #2 -** undertake a temporal analysis to determine coverage of SoE samples across the observed hydrograph at selected SoE sites to identify under-represented flow conditions for potential targeted monitoring.
- **Action #3 –** undertake desktop review to determine process coefficients across HRU's and reach types, demonstrating which processes have greater sensitivity on contaminant generation and transformation, as well determining which HRU's and reach types share similar process sets.

4.1 HRU coverage – desktop review and analysis

The purpose of this analysis is to assess the representativeness of the SoE monitoring sites in relation to the regional coverage of HRU types, to identify HRU types that are under-represented in the existing SoE dataset, thus identifying priority HRU types for future monitoring.

The core spatial modelling unit within the FWMT is the HRU, which are unique combinations of factors (i.e., slope, soil, land cover and impact (intensity of land use)) influencing the generation and transport of both water and contaminant from land to waterway. There are 106 unique HRU types and the details of the configuration and rationale for the HRU types are provided elsewhere (Auckland Council, 2021a & b). For this analysis we use the spatial extent of the 106 HRUs to assess coverage across the region and the catchments of the SoE sites and each of the sub-catchments with the FWMT.

As stated above, the SoE network has recently been expanded from the 36 sites available at the start of the FWMT project, to 48 sites from July 2022 (Auckland Council, 2022). This analysis is based on the 48 sites in the expanded programme as we anticipate monitoring will be ongoing at these sites for the foreseeable future.

Regional extent

The spatial extent of HRUs within the Auckland region varies from 0.17 hectares (or 0.00004% of the region) to 58,551 hectares (12% of the region) (Appendix C). The mean spatial extent is 4,517 hectares, with a lower median coverage (1,312 hectares) indicating the spatial coverage of HRUs is skewed towards smaller spatial extents. This is evidenced by 35 HRUs having a regional coverage of less than 500 hectares (or 0.1% of the region).

There are 24 HRUs that have an individual spatial extent of more than 1% of the region, which are predominantly in pasture (12) and forest (eight) land cover. The results of the spatial analysis are provided in Table 2 for these 24 HRUs, with the results for all HRUs in Appendix C.

HRU coverage of SoE sites

Of the 106 HRU types, only 11 are not present within the catchment of an SoE site. The HRUs not present are generally HRU types with relatively low regional coverage (Appendix C), but three of these HRU types have a regional coverage greater than 1% and hence are included in Table 2 (Max column = 0 for Pasture-A-High-2; Forest-A-High-2; Forest-A-Low-2).

Whilst 95 of the HRUs are present with SoE catchments, 66 of these HRUs are present at a maximum coverage of less than 10%. Only four of the HRUs are present in the catchment of an SoE site at greater than 50% coverage. Three of these HRUs are in Forest land cover (seven SoE sites), with the other in Developed-Pervious land cover (one SoE site). Essentially, the catchments above the SoE sites are generally a mix of HRUs and only a small minority of these sites have relatively homogenous HRU cover (i.e., >50% of catchment area covered by a single HRU type).

HRU coverage of FWMT sub-catchments

All 106 HRUs are present to some extent within the 5,465 sub-catchments.

Sixty-two of the HRU types are present in a sub-catchment at greater than 50% coverage (2,360 sub-catchments have an HRU present at greater than 50% cover). These 62 HRUs represent 95% the regional extent, covering 454,206 hectares.

In contrast, 44 HRU types are not present in any sub-catchment at greater than 50% coverage. All of these HRUs have a regional coverage of <1% (maximum 0.7%) and collectively cover 24,574 hectares (or 5% of the region). Most of these HRUs are in Horticulture (18) or Road (13) land cover classes.

Discussion

Overall, the SoE sites do not provide a good coverage of the HRUs used in the FWMT. Only eight SoE sites have greater than 50% coverage of a single HRU in the catchment and seven of these are in forest land cover. This finding is not unexpected as the SoE programme pre-dates the establishment of HRUs for the FWMT, and the SoE sites are designed using several criteria related to RMA environmental management functions (Ingley & Groom, 2022), rather than key factors governing contaminant and hydrological response in the FWMT.

Through the workshop discussions, there was a clear message that monitoring data from sub-catchments with uniform HRU coverage would be of greatest value in assessing the performance of the FWMT. This analysis has identified that there are 2,360 FWMT sub-catchments that offer the potential to collect data where the upstream catchment is dominated by a single HRU (i.e., > 50%) for 62 HRU types.

We consider than prioritizing data collection within this ‘population’ of sub-catchments should be an iterative process by the FWMT modelling team. This is because the modelling team have the best understanding of which of the 62 HRU types are most important to the functioning of the FWMT and sensitivity of base models (LSPC, SUSTAIN) to HRU parameterisation. Notwithstanding this recommendation, we have provided a worked example of how the population of sub-catchments for a particular HRU type can be further filtered to support a site selection process as part of a monitoring plan.

To assist in this iterative process, we have also provided the upstream catchment areas for the sub-catchments with greater than 50% coverage of the 24 HRU types listed in Table 2 as Appendix E.

Table 2: Spatial information for the 24 HRUs with greater than 1% coverage of the Auckland Region. For SoE sites the maximum coverage of the HRU at any of the 48 SoE sites is provided with a count of the number of SoE sites with HRU catchment coverage above the area thresholds. For FWMT sub-catchments, the number of the 5,465 sub-catchments above the area thresholds is provided for the entire contributing upstream catchment. Area threshold column are colour coded to assist comparison of SoE sites and FWMT sub-catchments.

HRU	Regional extent		HRU coverage of SoE sites				HRU coverage of FWMT sub-catchments		
	Hectares	%	Max	>90%	>70%	>50%	>90%	>70%	>50%
Forest-C-High-1	58551	12.2%	83%	0	1	2	61	158	354
Forest-B-High-1	51734	10.8%	97%	1	2	4	77	199	397
Pasture-C-High-2	33889	7.0%	33%	0	0	0	6	48	146
Pasture-C-High-1	31066	6.4%	27%	0	0	0	3	25	80
Pasture-B-High-2	26565	5.5%	23%	0	0	0	10	44	121
Pasture-B-High-1	24080	5.0%	20%	0	0	0	5	19	85
Pasture-D-High-2	16706	3.5%	36%	0	0	0	8	54	136
Forest-C-High-2	15915	3.3%	91%	1	1	1	32	62	112
Dev_Pervious-C-High-All	14991	3.1%	56%	0	0	1	1	23	121
Pasture-D-High-1	13222	2.8%	29%	0	0	0	6	23	70
Dev_Pervious-C-Low-All	10585	2.2%	42%	0	0	0	2	18	93
Pasture-B-Low-2	10444	2.2%	7%	0	0	0	4	29	59
Pasture-B-Low-1	8802	1.8%	7%	0	0	0	2	12	34
Pasture-A-High-2	8026	1.7%	0%	0	0	0	2	14	47
Pasture-A-High-1	8001	1.7%	0.2%	0	0	0	7	28	53
Forest-B-High-2	6772	1.4%	15%	0	0	0	7	14	40
Pasture-C-Low-2	6109	1.3%	10%	0	0	0	2	12	23
Forest-D-High-1	6006	1.3%	14%	0	0	0	0	1	4
Pasture-C-Low-1	5693	1.2%	12%	0	0	0	3	4	10
Forest-A-High-2	5680	1.2%	0%	0	0	0	15	28	45
Rural_Grassland-C-High-1	5416	1.1%	24%	0	0	0	0	0	3
Forest-A-High-1	5258	1.1%	0.03%	0	0	0	0	2	16
Forest-A-Low-2	5239	1.1%	0%	0	0	0	21	34	49
Rural_Grassland-B-High-1	4799	1.0%	17%	0	0	0	1	4	7

We suggest there are two main approaches for dealing with the 44 HRU types that are not present at greater than 50% coverage in a sub-catchment. First, the coverage threshold may be reduced to below 50%. For example, if the coverage threshold was reduced to 40%, the number of sub-catchments increases to 3,586 and the number of HRU types to 68 (or reduced to 38 types not present). Second, consideration could be given to combining some of the smaller, but closely aligned HRU types. For example, there are eight Horticulture HRUs on A class soil that could be combined. However, these, or other, approaches for dealing with HRU types with low spatial coverage should be a decision informed by the modelling team.

A key consideration related to HRU spatial extent analysis and for future action, is that LSPC simulates contaminant and hydrological responses instream for the largest single stream reach within a sub-catchment. Therefore, targeted monitoring should focus on the single largest (and ideally furthest downstream) point in any HRU-prioritized sub-catchment to ensure any observational data is congruent with the location of sub-catchment outputs, a consideration which becomes more important for smaller net upstream drainage areas where relatively modest differences in locating a monitoring site will have potential for more marked disagreement with modelled time-series from FWMT).

Worked example – HRU Dev-Pervious-C-high-All[3]

This HRU was selected for the conceptual example as it is the only non-Forest land cover HRU in Table 2 with an SoE site at greater than 50% cover.

1. This HRU is present in 2,420 FWMT sub-catchments, although many of these are at low coverage (Figure 3a).
2. The sub-catchments were filtered to show only those with greater than a coverage threshold (in this case 30%) and existing SoE sites identified (Figure 3b)
3. The sub-catchments were filtered by sub-catchment type (i.e., headwater, coastal (with and without upstream sub-catchment), "normal").
4. Four sub-catchments were identified as potential sampling locations based on HRU coverage >60%, "normal" sub-catchment type (i.e., with modelled reach upstream, and not coastal) and catchment area of between 200 and 400 hectares.
    a. Sub-catchment 180100 (Waitemata watershed)
    b. Sub-catchment 180101 (Waitemata watershed)
    c. Sub-catchment 110392 (Islands watershed)
    d. Sub-catchment 110393 (Islands watershed)

[3] The HRU code Dev-Pervious-C-high-All represents the following combination of factors: Developed Pervious land cover (Dev-Pervious), soil type C, high slope, and all intensity/impact classes.

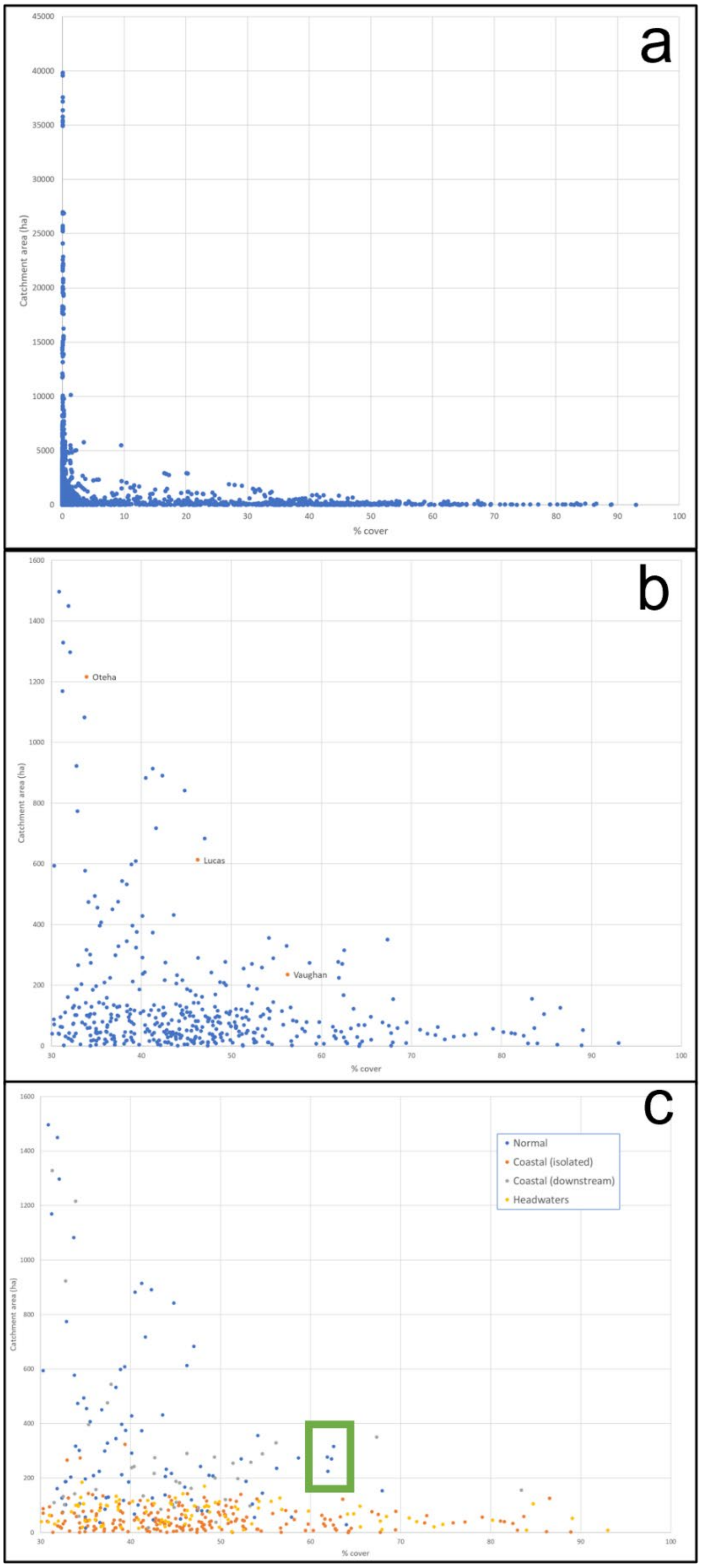

Figure 3: Scatter plot of FWMT sub-catchments showing occurrence of HRU Dev-Pervious-C-high-All. See worked example text for explanation.

4.2 Water quality/hydrograph coverage – temporal representativeness and gaps

The purpose of this analysis was to assess the hydrological conditions associated with SoE water quality data to identify representativeness of the data and opportunities for supplementary data collection to address under-represented parts of the flow regime.

Hydrological conditions at the time of each water quality sample were defined in two ways:

- where the flow sits on the long-term flow duration curve, to indicate the temporally weighted representativeness of the samples.
- hydrograph state, i.e., stormflow vs baseflow, to assess the range of conditions represented by the samples.

Overall hydrological conditions during the FWMT baseline period (2013–17) were also analysed to determine the representativeness of this period in the context of long-term hydrological variability (1980 to 2020).

Hydrological representativeness

Flow is often a major determinant of variation in instream contaminant concentrations and broader physicochemical conditions associated with processes governing contaminant form, availability and concentration (Walling & Foster, 1975; Evans & Davies, 1998; Rose et al., 2018; Bieroza et al., 2023). As such, when assessing the variation in water quality, and the potential for disagreement between modelled and monitoring datasets, it is important to determine the representativity of the monitoring data for flow and flow-status. Where flow is the magnitude of flow (discharge), and flow-status refers to comparative antecedent differences in flow derived from hydrograph-separation analysis. Notably, flow-status and flow are fundamentally distinct characteristics that can act independently of each other to cause variation in concentration (Sloto and Crouse, 1996). Therefore, both factors should be considered when assessing representation of flow-related effects on the concentration of contaminants in monitoring data. We note recent analysis undertaken for Auckland Council on statistical relationships between flow and concentration in SoE data assessed relationship with flow magnitude (Snelder and Kerr, 2022), but we are not aware of any previous analysis based on flow status.

For our analysis, paired (flow and water quality) sites, a measured flow rate was assigned to each SoE water quality sampling event and samples were then assigned into annual and seasonal flow exceedance percentile bins based on the long-term flow duration curves for each site. Flow duration curves for most sites with measured flow were either provided by Auckland Council or derived based on the flow record for the 2013-2017 period (Appendix D, Table D1). For water quality sites without measured flow, the FWMT-modelled flow for the corresponding model node was extracted and assigned to flow exceedance percentile bins based on a flow duration curve for the 2013-2017 period. While the use of FWMT-modelled flow is not ideal, it enabled the analysis to be expanded from 15 paired sites to 32 sites overall.

As a check on the appropriateness of using modelled flow, FWMT-derived flow was compared with measured flow at time of sampling at four sites. While there was some difference in measured and modelled flow rates, once the sample events were assigned into flow exceedance percentile bins the observed differences were relatively minor. It is also acknowledged that the use of modelled flow duration curves assumes that the 2013–17 period is representative of long-term hydrological variability; this was also tested (see below).

To characterise the hydrograph state associated with each sample, the flow in the three hours prior to each sampling event was analysed for rate of change. Each sample was then given one of four classifications:

- 'rising' (occurring on the rising limb of a storm hydrograph),
- 'stormflow recession' (i.e. the initial steep falling limb of the storm hydrograph),
- 'baseflow recession' (i.e. the later gradual recession following a storm event), or
- 'stable' flow conditions.

The thresholds to define the conditions at each site were set by qualitative judgement based on example hydrographs. Example periods of stable flow were assessed to determine an approximate threshold within which minor flow variations tend to occur. Flow increase above this threshold was defined as rising stormflow. Flow decrease beyond the threshold was defined as flow recession, with the change point between stormflow and baseflow recession a judgement based on examination of example hydrographs. Thus, the aim was to give a general indication of conditions represented by the sample data[4]. The 'stable' hydrograph state was further defined into 'high stable' (stable and above median) and 'low stable' (stable and below median) for graphing purposes.

Temporal representativeness of flow conditions

For each SoE site, between 55 and 60 sample events were assigned a flow and an equivalent annual exceedance probability. In general, sampling occurred relatively evenly across the flow exceedance percentiles, although there was a slight bias toward sampling of flows below median (50th percentile) in the Hibiscus Coast, Mahurangi, Wairoa, West Coast and South Kaipara watersheds (Figure 4).

Seasonal analysis (carried out only for sites with measured flow, as seasonal flow duration curves for modelled flow were not provided) indicates the bias towards sampling in lower flows tended occur in summer and autumn (possibly when high flow events are likely to be short, intense events that are harder to capture) and in winter (when flows tend to be higher and may not always be safe for sampling). Overall, flows that were under-represented by sampling during the five-year period (2013-17) were the highest tenth percentile of flows in winter (0-10th%) and flows above median in autumn (<50th%).

