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Defining a biophysical framework for Freshwater Management Units of the Te Awarua-o-Porirua Whaitua

November 2016

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LWP Client Report Number: LWP Client Report 2016-014

Report Date: November 2016

LWP Project: LWP Project 2016-014

Quality Assurance Statement

Version	Reviewed by		
1	Norton	4th November 2016	
Final			

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Executive Summary

The National Policy Statement for Freshwater Management 2014 (NPS-FM) directs regional councils to develop regional plans for managing freshwater quality and quantity. Plans must contain freshwater objectives, policies and limits.

The quality and quantity of water in water bodies, the values they support and the appropriate balance between water resource use and other values vary spatially. This means that it is generally inappropriate to set specific (i.e. numeric) freshwater objectives that apply broadly to all water bodies in a region. The NPS-FM requires that regional councils subdivide their regions into Freshwater Management Units (FMUs). The NPS-FM defines a FMU as a water body, multiple water bodies, or any part of a water body determined by a regional council as the appropriate spatial scale for setting freshwater objectives and limits and for freshwater accounting and management purposes.

Implicit in the NPS-FM definition is the idea that FMUs are to be established based on how water bodies, or parts of water bodies, are valued. There is therefore interdependence between establishing FMUs and determining the values (and associated objectives) for which they are to be managed.

Definition of spatial management frameworks, as represented by FMUs, is integral to setting objectives, policies and methods. Consequently, it is important that the process of defining FMU boundaries is transparent and alternative options can be considered by decision-makers. Some iterative refinement of the FMUs is likely to be necessary as part of the development of plan provisions.

This report offers a transparent and justifiable bio-physical starting point for defining FMUs for rivers within the Te Awarua-o-Porirua Whaitua. This report does not consider FMUs for lakes, wetland or aquifers but the approach taken by this study could be expanded to FMUs for these domains. The framework uses a modified version of the national River Environment Classification (REC) system to classify the Whaitua's rivers based on bio-physical characteristics that are relevant to managing water quality and quantity. In this document the bio-physically defined units are referred to as example FMUs but it is assumed that these may be modified, as the Whaitua planning process proceeds, following additional considerations such as specific values, human rather than bio-physical factors and/or additional bio-physical factors of particular water bodies, objectives and policies.

The example FMUs offered in this report are a framework of related spatial units that serve different purposes and may overlap each-other, rather than being a simple subdivision of the region. There are several reasons that this framework of spatial units is necessary including:

- To acknowledge and provide for the "source to sea" spatial structure of rivers, which is a key driver of variation in characteristics, values and objectives within a catchment, and requires the appropriate management of all upstream locations to achieve objectives.
- To provide for different plan development processes (e.g. community consultation versus developing specific management polices),
- The need to manage different issues (e.g. water quality versus water quantity, and surface and groundwater), and

- The need to provide a basis for different management functions (e.g. setting objectives versus accounting for resource use and consenting water takes).

The example FMUs were developed in three steps. The first step was to classify the region's rivers for water quality and quantity management, thus producing what is hereafter referred to as a "*management classification*". The region's rivers were represented as individual segments of a digital river network and each segment was classified on the basis of physiographic "factors" that drive variation in water quality and quantity comprising catchment climate, slope, geology and river size (as defined by average flow rate). The *management classification* broadly discriminates variation in the characteristics of the water bodies that are relevant to management, including their values and capacity for resource use. The Te Awarua-o-Porirua Whaitua committee had previously recognised land use and receiving environments are key drivers of variation in characteristics of rivers in the Whaitua and had suggested a preliminary set of FMUs on this basis. This report formalises the management classification, confirms its robustness and provides examples of how objectives could vary by class. Selecting objectives is ultimately a political decision and therefore the objectives in this report should be regarded as examples.

The second step defines *management zones*. *Management zones* recognise that many of the management actions (i.e. policies and rules) to achieve objectives apply to land areas (and associated land use and development) that drain to water bodies, and not only to the water body itself. Therefore, all land areas that drain to water bodies belonging to a particular *management class* become a *management zone*. Like the *management classes*, *management zone*s are not restricted to a single catchment and recur in a patchwork across a region. In addition, individual locations may belong to more than one *management zone*.

FMUs are defined by layering *management zones* in an order that is dependent on the policies and limits set for each of the management zones. The layering of the zones recognises that locations that lie in multiple management zones must comply with the policies and limits associated with the *most restrictive downstream objectives*.

Because the layering of management zones is dependent on objectives, policies and limits, the final definition of FMUs must be undertaken as part of the planning process. However, to provide examples of the approach in its entirety in this report, credible example objectives have been defined for each management class and an ordering of the resulting restrictiveness of policies and limits has been assumed. This has produced example FMUs for water quality and quantity management but it is anticipated that these will need adjustment as the plan process proceeds. The process for defining the final FMUs uses the *management classification* and associated *management zones* as building blocks. These building blocks can be combined in a variety of ways thereby allowing for adjustments to be made to the spatial framework (i.e. the FMUs) as plan development proceeds.

The third step recognises that administration and accounting for contaminant discharges and water takes must occur within individual catchments. A minimum set of individual catchments are defined by the points in the drainage network where there is a change in the management zone. These points represent a framework of *administrative points*, each of which defines a sub-catchment or catchment. This results in a large number of administrative points but this need not result in a complicated plan because administrative units are of relevance to plan implementation whereas plan provisions apply only to the management classes (water quality and quantity objectives) and associated management zones (controls on use and development). Quantitative limits (e.g., contaminant mass loads and volumetric allocation rates) can be determined for each individual administrative point provided that they are defined on a scalable basis such as proportion of a flow statistic that reflects stream size such as the Mean Annual Low Flow (MALF) for water quantity limits and an area basis for contaminant loads (e.g. kg/ha/yr).

It is noted that administrative points are not monitoring locations; for either water quality or quantity. Monitoring of both water quality and quantity (e.g. monitoring flows) would be carried out at representative sites (such as is currently provided by the water quality and flow monitoring networks) and the data collected at these sites would be used to inform on the achievement of objectives in management classes as a whole or to provide proxy measurements (e.g. flows) at specific administrative points.

Some water bodies have specific values or management issues that are not discriminated by the biophysical management classification described above but which may need to be provided for in the new regional plan. It is suggested that these water bodies can be handled by defining *special management zones* that over-ride the objectives set for the *management classes*. Examples of water bodies requiring separate management objectives in the Whaitua are the Taupo Swamp and the catchments draining to the open-coast. Both receiving environments may be judged to be different to the Porirua Harbour, which is the receiving environment for most streams in the Whaitua. All three receiving environments in the Whaitua (Taupo Swamp, Porirua Harbour and the open coast) are likely to be valued differently and have different sensitivities. Defining special management zones for the Taupo Swamp and the catchments draining to the open-coast would enable specific plan provisions (objectives and policies) to apply to all three receiving environments. It is noted that special management zones will add to the complexity of the plan (by creating exceptions to the policies that apply to the general FMUs). It is recommended that specific criteria are derived to avoid a proliferation of special management zones that will undermine the clarity and relative simplicity that is afforded by the general FMUs. Some special FMUs may only be identified because of consultation with community groups and could thus be added progressively to the framework as plan development proceeds.

The approach offered in this report has several benefits:

1. The use of physiographic classifications provides for variation in the characteristics of interest to be resolved at a level of detail that is appropriate to management,

2. The approach is transparent,

3. The logic that objectives apply to the water bodies and that the limits and actions apply to the catchments draining to those water bodies is inherent in the approach,

4. The need for limits to be set and actions taken to achieve the most constraining downstream objective is built into the approach,

5. The process is flexible and easily repeatable so that FMUs can be modified and their definition is integral to the plan development process.

6. The level of classification detail (i.e. coarse or fine) can be altered by varying the physiographic factors (and their categories) to suit the desired level of detail and spatial specificity of the plan provisions,

7. The layering of management zones can be altered to accommodate changes in the order of restrictiveness of policies and limits that may arise in the development of plan provisions,

8. Aspects of the plan's implementation (e.g., consenting and accounting for resource use) can be undertaken at appropriately fine levels of spatial resolution defined by the administrative points,

9. The framework provides an efficient and justifiable basis for water quality monitoring and reporting at the regional level based on having a representative number of monitoring sites in each management class, and

10. The framework is spatially clear and certain (i.e. mapped) about where limits need to be met and where accounting should occur (administrative points).

The approach offered in this report is based on a three class classifications for water quality as the starting point for defining FMUs. It may be that a classification is not needed for water quality because there is only minor variation in the rules needed across the Whaitua to achieve a specific set of water management objectives. The relatively coarse level of classification and subsequent discrimination of characteristics is consistent with the trading off detail (specificity) with coverage and simplicity. It is also anticipated that some special FMUs will need to be developed to manage specific water quality issues, for example specific swimming spots in certain rivers, and water quality issues in the Taupo Swamp and Te Awarua-o-Porirua Harbour. Thus, it is anticipated that a final FMU framework will ultimately require deciding how much complexity is appropriate beyond the three class units that are offered by this study.

1 Introduction

1.1 National Policy Statement for Freshwater Management

The National Policy Statement for Freshwater Management 2014 (NPS-FM, New Zealand Government 2014) directs regional councils to develop regional plans for managing freshwater quality and quantity. Plans must contain freshwater objectives, policies and limits.

The NPS-FM requires councils to identify community values that are associated with freshwater (for example environmental, cultural and social values such as recreation, and economic use values, namely contaminant assimilation and water supply) and to collect water quality and quantity information to assess the current state of water bodies within their regions. With reference to the current state and taking into account the community's values, councils are required to include objectives in regional plans that express numerically (where practicable) the desired environmental state of water bodies[1]. Under the NPS-FM, freshwater objectives must strike a balance between enabling water resource use and sustaining other values of water. However, they must also provide for overall maintenance or enhancement of regional water quality[2]. In addition, the NPS-FM requires councils to set objectives that are above specified minima or 'national bottom lines'[3]. Councils must develop policies, which may include limits and other management actions, to achieve the freshwater objectives[4]. Where objectives are not currently being achieved the NPS-FM directs regional councils to determine how and over what timeframes, those goals are to be achieved[5].

1.2 Freshwater management units

The quality and quantity of water in water bodies, the values they support and the appropriate balance between water resource use and other values vary spatially. This means that it is generally inappropriate to set specific (i.e. numeric) freshwater objectives that apply broadly to all water bodies in a catchment or region. The NPS-FM addresses this with the concept of the Freshwater Management Unit (FMU). A FMU refers to a water body, multiple water bodies, or any part of a water body designated to be managed for a particular value(s)[6] and for freshwater accounting and management purposes. A regional plan that addresses the management of water bodies in a catchment or region requires a spatial framework of FMUs that subdivides water bodies and their catchments into groups for which differing management regimes will apply.

FMUs are a significant component of a regional plan because they provide a framework for applying different plan provisions[7] and management functions including;

1. Setting freshwater objectives,

2. Defining management actions, including water quality and quantity limits, to achieve the objectives,

3. Accounting for resource use (within limits), and

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[1] See Policy CA2, NPS-FM
[2] See Objective A2 and Policy A1, NPS-FM
[3] See policies CA2 and CA3 , NPS-FM
[4] See policies A1 and B1, NPS-FM
[5] See policies A2 and B6, NPS-FM
[6] The NPS-FM defines a FMU to be the water body, multiple water bodies or any part of a water body determined by the regional council as the appropriate spatial scale for setting freshwater objectives and limits and for freshwater accounting and management purposes.
[7] Plan "provisions" refers to objectives, polices, methods and rules that are defined in the regional plan.

4. Monitoring progress towards, and the achievement of, freshwater objectives.

There is interdependence between defining FMUs and determining the plan provisions that apply to them. Therefore, the development of FMUs is integral to the plan development process and cannot be divorced from other normative[8] decisions that are required such as determining the level of protection for various water quality and quantity dependent values (i.e. setting freshwater objectives) and appropriate management actions. Because the development of FMUs is integral to the development of the regional water plan, the methodology should be transparent and the decision-maker(s) should be able to consider and weigh up alternative options.

The scale of FMUs is a key consideration. Large FMUs may not provide sufficient resolution of values, community aspirations for water quality maintenance and enhancement, and current state; consequently, large FMUs may not provide plan provisions of sufficient specificity. By contrast, many independently defined and small FMUs may produce overly detailed plan provisions that may be difficult to justify and result in inefficient water resource management.

1.3 Te Awarua-o-Porirua Whaitua Process

Greater Wellington Regional Council (GWRC) has divided the Wellington Region into five Whaitua, or sub-regions, as part of its community led collaborative planning process. The planning process will address a number of land and water management issues, and carry out GWRC's obligations under the National Policy Statement for Freshwater Management (NPS-FM). The Te Awarua-o-Porirua Whaitua was the second Whaitua to commence in the Wellington Region, with the Te Awarua-o-Porirua Whaitua Committee being established in December 2014.

The Te Awarua-o-Porirua Whaitua Committee is a partnership between the Regional Council, iwi, territorial authorities and the community, and will make recommendations to the Council through a Whaitua Implementation Programme (WIP) report. The WIP will contain strategies and actions which will form a programme of work to implement the NPS-FM in the Te Awarua-o-Porirua Whaitua. It will include recommendations for both statutory and non-statutory actions and methods.

Proposed regulatory provisions in the WIP will be incorporated into the Regional Plan through a plan change process. Non-regulatory programmes will also be developed further and implemented in conjunction with partners.

1.4 Structure of this report

This report is structured as follows:

- Section 2 provides an overview of the nature of FMUs, considers alternative approaches to defining FMUs and sets out a recommended approach for establishing FMU's for the rivers of the Te Awarua-o-Porirua Whaitua,
- Section 3 offers a bio-physical classification and spatial framework as a starting point for defining FMUs for managing river water quality,

[8] Normative decisions concern the prescriptive aspects of the plan such as the definition of objectives and rules and that are ultimately made by a political process.

- Section 4 offers a bio-physical classification and spatial framework as a starting point for defining FMUs for managing river water quantity, and
- Section 5 discusses the findings and recommendations.

2 Alternative approaches to defining FMUs

2.1 Overview

Most regional councils have either developed regional water plans or are in the process of doing so. Some councils have operational second generation plans that were developed prior to the release of the NPS-FM, but which address many NPS-FM requirements including numeric objectives and limits. All regional councils have had to account for regional differences in the values and characteristics of water bodies and generally have plan objectives and policies that recognise this variation to at least some extent. Some councils are well advanced with developing their second generation plans in response to the requirements of the NPS-FM, including defining FMUs. However, councils have approached this in various ways. The following is a brief summary of how five other councils in New Zealand have defined their FMUs.

Horizons (Manawatu-Wanganui) Regional Council has defined 44 water management zones and 117 subzones in the Manawatu-Wanganui region's One Plan. These zones are based on catchments or sub-catchments and encompass the water bodies within the zone and the surrounding catchment land area. Water quality and quantity related values for the water bodies in each zone have been identified and objectives defined. Because the Horizons water management zones/subzones are catchment-based, they enabled specific load-based nutrient limits to be defined for managing water quality in each zone. To assess compliance with the objectives and limits, a monitoring site is required at the downstream end of each zone. It is anticipated that some management functions will occur at the subzone level (e.g. surface water quantity allocation), while other management functions will occur at the zone level (e.g. water quality monitoring).

Environment Canterbury has defined management units at various scales. At the regional level, eight Water Management Zones[9] have been developed along socio-political and catchment boundaries, and these zones are used as a basis for collaborative management. At a lower level of spatial subdivision, the operative Land and Water Regional Plan (LWRP) has defined default objectives for all water bodies in the region based on bio-physical classifications of ten river classes and six lake classes. For rivers, the classes are based on the national system called the River Environment Classification (REC), which was developed by the Ministry for the Environment as a tool for various aspects of water management (Snelder and Biggs, 2002). Individual Zone plans are sub-regional sections of the Land and Water Plan that are specific to each of the eight Water Management Zones. These sub-regional plan sections are based on catchments and sub-catchments (for surface water) as well as recognising the physiographically defined river and lake classes of the parent LWRP. Water quantity limits (e.g. minimum flows and allocations), and nutrient load limits have been defined at catchment or sub-catchment scale. In some areas groundwater zones are also defined for the purpose of groundwater allocation and these may extend over just a part of, or more than one, surface water catchment.

[9] http://ecan.govt.nz/get-involved/canterburywater/Pages/canterbury-water-zone-map.aspx

Taranaki Regional Council has defined freshwater management units in its draft second generation regional plan based on a geo-physical subdivision of the region into four sub-regions. These sub-regions discriminate variation in the values, and physical and hydrological characteristics of the water bodies they contain. The sub-regions contain whole catchments and the sub-region boundaries therefore align with catchment boundaries. The Taranaki FMUs broadly differentiate the streams and catchments draining Mount Taranaki (the "ring plain"), the northern and southern coastal terraces and eastern hill-country. In addition, one FMU differentiates three non-contiguous "Outstanding" rivers and their catchments.

Finally, Northland Regional Council (NRC), Bay of Plenty Regional Council (BoPRC) and GWRC have considered how to define FMUs for their geographically complex regions. Both regions comprise many (i.e. > 100) "sea-draining" catchments that exhibit considerable variation in natural factors such as topography, geology and land use. Data describing the characteristics of these water bodies is limited. For example, long term water quality is monitored at only 35 sites in Northland and 50 sites in the Bay of Plenty. In addition, some sea-draining catchments are too heterogeneous with respect to values and capacity for resource use[10] for a single set of plan provisions to be justifiably applied, and many catchments and sub-catchments are very similar to each other with respect to values and capacity for resource use. The same approach to that taken by NRC and BoPRC has been taken by GWRC in the Ruamahunga Whaitua.

The approach taken by NRC, BoPRC and GWRC has been to define FMUs based on grouping water bodies into bio-physical classes that are relatively homogeneous with respect to their values and capacity for resource use. These classes will be the basis for plan objectives and it is anticipated that the detail of the classification (i.e. the number of classes) will allow objectives and subsequent policies to be drafted at an appropriate level of specificity. A benefit of this approach is that available data are used to represent the state of water quality in the FMUs and the current monitoring sites could be used to monitor their progress toward objectives in the future.

2.2 Catchments and scale

The purpose of FMUs is to provide a basis for setting water quality and quantity objectives and associated limits, and for managing and accounting for water resource use. It is fundamental to the approach taken in this report that FMUs are based on catchments because the nature of water bodies[11] including their values, physical and ecological functioning, and their state (i.e. their condition) is largely determined by the character of their upstream drainages (e.g. climate, topography, land use) and the nature of the resource use that occurs within them (e.g. land use and management, water takes, and point source discharges). It is noted that the NPS-FM definition of FMUs does not explicitly mention

[10] The term 'capacity for use' refers to the amount of resource use that can be made while sustaining all competing values at some agreed level. Because value judgements are required to determine the acceptable level for supporting values, so too the capacity for resource use depends on these value judgements. Capacity for use varies widely between water bodies; some water bodies that support very sensitive and significant in-stream values may have zero capacity for use, while other water bodies may have significant capacity for use. In the context of water quality, the capacity for use is the capacity of the water body to dilute and/or assimilate contaminants derived from resource use, while sustaining all other values at desired levels. In the context of water quantity, the capacity for use is the rate at which water can be removed from the water body (or be diverted or dammed) while sustaining all other values at the desired level.

[11] In this report a water body is defined as a physiographical feature such as a stream, river, lake or wetland or any part thereof. Furthermore, a catchment is defined as the upstream drainage of a water body. It is unclear from the NPS-FM definition of a FMU whether a water body is defined as per this report or if it includes the catchment. However, in this report an FMU is assumed to include the catchment because objectives set for water bodies must primarily be achieved by managing resource use in their catchments.

catchments but it is implicit in other parts of the NPS-FM that FMUs must involve consideration of catchments.[12]

Catchments can be defined at different scales, for example, an entire land area that drains to a river mouth at the coast (referred to in this report as a sea-draining catchment) or a smaller scale subdivision of tributary streams.

A sea-draining catchment might be an appropriate scale for managing sedimentation rates or nutrient enrichment in estuaries and harbours. However, subdivision of large sea-draining catchments may be appropriate if, for example, there is variation in water quality or the values within the catchment (e.g. if the catchment includes a lake or parts of the same river system support significantly different values). The scale at which FMUs need to be defined ultimately depends on achieving reasonable (and practical) homogeneity (i.e. degree of similarity) with respect to several characteristics of the water bodies they contain, including; (1) their values, (2) their capacity for use, and (3) management requirements resulting from their bio-physical functioning[13]. Where there are multiple water related values, and/or differences in other relevant water quantity or quality characteristics, this may require that catchments of differing sizes are defined and that smaller catchments are 'nested' within larger catchments.

Sub-catchments can be defined at any scale from fine-scale first order (i.e. headwater) catchments to coarse-scale drainages of significant tributaries and entire sea-draining catchments. The size of a sub-catchment generally determines its homogeneity with respect to values and other characteristics. Water bodies in small sub-catchments such as headwater areas are likely to be relatively similar, whereas large sea draining catchments may contain a more diverse range of values and other characteristics. Defining a regional framework of FMUs therefore involves subdividing catchments such that the values and other characteristics they contain are sufficiently homogeneous that a set of plan provisions can be justifiably applied, and that the level of detail and complexity is minimised (i.e. the scale is as coarse as possible).

2.3 Use of river classification in regional water plans

Classification of water bodies provides a basis for discriminating variation so that appropriate objectives can be set for different groups (or classes) of water body. The River Environment Classification (REC; Snelder and Biggs; 2002) is a national classification of rivers that has been used extensively since 2002 as a basis for various aspects of water management including state of environment reporting, catchment contaminant modelling (e.g. CLUES) and a basis for classifying rivers for different management purposes in regional plans. In particular, the REC has been used as a basis for defining objectives in regional plans (e.g., Canterbury LWRP, Southland Regional Water Plan, Horizons One Plan).

REC classes provide a basis for grouping similar water bodies, which are defined by individual segments of the river network. All segments belonging to a particular class are considered sufficiently similar that the same objective can justifiably apply to them. Furthermore, objectives can also vary appropriately between different REC classes, reflecting their different physical, chemical and ecological processes. However, REC classes are not an adequate basis for defining management actions or limits because many of these

[12] Policy C1 of the NPS-FM directs regional councils to "manage fresh water and land use and development in catchments in an integrated and sustainable way, so as to avoid, remedy or mitigate adverse effects, including cumulative effects."
[13] For example, differences in the flow regimes and morphology of streams and rivers within large sea-draining catchments may be sufficiently large that different nutrient concentration criteria are appropriate.

will need to apply to land areas draining to the water bodies, not only to the waterbodies themselves. In addition, REC classes do not provide a basis for administrative functions such as accounting for resource use because these must be based on individual catchments. However, the REC and its underlying representation of the drainage network provides a starting point for the development of a system of FMUs that is described in the next section.

