Benthic cyanobacteria blooms in rivers in the Wellington Region

Findings from a decade of monitoring and research

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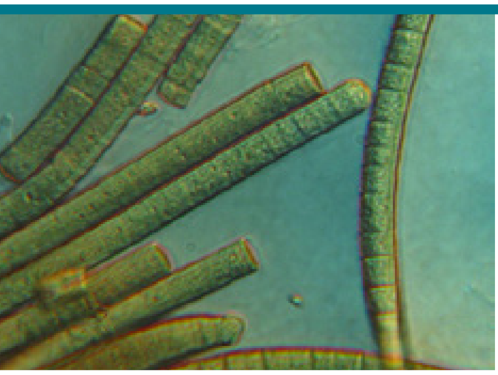
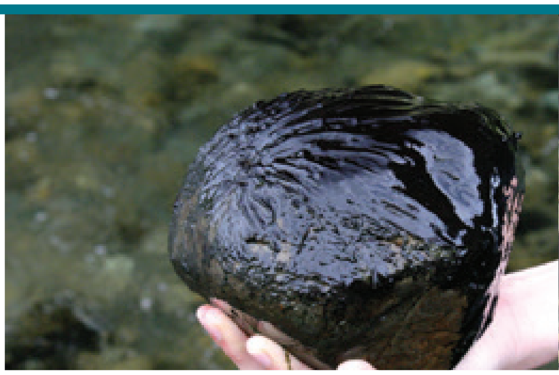

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Executive summary

Benthic cyanobacteria (commonly referred to as 'toxic algae') blooms are a frequent and widespread occurrence in many rivers and streams across the Wellington Region. The most widespread bloom-forming benthic cyanobacteria genus is *Phormidium*. In affected rivers, *Phormidium* can form expansive proliferations (blooms) of thick leathery black/brown mats across large areas of riverbed. Since 1999, at least 17 dogs have been reported to have died after coming into contact with *Phormidium*-dominated mats in the Wellington Region. Some *Phormidium* species can produce a range of powerful neurotoxins, known as anatoxins, resulting in concerns for the safety of recreational water users and drinking water supplies.

Following the death of five dogs linked to benthic cyanobacteria in the Hutt River in 2005/06, Greater Wellington Regional Council (GWRC) prepared a report documenting the blooms and likely causal factors. Before this initial report (and Hutt River dog deaths) benthic cyanobacteria in the Wellington Region were poorly understood and generally considered harmless. Following the recommendations of the 2006 report, cyanobacteria-specific monitoring and investigations commenced. This report consolidates the last 10 years of *Phormidium*-related monitoring and research undertaken in the Wellington Region.

An assessment of GWRC's Rivers State of the Environment (RSoE) and recreational water quality monitoring data confirmed *Phormidium* as the dominant bloom-forming cyanobacterium in the Wellington Region. The most frequent and expansive *Phormidium* blooms tended to occur in the larger, gravel-bed rivers in Kapiti, Hutt and central Wairarapa, with the Hutt and Waipoua rivers being particularly problematic. Anatoxins were detected in 59% (121) of all 223 *Phormidium*-dominated mats tested over the last decade from 28 different rivers and artificial lakes across the region.

Flushing flows were identified as the key variable regulating *Phormidium* abundance. However, it remains unclear how the length of the accrual (growth) period between flushing flows affects *Phormidium* growth. Longer accrual periods between large flushes (>9x median flow events) were associated with a greater magnitude of *Phormidium* growth. However, there was no relationship between *Phormidium* growth and accrual period length for smaller (and more generically used) >3x median flushing flow events. It is likely that the magnitude of flushing flow required to remove *Phormidium* from the riverbed varies greatly depending on the physical characteristics of each river, making it difficult to assess the relationship between flushing flow frequency and *Phormidium* growth. In the Hutt River, analysis of GWRC's long-term flow record at Taita Gorge (from 1979 to 2013) revealed that there has been no significant change in the annual frequency of flushing flows and average accrual period. While flushing flow frequency is likely to be an important driver of *Phormidium* growth in rivers where it occurs, it did not explain why some rivers in the Wellington Region experience *Phormidium* blooms and others do not.

Hutt River habitat suitability modelling showed *Phormidium* can grow in a wide range of flows and that water abstraction during summer low flows is unlikely to result in more suitable habitat for *Phormidium* growth. However, water abstraction during dry weather appears to reduce the capacity of the river to dilute nutrient inputs which may contribute to *Phormidium* bloom development.

Assessment of both annual and bloom-specific water column nutrient data suggests that *Phormidium* blooms under a wide range of nitrogen concentrations but generally only at low soluble phosphorus concentrations (<0.01 mg/L). Water column nutrient availability appears to be a strong driver of why *Phormidium* blooms occur in some rivers in the region and not others. However, it does not explain why *Phormidium* blooms occur in some rivers in one year but not the next. Future research investigating fine sediment availability, climatic variables (such as UV radiation levels) and flushing flow timing and magnitude may help to explain the year to year variability in *Phormidium* abundance.

In the Hutt River, water column nitrogen concentrations appear to be an important driver of *Phormidium* bloom development. The Pakuratahi and Mangaroa rivers as well as groundwater inputs upstream of Silverstream Bridge were identified as the largest sources of nitrogen to the Hutt River. During summer low-flows groundwater inputs were found to more than double the nitrogen loads in a 950 m reach between the Whakatikei River confluence and Taita Gorge. In this reach, groundwater samples collected from the riverbed had dissolved inorganic nitrogen (DIN) concentrations 10-fold higher than the overlying surface-water.

Management of catchment nitrogen sources in problematic rivers may help reduce *Phormidium* bloom occurrence and magnitude. This will be a challenge in the Hutt River catchment where DIN concentrations in the Hutt River are ‘low’ to ‘moderate’ (ranging between a median of 0.076 mg/L at Te Marua to 0.198 mg/L at Manor Park) and groundwater concentrations in the unconfined Upper Hutt aquifer are also relatively low at ~1 mg/L. Encouragingly, trend analysis on GWRC’s RSoE data between 2006 and 2015 showed DIN concentrations are already significantly decreasing at rates between 2.5 and 5.2% per year across most of the catchment. Further, age-dating of selected riverbed/groundwater samples revealed that the groundwater was between 2.3 and 2.8 years old. This suggests that the results from any management actions to reduce groundwater nutrient inputs are likely to be realised within a relatively short time period.

Although reducing water column phosphorus concentrations is unlikely to result in a reduction in *Phormidium* bloom occurrence, there is mounting evidence that phosphorus and other nutrients associated with sediment particles are an important driver of *Phormidium* blooms. This means well-developed *Phormidium* mats may not be reliant on the water column for nutrients and can essentially self-regulate their access to nutrients. This may in part help explain why *Phormidium* mats/blooms are found in low water column phosphorus concentrations yet can still form expansive blooms. If this is the case, then management of fine sediment and/or sediment-bound phosphorus entering large gravel-bed rivers may help to prevent bloom development. Further research is currently underway to quantify the importance of fine sediment in *Phormidium* bloom development.

A significant amount of knowledge about *Phormidium* blooms in the Wellington Region has been gained over the last decade, particularly in the Hutt River catchment. However, a number of knowledge gaps remain. One priority gap is improving our understanding of the relationship between fine sediment, nutrients (notably phosphorus but also micronutrients such as iron, potassium and zinc) and *Phormidium* bloom development. Other knowledge gaps and recommendations to address these are outlined in the body of this report. The knowledge gaps, coupled with spatial and temporal variability in both *Phormidium* growth and toxicity, necessitates the importance of ongoing risk communication and education initiatives to improve public awareness and river user safety.

Contents

1. Introduction

During the last decade, benthic cyanobacteria (commonly referred to as 'toxic algae') proliferations (blooms) have been a frequent and widespread occurrence in many of New Zealand's rivers and streams. The most widespread benthic cyanobacteria genus that forms blooms in New Zealand cobble bedded rivers is *Phormidium* (Heath et al. 2010; McAllister et al. 2016). In affected rivers, *Phormidium* can form expansive proliferations of thick leathery black/brown mats across large areas of riverbed. Several *Phormidium* species are known to produce natural toxins, known as cyanotoxins (Quibler et al. 2013). In the Wellington Region at least 17 dogs have been reported to have died after ingestion of cyanotoxin producing *Phormidium* mats. The presence of cyanotoxin producing *Phormidium* mats in rivers pose a risk to both animal and human health, particularly where they occur in rivers used for recreation or drinking water supply.

The first New Zealand recorded incidence of dog deaths as a result of benthic cyanobacteria occurred in the Waikanae River, where six dogs died during the summer of 1998/99 (Hamill 2001). The species of cyanobacteria was not confirmed but was almost certainly from the *Phormidium* genus. *Phormidium* was confirmed as being responsible for dog deaths in New Zealand, when in the summer of 2005/06 five dogs died after coming in contact with *Phormidium* mats in the Hutt River (Milne & Watts 2007; Wood et al. 2007). Since then, significant *Phormidium* blooms have been recorded across the Wellington Region in the Hutt, Mangaroa, Ruamahanga, Waipoua, Huangarua and Kopuaranga rivers. In response, specific monitoring of benthic cyanobacteria was incorporated into Greater Wellington Regional Council's (GWRC) Rivers State of the Environment (RSoE) and Recreational Water Quality (RWQ) monitoring programmes and a multi-agency risk communication strategy developed to inform river users of the risks associated with toxic algae.

In the 10 years since the first Hutt River dog deaths a significant amount of monitoring and multi-agency research has been undertaken in the Wellington Region to better understand *Phormidium* blooms and the environmental factors that contribute to them. This report presents a comprehensive analysis of the information gained from this monitoring and research.

1.1 Report purpose

This technical report has been prepared with the primary purpose of updating our knowledge of *Phormidium* blooms in the Wellington Region, in particular, the likely causal factors of bloom events.[1] It is intended that this knowledge will contribute to implementation of Method 10 (c and d) of GWRC's Proposed Natural Resources Management Plan (PNRP, GWRC 2015) that seeks to better understand the causes of bloom events. The report will also inform GWRC's current sub-regional (whaitua) community-led collaborative regional plan processes. These processes are being used to establish quantity

[1] The first technical report on benthic cyanobacteria blooms in rivers in the Wellington Region was prepared by Milne and Watts (2007); this report focussed largely on the 2005/06 Hutt River bloom event.

and quality limits for fresh waters across the region in accordance with the National Policy Statement for Freshwater Management (NPS-FM, MfE 2014a).

In assessing all relevant monitoring and investigation data collected to date, the report also provides an opportunity to identify further research priorities.

1.2 Report outline

This report comprises six sections:

- Section 2 provides a summary of benthic cyanobacteria blooms and their diversity, toxicity, and known causal factors.
- Section 3 examines the diversity, toxicity and abundance of benthic cyanobacteria in rivers across the Wellington Region. In addition, the relationship among key environmental drivers and benthic cyanobacteria abundance are investigated at a regional scale.
- Section 4 focusses on benthic *Phormidium* blooms in the Hutt River and presents various investigations and assessments relating to two key environmental drivers – river hydrology and nutrients.
- Section 5 discusses the key findings from Sections 2 to 4 and the implications for *Phormidium* bloom management. Future research priorities that will further our understanding of *Phormidium* blooms in the Wellington Region are also outlined.
- Section 6 presents overall conclusions and recommendations.

1.3 Terminology and abbreviations

A number of environmental variables, reference documents and organisations have been abbreviated in this report. Generally, the names are mentioned in full on their first use in each section. The principal acronyms used are listed in Table 1.1.

Table 1.1: List of main abbreviations used in this report

Abbreviation	Definition
Amm. N	Ammoniacal nitrogen
cf.	compare
DIN	Dissolved inorganic nitrogen (ie, the sum of NNN + Amm. N)
DRP	Dissolved reactive phosphorus
D/S	Downstream
GWRC	Greater Wellington Regional Council
LCDB	New Zealand Land Cover Database
MfE	Ministry for the Environment
MoH	Ministry of Health
NIWA	National Institute of Water and Atmospheric Research
NNN	Nitrate nitrite nitrogen
RSoE	Rivers State of the Environment
RWQ	Recreational water quality
TN	Total nitrogen
TOC	Total organic carbon
TP	Total phosphorus
UHCC	Upper Hutt City Council
U/S	Upstream
WWL	Wellington Water Ltd

2. Benthic cyanobacteria overview

2.1 What are cyanobacteria?

Cyanobacteria are an ancient group of photosynthetic organisms that have occupied the Earth for over 3.5 billion years (Schopf 2012). There are over 2,000 species described worldwide, occurring naturally in almost every conceivable environment ranging from desert soils to Antarctic melt ponds, freshwater to marine habitats, and oligotrophic (nutrient poor) to eutrophic (nutrient rich) waters (Whitton 2012). In freshwater environments, cyanobacteria can grow in the water column (planktonic), aggregated on the water surface (metaphytic), attached to other algae or macrophytes (epiphytic), or attached to substrates (eg, rocks) and in biofilms (benthic; Quiblier et al. 2014). In all these environments cyanobacteria perform important ecological functions (eg, nitrogen fixation and nutrient recycling) and provide food and habitat for a variety of aquatic invertebrates and other organisms (Biggs 2000).

2.2 Benthic cyanobacteria

In New Zealand rivers the dominant bloom-forming benthic cyanobacteria genus is *Phormidium*, a member of the Oscillatoriales order (Wood et al. 2007; Heath et al. 2010; Figures 2.1 a, b, and d-f). *Phormidium* blooms are primarily associated with river or stream environments where they form leathery dark brown or black mats, but they can also establish in lakes and ponds (Quiblier et al. 2014). Mats can also be red or green in appearance, particularly at shaded sites (Figure 2.1 b). *Phormidium* commonly produces distinctive musty/earthy odour compounds (geosmin and 2-methylisoborneol), a key diagnostic feature for distinguishing them from other types of algae in the field (Heath 2015).

In settled summer weather and stable river flows *Phormidium* cells can rapidly multiply, forming expansive blooms across the riverbed. During this rapid growth *Phormidium* mats are often covered in oxygen bubbles, the result of photosynthesis. These oxygen bubbles can become trapped under the mat matrix causing them to become buoyant. Thick well-developed mats and/or those with abundant oxygen bubbles can become detached from the river substrate forming ‘floating rafts’ and can accumulate as scums at river edges. When *Phormidium* mats die and dry out on the river margins they become light brown or white in colour.

Other genera of the Oscillatoriales, such as *Oscillatoria, Microcoleus* and *Lyngbya*, are also commonly observed in New Zealand rivers (Biggs & Kilroy 2000; Heath et al. 2010). However, these other Oscillatoriales genera do not commonly form blooms (greater than 20% cover; MfE/MoH 2009). Similarly, genera of benthic cyanobacteria from the Nostocales order, such as *Nostoc* (Figure 2.1c) and *Calthorix/Dichothrix* spp., are also commonly observed in low abundance in rivers and streams throughout New Zealand. These other cyanobacteria and their occurrence in Wellington rivers and streams are described in more detail in Section 3.

Figure 2.1: Photographs of cyanobacterial mats. a, *Phormidium* mat in the Hutt River at Silverstream. b, *Phormidium* mat in the Waipoua River opposite Bentley Street. c, *Nostoc* mat in the Wainuiomata River at Richard Prouse Park. d, *Phormidium* mat in the Hutt River at Birchville. e, ×400 micrograph of *Phormidium* sp. from Hutt River. f, *Phormidium* mats in the Hutt River at Silverstream

2.3 Benthic cyanobacteria toxin production

In New Zealand, *Phormidium* is the most common and widespread cyanotoxin producing benthic cyanobacteria genera and has been linked to over 100 dog deaths in the last decade (Wood et al. 2007; Heath et al. 2010; Wood et al. 2010a). *Phormidium* can produce a suite of lethal neurotoxins known as anatoxins. Anatoxin is a collective term used to describe four variants of neurotoxins; anatoxin-a (ATX), homoanatoxin-a (HTX), dihydroanatoxin-a (dhATX) and dihydrohomoanatoxin-a (dhHTX). Although all four variants are lethal neurotoxins, dhATX and dhHTX are thought to have an approximate ten-fold reduced toxicity in comparison to ATX and HTX (Bates & Rapoport 1979; Wonnacott et al. 1991). In a recent review, 67% (520) of 771 *Phormidium*-dominated mats samples collected from across New Zealand were found to contain anatoxins (McAllister et al. 2016). However, the concentration of all four variants is highly spatially and temporally variable (Wood et al. 2010b, 2012a, b; Heath et al. 2011, 2014) Anatoxins are powerful neuromuscular blocking agents that act through the nicotinic acetycholine receptor (Carmichael 1994). In affected animals, these neurotoxins cause convulsions, coma, rigors, cyanosis (discoloration of the skin due to poor circulation or inadequate oxygenation of the blood), limb twitching, hyper salivation and/or death. Scientific investigations of anatoxin-producing mats, from across the country, have identified *Phormidium autumnale* as the toxin producing species in New Zealand (Heath et al. 2010).

The only other benthic cyanobacterium documented to have caused an animal poisoning (a single dog death) in New Zealand and be formally identified, is a microcystin producing *Planktothrix* sp. isolated from the Waitaki River (Canterbury) in 2008 (Wood et al. 2010a). Microcystins are hepatotoxins that inhibit protein phosphatases causing liver necrosis and/or death. No *Planktothrix* blooms have been documented since this initial identification in the Waitaki River. However, it is possible that this species is mistaken for *Phormidium* in field studies as it has a very similar morphology (Heath 2009).

Nostoc commune and *Scytonema* cf. *cripsum* are the only other benthic cyanobacteria identified, to date, known to produce cyanotoxins in New Zealand. *Nostoc commune* was isolated from scum samples collected from the shores of Lake Taupo and identified to produce microcystins (Wood et al. 2012c). *Scytonema* cf. *cripsum* has been identified in a number of lakes in Canterbury and produces saxitoxins (Smith et al. 2011, 2012). Saxitoxins are lethal neurotoxins that act in the sodium channels of neurons, preventing normal cellular function and leading to paralysis. *Nostoc commune* and *Scytonema cf. cripsum* have not been linked with any animal poisonings to date.

2.4 Environmental drivers of benthic cyanobacteria blooms

Flow conditions, nutrient availability (in particular nitrogen and phosphorus), water temperature, light availability and invertebrate grazing have all been identified as the major environmental drivers of benthic cyanobacteria diversity and biomass in fresh waters (Scott & Marcarelli 2012). However, there is limited research that has investigated how these major drivers regulate benthic cyanobacteria blooms worldwide (Quiblier 2013).

In New Zealand, *Phormidium* blooms have received increasing scientific attention over the last decade. This research has identified flushing flows[2] as the main regulator of *Phormidium* blooms (Wood et al. 2007; Heath et al. 2010). The strong relationship between *Phormidium* abundance and accrual period (time between flushing flow events) has seen GWRC and some other regional councils use the number of days since the last flushing flow as an early warning indicator of bloom formation in troublesome rivers and streams (MfE/MoH 2009). Three times the yearly median flow has generally been used as an indicator of a flushing flow (Milne & Watts 2007). However, the magnitude of flow required to flush *Phormidium*-dominated mats has been

[2] This is the flow required to remove all visible periphyton from river substrate.

shown to vary greatly among rivers (Wood et al. 2014). In non-flushing flows, nutrients (particularly nitrogen and phosphorus), substrate stability, water velocity, mat dynamics, other micro-organisms and fine sediment all play an important role in *Phormidium* bloom formation (Heath 2015; Wood et al. 2015a, b; McAllister et al. 2016). However, the complex interactions among these factors are not fully understood. In Sections 3, 4 and 5 the current understanding of how these key environmental and ecological drivers interact and regulate *Phormidium* blooms is examined in greater detail.

3. Benthic cyanobacteria in the Wellington Region

This section examines the abundance, diversity, toxicity and environmental drivers of benthic cyanobacteria in Wellington rivers, through an analysis of monitoring data from GWRC's core river monitoring programmes.

3.1 Cyanobacteria presence and abundance

The presence of benthic cyanobacteria in rivers and streams in the Wellington Region is recorded primarily via two GWRC monitoring programmes; the Recreational Water Quality (RWQ) monitoring programme and the Rivers State of the Environment (RSoE) monitoring programme. Under the RWQ monitoring programme, periphyton cover is assessed on a weekly basis during summer months (mid-November until end of March) at 20 popular swimming sites throughout the region (Appendix 1). Under the RSoE programme, periphyton cover is assessed on a monthly basis year-round at 46 hard bottomed sites and measurements of periphyton biomass (measured as mg/m^2 of chlorophyll *a*) are made annually during summer/autumn.[3] Until 2014, annual assessment of the taxonomic composition of periphyton samples was also undertaken at RSoE sites. Periphyton taxa were identified and their relative abundance assessed on a scale of 1 (rare) to 8 (dominant). Taxonomic identification of periphyton samples was undertaken by the Cawthron Institute between 2004 and 2006 and by NIWA from 2007 until 2014.

Over the years, methods used to assess periphyton cover and composition as part of the RSoE and RWQ programmes have varied (Table 3.1), resulting in a number of different data sets with which to assess cyanobacterial presence and abundance. In this report, RSoE periphyton taxa data were used to identify which cyanobacteria species are present across the Wellington Region. Then, to assess the maximum benthic cyanobacterial abundance (ie, growth) at each monitoring site a combination of RSoE periphyton biomass, taxa and cover data and RWQ periphyton cover data was used. Benthic cyanobacterial abundance at each site was categorised into one of four categories; no significant growth, low, medium and high (Table 3.2). The relative abundance threshold of 5 or greater equates to cyanobacteria taxa being 'common' to 'dominant'. The biomass thresholds in Table 3.2 are based on those used in the national periphyton guidelines (Biggs 2000) while the cover thresholds align with the MfE/MoH (2009) interim guidelines for managing cyanobacteria in recreational fresh waters. Examination of data from sites where both biomass and cover data were available indicated that biomass and cover thresholds were roughly equivalent.

[3] 44 sites as of December 2015.

Table 3.1: Periphyton measures at RWQ and RSoE monitoring sites used to assess benthic cyanobacterial presence and abundance in the Wellington Region

Programme	Measure	Frequency	Data set length	Sampling method
Recreational water quality (RWQ)	Cyanobacterial mat cover >1mm thick (%)	Weekly during summer	December 2009–present	MfE and MoH (2009).
	Mat cover[1] >3mm thick (%)	Weekly during summer	November 2005 (Wairarapa sites) or November 2006 (Kapiti & Hutt sites)–present	2005–2009: Visual estimate at 10 points on a single transect (or 5 points on two transects) in run habitat using a 20 cm diameter hoop. 2009–present: Sampling procedure from MfE & MoH (2009) but assessing mat cover.
Rivers State of the Environment (RSoE)	Cyanobacterial mat cover >1mm thick (%)	Monthly year-round	July 2013–present	MfE and MoH (2009).
	Mat cover[1] >3mm thick (%)	Monthly year-round	June 2003–present	2003–2013: Visual estimate at 10 points on a single transect (or 5 points on two transects) in run habitat using a 20 cm diameter hoop. 2013–present: Sampling procedure from MfE & MoH (2009) but assessing mat cover.
	Periphyton biomass (mg/m^2 of chlorophyll *a*)	Annually during summer/ autumn	2004–present	Modified version of QM-1a, as outlined in Biggs and Kilroy (2000) involving pooling periphyton samples from 10 rocks in riffle habitat into a single composite sample. Samples are analysed for chlorophyll *a* concentration using the method outlined in Biggs and Kilroy (2000).
	Relative abundance of periphyton taxa (relative abundance scale is from 1 (rare) to 8 (dominant))	Annually during summer/ autumn	2004–2014	2004–2006: Additional sample collected using the method above for assessment of taxonomic composition. Samples are analysed for taxonomic composition using an inverted microscope at magnifications up to 400x. 2007–2014: Sub-sample removed from each biomass sample for assessment of taxonomic composition.

[1] Mat cover is generally dominated by cyanobacterial or diatom growth or a mixture of the two. Only RWQ mat cover data were used in the assessment of cyanobacteria abundance as these were generally accompanied by notes as to whether the mats present were cyanobacteria or not (ie, RSoE mat cover data lacked this information and were not able to be used).

Table 3.2: Periphyton taxa relative abundance, biomass and cover criteria used to categorise benthic cyanobacterial abundance at RSoE and RWQ monitoring sites

Benthic cyanobacterial abundance category	Criteria
No significant growth	Maximum cyanobacteria taxa relative abundance <5 and maximum cyanobacterial cover of 0%
Low	Maximum cyanobacteria taxa relative abundance ≥5 and periphyton biomass of <50 mg/m^2 or maximum cyanobacterial cover of 1–20%
Moderate	Maximum cyanobacteria taxa relative abundance ≥5 and periphyton biomass of 50–120 mg/m^2 or maximum cyanobacterial cover of 20–50%
High	Maximum cyanobacteria taxa relative abundance ≥5 and periphyton biomass of >120 mg/m^2 or maximum cyanobacterial cover of >50%

RSoE periphyton taxa data showed that cyanobacteria were present at all 46 RSoE sites, with 15 genera recorded in total (Table 3.3). The most common genera were *Phormidium* and *Heteroleibleinia*, followed by *Chaemaesiphon, Tolypothrix, Merismopedia, Oscillatoria, Leptolyngbya* and, to a much lesser extent, *Lyngbya*. However, there are some discrepancies in taxonomic identification of cyanobacteria between the two laboratories used to process the samples. For example, the genera *Tolypothrix* and *Dichothrix* were only identified in samples analysed by NIWA while *Chaemaesiphon* and *Leptolyngbya* were only identified in samples processed by Cawthron (Greenfield 2014). There was often uncertainty in the identification of cyanobacteria species with the cf. notation frequently used and in many cases the cyanobacteria taxa present were simply recorded as ‘blue-green algae’. The uncertainty in the identification of taxa likely reflects the ever-evolving cyanobacteria nomenclature and the difficulty in distinguishing different cyanobacteria genera based on morphology alone, especially members of the order Oscillatoriales (Heath et al. 2010).

Table 3.3: Cyanobacteria taxa and their maximum relative abundance recorded from annual (summer/autumn) periphyton samples taken at 46 RSoE monitoring sites between 2004 and 2014

Taxon	Number of times recorded	Maximum relative abundance	Known toxin producer?
Phormidium sp.	138	8	Yes
Heteroleibleinia sp.	97	8	No
cf. *Phormidium* sp.	90	8	Yes
cf. *Heteroleibleinia* sp.	44	4	No
Chamaesiphon sp.	40	5	No
cf.*Tolypothrix* sp.	27	6	No
Blue-green algae	21	8	Yes
cf. *Oscillatoria* sp.	21	5	Yes
Merismopedia	21	4	No
Oscillatoria sp.	19	4	Yes
Leptolyngbya sp.	14	5	Yes
Lyngbya sp.	14	8	Yes
Dichothrix sp.	8	3	No
Nostoc	8	2	Yes
cf. *Lyngbya* sp.	7	3	Yes
Pseudanabaena sp.	6	2	Yes
cf. *Nostoc*	5	2	Yes
Aphanocapsa sp.	2	1	No
Microcoleus sp.	2	8	Yes
Anabaena sp.	1	1	Yes
cf. *Leptolyngbya* sp.	1	4	Yes
cf. *Merismopedia* sp.	1	4	No
cf. *Pseudanabaena* sp.	1	1	Yes
Coleodesmium sp.	1	8	No
Nostocales	1	2	Yes

Maximum cyanobacterial abundance at 12 out of the 66 RSoE and RWQ sites monitored was categorised as ‘not significant’ (Figure 3.1). Sites in this category tended to be small streams such as the Whareroa Stream near Paekakariki or rivers in eastern Wairarapa such as the Awhea River. Although cyanobacteria were present at these sites, they only formed a small part of the periphyton community.

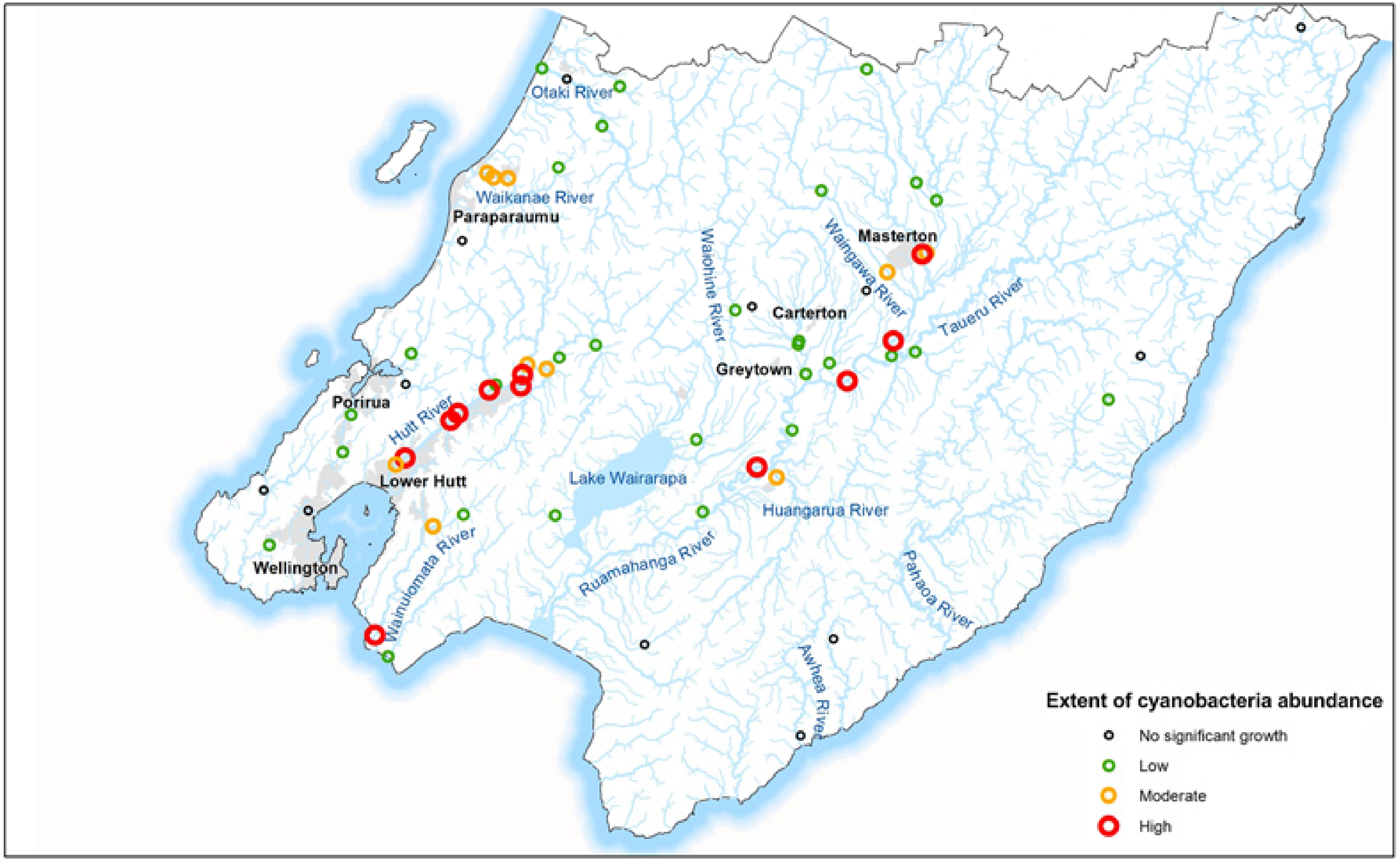

Figure 3.1: Extent of cyanobacterial abundance at river and stream sites in the Wellington Region, based on maximum cyanobacterial abundance (see Table 3.2) at GWRC RSoE and RWQ monitoring sites between 2004 and 2015

Thirty sites were categorised as having ‘low’ cyanobacterial abundance. Many of the sites in this category are located in the headwaters of larger rivers such the Waitohu, Otaki, Waikanae, Hutt, Ruamahanga and Waiohine rivers. Periphyton communities at these sites were sometimes dominated by the cyanobacteria taxa *Heteroleibleinia* or *Phormidium* but periphyton growth was not extensive.