Coverage of hydrograph states

At all sites there was a strong bias towards sampling during stable flow conditions (Figure 5). Approximately 4% of samples were taken during the rising limb phase of storm hydrographs, noting these conditions may be difficult to manually sample due to the short period over which they occur (particularly in small urban catchments) and health and safety considerations. Similarly, around 4% of samples were taken during quickflow/stormflow recessions, which will occur quite rapidly in many of Auckland's catchments. There was no obvious difference in the spread of sampling event flow state between the receiving environments (i.e., the dominance of stable-flow samples occurred at all sites). The dominance of sampling under stable flows has the potential to be particularly problematic in assessing the performance of a build-up/wash off model such as LSPC.

Hydrological representativeness of the FWMT period

To assess how representative the 2013–17 baseline period is of long-term hydrological variability (and corresponding flow-driven variation in contaminants and physicochemistry), data from three key rainfall sites (Oldfields, Zanders and Albert Park) and two streamflow sites (Wairoa River at Tourist Rd and Rangitopuni River at Walkers) were analysed. The 2013–17 period was compared with long-term statistics of mean annual flow, mean annual rainfall, seasonal rainfall totals, low flow days per year, high flow days per year, and wet days per year.

The years 2013 and 2014, despite having relatively dry summer/autumn periods, were close to average in terms of annual rainfall, number of wet days and mean river flows. The year 2015 was very dry year (around 10th percentile low rainfall) with significantly fewer wet days and days with heavy rainfall compared to the long-term average, and more severe low flows. Conversely, 2016 and 2017 were 'wet' years, with slightly more wet days and high flow days than average; 2016 had a very wet February and spring and 2017 had high rainfall in autumn. However, for the statistics examined there were no record-setting occurrences within the FWMT period.

Overall, the statistics examined indicated that general hydrological conditions during 2013–17 fit into the historic range of variability. While a range of wetter and drier periods were experienced within the five years, the hydrological conditions experienced can be considered representative and appropriate for the FWMT calibration.

[4] A parallel in-progress FWMT report for baseline evaluation and ongoing improvement undertakes hydrograph separation using US-GS automated routines. In due course, readers are directed to this parallel report for corresponding results that show a similar pattern to those reported here (email: fwmt@aucklandcouncil.govt.nz for updates on report release).

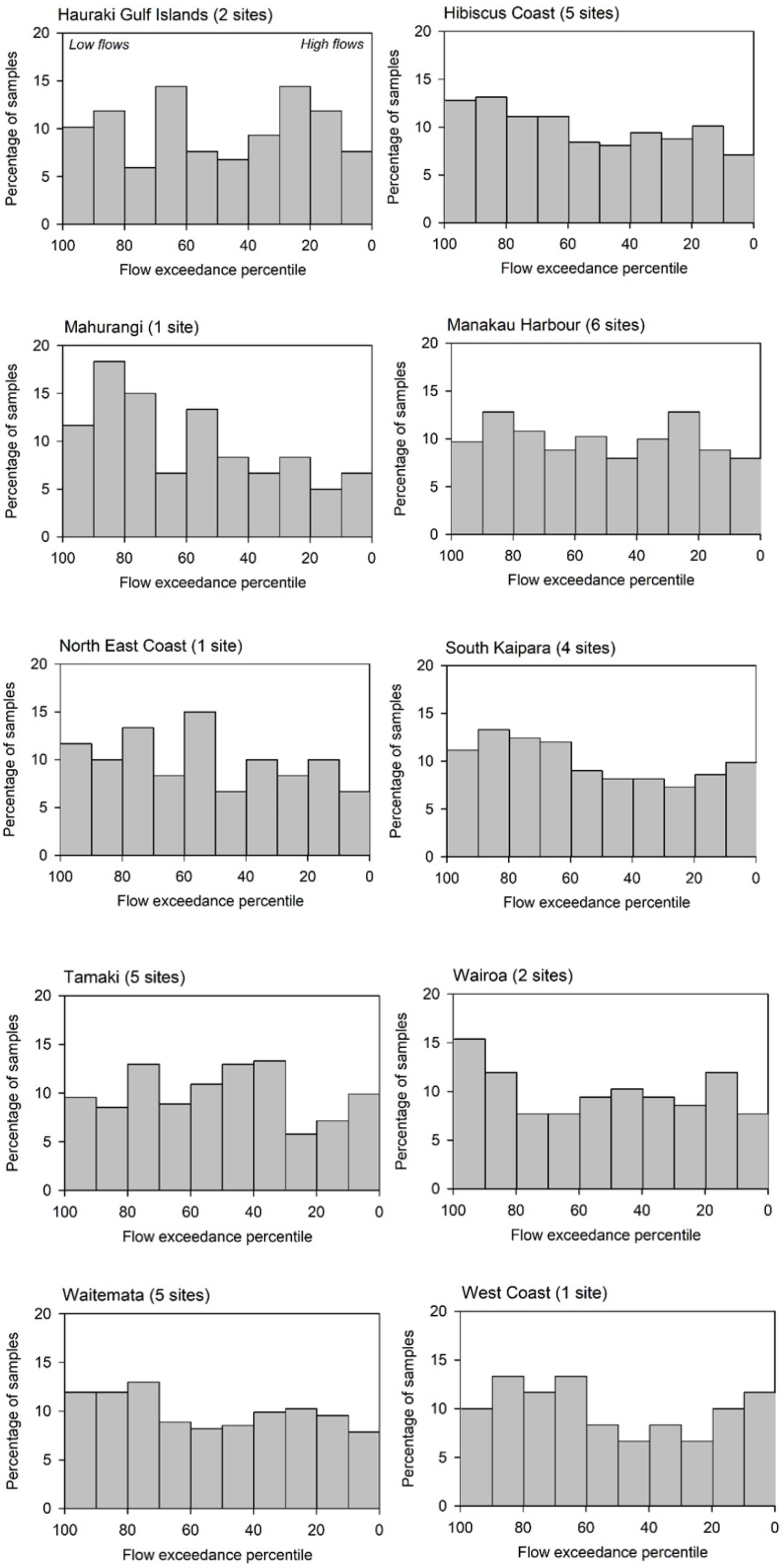

Figure 4: Graphs showing representativeness of SoE samples by flow conditions, with sites grouped by receiving environment and 10 percentile flow bins.

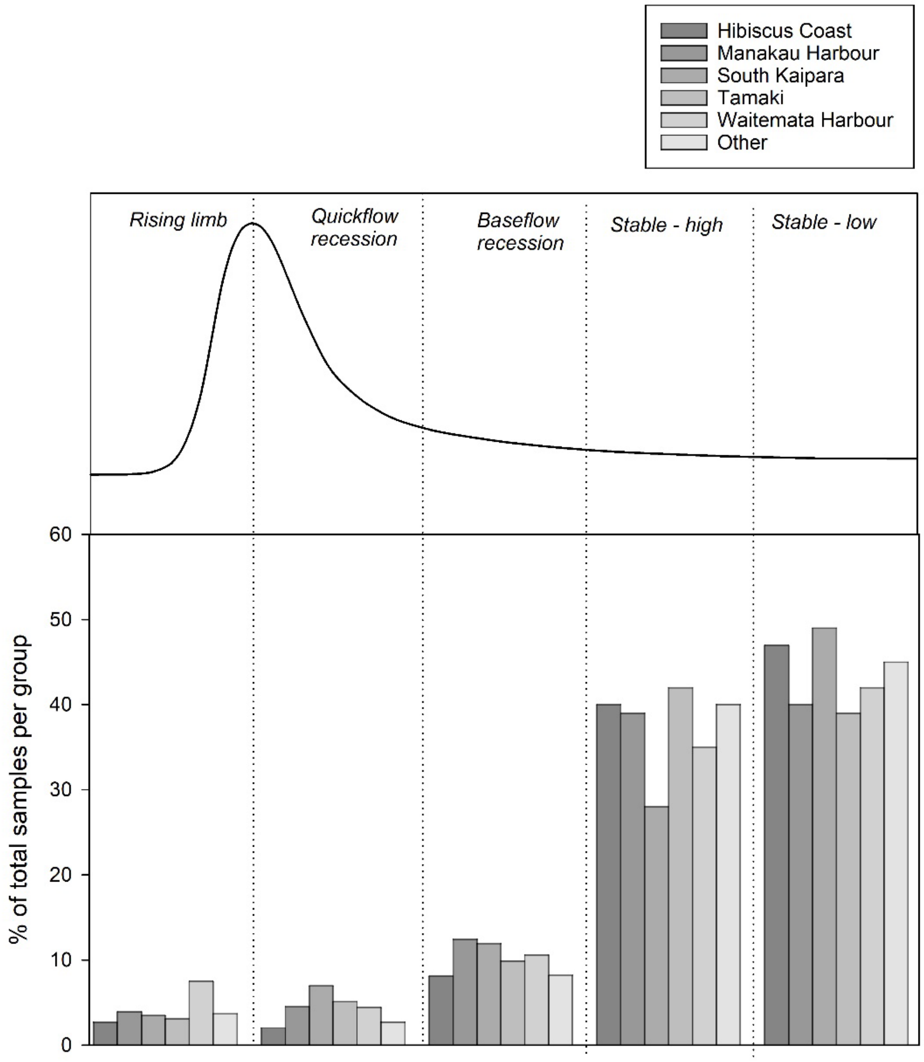

Figure 5: Distribution of SoE samples over the hydrograph states.

Discussion

Overall, the SOE water quality samples used for FWMT calibration period 2013-2017) offer good representativity of the long-term flow duration curve at paired sites, with only a very slight bias towards lower flows (i.e., coverage of flow rate is good). However, when flow status or position on the hydrograph is considered (i.e., rate of flow change) the sample events are not representative, with a strong bias towards sampling during stable flow conditions.

This bias is evident in the majority of the SoE sites for which data was available to perform the analysis (Table 3). The corollary is that rising limb samples are under-represented, with the % of time in the rising limb flow category notably greater than the % of samples in the rising limb category for 25 of the sites. Indeed, four of the sites have no samples in the rising limb flow category.

The potential implications for assessing the performance of the FWMT can be seen when examining the relationship between water quality measures and flow characteristics. For five of the FWMT Stage 1 parameters, higher concentrations tend to occur at higher flows and in the rising limb and stormflow recession flow categories. For example, this pattern is evident for TP, TSS, TCu, TZn, *E.coli* in the SoE data from Lucas Creek (Figure 6 to Figure 8), with further examples provided in Appendix D. It is also noteworthy that the observed concentrations in the rising limb and stormflow recession flow categories are markedly more variable than under the stable flow categories (note the logarithmic scales on the plots in Figure 6). Neither of these patterns are apparent for TN, where higher concentrations occur at a range of flow conditions – likely reflecting some SoE sites having TN-enriched groundwater contributions and others having TN-enriched stormwater contributions.

These issues have two key implications for the performance assessment of the FWMT. First, because it provides predictions across the full range of flow conditions, the FWMT is likely to provide higher estimates of non-central statistics (e.g., 95th percentile, maxima) than SoE data (which is based on samples primarily collected at stable flows).

Second, and related to the first, using SoE data to assess performance of FWMT predictions for concentrations far from the median, and especially those occurring under rising limb or receding limb stormflow conditions, would likely be unreliable. Identifying these critical conditions, including the 95th% concentrations of TN, TP, TSS, E.coli, TCu and TZn, is a key function of the FWMT and we agree with the peer review panel's concerns about the comparison between FWMT modelled estimates of 95th% and monthly sampled SoE data, for being potentially highly uncertain.

In order to improve the representativeness of water quality data in terms of hydrological conditions, it is recommended that future sampling for performance assessment of the FWMT ensures the following flow conditions are captured:

- streams flow above median during summer and autumn.
- high flows during winter.
- rising and quickflow (initial) recession limbs of storm events.

Table 3: Comparison of % of time in each flow category during the baseline FWMT period (2013-2017) and % of SoE samples collected during each flow category for 32 SoE sites.

Station number	River name	% of time in flow category				% of samples in flow category			
		Rising limb	Quickflow recession	Baseflow recession	Stable flows	Rising limb	Quickflow recession	Baseflow recession	Stable flows
6604	Matakana Stream	5	4	13	78	3	0	5	92
6804	Mahurangi River	12	11	23	54	7	7	13	73
7104	Waiwera Stream	6	9	12	73	3	7	12	78
7171	Nukumea Stream	5	5	10	80	2	2	12	85
7206	West Hoe Stream	1	1	1	96	2	0	0	98
7502	Okura Creek	6	3	14	78	3	2	15	80
7506	Vaughn Stream	3	1	3	88	4	0	4	93
7811	Oteha River	9	10	10	70	8	3	13	75
7830	Lucas Creek	7	7	8	78	7	5	7	82
7904	Opanuku Stream	9	7	20	61	5	12	7	75
8019	Avondale Stream	7	4	6	84	8	0	13	78
8110	Oakley Creek	9	4	15	72	9	2	13	77
8205	Otara Stream (KH)	12	10	20	59	0	7	12	81
8214	Otara Creek (ET)	10	7	10	73	5	3	10	81
8215	Pakuranga Creek (GD)	9	6	6	80	3	5	9	83
8217	Pakuranga Creek (BR)	10	9	10	72	3	8	8	80
8249	Omaru Creek	10	7	8	76	3	2	12	83
8516	Wairoa River	7	5	8	80	7	0	8	85
8568	Wairoa Trib	2	0	1	97	2	0	4	95
43601	Waitangi Stream	7	8	5	80	3	9	12	76
43807	Puhunui Stream	10	6	17	66	3	9	12	76
43829	Ngakaroa Stream	6	1	7	86	2	0	7	91
43856	Papakura Stream (Porchester)	10	12	15	63	8	5	20	67
44603	Cascades Stream (Waitakere)	6	5	9	80	5	5	8	82
45313	Kumeu River	10	9	13	68	0	7	18	75
45373	Riverhead Stream	4	1	7	88	3	2	10	85
45415	Kaukapakapa River	9	11	15	64	3	13	8	75
45505	Makarau Stream	10	7	24	59	6	6	15	74
74401	Onetangi Stream	1	0	2	97	0	0	2	98
74701	Cascades Stream (Waiheke)	3	1	7	89	2	0	5	93
438100	Whangamaire Stream	7	7	6	80	2	0	12	87
1403837	Papakure (Alfriston)	6	6	10	78	0	5	12	82

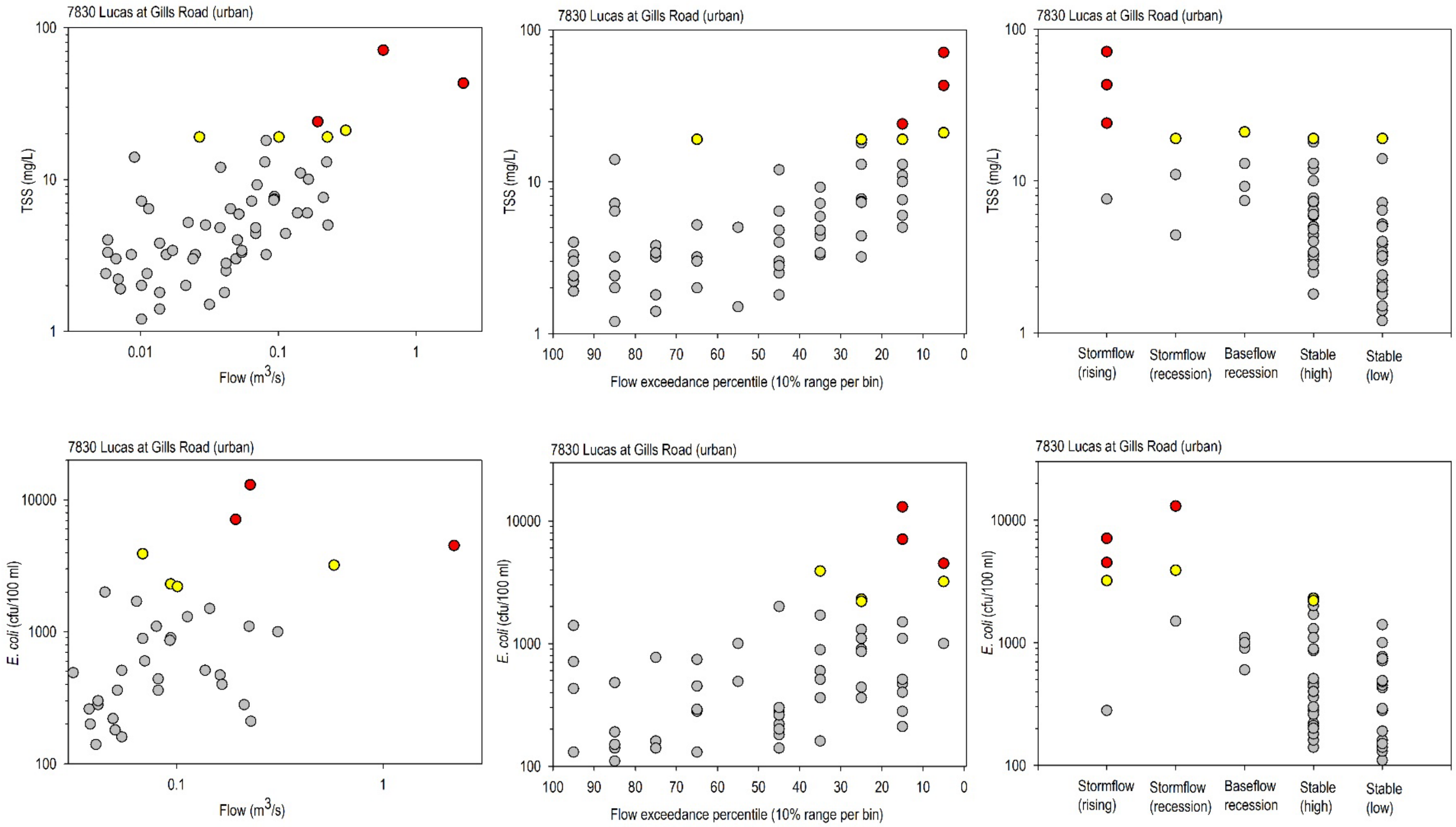

Figure 6: Relationship between TSS and *E.coli* SoE data with flow characteristics for Lucas Creek. Red symbols are 95th percentile and above, yellow symbols are between 90th and 95th percentile.

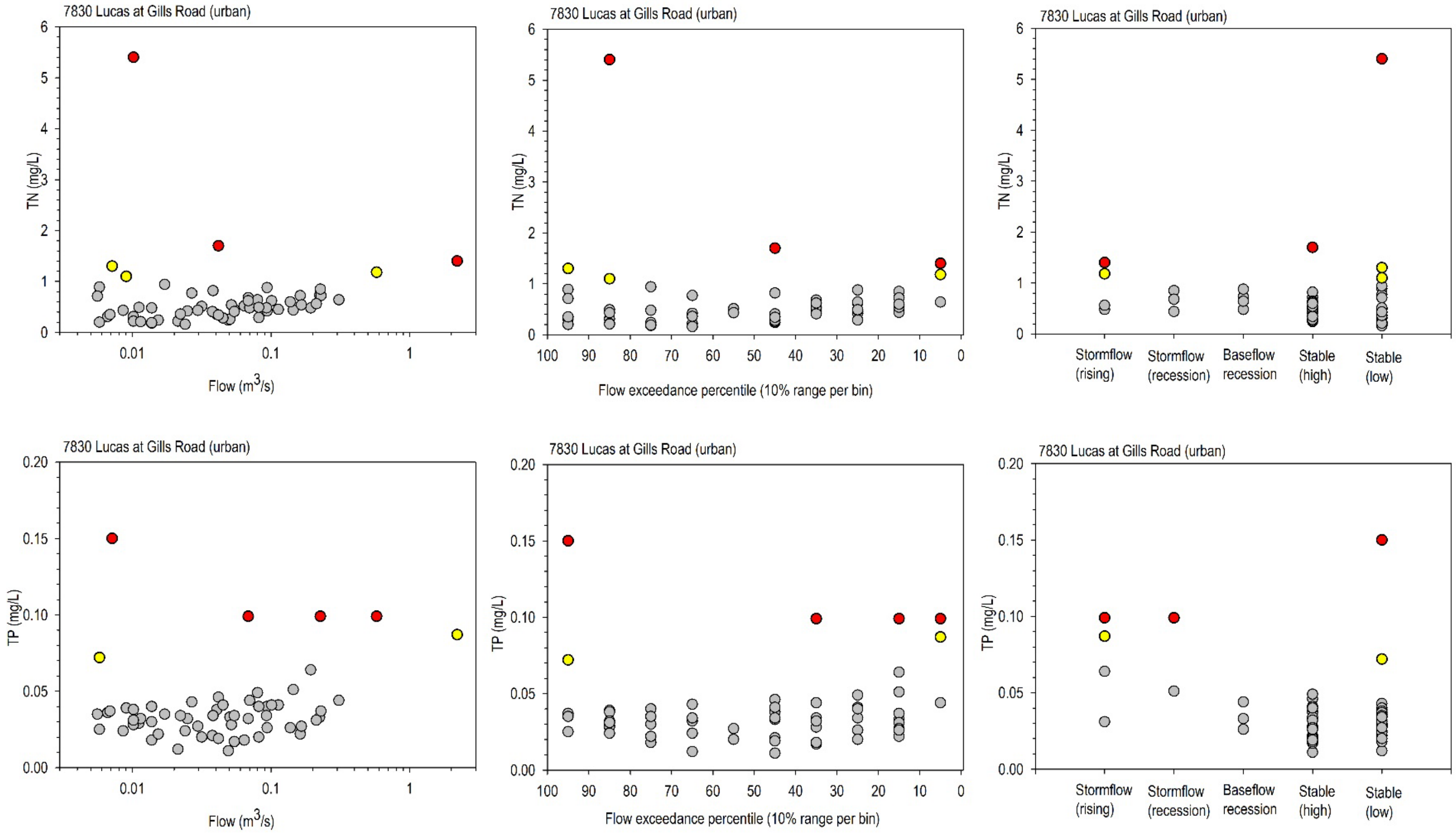

Figure 7: Relationship between TN and TP SoE data with flow characteristics for Lucas Creek. Red symbols are 95th percentile and above, yellow symbols are between 90th and 95th percentile.

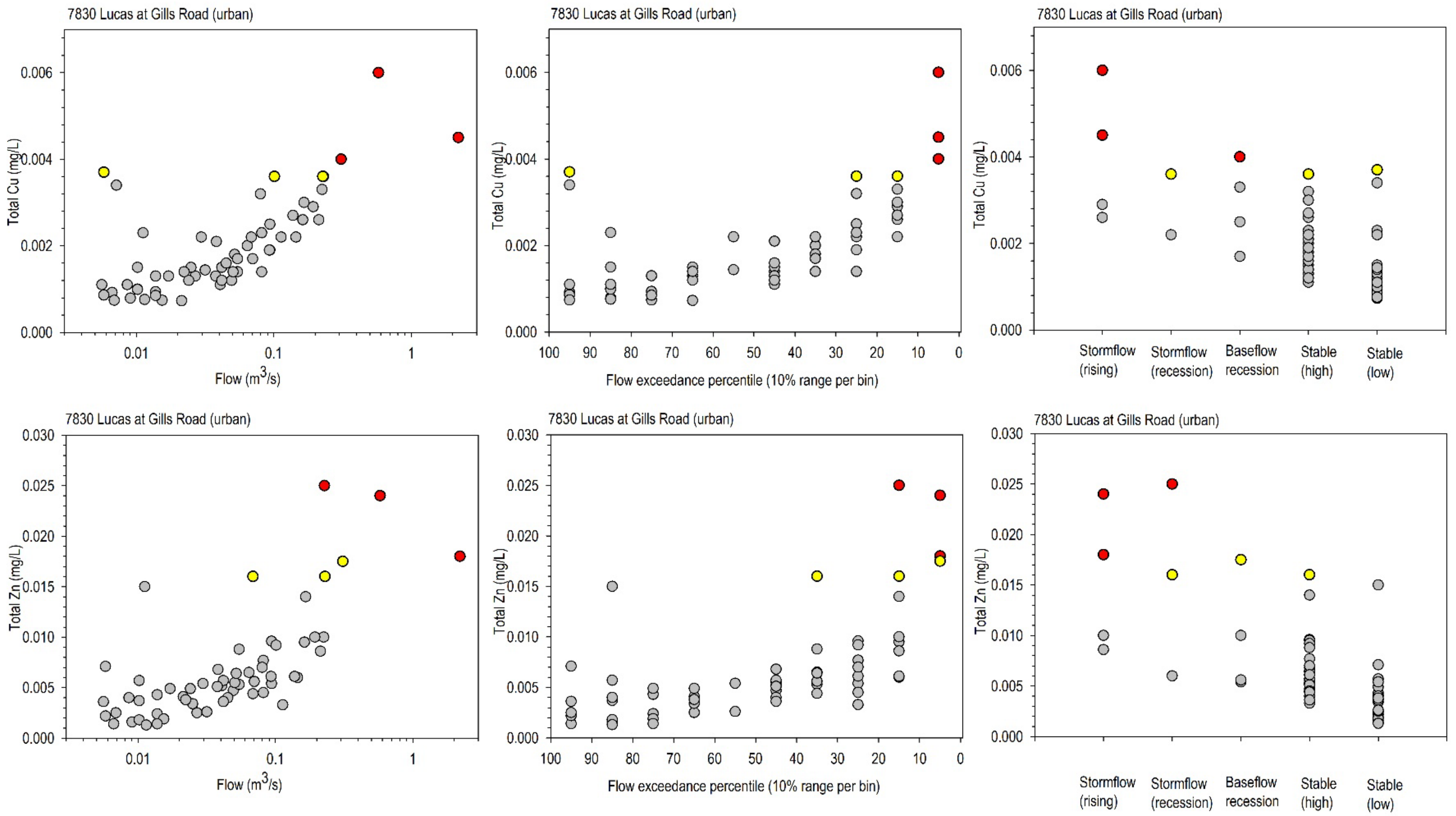

Figure 8: Relationship between TCu and TZn SoE data with flow characteristics for Lucas Creek. Red symbols are 95th percentile and above, yellow symbols are between 90th and 95th percentile.

REFERENCES

Auckland Council (2021a). Freshwater Management Tool: report 1. Baseline data inputs. Prepared by Healthy Waters, Paradigm Environmental and Morphum Environmental for Auckland Council. FWMT report 2021/1.

Auckland Council (2021b). Freshwater Management Tool: report 2. Baseline configuration and performance. Prepared by Healthy Waters, Paradigm Environmental and Morphum Environmental for Auckland Council. FWMT report 2021/2.

Auckland Council (2021c). Freshwater Management Tool: report 3. Baseline state assessment (rivers). Prepared by Healthy Waters, Paradigm Environmental and Morphum Environmental for Auckland Council. FWMT report 2021/3.

Auckland Council. (2022). Monitoring Research Quarterly. Published by Research and Evaluation Unit RIMU in December 2022

Beiroza, M., Acharya, S., Benisch, J., ter Borg, R.N., Hallberg, L., et al. 2023. Advances in catchment science, hydrochemistry, and aquatic ecology enabled by high-frequency water quality measurements. Environmental Science and Technology **57**;4701-4719.

Chaffe, A. (2021). River ecology state and trends in the Tamaki Makaurau / Auckland 2010-2019. State of the environment reporting. Auckland Council technical report, TR2021/05.

Defew, L.H, May, L., and Heal, K.V. (2013) Uncertainties in estimated phosphorus loads as a function of different sampling frequencies and common calculation methods. Marine and Freshwater Research **64**;373-386.

Evans, C. and Davies, T.D. 1998. Causes of concentration/discharge hysteresis and its potential as a tool for analysis of episode hydrochemistry. Water Resources Research **34**;129-137.

Hamilton, D.P., Rutherford, J.C. and Conland, N. (2021). Review of Freshwater Management Tool Current State Assessment. Report to Auckland Council by the Peer Review Team. Australian Rivers Institute, NIWA and Taiao Natural Resource Management.

Hicks, D. M., Holwerda, N., and Grant, C. M. (2021) Rural Catchment Sediment Yields from the Auckland Region. State of the environment reporting. Auckland Council technical report, TR2021/12

Ingley, R. and Groom, J. (2021). River water quality in Tamaki Makaurau / Auckland 2019 annual reporting and National Policy Statement for Freshwater Management current state assessment. Auckland Council technical report, TR2021/11.

Lowe, M., Ingley, R., and Young, D. (2014). Watercourse Assessment Methodology: Infrastructure and Ecology. Prepared by Morphum Environmental for Auckland Council.

Muller, C., Ira, S. and Stephens, T. (2020) Incorporating cost and benefit information for rural sector mitigations into Auckland Council's FWMT-Stage 1. Final report for Auckland Council.

Muller, C., and Stephens, T. (2020) Roadmap for refining rural sector mitigations in Auckland Council's FWMT-Stage 2. Final report for Auckland Council.

Rieger, A. (2016) Open Watercourse Geometry Assessment and Methodology Report. [Prepared by Morphum Environmental] for Auckland Council.

Rose, L.A., Karwan, D.L. and Godsey, S.E. 2018. Concentration-discharge relationships describe solute and sediment mobilization, reaction, and transport at event and longer timescales. Hydrological Processes **32**; 2829-2844.

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 1996–4040, 46 p., https://pubs.er.usgs.gov/publication/wri964040.

Smith, D.G. and McBride, G.B. (1990) New Zealand's National Water Quality Monitoring Network – Design and First Year's Operation. Water Resources Bulletin **26**;767-775.

Smith, D.G., McBride, G.B., Bryers, G.G., Wisse, J., and Mink, D.F.J. (1996) Trends in New Zealand's National River Water Quality Network. New Zealand Journal of Marine and Freshwater Research **30**;485-500.

Snelder, T., and Kerr, T. 2022. Relationships between flow and river water quality monitoring data and recommendations for assessing NPS-FM attribute states and trends. Prepared for Auckland Council by LWP, Land Water People.

Stephens, T., Kpodonu, T., Brown, N., Bambic, D., and Clarke, C. (2020) Water Quality in Auckland- FWMT current state and process modelling advances (Paper Presentation). Stormwater 2020 Conference, Auckland, New Zealand.

Walling, D.E. and Foster, I.D.L. 1975. Variations in the natural chemical concentration of river water during flood flows, and the lag effect. Journal of Hydrology **26**;237-244.

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APPENDICES

Appendix A: National Policy Statement for Freshwater Management – Monitoring Policies

Policy 3.18 sets the following monitoring requirements with regards to progress towards achieving environmental outcomes:

1. Every regional council must establish methods for monitoring progress towards achieving target attributes states and environmental outcomes.
2. The methods must include measures of:
    a. mātauranga Māori; and
    b. the health of indigenous flora and fauna.
3. Monitoring methods must recognise the importance of long-term trends, and the relationship between results and their contribution to evaluating progress towards achieving long-term visions and environmental outcomes for FMUs and parts of FMUs.

Policy 3.19 specifically addresses how temporal trends in attribute states (whether improving or deteriorating) must be assessed, including the need to determine appropriate assessment periods and sampling frequency and distribution. It also sets clear requirements to investigate the cause of any deteriorating trend.

Policy 3.20 sets that a regional council must respond to a degraded or degrading FMU, for example by preparing an action plan. Any action plans must include actions to identify the causes of the deterioration, methods to address those causes, and an evaluation of the effectiveness of the methods.

Policy 3.29 sets that regional councils must operate and maintain a freshwater quality and quantity accounting system for each FMU. Information from these systems must be published regularly.

The purpose of the accounting systems is to provide the baseline information required:

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

The freshwater quality accounting system must (where practicable) record, aggregate, and regularly update, for each FMU, information on the measured, modelled, or estimated:

a. loads and concentrations of relevant contaminants; and
b. 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
c. sources of relevant contaminants; and
d. the amount of each contaminant attributable to each source.

Policy 3.30 (Assessing and reporting) sets that regional councils must, for each FMU (or part of)

(1) publish (and thus collect) data about each component of the ecosystem health and human contact values

(2) prepare a comprehensive report freshwater state and trends, but also environmental pressures and actions contributing to the implementation of the NPS-FM

(3) publish and ecosystem health score card.

Appendix B: Summary of Auckland Council's monitoring sites and programmes

Station Number	Site (Reporting Name)	Site	Coordinates		Type of Monitoring				
			Easting (NZTM)	Northing (NZTM)	Flow	Water Quality	Ecology:	River Metabolism	Sediment Monitoring
8019	Avondale Stream (Lower)	Avondale Stream @ Shadbolt Park	1750600	5912264		*	*		
8023	Parahiku Stream (Upper)	Avondale @ Reserve	1748402	5911129			*		
8022	Avondale Stream (Mid)	Avondale @ Thuja Pl	1749503	5911643			*		
7834	Alexandra Stream	Alexandra Stream	1752378	5932435	*				
8557	Aroaro Stream	Aroaro @ Phillips	1789897	5903472			*		
44030	Anns Creek	Anns Creek @ Hamlins Hill	1763107	5912095			*		
45326	Ararimu River	Ararimu River @ Old North Rd Bridge	1734999	5932630	*			*	
108123	Auckland Domain	Auckland Domain @ Lower Domain Dr	1758082	5919748			*		
7308	Awanohi Stream	Awanohi Lower	1751424	5938711			*		
7516	Awaruku Stream	Awaruku Stream @ Glenvar Rodad	1755674	5937597	*				
8268	Pakuranga Stream	Botany Creek @ Tangello Place	1769802	5915087			*		
74701	Cascades Stream (Waiheke)	Cascades @ Whakanewha	1785942	5923254		*	*		
44603/44618	Cascades Stream (Waitakere)	Cascades Stream @ Confluence	1735628	5916378		*	*		
7548	Castor Stream	Castor @ Braemar	1757497	5930670			*		
6606	Duck Creek	Duck Creek @ Trotters	1752605	5970451			*		
8407	Duders Park	Duders	1785588	5913500			*		
6847	Dyers Creek (Forest)	Dyers Creek @ Bush	1751076	5963704			*		
6852	Dyers Creek (Pasture)	Dyers Creek @ Mid Paddock	1750910	5963846			*		
10713	Edgars Creek	Edgar @ Maxwell Av	1753970	5919393			*		
7722/7706	Eskdale Stream	Eskdale Lower	1752448	5926772	*		*		
8267	Glendowie Stream	Glendowie Stream @ Athlone Road	1766987	5919411			*		
45703	Hoteo River (NIWA)	Hoteo River @ Gubbs	1735254	5972546	*	*		*	*
45311	Kaipara River	Kaipara River @ Waimauku	1733345	5930348	*			*	*
7719	Kaipatiki Stream	Kaipatiki Stream at Kaipatiki road	1752666	5927948	*				
6990	Kaitoke Creek (GBI)	Kaitoke Creek @ Hotsprings Tk	1817856	5987872			*		
45415	Kaukapakapa River	Kaukapakapa @ Taylors	1735833	5944978	*	*		*	*
45416	Kaukapakapa River	Kaupapa Ref	1730803	5945157				*	
45313/45369	Kumeu River	Kumeu River At Weza Lane	1739252	5928781		*	*		
45315	Kumeu River	Kumeu @ Maddrens Weir	1739254	5929059	*	*		*	

Station Number	Site (Reporting Name)	Site	Coordinates		Type of Monitoring				
			Easting (NZTM)	Northing (NZTM)	Flow	Water Quality	Ecology:	River Metabolism	Sediment Monitoring
8027	Avondale Stream (Upper)	La Rosa Reserve TL (North Stream)	1749288	5911619			*		
8026	Parahiku Stream (Lower)	La Rosa Reserve TR (South Stream)	1749303	5911539			*		
7830/7899	Lucas Creek	Lucas @ Gills Road	1751468	5934510	*	*	*		
8529	Mangawheau Stream	Mangawheau Stream @ Weir	1783781	5891411	*				
6811	Mahurangi River (Forestry)	Redwood Stream @ Forestry H.Q.	1747750	5965035		*			
6989	Mabey Stream (GBI)	Mabey Rd	1816457	6000276			*		
6862	Mahurangi River (Native)	Mahu Ref @ Trappit	1748961	5965371			*		
6869/6863	Mahurangi River (Pasture)	Mahurangi @ College	1748269	5969810	*	*	*	*	
6850	Mahurangi River (Forestry)	Mahurangi LTB	1747626	5964882			*		
6804	Mahurangi River (Warkworth)	Mahurangi @ Warkworth Water Treatment Plant	1748864	5970457		*			
7514	Mairangi Bay Stream	Mairangi Bay Stream at Tennis Club	1756356	5932536	*				
45504	Makarau River	Makarau @ Coles	1735412	5953253	*	*			*
45505	Makarau River	Makarau @ Railway	1736150	5953126		*	*		
8304/8301	Mangemangeroa Stream	Mangemangeroa Stream at Craigs	1772261	5910514	*				*
44460	Marawhara Stream	Marawhara	1730774	5910762			*		
6604	Matakana River	Matakana @ Wenzlicks Farm	1753500	5976481		*	*		
8106	Meola Creek	Meola Creek at Motions Road	1753212	5918641	*		*		
8104	Motions Stream	Motions Stream	1753745	5918720	*				
7407	Motutapu	Motutapu					*		
45605	Omaumau River	Mt Auckland	1730852	5964294			*		
8217	Botany Creek	Pakuranga @ Botany Rd	1770686	5913036		*	*		
8215	Pakuranga Creek	Pakuranga Creek @ Greenmount Dr	1769462	5910964			*		
10814/8176	Newmarket Stream	Newmarket Stream @ Ayr St	1759158	5918650	*		*		
43829/1043824	Ngakoroa Stream	Ngakoroa Stream @ Mill Rd	1775164	5881624	*	*	*	*	
107892	Nimrod Stream	Nimrod Stream @ Scott Point	1748221	5925949			*		
7171	Nukumea Stream	Nukumea @ Upper Site	1749411	5951400		*	*		
108144	Oakley Creek (Mid 2)	Oakley @ Beagle Road	1753792	5915208			*		
8110	Oakley Creek	Oakley Creek @ Carrington	1751963	5917636		*			
8128	Oakley Creek (Mid 1)	Oakley Creek @ Richardson Road	1753326	5915131	*	*	*		
108127	Oakley (Mid 3)	Oakley @ Walmsley Park	1754146	5914953			*		
108126	Oakley (Mid 4)	Oakley @ War Memorial Park	1754457	5914549			*		

Station Number	Site (Reporting Name)	Site	Coordinates		Type of Monitoring				
			Easting (NZTM)	Northing (NZTM)	Flow	Water Quality	Ecology:	River Metabolism	Sediment Monitoring
10812	Oakley Upper	Oakley Creek @ May Road	1754919	5914268			*		
8177	Oakley Lower	Oakley LTB	1751936	5917508			*		
7502	Okura Creek	Okura Creek @ Awanohi Rd	1751405	5938716	*	*			*
7505		Okura @ Weiti Forest	1751885	5940971	*	*			*
7313	Okura Reserve	Okura Reserve	1753241	5940408			*		
7314	Okura Tributary 1	Okura Trib 1	1754059	5939002			*		
7315	Okura Tributary 2	Okura Trib 2	1752669	5938790			*		
8249	Omaru Creek	Omaru @ Maybury Street	1766268	5916749		*	*		
74401	Onetangi Stream	Onetangi @ Waiheke Rd	1786243	5926204		*	*		
7904/7925	Opanuku Stream	Opanuku Stream @ Candia Road Bridge	1742086	5915581	*	*	*	*	*
7912	Opanuku Stream at Vintage Reserve	Opanuku @ Vintage Reserve	1744587	5917203	*				
8219	Otaki Creek	Otaki @ Middlemore Crescent	1764306	5907216		*			
7172	Otaneura Stream	Otaneura	1749829	5952217			*		
8208	Otara Stream	Otara Stream	1767628	5908076	*				
8241	Otara Creek	Otara LTB	1768326	5908371			*		
8205	Otara Creek (East)	Otara Stream @ Kennel Hill	1768335	5908376		*			
8214	Otara Creek (South)	Otara @ East Tamaki Rd	1767422	5907535		*			
7811	Oteha River	Oteha River @ Days Bridge	1751325	5933519	*	*			
107801	Oteha Stream	Oteha LTB	1751903	5932876			*		
7911	Oratia Stream	Oratia @ Millbrook	1745528	5916176	*		*		
7955	Oratia Stream	Oratia @ Parrs Cross Road	1744766	5914229	*	*			
8609	Orere Tributary	Orere B	1796917	5903677			*		
7202	Orewa Stream	Orewa @ Kowhai Ave	1748295	5948502	*				*
8215	Pakuranga Creek	Pakuranga @ Greenmount Drive	1769473	5910813		*			
1043825	Papakura Stream	Papakura LTB	1771066	5900274			*		
43803	Papakura Stream	Papakura @ Great South Road Bridge	1769579	5899729	*				
43856	Papakura Stream (Lower)	Papakura Stream @ Porchester Road Bridge	1771240	5900290		*			
1043835	Papakura Tributary	Papakura Trib @ Alfriston Rd	1771523	5901203			*		
1043837	Papakura Stream (Upper)	Papakura @ Alfriston/Ardmore Rd	1774247	5902648		*			
7939	Paramuka Stream	Paramuka Stream @ Brookwood Drive	1743365	5917644			*		
1043828	Puhinui Stream	Puhinui Upper (hard)	1770055	5903290			*		
43807	Puhinui Stream	Puhinui @ Drop Structure	1766440	5904295	*	*		*	

Station Number	Site (Reporting Name)	Site	Coordinates		Type of Monitoring				
			Easting (NZTM)	Northing (NZTM)	Flow	Water Quality	Ecology:	River Metabolism	Sediment Monitoring
7805	Rangitopuni River(NIWA)	Rangitopuni River @ Walkers	1744450	5932301	*	*		*	
45373/45371	Riverhead Stream	Riverhead @ Ararimu Valley Road	1737125	5933216		*	*		
7907	Swanson Stream	Swanson Stream @ Woodside Reserve	1743783	5919897	*				
7515	Taiaotea Stream	Taiaotea stream at Freyberg Park	1755362	5935169	*				
7519	Taiorahi Stream	Taiorahi Stream at Westbourne ave	1756374	5933485	*				
6501	Tamahunga Stream	Tamahunga River @ Quintals Falls	1755631	5978391	*				
8222	Tamaki Stream Tributary	Tamaki Trib at Bowden Road Crump Weir	1764880	5912818	*				
43929	Tararata Creek	Tararata Creek @ Elmdon Street	1759795	5908043			*		
6996	Te-Muri-Ō-Tarariki Stream	Te Muri @ Fenceline	1752857	5957744			*		
6995	Te-Muri-Ō-Tarariki Stream	Te Muri @ Weir	1752915	5957910			*	*	*
6931	Tryphena Stream (GBI)	Tryphena @ Medlands Rd	1823430	5979941			*		
7526	Vaughan Upper	Vaughan Upper	1754271	5938178			*		
7506/7527	Vaughan Stream	Vaughan Stream @ Lower Weir	1755414	5938729	*	*	*	*	*
8516/8553	Wairoa River	Wairoa River @ Tourist Road	1782682	5901720	*	*	*	*	*
8568/8569	Wairoa Tributary	Wairoa Trib @ Caitcheons Rd	1786700	5892817		*	*		
43601	Waitangi Stream	Waitangi @ Waitangi Falls Bridge.	1754343	5878534		*	*		
43602	Waitangi Stream	Waitangi @ SH Bridge	1755195	5878315	*			*	
45705	Waiteitei River	Waiteitei River @ Sandersons	1742460	5985481	*				*
7173	Waiwera River	Waiwera R @ Waiwera Rd	1747580	5953924			*		
7104	Waiwera Stream	Waiwera Stream @ Upper Waiwera Road	1748628	5953665		*			
7604	Wairau Creek at Motorway	Wairau Creek @ Motorway	1756064	5928087	*				
7607	Wairau Creek at Chartwell Road	Wairau Creek @ Chartwell Road	1754730	5927652	*				
44470	Wekatahi Stream	Wekatahi	1735633	5916371			*		
7213	West Hoe Stream	West Hoe LTB	1748300	5950608			*		
7206	West Hoe Stream	West Hoe @ Halls	1748314	5950610	*	*		*	*
438100	Whangamaire Stream	Whangamaire @ Woodhouse Road	1763578	5884625		*			
104300	Whangamaire Stream	Whangamarie Stream @ Hunter Rd	1763241	5882752			*		
43968	Whangapouri Creek	Whangapouri @ Paerata	1768327	5887871			*		
8006	Whau Stream	Whau Stream at Blockhouse Bay Road Crump Weir	1751679	5913591	*				

Appendix C: HRU coverage table

HRU	Regional extent		HRU coverage of SoE sites				HRU coverage of FWMT sub-catchments		
	Hectares	%	Max	>90%	>70%	>50%	>90%	>70%	>50%
Bare_Earth-D-All-All	988.6	0.21%	0.5%	0	0	0	0	1	6
Dev_Commercial-All-All-All	948.3	0.20%	5.4%	0	0	0	1	1	2
Dev_Industrial-All-All-All	1321.4	0.28%	4.4%	0	0	0	0	0	1
Dev_Pervious-A+-High-All	1904.1	0.40%	17.7%	0	0	0	1	4	15
Dev_Pervious-A+-Low-All	2974.1	0.62%	16.2%	0	0	0	0	7	13
Dev_Pervious-A-High-All	308.0	0.06%	0.0%	0	0	0	0	0	1
Dev_Pervious-A-Low-All	208.9	0.04%	0.0%	0	0	0	0	0	1
Dev_Pervious-B-High-All	3406.6	0.71%	10.6%	0	0	0	1	6	25
Dev_Pervious-B-Low-All	4174.3	0.87%	18.9%	0	0	0	5	12	22
Dev_Pervious-C-High-All	14991.2	3.13%	56.2%	0	0	1	1	23	121
Dev_Pervious-C-Low-All	10584.7	2.21%	41.9%	0	0	0	2	18	93
Dev_Residential-All-All-All	3027.2	0.63%	9.6%	0	0	0	0	0	0
Dev_Road-All-All-1	1998.0	0.42%	3.8%	0	0	0	0	0	0
Dev_Road-All-All-2	1460.6	0.31%	3.2%	0	0	0	0	0	0
Dev_Road-All-All-3	1129.2	0.24%	4.0%	0	0	0	0	0	0
Dev_Road-All-All-4	424.3	0.09%	2.1%	0	0	0	0	0	0
Dev_Road-All-All-5	128.8	0.03%	0.8%	0	0	0	0	0	0
Dev_Road-All-All-6	139.9	0.03%	1.1%	0	0	0	0	0	1
Dev_Roof-All-All-1	3519.0	0.73%	12.8%	0	0	0	0	0	0
Dev_Roof-All-All-2	733.6	0.15%	2.6%	0	0	0	0	0	0
Dev_Roof-All-All-3	1638.2	0.34%	6.1%	0	0	0	0	0	0
Dev_Septics-B-All-All	340.3	0.07%	0.7%	0	0	0	0	0	0
Dev_Septics-C-All-All	347.6	0.07%	0.7%	0	0	0	0	0	0
Forest-A+-High-1	1891.8	0.40%	16.6%	0	0	0	0	1	3
Forest-A+-High-2	19.1	0.00%	0.1%	0	0	0	0	0	0
Forest-A+-Low-1	1641.0	0.34%	8.2%	0	0	0	0	0	0
Forest-A+-Low-2	6.7	0.00%	0.0%	0	0	0	0	0	0
Forest-A-High-1	5258.0	1.10%	0.0%	0	0	0	0	2	16
Forest-A-High-2	5680.3	1.19%	0.0%	0	0	0	15	28	45
Forest-A-Low-1	632.7	0.13%	0.0%	0	0	0	0	0	0
Forest-A-Low-2	5238.9	1.09%	0.0%	0	0	0	21	34	49
Forest-B-High-1	51734.0	10.81%	96.5%	1	2	4	77	199	397
Forest-B-High-2	6771.7	1.41%	15.4%	0	0	0	7	14	40
Forest-B-Low-1	3076.4	0.64%	18.1%	0	0	0	0	0	3
Forest-B-Low-2	265.9	0.06%	0.1%	0	0	0	0	0	0

HRU	Regional extent		HRU coverage of SoE sites				HRU coverage of FWMT sub-catchments		
	Hectares	%	Max	>90%	>70%	>50%	>90%	>70%	>50%
Forest-C-High-1	58551.4	12.23%	83.1%	0	1	2	61	158	354
Forest-C-High-2	15915.1	3.32%	90.9%	1	1	1	32	62	112
Forest-C-Low-1	3095.6	0.65%	8.2%	0	0	0	0	1	2
Forest-C-Low-2	73.2	0.02%	0.0%	0	0	0	0	0	0
Forest-D-High-1	6006.0	1.25%	14.2%	0	0	0	0	1	4
Forest-D-High-2	1993.0	0.42%	2.8%	0	0	0	2	6	13
Forest-D-Low-1	1553.8	0.32%	1.7%	0	0	0	0	0	2
Forest-D-Low-2	1673.3	0.35%	0.0%	0	0	0	2	5	6
Horticulture-A+-High-1	642.4	0.13%	9.1%	0	0	0	0	0	1
Horticulture-A+-High-2	149.4	0.03%	1.0%	0	0	0	0	0	0
Horticulture-A+-High-3	519.2	0.11%	4.4%	0	0	0	0	0	0
Horticulture-A+-Low-1	1194.4	0.25%	15.8%	0	0	0	0	0	2
Horticulture-A+-Low-2	218.1	0.05%	3.3%	0	0	0	0	0	0
Horticulture-A+-Low-3	1140.8	0.24%	16.8%	0	0	0	0	0	1
Horticulture-A-High-1	276.3	0.06%	0.0%	0	0	0	0	0	1
Horticulture-A-High-2	548.1	0.11%	0.0%	0	0	0	0	0	0
Horticulture-A-High-3	76.8	0.02%	0.0%	0	0	0	0	0	0
Horticulture-A-Low-1	151.1	0.03%	0.0%	0	0	0	0	0	0
Horticulture-A-Low-2	110.4	0.02%	0.0%	0	0	0	0	0	0
Horticulture-A-Low-3	78.3	0.02%	0.0%	0	0	0	0	0	0
Horticulture-B-High-1	269.0	0.06%	1.4%	0	0	0	0	0	0
Horticulture-B-High-2	471.5	0.10%	1.5%	0	0	0	0	0	0
Horticulture-B-High-3	272.3	0.06%	1.4%	0	0	0	0	0	0
Horticulture-B-Low-1	697.3	0.15%	6.2%	0	0	0	0	0	0
Horticulture-B-Low-2	447.0	0.09%	1.7%	0	0	0	0	0	0
Horticulture-B-Low-3	664.8	0.14%	7.9%	0	0	0	0	1	1
Horticulture-C-High-1	249.2	0.05%	1.0%	0	0	0	0	0	0
Horticulture-C-High-2	386.2	0.08%	0.3%	0	0	0	0	0	0
Horticulture-C-High-3	265.7	0.06%	0.2%	0	0	0	0	0	0
Horticulture-C-Low-1	582.5	0.12%	1.7%	0	0	0	0	0	0
Horticulture-C-Low-2	342.3	0.07%	0.9%	0	0	0	0	0	0
Horticulture-C-Low-3	324.5	0.07%	0.8%	0	0	0	0	0	1
Pasture-A+-High-1	3664.7	0.77%	33.8%	0	0	0	0	2	11
Pasture-A+-High-2	3185.2	0.67%	17.4%	0	0	0	0	1	3
Pasture-A+-Low-1	3792.5	0.79%	19.7%	0	0	0	0	5	12
Pasture-A+-Low-2	3257.4	0.68%	21.2%	0	0	0	0	2	6
Pasture-A-High-1	8000.5	1.67%	0.2%	0	0	0	7	28	53
Pasture-A-High-2	8025.5	1.68%	0.0%	0	0	0	2	14	47

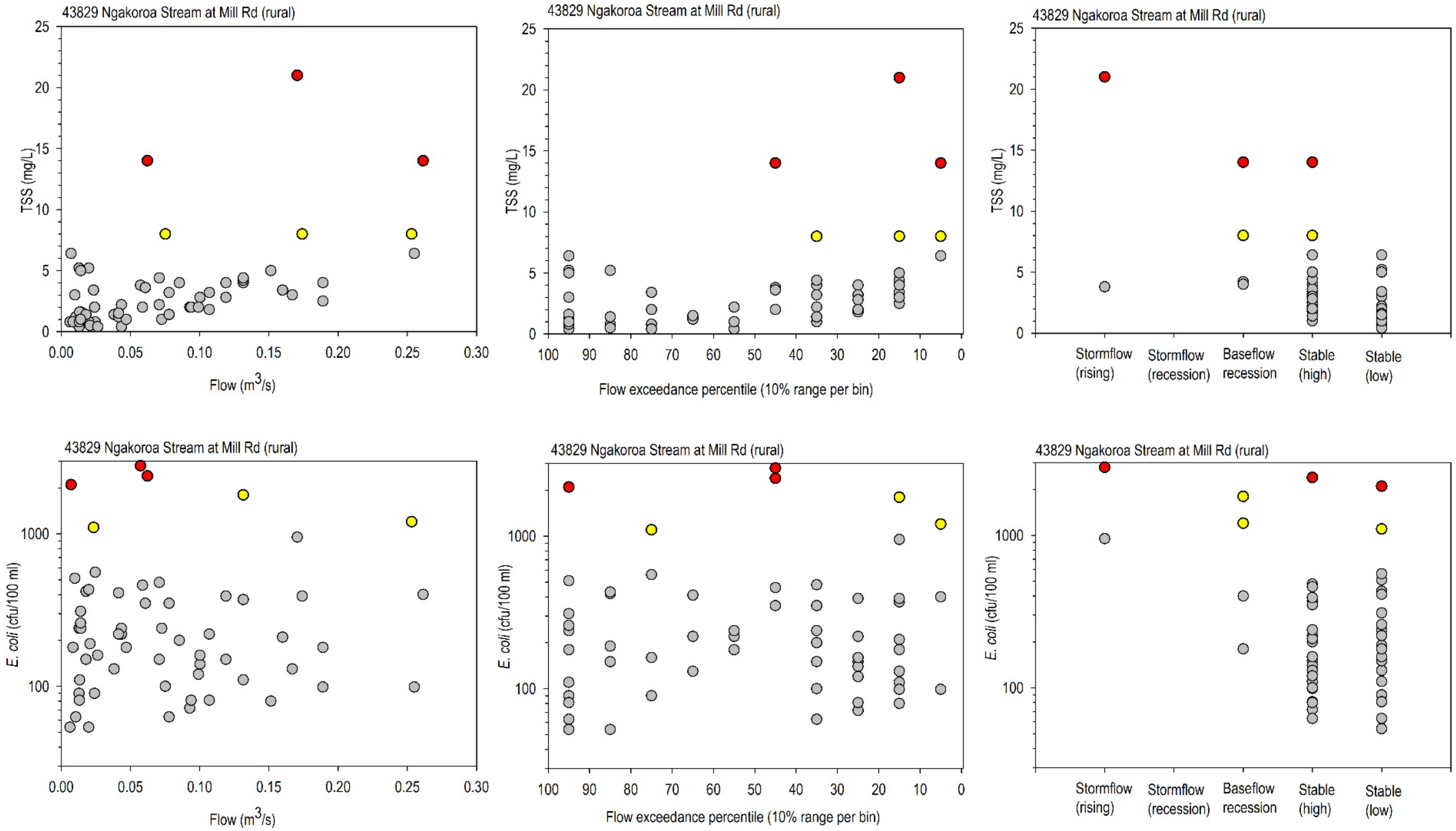
HRU	Regional extent		HRU coverage of SoE sites				HRU coverage of FWMT sub-catchments		
	Hectares	%	Max	>90%	>70%	>50%	>90%	>70%	>50%
Pasture-A-Low-1	1674.4	0.35%	0.0%	0	0	0	2	4	11
Pasture-A-Low-2	2373.9	0.50%	0.1%	0	0	0	2	13	20
Pasture-B-High-1	24080.0	5.03%	19.8%	0	0	0	5	19	85
Pasture-B-High-2	26564.9	5.55%	23.2%	0	0	0	10	44	121
Pasture-B-Low-1	8801.7	1.84%	7.1%	0	0	0	2	12	34
Pasture-B-Low-2	10444.1	2.18%	6.7%	0	0	0	4	29	59
Pasture-C-High-1	31065.9	6.49%	26.7%	0	0	0	3	25	80
Pasture-C-High-2	33889.3	7.08%	33.3%	0	0	0	6	48	146
Pasture-C-Low-1	5693.1	1.19%	11.9%	0	0	0	3	4	10
Pasture-C-Low-2	6109.2	1.28%	9.5%	0	0	0	2	12	23
Pasture-D-High-1	13222.1	2.76%	29.3%	0	0	0	6	23	70
Pasture-D-High-2	16705.7	3.49%	35.9%	0	0	0	8	54	136
Pasture-D-Low-1	3957.6	0.83%	5.6%	0	0	0	7	15	19
Pasture-D-Low-2	3963.2	0.83%	4.5%	0	0	0	6	17	22
Rural_Grassland-A+-High-1	442.3	0.09%	3.3%	0	0	0	0	0	0
Rural_Grassland-A+-Low-1	786.5	0.16%	4.3%	0	0	0	0	2	4
Rural_Grassland-A-High-1	1574.6	0.33%	0.0%	0	0	0	0	1	9
Rural_Grassland-A-Low-1	772.0	0.16%	0.0%	0	0	0	0	1	2
Rural_Grassland-B-High-1	4798.5	1.00%	17.3%	0	0	0	1	4	7
Rural_Grassland-B-Low-1	1303.2	0.27%	0.7%	0	0	0	0	1	3
Rural_Grassland-C-High-1	5416.0	1.13%	23.7%	0	0	0	0	0	3
Rural_Grassland-C-Low-1	1370.2	0.29%	1.4%	0	0	0	0	1	1
Rural_Grassland-D-High-1	1639.0	0.34%	3.2%	0	0	0	0	1	3
Rural_Grassland-D-Low-1	1199.3	0.25%	0.8%	0	0	0	1	3	5
Unsealed_Road-C-High-1	627.1	0.13%	0.7%	0	0	0	0	0	0
Unsealed_Road-C-High-2	7.2	0.00%	0.0%	0	0	0	0	0	0
Unsealed_Road-C-High-3	0.7	0.00%	0.0%	0	0	0	0	0	0
Unsealed_Road-C-High-4	0.2	0.00%	0.0%	0	0	0	0	0	0
Unsealed_Road-C-Low-1	270.9	0.06%	0.1%	0	0	0	0	0	0
Unsealed_Road-C-Low-2	4.7	0.00%	0.0%	0	0	0	0	0	0
Unsealed_Road-C-Low-3	0.5	0.00%	0.0%	0	0	0	0	0	0
Unsealed_Road-C-Low-4	0.3	0.00%	0.0%	0	0	0	0	0	0
Water-All-All-All	2243.4	0.47%	3.7%	0	0	0	0	0	1

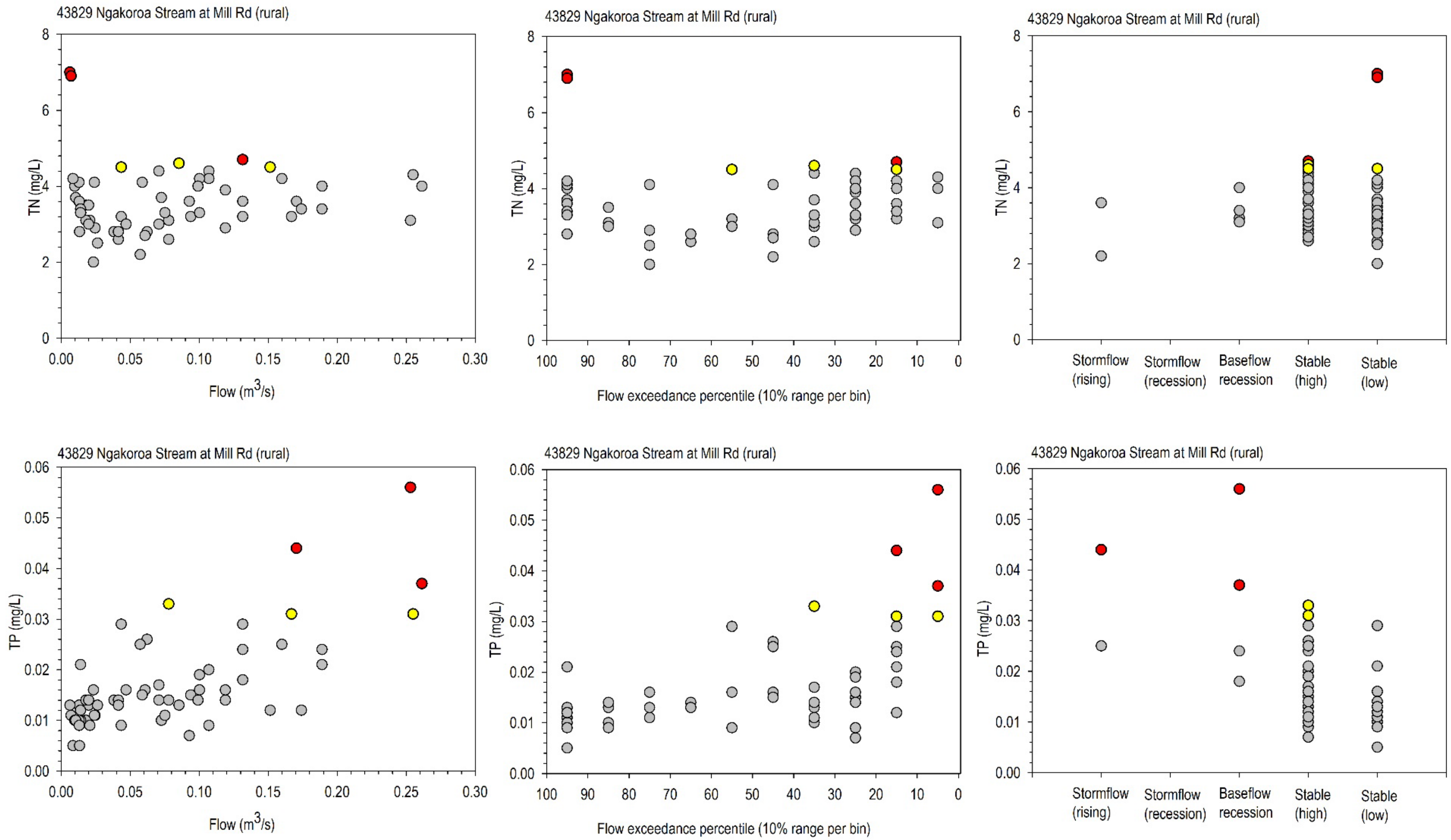
Appendix D: Additional water quality and flow regime graphs

Table D-1: Summary of date ranges used to derive flow duration curves for sites with available measured flow records.

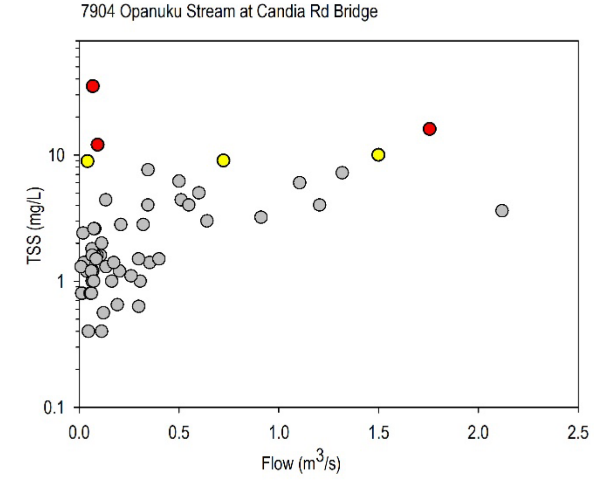
Site name	Start date	End date
Mahurangi @ Warkworth Water Treatment Plant / 6804	Jan-13	Dec-17
West Hoe @ Halls / 7206	Feb-03	Oct-21
Vaughn Stream @ Lower Weir / 7506	Dec-00	Mar-22
Oteha River @ Days Bridge / 7811	Dec-79	Apr-21
Lucas @ Gills Road / 7830	Oct-06	Nov-21
Opanuku Stream @ Candia Road Bridge / 7904	Aug-06	Aug-21
Oakley Creek @ Carrington. / 8110	May-02	May-22
Otara Stream @ Kennel Hill / 8205	Jan-13	Dec-17
Otara @ East Tamaki Rd / 8214	Jan-13	Dec-17
Wairoa River @ Tourist Road / 8516	Feb-79	Sep-21
Waitangi @ Waitangi Falls Bridge. / 43601	Jan-13	Dec-17
Puhinui @ Drop Structure / 43807	Dec-78	Oct-21
Ngakoroa Stream @ Mill Rd / 43829	Mar-80	Aug-21
Papakura Stream @ Porchester Road Bridge / 43856	Jan-13	Dec-17
Kumeu River At Weza Lane / 45313	Jan-13	Dec-17
Kaukapakapa @ Taylors / 45415	Jul-94	Nov-21
Makarau @ Railway / 45505	Jun-82	Dec-17

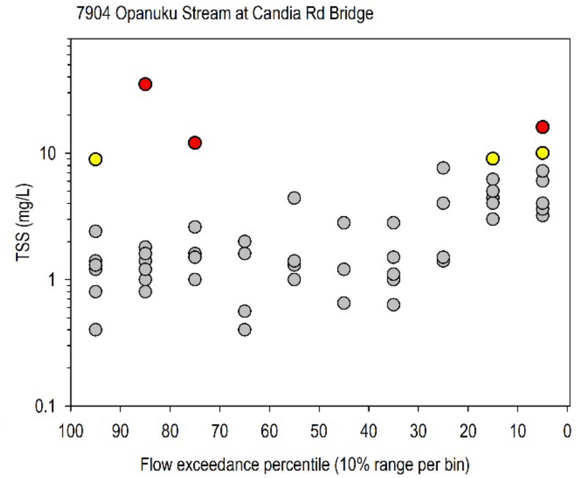
Ngakaroa Stream (no metals data for this site)

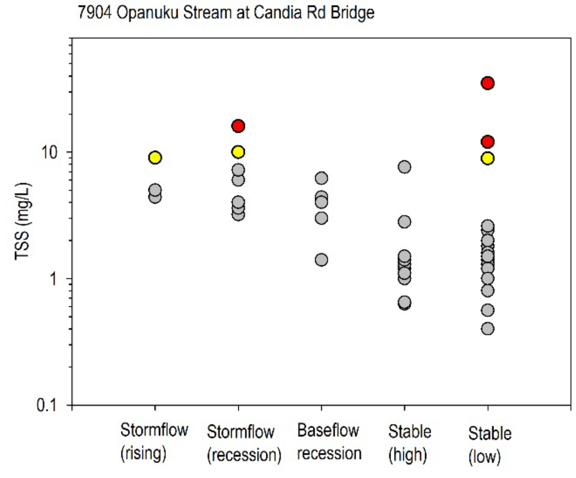


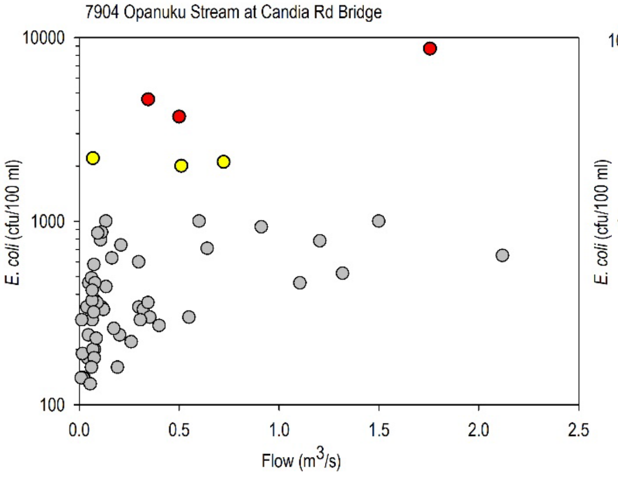

43829 Ngakoroa Stream at Mill Rd (rural)
TN (mg/L)
Flow (m3/s)
Flow exceedance percentile (10% range per bin)
Stormflow (rising)
Stormflow (recession)
Baseflow recession
Stable (high)
Stable (low)
TP (mg/L)

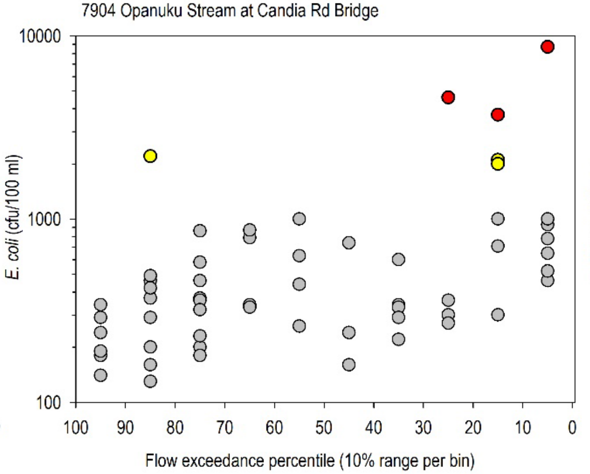
Opanuku Stream (no metals data for this site)

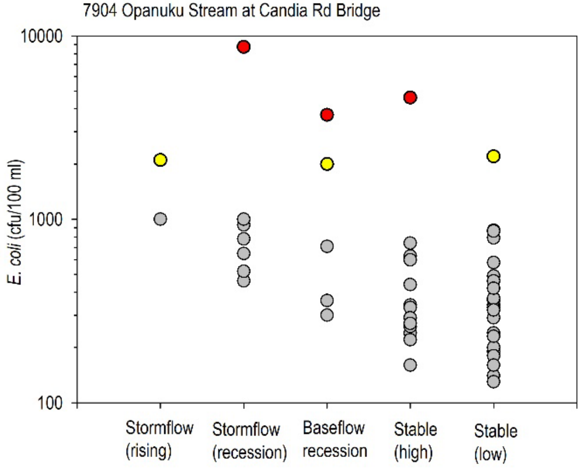


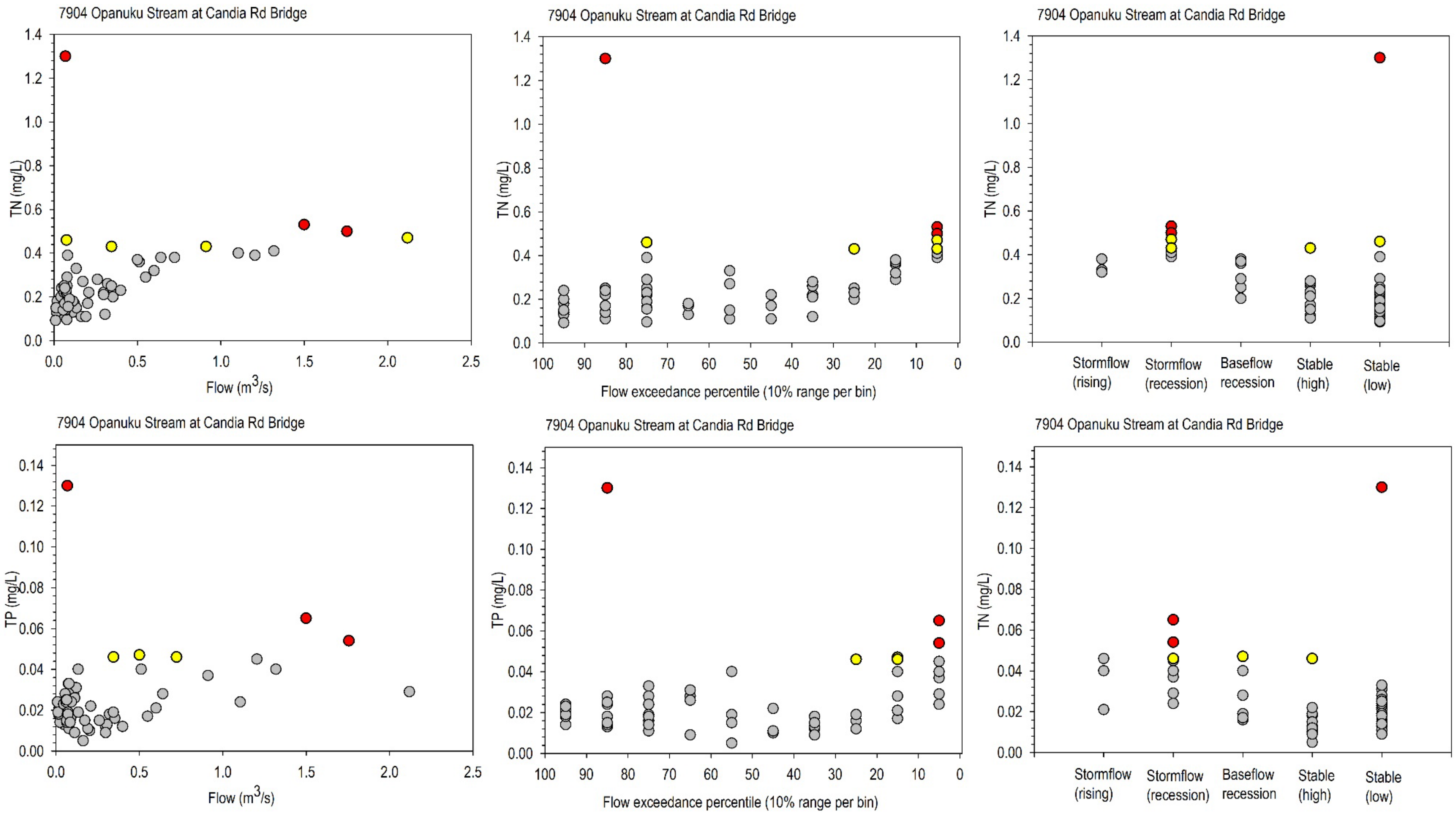


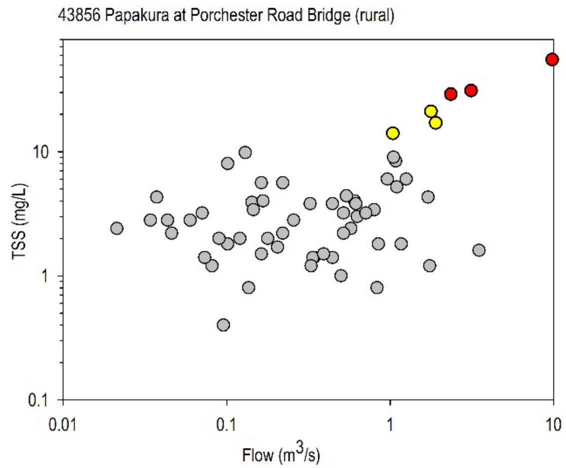


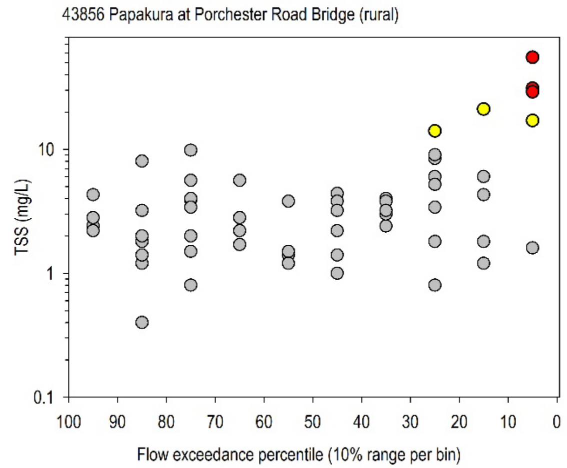


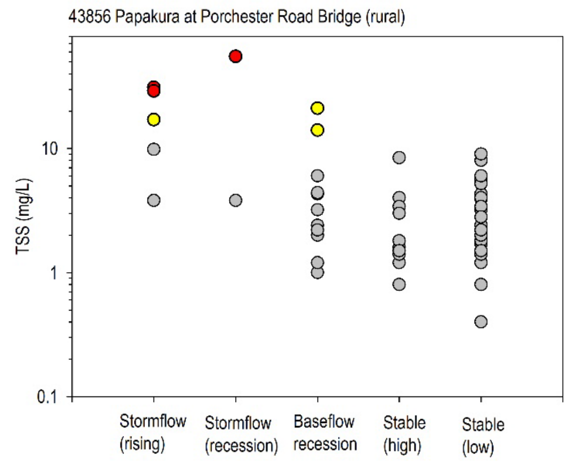


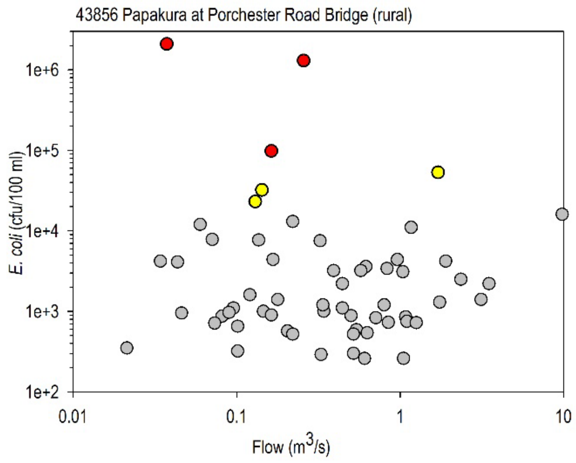


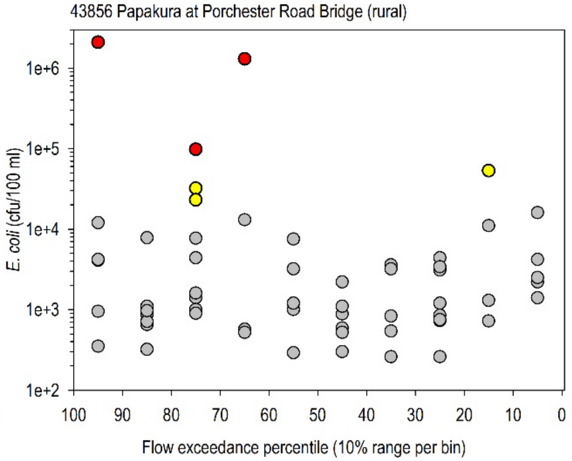

7904 Opanuku Stream at Candia Rd Bridge
TN (mg/L)
Flow (m3/s)
7904 Opanuku Stream at Candia Rd Bridge
TN (mg/L)
Flow exceedance percentile (10% range per bin)
7904 Opanuku Stream at Candia Rd Bridge
TN (mg/L)
Stormflow (rising)
Stormflow (recession)
Baseflow recession
Stable (high)
Stable (low)
7904 Opanuku Stream at Candia Rd Bridge
TP (mg/L)
Flow (m3/s)
7904 Opanuku Stream at Candia Rd Bridge
TP (mg/L)
Flow exceedance percentile (10% range per bin)
7904 Opanuku Stream at Candia Rd Bridge
TN (mg/L)
Stormflow (rising)
Stormflow (recession)
Baseflow recession
Stable (high)
Stable (low)

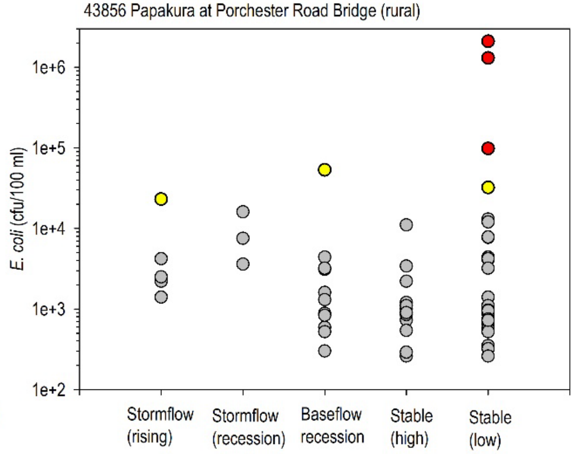

43856 Papakura at Porchester Road Bridge (rural)
TSS (mg/L)
Flow (m3/s)
0.1
1
10
0.01
0.1
1
10


43856 Papakura at Porchester Road Bridge (rural)
TSS (mg/L)
Flow exceedance percentile (10% range per bin)
0.1
1
10
100
90
80
70
60
50
40
30
20
10
0


43856 Papakura at Porchester Road Bridge (rural)
TSS (mg/L)
0.1
1
10
Stormflow (rising)
Stormflow (recession)
Baseflow recession
Stable (high)
Stable (low)

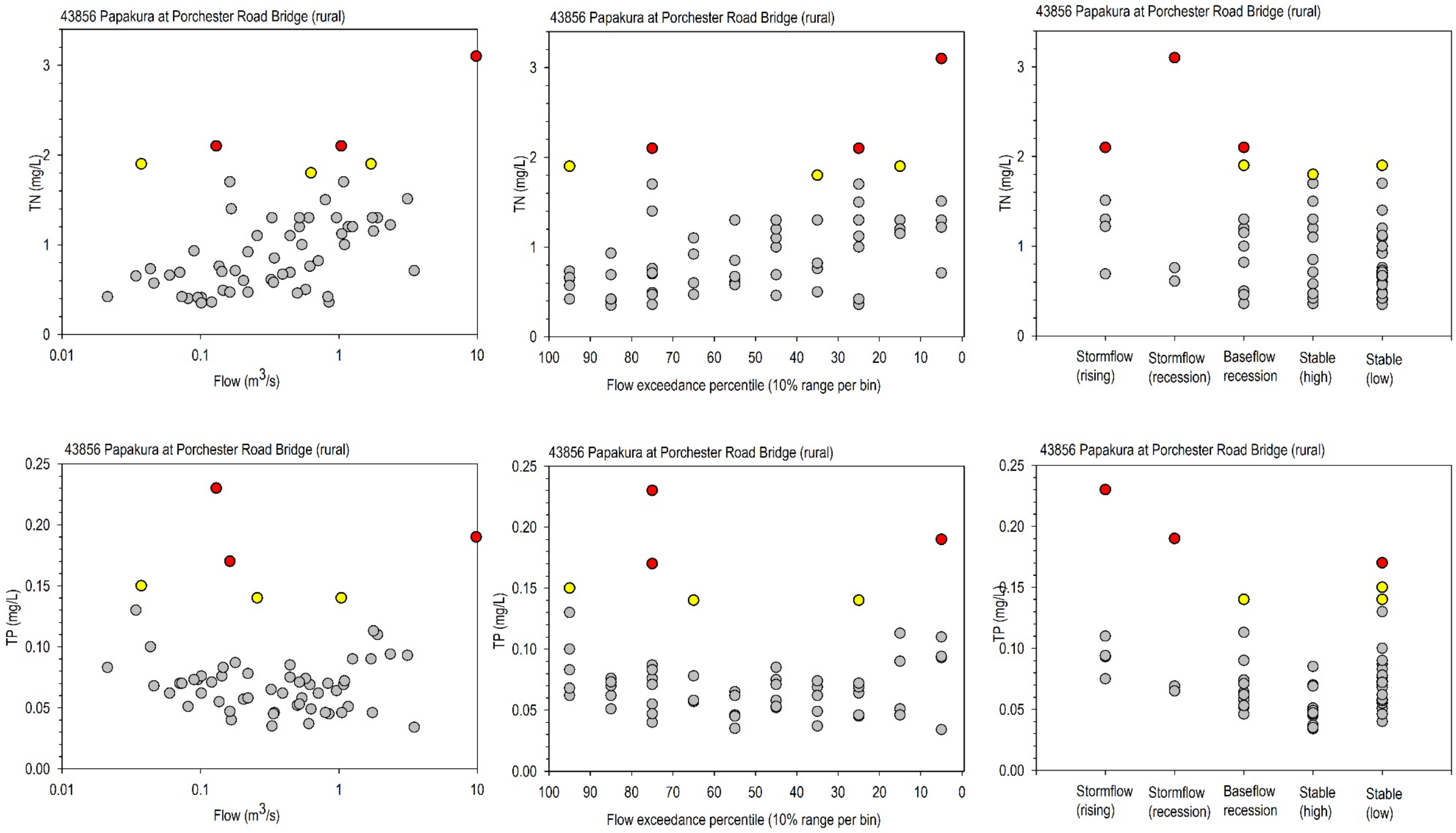

43856 Papakura at Porchester Road Bridge (rural)
E. coli (cfu/100 ml)
Flow (m3/s)
1e+2
1e+3
1e+4
1e+5
1e+6
0.01
0.1
1
10

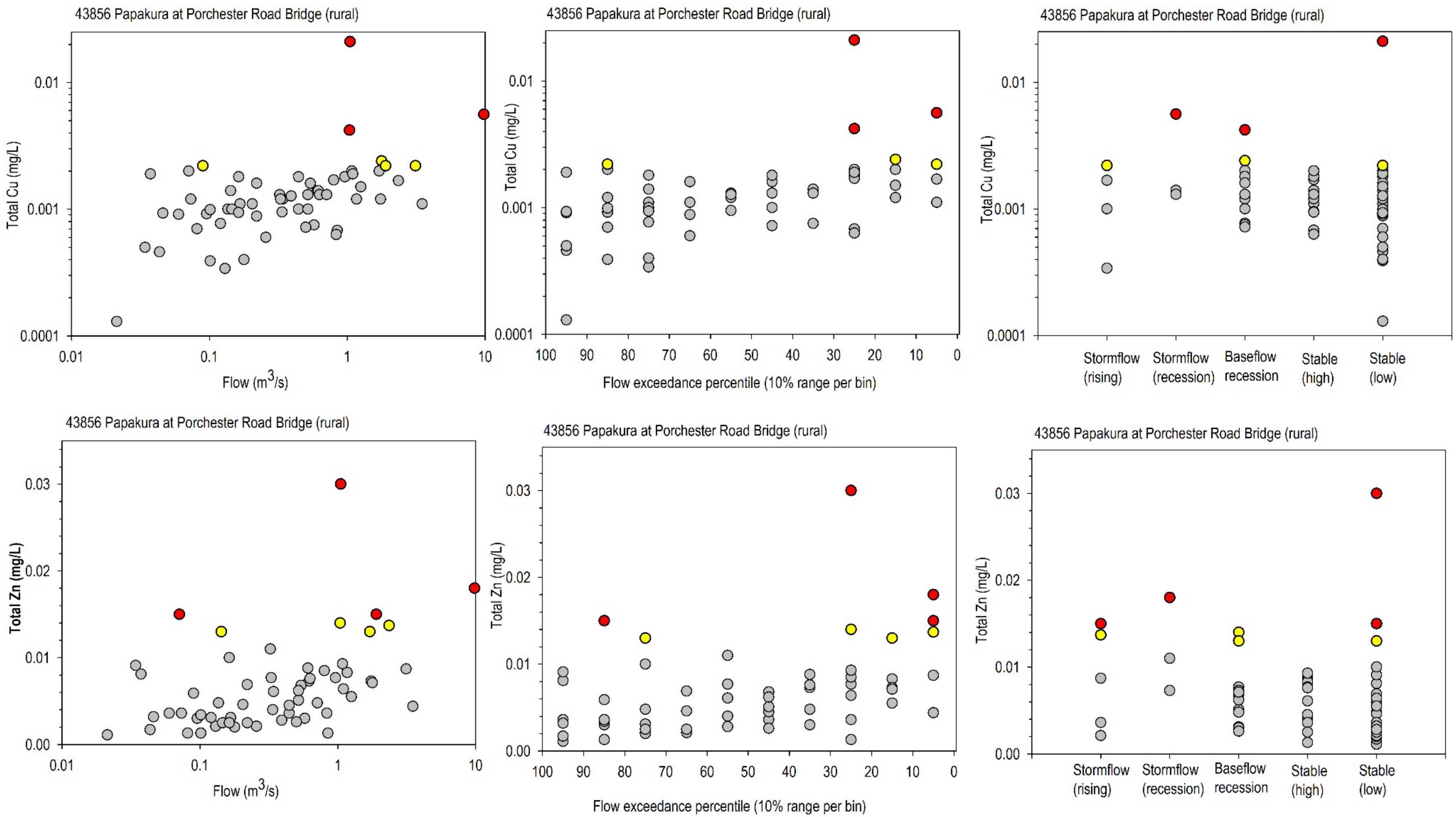

43856 Papakura at Porchester Road Bridge (rural)
E. coli (cfu/100 ml)
Flow exceedance percentile (10% range per bin)
1e+2
1e+3
1e+4
1e+5
1e+6
100
90
80
70
60
50
40
30
20
10
0

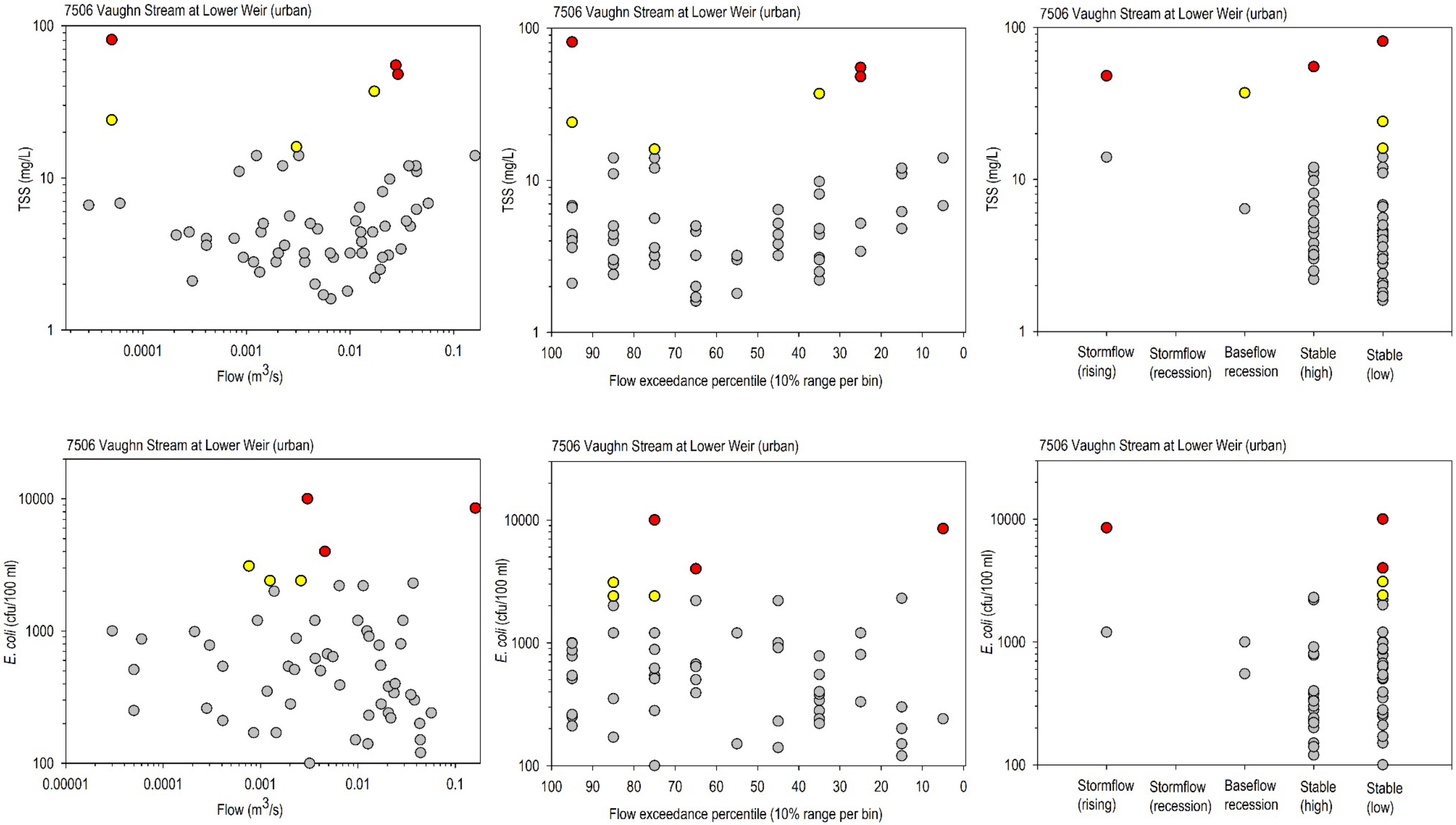

43856 Papakura at Porchester Road Bridge (rural)
E. coli (cfu/100 ml)
1e+2
1e+3
1e+4
1e+5
1e+6
Stormflow (rising)
Stormflow (recession)
Baseflow recession
Stable (high)
Stable (low)

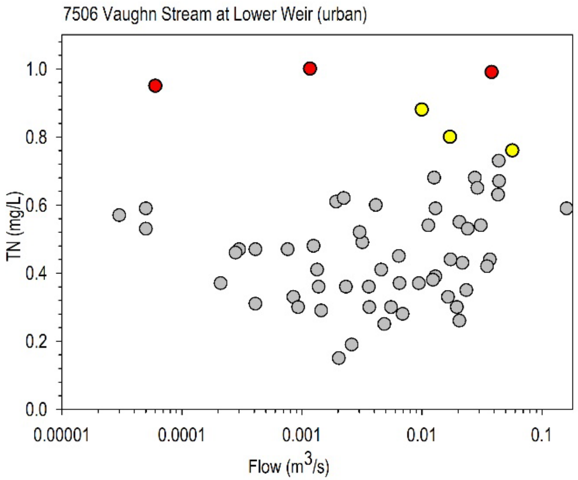
Puhoi Stour

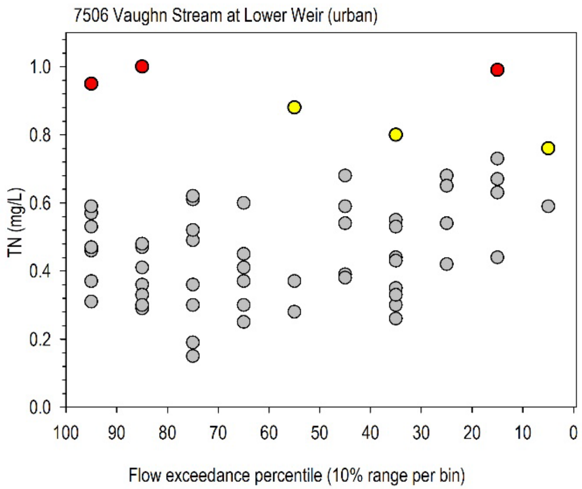
aquanet consulting ltd

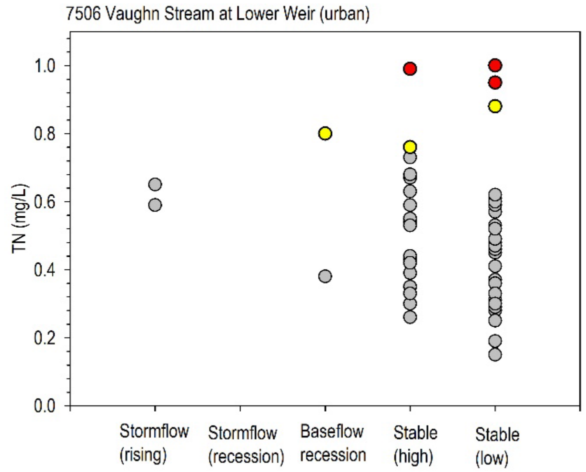


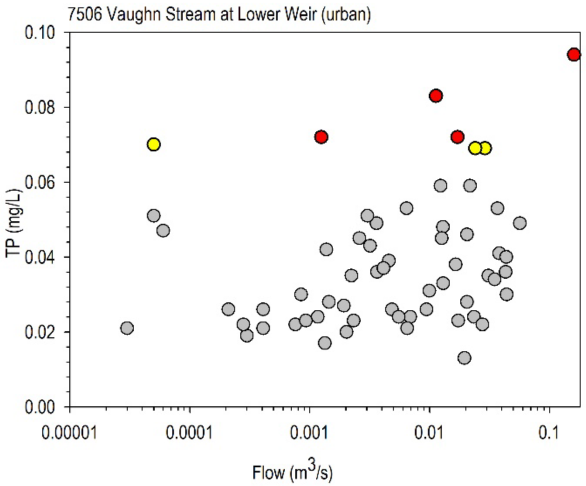

43856 Papakura at Porchester Road Bridge (rural)
Total Cu (mg/L)
0.01
0.001
0.0001
0.01
0.1
1
10
Flow (m3/s)
43856 Papakura at Porchester Road Bridge (rural)
Total Cu (mg/L)
100 90 80 70 60 50 40 30 20 10 0
Flow exceedance percentile (10% range per bin)
43856 Papakura at Porchester Road Bridge (rural)
Total Cu (mg/L)
Stormflow (rising)
Stormflow (recession)
Baseflow recession
Stable (high)
Stable (low)
43856 Papakura at Porchester Road Bridge (rural)
Total Zn (mg/L)
0.03
0.02
0.01
0.00
Flow (m3/s)
43856 Papakura at Porchester Road Bridge (rural)
Total Zn (mg/L)
Flow exceedance percentile (10% range per bin)
43856 Papakura at Porchester Road Bridge (rural)
Total Zn (mg/L)
Stormflow (rising)
Stormflow (recession)
Baseflow recession
Stable (high)
Stable (low)

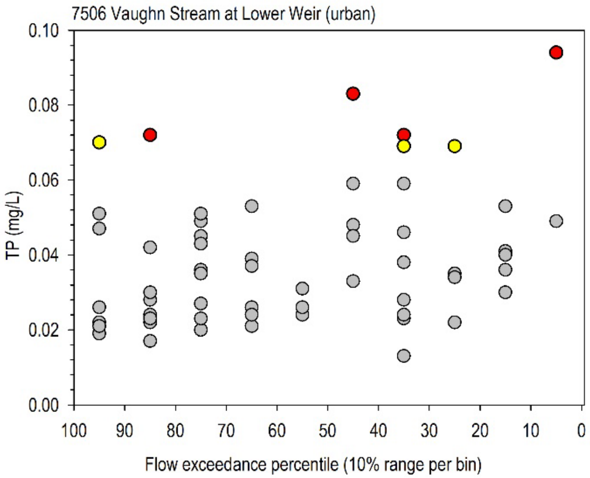

7506 Vaughn Stream at Lower Weir (urban)
TSS (mg/L)
100
10
1
0.0001
0.001
0.01
0.1
Flow (m^3/s)
7506 Vaughn Stream at Lower Weir (urban)
TSS (mg/L)
100 90 80 70 60 50 40 30 20 10 0
Flow exceedance percentile (10% range per bin)
7506 Vaughn Stream at Lower Weir (urban)
TSS (mg/L)
Stormflow (rising)
Stormflow (recession)
Baseflow recession
Stable (high)
Stable (low)
7506 Vaughn Stream at Lower Weir (urban)
E. coli (cfu/100 ml)
10000
1000
100
0.00001
0.0001
0.001
0.01
0.1
Flow (m^3/s)
7506 Vaughn Stream at Lower Weir (urban)
E. coli (cfu/100 ml)
100 90 80 70 60 50 40 30 20 10 0
Flow exceedance percentile (10% range per bin)
7506 Vaughn Stream at Lower Weir (urban)
E. coli (cfu/100 ml)
Stormflow (rising)
Stormflow (recession)
Baseflow recession
Stable (high)
Stable (low)

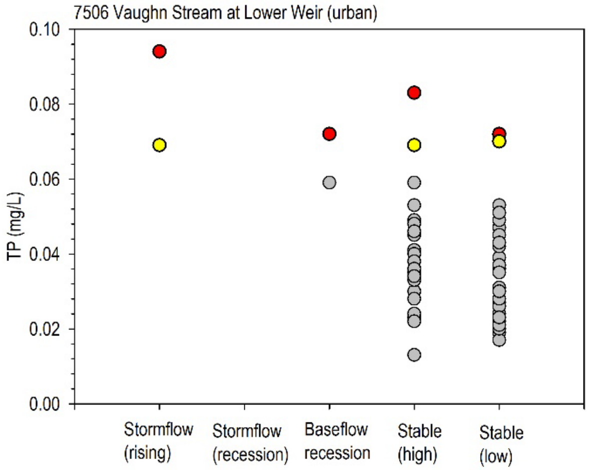

7506 Vaughn Stream at Lower Weir (urban)
TN (mg/L)
1.0
0.8
0.6
0.4
0.2
0.0
0.00001
0.0001
0.001
0.01
0.1
Flow (m3/s)

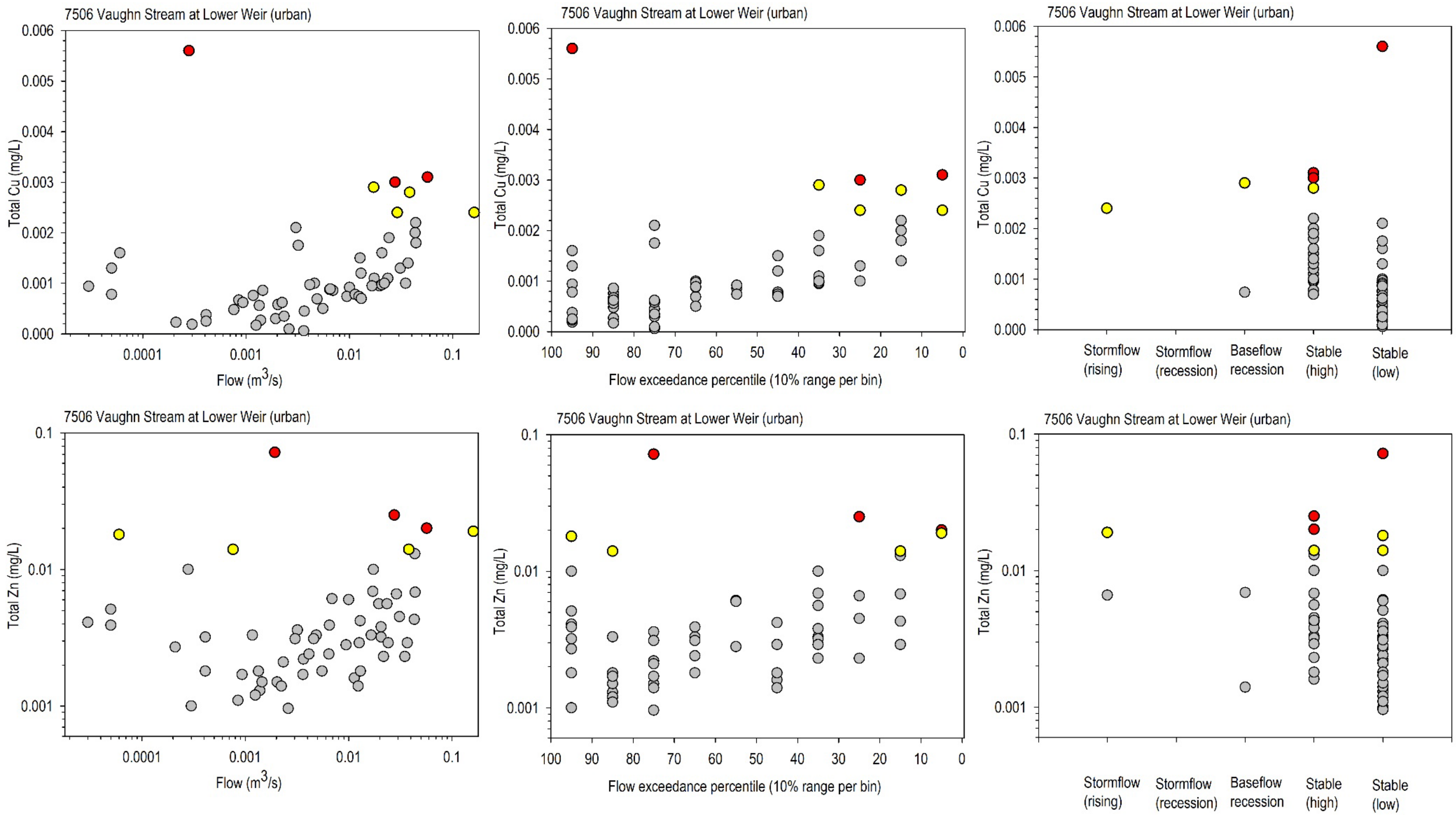

7506 Vaughn Stream at Lower Weir (urban)
TN (mg/L)
1.0
0.8
0.6
0.4
0.2
0.0
100
90
80
70
60
50
40
30
20
10
0
Flow exceedance percentile (10% range per bin)


7506 Vaughn Stream at Lower Weir (urban)
TN (mg/L)
1.0
0.8
0.6
0.4
0.2
0.0
Stormflow (rising)
Stormflow (recession)
Baseflow recession
Stable (high)
Stable (low)


7506 Vaughn Stream at Lower Weir (urban)
TP (mg/L)
0.10
0.08
0.06
0.04
0.02
0.00
0.00001
0.0001
0.001
0.01
0.1
Flow (m3/s)


7506 Vaughn Stream at Lower Weir (urban)
TP (mg/L)
0.10
0.08
0.06
0.04
0.02
0.00
100
90
80
70
60
50
40
30
20
10
0
Flow exceedance percentile (10% range per bin)


7506 Vaughn Stream at Lower Weir (urban)
TP (mg/L)
0.10
0.08
0.06
0.04
0.02
0.00
Stormflow (rising)
Stormflow (recession)
Baseflow recession
Stable (high)
Stable (low)


7506 Vaughn Stream at Lower Weir (urban)
Total Cu (mg/L)
Flow (m3/s)
Flow exceedance percentile (10% range per bin)
Total Zn (mg/L)
Stormflow (rising)
Stormflow (recession)
Baseflow recession
Stable (high)
Stable (low)

Appendix E: Upstream catchment size analysis for sub-catchments with greater than 50%, 70% and 90% coverage of the 24 HRUs with the greatest spatial extent (see Table 2)

Table E1: Summary statistics for sub-catchments with greater than 50% coverage of 24 HRUs with the greatest spatial extent. Catchment area percentiles only provided where number of sub-catchments is 10 or greater.

	Regional extent			Catchment area (ha)						
HRU	(ha)	(%)	Number of sub-catchments	Minimum	10th percentile	25th percentile	Median	75th percentile	90th percentile	Maximum
Forest-C-High-1	58551	12.2%	354	0.3	41.2	95.9	132.4	317.8	1043.2	6570
Forest-B-High-1	51734	10.8%	397	0.9	43.7	98.9	133.0	279.4	535.0	3113
Pasture-C-High-2	33889	7.0%	146	6.7	45.9	102.7	131.1	245.5	1068.5	3259
Pasture-C-High-1	31066	6.4%	80	1.5	29.3	51.3	103.3	119.9	206.4	777
Pasture-B-High-2	26565	5.5%	121	4.5	20.9	54.2	102.7	151.2	295.8	560
Pasture-B-High-1	24080	5.0%	85	0.2	12.7	45.2	100.8	145.8	253.6	464
Pasture-D-High-2	16706	3.5%	136	2.0	35.6	89.2	130.4	249.4	679.7	2073
Forest-C-High-2	15915	3.3%	112	46.4	101.0	113.7	235.0	453.6	930.4	4166
Dev_Pervious-C-High-All	14991	3.1%	121	0.1	8.6	26.5	57.0	104.8	233.7	356
Pasture-D-High-1	13222	2.8%	70	0.3	7.3	47.9	100.1	139.4	245.9	443
Dev_Pervious-C-Low-All	10585	2.2%	93	0.4	7.8	30.7	60.7	122.0	242.0	678
Pasture-B-Low-2	10444	2.2%	59	1.8	18.1	42.7	69.8	123.4	187.3	322
Pasture-B-Low-1	8802	1.8%	34	0.1	1.9	15.1	43.0	65.4	93.9	102
Pasture-A-High-2	8026	1.7%	47	2.5	40.2	77.5	101.1	262.6	459.3	855
Pasture-A-High-1	8001	1.7%	53	3.1	16.8	60.3	114.1	245.2	524.4	1257
Forest-B-High-2	6772	1.4%	40	5.7	69.9	108.3	152.5	348.9	706.2	1866
Pasture-C-Low-2	6109	1.3%	23	1.4	6.8	14.3	47.2	115.0	249.4	415
Forest-D-High-1	6006	1.3%	4	14.7	-	-	-	-	-	323
Pasture-C-Low-1	5693	1.2%	10	5.3	5.4	8.4	17.5	40.5	99.4	104
Forest-A-High-2	5680	1.2%	45	53.7	77.2	107.5	168.3	413.8	1013.0	1537
Rural_Grassland-C-High-1	5416	1.1%	3	1.8	-	-	-	-	-	54
Forest-A-High-1	5258	1.1%	16	0.3	1.1	13.4	37.3	91.6	159.2	170
Forest-A-Low-2	5239	1.1%	49	7.9	43.5	60.0	110.3	236.9	447.7	986
Rural_Grassland-B-High-1	4799	1.0%	7	0.1	-	-	-	-	-	123

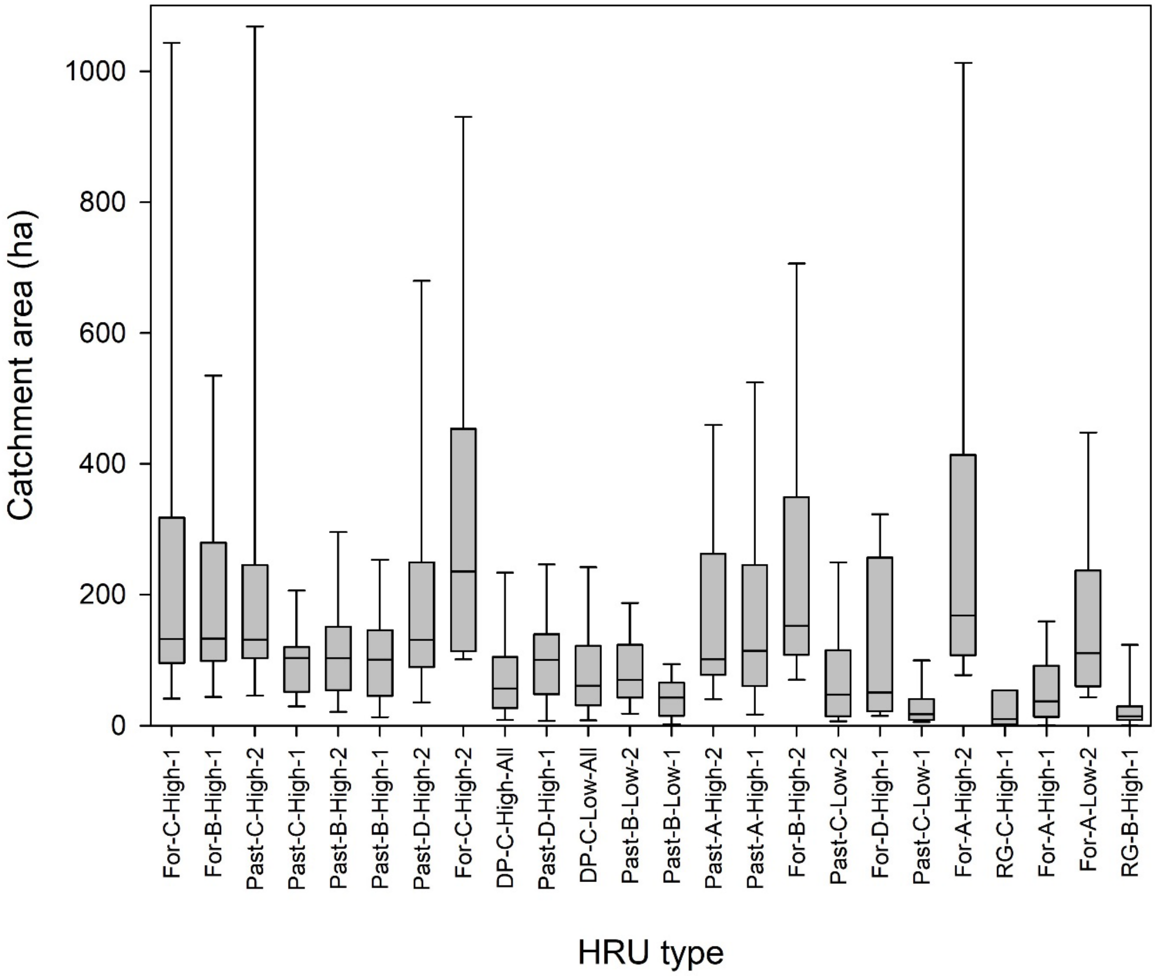


Figure E1: Boxplot showing catchment areas distribution for sub-catchments with greater than 50% coverage of the 24 HRUs with the greatest spatial extent in Auckland. Boxes represent 25th to 75th percentiles with median indicated by solid line; whiskers represent 10th and 90th percentiles.

Table E2: Summary statistics for sub-catchments with greater than 70% coverage of 24 HRUs with the greatest spatial extent. Catchment area percentiles only provided where number of sub-catchments is 10 or greater.

	Regional extent			Catchment area (ha)						
HRU	(ha)	(%)	Number of sub-catchments	Minimum	10th percentile	25th percentile	Median	75th percentile	90th percentile	Maximum
Forest-C-High-1	58551	12.2%	158	2.4	44.1	99.4	123.8	298.7	1105.1	2803
Forest-B-High-1	51734	10.8%	199	0.9	41.6	99.9	126.4	226.8	409.8	1382
Pasture-C-High-2	33889	7.0%	48	6.7	15.1	102.9	141.8	358.8	1723.7	2569
Pasture-C-High-1	31066	6.4%	25	4.6	7.8	33.6	53.2	102.0	122.0	219
Pasture-B-High-2	26565	5.5%	44	4.8	15.9	46.1	80.8	116.3	186.5	486
Pasture-B-High-1	24080	5.0%	19	0.2	2.2	18.3	47.2	102.1	201.2	219
Pasture-D-High-2	16706	3.5%	54	2.0	25.4	55.5	110.1	151.5	299.8	1473
Forest-C-High-2	15915	3.3%	62	46.4	91.4	107.7	183.5	393.8	517.2	956
Dev_Pervious-C-High-All	14991	3.1%	23	1.7	5.7	21.2	40.3	57.0	117.7	156
Pasture-D-High-1	13222	2.8%	23	0.3	1.8	11.1	57.3	95.3	153.7	253
Dev_Pervious-C-Low-All	10585	2.2%	18	0.6	2.7	5.2	20.7	45.8	213.5	244
Pasture-B-Low-2	10444	2.2%	29	1.8	6.1	36.4	53.1	72.6	129.3	187
Pasture-B-Low-1	8802	1.8%	12	1.4	1.7	4.8	14.1	20.7	43.5	44
Pasture-A-High-2	8026	1.7%	14	2.5	17.1	58.4	82.4	100.6	136.9	161
Pasture-A-High-1	8001	1.7%	28	3.1	9.2	39.8	95.9	129.1	316.8	435
Forest-B-High-2	6772	1.4%	14	104.9	107.6	116.4	140.5	221.2	471.7	523
Pasture-C-Low-2	6109	1.3%	12	1.4	3.0	7.0	45.0	68.2	263.9	307
Forest-D-High-1	6006	1.3%	1	43.1	-	-	-	-	-	43
Pasture-C-Low-1	5693	1.2%	4	14.0	-	-	-	-	-	35
Forest-A-High-2	5680	1.2%	28	53.7	71.5	100.9	150.9	317.7	482.4	900
Rural_Grassland-C-High-1	5416	1.1%	0	-	-	-	-	-	-	-
Forest-A-High-1	5258	1.1%	2	24.6	-	-	-	-	-	35
Forest-A-Low-2	5239	1.1%	34	7.9	48.4	61.0	100.7	187.4	310.2	482
Rural_Grassland-B-High-1	4799	1.0%	4	0.1	-	-	-	-	-	29

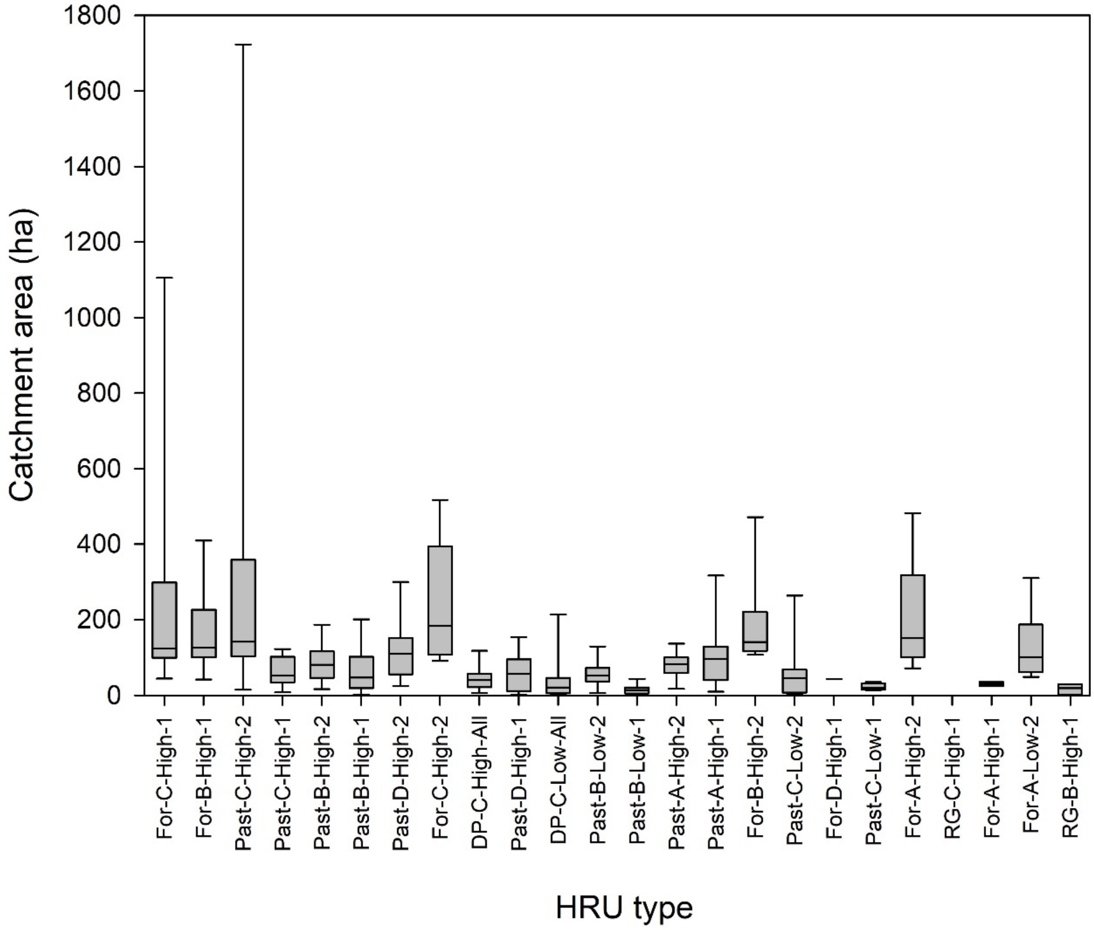


Figure E2: Boxplot showing catchment areas distribution for sub-catchments with greater than 70% coverage of the 24 HRUs with the greatest spatial extent in Auckland. Boxes represent 25th to 75th percentiles with median indicated by solid line; whiskers represent 10th and 90th percentiles.

Table E3: Summary statistics for sub-catchments with greater than 90% coverage of 24 HRUs with the greatest spatial extent. Catchment area percentiles only provided where number of sub-catchments is 10 or greater.

HRU	Regional extent (ha)	Regional extent (%)	Number of sub-catchments	Catchment area (ha) Minimum	10th percentile	25th percentile	Median	75th percentile	90th percentile	Maximum
Forest-C-High-1	58551	12.2%	61	4.9	51.6	99.2	117.1	258.7	792.8	1317.9
Forest-B-High-1	51734	10.8%	77	0.9	49.4	103.4	136.7	201.5	391.1	565.3
Pasture-C-High-2	33889	7.0%	6	12.5	-	-	-	-	-	115.1
Pasture-C-High-1	31066	6.4%	3	23.9	-	-	-	-	-	112.3
Pasture-B-High-2	26565	5.5%	10	5.8	6.0	16.2	40.2	81.5	114.8	116.8
Pasture-B-High-1	24080	5.0%	5	0.2	-	-	-	-	-	102.1
Pasture-D-High-2	16706	3.5%	8	26.7	-	-	-	-	-	99.1
Forest-C-High-2	15915	3.3%	32	60.8	91.4	104.1	142.8	310.9	450.5	845.8
Dev_Pervious-C-High-All	14991	3.1%	1	9.1	-	-	-	-	-	9.1
Pasture-D-High-1	13222	2.8%	6	1.5	-	-	-	-	-	252.5
Dev_Pervious-C-Low-All	10585	2.2%	2	0.6	-	-	-	-	-	3.0
Pasture-B-Low-2	10444	2.2%	4	1.8	-	-	-	-	-	123.4
Pasture-B-Low-1	8802	1.8%	2	1.4	-	-	-	-	-	20.1
Pasture-A-High-2	8026	1.7%	2	2.5	-	-	-	-	-	63.8
Pasture-A-High-1	8001	1.7%	7	9.8	-	-	-	-	-	154.5
Forest-B-High-2	6772	1.4%	7	104.9	-	-	-	-	-	163.5
Pasture-C-Low-2	6109	1.3%	2	62.3	-	-	-	-	-	162.5
Forest-D-High-1	6006	1.3%	0	-	-	-	-	-	-	-
Pasture-C-Low-1	5693	1.2%	3	17.1	-	-	-	-	-	34.9
Forest-A-High-2	5680	1.2%	15	80.6	92.3	104.3	141.9	307.8	523.3	616.5
Rural_Grassland-C-High-1	5416	1.1%	0	-	-	-	-	-	-	-
Forest-A-High-1	5258	1.1%	0	-	-	-	-	-	-	-
Forest-A-Low-2	5239	1.1%	21	54.0	57.7	81.2	101.5	151.0	236.1	302.4
Rural_Grassland-B-High-1	4799	1.0%	1	0.1	-	-	-	-	-	0.1

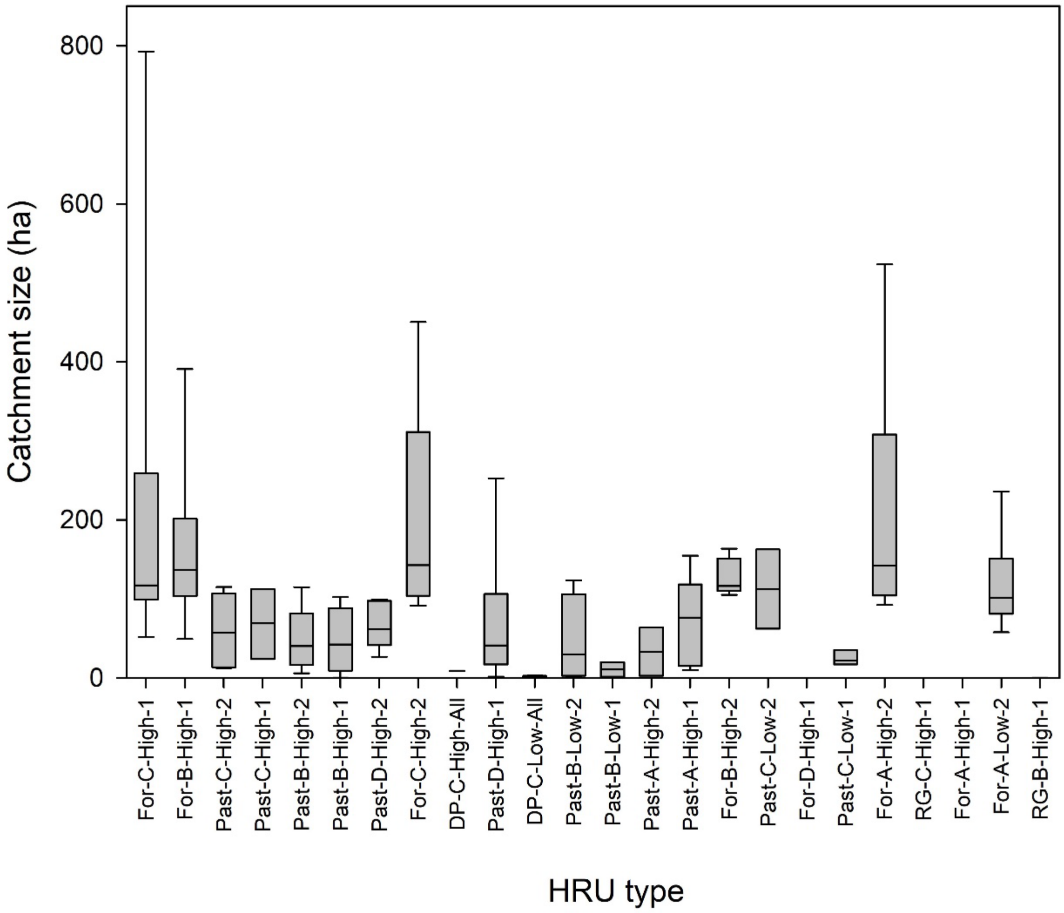


Figure E3: Boxplot showing catchment areas distribution for sub-catchments with greater than 90% coverage of the 24 HRUs with the greatest spatial extent in Auckland. Boxes represent 25th to 75th percentiles with median indicated by solid line; whiskers represent 10th and 90th percentiles.