2.4 FMUs based on bio-physical classification of the drainage network

An approach to the definition of FMUs that builds upon the concepts of the previous sections starts with a physiographic classification that resolves important differences in relatively unchanging and natural aspects of the environment (including topography, geology and river size, which are termed physiographic *factors* in this report) that are relevant to the management of water quality and quantity. The approach subdivides the factors into specific categories, for example, ‘hill’ and ‘lowland’ topography can be discriminated by differences in average catchment slopes. The classification is applied to a detailed (fine-scaled) subdivision of the region’s drainage network and associated sub-catchments. The benefit of such a category-based approach is that the basis for FMUs is transparent and alterable (by changing the factors and/or their categorisation) and can be applied generally to an entire region.

The benefit of using a drainage network as a basis for defining FMUs is that the catchment upstream of any specific point along a water body can be defined. Each point in the drainage network has its own unique sub-catchment defined by all the upstream land draining to that point. Because a drainage network allows subdivision of the region’s catchments to be carried out at any scale, the optimal scale (or alternative scales) of sub-division can also be explored.

This project has used three key steps to construct a framework of FMUs based on the drainage network:

1. Define the *management classification*,
2. Define the *management zone*s, and
3. Define the *administrative points*.

The first step is the definition of a ***management classification*** of the water bodies. This classification involves grouping water bodies into classes that are relatively homogeneous with respect to their biophysical characteristics including; (1) their environmental and ecological characteristics, (2) the capacity of both the water bodies and their catchments for resource use.

The approach taken in this report to investigate the *management classification* (i.e. groups of stream and river segments) that the Te Awarua-o-Porirua Whaitua Committee had previously recognised based on urban/rural land use and water receiving environments (swamp, estuary or open coast). Variation in physiographic factors within and between the Whaitua’s classification will be assessed. Physiographic factors are a relevant basis for defining classes because they broadly ‘control’ physical and biological processes that determine the quality and quantity of water bodies, their values and aspects of their bio-physical functioning. The classification approach allows the use of these physiographic factors to be formalised. The details of the physiographic factors are set out in subsequent sections but include, for example, the catchment slope, geology and size (as defined by average flow rate). In addition, variation in available relevant water quality data (physical, chemical and biology) within and between the Whaitua's classification will be assessed. The physiographic and water quality assessments will help formalise the Whaitua's classification.

The *management classification* forms the basis for defining freshwater objectives for all the water bodies in the region. The *management classification* contains a number of individual *management classes*, many of which are likely to extend across multiple catchments. Individual catchments are also likely to comprise more than one *management class*.

The second step defines ***management zones***. *Management zones* recognise that many of the management actions (i.e. policies and rules) to achieve objectives apply to land areas (and associated land use and development) that drain to water bodies, and not only to the water body itself. Therefore, all land areas that drain to water bodies belonging to a particular *management class* become a *management zone*. Like the *management classes*, *management zone*s are not restricted to a single catchment and recur in a patchwork across a region. In addition, individual catchments may comprise more than one *management zone*.

FMUs are defined by layering *management zones* in an order that is dependent on the policies and limits set for each of the management zones. The layering of the zones recognises that locations that lie in multiple management zones will have to comply with the policies and limits associated with the *most restrictive downstream objectives*. For example, in some circumstances land may drain to a river segment that is relatively insensitive to the effects of nutrient concentrations. However, further downstream, perhaps several kilometres away, the destination of water may be a lake or estuary that is more sensitive to elevated nutrients. In this case, limits set for point and diffuse source discharges in all upstream catchments need to ensure that the more restrictive management objective for that lake or estuary is achieved. *Management zone*s clarify these important concepts and clearly define land and associated development that needs to be managed to achieve a particular objective in a water body.

Because this study precedes the development of policies and limits, it is not yet possible to identify the most restrictive policies and limits for any location. Therefore, this study is not able to define the final layering of the *management zones* but provides them as building blocks, so that this process can be carried out as part of the policy development process. However, to illustrate the approach in its entirety, a set of credible *FMUs* are derived here as examples. It is anticipated that these example FMUs will be altered as the Whaitua process proceeds.

The third step defines the ***administrative points***. *Administrative points* recognise that controls on contaminant discharges and water takes must occur and be accounted for within individual catchments and sub-catchments. Therefore, a subdivision of the region into individual catchments and sub-catchments should occur at least at points in the drainage network where there is a change in the FMU. *Administrative points* are locations at which nutrient load limits for example (for water quality objectives) and volumetric allocation limits (for water quantity objectives) can be defined in absolute terms, and where resource use accounting should occur. Contaminant load limits and volumetric allocation limits can be determined in absolute terms for each individual administrative point provided that they are defined for the *FMUs* on a scalable basis. Scalable limits can be based on a proportion of a flow statistic that reflects stream size such as the Mean Annual Low Flow (MALF) for water quantity and an areal basis for nutrient loads (e.g. kg/ha/year).

Administrative points are important only in terms of plan implementation. There may be a large number of *administrative points* but this need not result in a complicated plan or a large amount of environmental monitoring because freshwater objectives and water quality and quantity limits are set for a limited number of *management classes* and associated *management zones*.

There are several advantages of FMUs that are defined based on the drainage network. First, classifying water bodies based on bio-physical factors allows spatially discrete but similar water bodies (e.g. different sea-draining catchments or different parts of the same catchment for which values and objectives are similar) to be managed under a common set of plan provisions. The same approach would apply to lakes where lakes belonging to a class would be subject to a specific set of plan provisions, which would differ for another class.

A second advantage of the drainage network approach is that the resolution (or level of detail) of the framework can be altered by varying the number of classes of the *management classification*. Greater resolution can be achieved by defining more *management classes*. Higher resolution enables more specific objectives and more nuanced policies and limits, but would increase the effort and data needed to justify them and the complexity and detail of the plan's provisions. There is also likely to be tension between the level of detail that is technically and scientifically justifiable (and achievable) and other considerations such as catering for the desire of stakeholders for spatially nuanced policies and limits. In addition, the management classification must allow for good representation of each class by the monitoring network. For a fixed number of environmental monitoring sites, increasing the number of classes will lead to a reduction in the representation of each class and can potentially induce statistical bias in assessments based on the classes.

A third advantage of using a classification of the drainage network as a basis of developing FMUs is associated with efficiency in the use of available data. If a classification provides good discrimination of variation in characteristics of interest (i.e. values, current state and management requirement), it is reasonable to infer that other locations in the same class have similar character. Thus, a classification system makes optimal use of limited data and provides a justifiable basis for monitoring based on a small set of representative sites.

2.5 A suggested approach for the Te Awarua-o-Porirua Whaitua

The remainder of this report presents a suggested approach to defining a framework of FMUs for the rivers of the Te Awarua-o-Porirua Whaitua that is based on a bio-physical classification of the drainage network. In this document these bio-physically defined units are referred to as 'example FMUs' but it is assumed that these may be modified following additional considerations including specific values, human rather than bio-physical factors or additional bio-physical factors of water bodies. The approach is a starting point for discussion and a final decision on a preferred approach should ultimately be made as part of the Whaitua Implementation Plan (WIP) decision making process.

The Te Awarua-o-Porirua Whaitua committee developed a preliminary definition of FMUs for the region. The approach taken by the committee was to define differences in river characteristics and values and to broadly delineate these based on catchment land use (urban/rural) and the downstream receiving waters (swamp, estuary or open coast (Figure 2-1). The approach taken in this report acknowledges the Whaitua committee's recognition that a logical starting point for defining FMUs is to subdivide the Whaitua based on these key catchment characteristics.

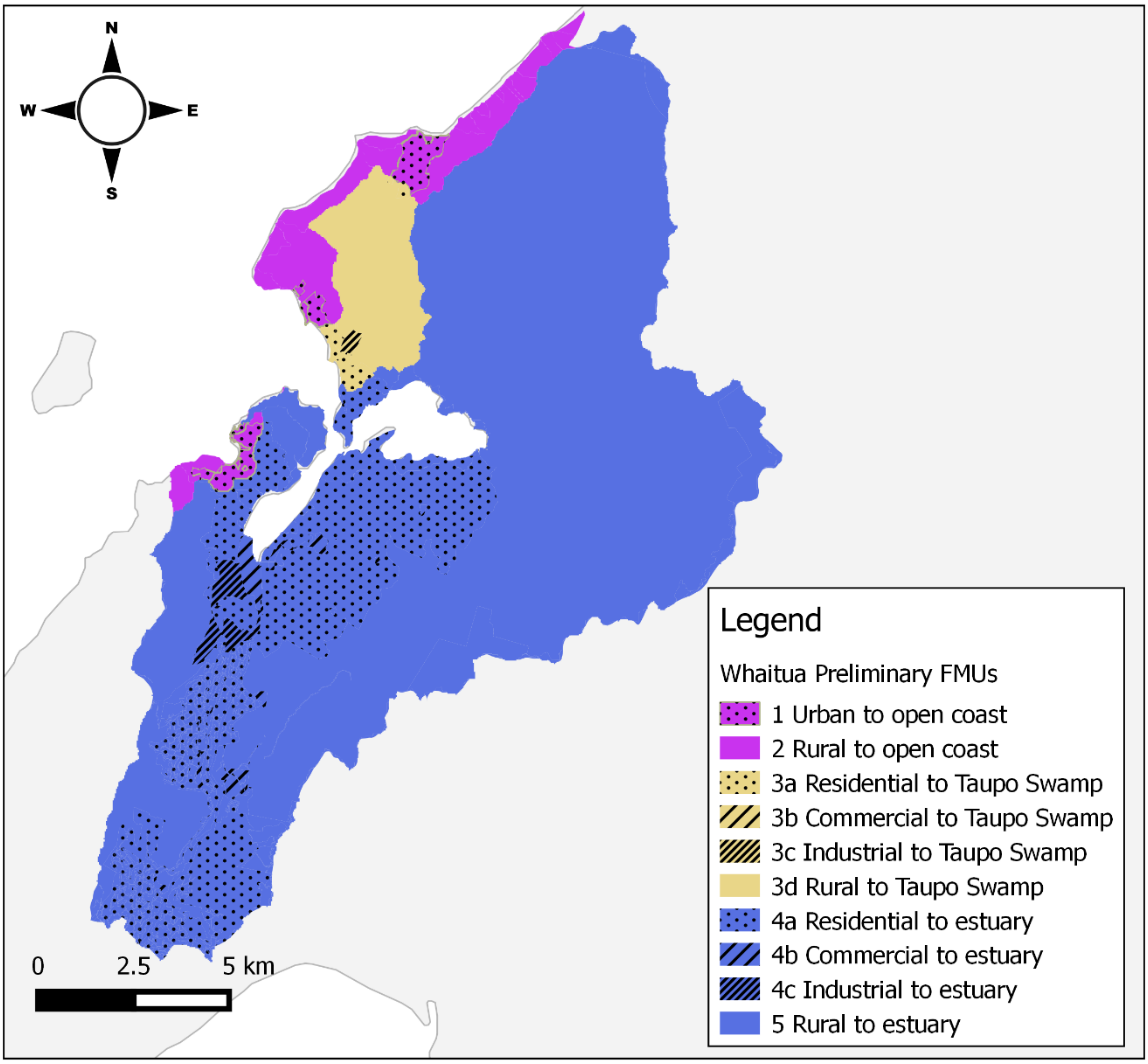

Figure 2-1: Preliminary FMUs defined by the Te Awarua-o-Porirua Whaitua committee

The approach to defining FMUs for the Te Awarua-o-Porirua Whaitua presented here is built using the REC as the basis for describing the river network and associated catchments and sub-catchments. The REC is based on a digital drainage network that was derived from a digital elevation model (DEM) with a spatial resolution of 50 m (Snelder and Biggs, 2002). Computer analysis of the DEM identified drainage paths, network segments and the associated sub-catchment boundaries. The REC represents the rivers of the Te Awarua-o-Porirua Whaitua Zone with approximately 460 unique river segments, with a mean segment length of 642 m, defined by upstream and downstream confluences with tributaries (the 'water bodies'). A key feature of the REC is a system of labels for the segments and their associated sub-catchments that allows rapid analysis of upstream–downstream connectivity and accumulation of catchment characteristics (e.g. land areas having different geological or land cover categories) in the downstream direction.

3 Water quality FMUs

This section describes a network based approach for defining a framework of FMUs for management of river water quality in the Te Awarua-o-Porirua Whaitua. This framework should be considered as a starting point that can be altered by changing the criteria for determining river classifications.

3.1 Proposed water quality management classification

The proposed[14] 'water quality *management classification*' is a coarse subdivision of the Te Awarua-o-Porirua Whaitua's water bodies for management purposes. This water quality *management classification* characterises variation in the characteristics of freshwater receiving environments and their current state across the Whaitua. The approach to defining the management classification follows the same logic as the REC by subdividing the drainage network based on factors that broadly 'control' physical and biological processes that determine the quality and quantity of water bodies, their values and aspects of their bio-physical functioning. At large scales, such as regions, relevant factors are often physiographic attributes (catchment topography, climate and geology). However, at smaller scales such as that of Te Awarua-o-Porirua Whaitua, land use may be a more relevant factor, as recognised by the Te Awarua-o-Porirua Whaitua committee (Figure 2-1).

Appendix A provides a description of a variety of alternative classifications based on different combinations of factors that were tested to generate alternative water quality classifications, as well as a comparison with an Urban/Rural classification based on the Whaitua Committee's preliminary FMU map (Figure 2-1). In general, we found that adding more factors led to a greater explanation of the observed patterns in water quality in the catchment; however, in selecting an optimal classification, simplicity, and incorporation of local and expert knowledge are also important considerations. The final classification adopted in this report is based on a combination of slope and urban/rural land use. This results in three water quality management classes (Figure 3-1). The proposed classification shows strong similarities with that developed by the Whaitua Committee (Figure 2-1), except that the rural class is further divided by the slope. Most other differences are associated with subdivision of the Whaitua related to the receiving waters. For example, Section 3.6 addresses how water bodies that may be regarded as having special characteristics such as those draining to the Taupo Swamp and open coast may be incorporated in the FMU framework. We note that the two rural classes created by the additional slope factor can be easily merged into a single class should the slope distinction be found to be unnecessary.

The existing GWRC regional plan has a biophysical classification of streams and rivers in the region for management purposes. Streams of Te Awarua-o-Porirua Whaitua belong to only two classes; class 2 and class 6. Class 2 streams are described as mid-gradient, coastal streams draining catchments with hard sedimentary geology. These streams broadly comprise the Rural + Hill class of the proposed water quality classification (Figure 3-1). Class 6 streams are described as lowland small streams. These streams broadly comprise the Rural + Low and Urban classes of the proposed water quality management classification (Figure 3-1). The proposed water quality management classification is therefore consistent with the operative regional plan, but increases the resolution of differences between streams within the Whaitua by adding the distinction between urban and rural land use that is not accounted for in the existing plan classification.

[14] This report has defined 'proposed management classifications' and associated management zones. We use 'proposed' to indicate that at this stage they appear to be a credible and robust starting point for formulating management provisions for the Whaitua (objectives and policies). We do not mean 'proposed' in the planning sense, in which is meant a fully developed, but not yet ratified, regional plan.

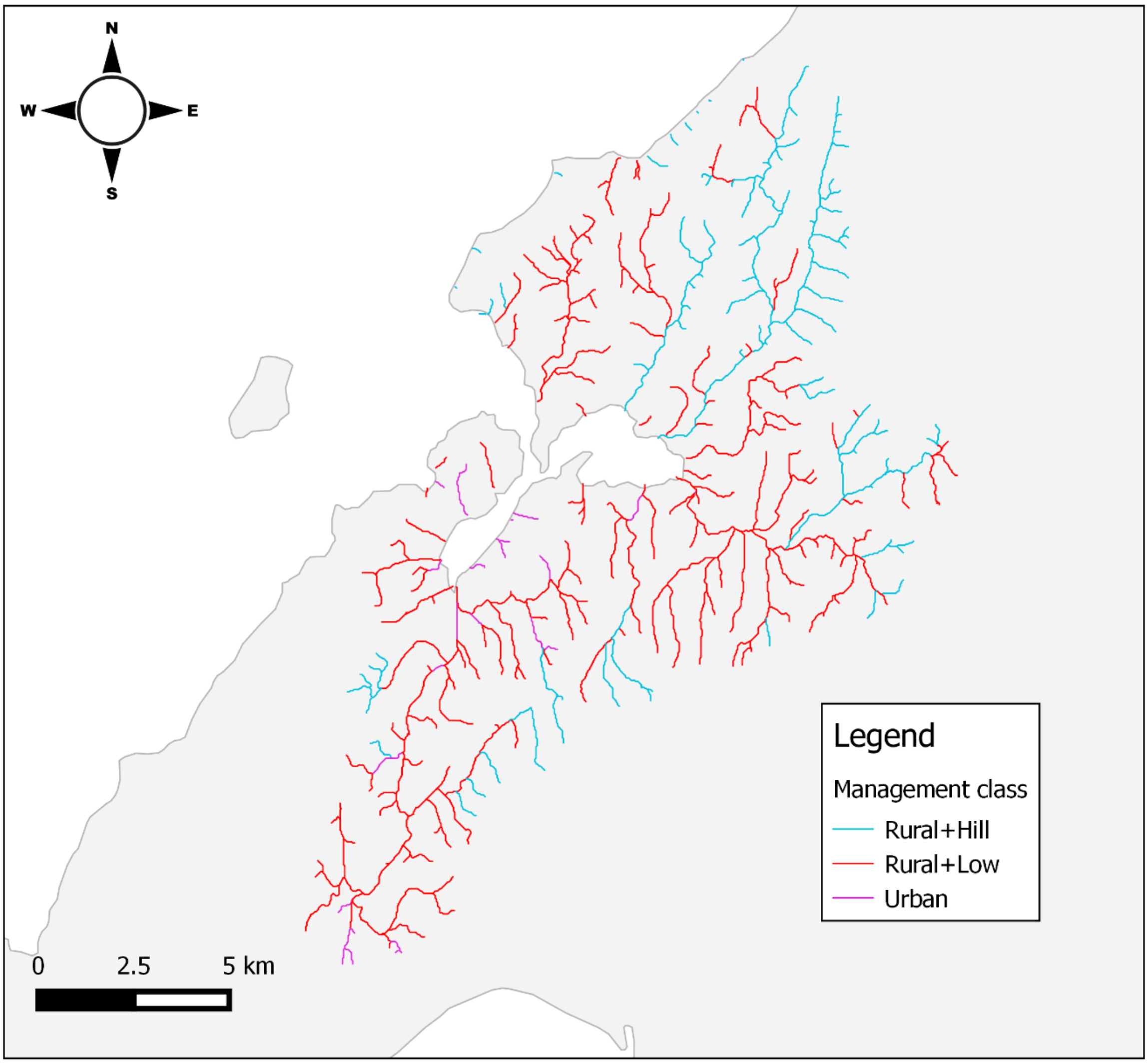

Figure 3-1: Water quality management classification based on urban/rural landcover, and slope.

3.2 Example water quality objectives

This section assesses example water quality objectives for aquatic ecosystem health and secondary contact recreation for each water quality *management class*. It is stressed that the objectives used here, including use of attributes not detailed in the national objectives framework (NOF) of the NPS-FM, and state bands for all attributes, are examples only and are not exhaustive. Although these objectives are credible, they are used purely to demonstrate the approach. The derivation of objectives will be a subject of the future planning process and will involve more comprehensive technical work once objectives have been clarified.

To explain the application of the FMU framework, it was assumed that objectives for a specific *management class* would apply generally to all locations within that class, and would be linked to values that are generally held for that *management class*. It was also assumed that objectives and policies would aim to at least maintain the current state of water quality (as per requirements of the NPS-FM[15]). Furthermore, in cases where the current state was

[15] Objective A2 and Policy A1, NPS-FM

below a minimum acceptable level, it was assumed that objectives and policies would be aimed at improvement. In the discussion that follows, it is assumed that objectives, management regimes and policies applying to a specific *management class* would apply to all locations within that class, and can be linked to values that are generally held for that *management class*. However, the WIP development process may result in more specific (local) objectives, particularly where these can be justified by data or specific values.

The NPS-FM has mandated “ecosystem health” and “human health for secondary contact recreation” as compulsory water quality and quantity related values that must be provided for in all water bodies. However, regional councils have the discretion to also manage rivers for other water quality related uses and values, such as primary contact recreation (swimming) and mahinga kai (aquatic food sources).

The NPS-FM has defined “attributes” as the foundation of numeric “freshwater” objectives. Attributes are defined in the NPS-FM to mean “a measurable characteristic of freshwater, including physical, chemical and biological properties, which supports particular values.” The NPS-FM attributes enable communities to choose the level of protection for values by defining numeric attribute states or “bands” (A, B or C bands) and defines minimum acceptable states (“bottom lines” or the boundary between C and D bands) for these attributes. A regional plan process must set freshwater objectives for FMUs regarding at least the NPS-FM attributes, although councils may choose to also include additional attributes suitable for their region.

The NPS-FM attributes that are relevant to rivers include: *Escherichia coli* (*E.coli*) concentrations (an indicator of the presence of pathogens or human health risk) to provide for human health for recreation secondary contact, ammoniacal nitrogen (NH_4-N) and nitrate nitrogen (NO_3-N) concentrations to manage toxicity, and periphyton biomass (expressed as chlorophyll-a concentration) to manage trophic state.

Attribute states for *E.coli*, NH_4-N and NO_3-N are based on median and 95th percentile concentrations (see Table 1). Objectives for periphyton are expressed in terms of biomass measured as Chlorophyll-*a* per square metre of river bed.

Two additional example objectives were also selected for analysis in this report: 1) water clarity; and 2) ecological health based on the Macroinvertebrate Community Index (MCI: see Stark 1985). Bands for visual clarity are based on the MFE (1994) guideline of clarity of > 1.6 m to be suitable for swimming. For the discussion that follows, this visual clarity objective was subsequently based on the median of all water quality samples collected, but we acknowledge that more detailed criteria (e.g. clarity values collected only during low flows and/or summer sampling occasions) are possibly more appropriate, and could be evaluated.

For the second objective (relating to ecological health), we used four “water quality” bands suggested by Stark and Maxted (2007) for the MCI scores. Thus, the A band referred to streams in “Excellent” condition, and the D band referred to streams in “Poor” condition. All example water quality objectives are summarised in Table 1.

Table 1: Band options for example water quality objectives. The asterisk indicates attributes that are compulsory under the NPS-FM. Note that E. coli < 540/100ml is the minimum acceptable state for Human health; primary contact.