Ten sites were categorised as having ‘moderate’ cyanobacterial abundance. The maximum cyanobacterial cover and biomass included in this category is equivalent to the alert threshold of the MfE/MoH (2009) guidelines and is considered a bloom. Sites in this category included those on the lower reaches of the Waikanae, Mangaroa, Akatarawa, Huangarua and Waingawa rivers and blooms were dominated by *Phormidium*.

Eleven sites were classified as having ‘high’ cyanobacterial abundance, including sites on the middle and lower reaches of the Hutt and Ruamahanga rivers and the lower reaches of the Wainuiomata and Waipoua rivers. Taxonomic relative abundance data from the two RSoE sites (Hutt River opposite Manor Park Golf Course and Wainuiomata River downstream of White Bridge) in this category as well as studies of benthic cyanobacterial blooms in the region (eg, Heath et al. 2011) indicate that blooms in these rivers are dominated by *Phormidium*. For this reason, cyanobacteria and *Phormidium* are used inter-changeably throughout the rest of the report.

With regard to sites with moderate or high maximum cyanobacterial abundance, weekly cyanobacterial cover assessments undertaken at RWQ sites over summers between 2009/10 and 2014/15 indicate that blooms occur most frequently at Ruamahanga River at Kokotau, Waipoua River at Colombo Road and Hutt River sites (Figure 3.2). A full list of cyanobacteria blooms (defined as >20% cover) recorded at both RWQ and RSoE sites is given in Appendix 2.

The Waipoua River at Colombo Road had the greatest number of blooms exceeding the alert threshold of the MfE/MoH (2009) guidelines. More than 20% cyanobacterial cover of the riverbed was recorded on 20 occasions at this site. Hutt River at Silverstream had the greatest number of exceedances of the action threshold. Cyanobacterial cover was greater than 50% of the riverbed on five occasions at this site.

Using a combination of periphyton mat (accompanied by comments confirming whether mats were cyanobacteria or not) and cyanobacterial cover data, the maximum cover of cyanobacteria each summer between 2005/06 and 2014/15 was identified for Hutt, Ruamahanga and Waipoua river sites (Figures 3.3 and 3.4). At Hutt River recreation sites (Figure 3.3) cyanobacterial cover greater than 50% of the riverbed was recorded on at least one occasion during the 2006/07, 2008/09, 2009/10, 2010/11 and 2011/12 summers. Generally these results were recorded at the Silverstream or Boulcott sites but during the summer of 2011/12 riverbed cover >50% was recorded at all sites apart from Melling Bridge. Cyanobacterial cover at Hutt River sites was considerably lower (<25%) during the summers of 2008/09, 2013/14 and 2014/15 than during other years.

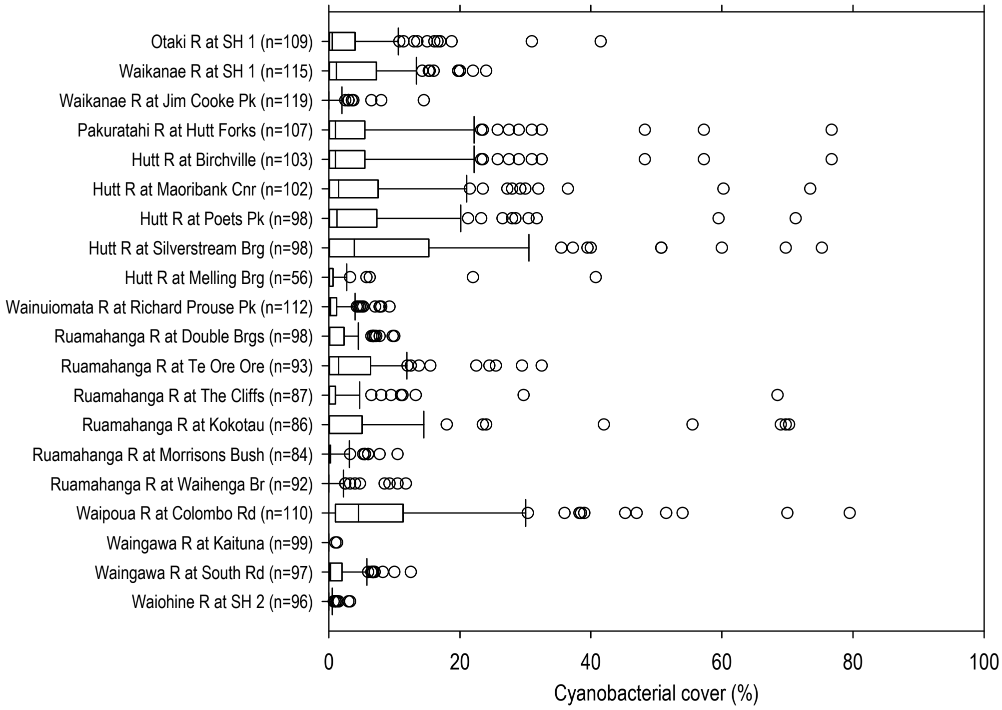

Figure 3.2: Box plots of weekly assessments of cyanobacterial cover at RWQ river sites during summer months between December 2009 and March 2015 where cyanobacteria was present. *n* = number of different assessments. Line inside box shows the median, box edges indicate 25th and 75th percentiles, whiskers extend to the last data point within the 90th percentile, and open circles are outliers

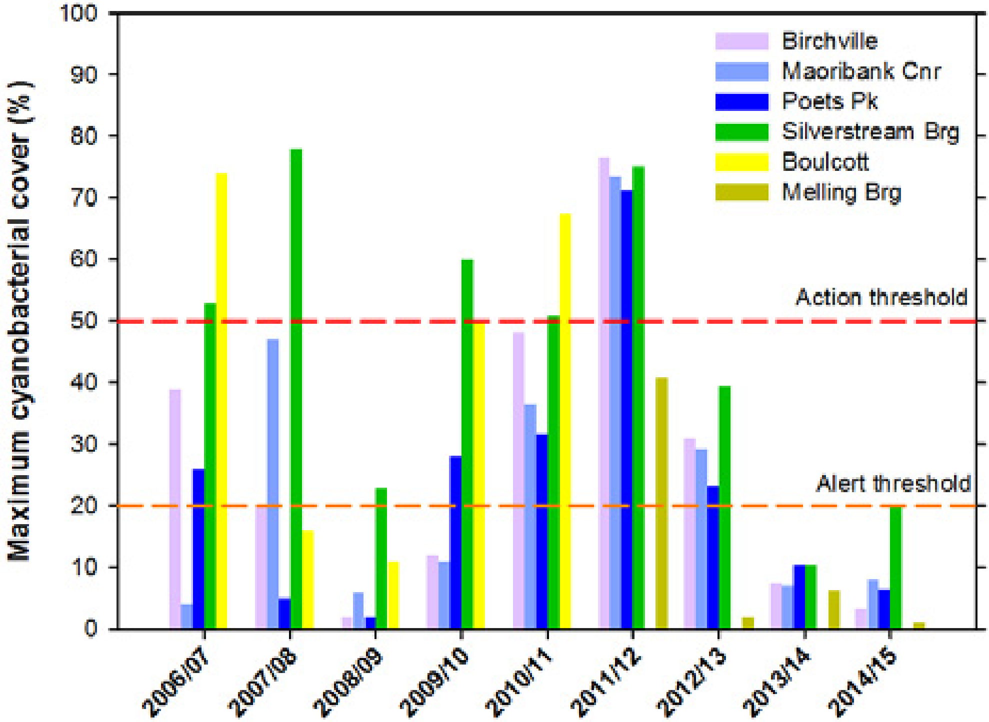

Figure 3.3: Maximum cyanobacterial cover recorded at Hutt River RWQ sites, based on weekly assessments during summer (November to March) bathing seasons between 2006/07 and 2014/15. Alert and action thresholds of the MfE/MoH (2009) interim guidelines for recreational fresh waters are shown

At Ruamahanga and Waipoua river recreation sites (Figure 3.4), cyanobacterial blooms that covered greater than 50% of the riverbed were recorded in the summers of 2006/07 and 2012/13. Cyanobacterial cover also exceeded this threshold in the Waipoua River at Colombo Road in 2011/12. The 2005/06, 2013/14 and 2014/15 summers had notably low maximum cyanobacterial cover at all Ruamahanga and Waipoua river sites.

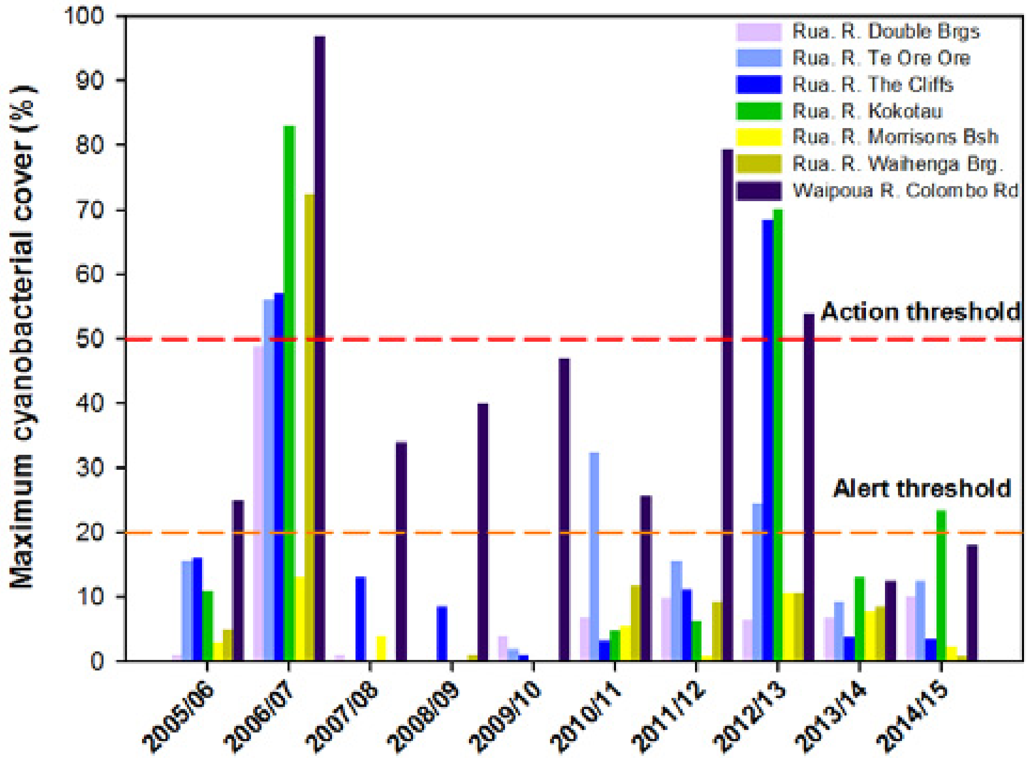

Figure 3.4: Maximum cyanobacterial cover recorded at Ruamahanga and Waipoua River RWQ sites based on weekly assessments during summer (November to March) bathing seasons between 2005/06 and 2014/15. Alert and action thresholds of the MfE/MoH (2009) interim guidelines for recreational fresh waters are shown

There are no clear spatial or temporal trends in *Phormidium* bloom occurrence based on monitoring data collected between 2005/06 and 2014/15. It is not possible to assess whether there have been any longer term trends in the occurrence of *Phormidium* blooms as monitoring of cyanobacteria mats only began in 2005/06 after investigations found *Phormidium* to be responsible for dog deaths in the Hutt River (Milne & Watts 2007). As a result it is unclear whether the large number of reported dog deaths associated with *Phormidium* blooms in recent years is the result of an increase in the frequency and/or toxicity of blooms or whether *Phormidium*-related dog deaths occurred previously but went unreported and bloom occurrence has remained constant. It is possible that a combination of both scenarios has occurred.

3.2 Cyanotoxin occurrence and variability

There is no routine monitoring of cyanobacterial blooms in the Wellington Region for cyanotoxin occurrence and concentration. However, toxin testing is occasionally undertaken by GWRC to provide further support for abundance (cover) based health risk assessments at popular recreation sites such as the Hutt River at Silverstream and the Waipoua River at Colombo Road (eg, Milne & Watts 2007). A large amount of cyanotoxin testing has also been undertaken in the Wellington Region as part of research by the Cawthron Institute and Victoria University of Wellington (Wood et al. 2010b, c; Heath et al. 2011). This testing has tended to focus on the Hutt and Waipoua rivers. Our records indicate there have been at least 223 toxin tests of predominantly *Phormidium*-dominated mat samples collected from 28 lake, river and stream sites across the region in the last decade (Figure 3.5; Table 3.4). Although planktonic cyanobacteria species are a greater problem in lakes and ponds, benthic cyanobacteria also exist in these lentic environments (Wood et al. 2012c, 2016). All cyanotoxin tests have been conducted at the Cawthron Institute using liquid chromatography-mass spectrometry.

Of the 223 cyanobacterial mat samples analysed, 59% (131) contained anatoxins. Anatoxins were detected on at least one occasion at 25 of the 28 lake, river and stream sites (Figure 3.5; Table 3.4). Henley Lake (Masterton), the Avalon Duck Pond (Lower Hutt) and the Mangatarere Stream at SH2 (Carterton) were the only sites where anatoxins were not detected. All three sites, however, were only sampled on one occasion and in the cases of Henley Lake and the Avalon Duck Pond only one sample was tested. None of the other known cyanotoxins (microcystin, cylindrospermopsin, nodularin and saxitoxin) were detected in any of the samples collected.

Morphological and molecular analysis of anatoxin-producing benthic cyanobacterial mats from the Wellington Region over the last decade has identified *Phormidium autumnale* as the causative cyanobacterium (Wood et al. 2007; Heath et al. 2010; Wood et al. 2012a). No other cyanobacteria species have been identified that produce anatoxins.[4]

At ten of the sites both anatoxin and non-anatoxin producing cyanobacterial mats were detected. These sites tended to be those that had been sampled on multiple occasions (≥ 5) such as the Mangaroa River at Te Marua and Akatarawa River at Hutt confluence (Table 3.4). These results support recent research that has demonstrated anatoxin presence is spatially and temporally variable in *Phormidium*-dominated mats due to the fact that not all strains of *Ph. autumnale* are capable of producing anatoxins (Heath et al. 2010; Wood et al. 2012a). Moreover, within a single 1 cm^2 mat both anatoxin producing and non-anatoxin producing strains of *Ph. autumnale* can co-exist (Wood et al. 2012a). Thus, the spatial and temporal variability observed in anatoxin occurrence and concentrations can, in part, be explained by the proportion of toxic and non-toxic strains and the toxin producing capabilities of those toxin strains. Currently, there is limited knowledge of the environmental drivers that regulate toxin production. Investigations examining water temperature and anatoxin production have revealed that *Phormidium* spp. can produce anatoxins across a wide range of temperatures (Heath & Wood 2010; Heath et al. 2011).

[4] Benthic cyanobacteria other than *Phormidium autumnale* have been found to produce anatoxins in other countries; ie, *Phormidium favosum* in France (Gugger et al. 2005).

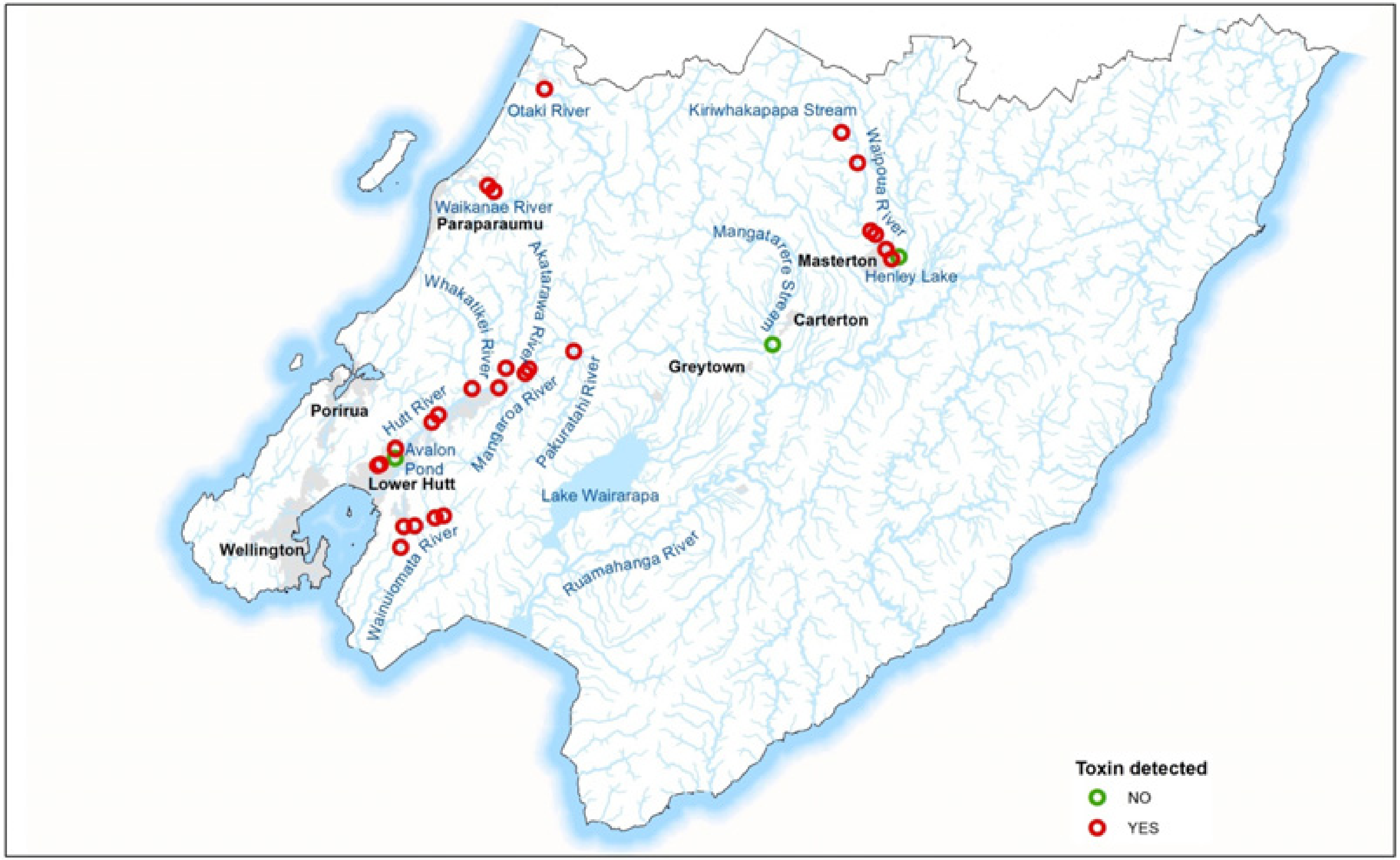

Figure 3.5: Location of lake, river and stream sites in the Wellington Region where anatoxin testing of benthic cyanobacteria mats is known to have been undertaken

Table 3.4: Summary of known cyanotoxin tests undertaken on benthic cyanobacterial mats from different lake, river and stream sites in the Wellington Region since 2005. Note multiple samples were collected for toxin analysis on some sampling occasions

Site	Number of cyanotoxin samples	Number of sampling occasions	Number of toxic samples
Akatarawa R at Hutt confluence	18	18	2
Avalon Duck Pond	1	1	0
Hutt R 500m u/s of Silverstream Br	26	4	19
Hutt R at Totara Br	1	1	1
Hutt R at Boulcott	17	17	12
Hutt R at Manor Pk	14	14	8
Hutt R at Melling Br	3	1	1
Hutt R at Silverstream Br	4	2	4
Hutt R at Te Marua	8	8	4
Mangaroa R at Te Marua	32	18	11
Pakuratahi R at Waterworks Rd	5	1	5
Whakatikei R at Riverstone	10	10	3
Wainuiomata R at Richard Prouse Pk	6	2	2
Wainuiomata R at Black Stm	1	1	1
Wainuiomata R at Landfill	1	1	1
Wainuiomata R at Water Treatment Plant	1	1	1
Wainuiomata R at Manuka Track	7	7	4
Henley Lake	1	1	0
Waipoua R 200m d/s of Paierau Rd	1	1	1
Waipoua R 200m u/s of Paierau Rd	17	2	17
Waipoua R at Colombo Rd	7	2	7
Waipoua R at Mikimiki	1	1	1
Waipoua R opposite Bentley St	16	3	16
Kiriwhakapapa S at Kiriwhakapapa Rd	3	1	3
Mangatarere S at SH2	15	1	0
Otaki R at SH1	1	1	1
Waikanae R at Water Treatment Plant	1	1	1
Waikanae R at SH1	5	1	5

All four anatoxin variants have been detected in the Wellington Region, however, their presence and concentration are spatially and temporally variable. Dihydroanatoxin-a was the most commonly detected anatoxin covariant; it was present in 39% of the benthic cyanobacterial mat samples in which it was tested. Anatoxin-a was only detected in 10% of the mat samples it was tested in, the least of any of the variants. Homoanotoxin-a and dhHTX were detected in 34 and 24% of mat samples they were tested in, respectively.

The highest total anatoxin concentration (the sum of ATX, HTX, dhATX and dhHTX) recorded from a single sample was 620 mg/kg (freeze dried samples only[5]) from a *Phormidium* mat collected from the Mangaroa River at Te Marua on 13 February 2008 (Figure 3.6). At this concentration a 20 kg dog would only require approximately 6.45[6] grams of cyanobacterial mat (dry weight) to receive a lethal dose (assuming dogs have an equivalent susceptibility to anatoxins as mice and based on toxicity data derived using intraperitoneal injection). Total anatoxin concentrations above 400 mg/kg have also been observed at the Waipoua River downstream of Paierau Road, the Waipoua River opposite Bentley Street and the Hutt River at Boulcott (Figure 3.6).

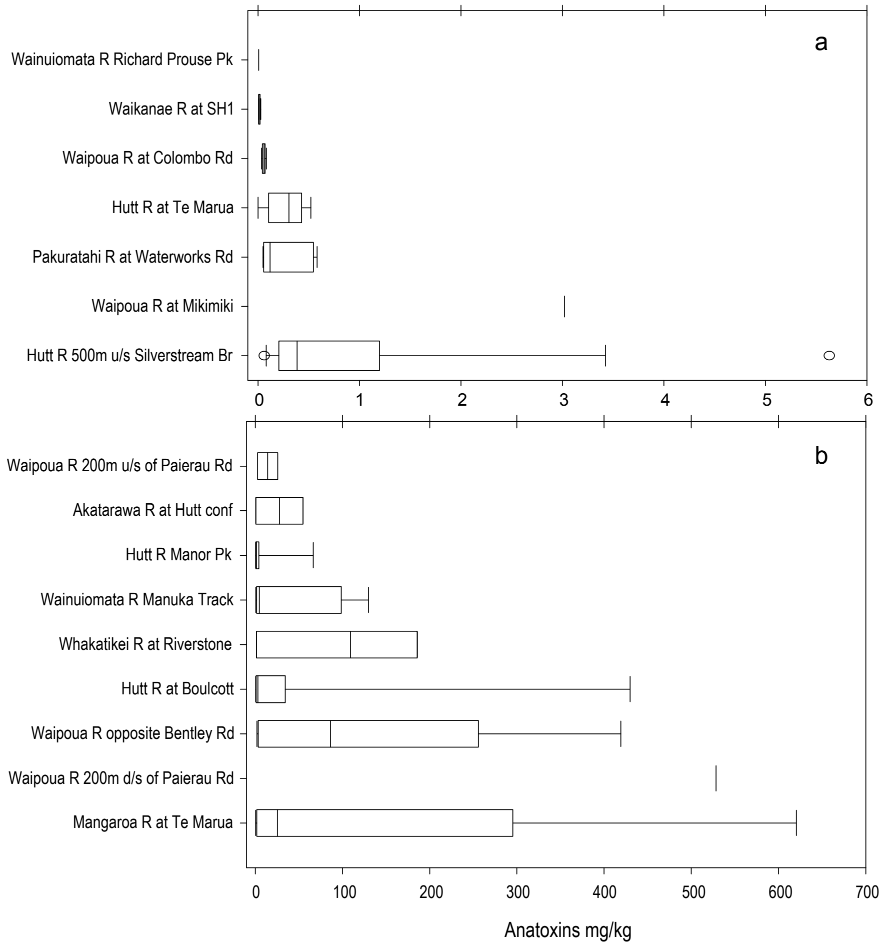

Figure 3.6: Box-plots of total anatoxin concentration (dry weight samples only) in *Phormidium*-dominated mats from 16 river sites in the Wellington Region (*n*=88). Toxins are expressed as mg/kg of dried weight. a) Sites where the maximum concentration is greater than 10 mg/kg, and b) sites where the maximum concentration is less than 10 mg/kg (note the different scale to a). Line inside box shows the median, box edges indicate the 25th and 75th percentiles, 'whiskers' extend to the last data point within the 10th and 90th percentiles, and open circles are outliers

5 Following animal poisonings or during blooms events cyanobacterial mats are sometimes collected by GWRC for anatoxin testing. This testing has been primarily undertaken using LC-MS at the Cawthron Institute. Whenever mat samples are tested by a commercial laboratory, results are reported as toxin concentration in mat (ie, an amount of toxin per kilogram of wet weight). *Phormidium*-dominated mats can vary depending on the mat composition and desiccation status when sampled. This makes comparison of historical datasets of this type challenging. To overcome the problems associated with varying quantities of water in mats, samples for research are freeze dried prior to analysis. In this section we considered freeze dried samples only.

6 6.45 grams assumes that the entire sample comprised a combination of ATX and HTX which has an approximate 10-fold higher toxicity that dhATX and dhHTX.

Cyanotoxin testing is almost always conducted on cyanobacterial mats rather than the surrounding water. However, in the summer of 2008/09 a water sample collected from the Waipoua River opposite Bentley Street was tested and found to have a homoanatoxin-a concentration (0.0085 mg/L) above the provisional Maximum Acceptable Value (0.002 mg/L) given in the Drinking-water Standards for New Zealand (MoH 2008; Wood et al. 2010c). Wood et al. (2010c) also detected low concentrations of extracellular (toxin released by cells into water column) anatoxins in the water column at the Waipoua River opposite Bentley Street using solid phase adsorption tracking technology (a special filter that binds anatoxins). Extracellular anatoxins in the water column are of considerable concern to recreation users and drinking water supplies because people and animals could get sick from swallowing river water. The extent and health risks of extracellular anatoxins in the water column during expansive benthic cyanobacterial blooms are largely unknown and require further investigation.

In the Wellington Region there have been at least 17 dog deaths attributed to anatoxin producing benthic cyanobacteria (Table 3.5). The first report of dog deaths in the region (and nationwide) from anatoxin producing benthic cyanobacteria occurred in 1998 when five dogs died at Edgewood Park near the Waikanae River (Hamill 2001). Since then, a further 12 dog deaths have been reported in the Wellington Region (Milne & Wyatt 2006; Wood et al. 2007; Ryan & Warr 2008; Ryan & Warr 2010; Morar & Warr 2011; Morar & Greenfield 2012). Dogs appear to be particularly susceptible to anatoxin poisoning as they tend to be attracted to the distinct deep earthy odour produced by benthic cyanobacterial mats that have become detached from the riverbed and accumulate at the river's edge. An autopsy found a large amount of *Phormidium*-dominated mats in the stomach contents of one of the dogs that died at the Hutt River in the 2005/06 summer (Wood et al. 2007). In 2008/09, stomach pains in a child were reported after swimming in the Kiriwhakapapa Stream (a tributary of the Waipoua River), which had *Phormidium* blooms with high levels of anatoxins (Warr 2009).

Table 3.5: Confirmed/known dog deaths and human illness linked to toxic benthic cyanobacterial blooms in the Wellington Region

Summer	River	Total dog deaths/human illness
1998/99	Waikanae River	5 dog deaths near Edgewood Park
2005/06	Hutt River	5 dog deaths in Boulcott and Avalon area
2007/08	Hutt River	3 dog deaths, 2 near Belmont School and one near Silverstream
2008/09	Kiriwhakapapa Stream	1 human illness
2009/10	Waipoua River	1 dog death near Bentley Street
2010/11	Hutt River	1 dog death near Melling Bridge
2011/12	Hutt River	2 dog deaths, 1 near Heretaunga Park and 1 between Melling and Ewen bridges

3.3 The role of flow in regulating benthic cyanobacteria

3.3.1 Flushing flows

Benthic cyanobacteria mats, like all periphyton growth, are removed from river substrate in elevated flows that cause increased shear stress and abrasion by mobilised sediments and substrate. These flows are known as ‘flushing flows’ and their frequency is a key variable regulating *Phormidium* abundance. Generally, the less frequent flushing flows are, the more abundant *Phormidium* will be (Heath et al. 2011). A flow three times the median has been widely used to represent a flushing flow (Clausen & Biggs 1997; Milne & Watts 2007). However, *Phormidium* blooms covering greater than 20% of the riverbed, as well as other periphyton species, can persist in much higher flows (Wood & Young 2012b; Wood et al. 2014). The flow required to remove *Phormidium* mats from the riverbed is thought to vary depending on a number of factors including substrate size, river/stream order and stage of mat development (Wood et al. 2014).

The time between flushing flows is called the accrual period and is a commonly used measurement to assess the susceptibility of rivers to periphyton growth. At RSoE sites the annual average accrual period between three times median flushing flow events ranges from 13 days at Ruamahanga River at McLays (which has its headwaters in the upper Tararua Range) to 49 days at Parkvale Stream at Weir (a spring-fed stream in the Wairarapa Valley; Appendix 3; Thompson & Gordon 2011). The annual average maximum accrual period ranges between 38 days at Ruamahanga at McLays to 180 days at Taueru River at Gladstone which has its catchment in the eastern Wairarapa hill country.

To assess the relationship between annual accrual statistics and *Phormidium* abundance, annual average accrual periods associated with RSoE sites in each cyanobacteria abundance category identified in Table 3.2 were compared using Kruskall-Wallis one-way ANOVA. There was no significant difference in the accrual periods experienced by sites in the four abundance categories (Figure 3.7). However, the median annual average accrual period at RSoE sites in the ‘no significant growth’ category was higher than that for the three other categories. Sites in this abundance category tend to be small lowland streams such as the Makara and Pauatahanui streams near Wellington or eastern Wairarapa streams or rivers such as the Awhea River and Motuwaireka Stream. Comparison of annual average maximum accrual periods across cyanobacteria abundance categories showed a similar pattern to that shown by average accrual periods.

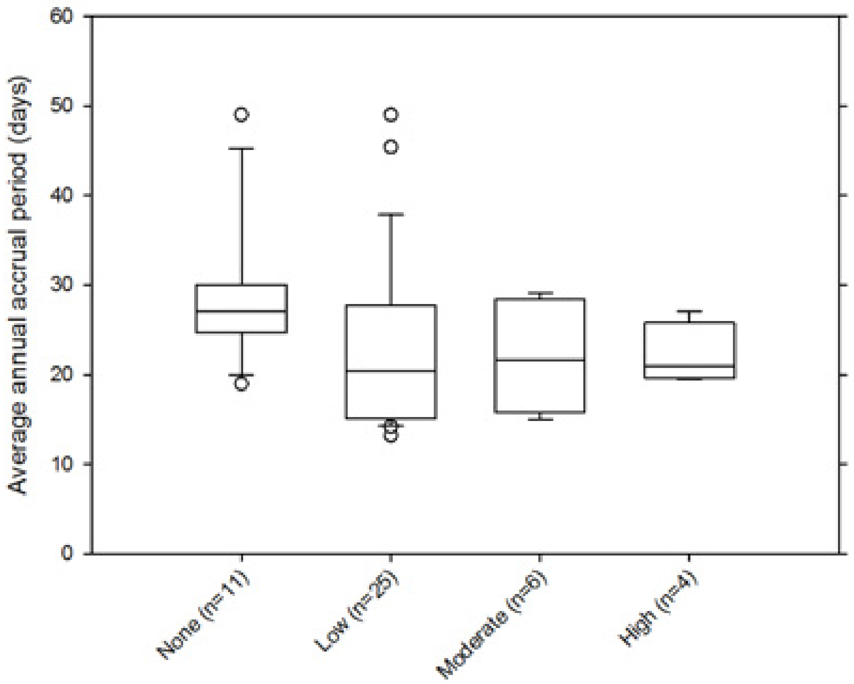

Figure 3.7: Box plot of average annual accrual period in days at RSoE sites categorised by maximum cyanobacteria abundance. Refer Table 3.2 for abundance category information. Line inside box shows median, box edges indicate the 25th and 75th percentiles, 'whiskers' extend to the last data point within the 10^{th} and 90th percentiles, and open circles are outliers

In order to assess accrual periods associated with the specific cyanobacteria bloom events recorded at RWQ and RSoE sites the time since the last flushing flow (based on mean daily flow) was identified for each bloom event. Two different sizes of flushing flows were used; three times (3x) median and nine times (9x) median. As mentioned earlier a >3x median flow event has been widely used to represent the flow at which periphyton are removed from the riverbed (Clausen & Biggs 1997). However, several studies (eg, Wood et al. 2014) have found that a larger flow magnitude is required to remove *Phormidium*-dominated mats in some rivers and for this reason a >9x median flow event has also been used. Cyanobacteria blooms were arbitrarily divided into four cover categories ranging between the MfE/MoH (2009) alert (20%) and action (>50%) cover guidelines and a Kruskall-Wallis one-way ANOVA was used to test whether there was a significant difference in the number of days since the last flushing flow between cover categories.

There was no significant difference in the number of days since the last >3x median flushing flow between cyanobacteria bloom categories (Figure 3.8). The minimum number of days since the last >3x median flushing flow associated with cyanobacteria blooms ranged from one day for the 20–29% cover category to 10 days from the >50% category, while the maximum accrual period ranged from 41 days for the >50% category to 75 days for the 40–49% category. For flushing flows >9x median, cyanobacteria blooms of 50% cover or higher were associated with a significantly ($p<0.05$) greater number of days since the last flushing flow than blooms in the 20–29% cover category. There were no significant differences between the number of days since the >9x median flushing between any *Phormidium* bloom categories.

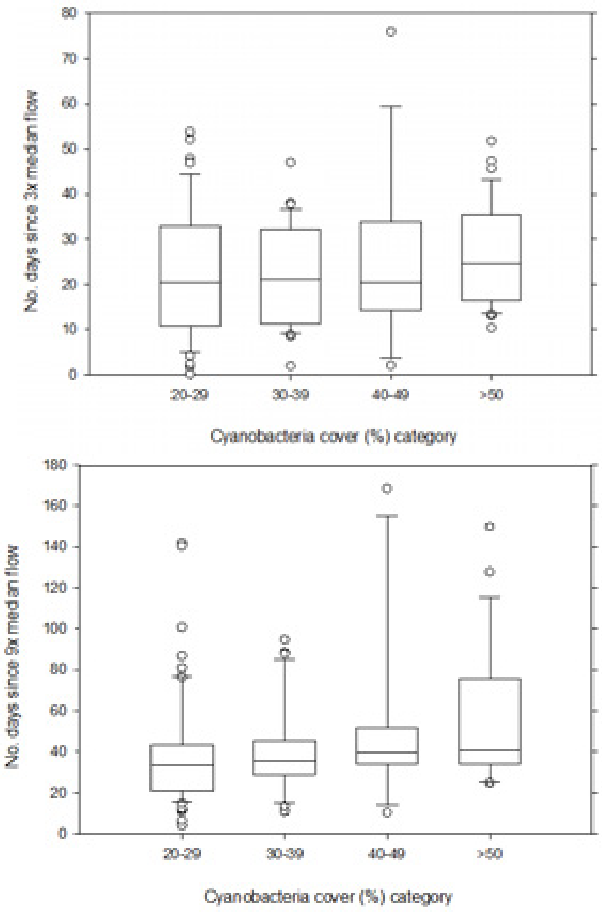

Figure 3.8: Number of days since last flushing flow associated with *Phormidium* blooms recorded at GWRC RWQ and RSoE monitoring sites between 2005 and 2015. Blooms are divided into cover categories and two flushing flow magnitudes are shown; >3x median and >9x median. Line inside box shows the median, box edges indicate 25th and 75th percentiles, whiskers extend to the last data point within the 10th and 90th percentiles, and open circles are outliers. Note the different scales of the *y*-axes

The role of flushing flow frequency in year to year differences in maximum *Phormidium* cover at RWQ monitoring sites (shown in Figures 3.3 and 3.4) over the summer period was assessed for Hutt River at Silverstream, Ruamahanga River at Waihenga and Waipoua River at Colombo Road between 2005/06 and 2014/15. Time between both >3x median and >9x median flushing flows was assessed using a five-day filter period (ie, if two flushes occurred within five days of each other they were counted as one). Based on these data the maximum accrual period for the two flushing flow magnitudes was identified for each site over each summer period.

For the Hutt River at Silverstream, the longest time between flushing flows occurred during the 2014/15 summer when maximum accrual periods of 89 and 102 days were recorded for >3x median and >9x median flushes, respectively (Figure 3.9). In contrast the shortest accrual periods occurred during the 2009/10 and 2011/12 summers. Comparing these results with the Hutt River *Phormidium* cover results shown in Figure 3.3 suggests that the frequency of flushing flows at Silverstream is not a key driver of year to year variability in maximum *Phormidium* cover as years where the longest accrual periods occurred were sometimes associated with low *Phormidium* cover and vice versa.

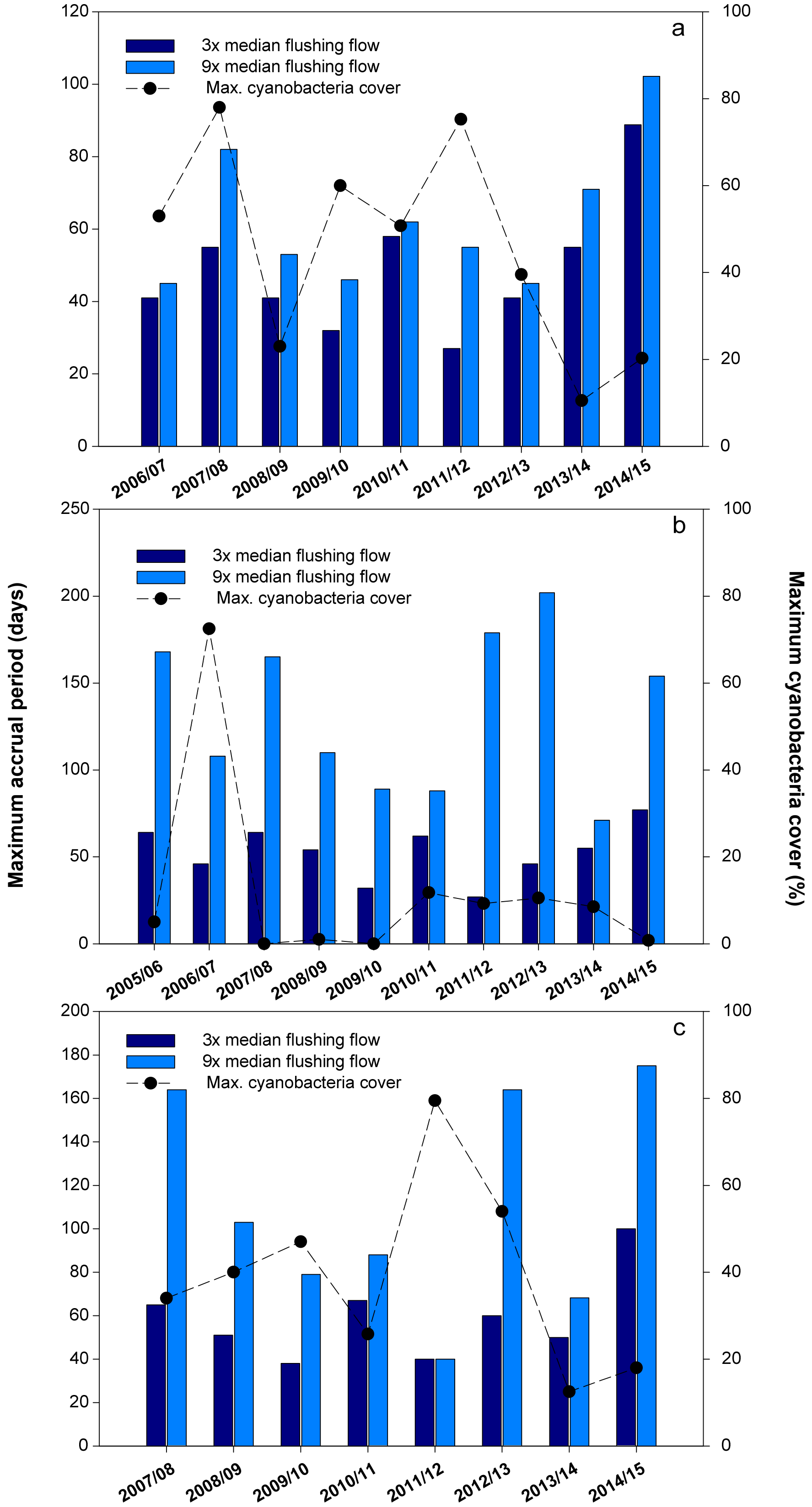

Figure 3.9: Duration of maximum summer time (November to March) accrual periods for two flushing flow magnitudes (>3x median and >9x median) at the (a) Hutt River at Silverstream, (b) Ruamahanga River at Waihenga and (c) Waipoua River at Colombo Rd between 2005/06 and 2014/15. Maximum cyanobacteria cover is also shown

Similar results were apparent for the Ruamahanga and Waipoua rivers where there appeared to be little relationship between the maximum time between flushing flows and maximum cyanobacteria cover from summer to summer.

3.3.2 Low flow

During low or stable flows, water velocity can have a marked effect on *Phormidium* blooms. In low river velocities *Phormidium* abundance and habitat availability can be reduced (Heath et al. 2012, 2015; McAlister 2015). Heath et al. (2015) showed that *Phormidium* mat cover in the Hutt River was reduced in point velocities (velocity directly above the rock) less than 0.5 m/s and optimal velocity for the *Phormidium* mats was between 0.6 and 1.1 m/s. *Phormidium* mats were able to withstand velocities greater than 2 m/s attached to stable cobble and bolder substrates. This suggests that *Phormidium* growth is likely to be greater in faster flowing run and riffle habitat than pool habitat. This may relate to the relationship between flow and nutrients (nutrient flux); ie, if water column nutrients are low, a faster flow rate may be required for sufficient nutrient up-take. Alternatively, *Phormidium* may have a competitive advantage over other algal species in elevated velocities.

3.4 The role of nutrients

3.4.1 Nutrients in the water column

Following the dog deaths that occurred as a result of contact with *Phormidium* blooms in the Hutt River in 2005/06, several studies have investigated the relationships between water column nutrient concentrations and *Phormidium* abundance. These studies have focussed on nitrogen and phosphorus and have generally demonstrated that while *Phormidium* blooms can occur across a range of nitrogen concentrations, they are usually only associated with low phosphorus concentrations (Heath et al. 2011; Wood & Young 2012; Wood et al. 2015b; McAllister 2015).

In a study of 12 rivers in the Manawatu-Wanganui Region *Phormidium* blooms usually only occurred when dissolved reactive phosphorus (DRP) water column concentrations were less than 0.01 mg/L (Wood & Young 2012). A DRP concentration of less than 0.01 mg/L has also been associated with *Phormidium* bloom formation in Canterbury rivers (McAllister 2015). These two recent studies support more coarse regional observations which have linked *Phormidium* blooms with low phosphorus concentrations over the last five years (Wood & Young 2012; Wood et al. 2014; Heath et al. 2011; Heath et al. 2015). The ability to form blooms when water column phosphorus is low indicates that *Phormidium* has a competitive advantage over other algal species in these conditions.

Phormidium strains found in New Zealand rivers do not possess the genes required to fix atmospheric nitrogen, an attribute that allows some cyanobacteria species to flourish under low nitrogen concentrations (Heath 2015). *Phormidium* blooms in New Zealand rivers have generally been associated with an annual or summer-time median water column dissolved inorganic nitrogen (DIN) concentration of 0.1 mg/L or greater (Wood & Young 2012; Wood et al. 2014; Heath 2015). Further to this, in their study of *Phormidium* blooms in the Manawatu-Wanganui Region Wood et al. (2014) identified that during the accrual period a DIN concentration greater than 0.2 mg/L was needed for bloom formation. In contrast, *Phormidium* blooms have been observed at DIN concentrations well below 0.1 mg/L in the Maitai River (Nelson), Tokomaru River (Manawatu) and rivers in Canterbury (McAllister 2015; Wood et al. 2015b). Furthermore, in Canterbury rivers *Phormidium* blooms were not observed in water column DIN concentrations >2 mg/L (McAllister 2015).

Phormidium-dominated mats are complex microbial environments containing a range of bacteria, fungi and other microbes from many functional groups and with varying metabolic capabilities (Bolhuis & Stal 2011; Stal 2012). Extracellular polymeric substances produced by mat-forming *Phormidium* forms the matrix in which various microorganisms are embedded (Bolhuis & Stal 2011). Multiple bacteria genera capable of nitrogen-fixing have been identified to inhabit *Phormidium* mats (Brasell et al. 2014) and these may provide a nitrogen source to *Phormidium* mats. This may help to explain why *Phormidium* blooms in some rivers can occur in low DIN concentrations.

To assess the water column nutrient concentrations associated with *Phormidium* mat occurrence in the Wellington Region, median concentrations of DIN and DRP were calculated for RSoE periphyton monitoring sites (nutrient data are not routinely collected at RWQ sites) using monthly data collected between July 2010 and June 2015. RSoE sites that fell into the 'moderate' or 'high' cyanobacteria abundance categories from Table 3.2 had median DRP concentrations between 0.002 and 0.011 mg/L and median DIN concentrations between 0.06 and 0.68 mg/L (Figure 3.10). This is similar to the range of nutrient concentrations associated with *Phormidium* blooms in other parts of the country.

Sites in the 'no significant growth' or 'low' cyanobacteria occurrence categories had median DRP and DIN concentrations across the range of those measured in the Wellington Region. However, only two sites in these categories, Whakatikei River at Riverstone and Pakuratahi River downstream of Farm Creek, had median nutrient concentrations within the range generally associated with *Phormidium* blooms in other parts of the country (ie, DRP concentrations <0.01 mg/L or DIN concentrations >0.1 mg/L). Both of these sites fall into the 'low' cyanobacteria occurrence category.

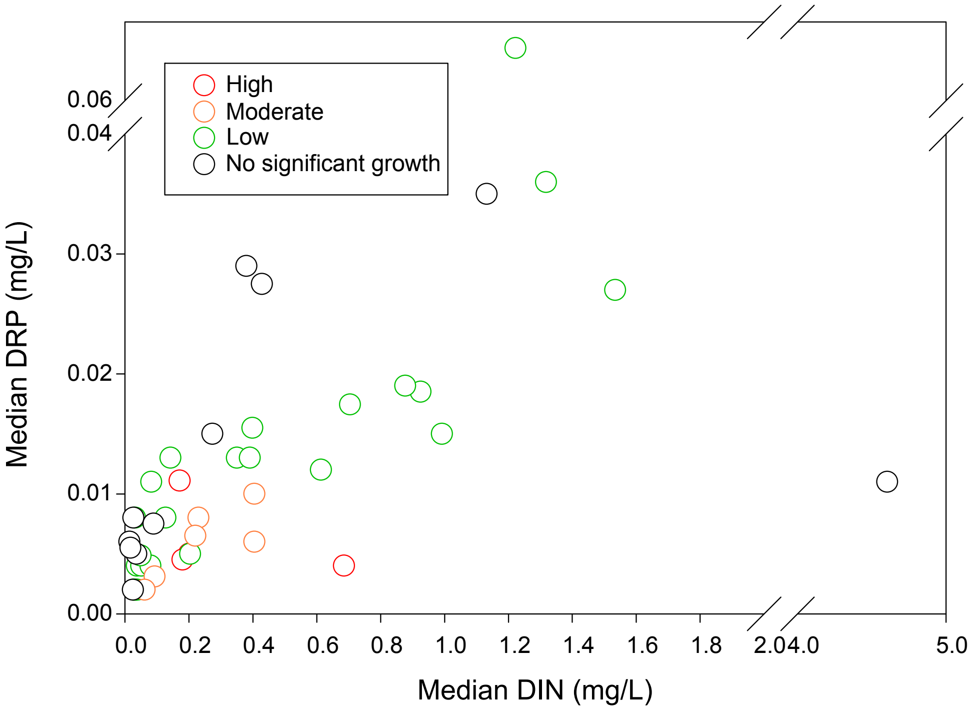

Figure 3.10: Scatter plot of median water column dissolved inorganic nitrogen (DIN) and dissolved reactive phosphorus (DRP) concentrations at RSoE monitoring sites based on results from monthly samples collected between July 2010 and June 2015. Sites are colour coded according to the cyanobacteria abundance category assigned in Section 3.1. Note the axes breaks at 2 mg/L DIN and 0.04 mg/L DRP

In order to assess water column nutrient concentrations associated with the specific cyanobacteria bloom events listed in Appendix 2, DIN and DRP results from samples collected during each bloom accrual period (in this case the time to the preceding >9x median flow event) were extracted from GWRC's Hilltop database. Nutrient data are not routinely collected at RWQ sites so this analysis could not be undertaken at all sites where *Phormidium* blooms have been recorded. However, four RWQ sites are also RSoE sites while at another four sites nutrient data from nearby RSoE sites were used as a proxy (Table 3.6). For Hutt River RWQ sites at Birchville and Silverstream, nutrient data collected by Wellington Water to monitor the effect of consented water abstraction from the Hutt River at the Kaitoke Weir for municipal water supply were used. As part of this monitoring, water samples have been collected for nutrient analysis on a fortnightly basis between November and April since 2011.[7] In total, accrual period nutrient data were available for 91 *Phormidium* bloom events at 14 different sites. For all sites, nutrient concentrations below the detection limit were set at half the analytical detection limit. Where more than one sample was taken over the course of the accrual period, nutrient results were averaged to give a mean accrual period concentration.

[7] Note that between November 2011 and November 2012 nitrite-nitrogen was not tested so DIN concentrations have been calculated as the sum of nitrate-nitrogen and ammoniacal-nitrogen concentrations only. Monitoring post-November 2012 has confirmed that nitrite-nitrogen concentrations are consistently below analytical detection limits (as expected in a highly oxygenated river).

Table 3.6: RWQ and RSoE monitoring sites for which nutrient data are available for assessment of *Phormidium* bloom accrual period nutrient concentrations

Site name (bloom location)	Site type	Nutrient monitoring site and location
Waikanae R at Jim Cooke Pk	RWQ	Waikanae R at Greenaway Rd, 1.2 km d/s
Waikanae R at Greenaway Rd	RSoE	Waikanae R at Greenaway Rd
Akatarawa R at Hutt Confluence	RSoE	Akatarawa R at Hutt Confluence
Hutt R at Birchville	RWQ	Water Supply consent monitoring site Hutt R d/s Akatarawa Confluence
Hutt R at Silverstream Br	RWQ	Hutt R opposite Manor Pk Golf Club (1.4 km d/s) and Silverstream Bridge water supply consent monitoring site
Hutt R opposite Manor Pk Golf Club	RSoE	Hutt R opposite Manor Park Golf Club
Hutt R at Boulcott	RWQ & RSoE	Hutt R at Boulcott
Hutt R at Melling Br	RWQ	Hutt R at Boulcott, 1.4 km u/s
Mangaroa R at Te Marua	RSoE	Mangaroa R at Te Marua
Wainuiomata R d/s of White Br	RSoE	Wainuiomata River d/s of White Br
Ruamahanga R at Te Ore Ore	RWQ & RSoE	Ruamahanga R at Te Ore Ore
Ruamahanga R at The Cliffs	RWQ	Ruamahanga R at Gladstone Br, 2.2 km d/s
Waipoua R at Colombo Rd Br	RWQ & RSoE	Waipoua R at Colombo Rd Br
Waingawa R at South Rd	RWQ & RSoE	Waingawa R at South Rd

Based on the assessed data, mean DIN concentrations recorded during the accrual period associated with *Phormidium* blooms in Wellington rivers ranged from 0.05 mg/L at Hutt River at Birchville during a bloom in February 2012 to 1.66 mg/L at Waipoua River at Colombo Road during a bloom in January 2008 (Figure 3.11). Mean accrual period DRP concentrations ranged from below detection at many sites to 0.04 mg/L at Ruamahanga River at the Cliffs during a bloom in February and March 2007.

These results suggest that water column nutrient conditions associated with *Phormidium* blooms in the Wellington Region are similar to those observed in other rivers in New Zealand. At all but one site, blooms occurred at water column DRP concentrations of 0.01 mg/L or less. The exception was Ruamahanga River at the Cliffs where three *Phormidium* blooms coincided with DRP concentrations between 0.027 and 0.045 mg/L. Ruamahanga River at the Cliffs is approximately 8 km below the discharge of treated wastewater (ie, a significant source of nutrients) from the township of Masterton to the Ruamahanga River. