Freshwater Management Tool

August 2021 FWMT Report 2021/3

Report 3
Baseline State Assessment (Rivers)

Auckland Council
Te Kaunihera o Tāmaki Makaurau

Freshwater Management Tool:
Report 3. Baseline State Assessment (Rivers)

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Freshwater Management Tool:
Baseline State Assessment (Rivers)
Overview

Freshwater Management Tool

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

Baseline reporting

- This report is 3 of 5 documenting baseline (2013-17) water quality for freshwater receiving environments in the Auckland region.

Report scope

- This report documents water quality for Auckland freshwater streams, region-wide over the baseline period of 2013-17 assessed using the FWMT Stage 1.
- Water quality outputs cover nutrients (N, P), sediment (TSS), heavy metals (Cu, Zn) and faecal indicator bacteria (*E. coli*) including numeric attribute states, grades and source apportionment for all sub-catchments aggregated into 10 coastal-draining watersheds.

Report messages

- FWMT Stage 1 is a continuous, process-based model able to generate 15-minute time series of contaminant and flow responses to climatic variation across 5,465 sub-catchments draining all of the Auckland region, from mountains to sea.
- FWMT Stage 1 uses an HRU library developed to span a range of soil, slope, land cover and activity or impact factors, with up to 106 unique HRUs able to be represented for their effects on a range of water quality parameters and processes, region-wide within the FWMT Stage 1. A 107th source of flow and contaminant includes 448 engineered overflow points for reticulated wastewater.
- National and regional objective framework (NOF) guidance is used to determine numeric attribute states (median, 95th%, %>260, %>540, maxima) for seven graded contaminants of human and ecosystem health. Total suspended sediment

apportionment, concentration and loading information is available but lacks grading under the NOF.

- Performance at grading is assessed for numeric attribute states and worst overall attribute state in three alternative approaches for 36 State of Environment water quality stations. Reasonable assurance is demonstrated for all grades with better performance at predicting “failing” and more degraded streams (C and D grade).
- A consistent regional pattern for degradation of human health occurs. FWMT accounting indicates 83% of Auckland streams are D or E graded at baseline state (failing national targets for moderate streams). FWMT accounting indicates widespread failure occurs in 95^{th}% *E. coli* numeric attribute state with farming the predominant source of faecal loading to stream (78% by mass).
- A consistent pattern occurs for limited ecosystem health degradation from total oxidised nitrogen (TON) toxicity (4% in C or D-grade). Toxicity risks to ecosystem health are widespread for total ammoniacal nitrogen (TAM) (50% in C or D-grade). Sources of nitrogen are dominated by pasture (76% by mass) with considerable, high-yielding horticultural inputs (16% by mass).
- Lesser degradation in regional freshwater ecosystem health occurs from copper (8% in D-grade), but with considerably greater extent of degradation in urban watersheds, caused largely by acute events. Sources of copper vary with most intense yields from roads and motorways, and paved urban surfaces. Similar patterns occur in degradation of ecosystem health by zinc (4% of freshwater streams in D-grade during baseline, predominantly in urban watersheds and for 95^{th}% numeric attribute state). Zinc sources are diverse, albeit with most intense yields derived from roofing, roads and motorways, and paved urban surfaces.

Quality assurance

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

Continuous improvement

- FWMT Stage 1 is the first generation of a paradigm shift in water quality accounting for Auckland – an advance on simpler, empirical and non-continuous modelling (CLM; C-CALM).

- Ongoing changes to the FWMT Stage 1 are expected in light of external peer review and end-user needs. Please contact the FWMT team to request data and updates to the FWMT.

Contact – fwmt@aucklandcouncil.govt.nz

Executive summary

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

This report grades outputs from the FWMT Stage 1 using national and regional objective framework guidance on seven freshwater contaminants. Continuous predicted contaminant time series spanning the calendar years of 2013 to 2017 were used to calculate numeric attribute states (i.e., percentiles of instream concentration). The most conservative (poorly) graded numeric attribute states assigned overall attribute grade. However, the availability of continuous outputs enabled investigation of which numeric attribute state conservatively grades overall state, enabling greater resolution of likely contaminant pressures on water quality state.

Predicted grades for 2013 to 2017 were compared to observed grades calculated from monitoring data at 36 instream locations. Corresponding grading-based performance was estimated for three alternative approaches: grades exactly alike (Approach 1); grades within an additional of observed (Approach 2); and grades within an absolute distance (range) of numeric attribute states (Approach 3). Approach 1 was generally more conservative, 2 more permissive and 3 more balanced. In all approaches, better performance was reported for “failing” location (e.g., in C and/or D grade depending on contaminant). For instance, performance across the seven contaminants for correctly predicting “all” grades varied from 22-86% (Approach 1), 67-100% (Approach 2) and 25-100% (Approach 3 – for numeric attribute states rather than grade). Equivalent performance across the seven contaminants for “failing” grades varied from 55-100% (Approach 1) and 50-100% (Approach 2). Combined, the grading performance indicates reasonable assurance in the FWMT Stage 1 being used for reporting baseline water quality, more so for determining more from less degraded (failing) waterways.

Detailed numeric attribute, grading, source apportionment and yield information has been generated and reported from the FWMT Stage 1 for the baseline (2013-2017) period. The sub-catchment basis and regional span of the FWMT Stage 1 enable integrated water quality assessments for region, watershed, local board or stormwater catchment.

Consistent regional patterns as well as marked watershed variation in contaminant grades and/or sources are reported by FWMT Stage 1 baseline outputs. For instance, *E. coli* was consistently graded poorly throughout all watersheds for 2013 to 2017, in both urban or rural waterways. Overall, 83% of the 3,085 km of FWMT reaches were graded below national human health targets (minimum C-grade), varying from 40-99% of modelled instream lengths between the West Coast and Tāmaki watersheds. Continuous outputs from the FWMT Stage 1 demonstrated nearly all such "failing" reaches exceeded *E. coli* 95^{th}% attribute state thresholds (e.g., >1200 MPN/100ml). Likewise, the minimum national target for *E. coli* median attribute states was exceeded in 53% of FWMT reaches (by length). Hence, ongoing pressures upon human health from *E. coli* contamination are otherwise lesser for chronic (median) than acute (95^{th}%) conditions instream. Regardless, pasture is the predominant source of *E. coli* to edge of streams (78% of *E. coli* loading) but with considerable contributions from wastewater and other urban sources in several watersheds, including: Manukau Harbour (8%); Hibiscus Coast (20%); Tāmaki (39%); and Waitematā watersheds (49%).

Other consistent regional patterns in ecosystem health contaminants included limited risk of total oxidised nitrogen (TON) toxicity whether acute or chronic. For instance, the proportion of FWMT reaches predicted in A-grade (>=99% community protection from nitrate-toxicity) varied from 62% (Manukau Harbour) to 100% by reach length (Hauraki Gulf Islands). Exceedance of national bottom-lines for nitrate-nitrogen toxicity was restricted largely to the Manukau watershed, which accounted for 102 or the 114 km C or D-graded FWMT reaches. Predominant sources of total nitrogen (TN) to streams in the Manukau watershed include horticulture (42%) and pasture (52% – of which more than nine tenths is derived from high-impact pastoral farming [e.g., dairying and beef finishing]).

TAM grading is broadly consistent across watersheds, with 94% (2,902 km) of FWMT reaches predicted in "B" or "C" grade. Whilst isolated areas of several watersheds were predicted in D-grade (4%, 116 km – notably in Tāmaki and Waitematā watersheds), large swathes of the region were predicted to fail national bottom-lines for ammoniacal-nitrogen (e.g., 50% or 1,422 km in C or D grade – exposing >5% of aquatic organisms to unacceptable risk of toxicity). The Hauraki Gulf Islands watershed is the only one without "failing" streams for TAM. Whereas, the proportion of FWMT reaches failing national bottom-lines for TAM over the baseline period (2013-2017) varied from 16% (West Coast) to 68% (Kaipara). Notably, nearly all prior TAM "failing" (C and D graded) reaches, failed for acute toxicity guidance and the maximum numeric attribute state (only 7 of 2,761 FWMT reaches failed for median TAM concentration). Using modelled maxima to grade is inherently more uncertain and contrary to recommendations for the NH4N attribute in the National Objective Framework (NOF) (e.g., Hickey, 2014). A more defensible approach to grading FWMT output has been recommended here, using modelled 95^{th}% TAM concentration (alongside the median numeric attribute state). Grading modelled 95^{th}% TAM as per maximum-based thresholds in the NOF so has a marked effect on regional water quality state with approximately three quarters of "failing" FWMT reaches otherwise A or B graded. Combined, the length of failing FWMT reaches declines from 1,422 km (50%) to 381 km (12%) by use of a 95^{th}% numeric attribute state for TAM. The Kaipara watershed remains the most degraded by reach length for TAM under the median and 95^{th}%-based approach, with 26% of FWMT reaches in C grade – as before, predominantly for risks of acute toxicity (e.g., for 95^{th}% rather than median concentration). Amongst TN-sources to freshwater streams, pastoral land uses are the single largest contributor (76%), followed by horticulture (16%). However, the latter belies the widespread "failing" FWMT reaches in urban watersheds where more diverse and locally enriched sources exist.

Dissolved inorganic nitrogen (DIN) grading utilised proposed rather than operative NOF guidance. Outcomes from DIN grading are more conservative than those for TON and nearer those of TAM, with 16% of FWMT reaches in D-grade (e.g., potentially at excessive risk of eutrophication rather than toxicity-driven effects from nitrogen availability instream). Only the Hauraki Gulf Islands lack any D-graded FWMT reaches for DIN, with between 2% (West Coast) and 32% (Manukau) of watersheds D-graded by length. Dissolved reactive phosphorus (DRP) grading used operative NOF guidance but which lacks a national bottom-line. Hence, despite being the worst-graded ecosystem health contaminant with 59% (1,814 km) of FWMT reaches predicted in D-grade, as with DIN it is unclear how the widespread potential risk of eutrophication should be acted upon. Regardless, the extent of D-graded FWMT reaches for DRP is notable, ranging from 33% (West Coast) to 74% (Kaipara). The extensive lengths of D-graded reaches within the region were graded as such for both median and 95^{th}% numeric attribute states (i.e., no dominance of either acute or chronic risk of eutrophication). Predominant regional sources for TP are largely pastoral (75%) with a considerable contribution from bankside erosion (22%).

Predicted total suspended solids (TSS) have not been graded here owing to a lack of national or regional objective guidance for TSS. However, continuous variation of TSS concentration is now available through the FWMT Stage 1 for 3,085 km, inclusive of source apportionment over the baseline period (2013-2017). From this, wide variation in sources is evident across the watersheds but as a region, the predominant source of sediment instream and to coast is bankside erosion (57%, 274,000 tonnes/year). The proportion of bankside sources to TSS loading into FWMT reaches varied amongst watersheds from 43% (Tāmaki) to 73% (Wairoa). Nonetheless, management of sediment-based objectives whether for freshwater or coastal receiving environments likely therefore requires reductions in bankside erosion (e.g., hydrological, geomorphic and/or riparian management). Amongst non-bankside sources for sediment, forestry/open space (24%) and pasture (17%) are modest contributors, more so when considering the large extent thereof regionally.

A provisional regional objective framework has been proposed for Auckland to manage for both chronic and acute risks from toxicity associated with dissolved copper (DCu) and zinc (DZn) (e.g., Gadd et al., 2019). Baseline water quality predictions from the FWMT Stage 1, suggest 8% (261km) of waterways are likely to exceed regional DCu bottom-lines (e.g., associated with <80% of instream organisms protected from regular toxic effects). Latter D-graded reaches are located predominantly in urbanised watersheds: Hibiscus Coast (21%, 33km); Waitematā (37%, 100km); and Tāmaki (47%, 47 km). Less than 5% of D-graded FWMT reaches failed the median numeric attribute state for DCu, meaning excessive risks of toxicity appear to be both urban and acute (e.g., failing on 95^{th}% numeric attribute state). Whilst regional total Cu (TCu) sources include extensive hydrological response units (HRU) including forest/open space (42%), pasture (27%) and bankside erosion (23%), this belies the intensity of urban yielding HRUs. For instance, greatest TCu yields are associated with roads and motorways (121 g/Ha/yr) followed by paved urban surfaces (55 g/Ha/yr) and forest/open space (38 g/Ha/yr). Similar patterns are evident in DZn albeit with additional enriched sources. For instance, 4% of FWMT reaches are predicted to be D-graded under baseline conditions (2013-2017) with the Waitematā watershed having the highest proportion of streams modelled to be excessively degraded by DZn (24%, 64 km D-graded). Other watersheds with notable lengths of D-graded FWMT reaches include the Hibiscus Coast (7%, 12 km) and Manukau Harbour (6%, 32 km). More than 95% of “failing” FWMT reaches, were D-graded for DZn due to enriched 95^{th}% numeric attribute state (i.e., for acute effects from DZn toxicity). Whilst the predominant regional sources of total Zn (TZn) are more diverse than those of TCu, including open space/forestry (35%), pasture (24%), bank erosion (18%), roofing (10%) and roads and motorways (8%), yields of urban HRUs remain severalfold greater than rural equivalent. For instance, FWMT Stage 1 baseline outputs indicate highest TZn yields from roofing (788 g/Ha/yr) followed by roads and motorways (604 g/Ha/yr) and paved urban surfaces (232 g/Ha/yr) – all four-fold or more greater than other HRU groups. Indeed, roofing sources yield nearly an order of magnitude more TZn than any rural HRU group.

The FWMT Baseline State (Rivers) report includes numerous appendices designed to support water quality management decision-making to catchment level, whilst ensuring integrated accounting (ki uta ki tai). Regional and watershed summaries should not be read as definitive with high diversity in simulated sub-catchment water quality throughout the Auckland region over the baseline period. However, the FWMT Stage 1 outputs represent the first comprehensive, deterministic and integrated water quality accounting for the Auckland region.

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Note – Appendices are published separately. All data available on request from fwmt@aucklandcouncil.govt.nz.[1]

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Appendix B – Ecosystem and human health

Appendix C – Watershed grade summaries for all sub-catchments

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Appendix E – Source apportionment summary tables by contaminant

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Appendix G1 – *E. coli* source assessment for large rivers and additional points of interest

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Appendix G4 – Total nitrogen source assessment for large rivers and additional points of interest

Appendix G5 – Total phosphorus source assessment for large rivers and additional points of interest

Appendix G6 – Total suspended solids source assessment for large rivers and additional points of interest

Appendix H – Mapping of model categories to source categories

[1] Note Appendices use outdated naming convention ("Current State") which is directly analogous here to "Baseline State" (e.g., appendices have a different naming convention but are valid for Baseline v1.0 FWMT outputs).

Appendix I – Summaries using integrated data

Appendix J – Proportion of watershed sub-catchments upstream of failing FWMT reaches

Appendix K – Grade comparisons

Glossary of key terms

Term	Abbreviation	Definition
Attribute		A measurable characteristic of fresh water, including physical, chemical and biological properties, which supports particular values.
Attribute measure		One of several statistics for an attribute, each of which is graded and from which overall grade is determined as the least of measures (e.g., median, 95th%).
Attribute state		The level to which an attribute is to be managed for those attributes specified in Appendix 2 of the National Policy Statement for Freshwater Management (2014).
Contaminant		Chemical or physical stressors of water quality.
Grade		The lesser of any attribute measure's grades under the National Objective Framework (NOF) or any regional objective framework. Interchangeable with attribute state for purposes of report.
Hydrological Response Unit	HRU	A watershed area assumed to be homogeneous in hydrologic response due to similar land use and soil characteristics and used in the LSPC model.
Hydrological Soil Groups	HSG	Soil classification (A+ through to D) by soil runoff potential. Soils classified as HSG A have the smallest runoff potential whereas D soils have the greatest.
Land cover		The material covering the earth (e.g., pasture, horticulture, developed pervious)
Land use		Activity undertaken on the land, usually grouped into classes (e.g., intensity of pastoral farming).
Local Government Act 2002	LGA	The Local Government Act 2002 is an act of Parliament that defines local government in the New Zealand.
Loading Simulation Program in C++	LSPC	The watershed modelling system used to simulate the state (concentrations and loads) of freshwater quality and recharge rates of shallow aquifers across the Auckland region. LSPC is an open-source, process-based watershed modelling system developed by the U.S. EPA for simulating watershed hydrology, sediment erosion and transport, and water quality processes from both upland contributing areas and receiving streams.
The National Policy Statement for Freshwater Management	NPS-FM	National policy providing direction about how local authorities should carry out their responsibilities under the Resource Management Act 1991 for managing fresh water. The NPS-FM directs regional policy statements and regional (unitary) plans to consider specific matters and to meet certain requirements of water quality through a series of values, attributes and objectives for those – either at national bottom-lines or for more improved state. The NPS-FM came into effect on 1 August 2014.
On-site wastewater treatment	OSWW	Onsite wastewater treatment systems are systems that are used to treat wastewater from a home or business and return treated wastewater back into the receiving environment.
Pastoral		Land use for keeping and grazing livestock.

Term	Abbreviation	Definition
Resource Management Act 1991	RMA	The Resource Management Act 1991 promotes the sustainable management of natural and physical resources such as land, air and water in New Zealand.
Riparian		Relating to, or situated on, the bank of a river or other water body.
Runoff		Water flows which result from rainwater which is not absorbed by permeable surfaces or that which falls on impermeable surfaces.
Rural		Outside of the defined urban area under the Auckland Unitary Plan. HRUs with land uses classified as forest, horticulture, pasture or open space
Sub-catchment		Area of land in which rainfall drains toward a common stream, river, lake, or estuary. Sub-catchments in the FWMT function as spatial accounting units for the model and are nested within Auckland Council's 233 Stormwater Catchments.
Urban area		HRUs with land uses classified as residential, commercial, industrial, or otherwise developed
Wastewater	WW	Water that has been used in the home, in a business, or as part of an industrial process. Also known as sewage.
Waterbody		Distinct and significant volume of water. For example, for surface water: a lake, a reservoir, a river or part of a river, a stream or part of a stream.
Watershed		Planning units that refer to the area from which surface water drains into a common lake or river system or directly into the ocean; also referred to as a drainage basin or catchment basin. Stormwater management across Auckland is organised into 10 major watersheds.

1.0 Introduction

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

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

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

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

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

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

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

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

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

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

Our Water Values

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

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

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

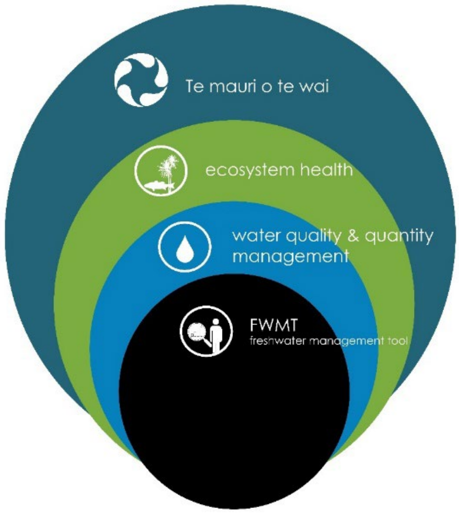


Figure 1-2. FWMT connections to wider objectives

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

1.2 Auckland Council Freshwater Accounting

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

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

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

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

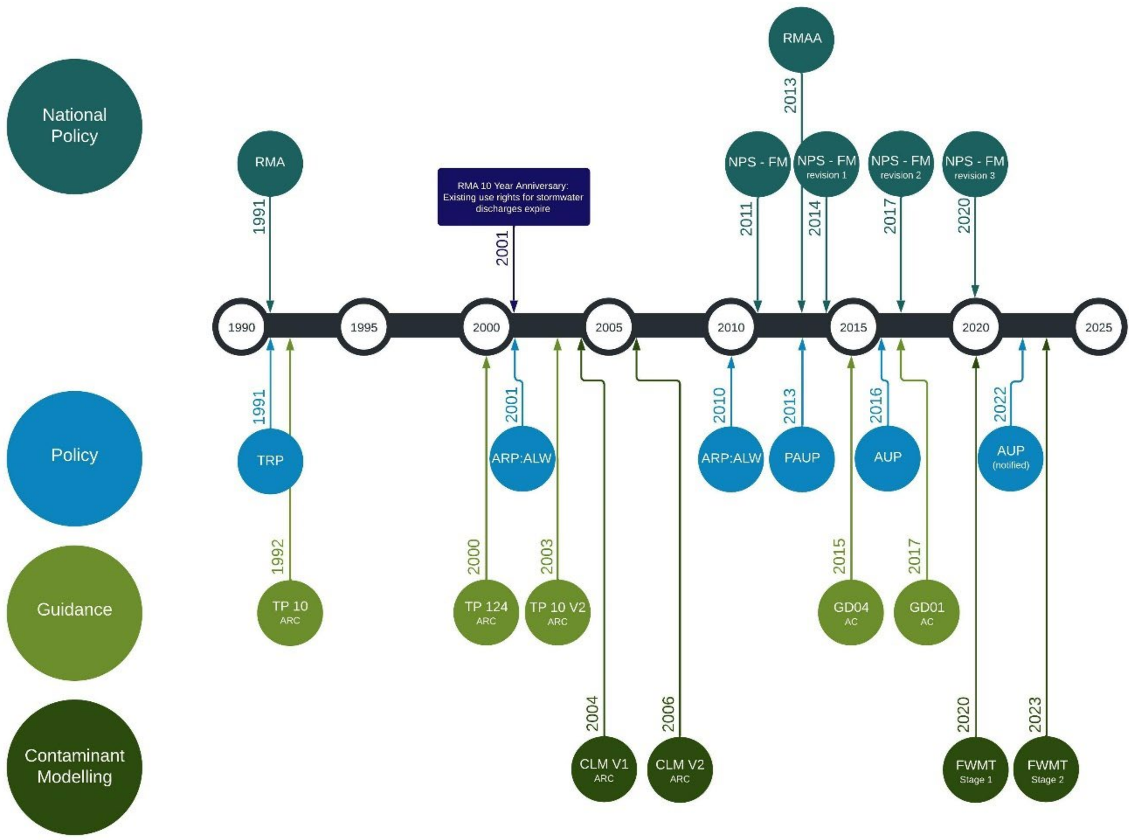


Figure 1-3. Timeline of policy, guidance and contaminant modelling in Auckland from 1990-2025

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

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

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

The FWMT continues this work and will support the development of a range of rules and implementation programs for the NPS-FM. Combined, the sources of freshwater quality accounting available to Auckland Council include:

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

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

This report integrates predictive outputs from the FWMT and observed data from the SoE network for the period 2013-2017 (five years) to calculate numeric attribute states, or "grades", for seven contaminants across Auckland: *E. coli*, dissolved copper (DCu), dissolved zinc (DZn), total oxidised nitrogen (TON), total ammoniacal nitrogen (TAM), dissolved inorganic nitrogen (DIN), and dissolved reactive phosphorus (DRP). Total oxidised nitrogen (TON) is the sum of nitrate and nitrite and was used to grade against the NPS-FM nitrate (NO_3-N) toxicity attribute. A more robust observed dataset was available for TON than just nitrate, furthermore, nitrite is usually quickly converted to nitrate, so using TON against nitrate toxicity attribute was deemed appropriate. Similarly, TAM was used to grade against the NPS-FM ammonia (NH4-N). Modelled stream and river grades for the seven contaminants are summarised regionally and by watershed, as five-year integrated numeric attribute states, before reporting conservatively on the worst thereof as the overall attribute grade. The findings provide the first comprehensive evaluation of freshwater quality conditions across Auckland and first such spanning an entire region from continuous, process-based modelling in New Zealand (e.g., for the NPS-FM).

In addition, this report contains the first region-wide, process-based source-apportionment analysis nationally and for the Auckland region. Via hydrological and contaminant process responses to land use and climate, key sources of contaminants are highlighted, including a comparison of point versus non-point and urban versus rural sources.

***Note**: this report summarises regional output from the FWMT but more detailed summary information is available directly from Healthy Waters (Auckland Council) for the 10 watersheds through to the region's 233 stormwater catchments and ultimately, to 5,465 sub-catchments distributed across the region in the FWMT.*

1.3 FWMT Purpose

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

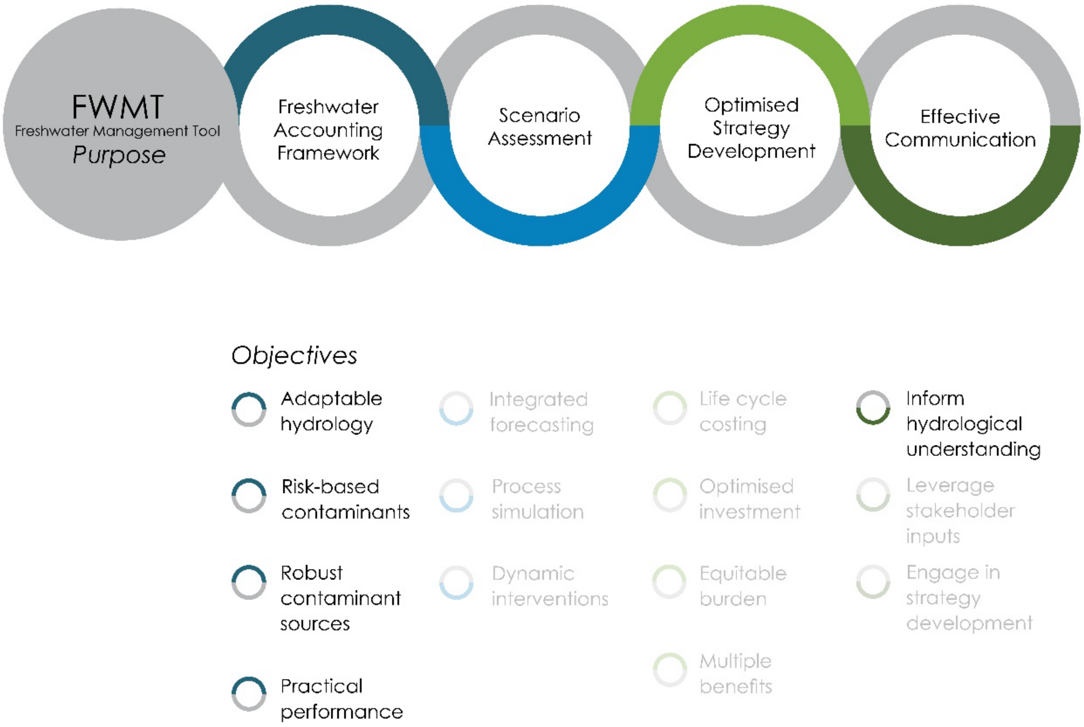


Figure 1-4. FWMT value chain of purposes and objectives. The FWMT supports four linked purposes, each with a range of objectives listed beneath

1.4 FWMT Objectives

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

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

1.4.1 Adaptable Hydrology

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

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

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

1.4.2 Risk-based Contaminants

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

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

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

1.4.3 Robust Contaminant Sources

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

1.4.4 Practical Performance

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

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

1.4.5 Inform Hydrological Understanding

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

1.5 FWMT Scenario Assessment Objectives

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

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

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

1.6 FWMT Optimised Strategy Development Objectives

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

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

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

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

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

1.7 FWMT Effective Communication Objectives

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

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

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

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

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

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

1.8 FWMT Scope

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

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

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

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

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

1.8.1 FWMT Staging – Iterative approach to development

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

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

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

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

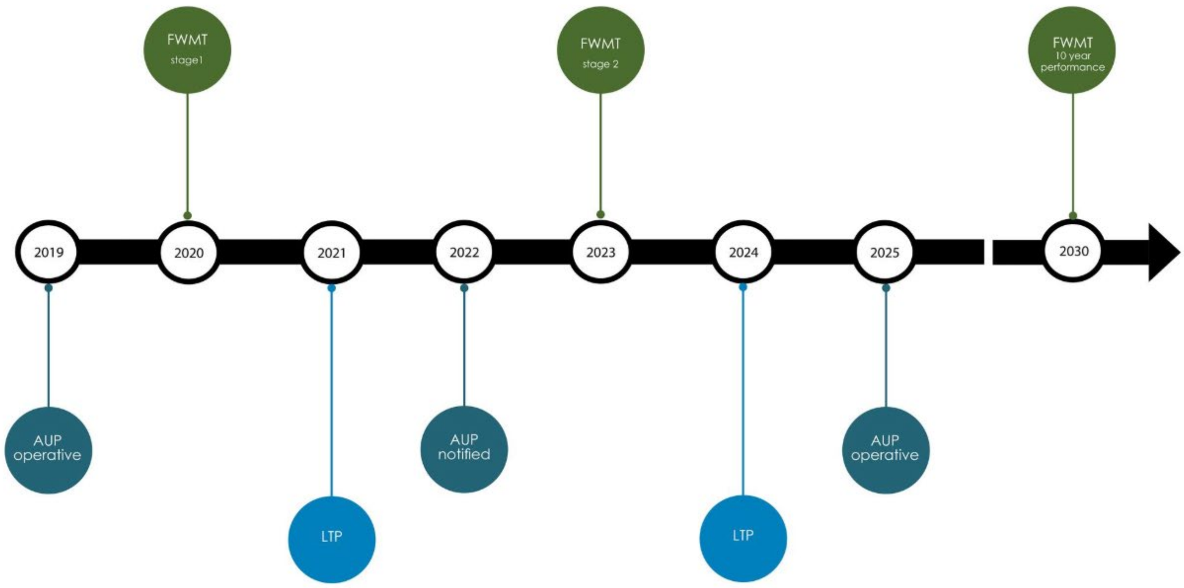


Figure 1-5. Delivery timeline of the FWMT through three iterative stages, with consistent scope between to deliver both baseline and scenario evidence on freshwater quality attribute states under existing and alternate management actions

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

1.8.2 Baseline Modelling

Catchment modelling of baseline freshwater quality typically aims to establish the baseline state of hydrological and contaminant distributions, across a catchment and either as generalised or continuous state. Baseline modelling is acknowledged in NPS-FM supporting guidance (MfE, 2015) as necessary to ensure variation in contaminant concentration or loading, is understood: throughout an FMU/watershed, across acute and chronic conditions, and for variation in natural and anthropogenic drivers (soil, land cover, intensity of use, climate).

The objectives for baseline modelling can include:

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

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

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

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

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

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

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

1.8.3 Scenario Modelling

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

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

1.9 FWMT Modelling Approach

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

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

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

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

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

1.10 FWMT Reporting Approach

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

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

Table 1-2. FWMT Reporting Framework

Report #	Report	Purpose
1	**Integration**	Defines the context, purpose, objectives, development and reporting approach for the FWMT. Included is discussion of how to integrate the FWMT with wider Auckland Council planning and operational functions (e.g., wider national policy statements, local government functions).
2	**Baseline Data Inventory**	References and documents all pre-existing datasets used in baseline modelling. Describes how all other modified or new datasets were generated, describes limitations. Includes meteorology, topography, stream network and geometry, soil, land cover and use, impervious surfaces, on-site wastewater, reticulated wastewater, stormwater, pre-existing devices.
3	**Baseline Configuration and Calibration**	Describes the configuration of LSPC to represent baseline. Describes which processes are accounted for and how these are generalised. Acknowledges limitations of configuration. Documents calibration performance against a range of metrics.
4	**Baseline State (rivers)**	Describes output of baseline accounting. Assesses spread of predicted hydrology, distribution of yields and instream loads – describing that by watershed, source and pathway, for 5-year baseline state interval (2013-17). Assesses instream gradings by contaminant over full 5-year interval (2013-17) and subsets of (wet vs. dry years; storm vs. base flow) – linking back to calibration findings on robustness of such output for FWMT purposes and objectives.

Report #	Report	Purpose
5	**Baseline State (lakes)**	Describes output of LSPC and post process assessment on baseline lake conditions utilising optimised Vollenweider equations for predicting steady-state in-lake TN, TP, Chl-a and SD from continuous external TN and TP inputs.
6	**Scenario Data Inventory**	References and documents all pre-existing datasets used. Describes how all other modified or new datasets were generated. Describes limitations thereof. Includes future climate, future land use, structural device menu and maximum opportunity, source control menu, future wastewater network performance, rural interventions, intervention cost and benefit.
7	**Scenario Configuration and Optimisation**	Describes configuration of LSPC to represent future state or scenarios (e.g., AUP, development, climate change). Describes configuration of SUSTAIN to represent mitigation strategies, costs and effects as well as optimisation process (e.g., for nodes instream or downstream, for which limiting contaminant or hydrology).
8	**Scenario Outcomes**	Frames changes in contaminant outcomes (loads, grading) resulting from climate change, development, and interventions including regulation, non-regulatory policy, infrastructure delivery and lifecycle management. Limited as per Baseline state – Rivers and Lakes reports, to relevant contaminants, sources and interventions.

2.0 Grading Reporting Process

This section describes the methods used to generate region-wide and watershed grading summaries of instream numeric attribute states. The methods used to process FWMT outputs for source apportionment are also presented (Section 2.2).

The region-wide grading process assessed both observed SoE data and predicted FWMT outputs. Grading is also reported using an integrated dataset, discussed further in Appendix I. The grading period covers 2013-2017, which is the most recent five-year period with both observed data and predicted outputs available.

The freshwater quality attribute grading process covered seven contaminants that had either agreed or proposed numeric attribute states (as of 2020), from both the NOF (NPS-FM 2020) and a regional objective framework (ROF) for heavy metals (Gadd et al., 2019). Combined, both national and regional objective frameworks utilise a grading system (A, B, C, D, or E) applicable to all freshwater streams across Auckland, for

- Ecosystem health – eutrophication (DIN, DRP), nitrogen toxicity (TON, TAM), and heavy metal toxicity (DCu, DZn);
- Human health – risk of illness from primary contact recreation (faecal indicator bacteria – *E. coli*).

Note that FWMT simulations extend to sediment (total suspended sediment – TSS) at all 2,761 freshwater accounting nodes, inclusive of bankside (scour and gully) and overland erosional processes (for all 5,465 sub-catchments). However, the lack of TSS guidance and preference for visual clarity-based grading in the NPS-FM will require further empirical modelling assign sediment grades from baseline FWMT Stage 1 outputs.

2.1 Predicted Outputs from FWMT

The FWMT Stage 1 was used to generate predicted outputs. The Auckland region is represented through a total of 5,465 modelled sub-catchments, with 2,761 containing modelled stream segments (Figure 2-1). FWMT predicted outputs include yield and loading from the 5,465 sub-catchments, apportioned to HRU sources, as well as corresponding instream concentration and loading time series for the 2,761 modelled stream segments.

Sub-catchments without modelled reaches include headwater sub-catchments and those draining directly to the coast. Additional information on sub-catchment and stream network configuration can be found in the [FWMT Baseline Configuration and Calibration Report]. The report also contains detailed information about the broader boundary configuration and calibration process. The report includes assessment of accuracy of continuous simulated predictions compared to monthly observed data (e.g., NSE, r^2, PBias) across flow and contaminant concentration and loading.

The FWMT Stage 1 LSPC model simulates water quality (contaminants) at 15-minute intervals for each modelled reach in the Auckland region, which were averaged to a daily time-step – the 1,826 daily concentrations between 2013-2017 are the primary ‘predicted’ dataset for region-wide grading. Predicted contaminant concentrations are available for dissolved and total nutrients, including total nitrogen (TN), total oxidised nitrogen (TON), total ammoniacal nitrogen (TAM), dissolved inorganic nitrogen (DIN), total phosphorus (TP) and dissolved reactive phosphorus (DRP). Other contaminants predicted by the FWMT Stage 1 include total copper (TCu) and total zinc (TZn), total suspended solids (TSS) and faecal indicator bacteria (*E. coli*). In addition, monthly average outputs were evaluated for two contaminants frequently predicted in D grade, to evaluate the sensitivity of findings to the averaging period (e.g., questioning whether the approach used to derive some numeric attribute statistic has marked influence on grading).

FWMT Stage 1 simulates total copper and total zinc, while ROF numeric attributes are for dissolved copper and zinc. To enable application of the ROF guidance to predicted TCu and TZn contaminant concentrations, a region-wide conversion approach was adopted. Utilising SoE observations, the dissolved proportion of TCu and TZn was estimated for each watershed and for the entire region (Figure 2-2). Based on visual inspection showing relatively even distribution of watershed-based ratios about the region-wide ratio, simulated TCu and TZn were corrected by the region-wide factors of 0.676 and 0.688, respectively (blue dotted lines in Figure 2-2), to estimate dissolved copper (DCu) and dissolved zinc (DZn) concentration (e.g., converted flow-weighted average). Whilst the investigation did not determine if seasonal or percentile-based variation in any such dissolved-to-total relationships exist, it represents the simplest defensible approach. Such variation in the relationship of dissolved and total metals is a priority for targeted validation monitoring.

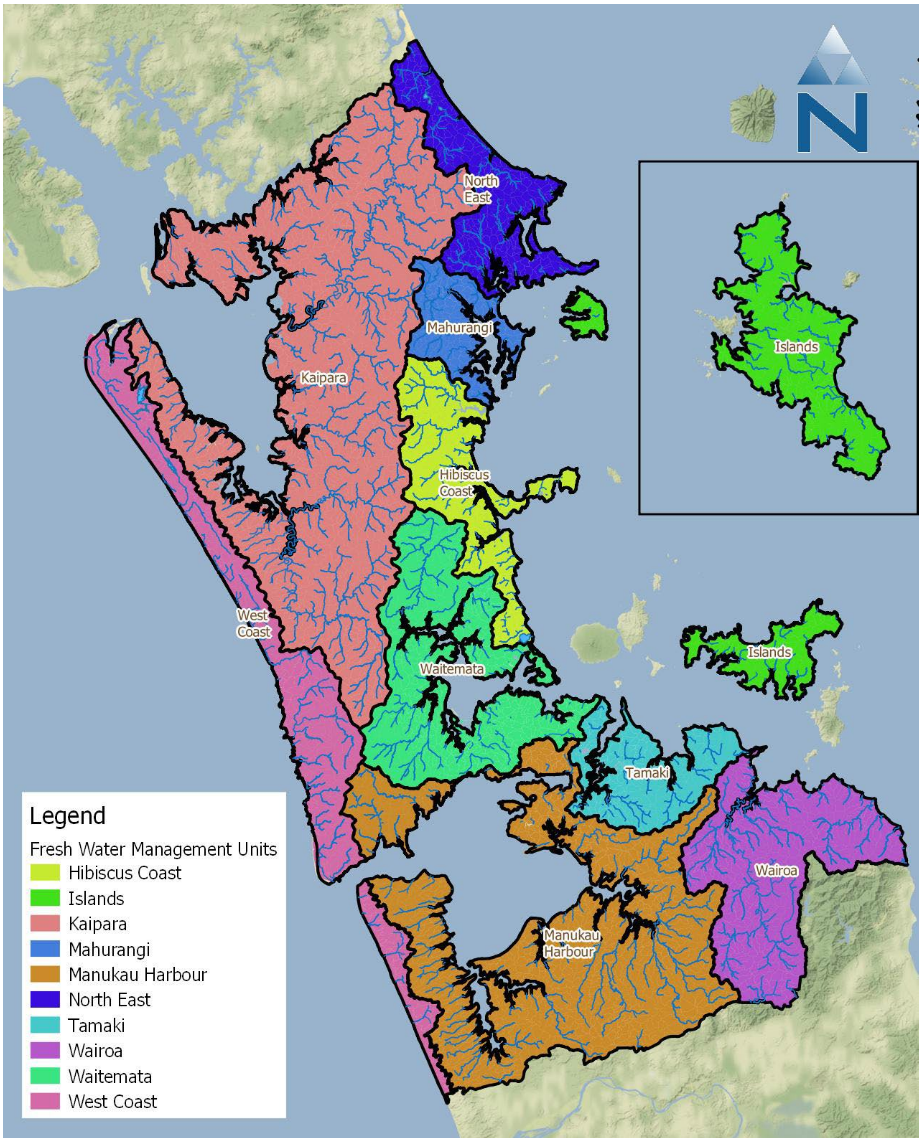


Figure 2-1. Fresh Water Management Tool watersheds and model reach segments (model reach segments shown in blue features)

2.2 Observed Data from SoE Monitoring

Monthly grab sample data from 36 SoE stations were used as the "observed" data component of region-wide grading. A list of the SoE stations and a summary of the observed data available at each station is presented in Table 2-1. (Figure 2-3) shows the SoE station locations and upstream catchment areas. This dataset was obtained directly from Auckland Council and supplemented at two sites with additional data from NIWA (Hoteo, Rangitopuni).

To enable direct comparison of "predicted" and "observed" contaminant grading, simulated data were post-processed as per the [FWMT Baseline Configuration and Calibration Report]. All observed data was utilised in grading, regardless of quality code (<1% flagged as low quality) and transformed as per relevant guidance, notably:

- Observed TAM samples were pH corrected based on paired pH values, when available. Paired pH samples were available for 2,078 of 2,139 samples. If there was no paired pH value, the sample was not used in the analysis.
- Observed DIN was calculated as TON plus TAM. DIN calculations used original TAM values not adjusted for pH. All monthly data contained paired TON and TAM observations.
- Observed soluble phosphorus was used for values of DRP.
- All censored values (concentrations below the detection limit at the time of analysis, which were uncommon) were replaced with ½ the detection limit (data supplied by Research and Evaluation Unit as half-detection – unclear if of consistent or time-varying detection threshold).

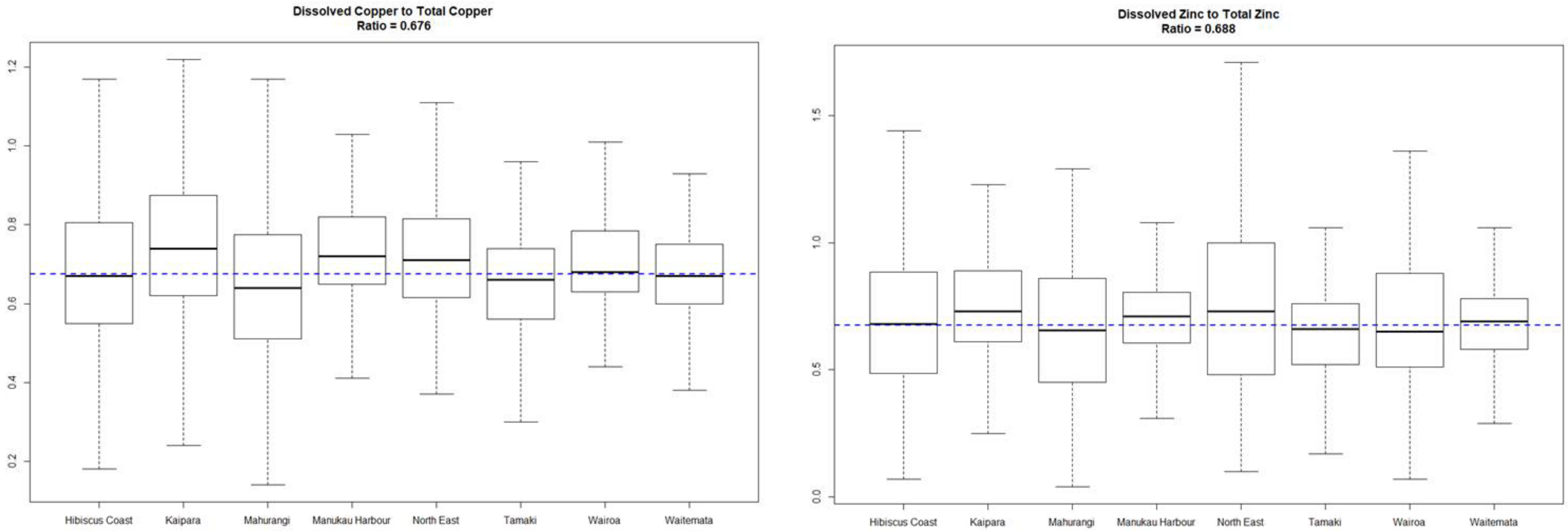


Figure 2-2. Watershed and region-wide (blue line) median ratios for total and dissolved metals

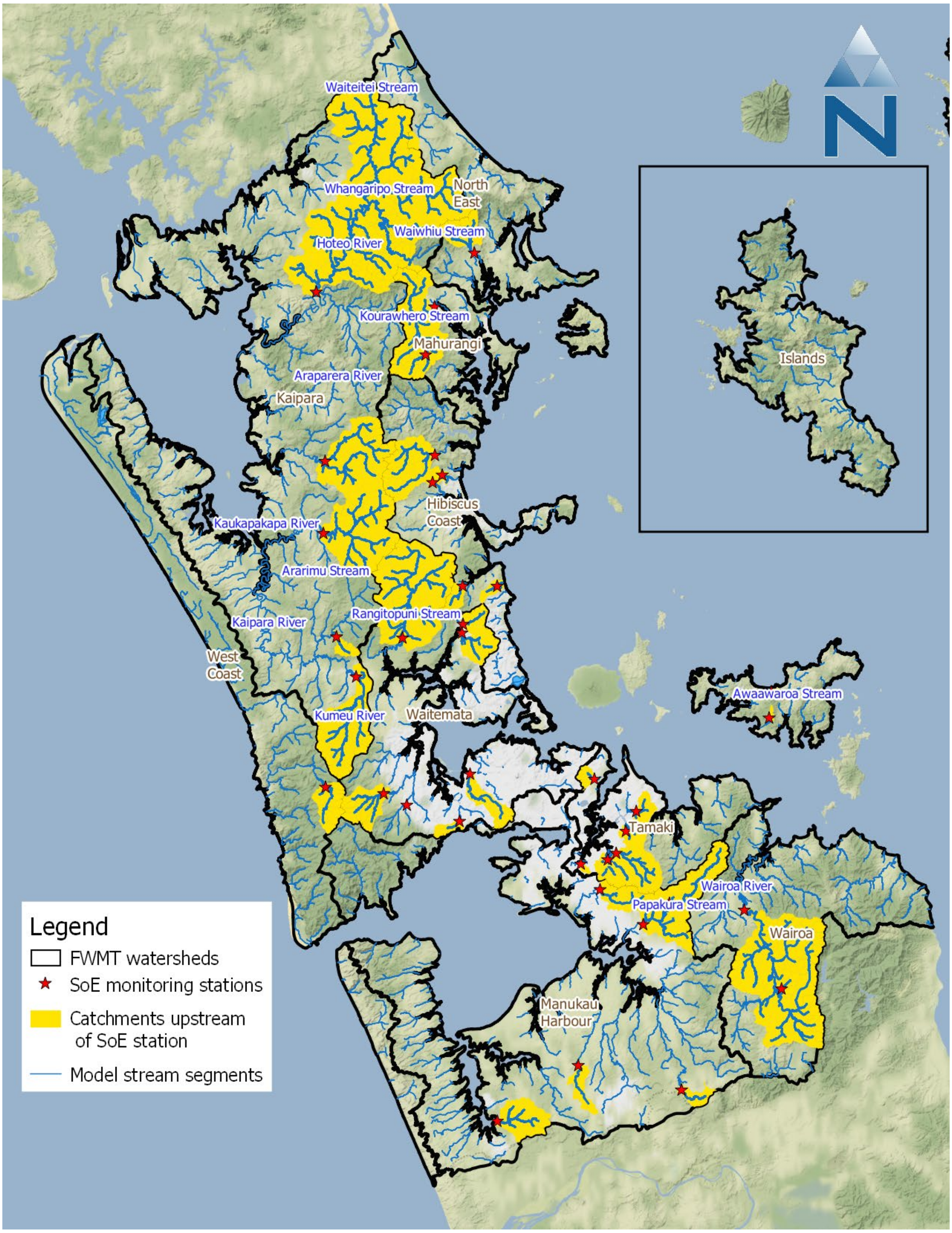


Figure 2-3. Locations of Auckland Council State of Environment (SoE) stream and river water quality monitoring stations. Yellow area indicates associated upstream catchments of SoE stations

For most stations, 60 samples were available, collected monthly for each contaminant for the period 2013-2017 (Table 2-1) – the calculated statistics for those samples were summarised by watershed and for the entire region and compared to the NPS-FM numeric attribute states.

Note that observed TSS cannot be graded for lack of TSS guidance under a ROF or NOF. Grading-based comparison to predicted TSS has not therefore been undertaken here.

The same grading routines were applied to both observed data and predicted outputs. Some adjustments were made to the datasets to achieve equivalent contaminant forms. Figure 2-4 presents a flow chart describing the method for applying adjustments and calculating each set of attribute grades for each of the seven (7) contaminants, at each SoE station or FWMT reach. The NPS-FM numeric attribute states and their grading guidance are described in detail in the sections 2.4 and 2.1.

2.3 Integration of Predicted and Observed Results

In addition to reporting predicted and observed grades separately, bar graphs in this report also present integrated grades. Integrated grading used observed grades from SoE stations instead of the predicted grade when the station was located on a modelled stream reach. The overwriting of predicted with observed grades continued along the reach length until stream order changed (i.e., contending that instream concentrations are expected to vary with stream order). The rationale for including integrated outputs is to ensure a comprehensive assessment of contaminant grading. Appendix I contains further discussion about the integration approach as well as a suite of maps that are based on integrated data.

2.4 Numeric Attribute States and Grades

Attainment of water quality (contaminant) numeric attributes states was assessed using regional and national objective frameworks, developed for *E. coli*, DCu, DZn, total oxidised nitrogen TON, TAM, DIN and DRP, based on the following:

- *E. coli*, TON, and TAM were based on 2020 NPS-FM and NOF (Ministry for the Environment, 2020). NOF guidance for NO3N and NH4N was applied to grade TON and TAM, respectively, as discussed in Section 0.
- Numeric attribute states for DIN and DRP were based on the 2019 draft NPS-FM and NOF (Ministry for the Environment, 2019) applied conservatively, to all FWMT reaches independent of likely substrate type or other controlling factors for eutrophication[3]. Note DRP lacks a national bottom line, albeit with grading A to D as per proposed guidance in 2019 draft NPS-FM.

[3] The NPS-FM (2020) omitted the proposed DIN grading guidance whilst noting its inclusion within 12 months. Reporting of DIN uses proposed NPS-FM (2019) as an indicative grading assessment.

- DCu and DZn were based on an interim regional objective framework developed from ANZECC (2000) and ANZ (2019) toxicity guidance for heavy metals in freshwater (Gadd et al., 2019). The NPS-FM (2017 and proposed draft 2019) both include provisions for relevant regional contaminants to be accounted for and included in objective-setting exercises. Both copper and zinc are elevated in the Auckland urban area and associated receiving environments, with high likelihood of toxicity-based effects on ecosystem health (Mills and Williamson, 2008).

Table 2-1. Auckland Council State of Environment (SoE) stream and river water quality observational records utilised in comparison to FWMT Stage 1 predicted contaminant concentrations. Note that FWMT calibration did not censored values but grading of observational used ½ detection limit

Watershed	Auckland Council SoE Water Quality Stream Station	Approximate Drainage Area (km^2)	Site ID	Start Date	End Date	Observed Sample Count						
						E. coli	Dissolved Copper	Dissolved Zinc	TON	TAM	DIN	DRP
Hibiscus Coast	Nukumea @ Upper	1.0	7171	1/9/2013	12/11/2017	60	60	60	60	60	60	60
	Okura Creek	4.2	7502	1/9/2013	12/11/2017	60	60	60	60	60	60	60
	Vaughn Stream *	2.3	7506	1/9/2013	12/11/2017	60	60	60	60	60	60	60
	Waiwera Stream	30.2	7104	1/8/2013	12/5/2017	60	60	60	60	60	60	60
	West Hoe Stream *	0.5	7206	1/9/2013	12/11/2017	60	--	--	60	60	60	60
Islands	Cascades @ Whakanewha	0.6	74701	2/7/2013	12/13/2017	58	--	--	58	58	58	58
	Onetangi @ Waiheke R	0.7	74401	2/7/2013	12/13/2017	58	--	--	58	58	58	58
Kaipara	Kaukapakapa @Taylors *	61.9	45415	1/8/2013	12/5/2017	45	--	--	45	45	45	45
	Hoteo @ Gubbs	269.7	45703	1/15/2013	9/13/2016	60	--	--	60	60	60	60
	Kumeu River	38.7	45313	1/8/2013	12/5/2017	60	60	60	60	60	60	60
	Makarau @ Railway *	53.7	45505	1/8/2013	12/5/2017	60	60	60	60	60	60	60
	Riverhead Stream	4.6	45373	1/8/2013	12/5/2017	60	60	60	60	60	60	60
Mahurangi	Mahurangi River FHQ	4.9	6811	1/8/2013	12/11/2017	60	60	60	60	60	60	60
	Mahurangi River WS *	46.8	6804	1/8/2013	12/11/2017	60	60	60	60	60	60	60
Manukau Harbour	Ngakaroa Stream *	4.7	43829	1/9/2013	12/6/2017	60	--	--	60	60	60	60
	Papakura @ Alfriston *	51.6	1043837	1/9/2013	12/6/2017	59	58	57	59	59	59	59
	Papakura Stream *	51.6	43856	1/9/2013	12/6/2017	59	60	59	60	60	60	60
	Puhinui Stream *	11.6	43807	1/9/2013	12/6/2017	60	60	59	60	60	60	60
	Waitangi Falls Br. *	17.6	43601	1/9/2013	12/6/2017	60	--	--	60	60	60	60
	Whangamaire Woodhouse	8.0	438100	1/9/2013	12/6/2017	60	--	--	60	60	60	60
North East	Matakana River	13.4	6604	1/8/2013	12/11/2017	60	59	59	60	60	60	60
Tāmaki	Omaru @ Maybury	3.5	8249	1/25/2013	12/21/2017	60	60	60	60	60	60	60
	Otaki Creek	1.0	8219	1/25/2013	12/21/2017	59	59	59	59	59	59	59
	Otara Ck East Tāmaki	29.0	8214	1/25/2013	12/21/2017	60	60	60	60	60	60	60
	Otara Ck Kennel Hill *	18.9	8205	1/25/2013	12/21/2017	60	60	60	60	60	60	60
	Pakuranga Ck Botany	6.6	8217	1/25/2013	12/21/2017	60	60	60	60	60	60	60
	Pakuranga Ck Greenmt	6.6	8215	1/25/2013	12/21/2017	60	60	60	60	60	60	60
Wairoa	Wairoa @ Caitchons	2.5	8568	1/9/2013	12/6/2017	60	--	--	60	60	60	60
	Wairoa River	148.9	8516	1/9/2013	12/6/2017	60	60	59	60	60	60	60
Waitematā	Avondale Stream @ SH	3.5	8019	1/9/2013	12/21/2017	60	60	59	60	60	60	60
	Lucas Creek *	6.3	7830	1/9/2013	12/11/2017	60	60	60	60	60	60	60
	Oakley Creek	12.3	8110	1/9/2013	12/21/2017	60	60	59	60	60	60	60
	Opanuku Stream *	15.9	7904	1/8/2013	12/5/2017	60	--	--	60	60	60	60
	Oteha Stream *	12.2	7811	1/9/2013	12/11/2017	60	60	60	60	60	60	60
	Rangitopuni River *	81.5	7805	7/6/2016	12/5/2017	60	--	--	60	60	60	60
West Coast	Cascade Stream	14.1	44603	1/8/2013	12/5/2017	60	--	--	60	60	60	60

* Approximate drainage area was provided by Auckland Council for co-located flow stations. All other drainage areas based on FWMT model sub-catchments.

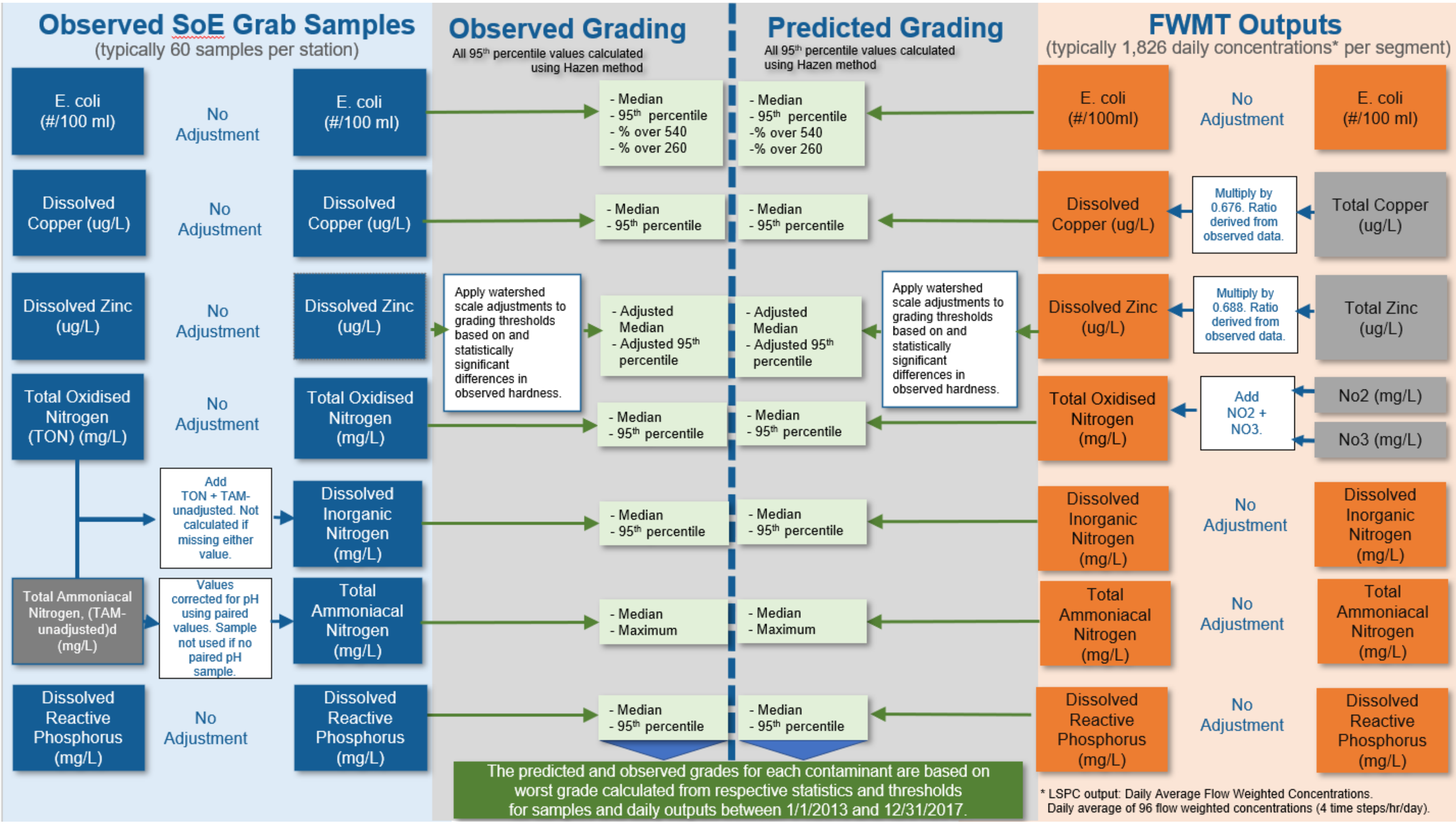


Figure 2-4. Methods for deriving river water quality (contaminant) attribute grades from FWMT LSPC outputs and observed SoE data

Table 2-2 and Table 2-3 present the numeric attribute states and corresponding grades for above contaminants. All contaminants are graded overall, using multiple statistics with the worst attribute measure (statistic) assigning overall grade to FWMT reaches. Statistics and respective thresholds were applied to the entire dataset of observed samples and daily outputs for the period 1/1/2013 to 12/31/2017. All contaminants were assessed using median and the 95^{th}% concentrations (five-year). Additionally, NH4N was assessed using median and maximum concentrations per NPSFM guidance (MoE, 2020) while *E. coli* was assessed using both median and 95^{th}% statistics as well as %> 540 MPN/100ml and % >260 MPN/100 ml (observational data is CFU/100ml which for purposes of report is directly translated to equivalent MPN/100ml). While median and maximum concentrations are suitable for identifying attribute states for NH4N using discrete monitoring data, it may provide an overly conservative assessment when using continuous modelling data. Therefore, NH4N results area presented as the worst of median and maximum concentrations, and when noted, as the worse of median and 95^{th} percentile concentrations. All 95^{th} % calculations were derived with the Hazen method (e.g., as per McBride, 2016). For both modelled and observed results, attribute states are reported for the period 2013-2017.

Observed NH4N compliance thresholds were adjusted by observed pH, in line with NOF guidance (NPSFM, 2020) (e.g., standardised to pH 8 and 20°C). Predicted TAM was not pH or temperature adjusted owing to lack of calibration of latter processes in the FWMT Stage 1 development. The conversion table for calculating thresholds relative to pH 8 is provided in Hickey (2014, Appendix 3). Whereby a ratio relative to pH 8, ranging from 0.2 to 2.6, from alkaline to acidic, respectively, with a ratio of 1.0 at pH = 8, was applied to NH4N samples.

In line with ANZ (2019) numeric attribute states for DZn were adjusted for hardness (Table 2-3) to account for variation in zinc toxicity with availability of divalent cations (calcium and magnesium) (i.e., increasing hardness reduces associated toxicity of equivalent dissolved zinc concentration). Observed DZn were corrected by observed hardness ($CaCO_3$) whilst observed variation in hardness was analysed for watershed-specific differences. As per analysis of variation in dissolved metal proportions, observations were assessed by KW-ANOVA for differences in median hardness (CaCO3 concentration) across the 10 major Auckland watersheds (supplemented by Kruskal-Wallis with pairwise Wilcoxon and simultaneous Tukey contrasts testing). Results demonstrated significant differences in mean hardness across watersheds (KW-ANOVA F 9,305, p<0.05), with post-hoc inspection revealing insignificant variation across eight watersheds; the Tāmaki was significantly harder whilst the Wairoa was significantly softer, than the other watersheds. Figure 2-5 presents boxplots of total hardness as CaCO3 (mg/L) observations by watershed measured between 2018 and 2020 for the river water quality SoE programme (supplied by Research and Evaluation Unit – Auckland Council). A summary of hardness statistics that further describes the information presented in Figure 2-5 is outlined in Table 2-4. The limited length of hardness monitoring meant a conservative approach to hardness-correction was then applied (e.g., in case lesser hardness is common over the five-year grading interval for the FWMT Stage 1). Instead of the regional average, the 25^{th}% hardness value was used for Wairoa and Tāmaki separately, and for the remaining eight watersheds separately. Notably, the 25^{th}% hardness across watersheds excluding the Tāmaki and Wairoa, was 38.3 mg/L $CaCO_3$ which is above the general NOF guidance of 30 g/m^3 and thereby results in DZn concentrations of associated NOF grades A to D that are in excess of defaults. Also in line with Warne et al., (2018), no hardness adjustment was performed for DCu (predicted and observed).

All calculations were performed in R (R Core Team, 2019). R code was also developed for the FWMT to generate output by attribute measure (statistic) and overall, which may be used to update interactive tabular and graphical data to the web. As new attribute state standards are developed or new data become available, the code can be readily updated to re-calculate attribute states and streamline future analyses, ultimately serving as a living tool for freshwater quality (contaminant) accounting as advances in the corresponding NOF or ROF guidance is developed for New Zealand and Auckland.

Table 2-2. Numeric Attribute States for Freshwater Quality (Contaminants) in FWMT reaches used for Stage 1 Baseline State Analysis (excluding dissolved zinc)

Attribute Grade	FRESHWATER CONTAMINANTS CALIBRATED and GRADED IN FWMT STAGE 1											
	E. coli		Dissolved Copper[1] (DCu)		Total Oxidised Nitrogen (NO3N)		Total Ammoniacal Nitrogen[2] (NH4N)		Dissolved Inorganic Nitrogen (DIN)[3]		Dissolved Reactive Phosphorus (DRP)[3]	
	Statistic	MPN/100 mL	Statistic	µg/L	Statistic	mg/L	Statistic	mg/L	Statistic	mg/L	Statistic	mg/L
A	% over 540	< 5 %	Median	≤1	Median	≤1.0	Median	≤0.03	Median	≤0.24	Median	≤0.006
	% over 260	< 20 %										
	Median	≤130	95^{th}%	≤1.4	95^{th}%	≤1.5	Maximum	≤0.05	95^{th}%	≤0.56	95^{th}%	≤0.021
	95^{th}%	≤540										
B	% over 540	5 - 10 %	Median	>1 and ≤1.4	Median	>1.0 and ≤2.4	Median	>0.03 and ≤0.24	Median	>0.24 and ≤0.50	Median	> 0.006 and ≤ 0.010
	% over 260	20 - 30 %										
	Median	≤130	95^{th}%	>1.4 and ≤1.8	95^{th}%	>1.5 and ≤3.5	Maximum	>0.05 and ≤0.40	95^{th}%	>0.56 and ≤ 1.10	95^{th}%	>0.021 and ≤0.030
	95^{th}%	≤1000										
					National or Regional Bottom Line							
C	% over 540	10 - 20 %	Median	>1.4 and ≤2.5	Median	>2.4 and ≤6.9	Median	>0.24 and ≤1.30	Median	>0.5 and ≤ 1.0	Median	>0.010 and ≤ 0.018
	% over 260	20 - 34 %										
	Median	≤130	95^{th}%	>1.8 and ≤4.3	95^{th}%	>3.5 and ≤9.8	Maximum	>0.40 and ≤2.20	95^{th}%	>1.10 and ≤ 2.05	95^{th}%	>0.030 and ≤ 0.054
	95^{th}%	≤1200										
	National or Regional Bottom Line											
D	% over 540	20 - 30 %	Median	>2.5	Median	>6.9	Median	>1.30	Median	>1.0	Median	>0.018
	% over 260	>34 %										
	Median	>130	95^{th}%	>4.3	95^{th}%	>9.8	Maximum	>2.20	95^{th}%	>2.05	95^{th}%	>0.054
	95^{th}%	>1200										
E	% over 540	> 30 %										
	% over 260	> 50 %										
	Median	>260										
	95^{th}%	>1200										
Guidance	NPS-FM (2020)		Warne et al., (2018)		NPS-FM (2020)		NPS-FM (2020)		NPS-FM (2020)		NPS-FM (2020)	

[1]No Dissolved organic carbon adjustments have been made for this analysis.

[2]Attribute states shown are based on pH 8 and temperature of 20° C.

[3]Proposed guidance subject to ongoing review in Essential Freshwater: Healthy Water, fairly allocated (MfE, 2019).

Table 2-3. Numeric Attribute States following hardness-adjustment for Dissolved Zinc (DZn) in FWMT reaches used for Stage 1 Baseline State Analysis

Attribute Grade	Dissolved Zinc[1]							
	Default Hardness = 30mg/L		Regional Hardness = 38.30 mg/L		Tāmaki Hardness = 64.40 mg/L		Wairoa Hardness = 19.20 mg/L	
	Statistic	Value (ug/L)	Statistic	Value (ug/L)	Statistic	Value (ug/L)	Statistic	Value (ug/L)
A	Median	≤2.4	Median	≤ 2.9	Median	≤4.6	Median	≤1.7
	95th%	≤8	95th%	≤ 9.6	95th%	≤15.2	95th%	≤5.6
B	Median	>2.4 and ≤8	Annual Median	> 2.9 and ≤ 9.6	Median	>4.6 and ≤15.2	Median	>1.7 and ≤5.6
	95th%	>8 and ≤15	95th%	> 9.6 and ≤ 18.0	95th%	>15.2 and ≤28.5	95th%	>5.6 and ≤10.5
C	Median	>8 and ≤31	Median	> 9.6 and ≤ 37.2	Median	>15.2 and ≤58.9	Median	>5.6 and ≤21.7
	95th%	>15 and ≤42	95th%	> 18.0 and ≤ 50.4	95th%	>30.0 and ≤79.8	95th%	>10.5 and ≤29.4
Regional Bottom Line								
D	Median	>31	Median	> 37.2	Median	>58.9	Median	>21.7
	95th%	>42	95th%	> 50.4	95th%	>79.8	95th%	>29.4
Hardness multiplier ANZ (2019)[2]	1.0		1.2		1.9		0.7	

[1]No Dissolved Organic Carbon or pH adjustments have been made for zinc.

[2]Hardness-dependent algorithms applied for zinc: HMTV = TV (H/30)^0.85 (ANZ, 2019)

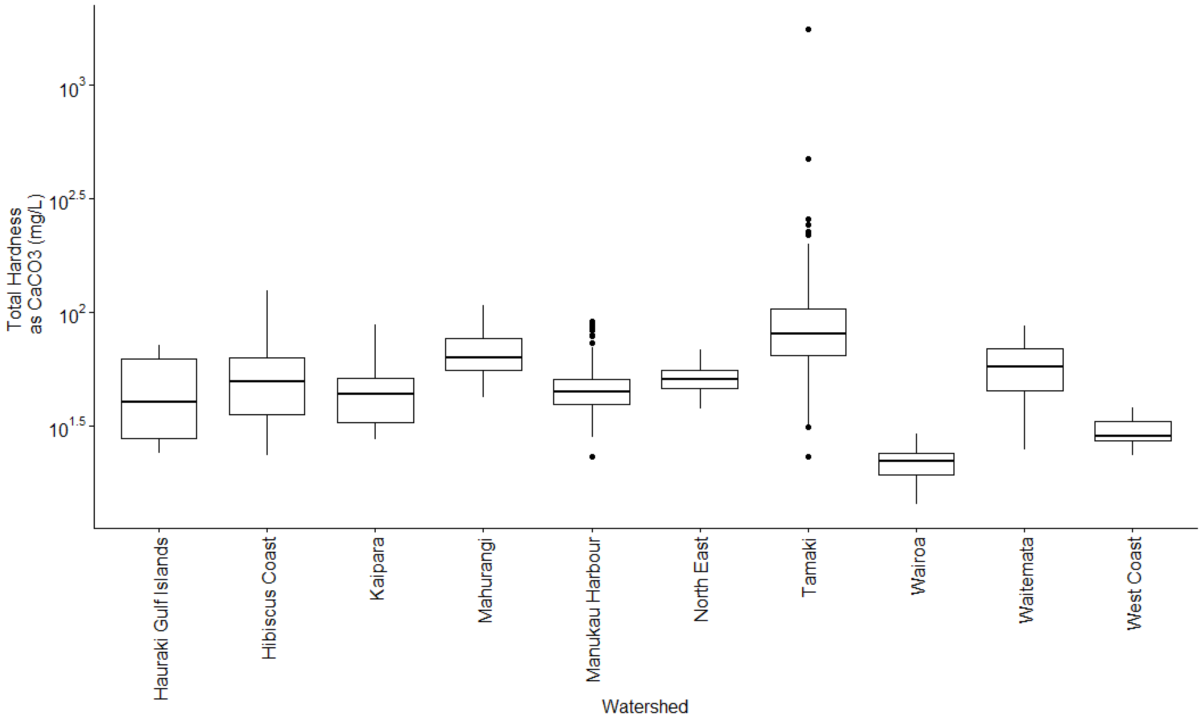


Figure 2-5. Boxplots of observed hardness (CaCO3 mg/L) across 36 Auckland river water quality SoE stations (2018-2010)

Table 2-4. Hardness (CaCO3 mg/L) observed at Auckland river water quality SoE stations across the 10 major watersheds in Auckland (2018-2020)

Watershed	Median Statistically Different from Other Sites[1]	Sample Count[2]	Hardness as CaCO3 Statistics Measured at SoE River Stations in the Watershed (mg/L)						
			10th %ile	25th %ile	Mean	Median	75th %ile	90th %ile	95th %ile
West Coast	No	16	25.8	27.20	29.8	28.3	33.1	34.4	35.4
North East	No	17	40.4	46.00	50.5	50.4	55.2	58.3	61.8
Mahurangi	No	34	46	55.40	66.2	63.3	76.6	84.6	98
Wairoa	Yes	34	17.9	19.20	21.6	22	23.9	25.2	27.2
Islands	No	35	25.3	27.7	44.6	40.9	62.1	69.7	70.9
Kaipara	No	64	31.6	32.7	43.5	43.4	51.2	56	63.7
Hibiscus Coast	No	80	28.5	35.2	52.8	49.3	63.2	84.3	89.8
Waitematā	No	116	30.3	45.1	55.9	57.7	68.7	75.4	82.6
Manukau Harbour	No	118	35.1	39.4	48.7	44.8	50.3	78.7	88.1
Tāmaki	Yes	180	43.3	64.40	100.0	80.3	104	143	192
All	**---**	**694**	28.1	**38.30**	62.1	52.2	70.6	91.4	119

Notes:

These site-specific hardness values were applied to calculate site-specific zinc numeric attribute states for all segments within the associated watersheds, using the equations in Table 3.4.3 in ANZECC, 2000. For all other segments / watersheds, the regional 25th percentile hardness was applied (bolded value in 'ALL' row).

1: Based on Kruskal-Wallis, One-Way ANOVA, Pairwise Wilcoxon, and a Simultaneous Tukey Contrasts test at p-value <0.01

2: Initial hardness statistics based on limited sample counts; these hardness assumptions may be updated as additional data are collected.

2.5 Grading Accuracy

The continuous accuracy of the FWMT Stage 1 has been reported in the [FWMT Baseline Configuration and Calibration Report] (e.g., NSE, r^2, PBias of all and subsets of flow and season). However, an important application of the FWMT is to support grading-based decision-making. Prior continuous water quality catchment modelling in the Bay of Plenty (Loft et al., in prep) and Greater Wellington regions (Blyth et al., 2018; Easton et al., 2019) have reported on continuous accuracy (e.g., PBias). However, the latter have not attempted to report on grading-based accuracy (i.e., the ability to correctly predict observed grading, including failures of national bottom-lines).

Grading accuracy is an important measure of the FWMT Stage 1 performance, linked to grading outputs, and distinct from more continuous measures of accuracy. Grading accuracy is strongly aligned to objective and grading-based decisions expected under the NPS-FM. Such approaches are already widely practised in public health environmental modelling, where modelling performance is linked to determining true positives (failing grades, precautionary reporting) and true negatives (passing grades, permissive reporting) (e.g., Nevers et al., 2013; Thoe et al., 2015).

To report on grading accuracy, three complementary approaches have been undertaken for the FWMT Stage 1, across the seven water quality (contaminant) attributes with freshwater ROF or NOF grading guidance, including:

1. Reporting equivalent grades as those exactly alike (e.g., predicted B = observed B);
2. Reporting equivalent grades as those within one grade of observed (e.g., predicted A, B, C = observed B);
3. Reporting equivalent grades as those within an absolute range in median or 95^{th}% of observed statistic. Ranges were derived as the average of upper and lower concentrations of A and B grades (applied to observed A and B graded stations) or the range in median or 95^{th}% of C grades (applied to observed C and D graded stations). The choice to utilise an average of range in A and B graded medians, to develop a buffer applied to a corresponding A or B-graded station median, was made to account for the inconsistent and non-increasing range of medians with decreasing grade. For instance, that the range in median DCu for A band is 0-1 ug/L, resulting in a range of 1 ug/L buffer on observed A-graded median DCu concentrations. Whereas the corresponding range in median DCu for B-graded stations is 1-1.4, resulting in a range of 0.4 ug/L. Few attributes have a consistently increasing range between A, B and C grades, and aside from *E. coli*, no attributes include a lower limit for D-graded median or 95^{th}% concentration. For *E. coli* the D-graded range width in median, 95^{th}%, %>540 MPN/100ml and >260 MPN/100ml was also generally

of minor change with no maxima for corresponding statistics in E grade. So, the range in *E. coli* measures for the C grade was applied to both D and E graded observed statistics. The corresponding ranges in numeric attribute states, for each of the seven graded contaminants is presented in Table 2-5.

The three grading accuracy approaches offer complementary but varying assessment of FWMT Stage 1 performance: (1) being most conservative, (2) being least conservative and (3) being moderately conservative. All three are potentially valid assessments of grading performance, with the first failing to account for minor absolute (concentration) error about sites near the grading thresholds amounting to entire grade differences, the second being overly generous if later optimisation and use of baseline outputs is to assess a particular grade, and the third offering benefits over the first in terms of applying grading-based buffers to any observed concentration. Equally, in all three approaches a monthly discrete (non-integrated or event-sampled) observation over five years (*n* = 60 samples), is compared to the continuously-simulated daily flow-weighted concentration (and numeric attribute states) from FWMT Stage 1 (*n* = 1,826 predictions). The likelihood of the two agreeing is unknown in the absence of detailed continuous sampling and power-analysis for each numeric attribute states, which has not been conducted for NOF attributes in any Auckland streams to date (e.g., the comparison will reveal differences, but not which is the more accurate estimate of grade).

Table 2-5. Ranges in median or 95th% applied defining "equivalent" grade from approach (3) above (also including %>540 MPN/100ml and %>260 MPN/100ml for *E. coli*). Values represent the range in corresponding median or 95th% within which predicted median or 95th% are a grade's distance from observed

Grading Measure		*E. coli*	DRP	DIN	NO3N	NH4N	Cu	Zn Region	Zn Tāmaki	Zn Wairoa
Median	A or B	130	0.005	0.25	1.2	0.12	0.7	4.8	7.6	2.8
	C, D or E	130	0.008	0.5	4.5	1.06	1.1	27.6	43.7	16.1
95th%	A or B	500	0.015	0.55	1.75	0.2	0.9	9	14.25	5.25
	C, D or E	500	0.024	0.95	6.3	1.8	2.5	32.4	51.3	18.9

The three approaches to assessing grading accuracy were applied both for median and 95th % grades. Additional analysis investigated "fail" grades (e.g., exceedances of national or regional bottom-lines; "D" and "E" grades) as well as "all" grades (e.g., "A" through to "E" grades) for the first two approaches. To align with grading output, grading accuracy was assessed for the period 2013-2017, utilising the corresponding attribute numeric grades and overall grades of the five-year period (e.g., five-year median).

2.6 Source Apportionment Methods

The FWMT Stage 1 simulates process-based responses of contaminants to land use and climate, linking responses to overlying land surface or HRU types. Contaminants from up to 106 HRUs are accounted for as yields, region-wide in all 5,465 sub-catchments, with the ability to source-apportion corresponding instream loads of contaminants at the 2,761 sub-catchments with FWMT reaches. Processes simulated include both within HRU and instream, enabling loading at "edge-of-stream" and subsequently, "instream" to be delivered – the latter at any of the 2,761 reporting nodes within the FWMT reach network. Collectively, the process-basis and high resolution of spatial information across Auckland, enable the FWMT Stage 1 to account from sub-catchment to FMU for both water quality (contaminant) state and sources of loading, for all contaminants listed in Section 2.4 (including the addition of TSS otherwise unable to be graded by NOF or ROF). All source outputs are based on the total load simulated by FWMT over the five-year period 2013-2017 (i.e., all loads from each daily time step are summed to provide a five-year total discharge). Notably, source-apportionment of total copper and total zinc is equivalent to that for dissolved copper and dissolved zinc (i.e., due to consistent region-wide dissolved proportional factors being applied to TCu and TZn).

The source apportionment included summarising contaminant load from multiple contaminant delivery pathways in the FWMT Stage 1, including: (1) simulated land runoff, interflow and active groundwater (2) point sources including WWTP discharges and engineered overflow points parametrised with typical residential and industrial concentrations, however, point sources do not include industrial effluent or rural production discharges such as those from greenhouses and dairy farms that discharge directly to stream, and (3) bank erosion (combination of stream scour on FWMT reaches and gully erosion of HRUs to represent the 85% of permanent and intermittent streams not directly simulated). While the FWMT represents 106 unique land types, these were regrouped into 19 broader source categories (land uses) for bar graphs and 10 broader still source super-categories for pie charts. Simplification of the categories was necessary to provide an easier method of interpreting the results (see Appendix H for further information on amalgamation of HRUs into categories and super-categories for reporting purposes).

Source loads were estimated as both, delivered to:

- **Edge-of-Stream (EOS)** – the loading generated from the land-based processes in LSPC via runoff, interflow and active groundwater (e.g., exclusive of instream attenuation). This approach is used for summarising loads from entire watersheds which may have multiple terminal nodes, distributed at varying distances upstream (and subject to varying instream attenuation). EOS loads represent a standardised assessment of contaminant effect on immediate freshwater receiving streams in Auckland.

- **Instream (IS)** – the loading at any instream point accounting for sediment resuspension and settling, and instream nutrient transformation processes (e.g., ammonification, nitrification, denitrification and DRP-desorption). IS hereafter refers explicitly to loads at all terminal nodes in the FWMT but are otherwise available for all FWMT reaches (e.g., 2,761 locations upstream as well as terminal reaches at coast).

The length of a river segment, presence of impoundments, or special features, such as withdrawals affect contaminant attenuation by the routing network and vary the source apportionment of EOS through to IS loading. The proportion of EOS loading transformed to IS (delivered to coast via streams) is expressed as a delivery ratio (DRAT) of flow and/or contaminant load from an upstream source to a downstream assessment point. Sub-catchments that drain directly to the coast and do not have a modelled stream segment have a DRAT of 1.0 indicating no transformations occur and the entire load is conveyed to the sub-catchment outlet. The conceptual model for calculating the DRAT involves a recursive trace through the FWMT reach network. This is analogous to a tracer model where a drop of water or a pollutant particle is followed from its origin, along its entire travel path, to the outlet. For the FWMT, the following assumptions apply:

1. Each reach segment is modelled as a completely mixed tank reactor.
2. Upstream, point source, and land-based nonpoint source inflows to any given reach segment mix equally and completely within that reach segment.
3. All outflows, withdrawals, or diversions from a given reach segment are proportional to inflows to that segment—outflow water quality concentrations are equal to the completely-mixed instream concentrations.
4. Sediment-associated pollutants will mimic the fate and transport behaviour of sediment.

Based on these assumptions, the DRAT for a reach segment *N* can be calculated (in isolation of all other segments) using a mass balance relationship of inflows and outflows to that reach only. Figure 2-6 provides an illustration of this calculation for a small, hypothetical stream network. Through the assumed complete mixing, the ratio of outflows exiting the reach segment to inflows applies proportionally to all sources entering the reach segment.

Totals (i.e., total nitrogen, total phosphorous, etc.) are presented for both EOS and delivered loads, as opposed to the individual species discussed in other sections of this report. Only totals are reported for source apportionment as EOS loads were simulated in LSPC as totals for metals, nutrients, and sediment. Once these totals enter the stream network, they become completely mixed whereby they are then subject to various processes and transformations. Source apportionment therefore relies on tracing delivered contaminant loads back to the land using the form in which they were generated. Additionally, some post-processing was required (Figure 2-4) in order to perform gradings analysis for certain contaminants like metals by translating totals from the FWMT to dissolved.

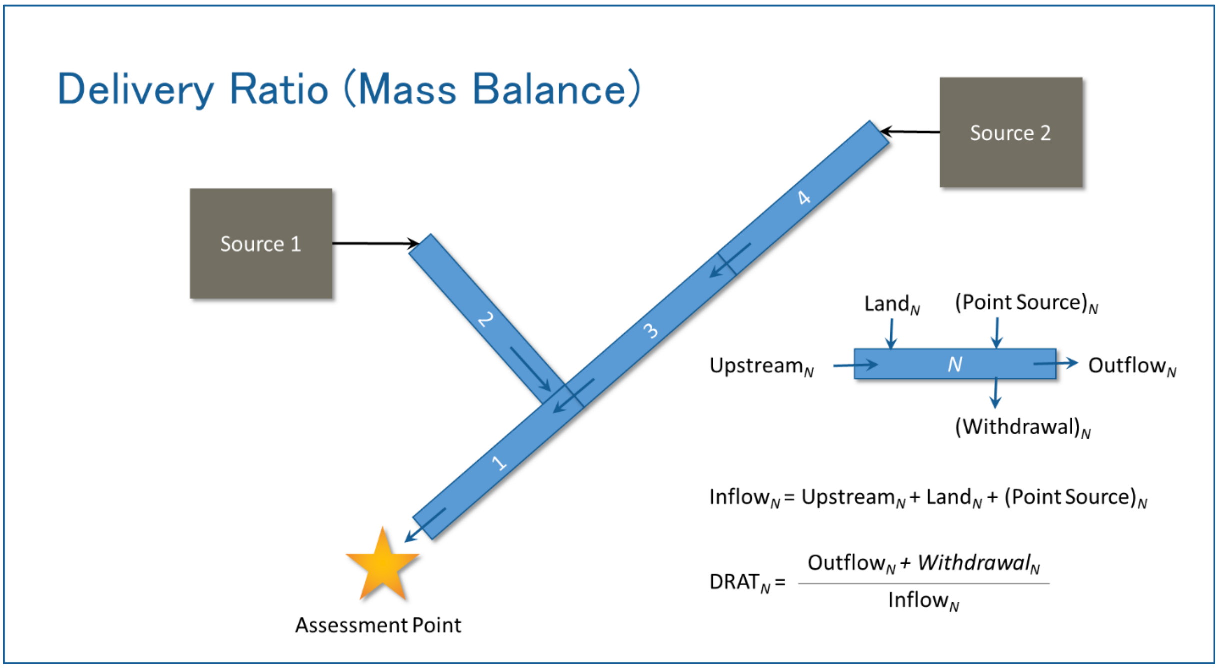


Figure 2-6. Delivery ratio (DRAT) mass balance calculations for segment *N* in a reach-routing network

3.0 Results and Discussion

This report presents the first comprehensive, region-wide assessment of water quality (contaminant) conditions throughout the Auckland region for 3,085 km of stream network and from 489,000 ha of land parcels. It is intended to be used alongside monitoring reports for SoE stations to ensure an integrated assessment of water quality with benefits and limitations of both predicted and observed datasets for assessing region-wide spread in baseline state. This report also presents the most comprehensive and first process-based assessment of the sources for water quality contaminants region-wide to streams and the coast.

Results are organised for regional and watershed scale here, but available from the FWMT Stage 1 to sub-catchment (e.g., for 5,465 sub-catchments and 2,761 FWMT reaches in Auckland). Results are presented in several formats, enabled by the process-based and continuous simulation capability of the FWMT (e.g., LSPC).

Results are presented for:

- Baseline state (2013-2017) as the proportion of streams or stations by grade, including (Section 3.1 and 3.2):
    - Graphical attribute state bar chart outputs that summarise the proportion of model stream segments and observed SoE stations achieving each grade by watershed and region-wide (presented in subsections below);
    - Attribute state maps to show the grading of each model stream segment for contaminants and areas that are upstream of stream segments with failing grades, for each of the 10 major watersheds (Appendix A);
    - Radar attribute plots that summarise the proportion of model stream segments attaining A or B grades in each major watershed and region-wide (Appendix A) – the choice of A and B grades reflects decreasing continuous accuracy with decreasing concentration (i.e., lesser ability to distinguish A from B than from C and D – but see Section 3.1 for grading accuracy results).
    - Attribute maps that combine attributes by value (e.g., ecosystem health, human health), presenting the poorest grade for each stream segment among DIN, DRP, DCu, DZn, TON and TAM, or *E. coli*, for each of the 10 major watersheds (next section and Appendix B)
    - Attribute state maps that show the grading by sub-catchment, including those that lack modelled stream features (Appendix C)

  - Numeric attribute boxplots (e.g., median versus 95th percentile, daily versus monthly averaging period), highlighting conditions driving non-attainment for contaminants (presented in subsections below)
- Baseline load source apportionment (2013-2017) including of EOS and IS loads, to identify the sources and processes responsible for contaminant generation (e.g., by HRU and pathway) (Section 3.3), including:
  - Heat maps of EOS and IS contaminant yields region-wide (Appendix D)
  - Summary tables of EOS and IS contaminant loads for the outlets of approximately 50 regionally relevant streams (i.e., those of size, location or ongoing investment interest to Healthy Waters) (Appendix E)
  - Pie charts for EOS and IS contaminant loads region-wide and for each of the 10 watersheds (Appendix F1 through F6). Repeated for the 50 regionally relevant streams in (Appendix G1 through G6)

The following subsections present grading accuracy results region-wide for ecosystem health and human health (Section 3.1), grading summary output (Section 3.2), grading contaminant output (Section 3.3) and finally source apportionment output (Section 3.4).

Note all grading summaries are for instream freshwater quality – assessment here relies on national or regional guidance of contaminant effects on the immediate freshwater receiving environment *only*. There is *no assessment of contaminant loading effects on estuarine or coastal receiving environments*. Although that is readily supported by the FWMT Stage 1 through its capability to simulate contaminant loads discharged to coastal receiving waterways of nutrients (total, dissolved), heavy metals (Cu, Zn), sediment (TSS) and *E. coli*.

3.1 Grading Accuracy

Contaminant grading predictive performance is presented for the three approaches applied to FWMT Stage 1, in Table 3-1 to Table 3-3. Additional analyses presenting the distribution of satisfactory and unsatisfactory grading using pairwise comparisons of observed and predicted grades is found in Appendix K. As before, Approach 1 is most conservative, Approach 2 most permissive and Approach 3 is balanced. None of the three is without limitations, the first penalises stations predictions at the threshold of grade changes, the second rewards stations poorly predicted at opposite ends of two grading bands and the third applies an absolute buffer to a station but that NOF thresholds do not consistently increase in width with grading (e.g., the range of median concentrations in A band are not necessarily less than those in B) thereby favouring attributes with broader band ranges. Similarly, the approaches all suffer the same limitation in that they are comparing monthly grab-samples with continuously predicted output (e.g., comparing observed on 60 days to predicted flow-weighted concentrations from 1,826 days; 2013-2017). Predicted grades might well be more strongly influenced by concentrations not sampled by the SoE monthly monitoring programmes leading to “state switching” or apparent differences in grading and “poorer” model performance due to inaccurate grade estimates from too limited a sampling programme (e.g., see McBride, 2016 for more commentary).

Table 3-1. Approach 1 – Region-wide grading performance assessment for 36 SoE river stations in Auckland, predicted at grade of observed (2013-2017)

	% of SoE Stations with FWMT-Predicted Grade of Adjacent Segment Equal to Observed Grade*							
	Human Health	Ecosystem Health						
	E. coli	Dissolved Reactive Phosphorus	Dissolved Inorganic Nitrogen	Total Oxidised Nitrogen	Total Ammoniacal Nitrogen		Dissolved Copper	Dissolved Zinc
					Median and 95th	Median and Max		
All grades (overall)	**86.1% (31/36)**	**27.8% (10/36)**	**55.6% (20/36)**	**77.8% (28/36)**	**22.2% (8/36)**	**27.8% (10/36)**	25.0% (6/24)	75.0% (18/24)
Pass Grades (overall)**	**16.7% (1/6)**	**16.0% (4/25)**	**51.7% (15/29)**	**76.5% (26/34)**	**24.2% (8/33)**	**25.7% (9/35)**	25.0% (6/24)	75.0% (15/20)
Fail Grades* (overall)**	**100.0% (30/30)**	**54.5% (6/11)**	**71.4% (5/7)**	**100.0% (2/2)**	**NA (0/3)**	**100.0% (1/1)**	NA (0/0)	75.0% (3/4)
All grades (median)	44.4% (16/36)	50.0% (18/36)	69.4% (25/36)	97.2% (35/36)	91.7% (33/36)	**91.7% (33/36)**	58.3% (14/24)	45.8% (11/24)
All grades (95th%)	86.1% (31/36)	25.0% (9/36)	52.8% (19/36)	77.8% (28/36)	22.2% (8/36)		25.0% (6/24)	75.0% (18/24)
All grades (Max)						27.8% (10/36)		

*At grade is based on adjacent FWMT reach. **Limited to stations observed in A, B or C grade, for TAM and TON, only grade A or B. *** Limited to stations observed in D grade and predicted in D grade (for *E. coli* the number of stations observed in D or E grade and predicted in D or E grade. For TAM and TON, number of stations observed in C or D grade and predicted in C or D grade).

Table 3-2. Approach 2 – Region-wide grading performance assessment for 36 SoE river stations in Auckland, predicted within a grade of observed (2013-2017)

Grade Type	% of SoE Stations with FWMT-Predicted Grade of Adjacent Segment within 1 Grade of Observed Grade*							
	Human Health	Ecosystem Health						
	E. coli	Dissolved Reactive Phosphorus	Dissolved Inorganic Nitrogen	Total Oxidised Nitrogen	Total Ammoniacal Nitrogen		Dissolved Copper	Dissolved Zinc
					Median and 95th	Median and Max		
All grades (overall)	**86.1% (31/36)**	**94.4% (34/36)**	**86.1% (31/36)**	**100.0% (36/36)**	**86.1% (31/36)**	**66.7% (24/36)**	**70.8% (17/24)**	**95.8% (23/24)**
Fail Grades**	**100% (30/30)**	**91% (10/11)**	**100% (7/7)**	**100% (2/2)**	**66.7% (2/3)**	**50% (3/6)**	**NA (0/0)**	**100% (4/4)**
All grades (median)	77.8% (28/36)	86.1% (31/36)	83.3% (30/36)	100.0% (36/36)	100.0% (36/36)	100.0% (36/36)	87.5% (21/24)	87.5% (21/24)
All grades (95th%)	86.1% (31/36)	52.8% (19/36)	86.1% (31/36)	100.0% (36/36)	86.1% (31/36)	66.7% (24/36)	70.8% (17/24)	91.7% (22/24)

*Within a grade is based on adjacent FWMT reach. **Limited to stations observed in D grade and predicted in C or D grades (for *E. coli* the number of stations observed in D or E grade and predicted in D or E grade. For TAM and TON, number of stations observed in C or D grade and predicted in C or D grade).).

Table 3-3. Approach 3 – Region-wide grading performance assessment for 36 SoE river stations in Auckland, predicted within grade-based absolute range of observed (2013-2017)

Grade Type	% of SoE Stations with FWMT-Predicted Concentration within Satisfactory Concentration Range*						
	Human Health	Ecosystem Health					
	E. coli	Dissolved Reactive Phosphorus	Dissolved Inorganic Nitrogen	Total Oxidised Nitrogen	Total Ammoniacal Nitrogen	Dissolved Copper	Dissolved Zinc
Median grades	55.6% (20/36)	69.4% (25/36)	77.8% (28/36)	100.0% (36/36)	97.2% (35/36)	75.0% (18/24)	91.7% (22/24)
95th Percentile Grades	25.0% (9/36)	30.6% (11/36)	72.2% (26/36)	100.0% (36/36)	77.8% (28/36)	50.0% (12/24)	75.0% (18/24)
Maximum Grades					41.7% (15/36)		

*Within concentration range is based on adjacent FWMT reach and Table 2-2 and Table 2-3 **Limited to stations observed in D grade and predicted in D grade (and for *E. coli* the number of stations observed in E grade and predicted in E grade).

Under Approach 2, 67-100% of “all grades” (A through to E) across all seven graded attributes (*E. coli*, DRP, DIN, TON, TAM, DCu, DZn) are correctly graded to within an additional grade of observed (using overall grades, or worst of numeric attribute states). Under Approach 1, the equivalent correctly graded range is 25-86.1%.

Grading performance can also be assessed individually for each numeric attribute state at all 36 river SoE stations and for “all” grades. The range of “all” correctly graded medians for the seven contaminants (in which we can have greater confidence of 60 observations accurately representing true variation) is, 44-97% under Approach 1, 78%-100% under Approach 2 and 56-100% under Approach 3. The corresponding ranges of 95^{th}% correctly graded is 25-86% under Approach 1, 53-100% under Approach 2 and 25-100% under Approach 3. Clearly, grading performance appears better for more central (median) than extreme statistics (95^{th}%), as one would expect of any model whether empirical or process-based (i.e., the ability to accurately estimate any extreme for which absolute fewer observations are available must necessarily be reduced). Note that attribute state assessments previously are across “all” grades, with 95^{th}% numeric attribute grading performance nearer to overall grading performance indicating most attributes are better-graded for median contaminant conditions.

Whilst Approach 3 generally is arguably a fairer test for modelled grading performance (e.g., accounts for SoE stations being observed at the margins of grade thresholds without penalising minor absolute errors resulting in grade differences), the absolute range of either median or 95^{th}% *E. coli* concentrations is modest for “failing” sites – being based on the range permitted in C-grade for both numeric attributes. Whereas under the most conservative Approach 1, a predicted grade must simply be in “D” or “E” grade with much large ranges in corresponding numeric attribute states.

This is a peculiarity of the *E. coli* attribute guidance for which an additional failing grade exists and means that *E. coli* 95th% numeric attribute state is assessed to perform worst under Approach 3. In all other numeric attribute states for all seven contaminants, Approach 1 consistently offers the most conservative grading performance assessment (e.g., worse or equivalent to Approach 2 and 3).

Examination of individual contaminants reveals exceptional performance under Approach 2, at predicting “all” TON (100%), DZn (96%), DRP (94%), *E. coli* (86%) and DIN (86%) gradings (numbers in parentheses indicating correctly predicted per cent of SoE stations for 2013-2017 overall grade). Both DCu (71%) and TAM (67%) are still correctly predicted within a grade at more than two thirds of SoE stations. Approach 1 offers a more conservative assessment but continues to highlight that *E. coli* (86%), TON (78%) and DZn (75%) are predicted correctly (at exactly alike grade) in more than three quarters of SoE stations. Hence, confidence in predicting "all" grades is better for the likes of human health, nitrogen toxicity and zinc toxicity than eutrophication and copper toxicity[4].

Similar attribute-specific findings occur for "failing" as per "all" grades, albeit FWMT Stage 1 simulations performing better for excessively-degraded than all conditions. For instance, under Approach 2 all exceedances of national and regional bottom lines (proposed or operative) in *E. coli*, DIN, TON, TAM and DZn were predicted within a grade – for DRP, 91% of D-graded SoE stations were predicted within either "C" or "D" grade (note: there were no observed SoE stations failing proposed DCu bottom lines). Under Approach 2, all exceedances of *E. coli*, TON and TAM, and two thirds or more of DZn (75%) and DIN (71%) failing stations, were predicted exactly as such. Only failures of DRP proposed national bottom lines proved challenging to predict exactly alike; six failing SoE stations were predicted in D grade and a further four were predicted in C grade.

Combined, the performance assessment results indicate the FWMT Stage 1 can offer *reasonable assurance*[5] to Auckland Council of failing overall contaminant grades across *E. coli*, DRP, DIN, TON, TAM, DCu and DZn. Whereas, all overall grades are predicted with lesser accuracy in all contaminants, more so under Approach 1 (e.g., for exactly alike grading purpose). Notably, overall grading is governed predominantly by more extreme percentile statistics ($95^{th}\%$, maximum), with better overall grading generally predicted and observed for median numeric attribute state. This limits findings about the performance of FWMT Stage 1 because of marked differences in the resolution of observed and simulated time series (n = 60, 1825 respectively). It is strongly recommended that further development of the FWMT is underpinned by equivalently resolved observational datasets (e.g., continuous or integrated observational data available for daily or greater period).

3.2 Region-wide Grading Summary

The grading process resulted in three sources of water quality state information for the baseline period (2013-2017): observed, predicted, and integrated grading (integrated where observed and predicted outputs have been combined – see Appendix I for methodology and outputs using FWMT reach order based

[4] Acknowledging the SoE river network is heavily biased to urban locations for monitoring heavy metals and that such inferences do not account for SoE stations being biased to only some rather than representative of all grades (e.g., SoE observed TON grades are heavily weighted to A and *E. coli* grades to E).

[5] Reasonable assurance is used by the US Environmental Protection Agency (USEPA) to assess predictive model performance and confidence in modelled outputs, whether numeric or narrative, for intended purposes – with the FWMT Stage 1 purpose in baseline state assessment being principally for grading and especially identification of unacceptably degraded water quality (e.g., failing grades in the absence of more detailed understanding of community requirements for better than C graded outcomes across Auckland streams). See EPA (2017) for further description but in keeping with the USEPA's development of LSPC and SUSTAIN, the FWMT performance will be linked to mature understandings of model accounting frameworks for regulatory purposes in the US for the Clean Water Act. The assessment here by considering numerous factors governing grading output, at regional scale in-line with intended FWMT Stage 1 application, and across continuous conditions linked to stormwater improvement goals meets the recommended methodology for assigning reasonable assurance (e.g., variation between numeric attribute states, across contaminants, multiple performance measures and multiple performance assessment approaches).

replacement of modelled with monitoring based grades). All three grading outputs are presented in this section region-wide for the seven attributes graded by the FWMT Stage 1. The subsequent sections present predicted results by contaminant for the 10 major watersheds.

Figure 3-1 summarises the region-wide attribute grading based on predicted, observed and integrated datasets for 2013-2017. The Predicted and Integrated summaries are based on total model stream length assigned to each grade while the observed summaries are based on number of SoE stations.

A summary of grading outcomes for each contaminant is presented below (Figure 3-1):

- *E. coli* recorded the highest percentage of stations failing national targets (applied conservatively to all SoE stations and modelled reaches) amongst contaminants assessed here. Approximately 17% of SoE Stations and modelled reaches were reported in A, B or C grade for *E. coli* over the baseline period (i.e., compared to a national target of 90% by 2040). The prevalence of failing grades is high across most watersheds. Both West Coast and Hauraki Gulf Island watersheds possess better human health (*E. coli*) water quality conditions with higher proportions of “A”, “B”, and “C”, at 40% and 43%, respectively (predicted – more details provided in Section 3.3.1. Predicted *E. coli* grading in Wairoa watershed reported a modest proportion of stream length above national targets (25%). Appendix F1 shows the prevalence of open space as the cause for lower *E. coli* concentrations in West Coast, Hauraki Gulf Islands and Wairoa watersheds. Overall, observed and predicted grades concur at a regional level that the vast majority of freshwater stations and modelled reaches do not attain national targets for *E. coli*.
- Dissolved zinc (DZn) reported 17% of stations with a failing grade based on observed data at the regional scale. Fewer streams (4%) were assigned a failing grade based on modelled data. Based on modelled results, DZn recorded 84% of FWMT reaches by length achieving “A” grades, which is the highest rate regionally for all contaminants. Many watersheds show almost no instances of predicted or observed “D” graded streams for DZn. FWMT reaches of lower predicted DZn grading are most impacted by urban land uses (e.g., in Waitematā, Tāmaki, and Manukau Harbour watersheds less FWMT reach kilometres graded “A” for predicted DZn; Waitematā and Tāmaki watersheds both reported approximately 50% of FWMT reaches predicted at “A” grade). The source assessment for total zinc show that Waitematā, Tāmaki, and Manukau Harbour watersheds possess a markedly higher proportion of the total zinc EOS loading by rooves (≥20%) and, to a lesser extent, roads and motorways (≥23%) (more details provided in Section 3.3.3,

Appendix F3). Rooves, roads, and motorways in the Tāmaki watershed account for over 50% of the TZn EOS load, underscoring the effects of urban development and a higher prevalence of painted roof HRUs as the likely sources of the grade distribution for predicted FWMT reaches in the watershed. Hibiscus Coast watershed possessed a similar distribution of predicted grades for DZn, spread largely over "B", "C", and "D" grades, likely again due to urban land uses but, notably at a lower proportion of such grading than the other three urbanised watersheds (e.g., Waitematā, Tāmaki and Manukau Harbour). Notably, predicted and observed DZn reach grading differ in terms of "A" grades (e.g., 84% and 38%, respectively). Given high grading accuracy between the FWMT and observed SoE stations (e.g., 75% of stations graded to exact identical grade, 96% graded within an additional grade – see Section 3.1), the disagreement highlights the unrepresentative distribution of SoE stations for DZn reporting (i.e., are biased to urban-effected areas with greater DZn and generally lesser grade). Hence, the FWMT has demonstrated its value in better capturing the likely spread of regional grading for contaminants and the apparent difference in predicted output, is due to better representativity of the region's waterways.

- Total oxidised nitrogen (TON) was reported to result in the highest percentage of stations graded A or B (95%) based on observations for all contaminants at the regional scale. Modelled results were in good agreement, with 96% of streams assigned an A or B grade. With the exception of the Manukau Harbour watershed, few streams in any other watershed show predicted grades lower than "B" (e.g., 4% or 114km – more details provided in Section 3.3.4). Within the Manukau Harbour watershed, 80% of FWMT reaches are predicted by length in "A" or "B" grade span 80% of the modelled reach network. The region's 51 km of FWMT reaches D-graded for TON are all located in the Manukau Harbour watershed. Additionally, 51 of 63 km of FWMT reaches C-graded for TON are also located in the Manukau Harbour watershed. Appendix F4 reveals horticulture is the predominant source of TN to freshwater streams in the Manukau Harbour watershed.
- Total ammoniacal nitrogen (TAM) reported good agreement between observed and failing proportions of SoE stations and FWMT reaches in D-grade (2% and 4%, respectively). However, much less agreement arose for "C" grades where 17% of SoE stations and 46% of FWMT reach length was C-graded. Consequently, marked disagreement arises in proportion of SoE stations (50%) and FWMT reaches (19%) failing national bottom lines (e.g., C and D graded). The distribution of predicted grades was highly variable across the 10 major watersheds in both observed and predicted output.. Amongst all seven attributes, predicted TAM grading was most frequently graded "B" or "C" by length (e.g., 94% or 2,902 km of FWMT reaches). While predicted

grades generally attain the “C” grade or better, isolated areas of certain watersheds reported “D” grades, including the southern portion of Waitematā and the northern reaches of Auckland in the Kaipara and North East watershed (more details provided in Section 3.3.5). There is a noted impact whereby both predicted and observed grades improve when assessed using median and 95th percentile concentrations, the number of “A” stations increased by a factor of 1.8 while 26% of stream lengths were also graded A (see section 3.3.5 for additional information). Predicted and observed grading proportions for TAM differ quite markedly, with between 22% and 86% of all TAM grades observed at or within one additional grade, respectively. Further inspection reveals high agreement of observed and predicted median but lesser agreement of maximum TAM attribute states (e.g., 92% and 28% of respective numeric attribute states predicted exactly alike under approach 1). Amongst the 36 SoE sites with TAM data, 22 were predicted in worse than observed numeric attribute state for maximum concentrations (Appendix K), suggesting either the presence of short-duration peak concentration events otherwise poorly detected by monthly SoE grab sampling, or modelling error in maximum daily average flow-weighted concentration. Targeted validation monitoring is required to determine if the greater predicted than observed concentration of 95th% TAM concentrations is a consequence of events from both urbanised and rural areas. Note that TAM source apportionment results are not presented individually because apportionment herein is limited to total nitrogen (not species).

- Dissolved inorganic nitrogen (DIN) reported good agreement between observations and predictions, with 19% of stations achieving an observed failing grade while 16% of streams predicted to fail. There was an even distribution of predicted and observed grades across the four proposed NOF tiers. Nearly half of FWMT stream kilometres across the region are predicted at “A” grade (41% or 1,276 km) while the remaining 1,809 km of FWMT reaches are predicted in an even spread across “B”, “C”, and “D” grades. Observed grades differ little regionally, with a fifth of regional streams failing proposed national bottom-lines for DIN (16% predicted). The Manukau Harbour and Waitematā watersheds reported a lower proportion of streams predicted at “A” and higher proportion of streams predicted at “D” grades than the wider region. While the West Coast and Hauraki Gulf Island watersheds show the opposite pattern (i.e., higher proportion of streams attaining “A” compared to the regional trend; more details provided in Section 3.3.6). As before, Manukau Harbour watershed receives a disproportionate amount of TN from horticulture (42% – see Appendix F4).
- Dissolved reactive phosphorus (DRP) differed in observed (31%) versus predicted (59%) failing grades. However, 81% of stations achieved either "C"

or "D" based on observations while 80% of streams were assigned C or D based on predictions. After *E. coli*, DRP reported the 2nd greatest length of FWMT reaches (1,814 km) predicted in D-grade. Approximately 21% of FWMT reaches by length are predicted to be in "A" or "B" grade regionally. While the distribution of grades varies by watershed, over half the watersheds show 50% or more of FWMT reaches predicted to be of "D" grades (more details provided in Section 3.3.7). FWMT reaches predicted in "A" grade make up less than 5% of stream kilometres in most watersheds and 9% regionally (283 km). The Hauraki Gulf Islands and West Coast watersheds are predicted to be the only watersheds with more than 5% of FWMT reaches in "A" grade. Pastoral HRUs predominate TP loads in each of the 10 major watersheds (≥64%) and sediment-associated phosphorus from bank erosion is predicted to be the second highest source of TP regionally (≥15%) (Appendix F5). Combined, these two sources account for greater than 80% of the TP loading in each of the 10 watersheds, though individual river outlets in Manukau watersheds also show horticulture as a major source of phosphorus (~1-7% – see Appendix G5). Apparent differences in DRP predicted and observed gradings are notable with nearly double the proportion of FWMT reaches predicted than observed in D-grade by SoE stations. Inspection of grading accuracy results suggests modest performance across the three approaches (e.g., better for overall D grades; 55% of D-graded SoE sites predicted at their grade and 91% within a grade of observed). Notably, amongst 95th% numeric attribute states, the FWMT frequently predicts a worse than observe grade at SoE sites (e.g., 22 of 36 stations predicted in a worse than observed numeric attribute state). As per DZn and DCu, such behaviour could well be real reflecting greater ability to simulate short, peak concentration events for DRP than monthly grab sampling. Alternatively, that SoE stations are not representative of the spread in such concentrations regionally. The opposite might also be true in that modelled output might simply be inaccurate. Targeted validation monitoring is needed to determine whether predicted output is more accurately grading regional streams.. Regardless, if "D" grades and "C" grade are compared together, percentages of predicted and observed overall grades are similar (80% and 81% respectively, observed or predicted in D or C grade overall).

To streamline communication of the grading outcomes, predicted and observed water quality contaminants are organised into two categories – 'human health' and 'ecosystem health' – where human health is reported by *E. coli* grading and ecosystem health is based on the other six contaminant grades for toxicity and eutrophication effects (DCu, DZn, TON, TAM, DIN, and DRP).

Figure 3-2 presents radar plots of the percentage of FWMT reaches predicted in "A" or "B" grade across the region for ecosystem health and human health. The concept behind the radar plots is to easily represent spread in state for both values of freshwater quality across the varied attributes. Limited coverage of the radar area indicates more predominance of poorer water quality (C grade or worse). The radar plots also help emphasise which attribute is the most degraded by stream length, within the Auckland region (or by watershed in Appendix A).

Region-wide, over half the 3,085 km of FWMT reaches are predicted to be in "A" or "B" grade for TAM, TON, DIN, DZn and DCu – notably for DRP, approximately 20% of FWMT reaches achieved A or B grade. Amongst ecosystem health attributes <25% of FWMT reaches were predicted to be in an "A" or "B" grade for proposed DRP guidance. For human health and amongst numeric attribute states of *E. coli*, the 95th% and %>540 MPN/100ml metrics are both more frequently predicted at less than A or B grade, regionally. For instance, only 12% and 22% of FWMT reaches achieved A or B numeric attribute states for 95th% and %>540 MPN/100ml, respectively. Both median and %>260 MPN/100ml achieved A or B numeric attribute states for approximately half of the region's modelled streams.

Combined, radar plots indicate that regionally, management of DRP and TAM would be most pressing for ecosystem health (by stream length) if all attributes are equally important. Whilst, management of infrequent, higher *E. coli* concentration events is a more pressing cause for unacceptable recreational risks to primary contact users (e.g., >3% generalised risk of Campylobacteriosis in C grade or worse [McBride and Soller, 2017]). Importantly, radar plots do not recognise for any one or more attributes being more important to freshwater quality, nor too, the degree of change needed (e.g., magnitude of loading reduction required to achieve A or B grade). Hence, radar plots should be used in combination with other FWMT output to correctly frame the scale and magnitude of contaminant reductions required for Auckland waterways.

Radar plots also do not indicate which streams fail multiple contaminant bottom-lines concurrently. Instead, Figure 3-3 presents all 3,085 km of FWMT reaches that pass all national and proposed bottom-lines ("C" or better graded in all attributes – blue reaches) if not fail one or more ("D" or worse in any one or more attributes – red reaches), with the exception of TON and TAM whereby C and D grades are considered failing national bottom lines and are therefore coloured red . Upstream areas of reaches failing one or more bottom-lines are highlighted to indicate the extent of region potentially contributing to any instream failures of numeric attribute states (i.e., not all land necessarily has contributed to each contaminant failing a bottom-line). Note these maps do not shade direct coastal outlets (they will be white regardless of grading) because DRP, DIN and TAM grades were only readily available from the FWMT in explicitly modelled stream segments (e.g., generally the larger stream and river networks from 2nd order or greater). Gradings for all sub-catchments, both with and without explicitly modelled stream segments, is found in Appendix C.

The maps in Figure 3-3 are highly conservative and a “worst case” projection of the region’s waterways whereby all contaminants (whether proposed or operative) are included, and failure to achieve any regional or national contaminant bottom-line results in a reach being classed as “failing” overall. From the radar and split-bar graph output, the conservative regional picture shared by Figure 3-3 is driven predominantly by just two contaminants – *E. coli* and DRP. Further, as discussed in the subsections below there are individual numeric attribute states (statistical metrics) that are driving the proportion of “failing” streams (the effect of median versus upper percentile grading on *E. coli* can also be seen in Figure 3-2). The maps in Figure 3-3 are also conservative for not attempting to discriminate only medium-sized (4^{th} order) streams for reporting against *E. coli* national targets.

The FWMT’s capability to simulate contaminants continuously and region-wide has enabled a heightened level of reporting by Auckland Council on water quality. However, as with all output, enhanced capability to report requires careful evaluation of objectives and corresponding numeric attribute states to ensure accurate messaging on regional water quality conditions. For instance, while ecosystem health is a convenient value to group numerous attributes by, the differential impacts between toxicity (copper, zinc, TON, TAM) and eutrophication (DRP, DIN) may deserve separated reporting.

Regionwide		Attainment of Attribute State by Model Stream Length (km) or Number of Stations (#)				Percent of Stream Length or Stations Attaining Attribute State
		A	B	C	D or E	
Dissolved Inorganic Nitrogen	Predicted	1,276	667	664	478	41% 22% 22% 16%
	Observed	16	8	5	7	44% 22% 14% 19%
	Integrated	1,352	745	553	435	44% 24% 18% 14%
Dissolved Reactive Phopshorus	Predicted	283	351	636	1,814	9% 11% 21% 59%
	Observed	0	7	18	11	19% 50% 31%
	Integrated	278	362	799	1,647	9% 12% 26% 53%
Total Oxidised Nitrogen	Predicted	2,536	436	63	51	82% 14%
	Observed	29	5	1	1	81% 14%
	Integrated	2,620	350	65	51	85% 11%
Total Ammoniacal Nitrogen	Predicted	67	1,480	1,422	116	48% 46%
	Observed	19	10	6	1	53% 28% 17%
	Integrated	220	1,526	1,231	109	7% 49% 40%
Dissolved Copper	Predicted	1,538	399	888	261	50% 13% 29% 8%
	Observed	8	3	13	0	33% 13% 54%
	Integrated	1,576	401	887	220	51% 13% 29% 7%
Dissolved Zinc	Predicted	2,596	192	187	111	84% 6% 6%
	Observed	9	4	7	4	38% 17% 29% 17%
	Integrated	2,576	213	190	106	83% 7% 6%
E. coli*	Predicted	113	257	154	2,562	8% 83%
	Observed	1	5	0	30	14% 83%
	Integrated	124	264	149	2,548	9% 83%

*** D and E grades combined for grading, less than 0.05% of modelled stream length were assigned a grade "D" for *E. coli***

Figure 3-1. Region-wide grading of numeric attribute states from regional and national objective frameworks for FWMT predicted, SoE observed, and integrated approaches in Auckland (2013-2017), based on worst performing numeric attribute state. Note TAM summary uses worst of median and maximum concentrations

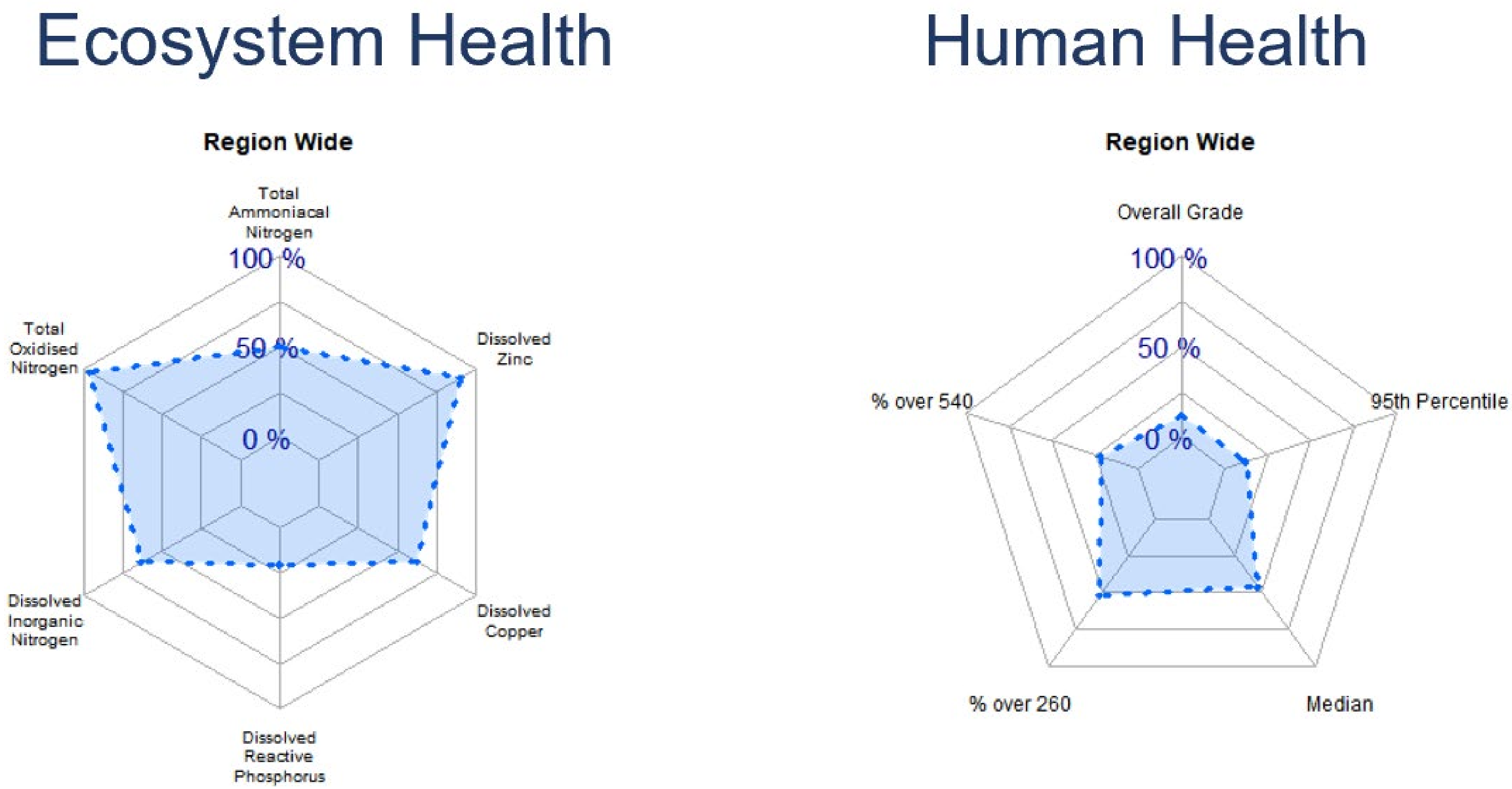


Figure 3-2. Radar plots of FWMT predicted reaches attaining grades of "A" or "B" for contaminants impacting ecosystem health (left) and human health (right) across the Auckland region (% by length; 2013-2017). Note TAM summary uses worst of median and maximum concentrations

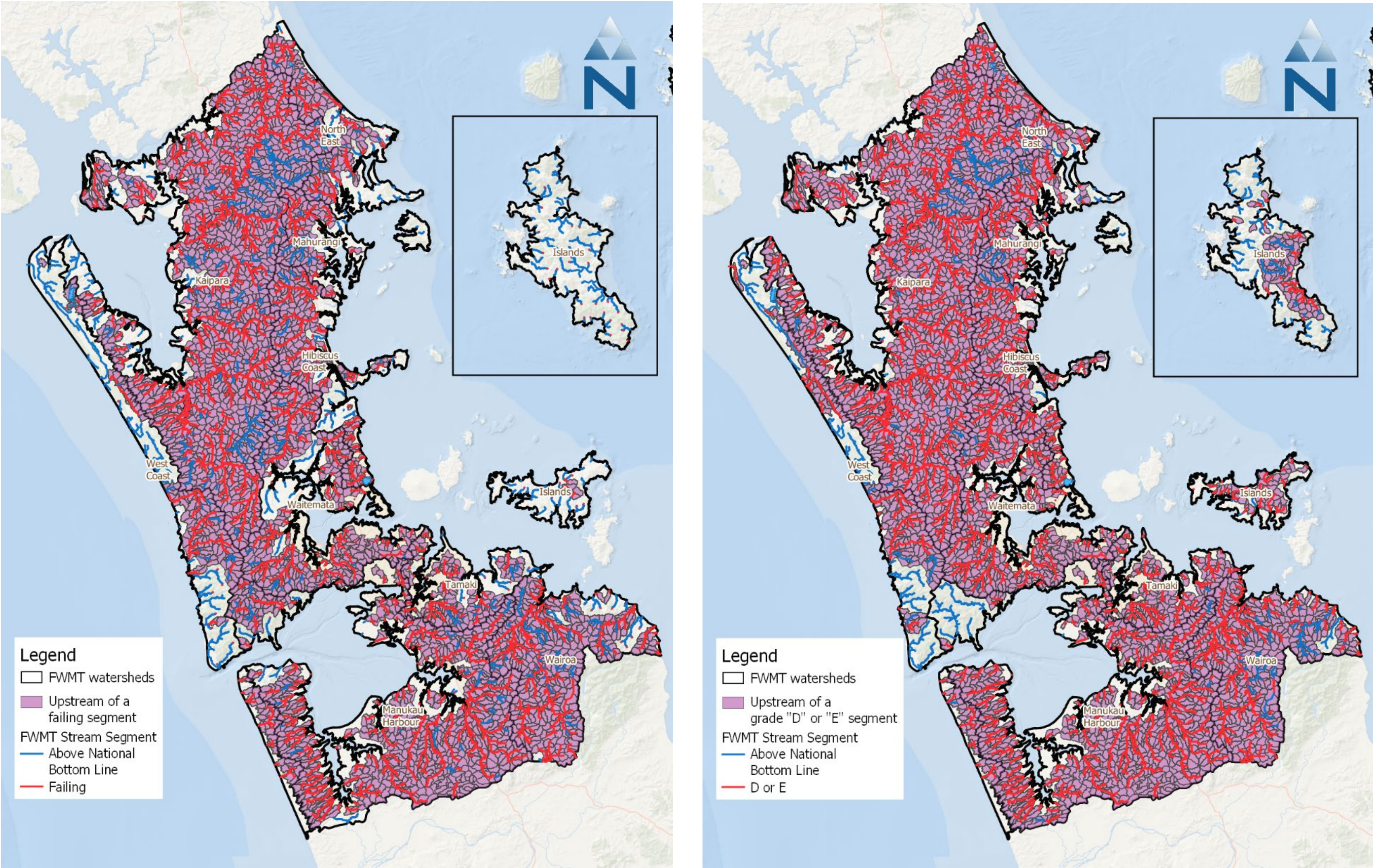


Figure 3-3. Predicted minimum (worst) grading outcomes across all attributes in FWMT reaches, and areas upstream of failing (D or E grade, C or D for TON and TAM) segments for ecosystem health (left) and human health (right), across the Auckland region (2013-2017). Note that for ecosystem health, a failing grade for any single contaminant results in a failing stream and associated upstream area being presented on the map. Note TAM summary uses worst of median and maximum concentrations

3.3 Gradings by Contaminant

The following subsections present contaminant-by-contaminant grading summaries, for the 10 major watersheds. For each contaminant, the individual numeric attribute state (statistic) driving failing grades are evaluated. Results are presented for predicted grading. Appendix I presents integrated data. Predicted and integrated summaries are near equivalent (e.g., <10% of FWMT reaches can potentially be over-ridden; less still actually differ). For all contaminants, comparison of grading based on 95th percentile versus median statistics is provided to demonstrate sensitivity of overall grading to individual numeric attribute state. Maximum concentrations are also addressed for TAM given national guidance. The sensitivity to averaging duration – daily versus monthly – is assessed for *E. coli* and DRP for which the greatest number of reaches are predicted to fail bottom lines (i.e., where reporting interval might have greater effect on defining the extent of regional exceedances of bottom lines).

Appendix A, B, and C contain detailed contaminant-by-contaminant and watershed-by-watershed output from FWMT Stage 1. Appendix J presents summaries of the areas in each watershed and region-wide that are upstream of failing segments.

As noted above, all grading summaries are for effects in freshwater throughout the FWMT reach network only.

3.3.1 *E. coli*

E. coli is an indicator of faecal contaminants in water and risk to human health during water contact (e.g., swimming). *E. coli* is unique for having specific national grading targets for swimming water quality in medium-sized rivers, under the NPS-FM (e.g., nationally 80% of fourth order rivers at grade “C” or better by 2030; 90% as such by 2040).

The *E. coli* baseline state (2013-2017) output is presented in Figure 3-4 to Figure 3-10 which includes:

- Figure 3-4 is a regional map of predicted *E. coli* grading based on the worst performing metric, as well as gradings based on median concentrations.
- Figure 3-5 presents predicted, observed and integrated gradings by watershed using the worst performing metric and median. In 8 of the 10 watersheds a majority of streams are predicted in E grade for *E. coli*, overall (by worst numeric attribute state). Less than 0.05% of the 3,085 km of modelled streams were assigned a D grade whilst nearly 83% were assigned an E grade – emphasising that failures of *E. coli* national targets were of high magnitude (e.g., very much higher concentration). Only the Hauraki Gulf Islands and West Coast watersheds were predicted with >50% of FWMT reaches above *E. coli* national targets, overall. Both watersheds are unusual, for their large forest extent (49-55% of watershed; compared to 16-28% in other eight watersheds).
- Figure 3-6 presents a comparison of predicted gradings based on daily and monthly[6] averaging periods. Overall monthly averages resulted in worse gradings because median monthly concentrations are increased by extremes occurring inconsistently within months (e.g., not repeatedly on all days). Region-wide, the percentages of streams “failing” national targets increased from 83% to 95% when based on daily and monthly averages, respectively. Daily average values were calculated as the flow-weighted average of simulation results generated at a 15-minute timestep, therefore each day was a flow weighted average of 96 concentrations. Monthly values were simple averages of daily flow weighted averages.
- Figure 3-7 presents “failing” stream segments and contributing upstream areas across the region (e.g., FWMT reaches that exceed national targets in any *E. coli* numeric attribute state).
- Figure 3-8 and Figure 3-9 provide box plots of numeric attribute states for all and failing FWMT reaches (e.g., median, 95th percentile, %>540 MPN/100ml, %>260 MPN/100ml). The results demonstrate that 95th% are the most

[6] Monthly averages were computed as the simple arithmetic mean of all the daily concentrations during the month (no flow weighting)

commonly failing numeric attribute and worst-performing *E. coli* metric. More than 50% of failing reaches require a halving or more of their concentrations to achieve national targets for 95th percentile.

- Figure 3-10 assesses the impact of computing predicted grades on daily and monthly averages. While monthly averaging result in lower 95th percentile concentrations, median concentrations become higher, as do the per cent of exceedances over 540 and 260. Overall, monthly grades appear worse than daily grades.

Combined, the FWMT baseline outputs demonstrate *E. coli* is a widespread contaminant resulting in frequent and marked exceedance of national targets across **several** numeric attributes, but predominantly in 95th% concentrations. Regionally, only 17% of FWMT reaches are “swimmable” when considering all four numeric attribute states, whereas 48% of FWMT reaches are “swimmable” when grading is based on median concentrations. That between 17-48% of the FWMT reaches are swimmable is in marked contrast to the national baseline (68.6% of moderate rivers are swimmable by length) but similar to previous estimates of 23% of moderate rivers swimmable for the Auckland region (MfE, 2018). Whilst latter estimates were derived from simplified, empirical modelling of steady-state without event-based responses and for a fraction of the stream length simulated by the FWMT (e.g., not process-driven, of limited sources and variation in source behaviour – CLUES [Elliott et al., 2016]), the similarity between model outcomes underscores how challenging a contaminant *E. coli* is likely to be in the Auckland region, for management to national targets for the NPS-FM. Notably, any assessment thereof is still hindered by insufficient detail about what the regional target contributing to that national outcome will be in Auckland (i.e., regional targets have not been set in the NPS-FM for *E. coli* grading in moderate streams).

The pattern of degraded baseline state (2013-2017) human health (*E. coli*) in Auckland’s waterways is not unexpected. *E. coli* is well-documented as one of the most ubiquitous challenges to achieving water quality standard internationally, demonstrated by the U.S. EPA estimating *E. coli* as the number one “impairing” pollutant with over 300,000 km of monitored streams in the United States being categorised as “impaired” and nearly 100% of urban streams categorised as such (US EPA, 2016). Further discussion on *E. coli* exceedances is provided in Section 4.

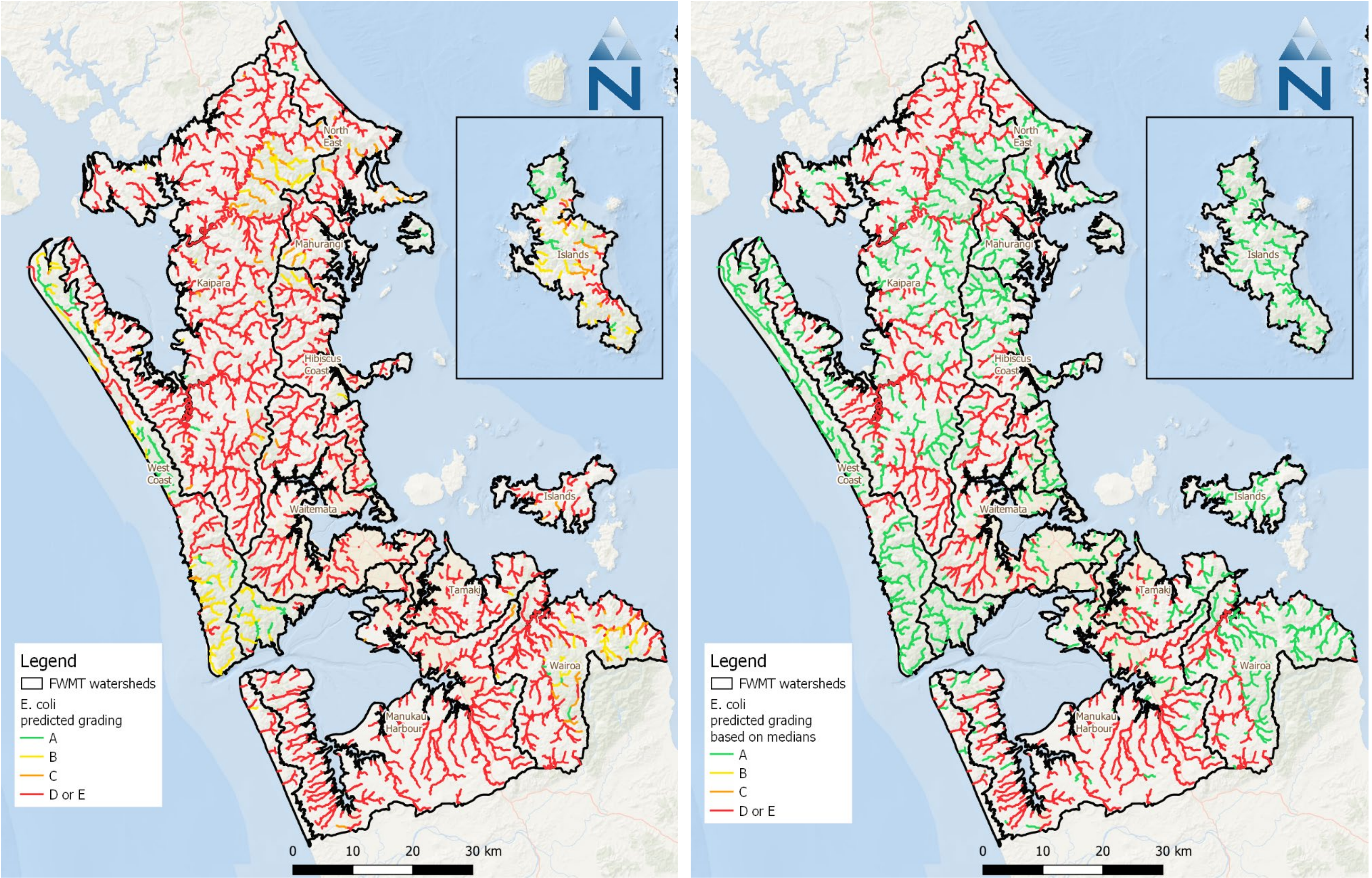


Figure 3-4. Predicted grading for *E. coli* based on worst performing numeric attribute state (left) and median concentration (right) (2013-2017)

Watershed	E. coli Grading Method	Attainment of Attribute State by Model Stream Length (km) or Number of Stations (#)				Percent of Stream Length or Stations Attaining Attribute State
		A	B	C	D	
Hibiscus Coast	Predicted (km)	1	9	3	144	6%, 92%
	Observed (#)	0	2	0	3	40%, 60%
	Integrated (km)	1	11	3	142	7%, 90%
Islands	Predicted (km)	27	36	29	68	17%, 22%, 18%, 43%
	Observed (#)	0	1	0	1	50%, 50%
	Integrated (km)	27	37	28	68	17%, 23%, 18%, 42%
Kaipara	Predicted (km)	1	41	49	950	91%
	Observed (#)	0	1	0	4	20%, 80%
	Integrated (km)	1	45	49	946	91%
Mahurangi	Predicted (km)	0	4	6	60	5%, 9%, 85%
	Observed (#)	0	0	0	2	100%
	Integrated (km)	0	3	4	64	5%, 91%
Manukau Harbour	Predicted (km)	11	28	5	485	5%, 92%
	Observed (#)	0	0	0	6	100%
	Integrated (km)	11	28	4	486	5%, 92%
North East	Predicted (km)	1	3	13	113	10%, 86%
	Observed (#)	0	0	0	1	100%
	Integrated (km)	1	3	13	113	10%, 86%
Tamaki	Predicted (km)	0	1	0	98	99%
	Observed (#)	0	0	0	6	100%
	Integrated (km)	0	1	0	98	99%
Wairoa	Predicted (km)	10	45	37	274	12%, 10%, 75%
	Observed (#)	0	1	0	1	50%, 50%
	Integrated (km)	10	47	37	272	13%, 10%, 74%
Waitemata	Predicted (km)	0	0	4	267	98%
	Observed (#)	0	0	0	6	100%
	Integrated (km)	0	0	4	267	98%
West Coast	Predicted (km)	60	90	9	104	23%, 34%, 40%
	Observed (#)	1	0	0	0	100%
	Integrated (km)	71	89	9	94	27%, 34%, 36%
Regionwide	Predicted (km)	113	257	154	2,562	8%, 83%
	Observed (#)	1	5	0	30	14%, 83%
	Integrated (km)	124	264	149	2,548	9%, 83%

Watershed	E. coli Grading Method	Attainment of Attribute State by Model Stream Length (km) or Number of Stations (#)				Percent of Stream Length or Stations Attaining Attribute State
		A	B	C	D	
Hibiscus Coast	Predicted (km)	112	0	0	45	71%, 29%
	Observed (#)	2	0	0	3	40%, 60%
	Integrated (km)	105	0	0	52	67%, 33%
Islands	Predicted (km)	160	0	0	0	100%
	Observed (#)	2	0	0	0	100%
	Integrated (km)	160	0	0	0	100%
Kaipara	Predicted (km)	383	0	0	658	37%, 63%
	Observed (#)	2	0	0	3	40%, 60%
	Integrated (km)	434	0	0	607	42%, 58%
Mahurangi	Predicted (km)	39	0	0	32	55%, 45%
	Observed (#)	0	0	0	2	100%
	Integrated (km)	33	0	0	37	48%, 52%
Manukau Harbour	Predicted (km)	107	0	0	421	20%, 80%
	Observed (#)	0	0	0	6	100%
	Integrated (km)	104	0	0	424	20%, 80%
North East	Predicted (km)	58	0	0	72	44%, 56%
	Observed (#)	0	0	0	1	100%
	Integrated (km)	54	0	0	76	42%, 58%
Tamaki	Predicted (km)	46	0	0	53	47%, 53%
	Observed (#)	0	0	0	6	100%
	Integrated (km)	44	0	0	55	44%, 56%
Wairoa	Predicted (km)	217	0	0	148	59%, 41%
	Observed (#)	1	0	0	1	50%, 50%
	Integrated (km)	217	0	0	148	59%, 41%
Waitemata	Predicted (km)	91	0	0	180	34%, 66%
	Observed (#)	0	0	0	6	100%
	Integrated (km)	91	0	0	181	33%, 67%
West Coast	Predicted (km)	226	0	0	37	86%, 14%
	Observed (#)	1	0	0	0	100%
	Integrated (km)	226	0	0	37	86%, 14%
Regionwide	Predicted (km)	1,439	0	0	1,647	47%, 53%
	Observed (#)	8	0	0	28	22%, 78%
	Integrated (km)	1,469	0	0	1,616	48%, 52%

Figure 3-5. Summary of watershed and region-wide predicted, observed, and integrated grading for *E. coli* across Auckland streams and rivers based on worst performing (left) and median numeric attribute state (right) (2013-2017)

Watershed	Total Ammoniacal Nitrogen Grading Method	Attainment of Attribute State by Model Stream Length (km) or Number of Stations (#)				Percent of Stream Length or Stations Attaining Attribute State
		A	B	C	D	
Hibiscus Coast	Predicted (Daily)	1	9	3	144	6%, 92%
	Predicted (Monthly)	2	1	0	154	98%
	Observed	0	2	0	3	40%, 60%
Islands	Predicted (Daily)	27	36	29	68	17%, 22%, 18%, 43%
	Predicted (Monthly)	31	0	0	129	19%, 81%
	Observed	0	1	0	1	50%, 50%
Kaipara	Predicted (Daily)	1	41	49	950	91%
	Predicted (Monthly)	2	0	1	1,038	100%
	Observed	0	1	0	4	20%, 80%
Mahurangi	Predicted (Daily)	0	4	6	60	5%, 9%, 85%
	Predicted (Monthly)	0	0	0	70	100%
	Observed	0	0	0	2	100%
Manukau Harbour	Predicted (Daily)	11	28	5	485	5%, 92%
	Predicted (Monthly)	16	0	0	513	97%
	Observed	0	0	0	6	100%
North East	Predicted (Daily)	1	3	13	113	10%, 86%
	Predicted (Monthly)	1	0	0	129	99%
	Observed	0	0	0	1	100%
Tamaki	Predicted (Daily)	0	1	0	98	99%
	Predicted (Monthly)	0	0	0	99	100%
	Observed	0	0	0	6	100%
Wairoa	Predicted (Daily)	10	45	37	274	12%, 10%, 75%
	Predicted (Monthly)	17	3	0	345	95%
	Observed	0	1	0	1	50%, 50%
Waitemata	Predicted (Daily)	0	0	4	267	98%
	Predicted (Monthly)	0	0	0	271	100%
	Observed	0	0	0	6	100%
West Coast	Predicted (Daily)	60	90	9	104	23%, 34%, 40%
	Predicted (Monthly)	67	12	2	181	26%, 69%
	Observed	1	0	0	0	100%
Regionwide	Predicted (Daily)	113	257	154	2,562	8%, 83%
	Predicted (Monthly)	137	16	2	2,929	95%
	Observed	1	5	0	30	14%, 83%

Figure 3-6. Summary of watershed and region-wide predictions based on daily flow-weighted and monthly simple averaged *E. coli* concentrations across Auckland streams and rivers (derived from all four numeric attribute states for *E. coli*; 2013-2017)

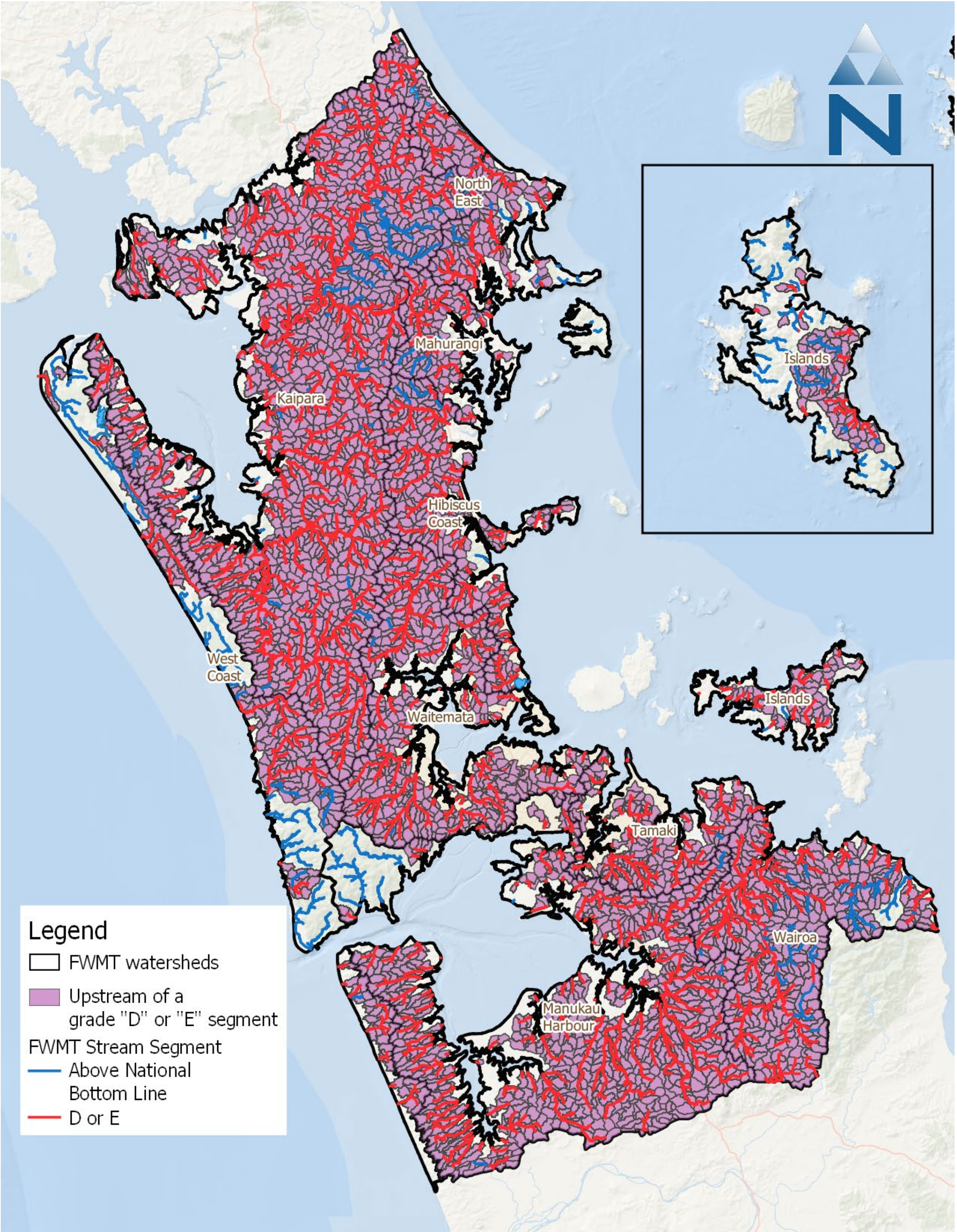


Figure 3-7. Predicted failing stream segments and upstream areas for *E. coli* based on worst performing metric numeric attribute state (2013-2017)

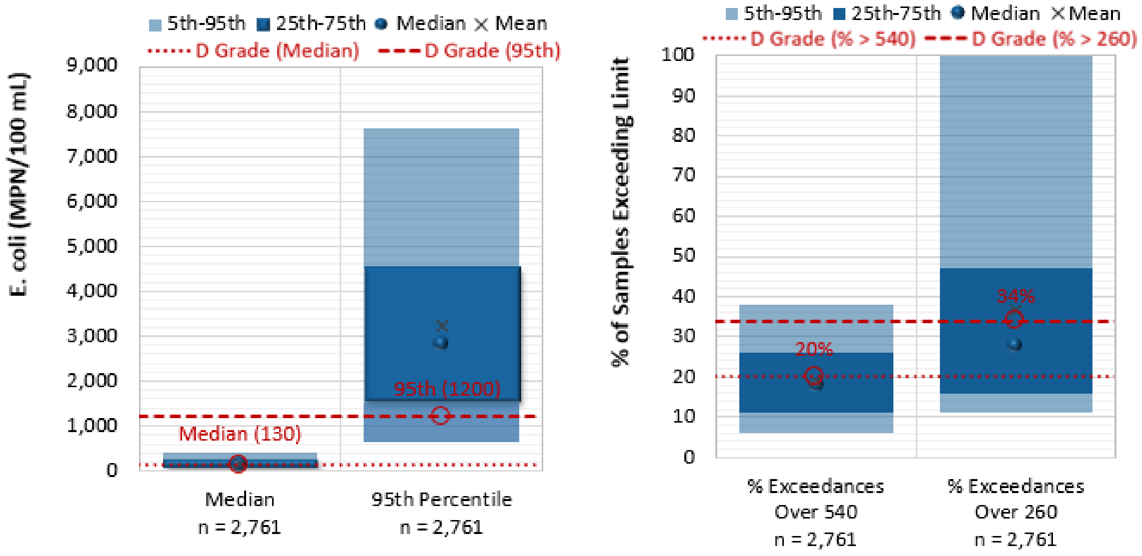


Figure 3-8. For all stream segments, comparison of spread in all four predicted *E. coli* numeric attribute states (2013-2017)

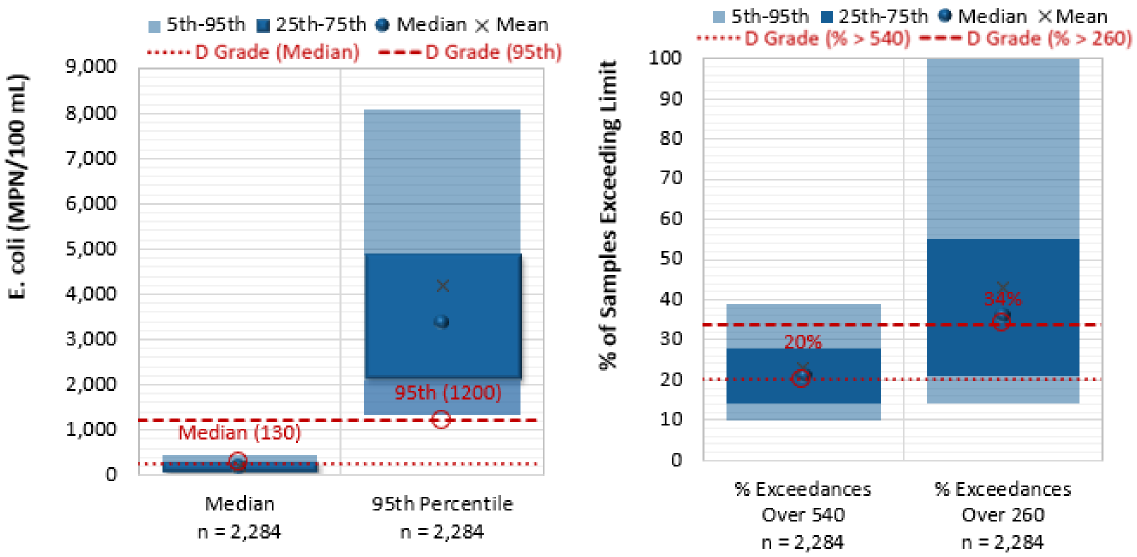


Figure 3-9. For failing stream segments, comparison of spread in all four predicted *E. coli* numeric attribute states (2013-2017)

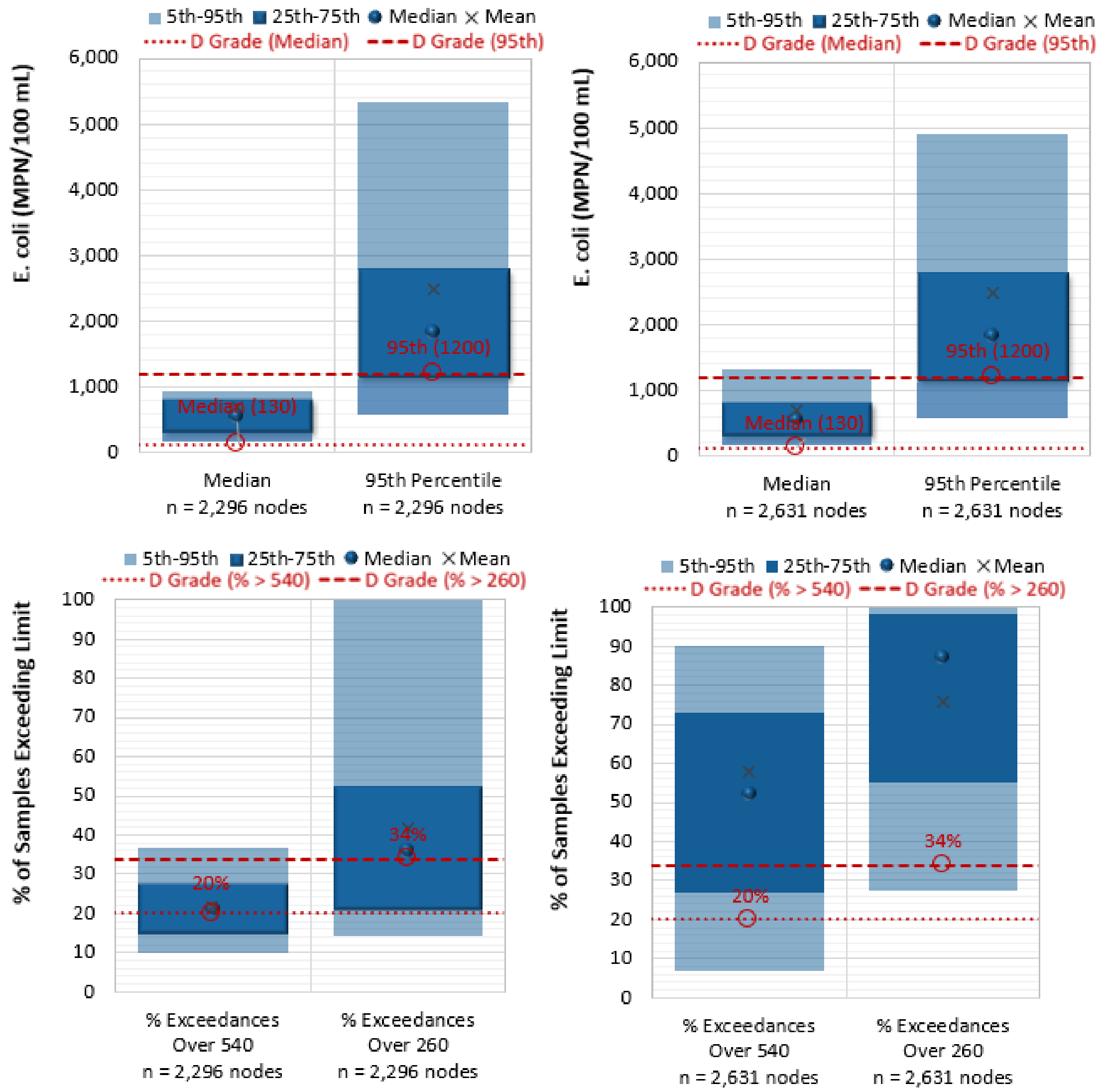


Figure 3-10. For failing stream segments, comparison of predicted daily (left) and monthly (right) numeric attributes states for *E. coli* (2013-2017)

3.3.2 Dissolved Copper

Dissolved copper (DCu) is a heavy metal that can be toxic to aquatic life, either from acute or chronic exposure. While metals are present in natural waters, concentrations tend to increase in urbanised areas where fossil fuel combustion and industrial activities occur (ANZECC, 2000). Both acute and chronic effects are managed for, through the regional objective guidance in Table 2-2 (e.g., Gadd et al., 2019).

The DCu baseline state (2013-2017) output is presented in Figure 3-11 to Figure 3-15, which includes:

- Figure 3-11 is a regional map of predicted DCu grading based on the worst performing metric, as well as for grading based on median concentration;
- Figure 3-12 presents predicted, observed and integrated gradings by watershed using the worst performing metric. Less than 8% (261 km) of FWMT reaches were predicted in D-grade (provisionally “failing” regional bottom lines), whilst 50% received an A grade. Both Tāmaki and Waitematā watersheds possessed greater proportion of failing reaches, 47% (47km) and 37% (100km) by length, respectively. Note the greater spread of “predicted” than “observed” grades in A through C bands, reflecting greater coverage and representativity of the FWMT than the 10 SoE sites in both Tāmaki and Waitematā watersheds (i.e., Section 3.1 demonstrates good agreement of observed and predicted grades at those few, unrepresentative SoE sites for DCu).
- Figure 3-13 presents stream segments and contributing upstream areas failing DCu regional bottom lines from predicted concentrations. Failing predicted grades were predominant in urbanised sub-catchments. Whilst grades of “B” and “C” were distributed throughout the region, some caution is needed in their interpretation as calibration and validation sites are limited largely to urban environments (see FWMT Baseline Configuration and Calibration Report).
- Figure 3-14 and Figure 3-15 provide box plots for both predicted numeric attribute states, in all and only failing FWMT reaches (respectively). Less than 5% of reaches exceeded the median numeric attribute bottom line for DCu, suggesting excessive toxicity effects from copper contamination of freshwater are primarily acute (rather than chronic) – albeit, as above limited to 261 km of the 3,085km of FWMT stream network. Predicted 95th% concentrations for at least half of failing streams only modestly exceeded the regional numeric attribute state bottom line (e.g., by less than a tenth of the bottom line). However, at least one quarter of failing FWMT reaches exceeded the proposed 95th% concentration bottom line by a factor of 0.25 to 3 (i.e.,

requires a 25% to 300% reduction in 95th% to not exceed 4.3 mg/L, along ~130km of stream).

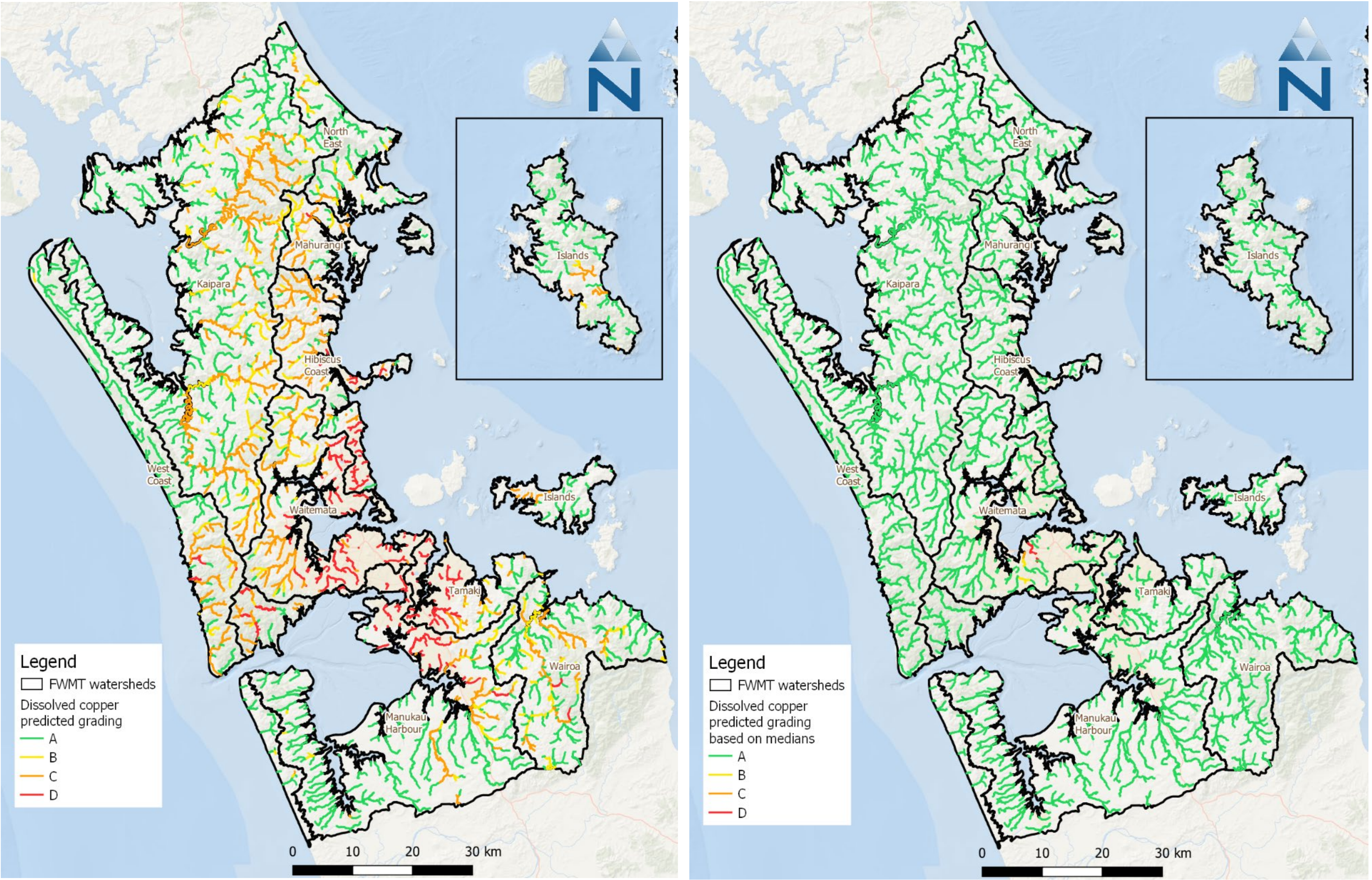


Figure 3-11. Predicted grading for dissolved copper based on worst performing numeric attribute state (left) and median (right) (2013-2017)

Watershed	Dissolved Copper Grading Method	Attainment of Attribute State by Model Stream Length (km) or Number of Stations (#)				Percent of Stream Length or Stations Attaining Attribute State
		A	B	C	D	
Hibiscus Coast	Predicted (km)	20	18	86	33	13% | 11% | 55% | 21%
	Observed (#)	2	1	1	0	50% | 25% | 25%
	Integrated (km)	26	19	79	33	17% | 12% | 50% | 21%
Islands	Predicted (km)	127	6	27	0	79% | 17%
	Observed (#)	0	0	0	0	N/A
	Integrated (km)	127	6	27	0	79% | 17%
Kaipara	Predicted (km)	518	153	369	0	50% | 15% | 35%
	Observed (#)	2	0	1	0	67% | 33%
	Integrated (km)	530	150	360	0	51% | 14% | 35%
Mahurangi	Predicted (km)	12	19	38	1	17% | 27% | 54%
	Observed (#)	2	0	0	0	100%
	Integrated (km)	23	19	27	1	33% | 27% | 38%
Manukau Harbour	Predicted (km)	346	36	84	63	65% | 7% | 16% | 12%
	Observed (#)	0	1	2	0	33% | 67%
	Integrated (km)	333	46	98	52	63% | 9% | 18% | 10%
North East	Predicted (km)	91	24	16	0	70% | 18% | 12%
	Observed (#)	1	0	0	0	100%
	Integrated (km)	91	24	16	0	70% | 18% | 12%
Tamaki	Predicted (km)	21	13	19	47	21% | 13% | 19% | 47%
	Observed (#)	0	1	5	0	17% | 83%
	Integrated (km)	21	14	29	35	21% | 15% | 29% | 35%
Wairoa	Predicted (km)	210	75	70	10	57% | 21% | 19%
	Observed (#)	1	0	0	0	100%
	Integrated (km)	231	69	54	10	63% | 19% | 15%
Waitemata	Predicted (km)	22	38	111	100	8% | 14% | 41% | 37%
	Observed (#)	0	0	4	0	100%
	Integrated (km)	22	38	129	82	8% | 14% | 47% | 30%
West Coast	Predicted (km)	170	16	69	7	65% | 6% | 26%
	Observed (#)	0	0	0	0	N/A
	Integrated (km)	170	16	69	7	65% | 6% | 26%
Regionwide	Predicted (km)	1,538	399	888	261	50% | 13% | 29% | 8%
	Observed (#)	8	3	13	0	33% | 13% | 54%
	Integrated (km)	1,576	401	887	220	51% | 13% | 29% | 7%

Figure 3-12. Summary of region-wide and watershed predicted, observed, and integrated grading for dissolved copper across Auckland streams and rivers based on worst performing numeric attribute state (2013-2017)

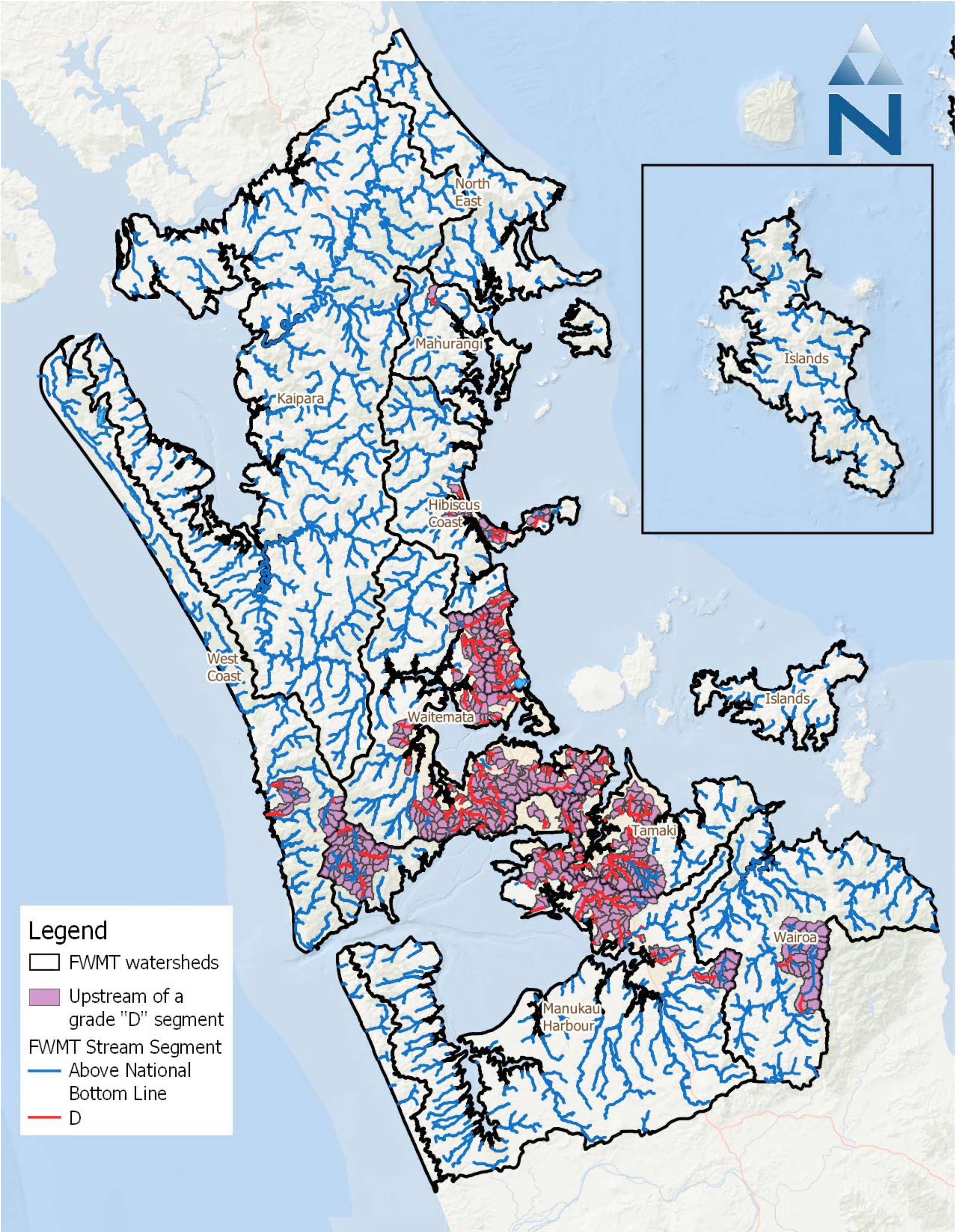


Figure 3-13. Predicted failing stream segments and upstream areas for dissolved copper based on worst performing numeric attribute state (2013-2017)

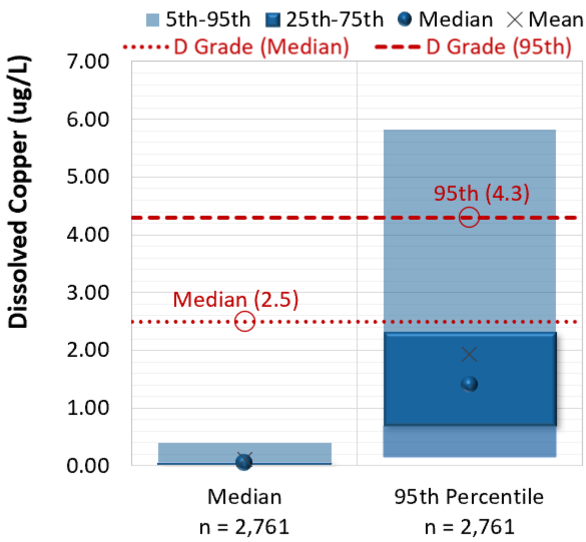


Figure 3-14. For <u>all</u> stream segments, comparison of their predicted median and 95th percentile concentrations compared to D attribute for dissolved copper.

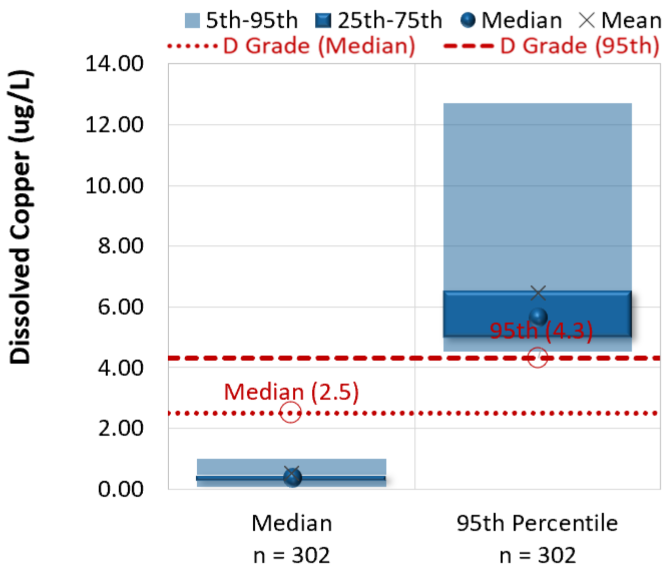


Figure 3-15. For <u>failing</u> stream segments, comparison of their predicted median and 95th percentile concentrations compared to D attribute for dissolved copper

3.3.3 Dissolved Zinc

Dissolved zinc (DZn) is a heavy metal that can be toxic to aquatic life, like copper either from acute or chronic exposure. While zinc is present in natural waters, entering streams through weathering and erosion, concentrations tend to increase in urbanised areas from a range of metal-based surfaces and metal-reinforced products (e.g., tyres) (ANZECC, 2000). Both acute and chronic effects are managed for through the regional objective guidance in Table 2-3 (e.g., Gadd et al., 2019).

The DZn baseline state (2013-2017) output is presented in Figure 3-16 to Figure 3-20, which includes:

- Figure 3-16 is a regional map of predicted DZn grading based on the worst performing metric as well as for grading based on median concentration.
- Figure 3-17 presents predicted, observed and integrated gradings by watershed using the worst performing metric. Regionally, only 4% of streams were predicted to fail proposed regional bottom lines, whilst 83% received an A grade. Similar patterns albeit of generally better state than DCu grading are evident, with Waitematā watershed possessing the greatest proportion of failing predicted grades at 24% (64km). However, both Hibiscus Coast and Manukau Harbour watersheds possess twice the predicted failing reaches than Tāmaki (7%, 6% and 3%, or 12, 32 and 3km in D grade, respectively). DZn patterns are driven by differing sources, with greater emphasis on roofing HRU types, supported by wider literature having identified zinc-alloy roofing as a critical source to New Zealand waterways (e.g., Mosley and Peake, 2001; Simmons et al., 2001; Abrahim and Parker, 2002). Whilst highest Zn-leaching rooves (HRU roof impact 3) are extensive in the Waitematā (0.9%, 40km^2), Hibiscus Coast (0.3%, 8km^2) and Manukau Harbour watersheds (0.2%, 19km^2), the Tāmaki watershed also possesses considerable extents of such roofing (0.6%, 12km^2). Also noteworthy is that Tāmaki watershed possessed significantly greater hardness ($CaCO_3$) enabling a more permissive (higher concentration) of DZn for D grade. Likewise, despite a less permissive (lower concentration) of DZn for D grade in Wairoa watershed, no FWMT reaches were predicted to fail proposed regional bottom lines therein.
- Figure 3-18 presents stream segments and contributing upstream areas predicted to fail DZn regional bottom lines. The majority of failing stream segments were located in urbanised areas. Compared to DCu considerably more FWMT reaches are graded A with far fewer in C grade. For instance, 888km (1,538km) and 190km (2,596km) of FWMT reaches were predicted in grade A for DCu and DZn, respectively. As before, caution should be noted for DZn predictions with few calibration and validation sites located in rural catchments.

- Figure 3-19 and Figure 3-20 provide box plots for both predicted numeric attribute states, in all and only failing FWMT reaches (respectively). Less than 5% of FWMT reaches failed either numeric attribute state for DZn, of which the vast majority failed for excessive 95^{th}% concentrations. Both DZn and DCu failures of proposed regional bottom lines are therefore both limited in extent (largely urban) and in duration (largely for acute stress). However, boxplots demonstrate that half of the 125 failing reaches require moderate or lower reductions in 95^{th}% (e.g., less than 25% reduction therein).

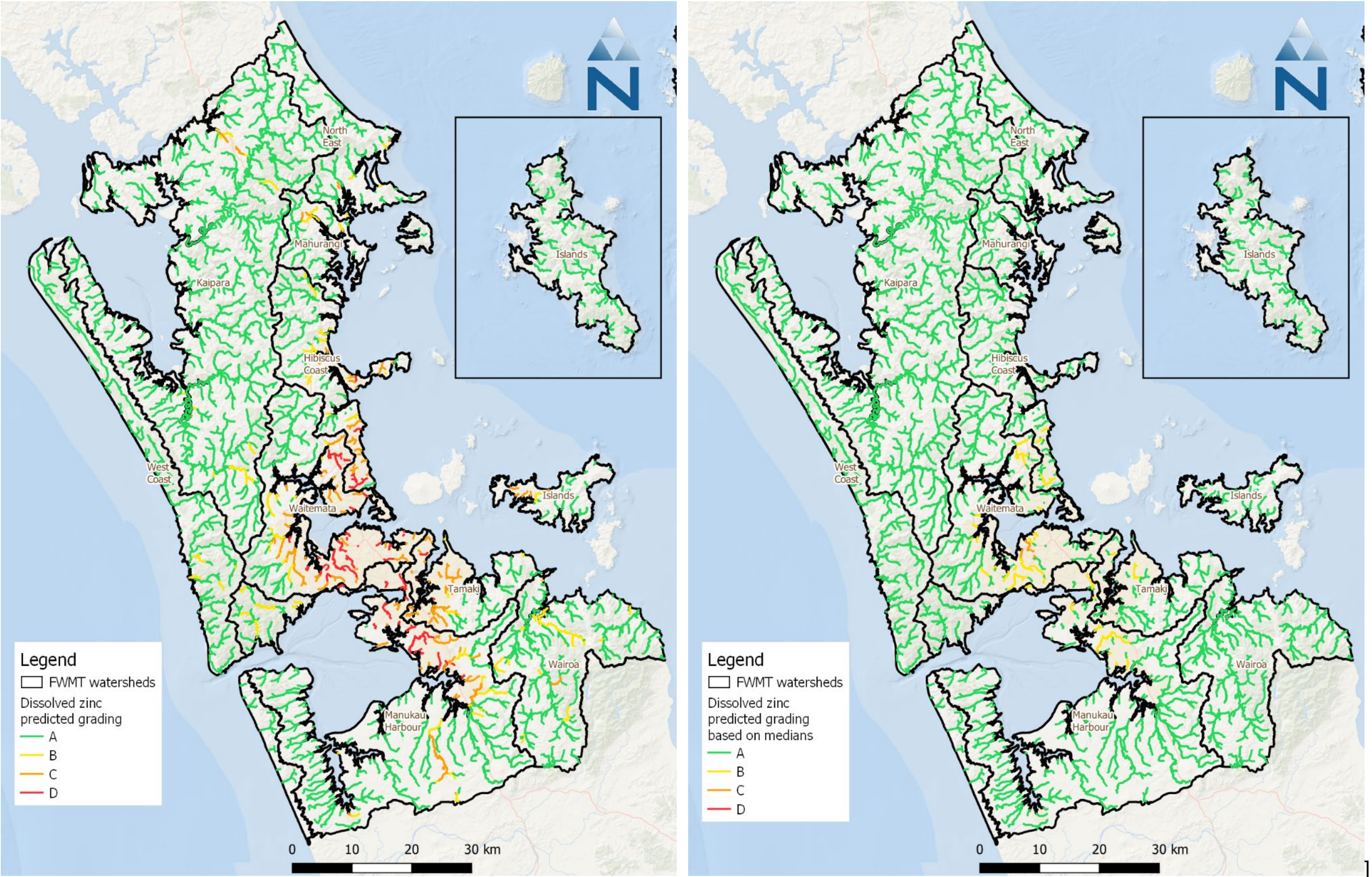


Figure 3-16. Predicted grading for dissolved zinc based on worst performing numeric attribute state (left) and median (right) (2013-2017)

Watershed	Dissolved Zinc Grading Method	Attainment of Attribute State by Model Stream Length (km) or Number of Stations (#)				Percent of Stream Length or Stations Attaining Attribute State
		A	B	C	D	
Hibiscus Coast	Predicted (km)	99	24	23	12	63% 16% 14% 7%
	Observed (#)	3	1	0	0	75% 25%
	Integrated (km)	99	24	23	12	63% 16% 14% 7%
Islands	Predicted (km)	153	3	5	0	95%
	Observed (#)	0	0	0	0	N/A
	Integrated (km)	153	3	5	0	95%
Kaipara	Predicted (km)	1,011	25	5	0	97%
	Observed (#)	1	1	1	0	33% 33% 33%
	Integrated (km)	987	45	9	0	95%
Mahurangi	Predicted (km)	59	8	3	0	85% 12%
	Observed (#)	2	0	0	0	100%
	Integrated (km)	64	4	2	0	92% 6%
Manukau Harbour	Predicted (km)	402	48	47	32	76% 9% 9% 6%
	Observed (#)	1	1	0	1	33% 33% 33%
	Integrated (km)	402	52	41	33	76% 10% 8% 6%
North East	Predicted (km)	125	4	2	0	96%
	Observed (#)	1	0	0	0	100%
	Integrated (km)	125	4	2	0	96%
Tamaki	Predicted (km)	51	6	40	3	51% 6% 40%
	Observed (#)	0	0	4	2	67% 33%
	Integrated (km)	51	4	39	5	51% 40%
Wairoa	Predicted (km)	317	43	6	0	87% 12%
	Observed (#)	1	0	0	0	100%
	Integrated (km)	317	43	6	0	87% 12%
Waitemata	Predicted (km)	126	22	59	64	47% 8% 22% 24%
	Observed (#)	0	1	2	1	25% 50% 25%
	Integrated (km)	126	25	63	57	47% 9% 23% 21%
West Coast	Predicted (km)	253	9	0	0	97%
	Observed (#)	0	0	0	0	N/A
	Integrated (km)	253	9	0	0	97%
Regionwide	Predicted (km)	2,596	192	187	111	84% 6% 6%
	Observed (#)	9	4	7	4	38% 17% 29% 17%
	Integrated (km)	2,576	213	190	106	83% 7% 6%

Figure 3-17. Summary of region-wide and watershed predicted, observed, and integrated grading for dissolved zinc across Auckland streams and rivers based on worst performing numeric attribute state (2013-2017)

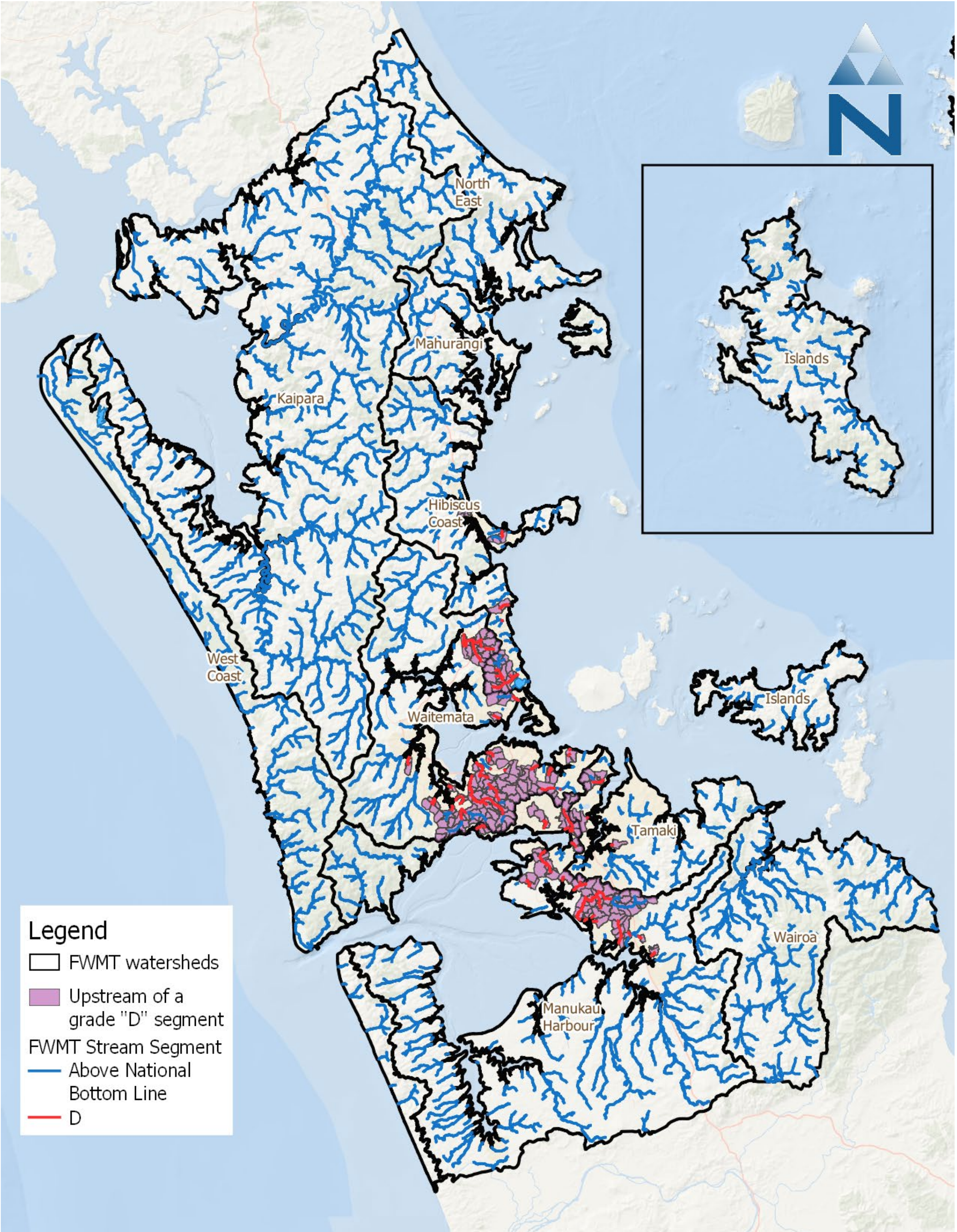


Figure 3-18. Predicted failing stream segments and upstream areas for dissolved zinc based on worst performing numeric attribute state (2013-2017)

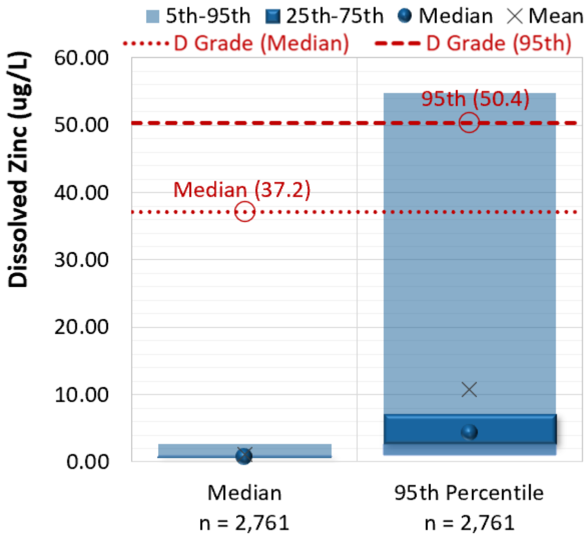


Figure 3-19. For all stream segments, comparison of their predicted median and 95th percentile concentrations compared to D attribute for dissolved zinc. Note regional bottom lines (D grade) numeric attribute states varied in Tāmaki (median >58.9 mg/L; 95th% >79.8 mg/L) and Wairoa (median >21.7 mg/L; 95th% >29.4 mg/L) due to their varying hardness correction

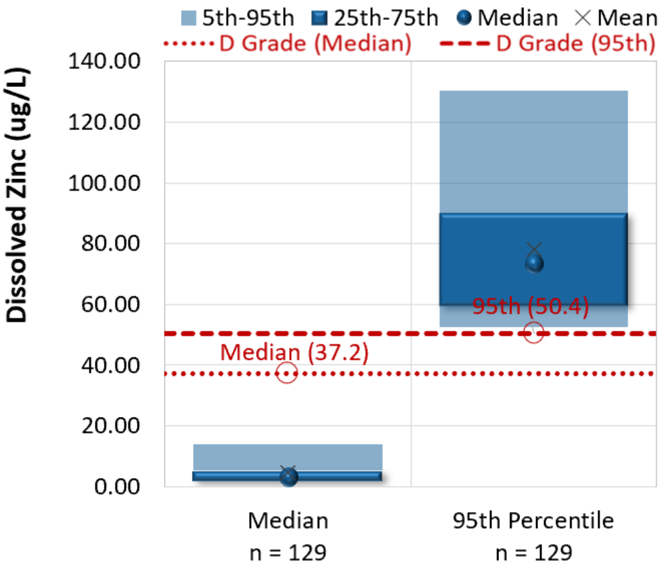


Figure 3-20. For failing stream segments, comparison of their predicted median and 95th percentile concentrations compared to D attribute for dissolved zinc. Note regional bottom lines (D grade) numeric attribute states varied in Tāmaki (median >58.9 mg/L; 95th% >79.8 mg/L) and Wairoa (median >21.7 mg/L; 95th% >29.4 mg/L) due to their varying hardness correction

3.3.4 Total Oxidised Nitrogen (TON)

Total oxidised nitrogen (TON) is the sum of two forms of readily plant-available and potentially toxic forms of nitrogen, nitrate-nitrogen (NO3N) and nitrite-nitrogen (NO2N). Nitrogen is an essential nutrient for plant growth associated with a range of urban and rural discharges (e.g., effluent, fertilizer, wastewater, industrial discharges [LAWA, 2019]). Excessive TON loading can result in nuisance growth of macrophytes and algae in fresh and coastal receiving waters (LAWA, 2019). Greater TON availability still results in deleterious toxicity effects for macroinvertebrates and fish fauna endemic to New Zealand waterways (Hickey, 2013). The numeric attribute states assigned here are derived from those for NO3N that are graded for macroinvertebrate and fish toxicity – a notable difference with subsequent grading in this report of dissolved inorganic nitrogen (DIN).

NO3N grading guidance in the NOF is mandatory and operational for all freshwater streams, rivers, ponds, and lakes under the NPS-FM (2014, 2017 and 2020 variants). However, TON grading output should be treated as potentially non-conservative for determining ecosystem health pressures from dissolved nitrogen availability. The Essential Freshwater proposals (MfE, 2019) included a DIN attribute graded far more conservatively for eutrophication effects than NO3N national bottom-lines. Whilst, the proposed DIN has not been included in the operative NPS-FM (2020), a DIN attribute has been indicated within 12 months.

The TON baseline state (2013-2017) output is presented in Figure 3-21 to Figure 3-25, which includes:

- Figure 3-21 is a regional map of integrated TON grading based on the worst performing metric, as well as grading based on median concentration.
- Figure 3-22 presents predicted, observed and integrated gradings by watershed using the worst performing metric. Regionally, 85% (2,536km) of FWMT reaches are predicted in A grade with less than 2% of FWMT reaches predicted in D grade. All 51km of D-graded FWMT reaches are located solely in the Manukau Harbour watershed. The 63 km of FWMT reaches predicted in C grade are also predominantly located in the Manukau Harbour (51km) with limited spread otherwise in Kaipara (8km), West Coast (2km) and Waitematā watersheds (1km). Overall, 114km of FWMT reaches are predicted to fail the national bottom line for TON (~4% by length of total FWMT reaches).
- Figure 3-23 presents stream segments and contributing upstream areas failing TON national bottom lines from predicted concentrations. Failing reaches are predominant to streams fed by the Franklin Volcanic Aquifer in the Manukau Harbour watershed, which have been observed to breach NO3N national bottom lines consistently (Auckland Council, 2016a). The latter has been linked to widespread horticulture and dairying land use (e.g., Cathcart, 1996; Di and Cameron, 2002; Francis et al., 2003) which have been linked

nationally, to nitrogen enrichment of waterways (Larned et al., 2016; PMCSA, 2017). While the FWMT configuration included regionally parameterised groundwater TN concentrations, a unique parameterisation was required for the area of the Franklin Volcanic Aquifer. The groundwater derived TN input for horticultural HRUs in the area of the Franklin Volcanic Aquifer enabled greater performance at replicating observed instream TON concentrations – and relied on observational records of enriched DIN in both local stream and groundwater concentrations to guide configuration (see [FWMT Baseline Configuration and Performance Report]).

- Figure 3-24 and Figure 3-25 provide box plots for both predicted numeric attribute states, in all and only failing FWMT reaches (respectively). Of the 114km of FWMT reaches failing (C and D grade) for TON (NO3N) bottom lines, more than 95% fail for both acute (95th) and chronic (median) toxicity effects. Combined, more than half of those 114km of failing TON streams require a greater than five-fold reduction in both numeric attribute state (e.g., more than 80% reduction in median and 95th% concentration).

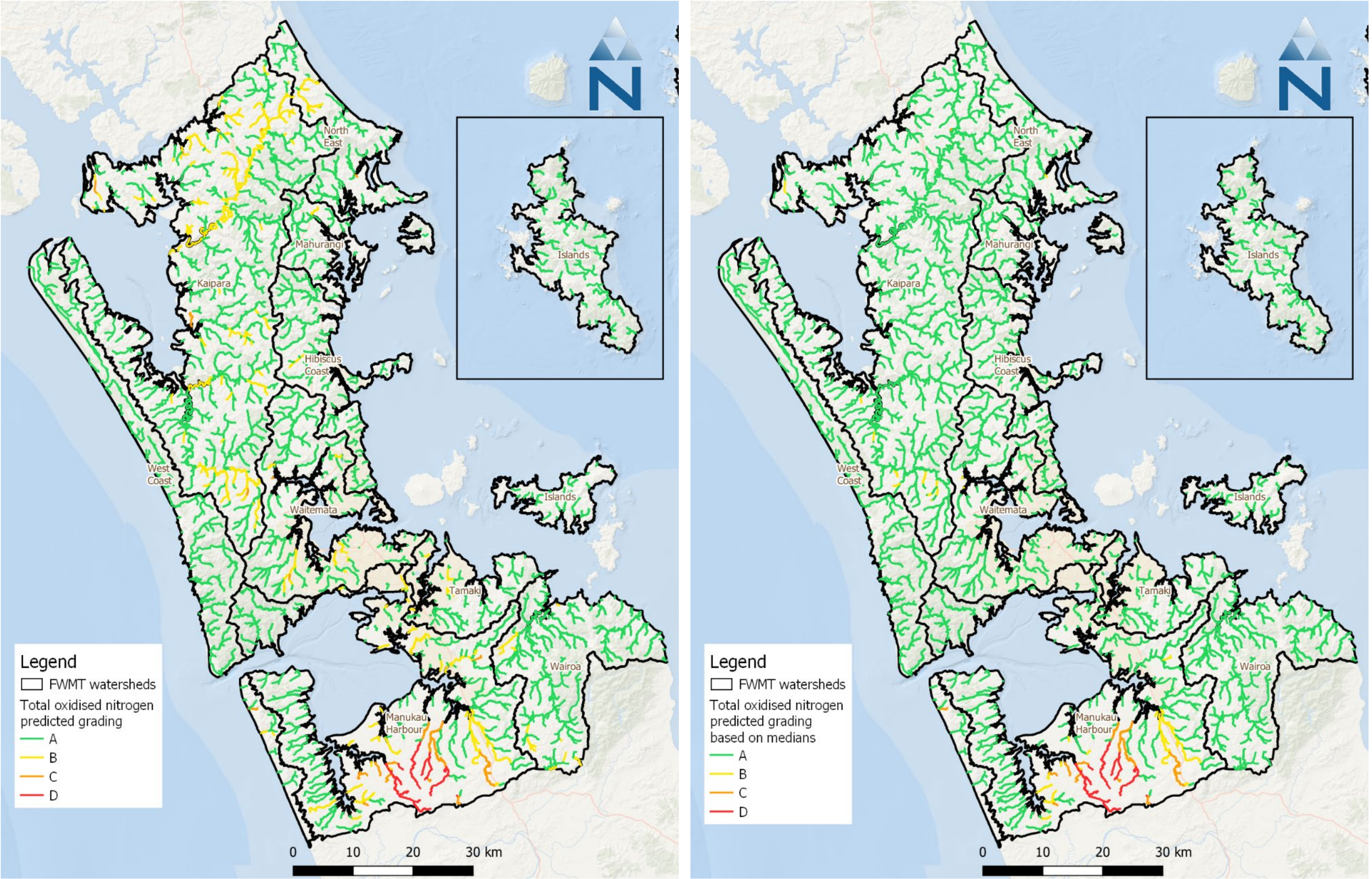


Figure 3-21. Predicted grading for total oxidised nitrogen based on worst performing numeric attribute state (left) and median (right) (2013-2017)

Watershed	Total Oxidised Nitrogen Grading Method	Attainment of Attribute State by Model Stream Length (km) or Number of Stations (#)				Percent of Stream Length or Stations Attaining Attribute State
		A	B	C	D	
Hibiscus Coast	Predicted (km)	152	5	0	0	97%
	Observed (#)	5	0	0	0	100%
	Integrated (km)	152	5	0	0	97%
Islands	Predicted (km)	160	0	0	0	100%
	Observed (#)	2	0	0	0	100%
	Integrated (km)	160	0	0	0	100%
Kaipara	Predicted (km)	782	251	8	0	75% 24%
	Observed (#)	5	0	0	0	100%
	Integrated (km)	850	183	8	0	82% 18%
Mahurangi	Predicted (km)	68	2	0	0	96%
	Observed (#)	2	0	0	0	100%
	Integrated (km)	68	2	0	0	96%
Manukau Harbour	Predicted (km)	326	100	51	51	62% 19% 10% 10%
	Observed (#)	3	1	1	1	50% 17% 17% 17%
	Integrated (km)	343	82	54	51	65% 15% 10% 10%
North East	Predicted (km)	111	18	0	0	86% 14%
	Observed (#)	1	0	0	0	100%
	Integrated (km)	111	18	0	0	86% 14%
Tamaki	Predicted (km)	90	9	0	0	91% 9%
	Observed (#)	3	3	0	0	50% 50%
	Integrated (km)	91	9	0	0	91% 9%
Wairoa	Predicted (km)	342	23	0	0	94% 6%
	Observed (#)	2	0	0	0	100%
	Integrated (km)	342	23	0	0	94% 6%
Waitemata	Predicted (km)	246	24	1	0	91% 9%
	Observed (#)	5	1	0	0	83% 17%
	Integrated (km)	244	26	1	0	90% 9%
West Coast	Predicted (km)	259	2	2	0	99%
	Observed (#)	1	0	0	0	100%
	Integrated (km)	259	2	2	0	99%
Regionwide	Predicted (km)	2,536	436	63	51	82% 14%
	Observed (#)	29	5	1	1	81% 14%
	Integrated (km)	2,620	350	65	51	85% 11%

Figure 3-22. Summary of region-wide and watershed predicted, observed, and integrated grading for total oxidised nitrogen across Auckland streams and rivers based on worst performing numeric attribute state (2013-2017)

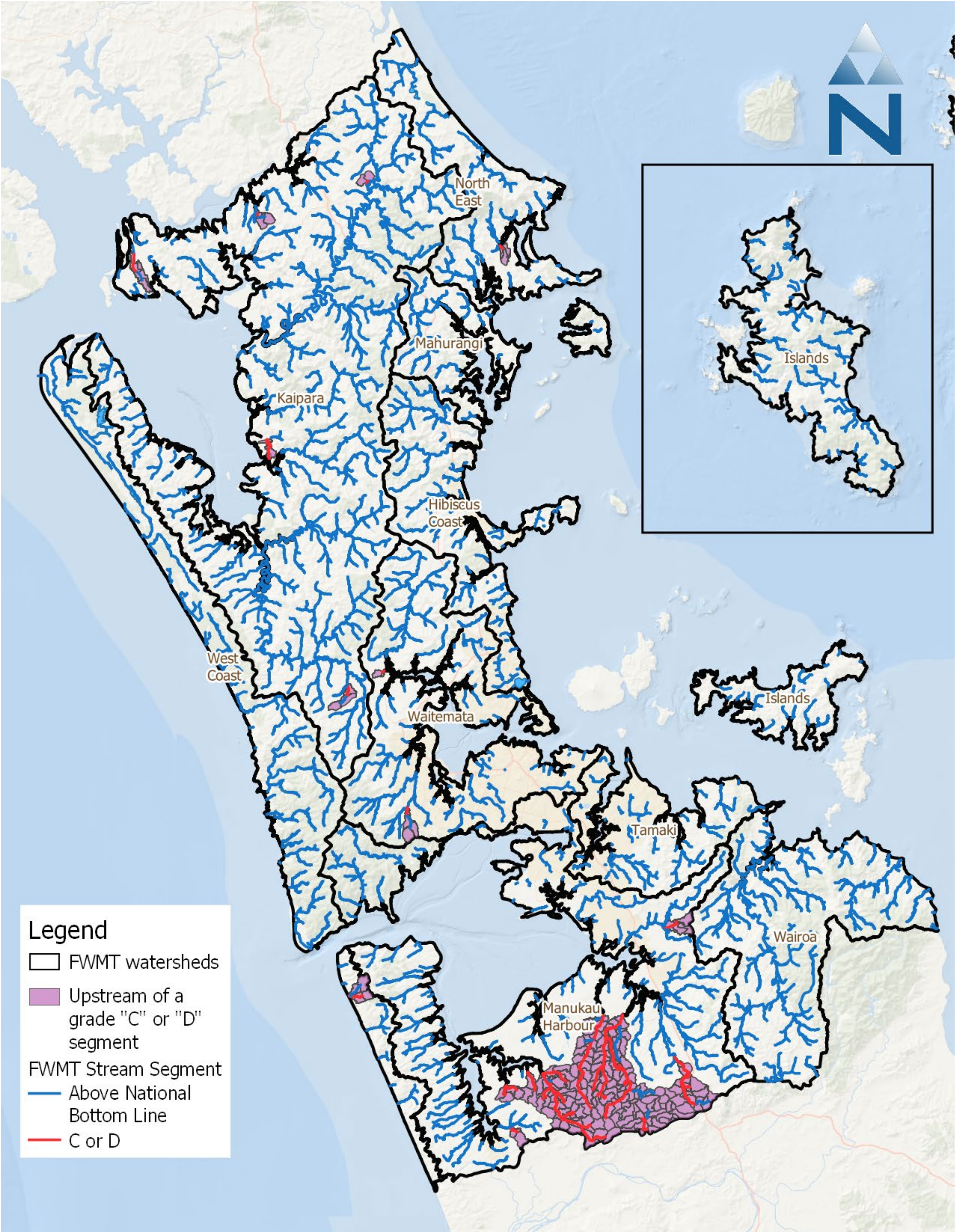


Figure 3-23. Predicted failing (C or D graded) stream segments and upstream areas for total oxidised nitrogen based on worst performing numeric attribute state (2013-2017)

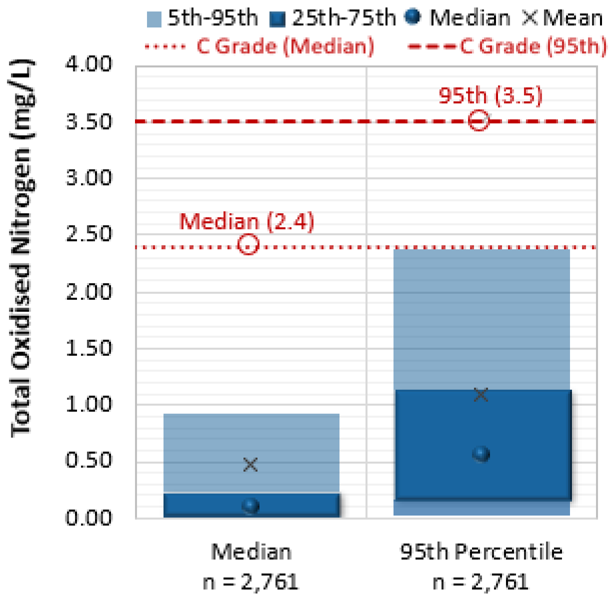


Figure 3-24. For all stream segments, comparison of their predicted median and 95th percentile concentrations compared to C attribute for total oxidised nitrogen

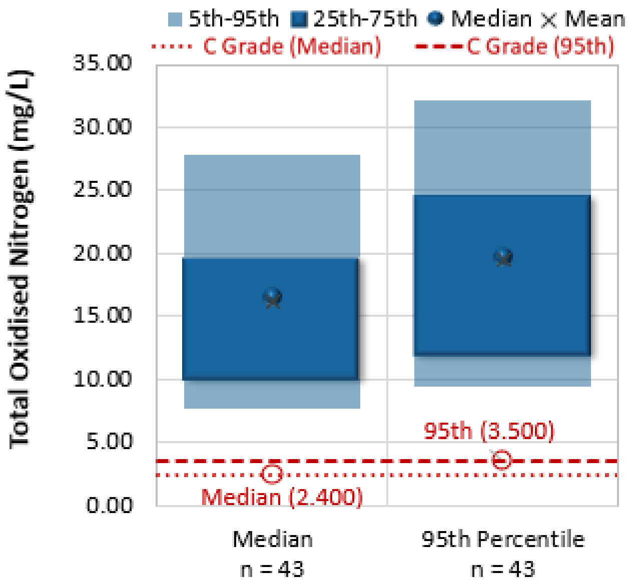


Figure 3-25. For failing stream segments, comparison of their predicted median and 95th percentile concentrations compared to C attribute for total oxidised nitrogen

3.3.5 Total Ammoniacal Nitrogen (TAM)

Total ammoniacal nitrogen (TAM) is one of several forms of nitrogen naturally occurring in the environment and otherwise contributed in discharges from both urban and rural sources (e.g., effluent, fertilizer, wastewater, industrial discharges [LAWA, 2019]). As with TON, excessive TAM loading can result in nuisance plant growth of macrophytes and algae, or even in relatively modest concentration, deleterious toxicity effects for macroinvertebrates and fish fauna endemic to New Zealand waterways (Hickey et al., 1999). TAM is interchangeable with NH4N in NOF guidance, but whose toxicity is primarily through the un-ionised NH3 form (although ammonium ions [$NH4^+$] are also toxic). Speciation of both toxic ammoniacal forms is heavily influenced by pH (greater NH3 proportion at higher pH) (ANZECC, 2000). Whilst the NOF provides for pH and temperature adjustment of observational datasets, neither is accounted for in FWMT Stage 1 reporting[7], instead directly grading predicted TAM into NOF guidance for pH 8 and 20°C. The NOF also specifies use of annual maxima as one of two numeric attribute states, misaligned with recommendations by NIWA (e.g., Table 1 in Hickey [2014] recommending use of 95^{th}% as the alternate numeric attribute state for surveillance grading). The NOF is arguably conservative in its NH4N-toxicity grading, both through a reliance on a maximum statistic and its predominant reliance on exotic (non-endemic) aquatic organism data (i.e., the sensitivity of native or resident New Zealand species including two mayflies, a sphaeriid clam, water flea and rainbow trout is markedly lower than the 95% protection guideline in earlier ANZECC [2000] guidance for 95% community protection – see Hickey, 2014). Use of a maximum is also at odds with good modelling practice, whereby confidence in modelled maxima will be considerably lesser than the 95^{th}% (e.g., increasing risks of misclassification, if maxima are the worst performing numeric attribute state).

To accommodate the potential inappropriateness of existing NOF guidance for modelling, particularly continuous modelling accounting purposes, and earlier recommendations for use of the 95^{th}% to grade surveillance toxicity risk, we have reproduced grading summaries using median and each of the maxima or 95^{th}% NH4N concentrations from the FWMT Stage 1 (note: using Hazen percentile methods). Table 3-4 and Table 3-5 summarise the grading response to alternate metrics, which is marked with 61% (1,690) of FWMT reaches improving by at least one grade (e.g., using 95^{th}% instead of modelled maximum and equivalent NH4N surveillance concentration thresholds for A to D grades; reporting overall grade outcomes or worst of median and surveillance metric). Using a 95^{th}% instead of maxima for surveillance grading of TAM results in 936 (75% less) FWMT reaches no longer failing national bottom-lines (C or D) from overall grade (Table 3-4). Such

[7] The RQUAL module has been activated in LSPC for the FWMT Stage 1, predicting variation in pH and temperature. However, neither have undergone calibration and are not reported here but are likely to undergo prioritisation for Stage 2 development.

marked responses are expected from a continuous and process-based model like the FWMT, particularly where frequent short-term stormwater discharges are represented (e.g., wastewater overflows, onsite wastewater systems and pastoral livestock storm responses are simulated).

TAM is the only freshwater river contaminant to incorporate a maximum-based numeric attribute state in the NOF (operative or proposed). Whilst both maximum and 95^{th}% surveillance output is reported here, the choice between which to grade FWMT outputs has a marked effect on the regional summary. However, a key finding is unaffected by the choice of surveillance numeric attribute, that both 95^{th}% or maxima are most frequently worst-graded (i.e., in 61% and 97% of the FWMT's reaches, respectively). Hence, any effects of NH4N toxicity are predicted to be largely acute in Auckland's freshwater streams.

Table 3-4. Number of FWMT reaches in each numeric attribute grade for surveillance reporting on NH4N toxicity (2013-2017; maxima NOF thresholds used for 95^{th}% and 90^{th}% predicted TAM).

NOF grade	Number of FWMT reaches in TAM grade by numeric attribute state (% of *n* = 2,761)		
	Median	95^{th}%	Max
A	2306 (84%)	827 (30%)	61 (2%)
B	448 (16%)	1628 (59%)	1458 (53%)
C	7 (0%)	276 (10%)	1129 (41%)
D	0 (0%)	30 (1)	113 (4%)

Table 3-5. Change in number of FWMT reaches predicted in corresponding overall NOF grade (from worst performing numeric attribute state) using modelled 95^{th}% instead of maxima (2013-2017)

Difference in overall NOF grading for TAM*	FWMT reaches	
	Count	% (*n* = 2,761)
+1 better (e.g., D to C, C to B, B to A)	1690	61%
+2 better (e.g., D to B, C to A)	31	1%
+3 better (e.g., D to A)	11	0%

*Applying the 95^{th}% instead of maximum precludes any reaches worsening; improvement in more than +3 grades is impossible (e.g., only four grades exist in NOF guidance for NH4N).

The TAM baseline state (2013-2017) output is presented in Figure 3-26 to Figure 3-30, which includes:

- Figure 3-26 presents a regional map of integrated TAM grading based on the worst performing metric comparing median and maxima and median and 95^{th} percentile.
- Figure 3-27 presents predicted, observed and integrated gradings by watershed for overall grading, using both surveillance metrics. Clear differences in regional grading are apparent depending on which of TAM 95^{th}% or maxima are used. If maxima and median are graded overall, approximately half (46%, 1,422 km) of FWMT reaches are C graded, the other half B graded (48%, 1,480km) and <2% A graded (67km). If 95^{th}% is used over half (62%, 1,909 km) of reaches are graded B and 26% are graded A.

- Figure 3-28 presents stream segments and contributing upstream areas failing NH4N national bottom lines from only predicted concentrations. Most failing streams are located in urbanised areas of the Waitematā, Kaipara and North East watersheds, following a pattern broadly aligned with configured wastewater point sources. Based on median and maxima concentrations, 58% of the area in the region is upstream of a failing stream segment, using median and 95^{th}% concentrations, the area is reduced to 19% (Appendix J).
- Figure 3-29 and Figure 3-30 provide box plots for all three numeric attribute states in all and only failing FWMT reaches (respectively). The failing reaches are based on comparison of median versus maxima concentrations. As above, all failing FWMT reaches exceeded only surveillance criteria (e.g., for acute stress from NH4N toxicity). The impact of grading based non 95^{th} percentile versus maxima is evident, with 75% of streams that failed based on maxima concentrations falling passing the same threshold based on 95^{th} percentile. Notably, the magnitude of failures were marked for maxima-based TAM grading, with at least half of the 1,242 such failing reaches requiring a reduction in maximum concentrations 60% or more. Hence, whilst failures of TAM bottom lines are not frequent, the magnitude of failures are high.

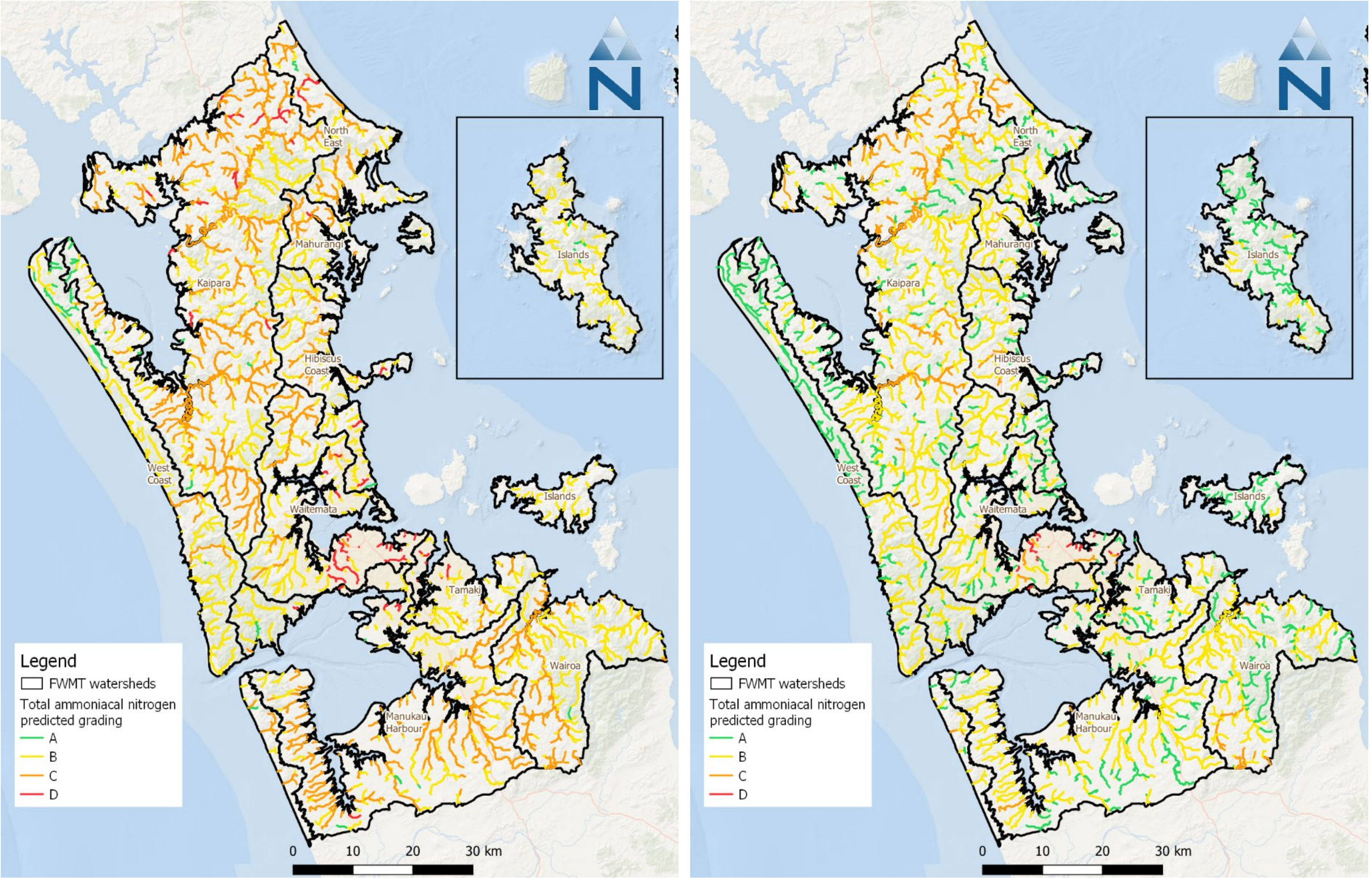
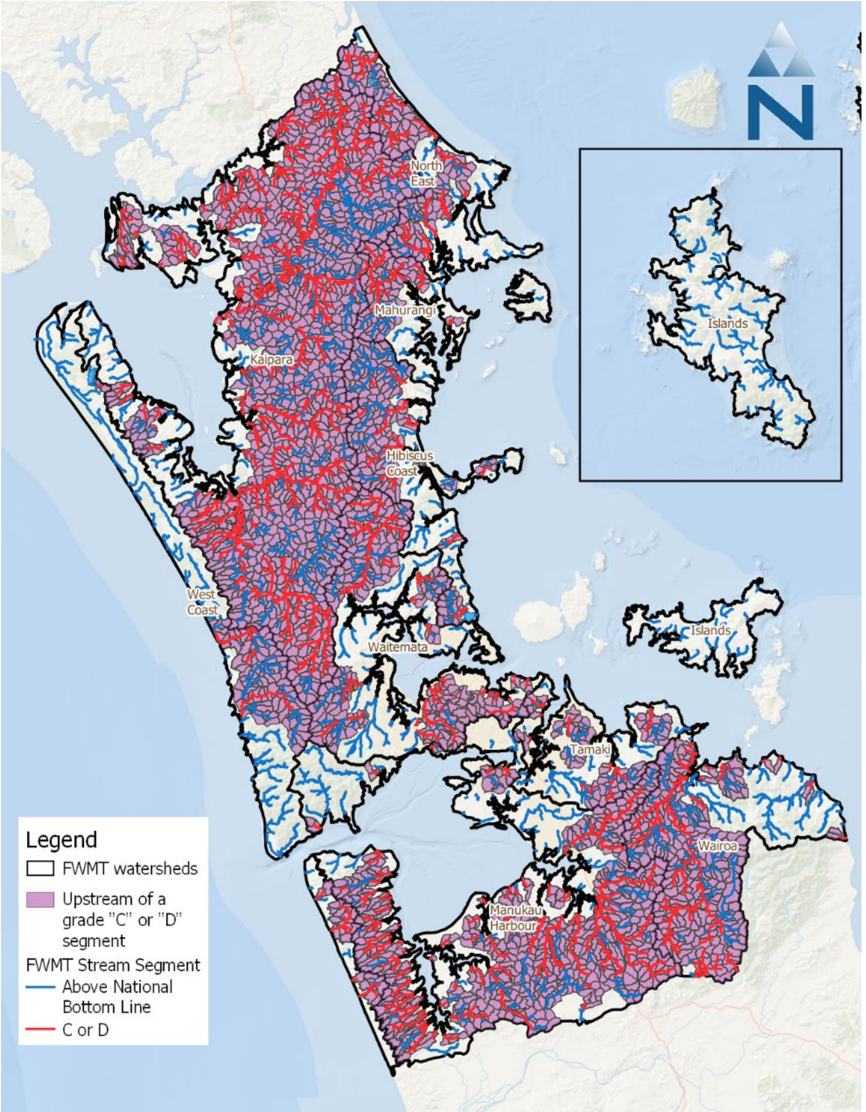


Figure 3-26. Predicted grading for total ammoniacal nitrogen based on worst performing metric attribute (2013-2017): median or maxima (left) and median or 95th% (right)

Watershed	Total Ammoniacal Nitrogen Grading Method	Attainment of Attribute State by Model Stream Length (km) or Number of Stations (#)				Percent of Stream Length or Stations Attaining Attribute State
		A	B	C	D	
Hibiscus Coast	Predicted (km)	1	105	41	9	67% 26% 6%
	Observed (#)	3	2	0	0	60% 40%
	Integrated (km)	11	103	35	9	7% 65% 22% 6%
Islands	Predicted (km)	9	152	0	0	5% 95%
	Observed (#)	2	0	0	0	100%
	Integrated (km)	11	149	0	0	7% 93%
Kaipara	Predicted (km)	13	324	671	32	31% 64%
	Observed (#)	3	2	0	0	60% 40%
	Integrated (km)	53	393	562	32	5% 38% 54%
Mahurangi	Predicted (km)	0	34	35	1	49% 50%
	Observed (#)	2	0	0	0	100%
	Integrated (km)	11	28	30	1	16% 40% 43%
Manukau Harbour	Predicted (km)	6	203	312	7	38% 59%
	Observed (#)	2	3	1	0	33% 50% 17%
	Integrated (km)	15	215	291	7	41% 55%
North East	Predicted (km)	1	46	74	8	36% 57% 6%
	Observed (#)	1	0	0	0	100%
	Integrated (km)	5	46	71	8	36% 54% 6%
Tamaki	Predicted (km)	0	75	16	8	75% 17% 8%
	Observed (#)	1	0	4	1	17% 67% 17%
	Integrated (km)	6	63	22	8	6% 63% 23% 8%
Wairoa	Predicted (km)	4	206	155	0	56% 42%
	Observed (#)	1	1	0	0	50% 50%
	Integrated (km)	26	206	133	0	7% 56% 36%
Waitemata	Predicted (km)	0	147	75	49	54% 28% 18%
	Observed (#)	3	2	1	0	50% 33% 17%
	Integrated (km)	33	140	56	42	12% 52% 20% 16%
West Coast	Predicted (km)	33	187	42	0	12% 71% 16%
	Observed (#)	1	0	0	0	100%
	Integrated (km)	48	182	32	0	18% 69% 12%
Regionwide	Predicted (km)	67	1,480	1,422	116	48% 46%
	Observed (#)	19	10	6	1	53% 28% 17%
	Integrated (km)	220	1,526	1,231	109	7% 49% 40%

Watershed	Total Ammoniacal Nitrogen Grading Method	Attainment of Attribute State by Model Stream Length (km) or Number of Stations (#)				Percent of Stream Length or Stations Attaining Attribute State
		A	B	C	D	
Hibiscus Coast	Predicted (km)	44	103	9	1	28% 66% 6%
	Observed (#)	4	1	0	0	80% 20%
	Integrated (km)	55	91	9	1	35% 58% 6%
Islands	Predicted (km)	126	35	0	0	78% 22%
	Observed (#)	2	0	0	0	100%
	Integrated (km)	126	35	0	0	78% 22%
Kaipara	Predicted (km)	146	624	271	0	14% 60% 26%
	Observed (#)	4	1	0	0	80% 20%
	Integrated (km)	258	584	199	0	25% 56% 19%
Mahurangi	Predicted (km)	6	63	1	0	9% 90%
	Observed (#)	2	0	0	0	100%
	Integrated (km)	17	52	1	0	24% 74%
Manukau Harbour	Predicted (km)	109	412	7	1	21% 78%
	Observed (#)	4	1	1	0	67% 17% 17%
	Integrated (km)	124	397	7	1	23% 75%
North East	Predicted (km)	32	79	19	0	24% 61% 15%
	Observed (#)	1	0	0	0	100%
	Integrated (km)	35	76	19	0	27% 58% 15%
Tamaki	Predicted (km)	42	55	1	2	42% 55%
	Observed (#)	3	1	2	0	50% 17% 33%
	Integrated (km)	44	50	4	1	44% 51%
Wairoa	Predicted (km)	94	241	30	0	26% 66% 8%
	Observed (#)	2	0	0	0	100%
	Integrated (km)	116	219	30	0	32% 60% 8%
Waitemata	Predicted (km)	71	163	15	22	26% 60% 6% 8%
	Observed (#)	5	1	0	0	83% 17%
	Integrated (km)	110	128	12	22	41% 47% 8%
West Coast	Predicted (km)	126	134	2	0	48% 51%
	Observed (#)	1	0	0	0	100%
	Integrated (km)	138	122	2	0	53% 47%
Regionwide	Predicted (km)	795	1,909	356	25	26% 62% 12%
	Observed (#)	28	5	3	0	78% 14% 8%
	Integrated (km)	1,023	1,754	283	24	33% 57% 9%

Figure 3-27. Summary of region-wide and watershed predicted, observed, and integrated grading for total ammoniacal nitrogen across Auckland streams and rivers based on worst performing numeric attribute state (2013-2017): median or maxima (left) and median or 95th% (right)



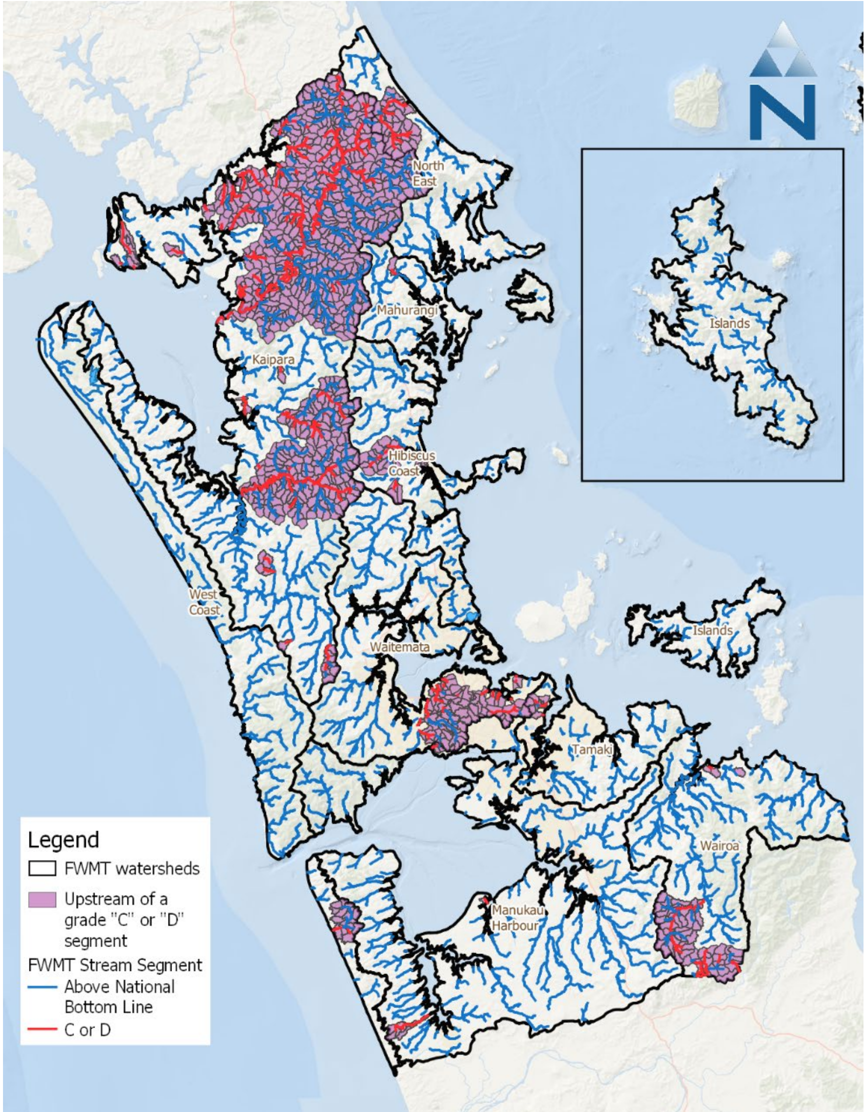


Figure 3-28. Predicted failing (C or D graded) stream segments and upstream areas for total ammoniacal nitrogen based on worst performing numeric attribute state (2013-2017): median or maxima (left) and median or 95th% (right)

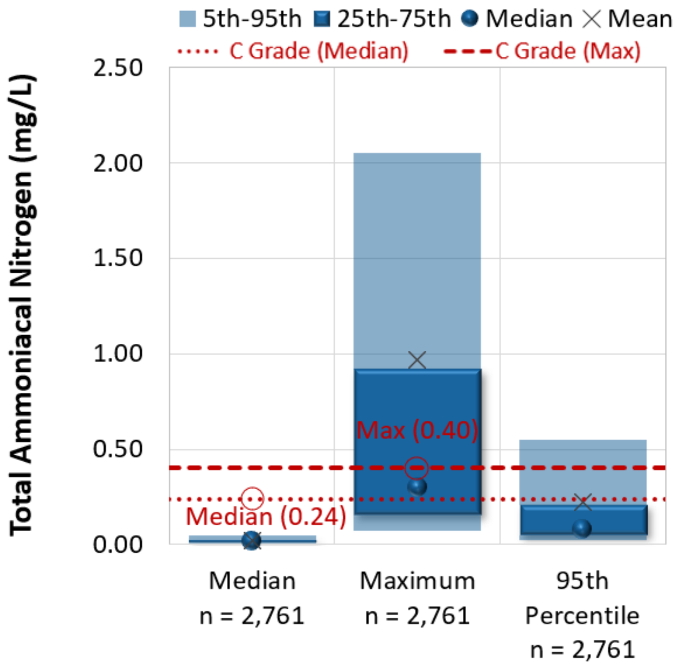


Figure 3-29. For all stream segments, comparison of their predicted median and maximum concentrations compared to C attribute for total ammoniacal nitrogen

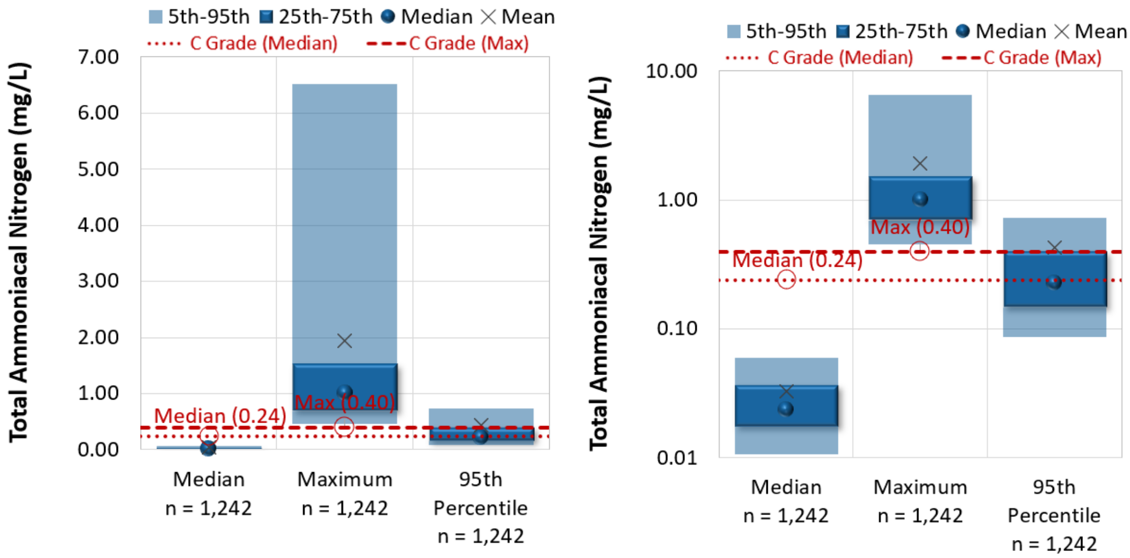
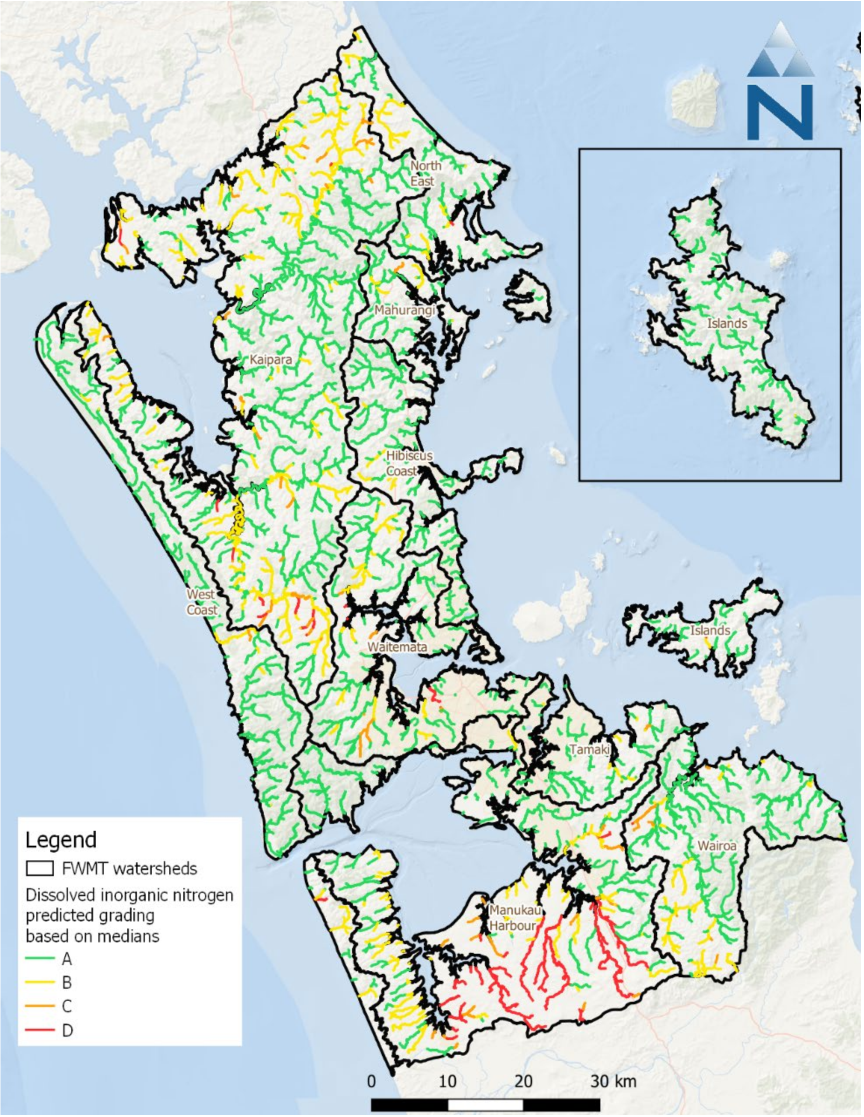


Figure 3-30. For failing stream segments based on median versus maxima concentrations, comparison of their predicted median and maximum concentrations compared to C attribute for total ammoniacal nitrogen. Data is presented on non-logarithmic (left) and logarithmic (right) scales

3.3.6 Dissolved Inorganic Nitrogen (DIN)

Dissolved inorganic nitrogen (DIN) is the sum of all dissolved and readily plant-available forms of nitrogen, predominantly nitrate-nitrogen and nitrite-nitrogen but with the addition of ammoniacal-nitrogen. It therefore differs in concentration to TON and unlike the latter, DIN has been proposed as a new NOF attribute grading for risks of eutrophication in freshwater streams and rivers. Eutrophic responses by algae and macrophytes generally occur at considerably lesser concentrations of DIN than otherwise necessary for nitrate or ammonia toxicity effects in freshwater invertebrates or fish (Camargo and Alonso, 2006). Hence, DIN grading criteria are more conservative than those for NO3N-toxicity under the NOF (e.g., despite including similar forms of nitrogen, concentrations for numeric attribute states are far less permissive for equivalent NOF grading). Note the DIN attribute proposed in the Essential Freshwater package (MfE, 2019) was not incorporated into the NPS-FM (2020) with a decision to incorporate the attribute deferred for 12 months. Hence DIN is reported here as proposed, simply to gauge reporting outcomes should it later become an attribute for limit-setting.

The DIN baseline state (2013-2017) output is presented in Figure 3-31 to Figure



3-35 which includes:

- Figure 3-31 is a regional map of predicted grading for DIN based on the worst performing metric, as well as grading based on median concentration.
- Figure 3-32 presents predicted, observed and integrated gradings by watershed using the worst performing metric. Regionally, 16% (478km) of FWMT reaches were predicted in D grade for DIN (compared to 2% graded D for TON) whilst 41% (1,276km) were predicted in A grade (compared to 85% graded A for TON). FWMT reaches predicted in D grade were located predominantly in the Manukau Harbour (32%, 170km) with notable failing streams also in the Kaipara (21%, 221km), Waitematā (16%, 44km) and North East watersheds (14%, 19km). DIN guidance for eutrophic effects being more sensitive than TON toxicity guidance, has resulted in equivalent Franklin aquifer-fed streams being highlighted as failing proposed national bottom lines but also, considerable extent of urban catchments.

- Figure 3-33 presents failing stream segments and contributing upstream areas failing DIN proposed national bottom lines from predicted concentrations.
- Figure 3-34 and Figure 3-35 provide box plots for both predicted numeric attribute states, in all and only failing FWMT reaches (respectively). 382 of 2,761 FWMT reaches failed the proposed national bottom line of which approximately half (three quarters) failed for median (95^{th}%) numeric attribute state. In both numeric attribute states, moderate reductions in DIN concentrations are necessary for those 382 failing reaches. For instance, three quarters of failing reaches require less than a halving in 95^{th}% DIN concentration and far less still, to median concentrations. At least half of the 363 failing reaches require less than a 25% reduction in associated 95^{th}% or median concentrations. Hence, collectively DIN failures are not particularly extensive or marked across watersheds, with the notable exception of the Manukau Harbour.

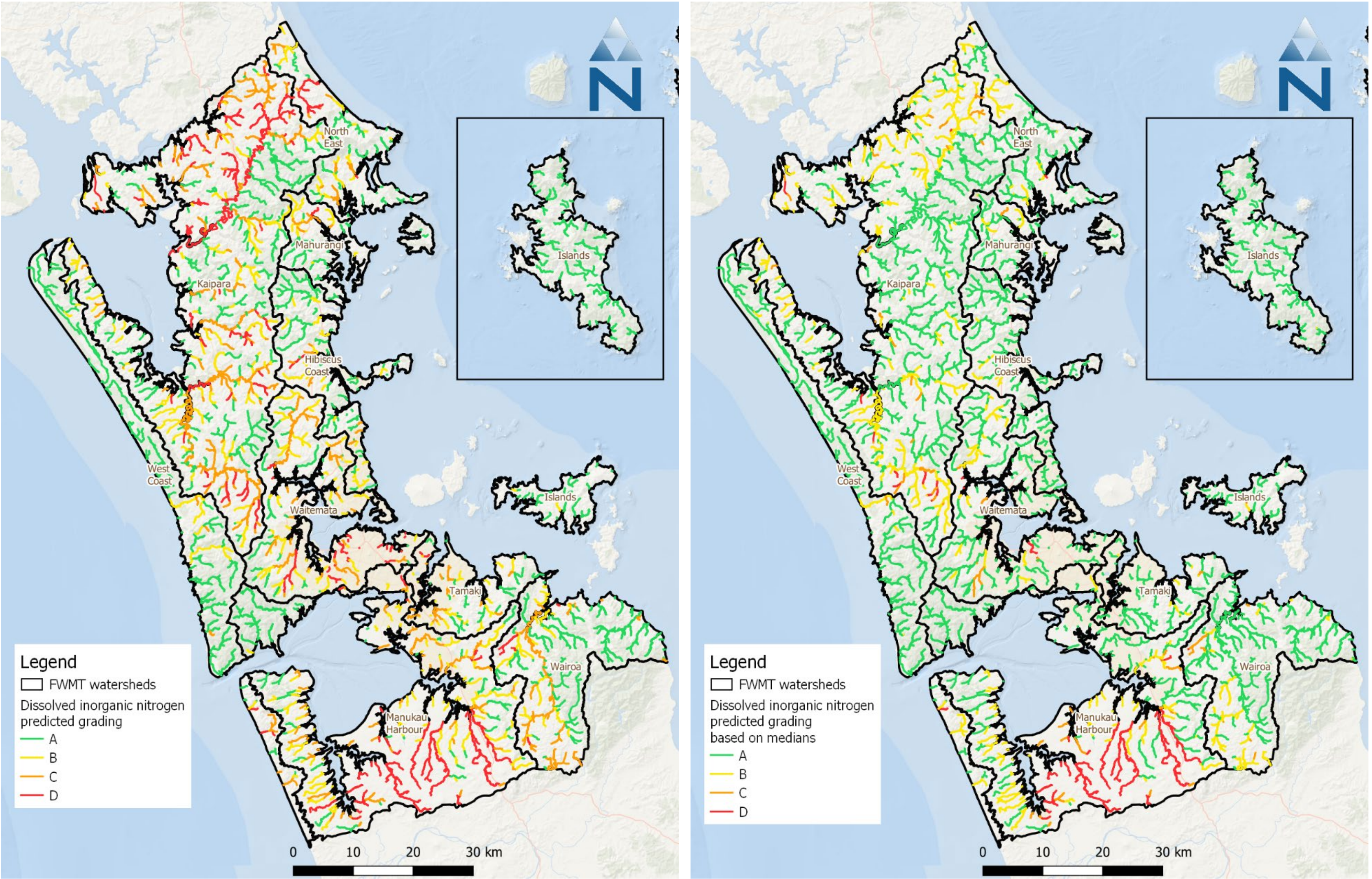


Figure 3-31. Predicted grading for dissolved inorganic nitrogen based on worst performing numeric attribute state (left) and median (right) (2013-2017)

Watershed	Dissolved Inorganic Nitrogen Grading Method	Attainment of Attribute State by Model Stream Length (km) or Number of Stations (#)				Percent of Stream Length or Stations Attaining Attribute State
		A	B	C	D	
Hibiscus Coast	Predicted (km)	96	41	14	6	61% / 26% / 9%
	Observed (#)	4	1	0	0	80% / 20%
	Integrated (km)	99	39	14	6	63% / 25% / 9%
Islands	Predicted (km)	158	2	0	0	98%
	Observed (#)	2	0	0	0	100%
	Integrated (km)	158	2	0	0	98%
Kaipara	Predicted (km)	321	192	307	221	31% / 18% / 30% / 21%
	Observed (#)	3	2	0	0	60% / 40%
	Integrated (km)	353	269	249	170	34% / 26% / 24% / 16%
Mahurangi	Predicted (km)	35	22	11	2	50% / 31% / 15%
	Observed (#)	2	0	0	0	100%
	Integrated (km)	41	21	6	2	59% / 30% / 8%
Manukau Harbour	Predicted (km)	110	151	98	170	21% / 28% / 19% / 32%
	Observed (#)	0	0	3	3	50% / 50%
	Integrated (km)	107	140	111	171	20% / 26% / 21% / 32%
North East	Predicted (km)	53	36	22	19	40% / 28% / 17% / 14%
	Observed (#)	1	0	0	0	100%
	Integrated (km)	56	33	22	19	43% / 25% / 17% / 14%
Tamaki	Predicted (km)	38	33	26	2	38% / 33% / 26%
	Observed (#)	0	1	2	3	17% / 33% / 50%
	Integrated (km)	37	35	23	4	38% / 36% / 23%
Wairoa	Predicted (km)	204	61	91	10	56% / 17% / 25%
	Observed (#)	1	1	0	0	50% / 50%
	Integrated (km)	204	82	69	10	56% / 23% / 19%
Waitemata	Predicted (km)	54	93	81	44	20% / 34% / 30% / 16%
	Observed (#)	2	3	0	1	33% / 50% / 17%
	Integrated (km)	81	97	46	48	30% / 36% / 17% / 18%
West Coast	Predicted (km)	206	37	15	4	79% / 14% / 6%
	Observed (#)	1	0	0	0	100%
	Integrated (km)	216	27	15	4	82% / 10% / 6%
Regionwide	Predicted (km)	1,276	667	664	478	41% / 22% / 22% / 16%
	Observed (#)	16	8	5	7	44% / 22% / 14% / 19%
	Integrated (km)	1,352	745	553	435	44% / 24% / 18% / 14%

Figure 3-32. Summary of region-wide and watershed predicted, observed, and integrated grading for dissolved inorganic nitrogen across Auckland streams and rivers based on worst performing numeric attribute state (2013-2017)

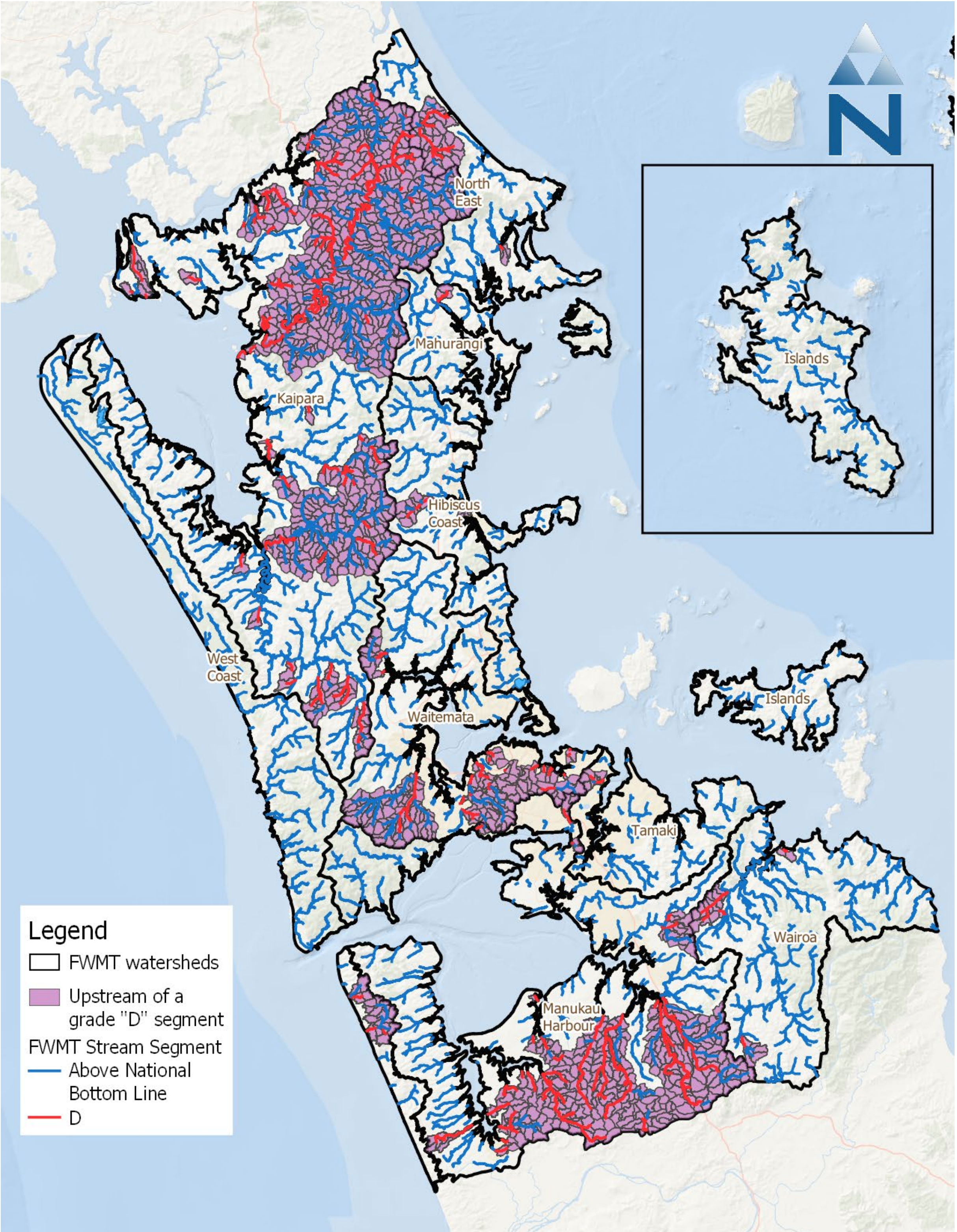


Figure 3-33. Predicted failing stream segments and upstream areas for dissolved inorganic nitrogen based on worst-performing numeric attribute state (2013-2017)

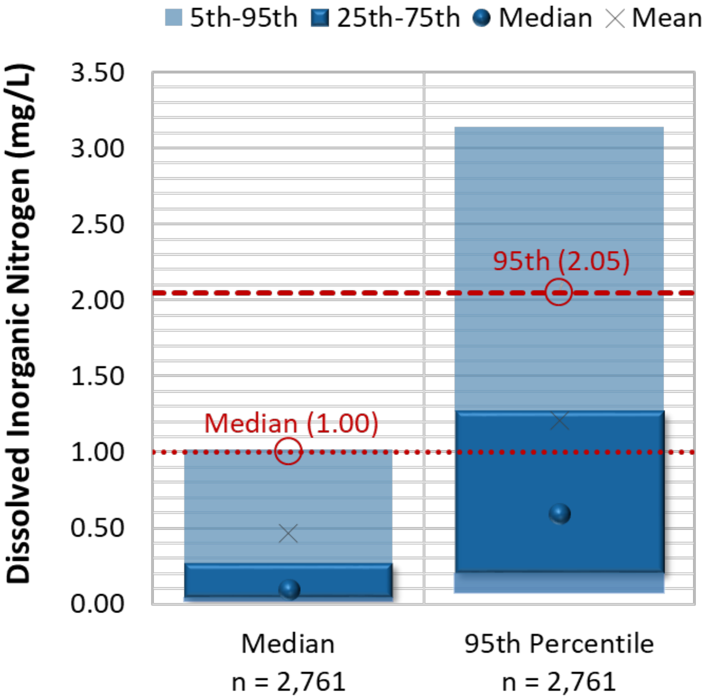


Figure 3-34. For <u>all</u> stream segments, comparison of their predicted median and 95th percentile concentrations compared to D attribute for dissolved inorganic nitrogen

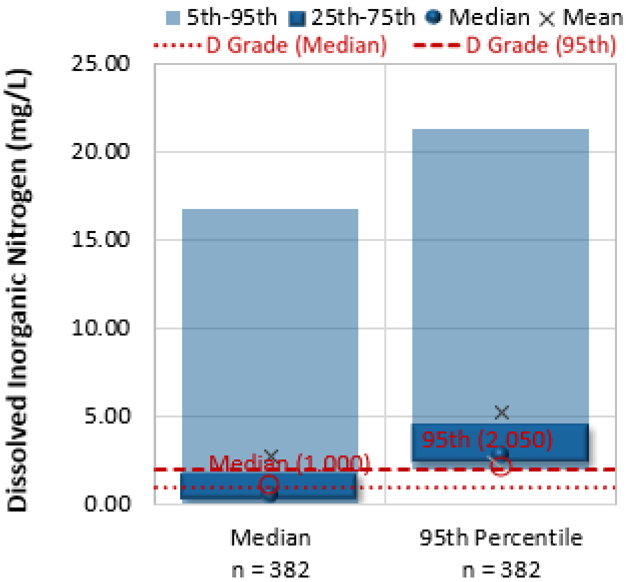


Figure 3-35. For <u>failing</u> stream segments, comparison of their predicted median and 95th percentile concentrations compared to D attribute for dissolved inorganic nitrogen

3.3.7 Dissolved Reactive Phosphorus (DRP)

Phosphorus, like nitrogen, is an essential nutrient for plant and algal growth with excessive amounts leading to degradation of ecological community structure and function. Dissolved reactive phosphorus (DRP) like DIN is a form of phosphorus that is readily plant available and whose inclusion in the NOF was proposed in the Essential Freshwater package to manage for the risks of eutrophication in freshwater rivers and streams (MfE, 2019). Since, the NPS-FM (2020) has incorporated DRP grading criteria but without a national bottom-line, and with DRP an attribute requiring action plans (e.g., differing from NO3N, NH4N and *E. coli* attributes requiring limits on resource use).

The basis for DRP grading thresholds on numeric attribute states is unclear, with limited evidence shared in the Essential Freshwater package. However, Local Government New Zealand (LGNZ, 2019) notes that the DIN and DRP attributes are intended to apply to all streams whether soft or hard-bottomed (i.e., ensure management of nutrients for effects at lower than toxic effect even where conspicuous periphyton growth is unlikely). LGNZ (2019) noted DRP guidance appears highly conservative with the B/C grading threshold (median numeric attribute state) located at the prior ANZECC (2000) trigger value (i.e., the median numeric attribute state marking “good” from “fair” state in the proposed DRP attribute is equivalent to ANZECC guidance to trigger investigation of whether degradation from reference state has occurred).

DRP grading has been examined for variation due to integration period (e.g., daily vs. monthly numeric attribute state). The rationale being that DRP was frequently D-graded in FWMT reaches (i.e., second only to *E. coli* at 59% and 83%, respectively by length of FWMT reaches). Assessment of integration period is useful for highlighting if the use of daily period has inflated (degraded) numeric attribute states.

The DRP baseline state (2013-2017) output is presented in Figure 3-36 to Figure 3-42, which includes:

- Figure 3-36 is a regional map of predicted DRP grading based on the worst performing metric, as well as gradings based on median concentration.
- Figure 3-37 presents predicted, observed and integrated gradings by watershed using the worst performing metric as well as the median. Clearly, proposed DRP guidance results in large swathes of the FWMT reach network being D-graded (e.g., over half the region’s modelled streams [53%, 1,814km] would possess ecological communities substantially impacted by eutrophication). Whilst the proportion of failing reaches differs between both numeric attributes, D-grades are widespread (overall grade) in all 10 watersheds, ranging from a third of West Coast (33%, 87km) to two-thirds of Kaipara (74%, 769km) watersheds. Urbanised watersheds were also predicted to possess extensive reaches of D-grade. For instance, both

Hibiscus Coast (57%, 90km) and Waitematā watersheds (60%, 162km) reported near equivalent D-graded FWMT reaches (overall grade).

- Figure 3-38 presents a comparison of predicted gradings based on daily flow-weighted and monthly simple averages. In seven watersheds, monthly periods are associated with worse overall grading – the exceptions being Tāmaki, Waitematā and West Coast watersheds. Region-wide, the percentage of D-graded FWMT reaches increased from 59% to 62% when based on monthly averages (by length and for overall grade). The increased lengths of FWMT reaches D-graded under monthly averages, varied from 1% more (Hibiscus Coast, Mahurangi) to 8% more (Manukau Harbour, North East).
- Figure 3-39 presents stream segments and contributing areas upstream of D-graded FWMT reaches for DRP.
- Figure 3-40 and Figure 3-41 provide box plots for both predicted numeric attribute states, in all and only D-graded FWMT reaches (respectively). Amongst D-graded FWMT reaches (1,394), nearly half were for median and over three quarters for 95^{th}% concentrations. Additionally, there are marked differences in the magnitude of reduction needed to both failing numeric attributes. At least 95% of failing reaches require less than a halving of corresponding median DRP concentrations whereas nearly half of failing reaches require more than a halving of 95^{th}% DRP concentrations. Hence, collectively DRP failures are both extensive and of marked magnitude.
- Figure 3-42 compares D-graded FWMT reaches based on daily and monthly averaging. While 95^{th} percentile concentrations are lower based on monthly averaging, median values increase, resulting in more D-graded stream segments. As above, a clear pattern for considerably more marked reduction needed in 95^{th}% concentrations than medians is evident regardless of averaging period and which appears substantial for half or so of D-graded reaches (e.g., greater than halving in 95^{th}% required for a quarter of failing sites).

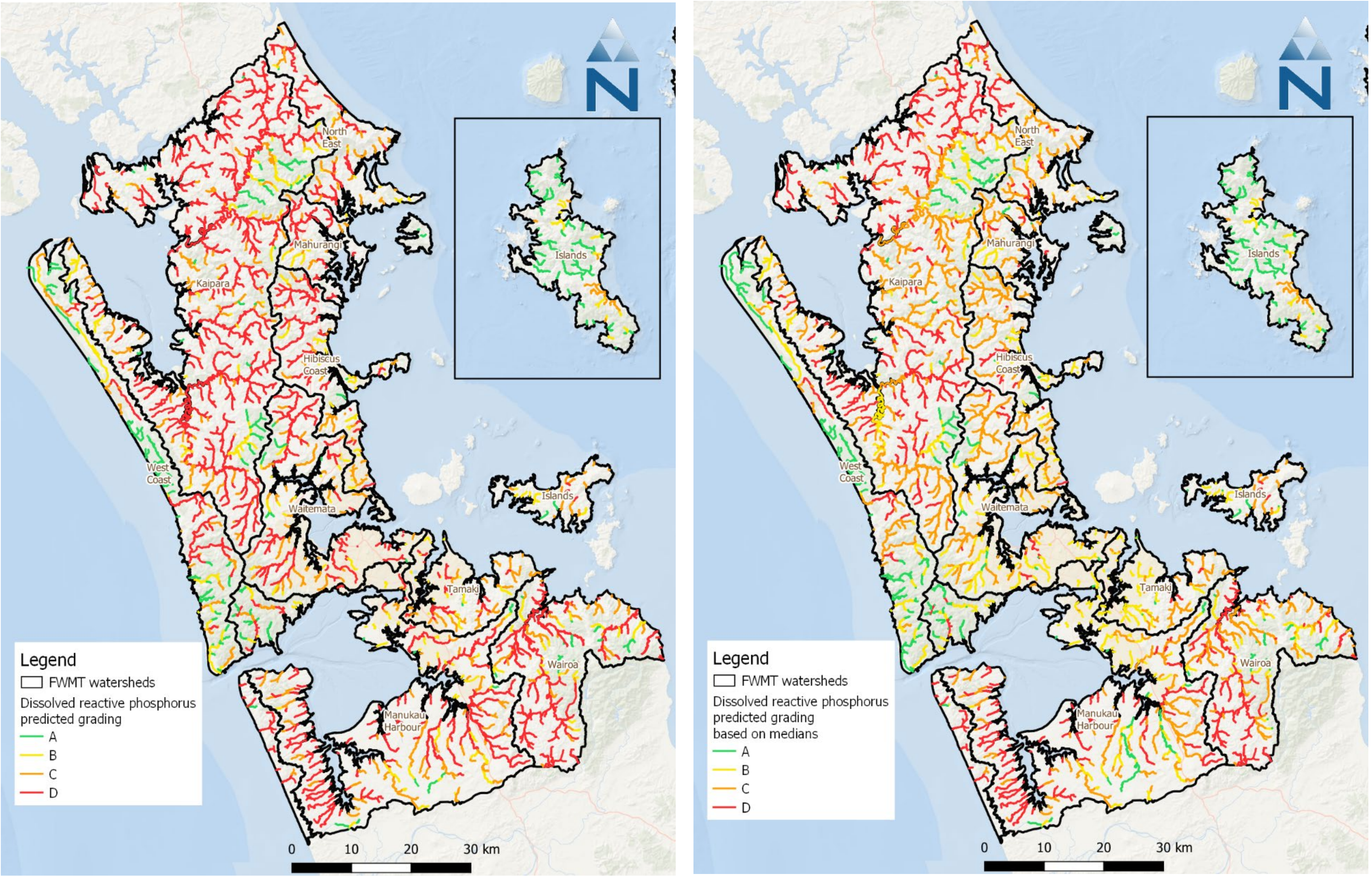


Figure 3-36. Predicted grading for DRP based on worst performing metric (left) and median (right) (2013-2017)

Watershed	Dissolved Reactive Phosphorus Grading Method	Attainment of Attribute State by Model Stream Length (km) or Number of Stations (#)				Percent of Stream Length or Stations Attaining Attribute State
		A	B	C	D	
Hibiscus Coast	Predicted (km)	2	27	38	90	17% 24% 57%
	Observed (#)	0	2	2	1	40% 40% 20%
	Integrated (km)	2	27	44	84	17% 28% 53%
Islands	Predicted (km)	89	32	37	3	55% 20% 23%
	Observed (#)	0	0	1	1	50% 50%
	Integrated (km)	87	32	38	4	54% 20% 23%
Kaipara	Predicted (km)	49	83	140	769	8% 13% 74%
	Observed (#)	0	1	3	1	20% 60% 20%
	Integrated (km)	47	84	227	682	8% 22% 66%
Mahurangi	Predicted (km)	0	10	16	44	14% 23% 63%
	Observed (#)	0	1	1	0	50% 50%
	Integrated (km)	0	11	21	38	16% 30% 54%
Manukau Harbour	Predicted (km)	28	59	143	299	5% 11% 27% 57%
	Observed (#)	0	3	1	2	50% 17% 33%
	Integrated (km)	26	66	143	293	13% 27% 55%
North East	Predicted (km)	0	6	46	77	35% 60%
	Observed (#)	0	0	1	0	100%
	Integrated (km)	0	6	49	74	38% 57%
Tamaki	Predicted (km)	1	20	45	33	20% 46% 34%
	Observed (#)	0	0	3	3	50% 50%
	Integrated (km)	1	19	54	26	19% 54% 26%
Wairoa	Predicted (km)	19	38	60	249	5% 10% 16% 68%
	Observed (#)	0	0	1	1	50% 50%
	Integrated (km)	19	38	82	227	5% 10% 22% 62%
Waitemata	Predicted (km)	10	32	67	162	12% 25% 60%
	Observed (#)	0	0	5	1	83% 17%
	Integrated (km)	10	32	102	127	12% 37% 47%
West Coast	Predicted (km)	86	45	45	87	33% 17% 17% 33%
	Observed (#)	0	0	0	1	100%
	Integrated (km)	86	45	41	91	33% 17% 16% 35%
Regionwide	Predicted (km)	283	351	636	1,814	9% 11% 21% 59%
	Observed (#)	0	7	18	11	19% 50% 31%
	Integrated (km)	278	362	799	1,647	9% 12% 26% 53%

Watershed	Dissolved Reactive Phosphorus Grading Method	Attainment of Attribute State by Model Stream Length (km) or Number of Stations (#)				Percent of Stream Length or Stations Attaining Attribute State
		A	B	C	D	
Hibiscus Coast	Predicted (km)	2	36	102	17	23% 65% 11%
	Observed (#)	0	2	3	0	40% 60%
	Integrated (km)	2	37	102	17	23% 65% 11%
Islands	Predicted (km)	89	34	35	3	55% 21% 22%
	Observed (#)	0	0	1	1	50% 50%
	Integrated (km)	87	33	37	4	54% 20% 23%
Kaipara	Predicted (km)	54	115	449	423	5% 11% 43% 41%
	Observed (#)	0	1	3	1	20% 60% 20%
	Integrated (km)	52	117	457	414	5% 11% 44% 40%
Mahurangi	Predicted (km)	2	15	46	7	21% 65% 10%
	Observed (#)	0	1	1	0	50% 50%
	Integrated (km)	2	15	46	7	21% 65% 10%
Manukau Harbour	Predicted (km)	61	99	194	174	12% 19% 37% 33%
	Observed (#)	0	3	1	2	50% 17% 33%
	Integrated (km)	59	101	168	201	11% 19% 32% 38%
North East	Predicted (km)	0	11	80	39	9% 61% 30%
	Observed (#)	0	0	1	0	100%
	Integrated (km)	0	11	80	39	9% 61% 30%
Tamaki	Predicted (km)	1	51	44	4	51% 44%
	Observed (#)	0	0	3	3	50% 50%
	Integrated (km)	1	39	52	7	40% 53% 7%
Wairoa	Predicted (km)	19	54	138	154	5% 15% 38% 42%
	Observed (#)	0	0	1	1	50% 50%
	Integrated (km)	19	54	160	132	5% 15% 44% 36%
Waitemata	Predicted (km)	17	103	133	19	6% 38% 49% 7%
	Observed (#)	0	0	5	1	83% 17%
	Integrated (km)	17	80	151	24	6% 29% 56% 9%
West Coast	Predicted (km)	118	48	49	47	45% 18% 19% 18%
	Observed (#)	0	0	0	1	100%
	Integrated (km)	116	43	41	62	44% 17% 16% 24%
Regionwide	Predicted (km)	363	567	1,269	886	12% 18% 41% 29%
	Observed (#)	0	7	19	10	19% 53% 28%
	Integrated (km)	355	530	1,294	907	11% 17% 42% 29%

Figure 3-37. Summary of region-wide and watershed predicted, observed, and integrated grading for DRP across Auckland streams and rivers based on worst performing numeric attribute state (left) and median (right) (2013-2017)

Watershed	Dissolved Reactive Phosphorus Grading Method	Attainment of Attribute State by Model Stream Length (km) or Number of Stations (#)				Percent of Stream Length or Stations Attaining Attribute State
		A	B	C	D	
Hibiscus Coast	Predicted (Daily)	2	27	38	90	17% 24% 57%
	Predicted (Monthly)	2	13	52	91	8% 33% 58%
	Observed	0	2	2	1	40% 40% 20%
Islands	Predicted (Daily)	89	32	37	3	55% 20% 23%
	Predicted (Monthly)	55	61	32	12	34% 38% 20% 8%
	Observed	0	0	1	1	50% 50%
Kaipara	Predicted (Daily)	49	83	140	769	8% 13% 74%
	Predicted (Monthly)	29	70	129	812	7% 12% 78%
	Observed	0	1	3	1	20% 60% 20%
Mahurangi	Predicted (Daily)	0	10	16	44	14% 23% 63%
	Predicted (Monthly)	0	4	21	45	6% 30% 64%
	Observed	0	1	1	0	50% 50%
Manukau Harbour	Predicted (Daily)	28	59	143	299	5% 11% 27% 57%
	Predicted (Monthly)	16	53	115	346	10% 22% 65%
	Observed	0	3	1	2	50% 17% 33%
North East	Predicted (Daily)	0	6	46	77	35% 60%
	Predicted (Monthly)	0	4	38	88	29% 68%
	Observed	0	0	1	0	100%
Tamaki	Predicted (Daily)	1	20	45	33	20% 46% 34%
	Predicted (Monthly)	1	7	71	20	8% 71% 21%
	Observed	0	0	3	3	50% 50%
Wairoa	Predicted (Daily)	19	38	60	249	5% 10% 16% 68%
	Predicted (Monthly)	10	30	66	259	8% 18% 71%
	Observed	0	0	1	1	50% 50%
Waitemata	Predicted (Daily)	10	32	67	162	12% 25% 60%
	Predicted (Monthly)	3	28	80	161	10% 29% 59%
	Observed	0	0	5	1	83% 17%
West Coast	Predicted (Daily)	86	45	45	87	33% 17% 17% 33%
	Predicted (Monthly)	75	67	37	83	29% 26% 14% 32%
	Observed	0	0	0	1	100%
Regionwide	Predicted (Daily)	283	351	636	1,814	9% 11% 21% 59%
	Predicted (Monthly)	191	337	641	1,916	6% 11% 21% 62%
	Observed	0	7	18	11	19% 50% 31%

Figure 3-38. Summary of region-wide and watershed predictions based on daily flow-weighted and monthly simple averages and observed data for DRP across Auckland streams and rivers based on worst performing numeric attribute state (2013-2017)

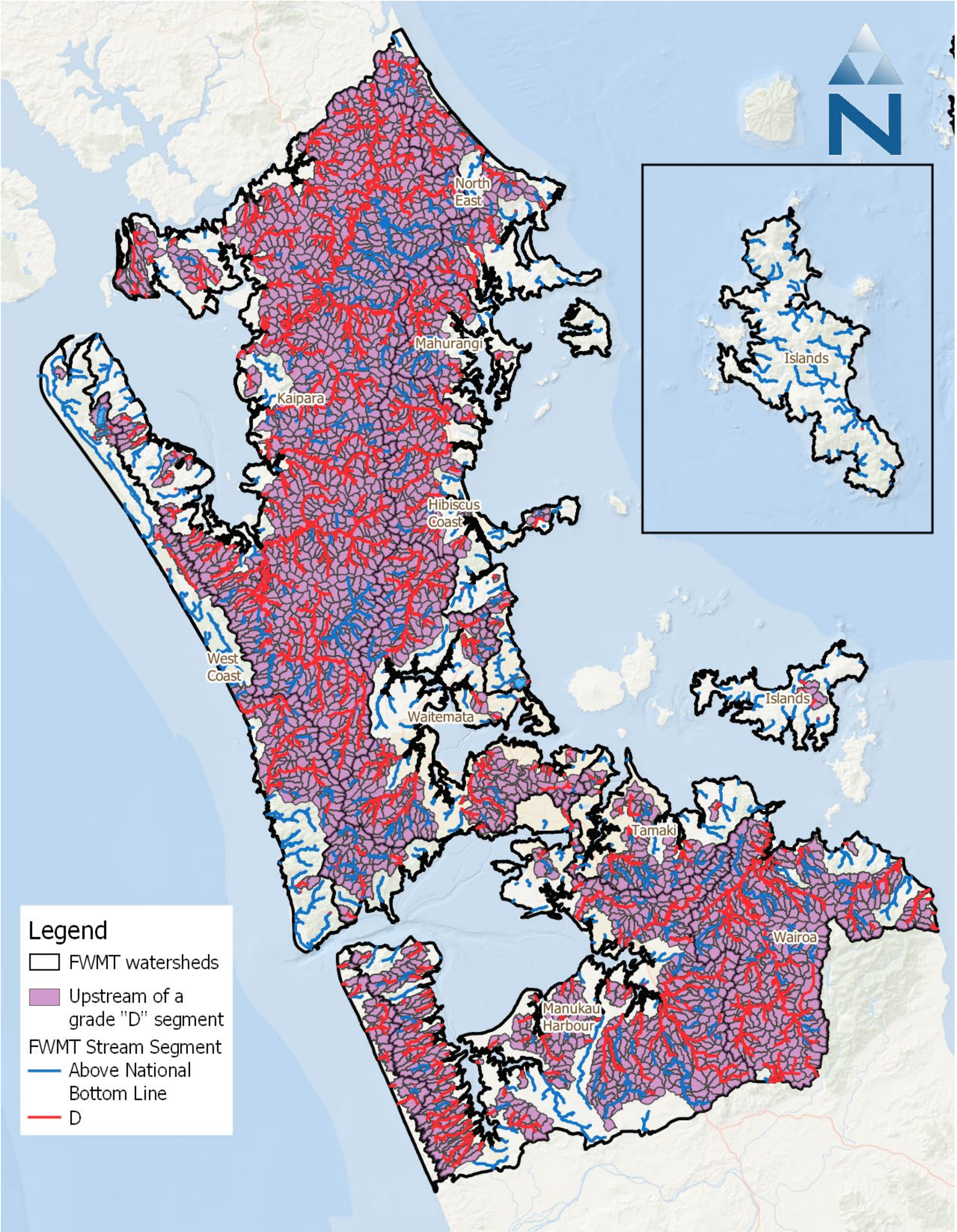


Figure 3-39. Predicted failing stream segments and upstream areas for dissolved reactive phosphorus based on worst performing metric (2013-2017)

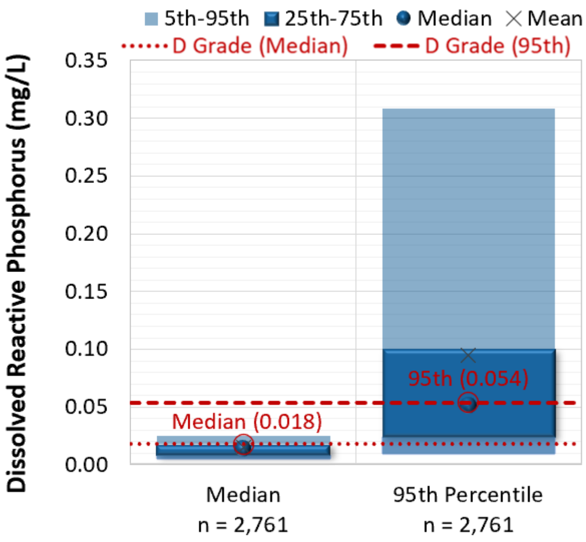


Figure 3-40. For <u>all</u> stream segments, comparison of their predicted median and 95th percentile concentrations compared to D attribute for dissolved reactive phosphorus

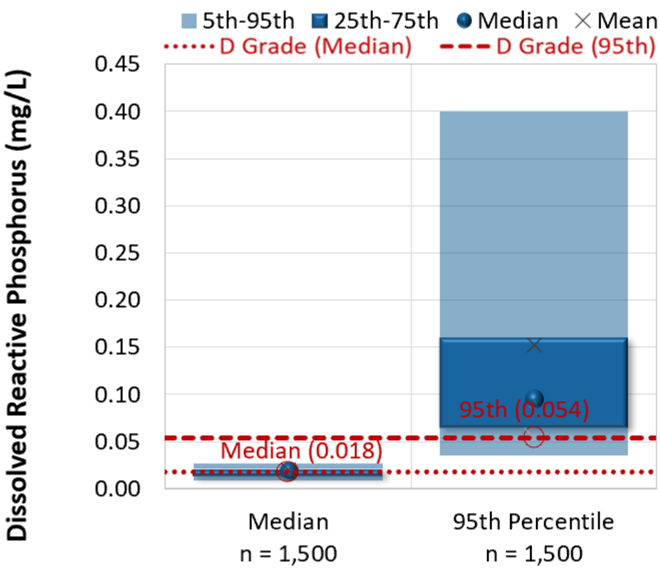
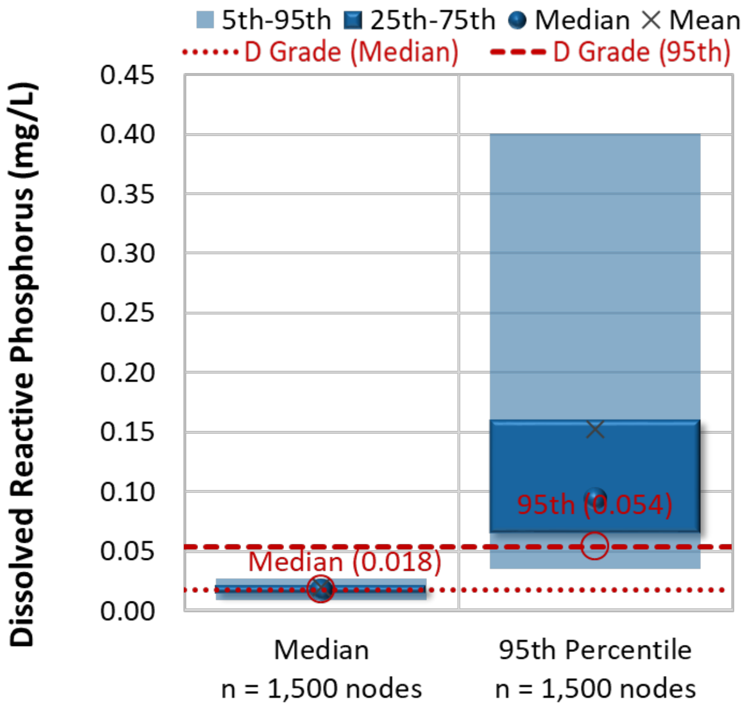


Figure 3-41. For <u>failing</u> stream segments, comparison of their predicted median and 95th percentile concentrations compared to D attribute for dissolved reactive phosphorus



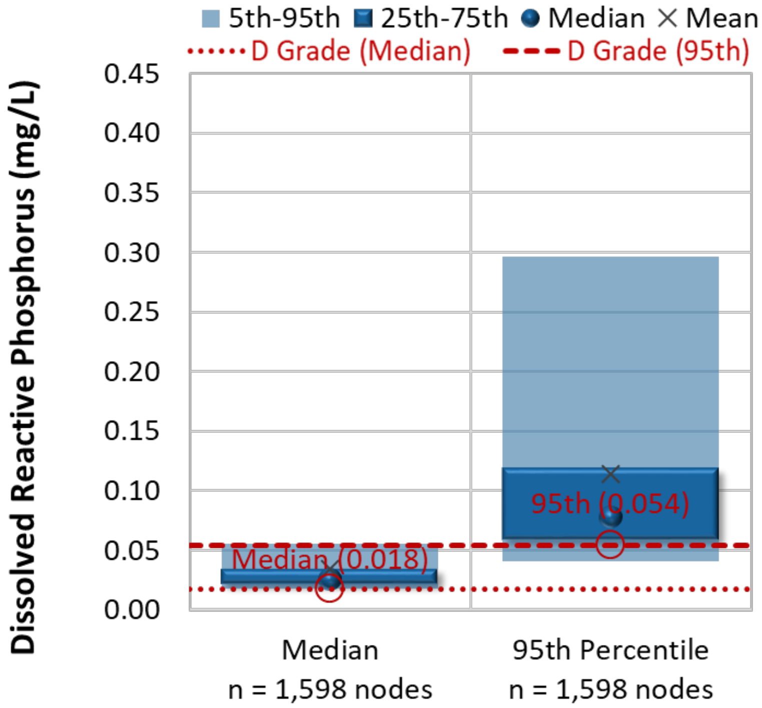


Figure 3-42. For failing stream segments, comparison of predicted daily median and 95th% concentrations (left) and predicted monthly median and 95th% concentrations to D attribute for DRP (right)

3.4 Source Apportionment

The FWMT Stage 1 has been used to estimate loadings for contaminants discharged from HRU classes to edge-of-stream (EOS): *E. coli*, total copper, total zinc, total nitrogen, total phosphorus and total sediment (see Section 2.5 for model post-processing methods for source apportionment). Note, LSPC simulates all nitrogen and phosphorus contaminant loss in total form, from HRUs to modelled reaches (and assumes complete mixing instream). Source apportionment is a key requirement of the FWMT purposes (e.g., for freshwater accounting and assessment of mitigation strategies for scenario assessment).

The FWMT Stage 1 is able to support source apportionment for 2,761 FWMT sub-catchment reporting nodes across the Auckland region for instream contaminants. However, in the absence of clear guidance on where water quality targets will be required, source apportionment reported here is simply to edge-of-stream.

While not assessed in the grading analysis, sediment can have considerable effects on water quality. Phosphorus, zinc and copper were modelled as sediment associated in the FWMT. Table 3-6 and Figure 3-43 present summaries of total sediment loading for the region (and major rivers in Figure 3-44). Figure 3-43 and Figure 3-44 include the per cent of total suspended sediment delivered to a receiving water body. Delivered loadings may be reduced due to sedimentation processes, additional information on edge of stream loads, delivery ratios and delivered loads, is presented in Appendix D. Land wash off and gully erosion are the two main sources of sediment in Auckland although sediment mobilised from the beds and banks of mainstem streams and rivers represent 15% of loading regionally. The large contribution of gully erosion is likely due in part to the configuration of the FWMT, which modelled the mainstem portions of rivers, and in general, did not explicitly represent headwater streams. Therefore, gully erosion values also implicitly represent the contribution of unmodeled first order streams and other permanent and intermittent streams which were not directly modelled and therefore did not have explicitly simulated streambed scour or bank erosion processes. Sub-catchments without a modelled stream or reporting node have a delivery ratio of 1.0 indicating no attenuation occurs when sediment or contaminants are mobilised.

Appendix D contains 'heat maps' of EOS loads, delivery ratios, and delivered loads, by watershed.

Appendix E presents summary tables of delivered contaminant loading at coast, for regionally important rivers at the locations presented in Figure 3-44. Figure 3-45 is an example of heat maps for TSS yields to EOS (left) and delivered to coast after instream attenuation (right – accounting for track settling, deposition and resuspension processes). Note that delivery ratios (proportions of edge-of-field loads transported to coast) are generally lower for TSS than other contaminants, as a substantial portion of the sediment load that deposits is simulated to be of sand and silt. Contaminants, on the other hand, are simulated as being associated with fine particles which settle much less during downstream transport.

EOS apportionment results are presented for the region in Figure 3-46 to Figure 3-51, and each watershed in Appendix F. Delivered load apportionment for 46 regionally important rivers is presented in Appendix G. For source apportionment, while region-wide results are illustrative, the watershed-specific source impacts are more meaningful and useful for planning purposes. The results in Appendix F and Appendix G provide the first comprehensive and process-based contaminant source assessment for Auckland's fresh waterways and to coast, since the NPS-FM became operative.

Table 3-6. Sediment loading and proportion by source from FWMT Stage 1 outputs

Watershed	Sediment Load by Source (× 1,000 tonnes/year)										
	Source Load	Delivered Load	Delivery Ratio	Mainstem bed scour		Mainstem bank erosion		Gully erosion		Land wash off	
				Load	%	Load	%	Load	%	Load	%
Hibiscus Coast	42.6	28.7	67%	3.8	9%	1.8	4%	16.2	38%	20.9	49%
Hauraki Gulf Islands	75.2	64.0	85%	4.3	6%	0.9	1%	33.5	45%	36.5	49%
Kaipara	193.6	102.0	53%	35.7	18%	11.4	6%	60.9	31%	85.5	44%
Mahurangi	29.7	21.8	73%	1.5	5%	0.6	2%	14.4	48%	13.2	44%
Manukau Harbour	88.6	50.4	57%	7.5	8%	3.0	3%	37.9	43%	40.3	45%
North East	49.9	36.3	73%	2.8	6%	1.5	3%	20.5	41%	25.1	50%
Tāmaki	16.8	12.1	72%	0.8	5%	1.3	8%	5.2	31%	9.4	56%
Wairoa	135.5	93.0	69%	12.5	9%	5.1	4%	76.8	57%	41.0	30%
Waitematā	64.0	42.5	66%	3.9	6%	2.7	4%	29.1	45%	28.3	44%
West Coast	46.7	29.9	64%	6.3	13%	1.0	2%	18.1	39%	21.3	46%
Regional	742.6	480.7	65%	**79.1**	**11%**	**29.5**	**4%**	**312.6**	**42%**	**321.4**	**43%**

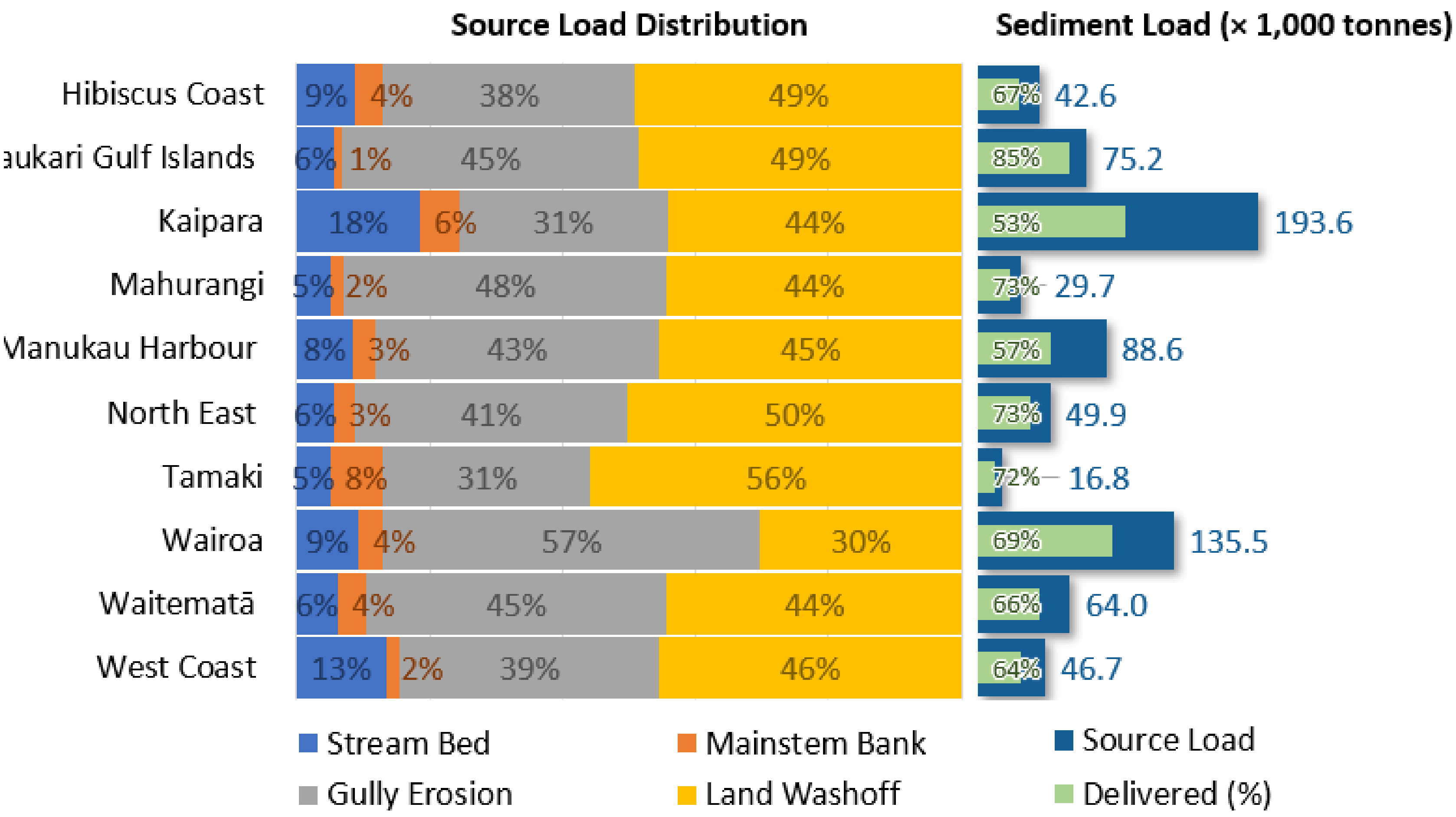


Figure 3-43. Sediment load proportion by source from FWMT Stage 1 outputs

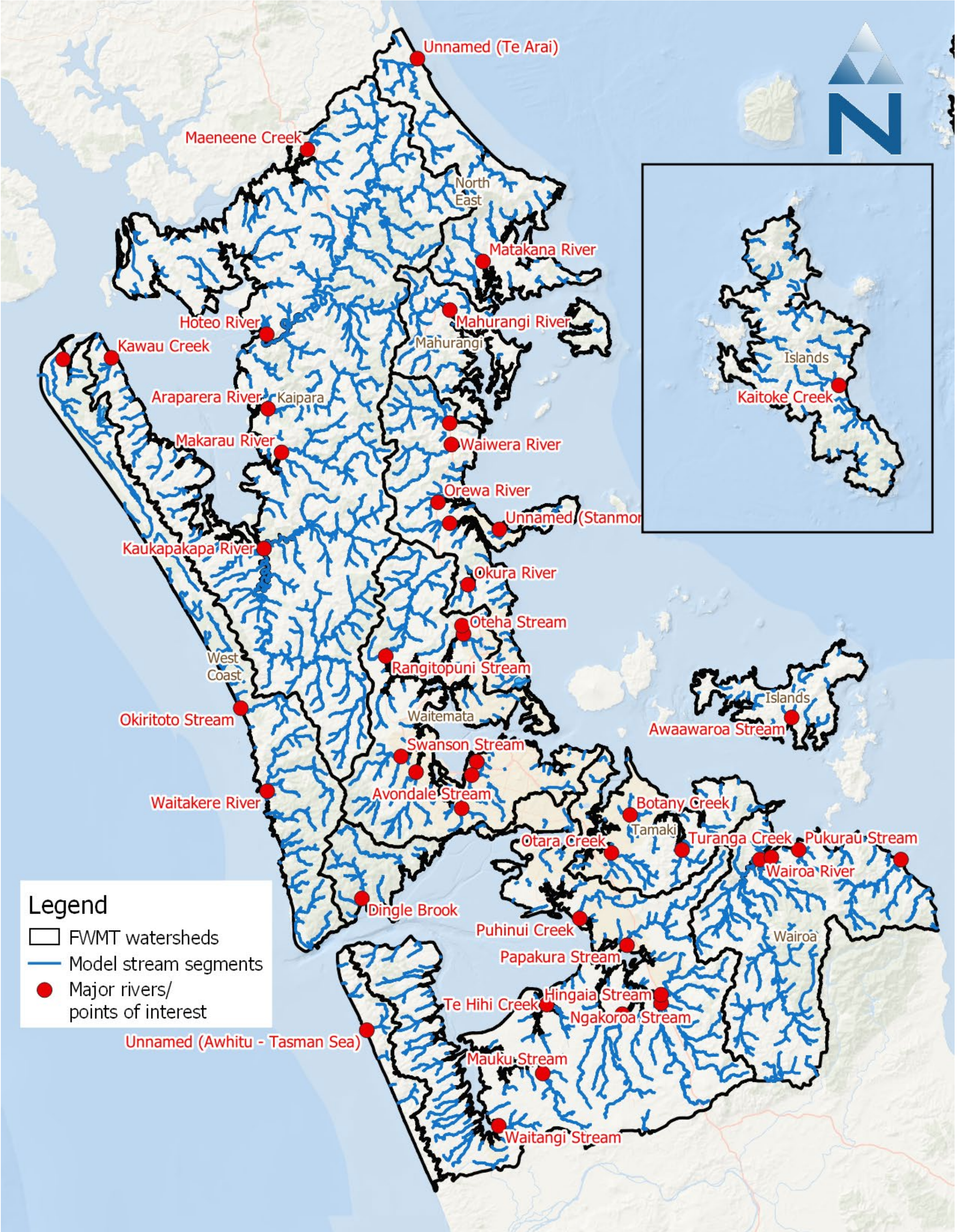
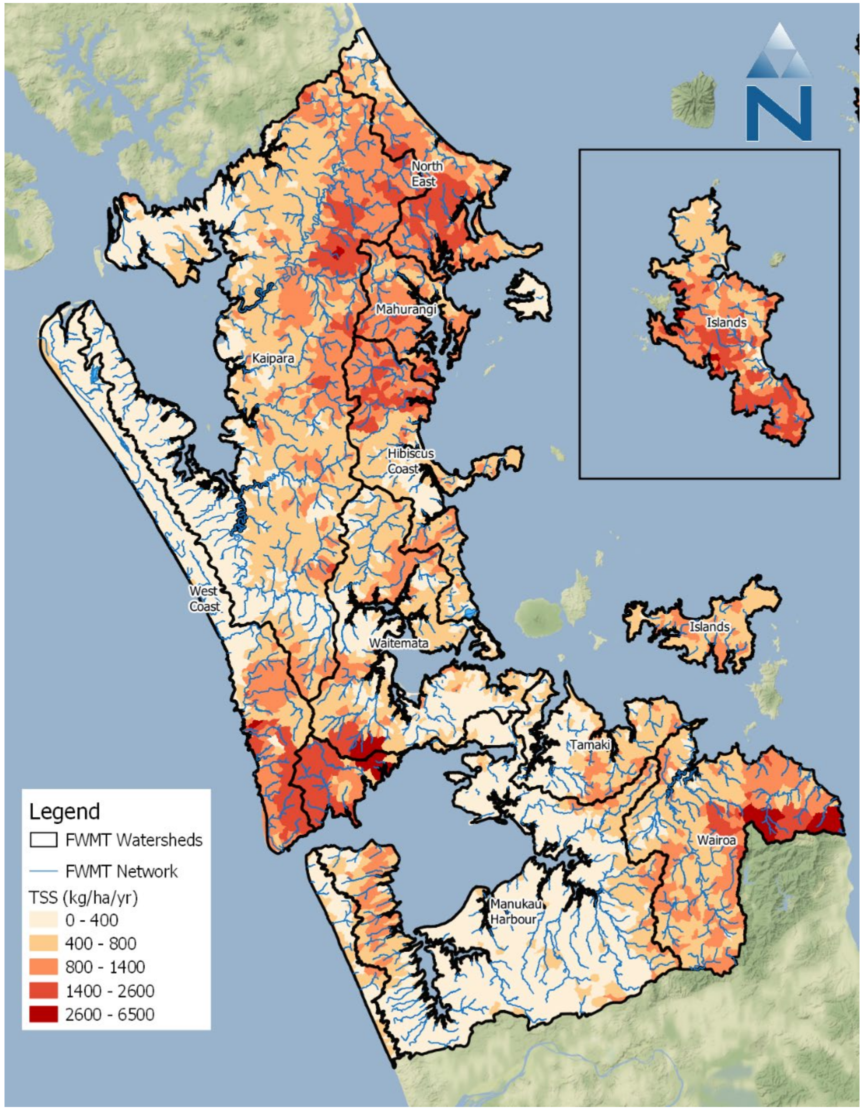


Figure 3-44. Regionally important rivers assessed for delivered loading in Appendix E and G



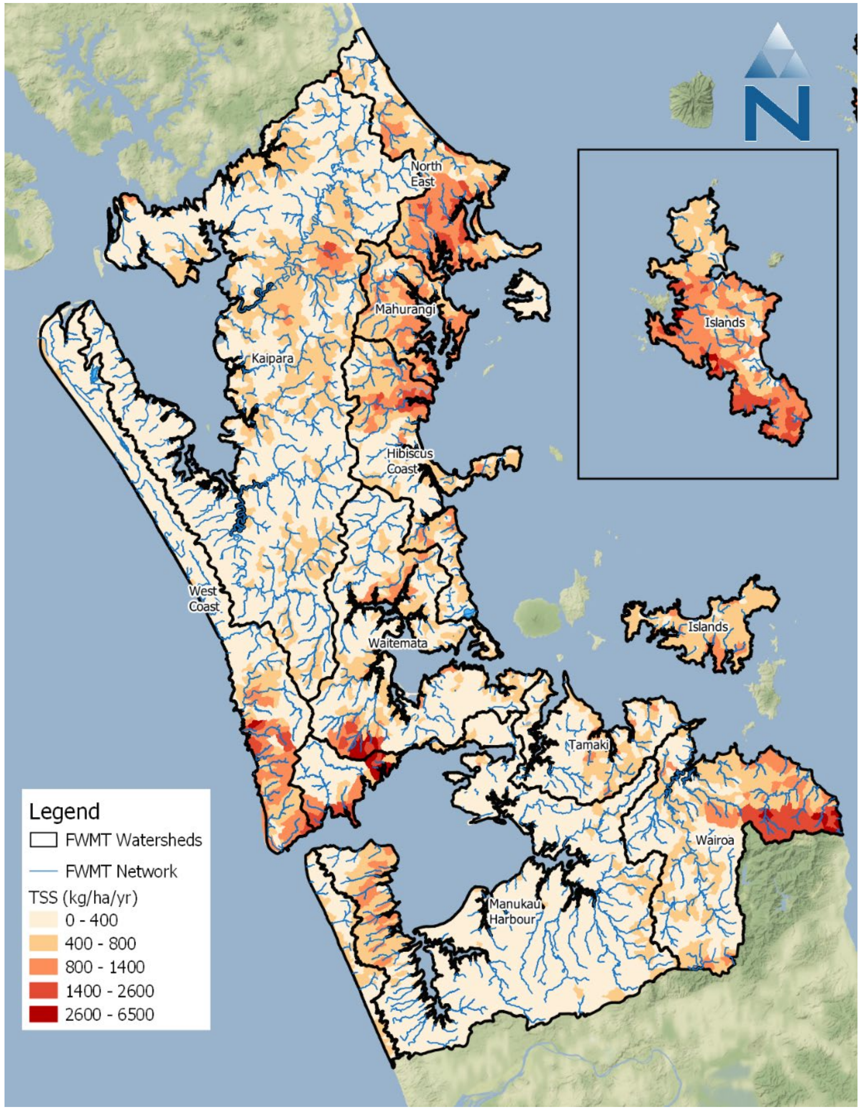


Figure 3-45. Heat maps of simulated total suspended sediment yield to edge-of-stream (left) and delivered to-coast (right) (2013-2017)

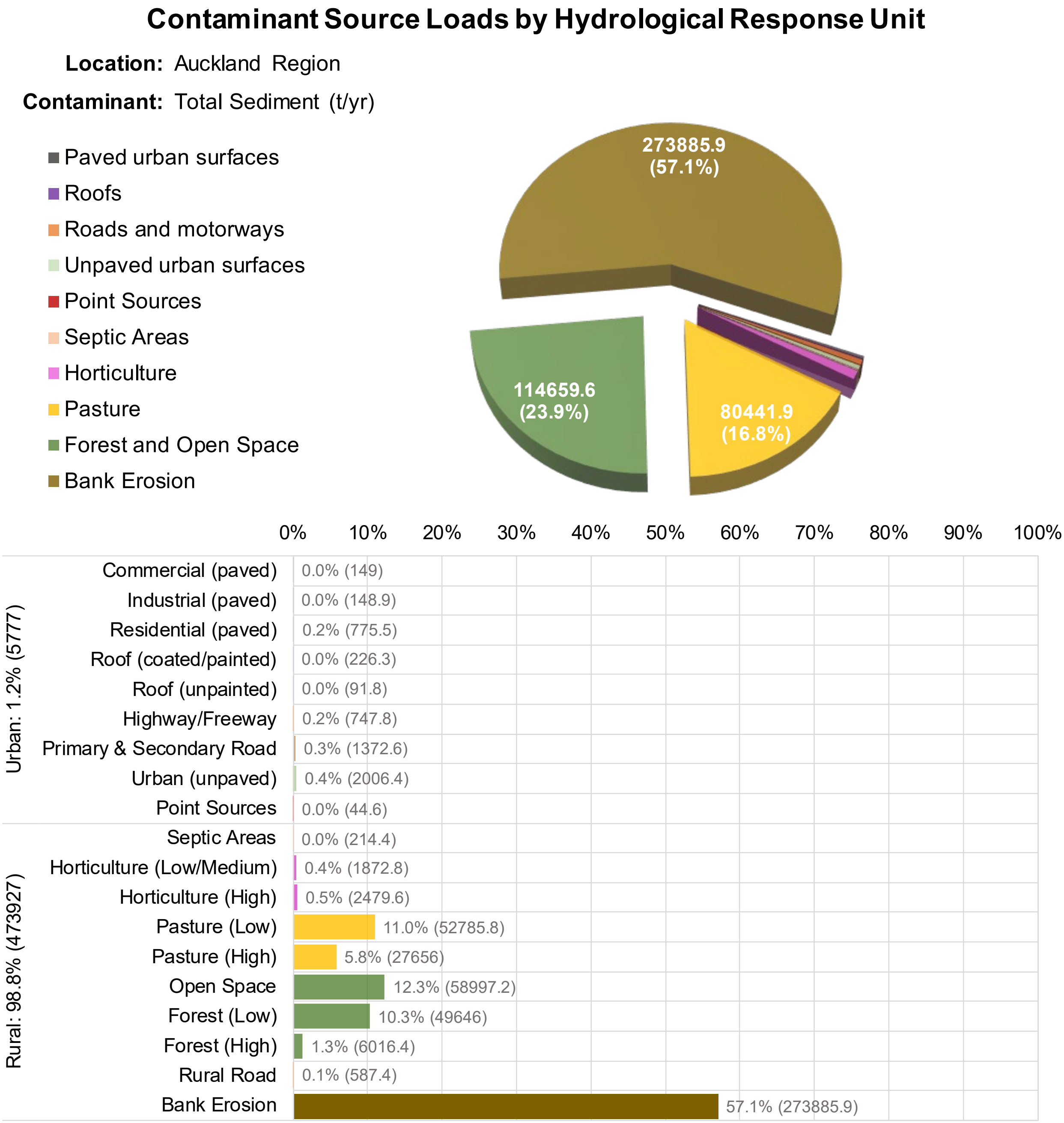


Figure 3-46. Total Suspended Sediment (t/yr) source apportionment analysis to edge-of-stream for FWMT reaches in the Auckland region (2013-2017)

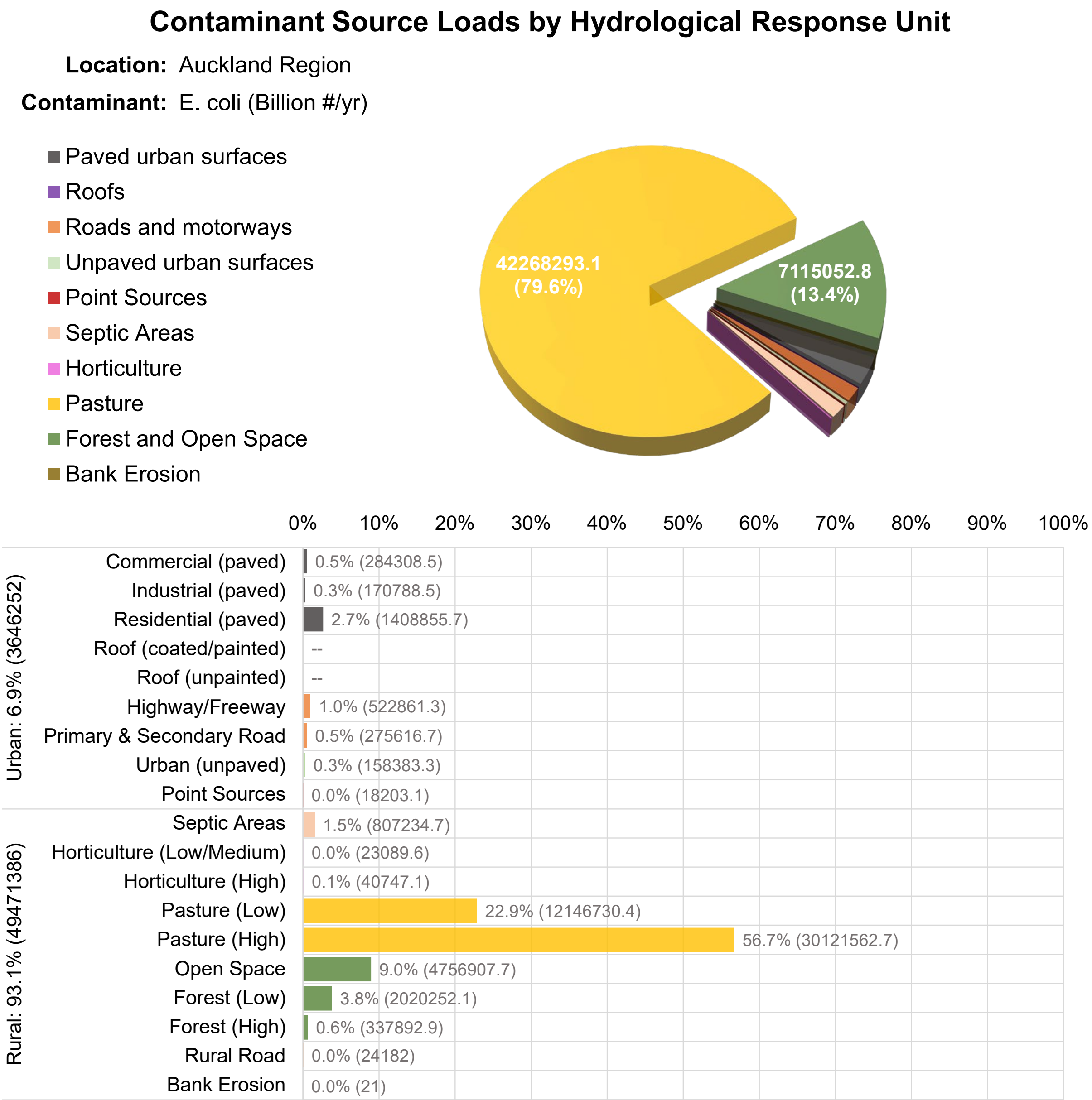


Figure 3-47. Total *E. coli* (billions MPN/yr) source apportionment analysis to edge-of-stream for FWMT reaches in the Auckland region (2013-2017)

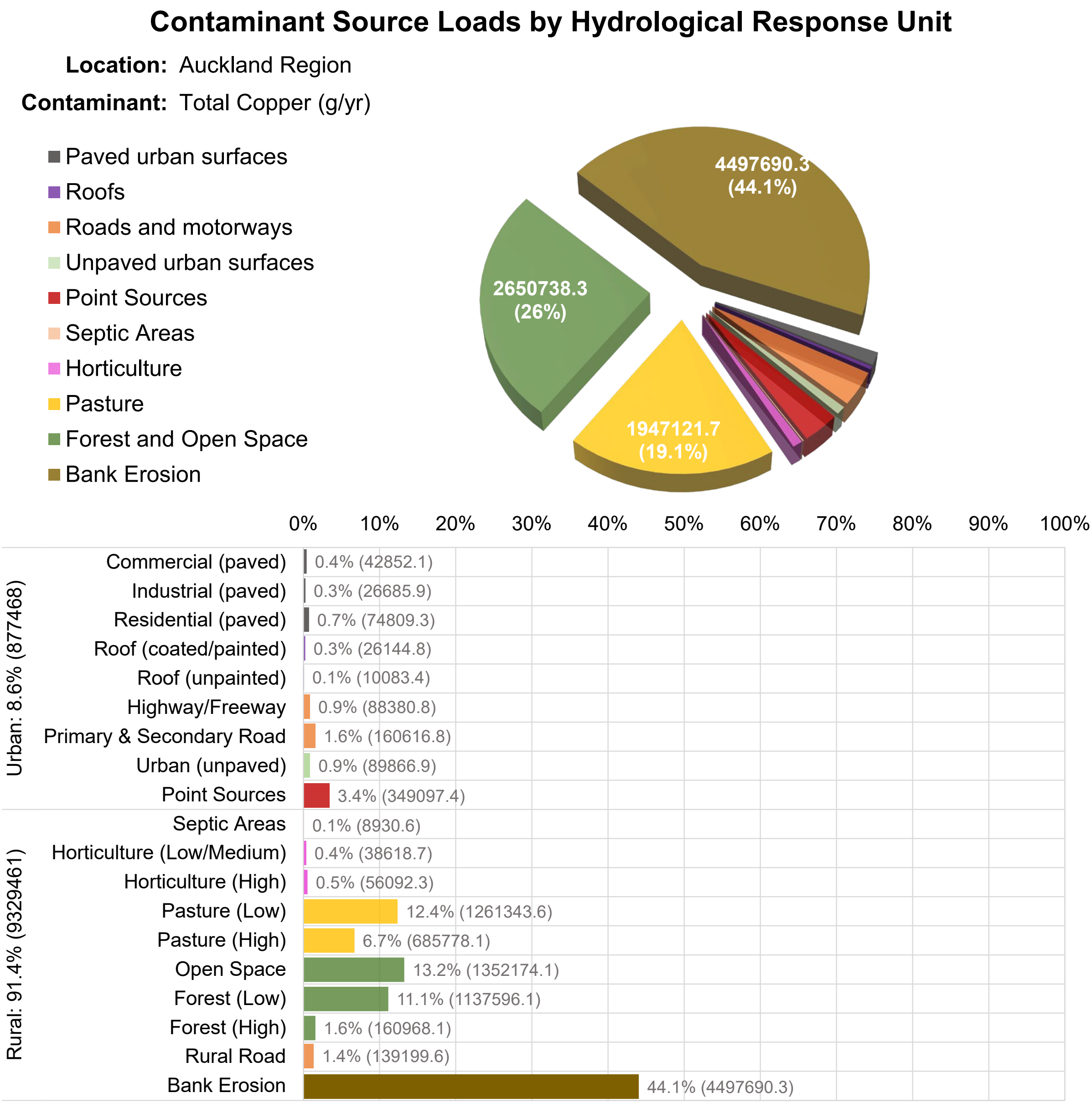


Figure 3-48. Total Copper (g/yr) source apportionment analysis to edge-of-stream for FWMT reaches in the Auckland region (2013-2017)

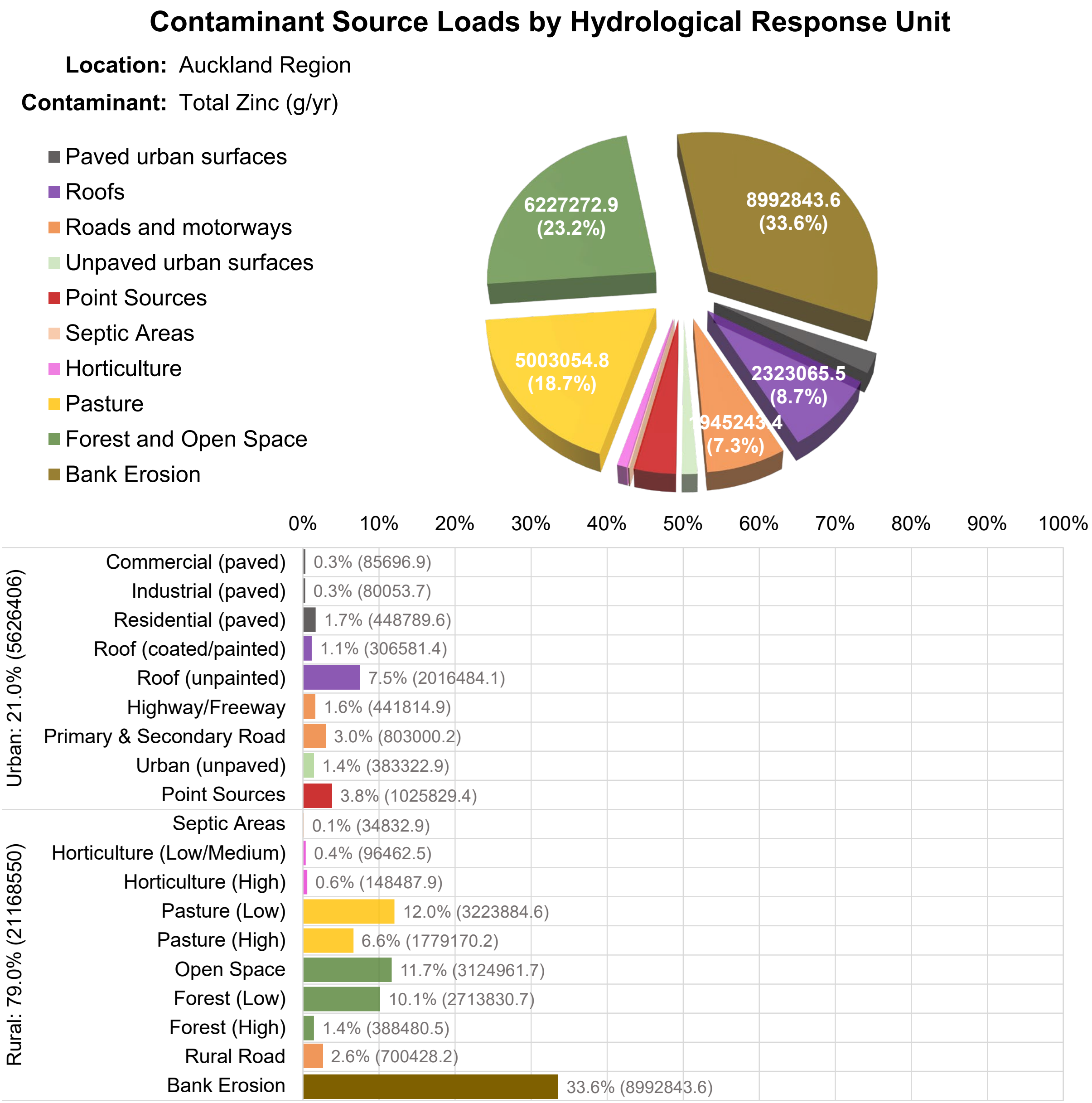


Figure 3-49. Total Zinc (g/yr) source apportionment analysis to edge-of-stream for FWMT reaches in the Auckland region (2013-2017)

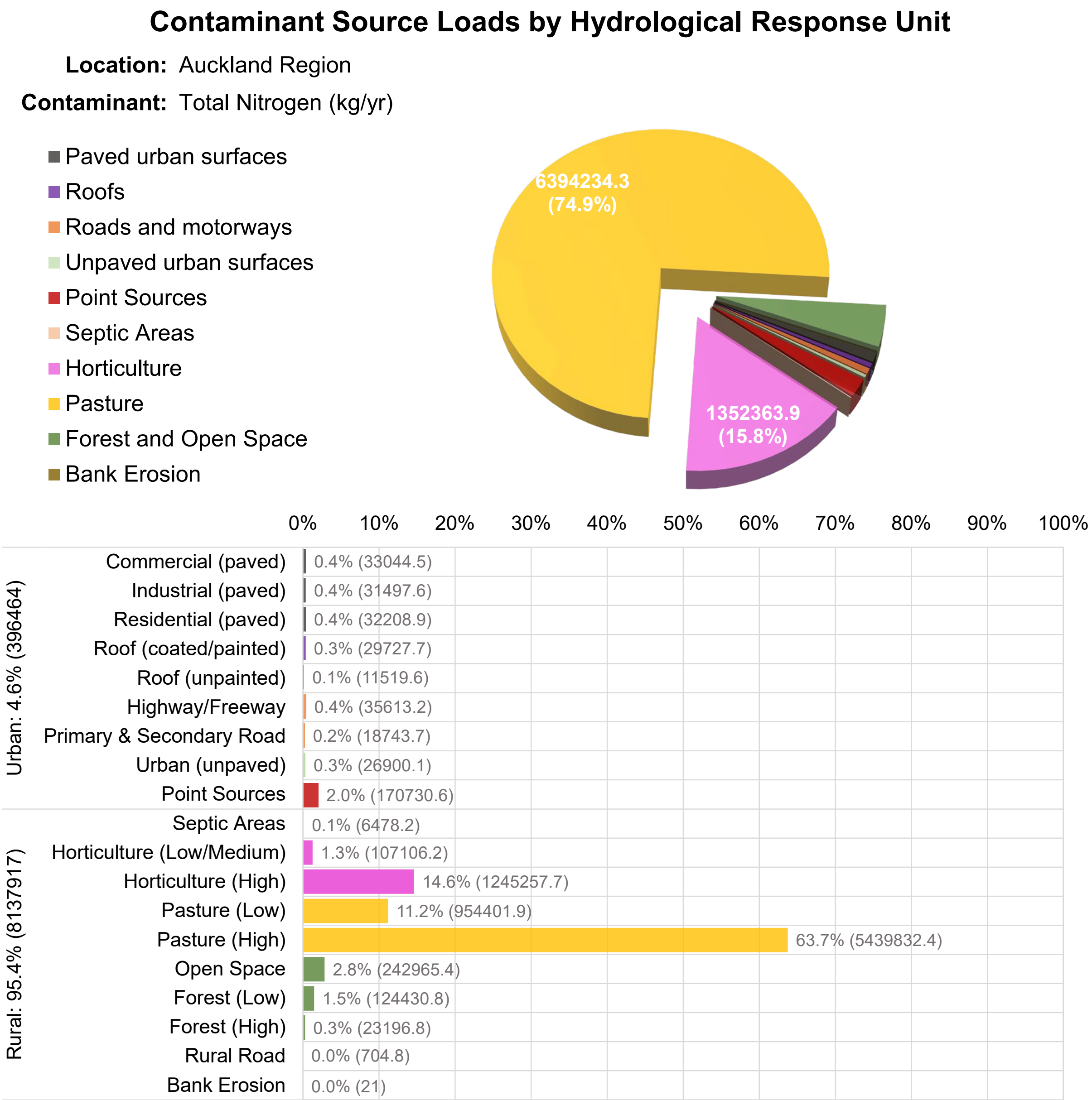


Figure 3-50. Total Nitrogen (kg/yr) source apportionment analysis to edge-of-stream for FWMT reaches in the Auckland region (2013-2017)

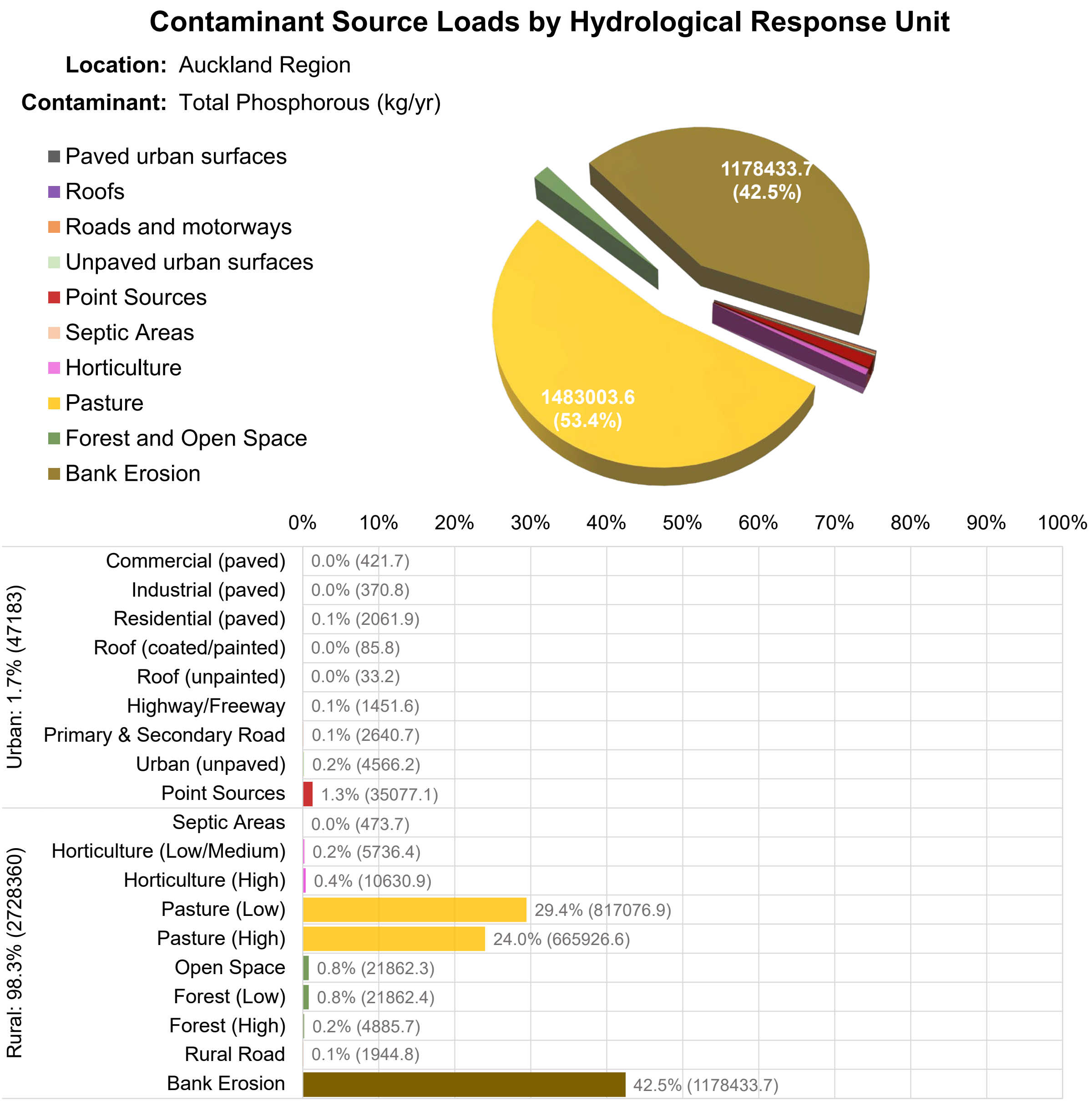


Figure 3-51. Total Phosphorus (kg/yr) source apportionment analysis to edge-of-stream for FWMT reaches in the Auckland region (2013-2017)

Table 3-7 presents EOS contaminant loads by source, grouping classes of HRU together as appropriate. An important feature of the FWMT is the ability to simulate diffuse, point source and bank erosion contaminant contributions. In urban areas for example, the impact of wastewater point sources is substantial (e.g., see Meola Creek source apportionment for total phosphorus in Appendix G5). In the source apportionment results, bank erosion includes both gully erosion (on-land representing the 85% of permanent and intermittent streams not directly simulated) and erosion from mainstem model stream segments (the 3,085 km of FWMT reach network).

Note that the source apportionment pie charts presented below are for loads to edge of stream. Normalisation to yields (by area) is possible but otherwise not as directly linked to concentration – concentration is the means of grading which warrants the greater emphasis on loading. Regardless, Figure 3-46 to Figure 3-51 bely the rate of contaminant generation with extensive HRUs generally responsible for greater loading (particularly in rural sub-catchments). The contrast of loading and yield for EOS contaminant contributions is demonstrated Table 3-7 and Table 3-8. Further analysis of yields is available in Appendix F of the FWMT Baseline Configuration and Calibration Report.

Lastly, note source apportionment is intended to guide later decision-making – only regional and watershed patterns are reported here to demonstrate the value of such freshwater accounting capability.

Key findings from the regional and watershed source apportionment exercise include:

- Rural HRUs dominate EOS and delivered loads of all six total contaminants (TN, TP, TSS, TZn, TCu, *E. coli*) – noting that the proportion of contaminants lost from rural HRUs to streams, varies regionally from 79% (TZn) to 98.3% (TP). Rural loading to EOS is greater for TN (95.4%, 8,138 tonnes/year), TP (98.3%, 1,728tonnes/year), TSS (98.6%, 473,927 tonnes/year) and *E. coli* (93.1%, 49 x10^{15} MPN/year) than for TCu (91.4%, 93.3 tonnes/year) or TZn (79%, 21.2 tonnes/year). The latter is unsurprising as the vast majority of HRUs are located in rural areas (e.g., 84% of regional area is rural); any other result would require urban sources of contaminants to be orders of magnitude greater yielding. Other modelling efforts in New Zealand has also suggested a predominantly rural origin for nutrients, sediment and faecal bacteria throughout the nation's fresh waterways for much the same reason (e.g., Larned et al., 2016; Julian et al., 2017; MfE, 2019)[8].

[8] Note that EOS loading contributions are not necessarily indicative of water quality outcome, with the vast majority of permanent streams rural by length (e.g., 93% of 16,650km permanent streams in the region are located outside the urban zone boundary [assessed from Storey and Wadhwa, 2009]).

- Bankside erosion is a considerable regional source of many contaminants to streams, including for TSS (57%), TP (42.5%), TCu (44.1%) and TZn (33.6%).
- Pastoral (commercially farmed) land is a considerable regional source of many contaminants to streams, including for *E. coli* (19.6%), TN (74.9%), TP (53.4%), TCu (19.1%), TZn (18.7%) and TSS (16.7%). Latter contributions exclude bankside loads, accounting only for contributions in runoff, interflow and active groundwater.
- Forests and open space are also a considerable regional source of many contaminants to streams, courtesy of large extent, including for TCu (41.7%), TZn (23.2%), TSS (23.9%) and *E. coli* (13.4%). Notably, open space is an amalgam of regional parks, reserves, non-commercial pastoral land and recreational areas spread over both urban and rural areas.
- Urban HRUs are relatively modest regional sources but predominant sources of urban reaches for TCu and TZn (e.g., of streams that have a higher proportion of "failing" water quality contaminant state).
- Overall, pastoral, forest and open space, and bankside erosion are the three recurring major sources of contaminants (between the three contributing about three quarters or more of regional EOS loads). Pastoral sources are the greatest regional source of three contaminants (*E. coli*, TN, TP). Forest and open space of both metals (TCu, TZn) and bankside erosion of sediment (TSS).

Table 3-7. Regionalised contaminant loading by HRU types as well as bank erosion and point sources for 2013-2017, to edge-of-stream in FWMT Stage 1 (numbers in brackets are % of regional loading)

Source (HRUs combined by surface type)	TSS (t/yr)	TN (kg/yr)	TP (kg/yr)	TZn (g/yr)	TCu (g/yr)	*E. coli* (billion MPN/yr)
Paved urban surfaces	1,073 (0.2%)	96,751 (1.1%)	2,854 (0.1%)	614,540 (2.3%)	144,347 (1.4%)	1,863,953 (3.5%)
Roofs	318 (0.1%)	41,247 (0.5%)	119 (0.0%)	2,323,065 (8.7%)	36,228 (0.4%)	0 (0.0%)
Roads and motorways	2,708 (0.6%)	55,062 (0.6%)	6,037 (0.2%)	1,945,243 (7.3%)	388,197 (3.8%)	822,660 (1.5%)
Unpaved urban surfaces	2,006 (0.4%)	26,900 (0.3%)	4,566 (0.2%)	383,323 (1.4%)	89,867 (0.9%)	158,383 (0.3%)
Septic Areas	214 (0.0%)	6,478 (0.1%)	474 (0.0%)	34,833 (0.1%)	8,931 (0.1%)	807,235 (1.5%)
Horticulture	4,352 (0.9%)	1,352,364 (15.8%)	16,367 (0.6%)	244,950 (0.9%)	94,711 (0.9%)	63,837 (0.1%)
Pasture	80,442 (16.7%)	6,394,234 (74.9%)	1,483,004 (53.4%)	5,003,055 (18.7%)	1,947,122 (19.1%)	42,268,293 (79.6%)
Forest and Open Space	114,660 (23.9%)	390,593 (4.6%)	48,610 (1.8%)	6,227,273 (23.2%)	2,650,738 (26.0%)	7,115,053 (13.4%)
Bank Erosion	273,886 (57.0%)	21 (0.0%)	1,178,434 (42.5%)	8,992,844 (33.6%)	4,497,690 (44.1%)	21 (0.0%)
Point Sources*	1,068 (0.2%)	170,731 (2.0%)	35,077 (1.3%)	1,025,829 (3.8%)	349,097 (3.4%)	18,203 (0.0%)

Darker red shading indicates higher percentage of total loading
*Point source yields presented relative to combined paved urban, roof, roading and unpaved urban areas.

Table 3-8. Regionalised contaminant yield by HRU types as well as bank erosion and point sources for 2013-2017, to edge-of-stream in FWMT Stage 1 (numbers in brackets are % of regional loading)

Source (HRUs combined by surface type)	TSS (t/Ha/yr)	TN (kg/Ha/yr)	TP (kg/Ha/yr)	TZn (g/Ha/yr)	TCu (g/Ha/yr)	*E. coli* ($x10^{12}$ MPN/yr)
Paved urban surfaces	0.20 (1.7%)	18.28 (6.1%)	0.54 (0.8%)	116.11 (6.1%)	27.27 (5.4%)	352.17 (18.5%)
Roofs	0.05 (0.4%)	7.00 (2.3%)	0.02 (0.0%)	393.98 (20.7%)	6.14 (1.2%)	0.00 (0.0%)
Roads and motorways	0.420 (3.5%)	8.56 (2.9%)	0.94 (1.3%)	302.47 (15.9%)	60.36 (11.9%)	127.92 (6.7%)
Unpaved urban surfaces	0.20 (1.7%)	2.69 (0.9%)	0.46 (0.6%)	38.40 (2.0%)	9.00 (1.8%)	15.87 (0.8%)
Septic Areas	0.31 (2.6%)	9.39 (3.2%)	0.69 (1.0%)	50.51 (2.6%)	12.95 (2.5%)	1170.64 (61.5%)
Horticulture	0.37 (3.1%)	115.29 (38.7%)	1.40 (2.0%)	20.88 (1.1%)	8.07 (1.6%)	5.44 (0.3%)
Pasture	0.36 (3.0%)	28.39 (9.5%)	6.59 (9.3%)	22.22 (1.2%)	8.65 (1.7%)	187.69 (9.9%)
Forest and Open Space	0.54 (4.5%)	1.83 (0.6%)	0.23 (0.3%)	29.16 (1.5%)	12.41 (2.4%)	33.32 (1.7%)
Bank Erosion (kg/100m/yr)	8.88 (74.0%)	0.00 (0.0%)	38.20 (53.8%)	291.50 (15.3%)	145.79 (28.7%)	0.00 (0.0%)
Point Sources	0.67 (5.6%)	106.71 (35.8%)	21.92 (30.9%)	641.14 (33.6%)	218.19 (42.9%)	11.38 (0.6%)

Darker red shading indicates higher percentage of total loading
*Point source yields presented relative to combined paved urban, roof, roading and unpaved urban areas.

More detailed TSS findings include:

- Regionally, the predominant source of sediment (TSS) lost to freshwater streams (and discharged to coast) is bankside erosion (57%, 274,000 tonnes/year). Bankside erosion represents the combination of gully (unmodelled tributaries) and mainstem (FWMT reaches) within FWMT Stage 1 (see [Baseline Configuration and Calibration Report]). Numerous independent studies have highlighted the predominance of streamside sources to Auckland (e.g., Simon et al., 2015, 2016). Good agreement was also noted between FWMT modelled sediment loads and several latter studies at 12 monitored locations[9]. Note that bankside erosion is classified as a "rural" source in the pie graphs presented in this report. Mainstem was simulated at the reach level regardless of the predominant land use of the associated sub-catchment, while gully erosion was only simulated on pervious, undeveloped HRUs. The two sources are grouped into the rural classification to distinguish from anthropomorphic urban development such as impervious surfaces and point sources. Therefore, bank erosion simulation included the 7% of FWMT reaches by length that are located within urban sub-catchments (i.e., within Auckland urban zone) through mainstem erosion and gully erosion from the pervious HRUs within those sub-catchments. Also note that bank erosion is not discriminated into mechanical or hydraulic causes within the FWMT and estimates presented here should not be used to indicate which predominates. Instead, a bank erosion modelling exercise is ongoing in Healthy Waters (Auckland Council) using a USDA process-based model (B-STEM) to more accurately disaggregate bankside contributions into their mechanical and scoured (hydraulic) origins (e.g., Klavon et al., 2016).
- The FWMT discriminates mainstem from tributary (gully) sources of bankside erosion. Earlier reporting for 12 monitored locations is available in the [FWMT Baseline Configuration and Calibration Report]. There, both bankside sources contributed between 39-54% of instream TSS loads with a consistent pattern of tributaries contributing far more sediment than FWMT-modelled mainstems. For instance, the ~17,500 km of unmodelled permanent and intermittent reaches are likely to contribute two thirds or greater of the total bankside TSS loading (i.e., 71-100% of total bankside loading at those 12 observed locations originates in "gully" erosion). The median bankside contribution along 3,085km of FWMT-modelled mainstems ("FWMT reaches") was less than a fifth (18%) of combined bankside TSS loads. Table 3-6 and Figure 3-43 present additional assessment of sediment sources. Region-wide,

[9] See [Baseline Configuration and Performance report] for discussion of the correspondence between FWMT Stage 1 modelled sediment yields to other empirical and process-based models at 12 SoE locations. Annualised loads generally matched well, although the FWMT was able to represent non-steady state changes (e.g., wet and dry years deviated markedly from the long-term estimated provided by SedNet, WANSY-CLUES and Loadest regression models).

source contributions are similar to those of the 12 monitoring locations, 57% per cent of sediment is from gully erosion and mainstem scour and bank erosion. Caution needs to be stressed in these estimates until B-STEM configuration is complete and numerous baseline model runs completed, discriminating rates of mechanical and hydraulic erosion of mainstem and tributaries across the Auckland region. However, results here align with recent empirical modelling suggesting contaminant loading is predominantly occurring into tributaries rather than higher order New Zealand rivers (McDowell et al., 2017). FWMT findings about TSS provenance have management implications for Auckland's sensitive coastal receiving environments where sediment loads are often the most pressing contaminant (i.e., resulting loss of water clarity, light transmission, burial of macrophytes, damage to benthic bivalves and geochemical changes within deposited sediment of estuaries and harbours – Gibbs and Hewitt, 2004; Thrush et al., 2004, 2013; Green, 2013). Considerable proportions of TSS loads to Auckland's coast are bankside in origin, eroded not simply on larger mainstems but predominantly on the smaller, more numerous tributaries. On the basis of FWMT baseline modelling, management of sediment for its degradational effects whether in freshwater or to coast, would need to prioritise interventions throughout the permanent and intermittent stream network – a finding that aligns with modelling in New Zealand identifying opportunities are more numerous and less costly to manage contaminants at source then attempt interventions further downstream (McDowell, 2007, 2014).

- Amongst non-bankside sources, forestry/open space and pastoral HRUs dominate regionalised TSS loads – accounting for 23.9% (115,000 tonnes/year) and 16.8% (80,000 tonnes/year) of sediment lost to waterways (annualised for 2013-2017). Note that the absence of a "urbanising" HRU nor assessment of the proportion of developing land in the region means that previous estimates omit intense erosional losses during development (i.e., whilst short-lived, erosion of urbanising sites has been reported at an order of magnitude greater than rural land uses [Hicks, 1994; Leersnyder et al., 2018]). Hence, FWMT Stage 1 findings will not simulate loading from "developing" land parcels and include error in baseline predictions for sub-catchments with recent development [10].
- Whilst the proportion of EOS and delivered sources of TSS vary between watersheds, earlier regional patterns remain consistent (see Appendices E3-E6). Notably that bankside erosion is the principal source of TSS loading in all 10 watersheds (varying 43.1-72.9% of annualised loads 2013-2017; least in

[10] At the time of writing "developing" HRUs are being configured for the FWMT, with results anticipated in 2021.

Tāmaki and greatest in Wairoa watershed; being half or more of the TSS loading to EOS in all bar one watershed). Forestry and open space as well as pasture account largely for the remainder. The former contributing up to 40.6% (25,980 tonne/year in Hauraki Gulf Islands) or at least 13.0% (12,060 tonnes/year in Wairoa) of TSS loading to EOS. Pastoral sources otherwise contributing between 7.0% (4,500 tonnes/year in Hauraki Gulf Islands) and 25.5% (9250 tonnes/year in North East). Even in highly urbanised watersheds, other sources are modest; sources other than pasture, forestry and open space, or bankside amounting to 8.1% and 8.5% of TSS loads to EOS in Tāmaki and Waitematā watersheds, respectively.

- TSS apportionment results indicate more extensive HRUs dominate regional sediment loading to waterways. However, regionalised TSS yield estimates are also informative and influence instream concentrations (e.g., can drive change to stream grading). Several HRU classes yield sediment at high rates including on average, unpaved urban surfaces (200 kg/Ha/year), paved urban surfaces (200 kg/Ha/year), septic areas (310 kg/Ha/year), pasture (360 kg/Ha/year), roads and motorways (420 kg/Ha/year) and, forest and open spaces (550 kg/Ha/year) (all yields regional and annualised for 2013-2017). Note that yield like loading estimates can mislead, given apparent variation might simply be due to climate overlying HRUs (i.e., differences in intensity of TSS loss could be consequence of local climate rather than necessarily difference in land use). Comparison to earlier CLM (Auckland Regional Council, 2010) yields can be made, but given the simplicity and limited performance assessment underpinning the CLM, differences are not necessarily informative of FWMT accuracy[11] – the only notable finding from a comparison indicates that the CLM ranked highest average yielding sources as paved urban surfaces (220-320 kg/Ha/yr), pasture (210-9,230 kg/Ha/yr), forestry (140-2,080 kg/Ha/yr) and roads and motorways (210-2,340 kg/Ha/yr) (i.e., FWMT regionalised and annualised HRU yields for TSS are reasonably alike).

More detailed *E. coli* findings include:

- Regionally, *E. coli* are contributed predominantly to waterways from pastoral sources (79.6%, annualised for 2013-2017 and from 47% of configured HRU area). Open space and forestry are also a modest contributor, albeit from equally extensive regional area (13.4% of *E. coli* EOS load from 44% of configured HRU area). Consequently, yields from pasture are in the order of about six times greater than forested areas. Forested areas will include faecal sources from pest and native fauna, whilst open spaces are largely

[11] Timperley et al. (2010) note that the CLM and C-CALM are not intended for use in rural catchments (e.g., >20% rural land cover).

contributed by non-productive pastoral properties (e.g., life-style “farmers”). Both have been configured and calibrated for observed SoE *E. coli* concentrations in Auckland rivers (2013-2017). Further targeted validation monitoring will be required given a dearth of research into faecal contributions from forested and open-space. However, FWMT yields are broadly in line with national modelling that suggests native (exotic) forest *E. coli* yields are generally 15-20 (4-5) fold less than pasture (Smith et al., 1993; Larned et al., 2018; Whitehead et al., 2018).

- There is stark variation in *E. coli* loading to waterways between watersheds. Barring Tāmaki, Waitematā, Hauraki Gulf Islands and Hibiscus Coast, the other six watersheds receive >75% of annualised *E. coli* EOS loading from pastoral sources (e.g., 77.5% [West Coast] to 90.5% [Kaipara] *E. coli* loads to EOS, 2013-2017). Despite having a relatively large urban extent (8%) the Manukau Harbour watershed is notable as pastoral sources continue to dominate EOS *E. coli* loads (84.5%)[12]. Amongst the six watersheds with highest pastoral *E. coli* contributions, high intensity pasture is also the principal source. For instance, high intensity pasture contributes between 51.8% (West Coast) and 72% (Manukau Harbour) of the *total rural* loads of *E. coli* to EOS (i.e., of the more-than-pastoral or *total* rural load). Combined, in six watersheds high intensity pastoral farming (dairying) is the predominant source of faecal indicator bacteria to waterways. In the other four watersheds pastoral sources are still the largest contributor of *E. coli* but ranging from 37.1% (Waitematā) to 57.4% (Hibiscus Coast) of total watershed loadings to streams. In the latter four watersheds, the lesser relative pastoral loads are also more heavily contributed by low intensity pastoral farms (e.g., low impact pasture accounting for up to 20% [Waitematā] to 35.8% [Hauraki Gulf Islands] of total rural *E. coli* losses to EOS).
- Amongst the 46 regionally important rivers in Appendix E, point sources of *E. coli* are particularly important for urban streams (e.g., accounting for 84% of loading to Meola Creek; 33% to Oakley Creek; 10% to Avondale Stream – all in Waitematā watershed). Regional and even watershed summaries are heavily weighted to the ~93% of permanent and intermittent streams that are located the Auckland urban boundary (e.g., estimated from Storey and Wadhwa [2009]). Hence, regional and watershed summaries are likely too coarse to represent the variety and differences in contaminant sources across urban waterways. More specific FWMT outputs at stormwater[13] catchment scale are required to assess the water quality impacts of land use on urban

[12] Note that EOS losses account for Type 1 and 2 overflow events from the wastewater network, so are likely an underestimate of actual (e.g., do not include Type 3 and 4 events owing to their being random and not linked to wider physical processes modelled by the FWMT).
[13] FWMT baseline (2013-2017) outputs (yields, load apportionment and grading summaries) are at the time of writing being drafted for the 233 stormwater catchments in Auckland. Request output from Auckland Council.

streams, but clearly like other contaminants loss of *E. coli* from pastoral land (particularly high intensity pastoral farming) is the single largest cause of degradation in human health value (water quality) along the greatest lengths of streams in the Auckland region. That finding is supported by previous contaminant modelling in New Zealand that identifies pastoral sources of *E. coli* as the principal causes for degradation of recreational (human health) values for waterways (e.g., Unwin et al., 2010; McDowell et al., 2012; Davies-Colley, 2013; Larned et al., 2016).

- Amongst yields, the greatest average annual sources of *E. coli* to waterways include septic areas (1,171 billion MPN/Ha/yr), paved urban surfaces (352 billion MPN/Ha/yr), pasture (188 billion MPN/Ha/yr), roads and motorways (128 billion MPN/Ha/yr). Limited evidence is available from mesocosm or largescale monitoring exercises as yet, to validate yield estimates, with the prior contaminant load model (CLM and C-CALM) excluding *E. coli* estimates. Similarly, few studies have attempted to quantify *E. coli* yields from surfaces in New Zealand, with pasture better served albeit still suffering a dearth of research. The few pastoral *E. coli* load and yield studies highlight wide variation in yields within and between farms due to variation in soil types, rainfall, stock type, stocking rates and grazing practices (period since grazing) (see review by Richie and Donnison, 2010): Wilcock (2006) reported cattle and sheep yields of 0.1-1000s of billion MPN/Ha/yr; Muirhead (2009) reported yields for cattle in order of 0.01 billion MPN/Ha/yr; and Muirhead et al. (2011) suggest a range from 0.01 million to 10 billion MPN/Ha/yr from dairy farms in New Zealand (although noting yields should be highly variable in line with stocking, riparian and effluent management infrastructure and practices). In more recent modelling utilising CLUES, Semadeni-Davies and Kachhara (2017) reported average annual yields for pastoral land uses ranging from 0.005 to 0.876 billion MPN/Ha/yr.

More detailed TCu and TZn findings include:

- Regionally, three large sources of total copper (TCu) dominate EOS loads throughout Auckland. Namely, bankside erosion (44%, 4,500 kg/year) forest and open space (26%, 2,650 kg/year), and pasture (19%, 1,950 kg/year). The large contribution from bankside erosion is simply a consequence of the TCu lost with sediment and the latter being predominant sources of sediment to streams. LSPC simulates TCu and TZn losses with and binding to sediment eroded from pervious surfaces and washed off from pervious and impervious surfaces. Once instream, attenuation of TCu and TZn is aligned to deposition and resuspension processes. Additionally, interflow and groundwater flows were parameterised with trace amounts for TCu and TZn as discussed in the [FWMT Baseline Configuration and Calibration Report]. As above, the loading contributions (kg/year) bely the considerably greater yields (intensity of loss) from urban impervious surfaces in the FWMT, nor too, concentration driven outcomes that are heavily influenced by intensity of yield (i.e., becoming more concentrated if impervious HRUs dominate a sub-catchment). The [FWMT Baseline Configuration and Calibration Report] contains the TCu and TZn potency factors for sediment associated with each HRU. Hence, whilst urban sources represent 8.6% (877kg/year) of all TCu loading, a notable finding is that roads and motorways contribute nearly five-fold more on average per annum than forests and open space (e.g., 60 g/Ha/yr and 12 g/Ha/yr, respectively – annualised for 2013-2017). Paved urban surfaces are another notably enriched source for TCu to EOS (27 g/Ha/yr – three-fold greater than pervious urban surfaces at 9 g/Ha/yr) as are rooves (6 g/Ha/yr). By contrast, CLM yield estimates were similar for rooves (3-33 g/Ha/yr, excluding copper roofing which was estimated to yield 21,200 g/Ha/yr), roading (15-2,430 g/Ha/yr) and paved surfaces (36-1,070) Regional total zinc (TZn) patterns are similar to those for TCu in terms of average annual EOS loading. Forestry and open spaces (23.2%, 62,272 kg/year), pasture (18.7%, 5,003 kg/year) and bankside sources predominate (33.6%, 8,992 kg/year) (annualised, 2013-2017). However urban sources combined, are more dominant for TZn (18.3%; 89,500 kg/year) than TCu (8.6%, 877 kg/year). Another notable difference is roofing being the largest urban regional EOS source of TZn (8.7%, 2,323 kg/year), with unpainted rooves contributing nearly 7-fold more than painted rooves (2,016 and 306 kg/year, respectively). Roads and motorways are nonetheless important sources of TZN to streams amounting to 7.3% of regionalised EOS loads (1,945 kg/year).

- Unlike TCu, marked variation in dominant EOS TZn loading occurs within urbanised watersheds. Focussing on the four urban watersheds previously, roading contributes between 9.4% (116 kg/year; Hibiscus Coast) and 16.8% (236 kg/year; Tāmaki). Whereas, roofing contributes between 11.4% (199 kg/year; Hibiscus Coast) and 33% (462 kg/yr; Tāmaki). Paved urban sources are also a notable contributor of TZn to streams, varying from 4.2% (73 kg/year; Hibiscus Coast) to 8.5% (120 kg/year Tāmaki). Despite its greater relative loading from urban sources, the Tāmaki watershed possesses a lower proportion of predicted “failing” reaches (3%) than the Hibiscus Coast watershed (7%). Instead the greater urban-derived loading in the Tāmaki watershed appears to have resulted in a greater proportion of reaches predicted in C grade (40%, 40km) than in Hibiscus Coast (14%, 23km). Hence, TZn contributions by urban sources appear localised to fewer reaches in the Hibiscus watershed.
- Both roading and roofing HRUs occupy relatively minor area regionally (~1%, 5300 ha and 5900 ha respectively), resulting in yields that are orders of magnitude greater than any rural source (Table 3-8). For instance, TZN yields

from roofing (394 g/Ha/yr) and roading and motorway (302 g/Ha/yr) are considerably higher than forest and open space (29 g/Ha/yr). Clearly both roofing and roading sources are disproportionate and coupled to localised exceedance of regional DZN bottom lines only in urban sub-catchments, and point to a highly urbanised water quality effect in Auckland waterways from zinc. For context, CLM yields of TZn for roofing and roading varied from 200-22,400 (g/Ha/yr) and 270-7,300 (g/Ha/yr), respectively (Auckland Regional Council, 2010). Both encompassing a wide range that includes unpainted galvanised steel through to inert roofing materials and vehicle frequencies of >100,000 vehicles/day. A University of Canterbury modelling exercise determined similar TZn yields for low frequency roading (<1000 vehicles/day) of 215-253 g/Ha/yr, at nearly fourfold greater rates than TCu (65-70 g/Ha/yr) (Wicke et al., 2009). A later study by the same authors also suggested a marked difference in TZn yields simply due to roading material, with coarse asphalt yielding 30% and 180% more than smooth asphalt or concrete, respectively (Wicke et al., 2011)[14]. A study of low-intensity roading (<2,000 vehicles/day) in Sydney demonstrated TZn yields of 500-1,600 g/Ha/yr are deposited in urban areas (Davis and Birch, 2011).

More detailed TN findings include:

- Two sources dominate regional loading of TN to waterways in Auckland: pasture (74.9%, 6,394 tonnes/year) and horticulture (15.8%, 1,352 tonnes/year) (annualised 2013-2017). All other sources collectively amount to ~9% of region-wide TN EOS loading, with the majority thereof from open space and forest (4.3% of region, 400 tonnes/year). Bankside sources are negligible (<0.001%, 21 tonnes/year) although configuration of the FWMT does not enable discrimination of direct-deposition to streams of effluent from livestock (i.e., livestock contributions are linked to the "pastoral" HRUs instead). Urban TN sources are minor regionally (4.6%, 396 tonnes/year), although this does not preclude urban sources being locally dominant. For instance, whilst 51 km of FWMT reaches fail national bottom lines for NO3N (all within rural Manukau sub-catchments), 435 km of FWMT reaches fail proposed national bottom lines for DIN (across numerous catchments including several heavily urbanised watersheds).
- Marked variation occurs in pastoral and horticultural TN loads between watersheds. Notably, pastoral sources account for nearly three-quarters of waterway TN loads across six watersheds: Hibiscus Coast (70.9%, 227 tonnes/year), Kaipara (91.2%, 3,506 tonnes/year), Mahurangi (79.2%, 154 tonnes/year), North East (82.2%, 510 tonnes/year), Wairoa (88.4%, 570

[14] The FWMT is not configured to explicitly represent roading surface differences in Auckland, with those otherwise captured implicitly if vehicle usage correlates strongly with road surface type.

tonnes/year) and West Coast (74.6%, 264 tonnes/year). Amongst the latter watersheds, high intensity systems contribute at least two thirds of pastoral TN loads lost to waterways (e.g., farmers >10SU/Ha – dairying, finishing beef). In the other four watersheds, pastoral TN loads still amount to between 28.5% (170 tonnes/year; Waitematā) and 48.1% (74 tonnes/year, Tāmaki) but otherwise the sources are diverse and inconsistent between watersheds. In the Hauraki Gulf Islands for instance, forest and open space accounts for nearly half of otherwise modest TN loads (46.3%, 60 tonnes/year). In the Manukau Harbour watershed, horticulture accounts for nearly half of quite considerable TN loads (41.6%, 700 tonnes/year). In the Tāmaki, TN sources are most diverse (if absolutely modest) including from paved urban surfaces (12.2%, 19 tonnes/year), forest and open space (10.3%, 16 tonnes/year), roading and motorways (6.2%, 9 tonnes/year), rooves (5.6%, 9 tonnes/year) and horticulture (538%, 8 tonnes/year). Similar diversity of TN sources exists in the Waitematā albeit with a much greater relative (and absolute) horticultural load (28.3%, 170 tonnes/year).

- Over half of the regional horticultural TN load is contributed by growers in the Manukau Harbour watershed (700 tonnes/year, of which 97% is sourced from high intensity horticulture – e.g., market gardening, stone and pipfruit, greenhouses). Horticultural sources account for >5% of TN loads to waterways in all watersheds and >10% in six watersheds (e.g., Hauraki Gulf Islands [16.1%, 20 tonnes/year], Mahurangi [11.7%, 23 tonnes/year], North East [13.7%, 850 tonnes/year], West Coast [15.3%, 54 tonnes/year], Waitematā [28.3%, 170 tonnes/year], Manukau Harbour [41.7%, 700 tonnes/year]). In five of those six watersheds with greatest horticultural TN loading, high intensity growers contribute more than two-thirds thereof. The Hauraki Gulf Islands are unusual for having both a relatively large proportion of TN loading by horticulture (16.1%) of which two thirds are lost to streams from low/medium intensity growers – although, the absolute TN loads involved are minor (i.e., total horticultural TN loading of 20 tonnes/year therein).
- Horticulture occupies 2.5% of the Auckland region (11,730 Ha) and being responsible for 15.8% of regional EOS loads, ensures horticulture is the highest yielding source of TN to waterways (115.3 kg/Ha/yr – annualised 2013-2017). Regional horticultural yields are nearly fivefold greater than either pastoral or paved urban yields (28.4 and 18.3 kg/Ha/yr, respectively) and an order of magnitude greater than either onsite wastewater systems, roads and motorways or rooves (9.4, 8.6 and 7.0 kg/Ha/yr, respectively). Notably half of the region's horticultural land is farmed in the Manukau Harbour (5,830 Ha), which combined with all of Auckland's TON-failing (51 km) and nearly a third of all DIN-failing (170 km) streams being located in the watershed, highlight

the importance of managing intense horticultural TN yields to waterways, to otherwise achieve water quality bottom lines for the NPS-FM.

- High intensity pasture occupies 14.8% of the Auckland region (70,720 Ha), accounts for 9.5% (5,440 tonnes/year) of regional TN loads to waterways and therefore like horticultural farming, possesses a disproportionately high TN yield (77kg/Ha/yr – annualised 2013-2017). For context, regional low intensity pastoral yields are an order of magnitude less (6.2 kg/Ha/yr). Approximately 23.8% (21,850 Ha) of the Manukau Harbour watershed is farmed for high intensity pasture. Hence, high intensity pastoral land uses are also likely to require prioritisation to achieve water quality national bottom lines for the NPS-FM, let alone improvement to B-grade or better in TON or DIN.
- The regional findings that both horticulture and high-intensity pastoral farming are responsible for disproportionate TN-loading to Auckland waterways, and that both are typified by generally higher TN-yields than other land uses, aligns well with water quality accounting studies in New Zealand. Simpler, empirical modelling by Unwin et al. (2010) and Larned et al. (2017) both determined that the Auckland region possessed relatively enriched TN-concentrations instream relative to other regions, largely from high-producing exotic grassland (high intensity pastoral farming) and horticulture. Broader, national assessments have also highlighted livestock (urine) as the greatest source of TN in New Zealand's waterways (PCE, 2012). Consequently, national water quality assessments have repeatedly also demonstrated trends for instream TON and TN concentrations are strongly associated with changes to intensive pastoral farming extent, principally dairying (Unwin et al., 2010; Larned et al., 2016). Targeted, validation monitoring will help inform if contaminant and hydrological processes would benefit from sub-regionalisation, including of regional groundwater TN contributions that were further refined for the Manukau Harbour watershed in FWMT Stage 1 (i.e., to better represent varying age and geochemical properties of the region's most extensive aquifer system [Meijer et al., 2016]). Similarly, whether dynamic configuration is needed to represent any lag time or "load to come" (i.e., if increased fertilizer used and productivity of horticulture and dairying has resulted in changes to DIN concentrations over the 16-99 year residence time of groundwater in the Franklin aquifer). N-loads to come have been identified in other groundwater-rich catchments with high intensity pasture and/or horticulture within the Bay of Plenty (Morgenstern et al., 2015) and Waikato (Aqualinc, 2013) but otherwise are relatively poorly understood in Auckland (e.g., no estimates of TN load to come if any, have been produced to date).
- Note that all yields discussed here are to EOS, so not directly comparable and preventing a comparison to edge-of-field (EOF) estimates either from OVERSEER® or SPASMO®. Instead, FWMT yields implicitly incorporate

regionalised attenuation – that is, reduction in TON of active groundwater or interflow by denitrification has been incorporated through the configuration and calibration/validation. Generally "satisfactory" or better TN loading performance for r^2 suggests that regional approximation of groundwater denitrification is reasonable – although noting PBias and NSE performance measures were more frequently "unsatisfactory" (i.e., due to extremes of continuous daily loads being more poorly simulated and/or more poorly represented by monthly grab sampling).

- The CLM and C-CALM not being configured for rural uses or TN contaminants, national modelling is the only source of information covering the Auckland region. Elliott et al. (2005) estimated national "dairy" and "other" pastoral TN-yields of 71.4 and 18.2 kg/Ha/yr, respectively. However, the latter were instream rather than to EOS and two decades old (1996-1999), meaning they potentially under-estimate yields in 2013-2017 given widespread increases since of N-fertilizer use, pastoral production and increasing instream DIN concentrations (e.g., Parfitt et al., 2008, 2012; Scarsbrook and Melland, 2015; Larned et al., 2016). Nonetheless, the Elliot et al., (2005) dairy yields accord well with high intensity pastoral yields from the FWMT Stage 1 (e.g., yields differing by <10%). Although FWMT Stage 1 low intensity pastoral yields are more markedly less than "other pastoral" yields in Elliot et al. (2005), the latter included a range of drystock systems classified into the high intensity HRU – low intensity pastoral yields being nearer the average national TN-yield (5.33 kg/Ha/yr). Other than national water quality modelling, FWMT TN-yields can be compared to other regional CLUES modelling but only after acknowledging such comparison is fraught with potential error (e.g., differing climate, farming practices and types, attenuation processes, timeframes). The most recent, Semadeni-Davies and Kachhara (2017) estimated rural land use yields in Greater Wellington for a 2012 baseline, including mean annual TN-yields of 3.9-8.0 kg/Ha/yr for sheep and beef, deer and other stock, highly similar to FWMT Stage 1 regional TN-yields of low intensity pasture (6.2 kg/Ha/yr) (the study did not attempt high intensity pastoral yield simulations). Note that wider yield information for more recent national and neighbouring regional contaminant modelling for the Waikato were not available (e.g., not noted in Parshotam et al. (2013) nor Semadeni-Davies et al. (2015). CLUES is undergoing model development for Northland currently, also without modelled yield information available.

More detailed TP findings include:

- Two sources dominate regional TP loading to waterways in Auckland: pasture (53.4%, 1,483 kg/year) and bankside erosion (42.5%, 1,178 kg/year) (annualised 2013-2017). All other sources collectively amount to <5%, meaning of the six contaminants lost from land in the region, TP is most heavily dominated by two sources. Urban sources combined amount to 1.7% of the regional TP loads (47 kgs/year) which as per TN, does not preclude urban sources being locally dominant with widespread failures of proposed DRP national bottom lines throughout all watersheds (e.g., 33-74% of watershed FWMT reaches failing).

- Pastoral sources contribute a higher percentage of TN (74.9%) than TP (53.4%). Although high intensity pasture dominated regional TN contributions (63.7%), low intensity pasture dominates regional TP contributions (29.4% – noting that high intensity pasture is also a considerable contributor of regional TP losses to waterways at 24%).
- Patterns in TP are relatively simple, with limited variation between watersheds in the origin of loading amongst HRUs. For instance, pastoral and bank erosion sources are the two largest sources in all 10 watersheds. In Wairoa and Waitematā, bank erosion is the largest source followed by pasture, while in the other 8 watersheds pasture was the dominant source followed by bank erosion. Hence, even watersheds with greater urbanised extent receive the vast majority of TP from pastoral land use and bank erosion. In three watersheds high intensity pastoral HRUs contribute more than their low intensity equivalents: Kaipara (34% to 30.4%, respectively); Manukau Harbour (42.3% to 18.1%, respectively); and North East watershed (31.1% to 26.9%, respectively). However, overall low intensity pastoral contributions predominate regionally.
- Inspection of Appendix E underscores a pastoral signature in TP loading, with pasture contributing the majority (>50%) of TP in 31 of the 46 regionally important rivers. With the widespread failures of proposed DRP national bottom lines, the focus of any regional or watershed management for eutrophication would therefore require a disproportionate emphasis on pastoral sources (noting LSPC does not simulate DRP from HRUs but splits TP into its particulate and dissolved fractions at the edge of stream, before processing each separately instream).
- Despite being extensive and occupying 225,200Ha (47%) of the region, pastoral TP-yields of 6.6 kg Ha/yr are greater than any other urban HRU grouping (Table 3-8). For instance, roading and motorways are the greatest TP-yielding urban HRU but contribute 1.3 kg/Ha/yr. Despite accounting for 0.8% of the regional TP loading to waterways, horticulture possesses a TP-yield of 1.4 kg/Ha/yr, making it the second most intense source of TP regionally with the exception of point sources (albeit horticulture is still fivefold less intense a source than pasture).
- FWMT Stage 1 estimated TP-yields for pastoral HRUs are higher than estimates from CLUES estimates for Greater Wellington of between 0.24-1.96

kg/Ha/yr across sheep and beef, deer and other stock (Semadeni-Davies and Kachhara, 2017). Although, the latter also found a five to eight-fold difference between sheep and beef, deer and horticultural TP-yields, also stressing the importance of pastoral TP-sources if managing for eutrophication effects instream. The simple representation of urban TP sources (modified from C-CALM) precludes value in a comparison to FWMT Stage 1 outputs and likely explains why Semadeni-Davies and Kachhara (2017) assigned greater yields than horticulture to urban surfaces.

- Elliott et al. (2005) reported national TP-yields for 1996-1999, of approximately 7.81 kg/Ha/yr from dairying and 4.36 from "other" pastoral farmland. Both are markedly greater than Greater Wellington estimates from Semadeni-Davies and Kachhara (2017) and more than TP-yields reported here by the FWMT Stage 1 for pasture (6.59 kg/Ha/yr). The FWMT Stage 1 results are within the range of yields presented by Semadeni-Davies and Kachhara (2017) and Elliott et al. (2005). As with all prior comparisons, while it is highly unlikely yields or proportionate contributions within the Auckland region exactly should match prior studies, it is encouraging FWMT results are within latter envelopes (noting that temporal differences should have arisen from marked increased high-intensity agricultural productivity over the past two decades). Output from the FWMT Stage 1 suggests the patterns in yields between various sources has generally remained consistent.

4.0 Summary

This report documents the first *comprehensive*, region-wide assessment of water quality (contaminant) state *throughout the Auckland region* predicted by the *FWMT Stage 1*. Continuously predicted, process-based water quality has been assessed for a baseline period of 2013 to 2017 in 3,085 km of fresh waterways and derived from all 489,000 ha of land in the Auckland region, classified into 106 regionalised types (HRU). The report supplements three others that describe the FWMT Stage 1 including, [Baseline Inputs], [Baseline Configuration and Calibration], and [Baseline State-Lakes outcomes].

The FWMT supports a wide range of purposes in Auckland Council, including its freshwater quality accounting framework for the NPS-FM. Core to Stage 1 purposes is correctly grading water quality to support prioritised management (e.g., identifying failing waterways; sources of contaminants; supporting targeted and optimal interventions).

Assessment of FWMT Stage 1 grading performance has demonstrated reasonable assurance at predicting all grades across seven contaminants able to degrade ecosystem and human health of water quality (*E. coli*, DRP, DIN, TON, TAM, DCu, DZn). Regionalised configuration and representation of up to 107 contaminant sources across 5,465 sub-catchments, has demonstrated greatest performance at identifying “failing” streams (i.e., those requiring mandatory improvement under the NPS-FM and/or D-graded). Across the seven contaminants, 43-100% of all failing SoE stations were predicted at exactly their observed grade whilst 91-100% of all failing streams were predicted within an additional grade.

Performance assessment has highlighted the need for ongoing targeted, validation monitoring (e.g., better representative of contaminant, HRU and meteorological gradients using equivalent data, either continuous or integrated observational data compared to continuous or integrated model output). However, Auckland Council is now impressively positioned to utilise a highly accurate regional accounting framework for determining ongoing pressures and cause or sources(s) of degradation in water quality.

Water quality appears most extensively (and markedly) degraded across the Auckland region for *E. coli* (human health). Indeed, 83% (2,562 km) of FWMT reaches are predicted to fail national bottom lines for primary contact recreation (if applied conservatively throughout the FWMT network) and otherwise, fail to achieve national targets for human health instream (if also applied conservatively to all FWMT reaches rather than only 4^{th} order freshwater streams). Exceedances of national targets in *E. coli* numeric attribute states were simulated in rural and urban FWMT reaches alike. All 30 “failing” SoE stations were predicted to exactly their observed grade – indicating high accuracy and likelihood of such a region-wide pattern.

Amongst the four numeric attribute states for *E. coli*, the 95th% concentrations were most frequently worst-graded and require (at least) a three-fold reduction in 95th% within half of failing reaches (1,282 km). A five-fold or greater reduction in 95th% *E. coli* concentrations is required throughout a quarter of D or E-graded reaches to achieve a C-grade. Consequently if national targets apply equivalently to all regions, managing *E. coli* losses to waterways is likely to require marked change throughout the Auckland region. That task would then require disproportionate reductions in *E. coli* loads from pastoral land uses. Source apportionment demonstrates that a vast majority of *E. coli* is lost from pastoral land users, particularly high-intensity pastoral farming (e.g., 80% of all edge-of-stream *E. coli* loads are pastoral in provenance, of which nearly two thirds is from the third of pastoral land and 15% of the region overall, in high-intensity pastoral production).

On a regional basis, few attributes of ecosystem health exceed national bottom lines extensively across the Auckland region. Ammoniacal nitrogen (TAM) toxicity is potentially most problematic with 4% (116 km) of FWMT reaches D-graded but 50% (1,538 km) failing national bottom lines (C or D-graded). Nearly all failing FWMT reaches were worst-graded for the TAM maximum attribute state. The continuous simulations of the FWMT are likely to better document short-lived, acute events than monthly one-off sampling (e.g., resulting in 1,826 modelled daily observations over five years, to just 60 observed samples). No direction is available on whether NOF attribute guidance has been developed only for discrete (monthly) SoE monitoring or is suitable also, for application to continuous modelling. However, sensitivity testing revealed if modelled NH4N 95th% is utilised instead of maxima, approximately 61% of FWMT reaches shift one grade better with a further 7% of reaches shifting two grades better. Overall, resulting in 38% of FWMT reaches improving above the national bottom-line for TAM (i.e., proportion of failing FWMT reaches to drop from 51% to 13%, regionally). Notably, the FWMT Stage 1 has crossed a milestone in New Zealand water quality management, creating new challenges for modelling rather than monitoring-based guidance to enabling accurate accounting for the NPS-FM.

Amongst attributes for ecosystem health not requiring limits on activity use in the NPS-FM (MfE, 2020), DRP grading is generally worst across the Auckland region. Approximately 59% (1,814 km) of FWMT reaches are predicted in D-grade, across both median and 95th% numeric attribute states (i.e., for both chronic and acute risks of excessive nuisance plant growth). Approximately one third of D-graded FWMT reaches will require a halving in 95th% or median DRP concentrations, with the remainder requiring more still. As with *E. coli* loads, the vast majority of TP is contributed to waterways in Auckland by pastoral farming (75%, 4,050 tonnes/year). Regionally, low-intensity pastoral farms contribute more TP load than higher intensity systems although TP-yields are notably greater for high-intensity (9 kg/Ha/yr) than low-intensity farms (5 kg/Ha/yr).

Other notable findings of Auckland Council's first comprehensive assessment of baseline water quality state and contaminant sources under the NPS-FM, include:

- Localised failures (114 km) in TON toxicity within four watershed (Kaipara, Manukau Harbour, Waitematā and West Coast). The Manukau Harbour is the most-degraded thereof for TON toxicity (102 km, 20% C or D-graded). The Manukau Harbour is also the most-degraded watershed by stream length for DIN, with 32% of reaches (170 km) predicted in D-grade. Over half of the horticultural sector's regional TN loads occur to streams in the Manukau Harbour, where horticulture accounts for 42% (700 tonnes/year) of the watershed's combined annual TN loading to streams (from 6% of the watershed extent). Horticultural TN yields are relatively high, at 115 kg/Ha/yr, nearly fivefold greater than pastoral or paved urban surface yields regionally, and an order of magnitude greater than any other HRU groups accounted for by the FWMT Stage 1. Management for nitrogen toxicity or eutrophication effects would therefore necessitate prioritisation of horticultural activity for its enriched TN yields and high intensity pasture for its great proportion of TN loads (e.g., pastoral HRUs account for 75% of regional TN loading to freshwater streams).
- Sediment (TSS) is lost in most-part from bankside erosion, which contributes 57% of regional and between 43-73% of watershed loading to waterways. Bankside TSS contributions are also associated with considerable proportions of regional TP loads (22% of regional loads). Whilst TSS-based guidance is not available for the NPS-FM, Auckland Council (Healthy Waters) is developing as much from proposed turbidity-based NOF guidance. An addendum will be incorporated once available explaining likely sedimentary pressures on freshwater quality, but a clear need exists for TSS-based coastal guidance with sedimentary-degradation of coastal receiving waterways widespread and widely acknowledged (e.g., Gibbs et al., 2004; Thrush et al., 2004, 2013; Green, 2017).[15]
- Dominant regional sources of TCu and TZn include forests and open spaces (>23%), pasture (>18%) and bankside erosion (>33%). However, both contaminants are not widely predicted to exceed regional bottom lines. Only 4% and 8% of streams are predicted to be in D grade for one or both DZn or DCu, solely for the corresponding 95th% numeric attribute state (e.g., acute toxicity effects). The distribution of provisionally failing streams for DZn and

[15] Note that all NOF and ROF guidance reported here is suitable only to local freshwater receiving environments and otherwise not intended to manage for coastal outcomes. The NPS-FM is clear though that such considerations are necessary of any regional planning response by Auckland Council.

DCu is focussed on urban locations, with greatest proportions of both the Waitematā (27%, 100km) and Tāmaki watersheds (47%, 47km) failing regional bottom lines for DCu and the largest proportion of Waitematā waterways (24%, 64 km) failing DZn bottom lines. Across the region, roading and motorways are the highest yielding sources for DCu (11.9 g/Ha/yr) and account for 12% of regional yield. Whilst, critical (intense) sources of DZn across Auckland include, roofing (394 g/Ha/yr, 20.7%) and roads and motorways (302 g/Ha/yr, 15.9%).

Finally, whilst regional and watershed summaries have been discussed and summarised here the FWMT Stage 1 is a full, regional model able to represent seven contaminants for grading and sources, at 2,761 instream locations. Further detail on these and watershed reporting is available in the Appendices or direct from Healthy Waters (Auckland Council – contact Regional Planning, fwmt@aucklandcouncil.govt.nz).

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Appendix A – Watershed summaries (radar charts and maps)

Note – Appendix A is published separately on Knowledge Auckland. Contact fwmt@aucklandcouncil.govt.nz for more information.

Appendix B – Ecosystem and human health assessment

Note – Appendix B is published separately on Knowledge Auckland. Contact fwmt@aucklandcouncil.govt.nz for more information.

Appendix C – Watershed grade summaries for all sub-catchments

Note – Appendix C is published separately on Knowledge Auckland. Contact fwmt@aucklandcouncil.govt.nz for more information.

Appendix D – Heat maps

Note – Appendix D is published separately on Knowledge Auckland. Contact fwmt@aucklandcouncil.govt.nz for more information.

Appendix E – Source apportionment summary tables by contaminant

Note – Appendix E is published separately on Knowledge Auckland. Contact fwmt@aucklandcouncil.govt.nz for more information.

Appendix F – Source assessments by major watershed

Note – Appendix F is published separately on Knowledge Auckland. Contact fwmt@aucklandcouncil.govt.nz for more information.

Appendix G – Source assessment for large rivers and additional points of interest

Note – Appendix G is published separately on Knowledge Auckland. Contact fwmt@aucklandcouncil.govt.nz for more information.

Appendix H – Mapping of model categories to source categories

Note – Appendix H is published separately on Knowledge Auckland. Contact fwmt@aucklandcouncil.govt.nz for more information.

Appendix I – Summaries using integrated data

Note – Appendix I is published separately on Knowledge Auckland. Contact fwmt@aucklandcouncil.govt.nz for more information.

Appendix J – Proportion of watershed sub-catchments upstream of failing FWMT reaches

Note – Appendix J is published separately on Knowledge Auckland. Contact fwmt@aucklandcouncil.govt.nz for more information.

Appendix K – Grade comparisons

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