Attribute	Units	Statistic	Criteria for bands			
			A (Excellent)	**B (good)**	**C (Poor)**	**D (not acceptable)**
Human health – secondary contact*	E.coli/100ml	Median	x ≤ 260	260≤ x ≤540	540 ≤ x ≤ 1000	x > 1000
Human health – primary contact	E.coli/100ml	95th	x ≤ 260	260 ≤ x ≤ 540	NA	NA
NO_3N toxicity*	mg/m^3	Median	x<1000	1000< x < 2400	2400 < x < 6900	>6900
	mg/m^3	95th	x<1500,	1500 < x < 3500	3500 < x < 9800	>9800
NH_4N toxicity*	mg/m^3	Median	x<30	30 < x < 240	240 < x < 1300	>1300
	mg/m^3	95th	x<50	50 < x < 400	400 < x < 2200	>2200
Periphyton cover*	chl-a/m^2	92nd	x<50	50 < x < 120	120 < x <200	>200
MCI	Not applicable	Median	x >119	100 < x < 119	80 < x <100	x < 80
Visual clarity	m	Median			>1.6	X < 1.6

3.3 Assessment of current state of river water quality

Within the Whaitua there are 4 water quality monitoring sites with at least 10 years of data (inset in Figure 3-2). Note that the Horokiri site is a combination of two nearby sites operating over different periods. Table 2 provides a summary of the number of sites within each of the *management classes*. The current state of each class in the management classification cannot be reliably established using so few sites. To resolve this, the current state of water quality in each class was estimated for all segments of the river network within the Whaitua based on a statistical model that used data from water quality sites from throughout the Greater Wellington region (Figure 3-2). Details of the statistical models are provided in Appendix D.

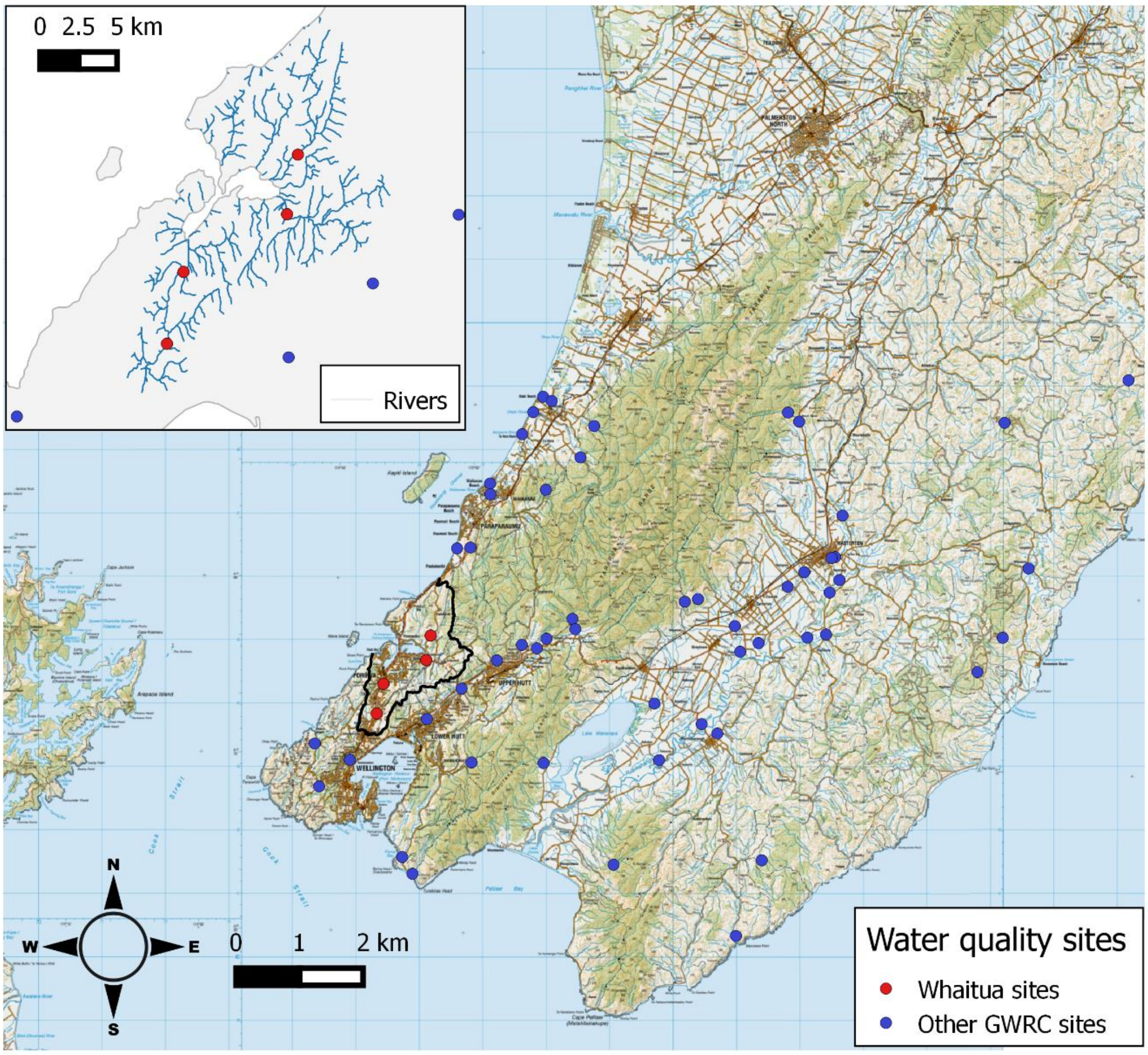

Figure 3-2: Location of water quality monitoring sites. Locations are shown for sites in the Te Awarua-o-Porirua Whaitua and for all other sites in the Wellington region.

Table 2: Distribution of water quality monitoring sites within the proposed management classes. See Figure 3-1 for explanation of the water quality management classes.

Water quality management class	**Number of water quality sites within the Whaitua**
Urban	1
Rural + Low	2
Rural + Hill	1

The current state of rivers and streams in the Te Awarua-o-Porirua Whaitua is illustrated in Figure 3-3 as the distribution of modelled median values for the various water quality variables. The distributions are shown for the three classes of the water quality *management classification*. Figure 3-3 indicates that, in general, water quality is highest in streams in the Rural + Hill management class, and is lowest in the urban class.

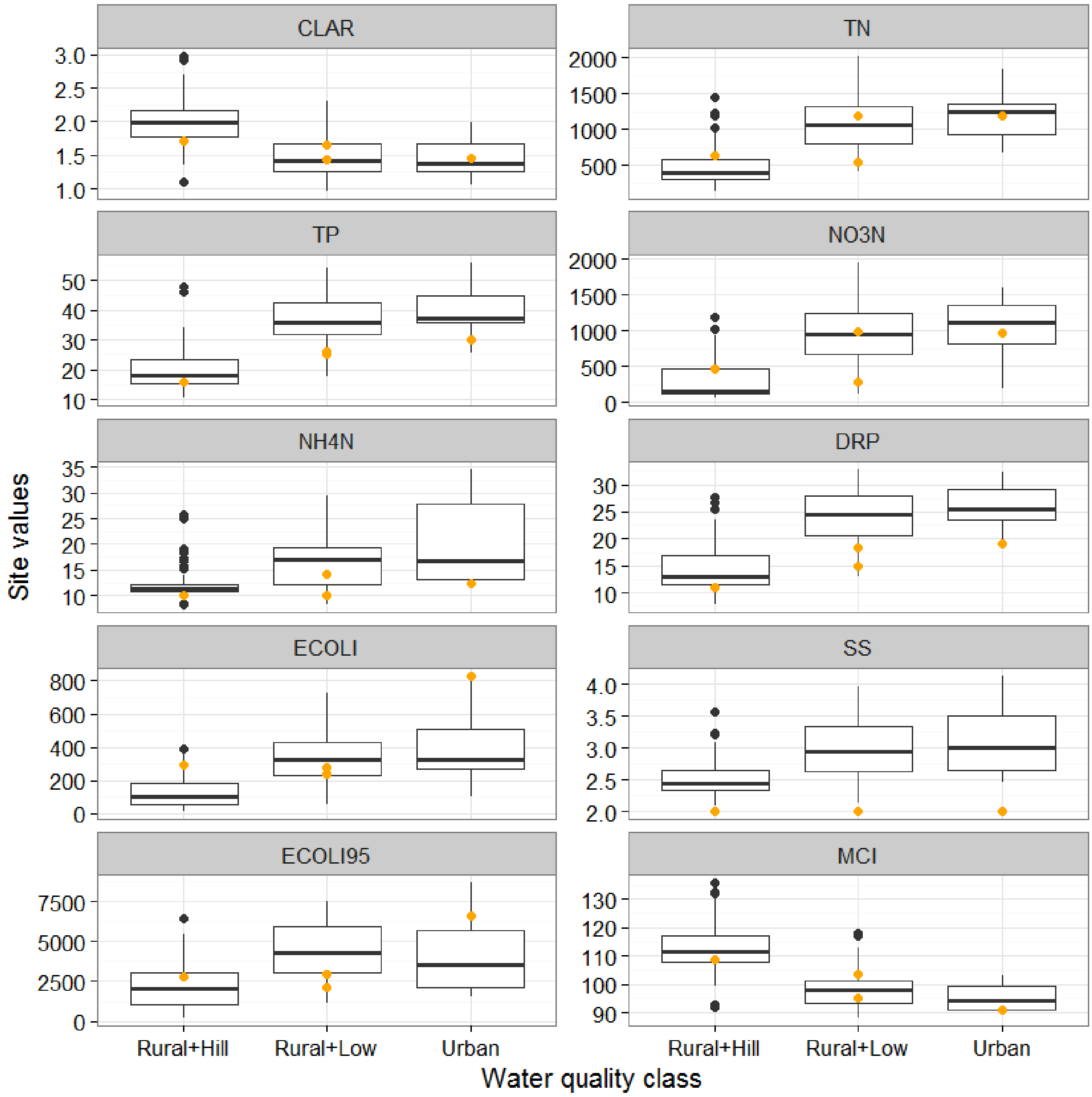

Figure 3-3: Box and whisker plots showing the distributions of water quality estimates for each segment of the river network in the Whaitua. The plots show data for nine variables derived from the Greater Wellington Regional Council's long-term monitoring sites. The variables include; clarity (CLAR), total nitrogen (TN), total phosphorus (TP), Nitrate nitrogen (NO3N), ammoniacal nitrogen (NH4N), dissolved reactive phosphorus (DRP), Escherichia coli (ECOLI), suspended sediments (SS), 95th percentile values for Escherichia coli (ECOLI Q0.95), and macroinvertebrate community index (MCI). The data are grouped by the three proposed water quality management classes: Rural + Hill, Rural + Low, Urban. The central horizontal line indicates the median, and the bottom and top of the box indicate the 25th and 75th percentile values. The 'whiskers' (vertical lines) extend to the 10th and 90th percentiles. Where the number of outlier sites exceeded 10, the black points indicate the 5th and 95th percentiles. The orange points show the observed values from water quality monitoring sites in the Whaitua.

An assessment of the current state of the three water quality *management classes* relative to example objectives (listed in Table 1) is shown in Table 3. The table groups the sites by water quality *management class* and uses the proportion of reaches in each band to assess the state of the class “overall”. Note, for NH_4-N and NO_3-N each site is assigned the lower class for either the median or 95th percentile criteria described in Table 1. Periphyton is assessed based on nutrient criteria for achieving periphyton objectives as defined by NOF bands, one based on DRP values and one based on TN values. These criteria and their derivation are fully described by Larned et al. (2015).

Table 3: Current state of the three proposed water quality management classes compared to several example objectives. The selected objective could be state band A, B or C, recognising that D band fails NPS-FM bottom lines, but must maintain overall water quality. Data are percentages of sites in each management class that achieve each of the state bands. The asterisk indicates attributes that are compulsory under the NPS-FM.

Objective	**State band**	**Proposed water quality management class**		
		Rural + Hill	**Rural+Low**	**Urban**
River Reaches		32%	62%	5%
MCI	A	20%	0%	0%
	B	79%	30%	24%
	C	1%	70%	76%
	D	0%	0%	0%
Periphyton*	A	0%	0%	0%
	B	2%	0%	0%
	C	68%	4%	0%
	D	30%	96%	100%
Clarity	Pass	90%	29%	24%
	Fail	10%	71%	76%
E.coli (Primary con. rec.)	Pass	7%	0%	0%
	Fail	93%	100%	100%
E.coli (Secondary con. rec.)	A	90%	27%	14%
	B	10%	60%	67%
	C	0%	13%	19%
	D	0%	0%	0%
NH_4-N toxicity*	A	100%	100%	95%
	B	0%	0%	5%
	C	0%	0%	0%
	D	0%	0%	0%
NO_3-N toxicity*	A	98%	53%	38%
	B	2%	47%	62%
	C	0%	0%	0%
	D	0%	0%	0%

The assessment indicates median reach MCI scores were predominantly in the B band in the Rural+Hill class, evenly divided in the B and C band for the Rural+Low class, and predominantly in C for the Urban class. No segments are assessed as being in the D band for MCI scores. Nutrient concentrations for periphyton exceeded those required to exceed the periphyton biomass bottom line at many reaches. This indicates that there is potential to exceed the NOF periphyton biomass attribute D band. However, whether this occurs in the Whaitua is dependent on stream conditions including substrate (i.e. bed material) and shading. This study has not assessed actual periphyton in the Whaitua and the significance of the nutrient criteria exceedances will need to be considered as part of a more detailed water quality assessment.

The Rural+Hill classed reaches generally met the MfE water clarity guidelines; in contrast to the Rural+Low and Urban classes, which generally failed the nominated criteria.

All reaches in all classes are above the bottom line for human health secondary contact and most are below the minimum acceptable state for primary contact (the exceptions being 7% of segments in the Rural + Hill class). The Urban class is generally in poorer state for secondary contact recreation than the rural classes.

All segments are above the bottom line for the two toxicants: NH_4-N and NO_3-N. For NH_4-N, segments are exclusively in the A band for the Rural reaches, predominantly in the A band in the Urban class. For NO_3-N segments are almost entirely (99%) in the A band in the Rural + Hill class, evenly distributed between the A and B band in the Rural + Low class and predominantly in the B band in the Urban class.

For water quality variables and periphyton, improvements are associated with decreases in measured concentrations (except for clarity, for which improvements are associated with increases in measured values), while improvements in MCI scores are associated with increases. Overall, there were very few sites within each of the classes to evaluate trends, and as such it is difficult to make meaningful generalisations and comparisons of the trend distributions between the other classes.

To develop a ranking of overall water quality across the three classes, we took the proportion of sites within each band (Table 3), and applied weights of 1, 2, 3 and 4 for each of the A, B, C and D bands respectively (or 1 for pass and 4 for fail). Summing across all variables provides a total water quality score, where a lower number indicates higher water quality. The scores and rankings derived based on this method for each of the three water quality management classes are shown in Table 4.

Table 4: Summary of overall water quality. The ranking is based on scores and associated rankings for each of the proposed water quality classes. Low rankings indicate higher water quality.

Management Class	WQ Score	WQ Ranking
Rural+Hill	10.51	1
Rural+Low	15.12	2
Urban	15.76	3

The minimum requirement of the NPS-FM is to maintain the overall quality of fresh water. The NPS-FM requires freshwater objectives to be set at better than current state for water bodies that are currently in the D-band (i.e., below national bottom lines) (e.g., the Rural + Low and Urban classes). Improvement of current state may also be considered an appropriate aspiration in other classes (i.e., seeking water quality improvements). Based on the results in Table 3, and a default objective of maintaining current state, it is likely that justifiable objectives will be more environmentally protective (i.e., nutrient, *E. coli* or periphyton values will be lower) in the Rural+Hill class, which will be more protective than the Rural + Low, which will, in turn, be more protective than the Urban class. Under these circumstances, policies and limits may need to be more restrictive (less enabling of resource use) in the catchments of the Rural+Hill class, followed by the catchments of Rural+Low class then the Urban class.

The aggregation of all catchments draining to each class is a *management zone* and the definition of these zones requires consideration of the relative levels of restrictiveness of the policies and limits to achieve the downstream objectives. We stress that this set of objectives is an example that we have selected to illustrate how FMUs can be derived.

3.4 Water quality management zones and definition of FMUs

The *management zone* for any given *management class* is defined as the land area that drains to that *management class.* The *management zone* delineates the land area that must be managed to achieve the objectives of the given *management class*. The management zones for each of the proposed water quality management classes are shown in Figure 3-4. Any given location within the Te Awarua-o-Porirua Whaitua may be within one or more management zones, depending on how many different management classes are downstream of that location. The management zone maps form building blocks for defining the FMU framework.

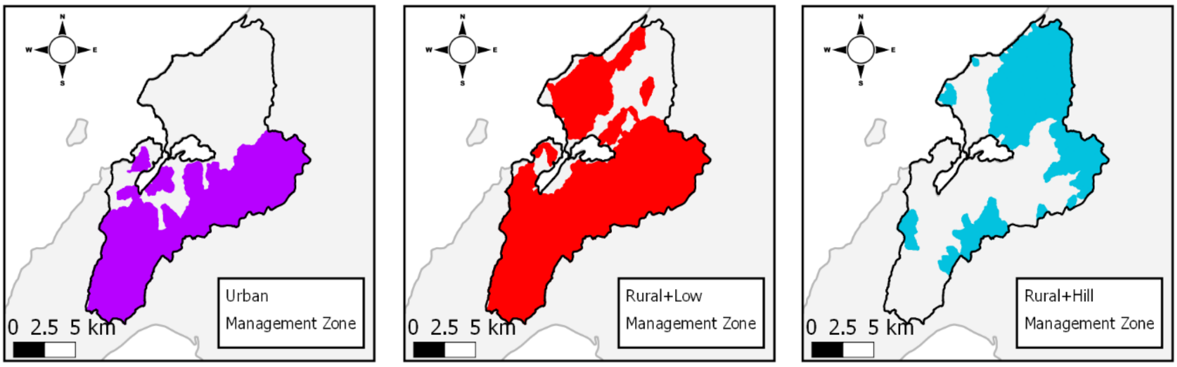

Figure 3-4: Management zones for each of the proposed management classes.

It is likely that management actions that are applied to all *management classes* in the Whaitua will need to explicitly address the effects of urban land uses that occur within all the *management zones*. We identify *urbanised land* as land that is either already or potentially used for residential, commercial, industrial, and transportation purposes. The *urbanised land* in the Whaitua is indicated in Figure 3-5. To achieve objectives in downstream water bodies, it is likely that special policies will need to be applied to *urbanised land* to manage the effects of urban land use. The *urbanised land* areas shown in Figure 3-5 need to be identified as sub-zones of all *management zones* to delineate where actions to manage the effects of urban land use apply. The *urbanised land* sub-zones for each of the three management zones are shown in Figure 3-6.

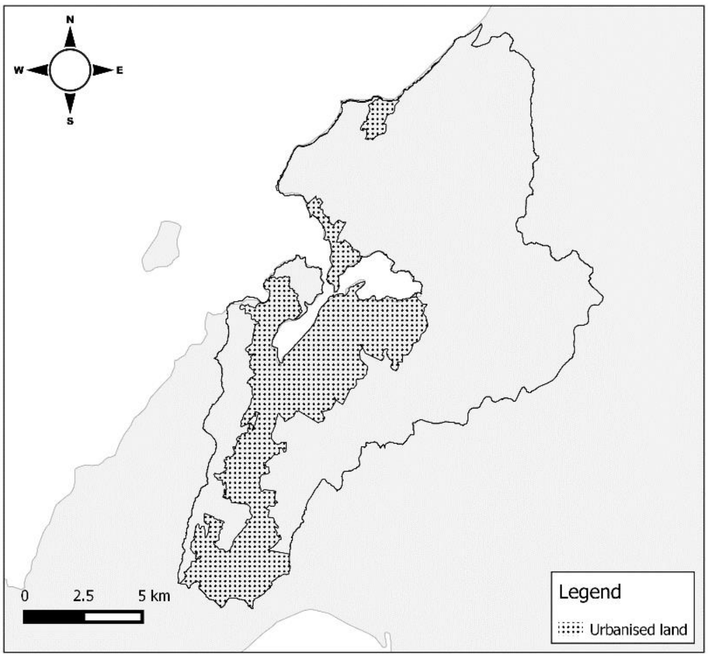

Figure 3-5. The urbanised land in the Whaitua It is likely that special policies will need to be applied to urbanised land to manage the effects of urban land use in downstream water bodies.

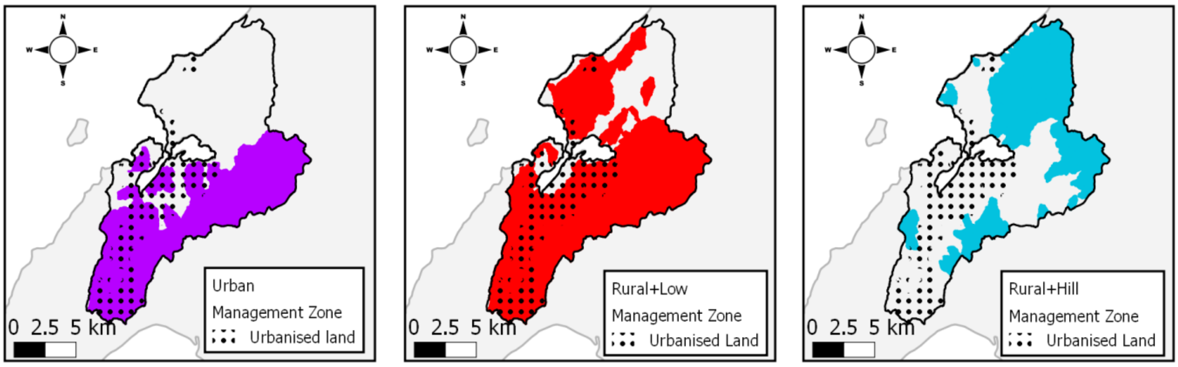

Figure 3-6. Proposed management zones including identification of the urbanised land sub-zones.The urbanised land subzones are areas within the broader management zone that may be subject to actions to manage the effects of urban land use on the associated management class.

FMUs are defined by layering management zones in an order that is dependent on the policies and limits set for each of the management zones. The layering of the zones recognises that locations that lie in multiple management zones must comply with the policies and limits associated with the most restrictive downstream objectives. This study is not able to define the final layering of the management zones because this is dependent on objectives and associated policies and limits. However, we provide a credible example of *FMUs* for the Whaitua based on the assessment of water quality provided above. It is anticipated that this set of example FMUs will be altered as the Whaitua process proceeds.

In this example, we have assumed that the *management zones* of *management classes* with the best water quality scores (Table 4) will be associated with the most restrictive policies and limits (because they will be likely to have more protective objectives), and therefore take precedence to those classes with lower water quality. This structure of *management zones* preserves the potential to define more restrictive policies and limits in the parts of the catchment that currently have better water quality and is illustrated in Figure 3-7.

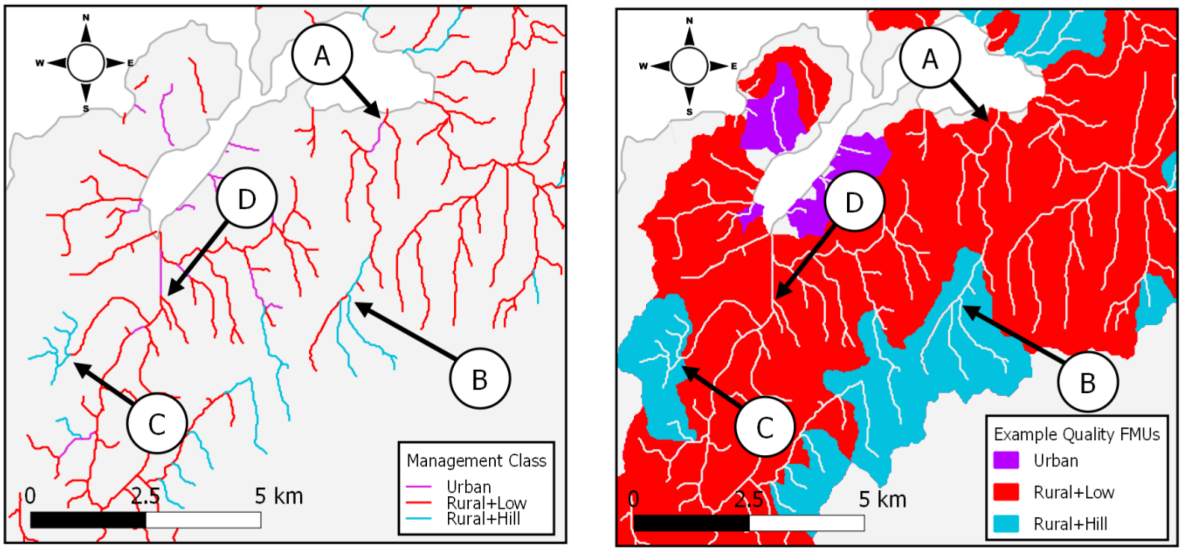

Figure 3-7: Relationship between the proposed management classification of the network segments (left) and the FMUs (right). The arrow marked A indicates segments belonging to the Urban (purple) class flowing into segments belonging to the more restrictive Rural+Low (red) class; the arrow marked B indicates segments belonging to the Rural+Low (red) class flowing into segments belonging to the more restrictive Rural+Hill (light blue) class; the arrow marked C indicates segments belonging to the Rural+Hill (light blue) class flowing into segments belonging to the less restrictive Urban (purple) class; the arrow marked D indicates segments belonging to the Urban (purple) class flowing into segments belonging to the more restrictive Rural+Hill (light blue) class. The FMU for any location reflects the most restrictive class downstream of that location. Therefore, catchments of Urban or Rural+Low class rivers flowing into Rural+Hill class (e.g. Point B, left map) belong to the Rural+Hill FMU (right map), and catchments of Urban class rivers flowing into Rural+Low class (see Point A, left map) belong to the Rural+Low FMU (right map).

If during plan development it becomes apparent that more restrictive policies and limits are required to meet objectives in downstream areas, the layering of the management zones would be reordered. This could allow for zones to be either merged or might require more restrictive policies to be applied in the upper catchments for achieving downstream objectives (e.g. objectives in the Urban class). Therefore, the example *FMUs* offered here may need adjustment as the plan process proceeds. However, assuming the proposed management classification proves to be appropriate, the *management zones* defined in this study (Figure 3-6) provide the building blocks to define FMUs for the Whaitua (see example FMUs in Figure 3-8). Furthermore, the building blocks can be assembled to reflect the objectives, policies and limits that are developed through the plan process; hence the approach preserves flexibility to adjust the FMUs as the process advances.

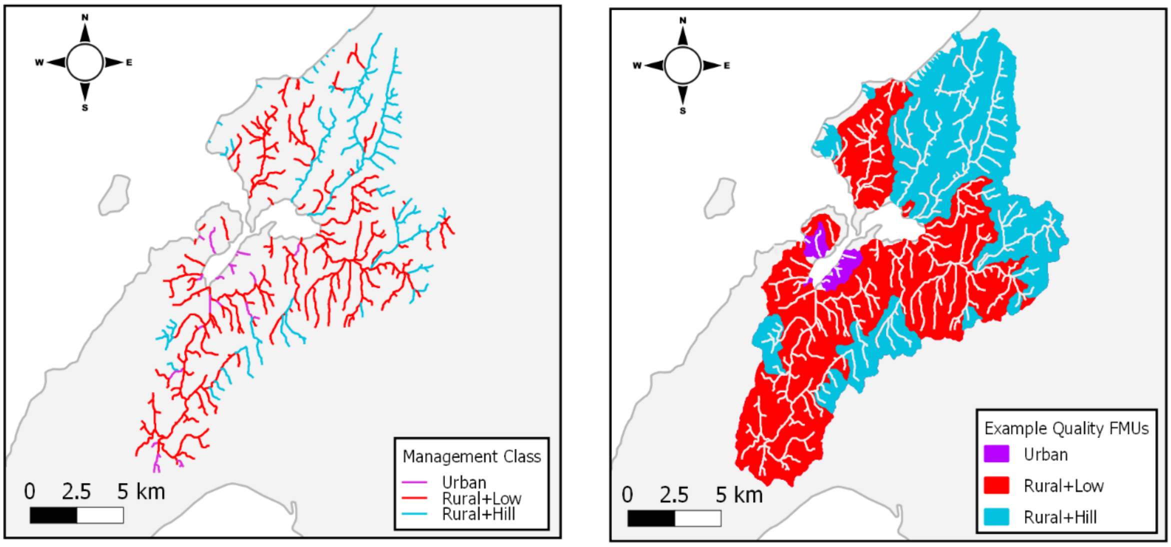

Figure 3-8: The proposed water quality management classes and example FMUs for the Te Awarua-o-Porirua Whaitua. The management classes are shown on the left, and the associated FMUs are shown on the right.

The three *management zones* are likely to be associated with differing policies, including limits. For example, the relatively good state of the Rural+Hill zone may be reflected in relatively few management actions but limits will be more restrictive to maintain current state. Consideration of development pressure and trends is likely to influence the actions and limits in this zone. The Urban zones may be associated with more management actions because the suggested objectives are not always being achieved but limits are likely to be less restrictive (i.e. more enabling of discharges of contaminants) than the other zones.

3.5 Water quality administrative points

The points where the *FMUs* change are locations in the network where management actions and limits also change. These points (along with the river coastal outlets) are therefore a minimum set of locations where contaminant load limits could apply, and where resource use accounting needs to occur, especially in any assessment process related to consents. These points define a minimum set of *administrative points* for the region. Administration points for streams with more than one branch (stream order greater than 1) are indicated by the black dots in *Figure 3-9*.

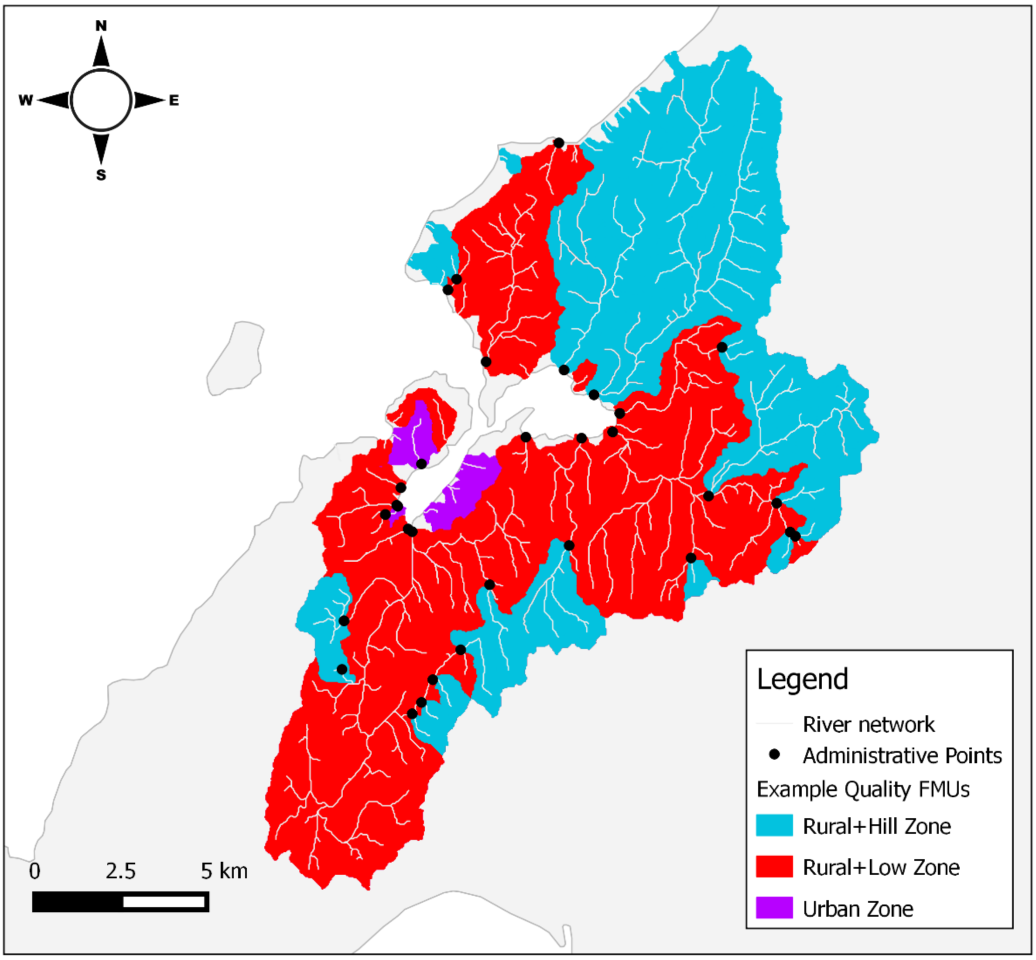

Figure 3-9: Zoomed in view of the example water quality FMUs. The grey lines represent the drainage network. The black dots represent points at which the FMU changes and are relevant administrative points where limits need to apply and resource use accounting needs to occur. The classes in this figure are based on classes defined with all rivers from order one and up.

3.6 Special Management Zones

It is recognised that some water bodies have specific values or water quality issues that are not discriminated by the water quality *management classification* but which may need to be associated with specific objectives and management actions. These water bodies are likely to require separate objectives and associated management actions and/or limits. Water bodies requiring separate management objectives are likely to be sites of significance e.g. swimming spots, or sites of special cultural or ecological significance.

Water bodies requiring special objectives can be identified and treated as a special class and the catchments upstream of these water bodies would be a *special management zone.*

Potential examples of *special management zones are* the Taupo Swamp and its catchment, and catchments draining to the open-coast (Figure 3-10). Objectives for these zones may be specific to the two receiving environments (swamp and open coast) and may differ from the remainder of the Whaitua, which drains to the Porirua Harbour. The actions to achieve those objectives may need to differ and therefore the land draining to these receiving environments may need to be special management zones. A special management zone can be added to the other management zone building blocks and incorporated into the FMU definition following the layering process described earlier.

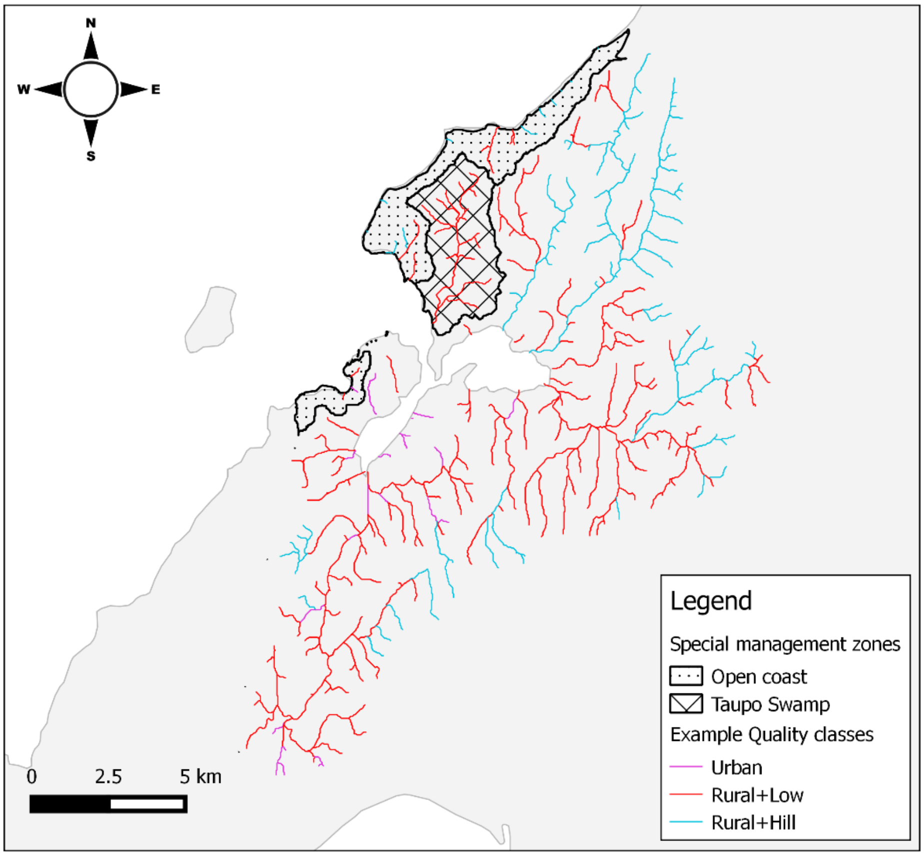

Figure 3-10: Example of areas that may require special management zones. The figure shows the Taupo Swamp and its upstream catchment (the management zone), and the catchments draining to the open-coast. Objectives for these water bodies may not be achieved by policies and limits that are relevant to the management class that segments belong to. Special management zones that comprise the entire catchment of the Taupo Swamp and all the open-coast-draining catchments would enable policies and limits that are relevant to their specific objectives to over-ride those set for the management classes.

3.7 Next steps – water quality FMUs

The analysis carried out by this study indicates that there are important differences in the current state of the three water quality management classes. These differences, plus differences in values and community aspirations, including development, will need to be considered to define objectives and management regimes for each management class and its management zone.

The structure of the final FMUs depends on which management classes require the most restrictive policies and limits and is defined by layering management zones in an appropriate order. The example FMUs defined in this study can be easily modified once the relevant objectives and management regimes are defined by using the *management classes* and associated *management zones* as building blocks. Special management zones can be used to define areas that have special values or require special management actions. Areas draining to one or more of the three receiving environments in the Whaitua (the Porirua Harbour, the open coast and the Taupo Swamp) may need to be subject to specific objectives or management actions. The study has identified these areas so that they can be included in the layers that may be used to define the FMUs.

Monitoring would be carried out at a network of sites judged to include sufficient representation of each class of the water management classification. This might comprise the existing river water quality monitoring network, which has at least one site in each of the three classes and an established period of record. Assessing the achievement of objectives, based on the monitoring data, would be carried out in a similar manner to the present study with the aggregate results for the class being used to evaluate the class at the Whaitua scale.

The points at which any resource use limits need to be met and accounting for resource use needs to occur are the *administrative points* (Figure 3-9). *Administrative points* would be relevant in assessments related to consents or any investigation associated with objectives that are not being achieved. There are many *administrative points* but these are important only in terms of implementation and need not necessarily result in a complicated plan.

If water quality limits were defined in terms of contaminant loads, limits for all *administrative points* could be defined on a scalable (area) basis (i.e., average kg/ha/yr) and the absolute loads could then be assessed as part of plan implementation and administration rather than needing to be defined in the plan. It is noted that the NPS-FM does not specify that limits need to be defined in terms of loads but in some regions this has been the approach taken (e.g. Canterbury and Horizons). Management based on contaminant load limits was considered necessary in these regions due to significant existing and increasing pressure on water quality. It remains to be determined whether load based contaminant limits are necessary and how they could work for the Te Awarua-o-Porirua Whaitua, but the framework suggested here would provide a basis for management of loads should that be considered necessary.

Finally, it is emphasized that the approach to defining FMUs using the bio-physically based approach offered in this report represents an initial step of a Whaitua planning process. This process and the consideration of values, objectives, limits and other plan provisions may identify reasons to review and refine the example FMUs offered in this report. The approach used here is flexible and able to accommodate change if this is found to be appropriate.

4 Water quantity FMUs

4.1 Overview of water quantity management objectives

The approach to defining FMUs for water quantity management follows the same process to that set out above for water quality. An important difference between water quantity and quality is that many water takes require consents, whereas the major pressure on water quality is diffuse discharges associated with the use of land, which has historically typically not been subject to individual resource consents. Significant water take activities have consents that are subject to conditions (e.g. the allowable rate or volume of the take, and minimum flows). There are also permitted uses of water for stock drinking and reasonable domestic use.

The second difference between quality and quantity objectives is that there are no NPS-FM attributes directly associated with water quantity. However, the trade-offs between environmental values and water resource use can be specifically evaluated and used to inform decisions about water quantity objectives. Broadly, surface water quantity (i.e. river flow) is managed through the application of two resource use limits: minimum flows and a total allocation (see NPS-FM, details are described by Snelder *et al.* 2013). The minimum flows and total allocation are imposed to achieve objectives that reflect both environmental protection and resource use objectives. These objectives can be thought of as defining a maximum level of habitat[16] loss, and both a maximum and a minimum level of reliability of supply. Moreover, habitat and reliability of supply can be considered as specific attributes[17] with respect to instream values and consumptive water takes, respectively.

The details of how water quantity objectives and their associated limits are defined are complicated; some key principles that are important to the definition of water quantity management objectives include:

1. The relationship between habitat and flow.
2. The critical instream value (e.g. a specific fish species, recreational use or landscape characteristic) and need to maintain it at a suitable level.
3. The reliability of takes.
4. The flow regime and the allocation rate.

Hydraulic habitat suitability involves measures of a river's width, depth and velocity, all of which determine the suitability of the stream or river to a specific instream value (e.g. aquatic species such as fish). Flow management decisions have been, to date, most commonly concerned with maintaining ecosystem values and focus on ecosystem components that have the highest flow requirements, which are generally fish. Therefore, it is the suitability of the hydraulic habitat (width, depth and velocity) for fish that is most often the basis for water quantity management objectives. It is noted that other instream values can have higher flow requirements than fish, such as some recreation activities (e.g. kayaking) or maintenance of natural character, and these have also been considered in specific limit setting process in parts of the country. These values are probably unlikely to drive flow requirements in the Porirua Whaitua but this will need to be addressed as part of the planning process.

Generally, the suitability of hydraulic habitat for fish is highest at some intermediate flow and decreases as flow either increases (e.g. velocities or depth become too high) or decrease (e.g. depth, width and velocity become too low). The shapes of these relationships vary for different fish species. Because abstractions reduce flows in rivers, they will also decrease the available hydraulic habitat during natural periods of low flow (generally during summer). Setting a minimum flow is therefore concerned with choosing a point on a specific habitat-flow curve at which any further reduction in hydraulic habitat due to abstraction is unacceptable. River flows naturally decrease during summer, and fish species can generally tolerate these natural low flows. The selected level of habitat availability to be maintained is therefore usually based on some percentage of hydraulic habitat available at natural low flows e.g. Mean Annual Low Flow (MALF).

[16] The habitat referred to here is the aspect of habitat that is directly related to the flow rate and comprises river width, velocity and depth. These are referred to as hydraulic habitat. Objectives for hydraulic habitat can be defined in terms of instantaneous minima and also maximum durations of stable minimum flows to limit "flat-lining" (i.e. where river flow is held for an extended period at a steady low flow).

[17] In the NPS-FM attributes are measurable quantities that are used to define freshwater (i.e. numeric) objectives. Hydraulic habitat and reliability are similarly measurable quantities that can be used to define objectives but they are not currently included as attributes in the NPS-FM.

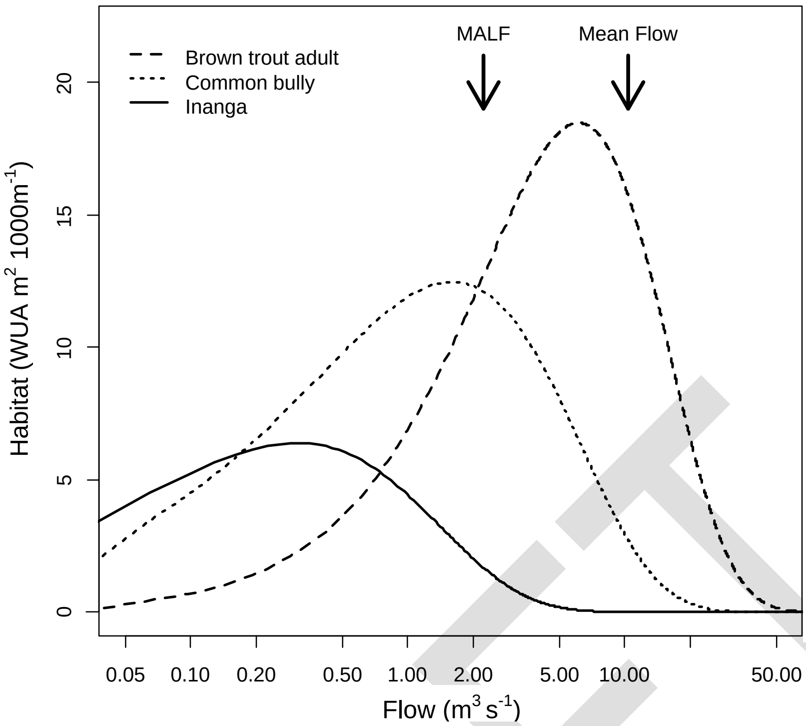

Figure 4-1: Change in hydraulic habitat with change in flow. The plot shows how Weighted Usable Area (WUA) changes with flow for three common fish species at a site. The Mean Annual Low Flow (MALF) and mean flow at the site are shown. The plot shows that reduction in habitat with flow varies by species and therefore decisions about minimum flows are sensitive to the adopted critical instream value. Figure adapted from Snelder et al. (2013).

The rate of reduction in hydraulic habitat suitability caused by flow modification varies between different fish species. For example, habitat suitability for large fishes such as trout generally decreases with flow reductions more quickly than it does for smaller fishes that can tolerate shallower and slower moving water (Figure 4-1). The choice of fish species (or more generally the “instream value”) for setting the minimum flow is therefore important, as the amount of available habitat, and therefore the level of habitat protection relative to MALF will differ between species at any specific flow.

There are often many different fish species in a river. Flow setting processes therefore tend to define a “critical instream value”, which is a species that is a) considered important or significant for some reason at a location and b) is the most sensitive to flow reductions. The assumption is that if the minimum flow is set to maintain the hydraulic habitat for the critical instream value at a specific level (i.e. the objective) then other less sensitive values such as different fish species that can tolerate lower flows will also be maintained to at least this level.

When a river’s flow reduces to the specified minimum, water takes must be restricted so that flow is not artificially reduced below the minimum flow. The distribution of river flows can be shown by a flow duration curve (FDC), which indicates the frequency that flows are equal to or greater than any specified flow (e.g., Figure 4-2). The position of the minimum flow on the FDC is a measure of the reliability of the river as a water supply for abstractors (the red lines in Figure 4-2). Setting a minimum flow is therefore concerned with assessing the trade-off between maintaining a minimum amount of habitat with the reliability of the water supply for the abstractor.

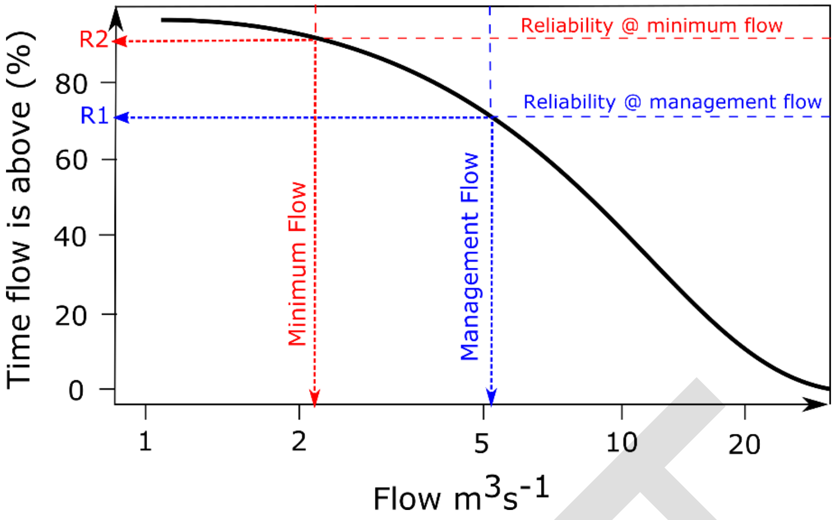

Figure 4-2: Example FDC. The minimum flow and management flows and their reliabilities (% of time these flows are exceeded) are indicated as positions on the FDC.

In theory, reductions in takes (the abstraction of water) need to commence when the river's natural flow equals the *minimum flow* plus the *allocation rate*. This flow is referred to as the '*management flow*' and its frequency can also be shown on a FDC (the blue lines in Figure 4-2). The frequency of the management flow is a second measure of reliability of supply, which indicates the proportion of time that the allocation must be restricted (or conversely, the proportion of time that the full allocation is not available for abstraction). The setting of the allocation limit therefore is a trade-off between the total take (i.e. how much water is allocated in total to all users) and the reliability of supply for each individual user that is deemed acceptable. The exact values of the two measures of reliability depend on the distribution of flows, which is often referred to as the flow regime and is broadly indicated by the shape of the FDC.

In this study, we have defined minimum flows and allocation limits in terms of the Mean Annual 7-day Low Flow (MALF). The MALF[18] is often used for setting water quality limits because it is a measure of water availability during periods of relative scarcity. Another measure to use is the Q_5 7-day low flow, which is the average 7-day low flow period that occurs once every 5 years. Scaling flow by MALF standardises the allocation and minimum flow by the size of the river. This allows rivers to be grouped irrespective of the size of the natural river flow (which is broadly a function of catchment area) and for generalised limits to be derived. Expressing hydraulic habitat at any given flow as a proportion of the habitat available at MALF has a similar benefit.

Flows less than MALF generally occur on average once in every two years. Thus, setting minimum flows to produce habitat that is a little less than that available at MALF means that habitat for aquatic species such as fish is maintained at levels that are not too reduced from natural low flows occurring in most years. The underlying assumption is that rivers and their instream values are robust to some degree of reduction in flow and/or that some limited level of impact is an acceptable trade-off for the utility gained from use of the water.

The present study uses model simulations to explore the impact of different minimum flow and allocation limits on supply reliability and environmental outcomes for all river segments

[18] MALF is frequently used as an index for setting total allocations. For example, the proposed National Environmental Standard for Flows and Levels (NES; MFE 2008) suggests default allocation limits of 30% and 50% of MALF for small and large streams respectively (and where the threshold for stream size is defined by a mean flow of 5 m^3/s).

within the region; the modelling is described in detail in section 4.3. We used the model simulations to explore classifications that group together river segments that have relatively similar responses to the same limits to define spatially distinct water quantity *management classes*.

4.2 Proposed water quantity management classification

For plan simplicity, it would be preferable to have the same FMUs for water quality and quantity. We considered the water quality management classification as a starting point by examining discrimination of variation in habitat (for Long-fin Eels and Trout) and reliability (R1 and R2; Figure 4-2) by the three water quality classes.

We used national scale models to evaluate water quantity management rules for all network segments in the Whaitua (see section 4.3 below for details). We started by assessing the GWRC regional plan default water allocation rules of 30% of MALF for maximum allocation, and 90% of MALF for minimum flow. The effect of these rules was assessed using four variables: the proportion of time that take restrictions occur (R1), the proportion of time that no take can occur (R2) and the change habitat for two species;long-fin eel and trout (deltaEEL and deltaTrout) (see Section 4.3 for details including the significance of these species). The distributions of the four variables, estimated for every segment in the Whaitua, are shown grouped by the three classes of the water quantity *management classification* in Figure 4-3.

The assessment indicated that the impact of the rules on habitat is relatively homogeneous over the entire Porirua Whaitua. Most segments had changes in eel and trout habitat over a very small range (97% - 98% for eels and 88% - 90% for trout). This means that the default plan rules would, if fully utilised, result in around 2% and 11% reduction in habitat for tuna (eels) and trout (respectively) compared to the habitat that would be available naturally at low flow. The impact on R1 and R2 was also reasonably homogeneous over the Whaitua. Most segments had R1 values between 86% and 90%. Most segments had R2 values between 91 and 94%, with a tendency for values to be lower in in the Rural + Hill class (Figure 4-3). This means that the default plan rules would, if fully utilised, result in around some level of water use restriction between 10% and 14% of the time and complete restriction between 6% and 9% of the time.

These results reflect the relatively homogeneous nature of the streams and streamflows (hydrology) in the Porirua Whaitua. For example, all streams in the Whaitua have estimated mean annual flows less than 5 $m^3 s^{-1}$ and climatic variation is minor. By contrast, equivalent values in the Ruamahunga Whaitua had greater variation (Snelder and Fraser, 2016). For example, for most stream segments in the Ruamahunga Whaitua, changes in eel and trout habitat ranged between 0% - 70% and 110% and 80% respectively. For most segments in the Ruamahunga Whaitua R1 values were in the range 95% - 80% and R2 values were in the range 100% - 80%. The variation in these values in the Ruamahunga Whaitua justified the use of a management classification for water quantity. However, the homogeneity of the effect of rules for the entire Porirua Whaitua indicates that a water quantity *management classification* may not be deemed necessary to discriminate hydrological or hydraulic habitat differences. In this case a single set of rules (that apply universally to all segments in the Whaitua) would be acceptable and a classification for water quantity management purposes is unnecessary. It may be that there is a desire to apply more protective objectives to some streams than others. In this case amanagement classification would have the function of clarifying the objectives applying to different classes of streams. If this is important in the context of water quantity management, we suggest that the proposed water quality management classification is sufficient. To illustrate how example objectives and associated limits might work we have used the three-class water quality management classification in Section 4.3 below.

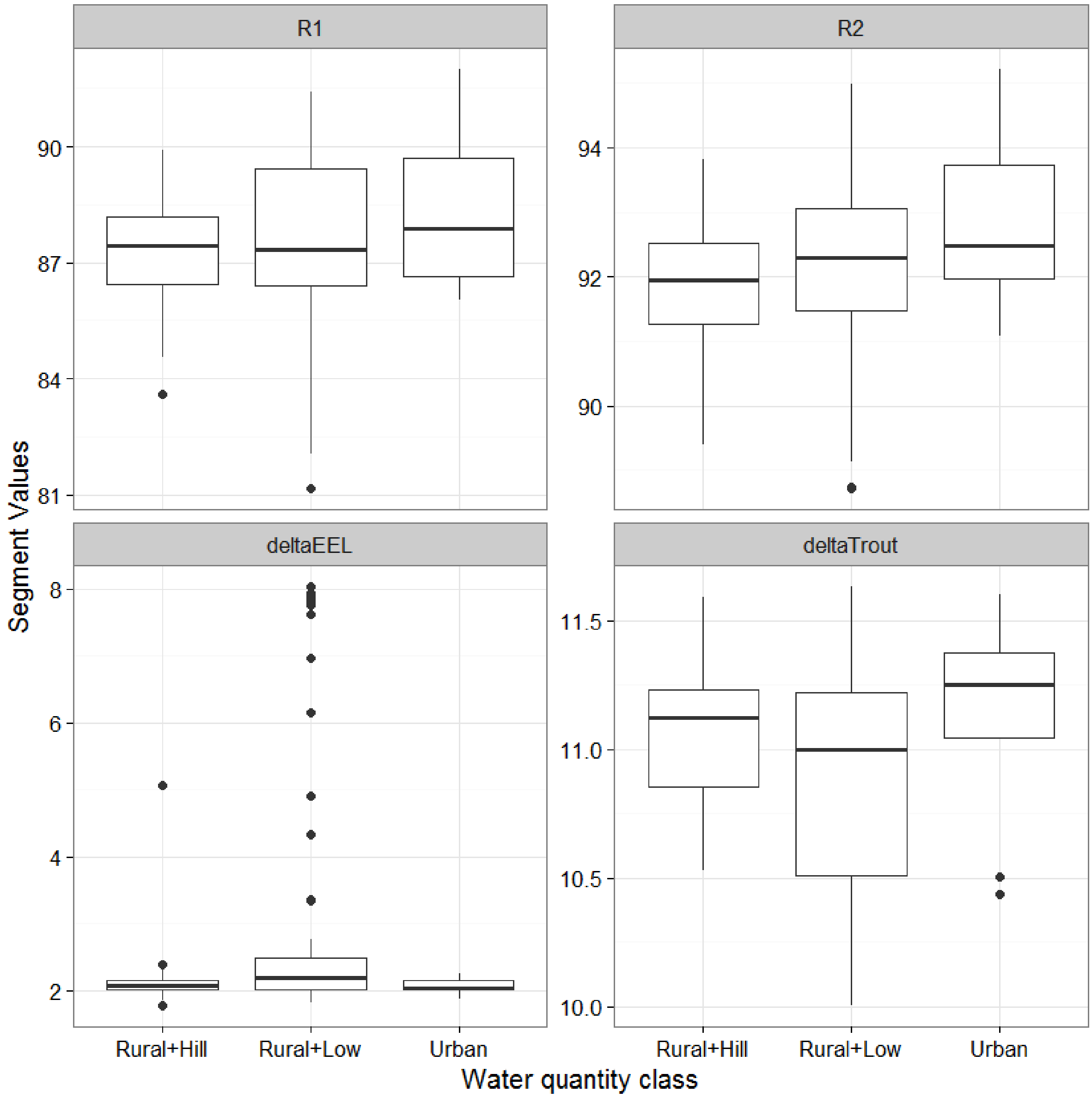

Figure 4-3 Box and whisker plot showing the distributions of variables indicating the effect of water quantity management rules on all network segments in the Whaitua. The data are grouped by the three proposed water management classes: Rural + Hill, Rural + Low, Urban. The central horizontal line indicates the median, and the bottom and top of the box indicate the 25th and 75th percentile values. The 'whiskers' (vertical lines) extend to the 10th and 90th percentiles. Where the number of outlier sites exceeded 10, the black points indicate the 5th and 95th percentiles.

4.3 Example water quantity objectives and limits

This section provides an example of water quantity objectives and associated limits for the three water quantity *management classes*. It is stressed that the objectives used here, including the critical values, habitat retention and reliability criteria, are examples only for demonstrating the approach. It is noted that the following analysis assesses flow requirement for a shortlist of four fish species. The Whaitua Committee and their modelling leadership group identified the following fish species as being significant within the Te Awarua-o-Porirua Whaitua: tuna (long and shortfin), inanga, giant kokopu, short-jawed kokopu, banded kokopu, koaro, kanakana (lamprey), redfin bully, common bully, giant bully, common smelt, koura, and brown trout. Of these species, it was possible to model 8 using the LIMSIM model (due to the availability of generalised models for these species): We further refined this list by removing species that had very similar responses to other species, leaving a short list of four: long fin eel, Inanga, adult brown trout, and spawning brown trout. Analysis of flow requirements for a wider range of species is possible. Flow requirements for values such as landscape and cultural values may have higher flow requirements and were not considered by this study. Assessments of flow requirements may also need to consider the effect of flow on water quality, which in some circumstances may be more restrictive than the effect on hydraulic conditions. The derivation of objectives and associated limits will be a subject of the future planning process and will need more comprehensive technical work once environmental values and objectives have been clarified.

Limits to meet example objectives for each of the three water quantity management classes were determined using model predictions from the Limits Simulator (LIMSIM) tool (Snelder et al., 2014). The LIMSIM tool has been developed to assess the consequences of different limits (water allocation and minimum flows) on habitat reduction for selected fish species and reliability of supply for out-of-stream users. The LIMSIM tool is based on several individual “components”, including:

1. The digital river network (REC) that provides a spatial framework;
2. Regional hydrology models of MALF estimates;
3. Regionalised flow duration curve tables extracted from EFSAP[19] (Booker and Snelder, 2012)
4. Generalised fish habitat – flow relationships (based on known habitat suitability curves) that provide hydraulic habitat estimates for a variety of target fish species at different flows (Jowett et al., 2008).

Details about the performance of LIMSIM in replicating observed hydrological characteristics (flow duration curves, mean flow, MALF) for five long-term, relatively natural, daily flow gauging stations within the Te Awarua-o-Porirua Whaitua are provided in Appendix C. Overall, we find that the models perform well, maintaining the relative responses between the different locations and with deviations within the expected model error.

LIMSIM is used to evaluate the effect of different management scenarios (minimum flows and allocations) on specific outcomes - defined by habitat reduction for target fish and reliability of supply. LIMSIM assessments are produced for all segments of the REC river network with specific inputs defining various scenarios for limits (e.g., setting a minimum flow of 90% MALF and a total allocation of 50% of MALF) and selected “critical values” (e.g. the need to maintain 90% of habitat for a species at MALF). LIMSIM calculates resultant outputs, showing habitat reduction for selected fish species and reliability of supply for these scenarios.

[19] The Environmental Flow Strategic Assessment Platform tool.

Results of many LIMSIM model runs that assessed the implications of a wide range of potential limit “scenarios” were used in this study for two purposes. First, the individual LIMSIM outputs were examined to assess the extent to which there were similar outcomes to a set of specific limits within each of the three water quantity *management classes*, and what differences there were between classes. Second, the outputs were used along with nominated example objectives for hydraulic habitat retention and reliability of supply to determine the minimum flow and allocation limits required to meet these objectives for each of the proposed *management classes*.

We examined the reliability of supply measures, looking at both the reliability at minimum flow (R2; Figure 4-2) and the reliability at management flow (R1; Figure 4-2). We defined the reliability as the proportion of the time (%) that the flow is at or above the specified flow.

The variability in habitat (for the four shortlisted species) and reliability outcomes across the three proposed water quantity *management classes* is demonstrated in Figure 4-4. These density plots are based on LIMSIM outputs for a management scenario with a minimum flow of 90% of MALF and a total allocation of 30% of MALF.

In general, the reliability and habitat (R1 and R2; Figure 4-4) show a relatively consistent response across the classes.

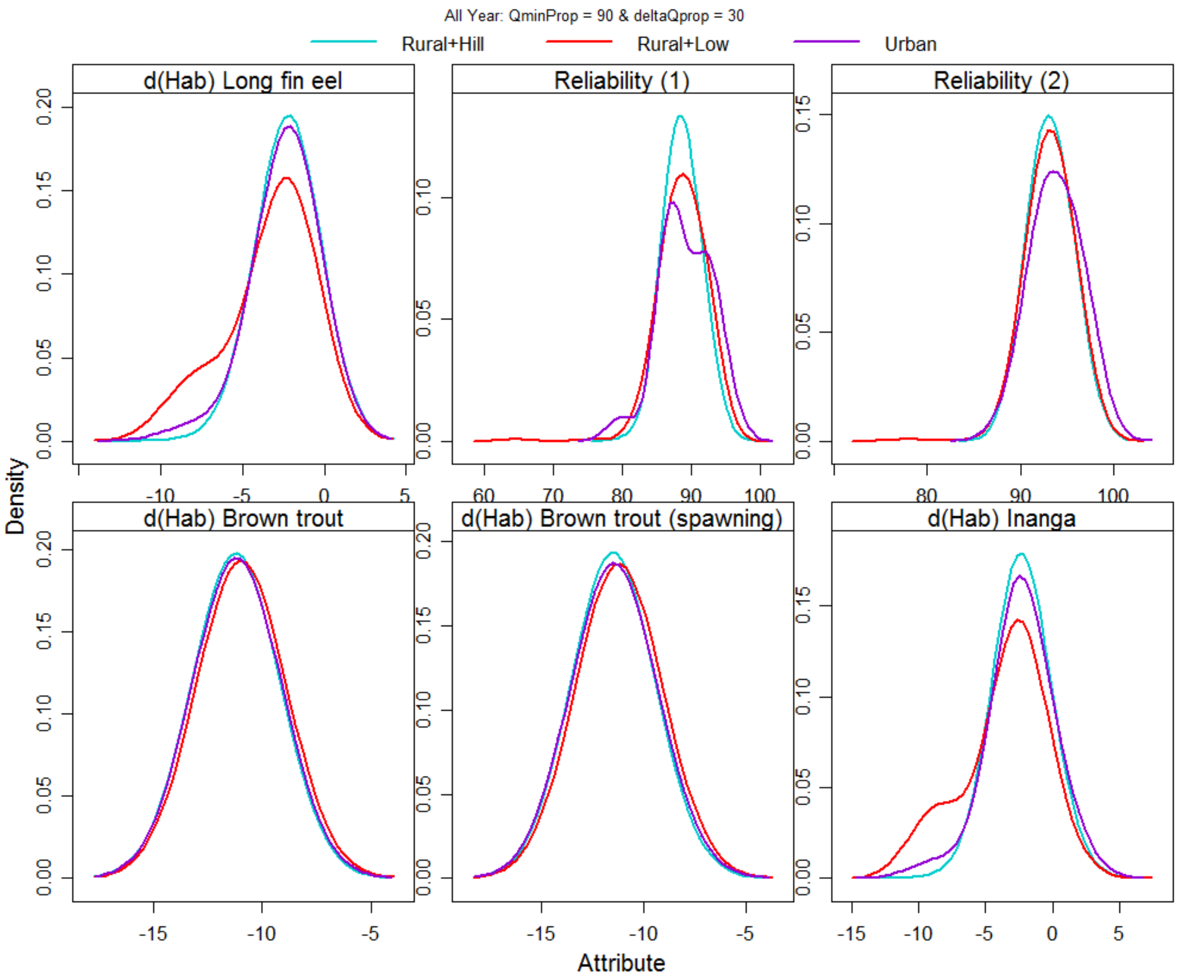

Figure 4-4: Density plots showing variation in reliability of supply at both the management flow (R1) and minimum flow (R2) and changes to predicted instream habitat (d(Hab)) of long fin eel,

adult brown trout, spawning brown trout and Inanga. The density plots are shown for the three proposed management classes for a management scenario with a minimum flow of 90% of MALF and a total allocation of 30% of MALF. The y-axis (labelled Density) shows the relative likelihood of any individual segment to be equal a given outcome (the x-axis).

To provide an example of how objectives and management regimes would vary in accordance with values, we adopted long finned eel as the critical species in the streams. For the example classification included below, the objective for habitat reduction was no more than 10% of the habitat compared to that available at MALF for at least 50% of segments within each *management class*. The example objectives for reliability are a total reliability of no less than 85% for R2 and 80% for R1 for at least 50% of segments within a management *class*.

It is stressed that these objectives are all examples and that objectives will need to be defined by the Whaitua process before the structure of FMUs can be finalised. We note that the reliability measures selected are most likely lower than would optimally be targeted, but in our selection one of our aims was that for each of the classes that there would be some combination of allocation and minimum flow that would be able to simultaneously achieve all three of these objectives.

The existing LIMSIM outputs could be used to evaluate limits associated with alternative objectives including different levels of habitat retention, different critical species and different levels of reliability of supply. For example, more environmentally conservative limits could be explored by requiring the objectives to be met at 90% or 75% of segments (as compared to 50% as used in our example).

The density plots shown in Figure 4-4 demonstrate how outcomes vary under a specific management scenario (minimum flow of 90% of MALF and a total allocation of 30% of MALF). By considering a range of possible limits (i.e. minimum flows and total allocations) defined by differing proportions of MALF, a more complete range of potential outcomes can be generated and this can help explore options. An alternative way of exploring the outcomes predicted from LIMSIM is to use decision space diagrams (Snelder et al., 2013). Decision space diagrams summarise the percentage of segments within a *management class* that meet the specified objectives for any given attribute across a range of limits (Figure 4-5). Decision space diagrams provide a way to identify the limits (i.e. minimum flows and total allocations) for any given attribute that will provide acceptable outcomes for a given water quantity *management class*.

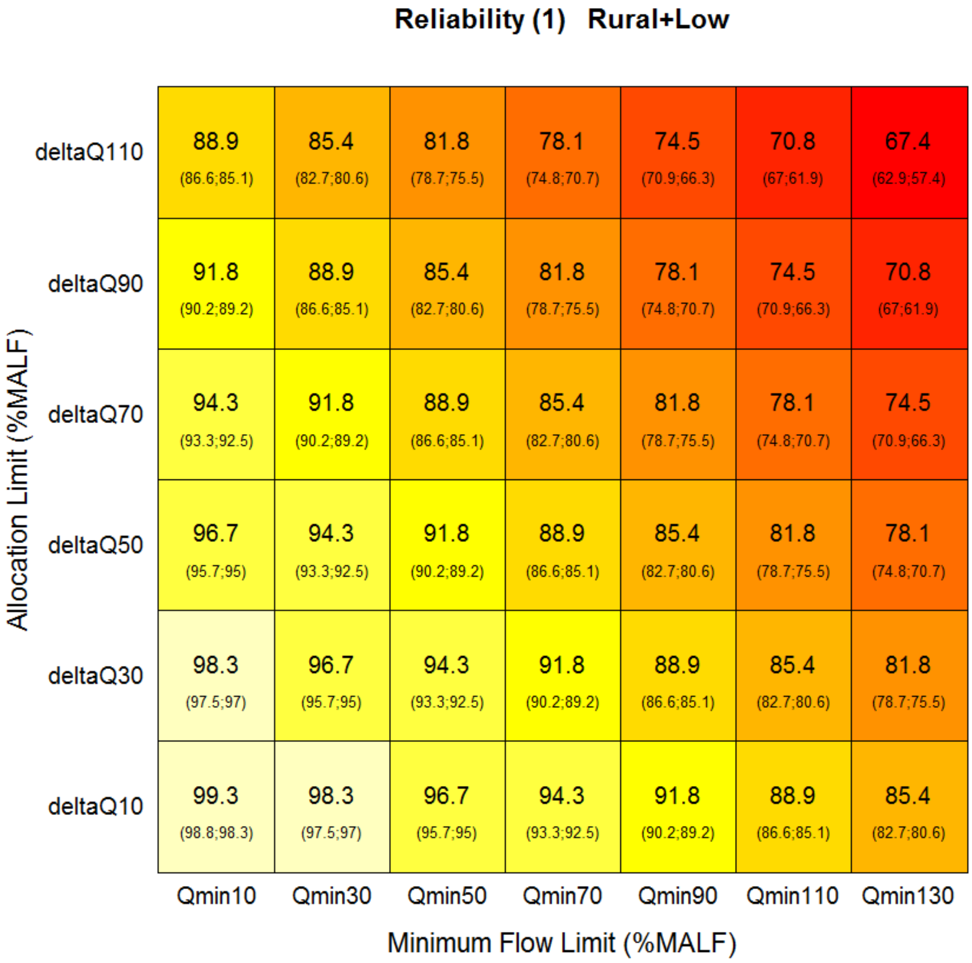

Figure 4-5: Example decision space diagram, The plot indicates the change in reliability at management flow (R1) in the Rural+Low management class. Numbers in the cells are the median change in % reliability across all segments within the management class for each set of limits (minimum flows and allocation). Values in the brackets are the 25th and 10th percentiles of the % reliability (i.e. 75% and 90% of sites achieve values greater than those listed).

However, when setting limits, acceptable outcomes must be achieved across *all* attributes (i.e. R1, R2 and d(Hab)). By overlapping the regions of acceptability for multiple attributes it is possible to generate a combined decision space diagram to identify a set of limits that achieves all the objectives. An example of a combined decision space diagram is shown in Figure 4-6.

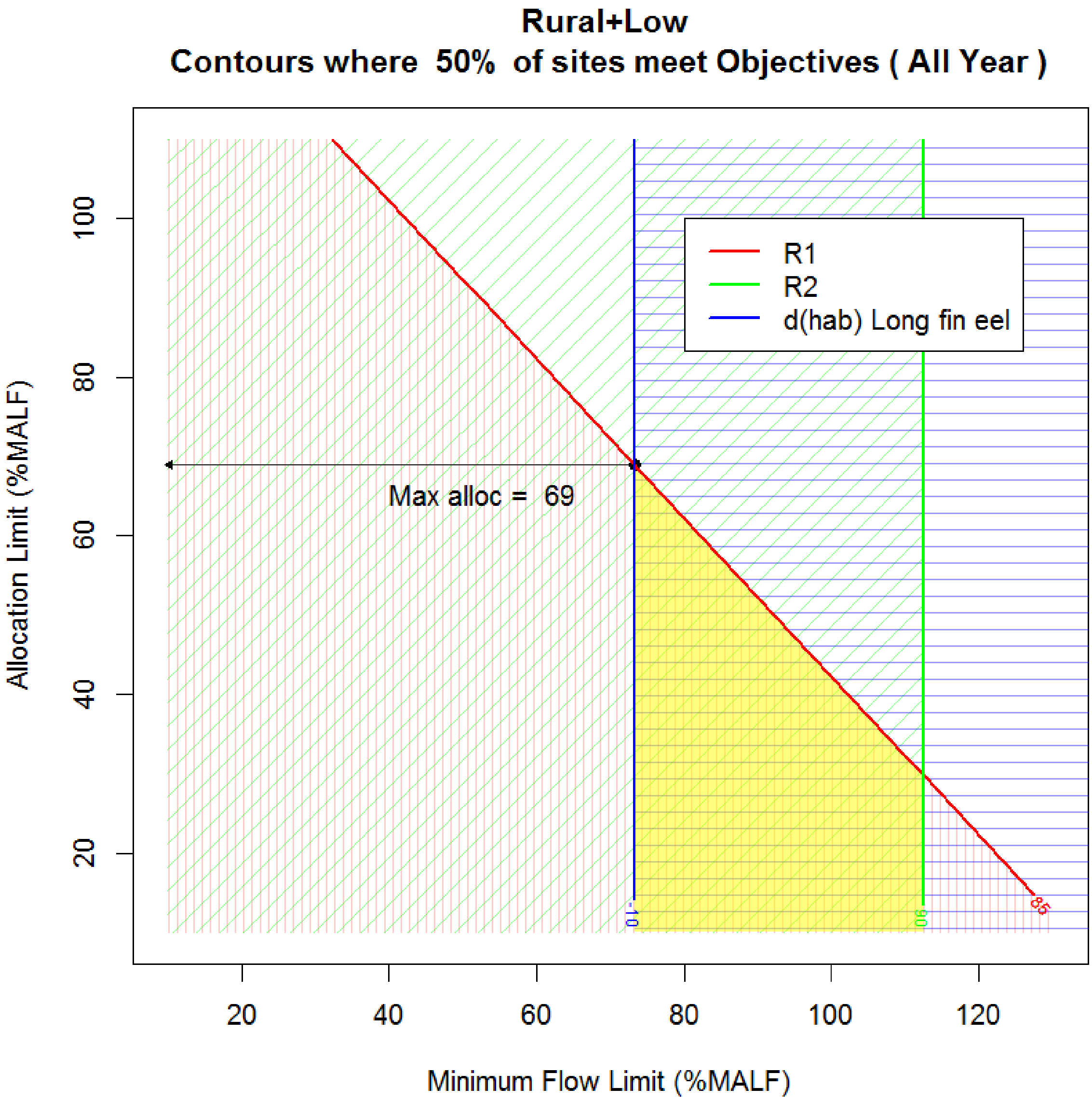

Figure 4-6: Combined decision space diagram for Rural+Low class. Solid lines are contours that achieve the minimum acceptable outcomes for each of: reliability at management flow (R1), reliability at minimum flow (R2) and change in long fin eel habitat (d(Hab) Long fin eel). The area within the decision space diagram with acceptable outcomes for each attribute is indicated by hashing: reliability and management flow (R1) – red vertical lines; reliability at minimum flow (R2) – green diagonal lines; and change in long fin eel habitat – blue horizontal lines. The region of the decision space diagram where all objectives are met is indicated in yellow. The maximum possible allocation limit that meets all objectives at 50% of sites within the class is 69% of MALF and is demonstrated by an arrow.

Example objectives and associated limits are summarised in Table 5. The first three rows of the table indicate the limits (minimum flows and allocations) required to achieve the stated objectives for habitat retention for long fin eel and reliability of supply for the three water quantity management classes. The limits have been derived from the LIMSIM analysis and decision space diagrams. The reported limits achieve the example objectives for 50% of segments in each water quantity *management class*. Even within this more constrained set of options for limits, value judgements are required to define a final choice of limits; in this example we have optimised for resource use, by maximising the abstraction limit (as demonstrated in Figure 4-6).

Table 5 indicates that, given a specific objective, there is only minor variation in the rules that are required in the three management classes. This is consistent with the relatively homogeneous nature of the streams and stream flows (hydrology) in the Porirua Whaitua and the homogeneous responses of habitat and impacts on reliability to specific rules (Figure 4-3). Table 5 also indicates differences in the outcomes (indicated by the objectives) achieved under different rules.

The fourth to sixth rows indicate the outcomes for three sets of specified limits. The outcomes have been derived from the LIMSIM analysis and decision space diagrams. The fifth row represents the current GWRC Regions Plan default limits and the outcomes represent the median outcome over all segments of the Whaitua. The fourth and sixth rows indicate changes to the outcomes resulting from relatively more enabling and restrictive limits respectively.

Table 5: Example water quantity management objectives and associated limits.

Water Quantity management class	**Objectives/Outcomes**			**Limits**	
	Habitat reduction (% at MALF)	**Reliability at minimum flow (% time)**	**Reliability at management flow (% time)**	**Allocation limit (% of MALF)**	**Minimum flow (% of MALF)**
Rural+Hill	-10	90	85	71	69
Rural+Low	-10	90	85	69	73
Urban	-10	90	85	67	73
Whole of Whaitua (example more enabling than default plan limits)	-10	89	96	50	70
Whole Whaitua (default regional plan limits)	-2	89	93	30	90
Whole Whaitua (example more restrictive than default plan limits)	2	89	90	10	110

4.4 Water quantity management zones and administrative points

As indicated in Section 4.2 and further elaborated in Table 5 above, there is only minor variation in the rules needed to achieve a specific set of water management objectives (i.e. reliability and habitat retention) across the Whaitua. We consider that this variation is too small to be important for management. Therefore, we consider that if a uniform set of objectives for both habitat and reliability across the Whaitua are acceptable, then no water quantity management classification is necessary. It may be that there is a desire to have varying objectives (either habitat retention and associated target species or the reliability) across the Whaitua. In this case, we propose that the water quality management classification (Figure 3-1) is appropriate. If this classification was used to define varying objectives, the management zones would be the same as for water quality management (i.e. Figure 3-4).

Administrative points would either be the outlet points for all subcatchments in the Whaitua in the case that no water quantity management classification is necessary, or the same administrative points as for water quality if the three-class water quality management classification (Figure 3-1) is deemed appropriate.

4.5 Next steps – water quantity FMUs

4.5.1 Developing plan provisions

Having defined example objectives and associated options for limits for each water quantity *management zone*, the next step that should be undertaken is to compare these options for allocation limits against the current estimated allocation, which comprises the consented allocation and estimated permitted uses. The total amounts of water allocated can be estimated (from consent data and permitted use estimates) for all locations in the river network and these accumulate in the downstream direction. This means that estimates of the potential abstraction, with respect to the allocation limit, can be made at all *administrative points*. This estimate does not represent the actual abstraction because it does not consider whether the allowable total abstraction (consented plus permitted) is occurring. However, the current total allocation compared to the allocation limit is an important indicator of locations that are potentially over-allocated.

The relevant locations for defining volumetric limits and accounting for allocation are the *administrative points*. If the limits set by the plan (e.g. Table 5) are expressed as proportion of MALF, they can be converted to volumetric limits or rates at the *administrative points* by multiplying by the estimated MALF at these locations. MALF can be estimated in a variety of ways including from regionalisation or more detailed analysis of nearby hydrological gauging station data. The *administrative points* that do not lie within over-allocated catchments could be considered locations for which water is available subject to existing upstream and downstream allocation and the limits set out in Table 5.

Because the LIMSIM tool is based on generalised models, the derived limits (e.g., the options in Table 5) are broadly accurate but are subject to larger uncertainties at the site scale than would be more detailed site specific analyses. However, we consider the LIMSIM tool reliably demonstrates the relative differences between the classes (Appendix C) and therefore justifies the general approach to defining the FMUs.

Specific management regimes (minimum flows and total allocations) could be derived for either sites or water quantity management classes based on detailed site specific analyses rather than the LIMSIM tool used here. Detailed assessments are commonly used to support water quantity management decisions when greater certainty is required and are commonly based on site scale hydraulic habitat models such as RYHABSIM[20], coupled with analysis of relevant hydrological data. These assessments provide the most accurate analysis of the effect of a proposed take relative to aquatic habitat objectives but they are expensive and time consuming and are probably not justified for small takes in situations of low risk.

[20] River Hydraulics and Habitat Simulation computer program: http://www.jowettconsulting.co.nz/home/rhyhabsim

Furthermore, RYHABSIM analysis only addresses ecological flow requirements. Flows needed to support other values (e.g., landscape and cultural values) or to keep river-mouths or flood drainage cuts open, require other assessment methods.

The inherent uncertainties associated with the use of LIMSIM could be acknowledged in the plan by using a tiered system for consenting water takes. Higher levels of discretion and lower levels of assessment effort could be allowed to enable resource use in an efficient manner where risks are low (i.e. where current allocation is well within the limits) but rigour could be increased in situations where current allocation is approaching the assessed limits. Essentially the consenting process needs to demonstrate that a new take will not prevent the objectives from being achieved. Assessments of new takes in situations where the current and proposed allocation is "small" relative to limits could be considered as low risk. In these situations, limits such as those shown in Table 5, which are based on the LIMSIM tool, could be used. Applications for water takes in situations where the current and new takes are "large", relative to the limits, however would need to be supported by more detailed analyses.

4.6 Accounting for groundwater takes and groundwater effects on surface water quality

We also note that our analysis is based on surface water only. Takes from groundwater and discharges from land into groundwater will affect surface water quantity and quality and therefore need to be accounted for in the management of the resource. The details of the joint management of the groundwater and surface water resources of the Whaitua need further consideration that is outside the scope of this study.

5 Discussion

This project has developed an approach to defining FMUs that provides a biophysical basis for implementation of the NPS-FM. A key finding of this project is that FMUs need to be a framework of spatial units (i.e., comprising management classes, zones and administrative points) rather than a simple single subdivision of the Whaitua. There are several reasons that a framework of spatial units is likely to be necessary. These include the need for plans to manage different issues (e.g. water quality versus water quantity) and to provide a basis for different management functions (e.g. setting objectives versus defining policies and accounting for resource use and consenting water takes).

The suggested approach to defining FMUs for the Te Awarua-o-Porirua Whaitua comprises three components: (1) the water bodies that are designated to be managed for a purpose (objective), termed the "*management classification*" in this report, (2) the associated land area (catchment or sub-catchment) that drains to a management class, termed the "*management zone*", and (3) the points in the network where the *management zone* changes, which are termed *administrative points*. It is important to note that an administrative point can be determined for any point on a river but it is suggested some minimum set of points should be defined as described here. FMUs are then defined by layering *management zones* in an order that is dependent on the policies and limits set for each of the management zones. The layering of the zones recognises that locations that lie in multiple management zones must comply with the policies and limits associated with the *most restrictive downstream objectives.*

It is suggested that water quality and quantity FMUs could be based, at least in the first instance, on the described three-class classification. These FMUs broadly discriminate variation in the characteristics of the water bodies that are relevant to management including their values, current state and capacity for resource use. These FMUs also identify the associated land areas that drain to the classes (i.e., the *management zones*). FMUs are defined by stacking the *management zone building* blocks so that management actions and limits that apply to them provide for the achievement of the most restrictive downstream objective.

Some water bodies have specific values or management issues that are not discriminated by the *management classification*s but which may need to be provided for. These water bodies can be associated with *special management zones* that have the potential to over-ride the objectives set for the *management classes*. Examples of water bodies requiring separate management objectives in the Te Awarua-o-Porirua Whaitua are the Taupo Swamp and the catchments draining to the open-coast (Figure 3-10). Both receiving environments may be judged to be different to the Porirua Harbour, which is the receiving environment for most streams in the Whaitua. All three receiving environments in the Whaitua (Taupo Swamp, Porirua Harbour and the open coast) are likely to be valued differently and have different sensitivities. Defining special management zones for the Taupo Swamp and the catchments draining to the open-coast would enable specific plan provisions (objectives and policies) to apply to all three receiving environments. It is noted that special management zones will add to the complexity of the plan (by creating exceptions to the policies that apply to the general FMUs). It is recommended that specific criteria are derived to avoid a proliferation of special management zones that will undermine the clarity and relative simplicity that is afforded by the general FMUs.

The suggested approach has several benefits including:

1. The use of physiographic classifications provides for variation in the characteristics of interest to be resolved at a level of detail that is appropriate to management,

2. The approach is transparent,

3. The logic that objectives apply to the water bodies and that the limits and actions apply to the catchments draining to those water bodies is inherent in the approach,

4. The need for limits to be set and actions taken to achieve the most constraining downstream objective is built into the approach,

5. The process is flexible and easily repeatable so that FMUs can be modified and their definition is integral to the plan development process.

6. The level of classification detail (i.e. coarse or fine) can be altered by varying the physiographic factors (and their categories) to suit the desired level of detail and spatial specificity of the plan provisions,

7. The layering of management zones can be altered to accommodate changes in the order of restrictiveness of policies and limits that may arise in the development of plan provisions,

8. Aspects of the plan’s implementation (e.g., consenting and accounting for resource use) can be undertaken at appropriately fine levels of spatial resolution defined by the administrative points,

9. The framework provides an efficient and justifiable basis for water quality monitoring and reporting at the regional level based on having a representative number of monitoring sites in each management class, and

10. The framework is spatially clear and certain (i.e. mapped) about where limits need to be met and where accounting should occur (administrative points).

It is emphasised that the FMUs and associated objectives and limits set out in this report are only examples that provide options for consideration and can be altered through the plan development process. It is recognised that example FMUs represent a coarse differentiation of the region's rivers with respect to their values, current state and other characteristics of relevance. This coarse level of classification and subsequent discrimination of characteristics is consistent with the requirements of a broad regional approach to management that requires trading off detail (specificity) with coverage and simplicity. The resolution of the suggested approach can be increased by increasing the number of classes in the *management classification*s and accordingly increasing plan complexity. However, the differences between classes will become less distinct as the number of classes increases and it will therefore become difficult to justify variation in the objectives, policies and limits if there is many classes.

The regional and coarse scaled approach offered in this report is most likely to be acceptable if it is a starting point and it is acknowledged there may be areas that have issues that warrant more detailed assessments, and that there will be opportunity to refine or develop provisions that apply to local issues as part of the WIP process. In these cases, more specific and nuanced objectives and policies may be developed that apply to the general FMUs but for specific locations.

6 Acknowledgements

We would like to thank the Te Awarua-o-Porirua Whaitua committee for their initial definition of a bio-physical classification of the Whaitua.

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Appendix A Classification testing

This appendix provides a description of the work that explored alternative management classifications for the Te Awarua-o-Porirua Whaitua. Selecting a classification must strike a balance between complexity (i.e. number of classes) and ability to discriminate important differences in a range of water quality and quantity characteristics. We explored this trade-off by characterising water quality using estimates of the median values of a range of water quality variables for each of the REC segments within the catchment. The estimates were prepared by applying models of each water quality variable, where the models were derived from the relationship between catchment characteristics and water quality observations collected throughout the Greater Wellington Region (see Appendix D for details). We characterised water quantity responses based on regionalised natural state flow duration curves and MALF for all REC segments within the catchment. Specifically, the variable used was the position of MALF on the flow duration curve, which is a measure of the inherent reliability as a water supply of a river location.

A1 Management classification based on catchment slope

If a simple two-class water quality management classification based on catchment slope is used an important question is: what is the appropriate threshold to define the class boundary?

An analysis of alternative criteria for the boundary between the two catchment slope-based classes was undertaken to answer this question. In this analysis the threshold for the two classes was varied from 5 degrees to 25 degrees in increments of one degree. For each increment the water quality monitoring sites were allocated to the ‘lowland’ and ‘hill’ class depending on whether the average catchment slopes for each site were less than or greater than the threshold respectively. The upper and lower limits of the thresholds used in the analysis were determined by the value of average catchment slope at which there were no monitoring sites in one of the classes.

The explanatory power of the classification was evaluated for each increment of catchment slope using analysis of variance (ANOVA). An ANOVA was performed on the estimates of water clarity (CLAR), total nitrogen (TN), nitrate-nitrogen (NO3N), total phosphorous (TP), dissolved reactive phosphorous (DRP), *E. coli* (ECOLI), ammoniacal nitrogen (NH4N); macroinvertebrate community index (MCI); suspended sediments (SS); and the location of the mean annual low flow (MALF) on the flow duration curve (FDC), for all REC segments within the catchment). The water quality variables were log10 transformed to make the distributions approximately normal. When the ANOVA was significant ($p < 0.05$), the coefficient of determination (i.e. r^2) was used as an indicator of the performance of the classification at the associated slope threshold.

A plot of the ANOVA values for each variable as a function of catchment slope indicated that the explanatory power of the classification generally had the maximum at a threshold of 16 degrees (Figure A-7-1).

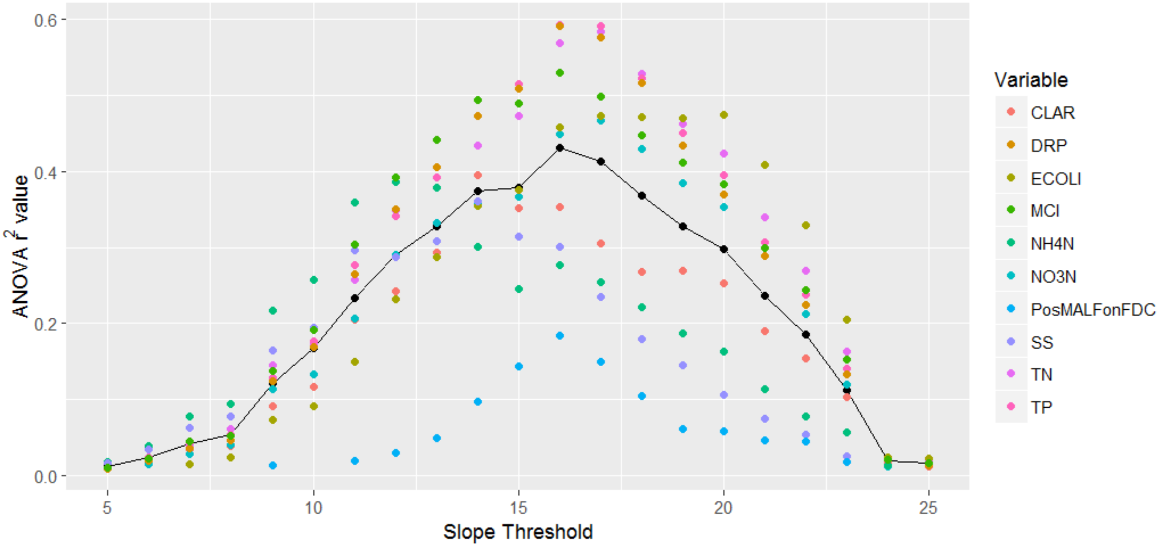

Figure A-7-1: ANOVA r² values for each variable as a function of catchment slope. The coloured points show the r² value of each variable where the ANOVA was significant (p < 0.05). The black line represents the mean value of r² over all variables.

We explored the distribution of the 58 GWRC water quality monitoring sites between the two slope classes at each of the slope thresholds and compared this against the distribution of the two classes across all REC reaches within the Te Awarua-o-Porirua Whaitua area. Generally the proportion of GWRC monitoring sites within the low class is within 10 % of the proportion of that class across the Whaitua area (Figure A-7-2). This indicates that, with regard slope, the GWRC monitoring sites provide a reasonable representation of the slopes that occur within the Whaitua.

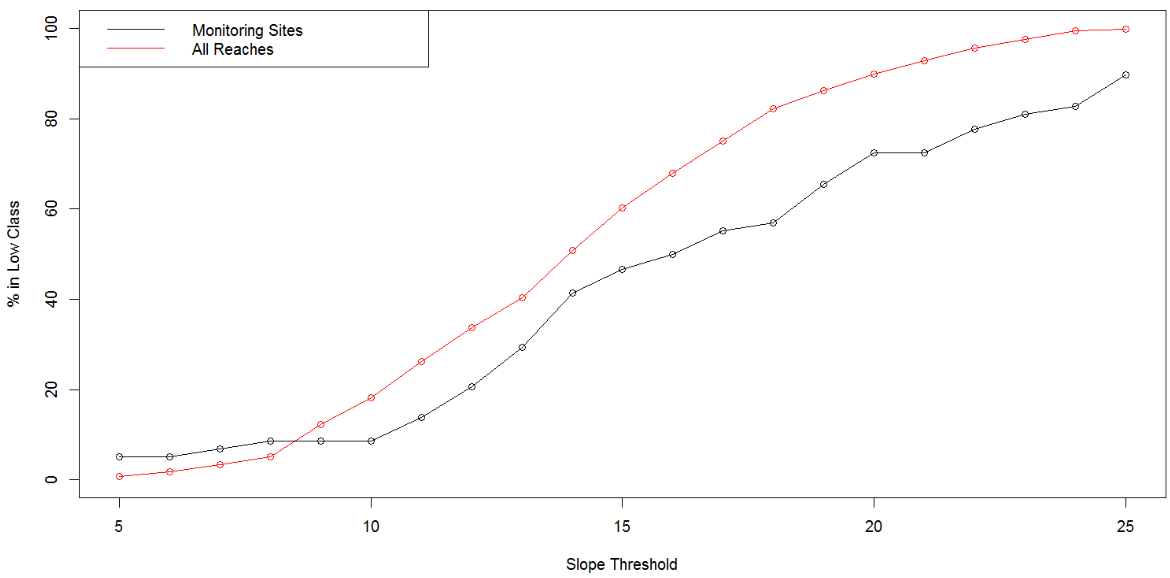

Figure A-7-2: Distribution of GWRC monitoring sites compared to Whaitual REC reaches within the "Low" slope class as a function of the slope threshold

A2 Exploring management classifications

We explored the ability of 17 alternative classifications to explain regional variation in the test data (i.e. water quality and quantity variables) using analysis of variance (ANOVA). These classifications were based on various combinations of the following 4 categorical factors:

- T: Temperature class (First letter of the REC climate variable (W=warm, C=cool)
- R: Rain class (Second letter of the REC climate variable, (Classes: “W” – wet, “D” – dry). Note that we merged X (extremely wet) into W.
- G: Geology (GEOLOGY from REC, (Classes: “SS” – soft sedimentary, “HS” – hard sedimentary). Note we simplified by making Al (alluvium) and M (miscellaneous) classes = HS.
- S “Slope”
    - S1: Slope with a 16 degree threshold (Classes: “Low” and “Hill”)
    - S2: Simplified REC Source of Flow (Classes: “L” - lowland and “H” - hill). Note we merged M into H and Lk into L.

The 16th classification used was based on urban/rural landuse (LU).

The 17th classification was based on a three class urban/rural low slope/rural hill slope, where the low and hill slopes were below and above 16 degrees (LU+S).

We considered two alternatives for the definition of the slope class. Firstly we used slope with a 16 degree threshold (based on the analysis provided in the previous section). The second classification used a simplified version of REC “Source of Flow” classification. This classification is widely used among regional councils for the categorisation of rivers. The REC “Source of Flow” classification is really a classification of elevation, not slope. It has the advantage that it can be taken as a “given” and no subjective threshold must be defined, as for the Slope categorisation. Below are two plots showing the difference in the spatial distribution between these two classifications (Figure A-7-3). Most of the Whaitua falls into a single category of the “Source of Flow” so it was rejected as an alternative slope classifier.

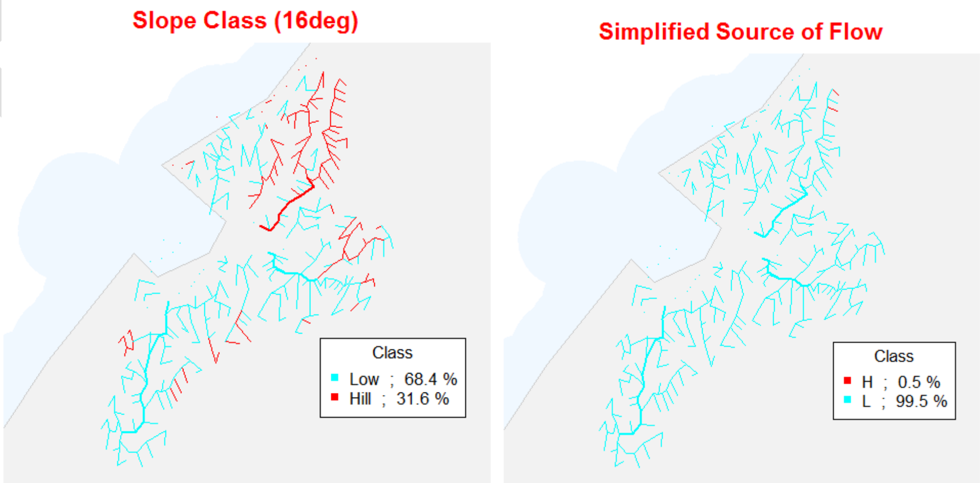

Figure A-7-3: Comparison of spatial distribution of alternative slope classifications

The distributions of the other three variables are shown in Figure A-7-4 below. We note that T (temperature) and R (rainfall) are highly correlated, and all four classifications demonstrate a strong east/west separation.

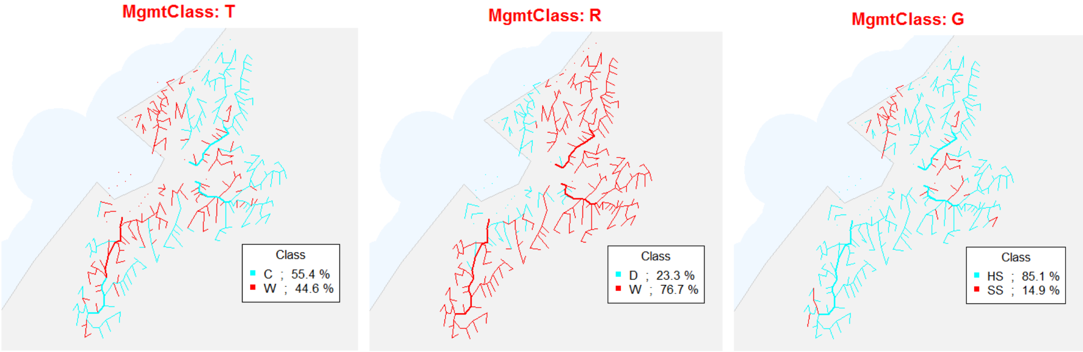

Figure A-7-4: Spatial distribution of Temperature (T), Rainfall (R) and Simplified Geology (G) classifications

An ANOVA was performed on the same variables used to explore the slope classification (9 water quality variables and 1 water quantity variable). When the ANOVA was significant ($p < 0.05$), the coefficient of determination (i.e. r^2) was used as an indicator of the performance of the classification. The results of the ANOVA tests are shown below (Table 6). The top part of the table is the r^2 values, where NA values indicate the relationship was not significant. The next section of table rows provides a summary of the mean of the non-NA r^2 values for each classification. In the bottom rows, the number of large classes defined by the classification regime (defined as >5% of the REC reaches) is shown, along with the percentage of all REC reaches that fall within these numbered large classes. It is assumed that classes <5% would be amalgamated with the larger classes. The distributions of the r^2 values for the difference variables across the classes are also shown graphically in Figure A-7-5.

Table 6: Summary of r^2 values for the 17 alternative management classifications. NA values indicate no significant relationship for the given variable. The number of large classes is the number of classes with more than 5% of the total REC network. The percentage of large classes is the total percentage of the REC network that is covered by the large classes.

	T	R	G	S	T+R	T+G	T+S	R+G	R+S	G+S	T+R+G	T+R+S	T+G+S	R+G+S	T+R+G+S	LU	LU+S
CLAR	0.45	0.22	0.17	0.39	0.46	0.48	0.56	0.33	0.47	0.45	0.49	0.57	0.58	0.52	0.60	0.07	0.38
TN	0.30	0.12	0.11	0.55	0.30	0.32	0.60	0.21	0.57	0.57	0.33	0.60	0.60	0.59	0.61	0.13	0.57
TP	0.37	0.18	0.12	0.60	0.38	0.39	0.67	0.26	0.64	0.62	0.40	0.67	0.67	0.66	0.68	0.12	0.60
NO3N	0.21	0.07	0.07	0.44	0.21	0.23	0.46	0.13	0.44	0.45	0.23	0.46	0.46	0.45	0.47	0.10	0.44
NH4N	0.32	0.28	0.09	0.27	0.38	0.33	0.40	0.35	0.43	0.30	0.41	0.47	0.40	0.47	0.50	0.16	0.33
DRP	0.37	0.18	0.09	0.56	0.38	0.38	0.64	0.25	0.61	0.58	0.39	0.65	0.64	0.62	0.65	0.15	0.58
ECOLI	0.23	0.09	0.06	0.46	0.23	0.24	0.49	0.13	0.47	0.46	0.25	0.49	0.49	0.47	0.49	0.12	0.47
SS	0.50	0.36	0.16	0.29	0.55	0.51	0.55	0.45	0.50	0.36	0.57	0.60	0.56	0.55	0.62	0.04	0.29
ECOLI95	0.11	0.02	0.05	0.32	0.12	0.13	0.32	0.07	0.32	0.33	0.14	0.33	0.33	0.33	0.34	0.03	0.32
MCI	0.39	0.20	0.12	0.55	0.40	0.40	0.63	0.28	0.60	0.57	0.41	0.64	0.64	0.62	0.65	0.17	0.58
PosMALFonFDC	0.13	0.03	0.04	0.18	0.14	0.14	0.23	0.05	0.20	0.18	0.17	0.24	0.23	0.22	0.26	NA	0.19
Average R2 (no FDC)	0.32	0.17	0.10	0.44	0.34	0.34	0.53	0.25	0.51	0.47	0.36	0.55	0.54	0.53	0.56	0.11	0.46
Average R2	0.31	0.16	0.10	0.42	0.32	0.32	0.50	0.23	0.48	0.44	0.34	0.52	0.51	0.50	0.53	0.11	0.43
No. sig relationships	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	11.00	12.00
No. lg classes	2	2	2	2	3	3	3	4	3	3	5	4	4	5	6	2	3
Perc. lg classes	100.00	100.00	100.00	100.00	99.76	98.82	98.11	100.00	99.06	100.00	98.58	97.88	96.93	99.06	96.70	100.00	100.00

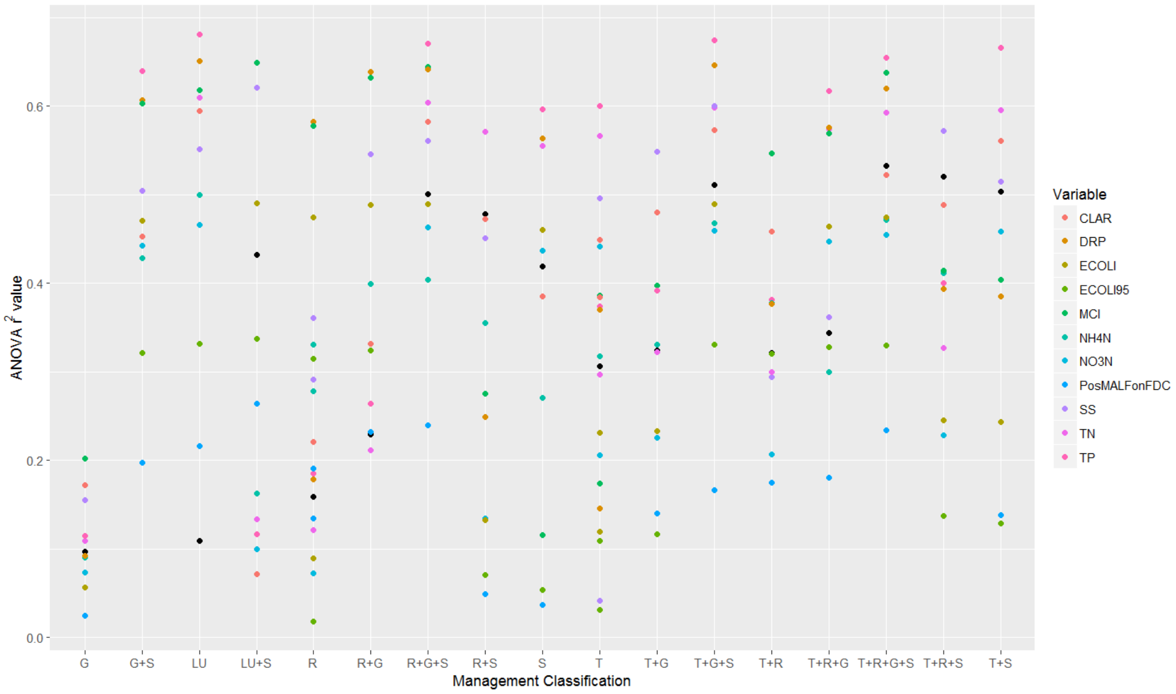

Figure A-7-5: ANOVA r^2 values for each variable for each of the management classes. The coloured points show the r^2 value of each variable where the ANOVA was significant ($p < 0.05$). The black dots represent the mean value of r^2 over all variables.

Based on the results from Table 6 and Figure A-7-5, we suggest that any classification with an r^2 of less than 0.5 would not be acceptable. We also suggest that the classification with all 4 categories was over classified, with at least one classifier being redundant. Balancing r^2 with the number of large classes, the most promising classification appears to be R+S. However, we also note that the Whaitua committee have also identified urban/rural landuse as playing an important role in defining the observed variability in the rivers of the Te Awarua-o-Porirua Whaitua. As such, we have selected the LU+S classification – this offers a lower r^2 value than the R+S classification, but includes the Urban/Rural classification.

Appendix B LIMSIM hydrological model component testing

We tested the performance of the hydrological model components within LIMSIM against five sets of long-term, relatively natural, daily stream flow records observed within the Te Awarua-o-Porirua Whaitua. Details of the flow observations sites used for these tests are provided in the table below:

Table 7: Details of the flow observation sites in the Te Awarua-o-Porirua Whaitua used to test the performance of the LIMSIM hydrological model components.

Gauge	NZReach	Easting	Northing	Start Date	End Date
Horokiri Stream at Snodgrass	9005786	1811469	5465421	16/02/2002	18/11/2011
Horokiri Stream at Grenlo	9005786	1811469	5465421	2/04/1963	19/09/1967
Pauatahanui Stream at gorge	9000870	1819318	5485239	2/06/1975	20/7/2010
Porirua Stream at town centre	9008990	1798066	5451001	9/09/1965	17/01/11
Taupo Stream at Flax Swamp	9002572	1825333	5477907	1/06/1985	18/11/2011

For each flow observation site we extracted the seven day mean annual low flow (MALF), mean flow and Flow Duration Curve (FDC) centiles. We did this for the maximum data length for each station. Figure A-7-6 below shows the observed and predicted flow duration curves for each of the sites. In general the shape and magnitude of the FDC's are well predicted.

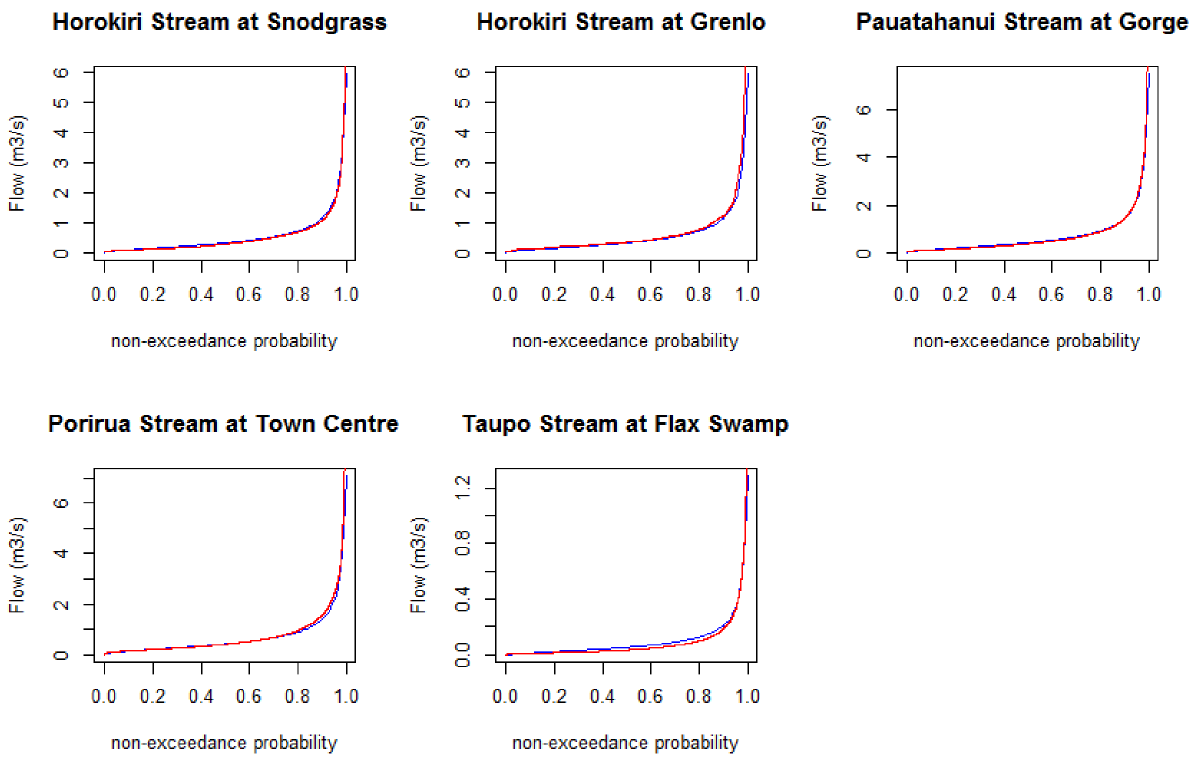

Figure A-7-6: Comparison of observed and predicted flow duration curves for flow observation sites. The red lines show the observed FDC's and the blue lines show the predicted FDC's (Booker and Snelder, 2012).

Figure A-7-7 below shows the observed versus predicted MALF and mean flow values, respectively. In general, the model reflects the relative differences in flows between locations. The absolute errors are within the range expected for the generalised models.

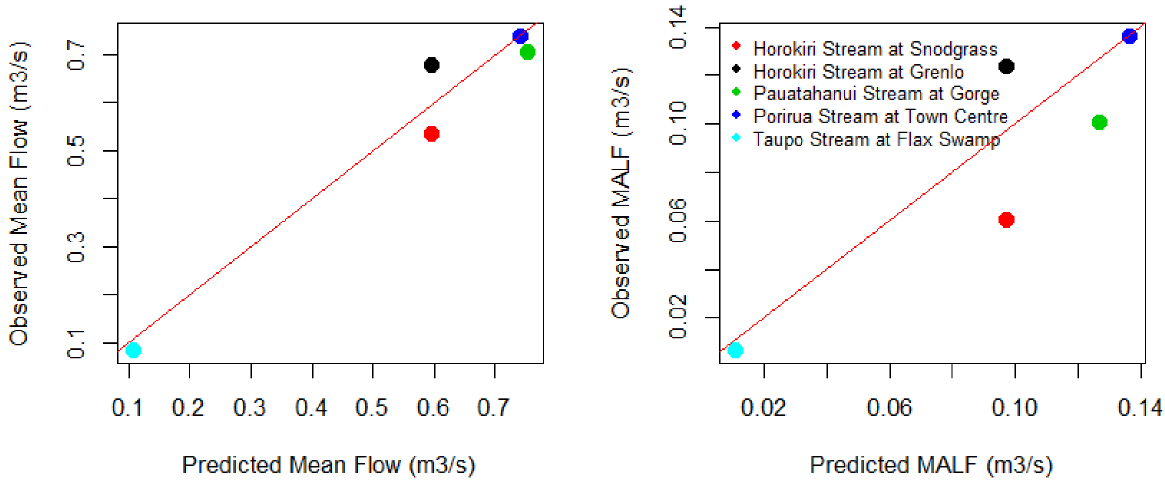

Figure A-7-7: Comparison of predicted versus observed flow. Mean flow (left) and MALF (right). The red lines indicate the 1:1 line (i.e. perfect model performance).

Appendix C LIMSIM outputs

This appendix provides a summary of the LIMSIM outputs as decision space diagrams. Each figure is for a separate critical value based on the whole year. Each figure includes three decision space diagrams – one for each of the suggested water management classes.

Numbers in the cells are the median change in the variable across all reaches within the management class for each management scenario. Values in the brackets are the 25th and 10th percentiles of the % change in habitat (i.e. 75% and 90% of sites achieve values greater than those listed).

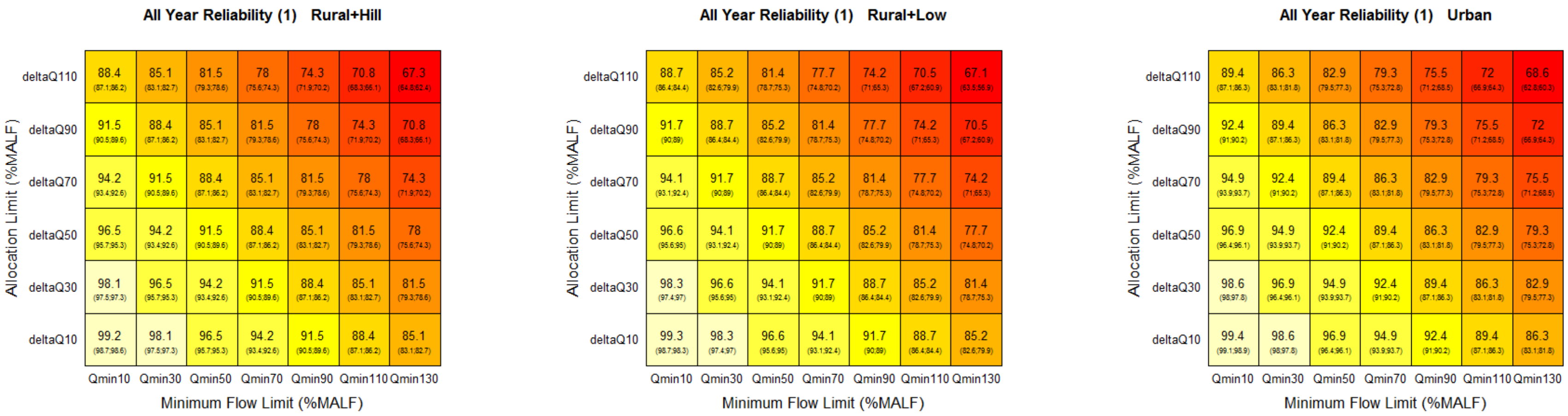

Figure A-7-8: Decision space diagrams for reliability at management flow for the whole year.

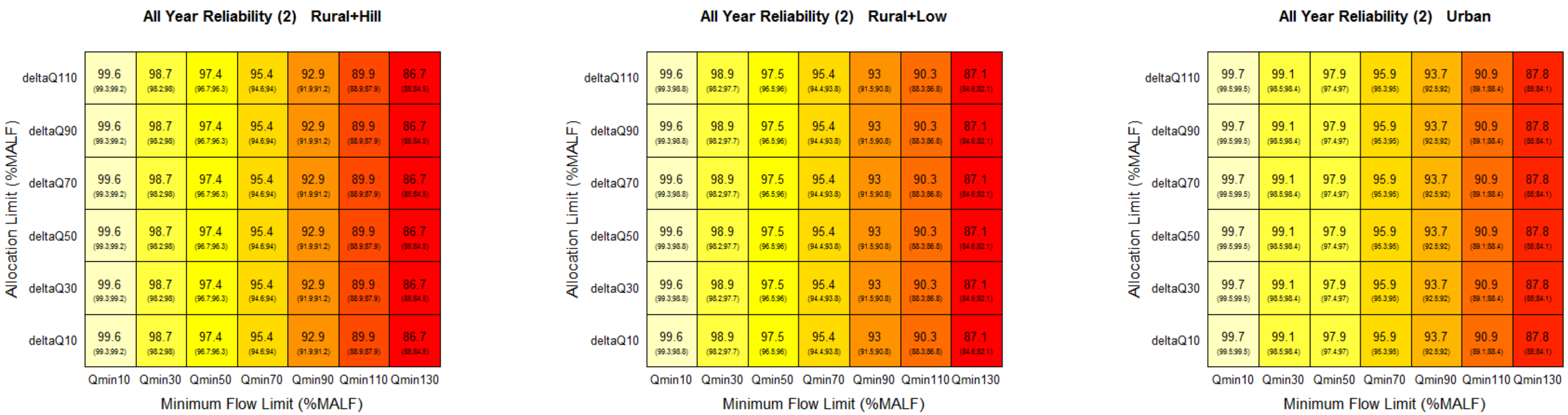

Figure A-7-9: Decision space diagrams for reliability at minimum flow for the whole year.

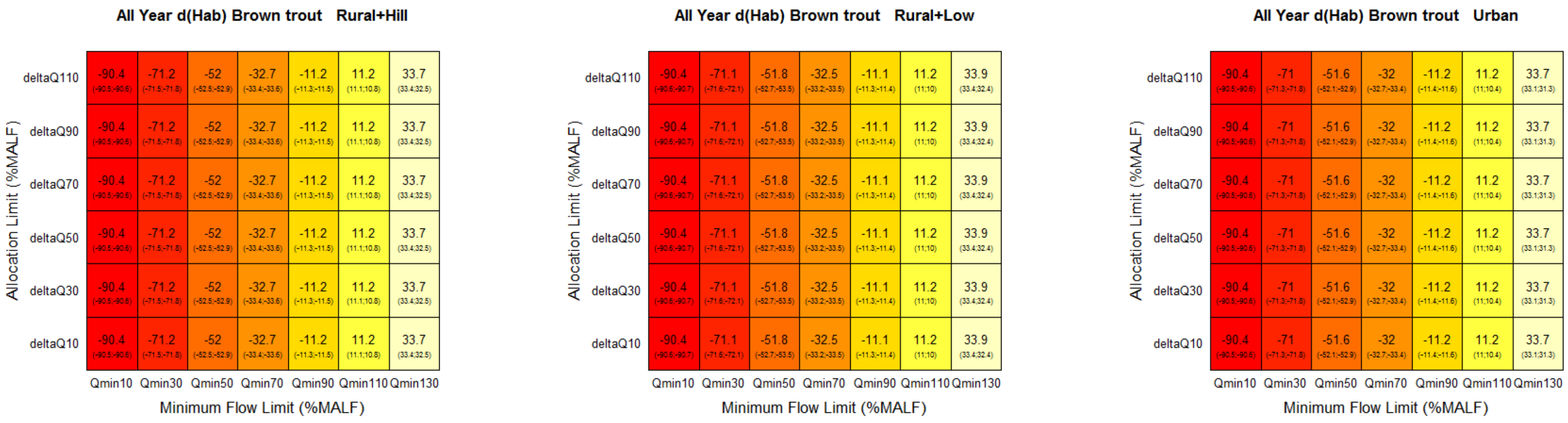

Figure A-7-10: Decision space diagrams for change in brown trout habitat for the whole year.

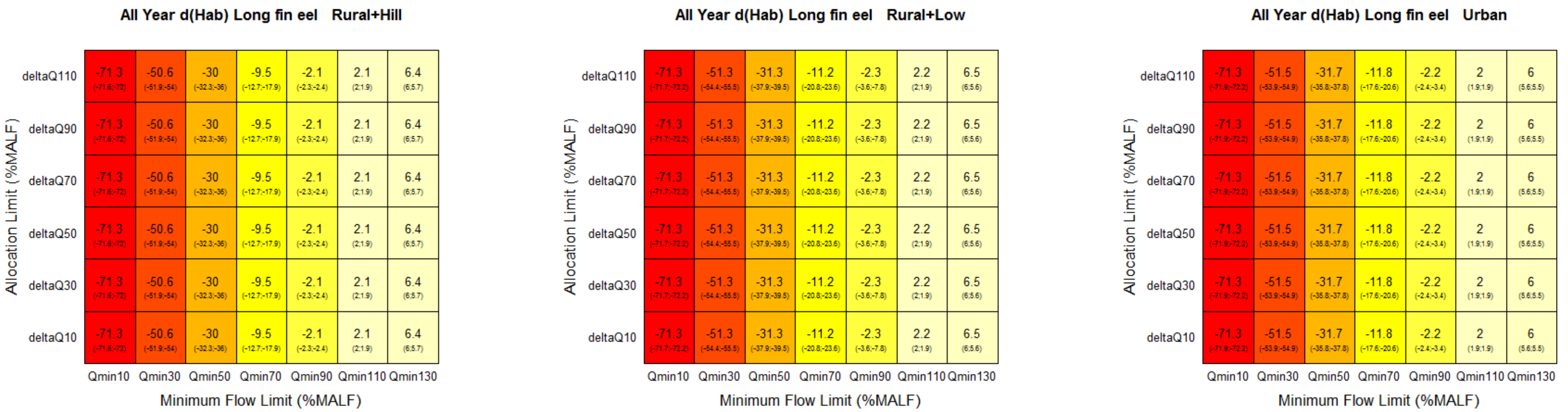

Figure A-7-11: Decision space diagrams for change in long fin eel habitat for the whole year.

Appendix D Random Forest Models of water quality

Data

Water quality data for between 53 and 58 state of environment monitoring sites across the entire Greater Wellington region were obtained for the current study. The water quality data consisted of monthly measurements of 9 physical, chemical, microbiological and invertebrate variables from river monitoring sites in council SOE networks and the NRWQN sites (Table 8). We took data for the period five years from 2009 to 2013 and computed the median values for all variables at each site and the 95^{th} percentile (Hazen method) for *Escherichia coli* (*E. coli*). These statistics became the response variables for the water quality models and are referred to hereafter as the water quality variables.

Table 8. River water quality variables, measurement units and site numbers used to develop Random Forest models.

Variable type	Variable	Abbreviation		Units	Number of monitoring sites
Physical	Visual clarity	CLAR	Median	m	58
	Suspended sediment	SS	Median	mg/m^3	53
Chemical	Ammoniacal nitrogen	NH4N	Median	mg/m^3	58
	Nitrate-nitrogen	NO3N	Median	mg/m^3	58
	Total nitrogen (unfiltered)	TN	Median	mg/m^3	58
	Dissolved reactive phosphorus	DRP	Median	mg/m^3	58
	Total phosphorus (unfiltered)	TP	Median	mg/m^3	58
Microbiological	*Escherichia coli*	ECOLI	Median	cfu/100 mL	58
	Escherichia coli	ECOLI95	95^{th} percentile	cfu/100 mL	58
Biotic Index	Macroinvertebrate Community Index	MCI	Median	unitless	56

Modelling methods

We related the water quality variables to a suite of environmental variables using random forests (RF), a type of non-parametric regression model (Breiman, 2001). RF is an ensemble machine learning method based on classification and regression trees. RF models have the advantage of being free from distributional assumptions and automatically fitting non-linear relationships and high-order interactions between variables. Although RF models cannot be described parametrically, the relationships between predictors and the response can be described (see below).

Potential predictors for the RF models were selected from data derived for a GIS representation of New Zealand's river network derived as part of the River Environment Classification (REC, version 2)(Snelder and Biggs, 2002). Predictors comprised variables representing catchment land cover derived from Version 2 of the New Zealand Land Cover Database (LCDB3) (MfE (Ministry for the Environment), 2004); variables developed as part of Freshwater Environments of New Zealand classification (FWENZ) (Leathwick *et al.*, 2011), and estimated mean flow (Woods *et al.*, 2006). Further details of the predictors are provided in (Unwin *et al.*, 2010).

An important feature of RF models is that each tree is grown with a bootstrap sample of the training data. During the fitting process, RF model predictions are made for each tree for the observations that were excluded from the bootstrap; the excluded observations are known as out-of-bag (OOB) observations. The predictions made to the OOB observations are independent from the training data and were used to evaluate the model's predictive performance. Model performance was assessed by comparing the OOB predictions to the observations using four statistics; regression r^2, Nash-Sutcliffe efficiency (NSE), bias and the root mean square error (RMSD). NSE indicates how closely the observations coincide with predictions (Nash and Sutcliffe, 1970). NSE values range from $-\infty$ to 1. An NSE of 1 corresponds to a perfect match between predictions and the observations, an NSE of 0 or less indicates that the model predictions are as accurate, or less accurate than the mean of the observed data respectively. We used the rule of thumb that model predictions are poor in NSE < 0.5, satisfactory if NSE > 0.50, and are good if 0.65 < NSE > 0.75, and excellent if NSE > 0.75 (Moriasi *et al.*, 2007). Bias measures the average tendency of the predicted values to be larger or smaller than the observed values. Optimal bias is zero, positive values indicate underestimation bias and negative values indicate overestimation bias (Piñeiro *et al.*, 2008).

RF models cannot be expressed parametrically but the relationships between predictor and response variables can be represented by importance measures and partial dependence plots (Breiman, 2001; Cutler et al., 2007). The importance of predictors is indicated by the degree to which predictive performance decreases when the predictor variable is randomly permuted. The Importance was defined in this study as the difference between the mean square error (MSE) for the original and permuted OOB data, averaged over all trees and normalized by the standard deviation of the differences (Cutler et al., 2007). Partial dependence plots (PDPs) were used to interpret the structure of the RF models. A PDP shows the marginal contribution of a predictor to a response variable and can be interpreted as an approximation of the fitted predictor-response relationships.

Model Performance

Independent predictions (i.e. the OOB predictions) of the water quality variables confirmed that the RF model represented the pattern in the Wellington region (Figure 7-12). NSE for the models ranged from 0.26 to more than 0.77, indicating poor to excellent performance. Performance was in the poor range (NSE < 0.5) for NH4N and SS. Performance was at least satisfactory for all other variables with NSE > 0.5 and no models having significant bias (i.e. bias was close to zero; Table 9).

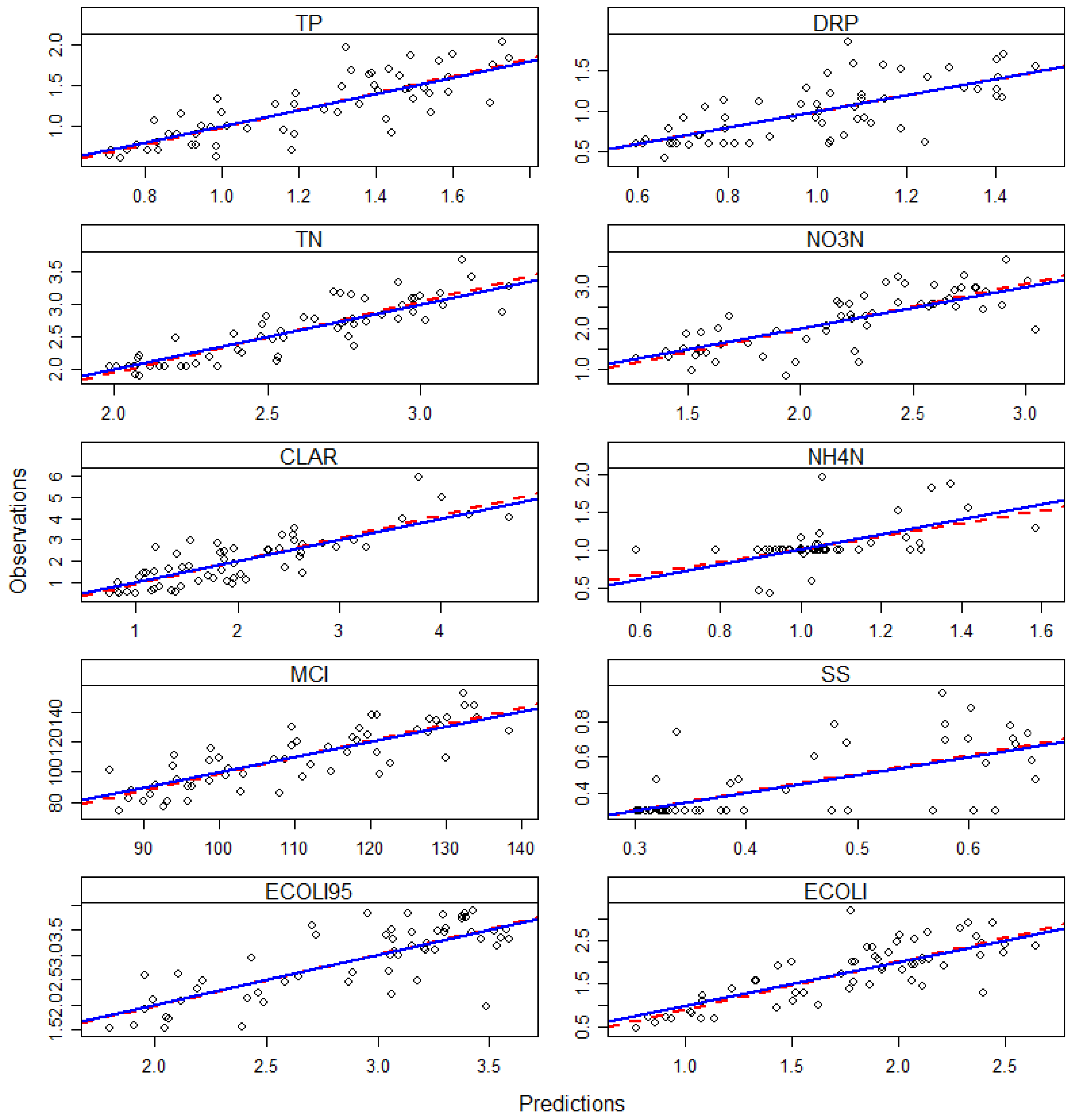

Figure 7-12. Performance of the water quality models. The plots show the observed median site values against the predicted values from the relevant models. The blue line is one to one and the red dashed line represents a regression of the observations versus the predictions.

Table 9 Details of the performance of regional water quality models for the SoE sites in the Wellington region. Where n *is the number of sites used to fit the model,* NSE *is Nash-Sutcliffe Efficiency,* RMSD *is root mean square deviation,* Bias *measures the average tendency of the predicted values to be larger or smaller than the observed.*

Variable	N	r^2	NSE	Bias	RMSD
CLAR	58	0.68	0.67	-0.01	0.68
TN	58	0.77	0.77	0	0.22
TP	58	0.67	0.67	0	0.23
NO3N	58	0.61	0.61	0	0.43
NH4N	58	0.27	0.26	0	0.22
DRP	58	0.49	0.50	0	0.25
ECOLI	58	0.64	0.64	0	0.41
SS	53	0.46	0.46	0.01	0.14
ECOLI95	58	0.61	0.61	0	0.44
MCI	56	0.69	0.68	-0.26	11.03

The predictor variables with high importance in all RF models reflected strong associations between water quality and land use and catchment topography. The three highest ranked predictors were usSlope (representing average catchment slope), usElev (representing average catchment elevation) and usIntensiveAg (representing the proportion of the catchment that is occupied by intensive agriculture land cover). Concentrations of all contaminants decreased with increasing values of usSlope and usElev (i.e. water quality as measured by these variables increased) and CLAR and MCI increased (i.e. water quality as measured by these variables increased). These associations with usIntensiveAg and topography are consistent with recent national scale evaluations of environmental patterns in river water quality (e.g. (Larned *et al.*, 2004, 2016).

The predictor usUrban represents the proportion of catchment occupied by urban land use. Concentrations of contaminants (e.g. ECOLI, ECOLI95, NO3N, TN and DRP increased as usUrban increased (particularly at low values) and MCI decreased. These associations with are consistent with recent national scale evaluations of environmental patterns in river water quality (e.g. (Larned *et al.*, 2004, 2016).

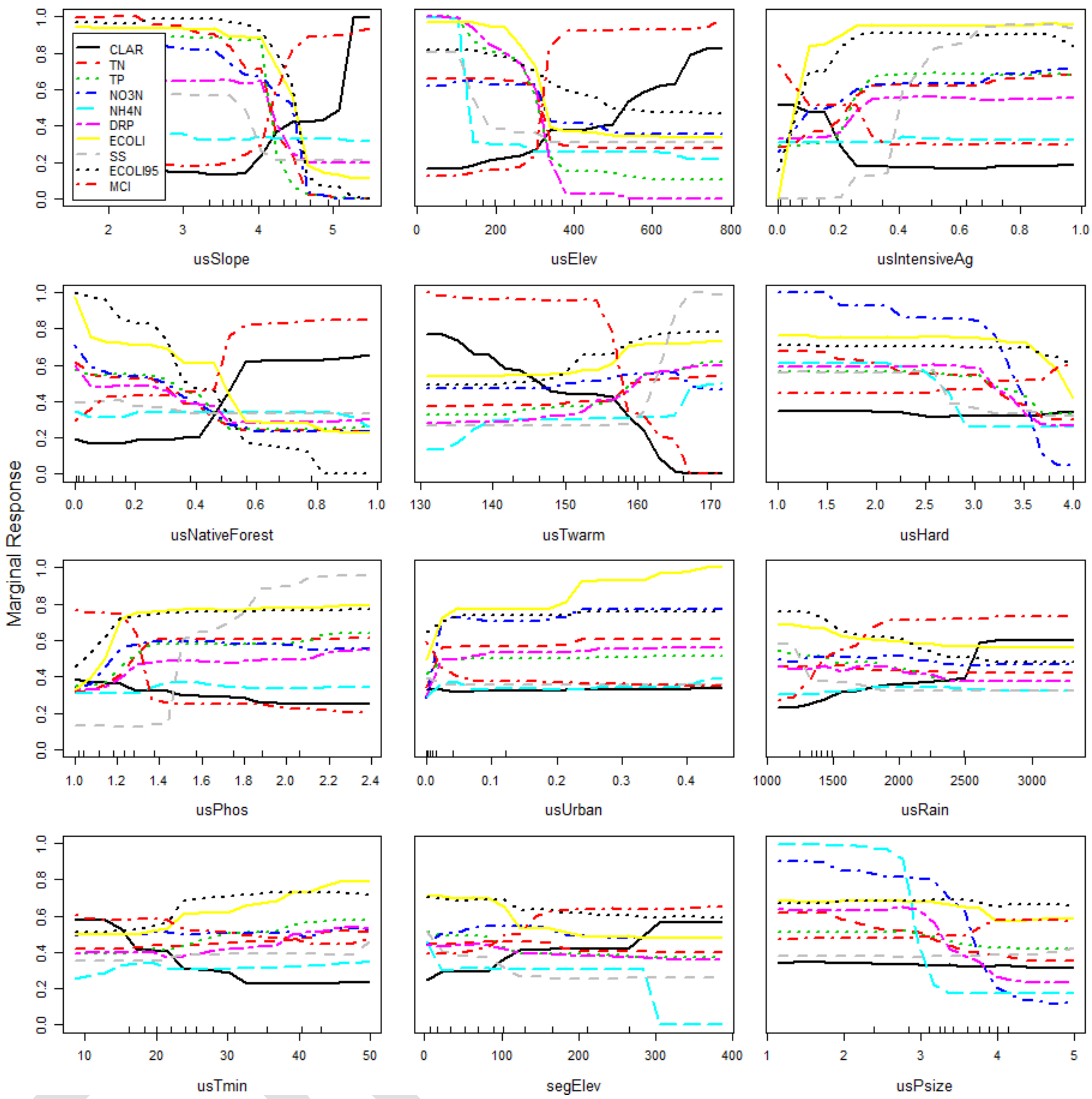

Figure 7-13. Partial dependence plots for the 12 overall most highly ranked predictors in the models. The Y-axis scale represents the standardised value of the marginal response where for each modelled variable the original marginal responses over all predictors were standardised to have a range between zero and one. The amplitudes of the plots (i.e. the range of the marginal response shown on the y-axis) is related to that variable's importance (amplitude is large when the variable has high importance).

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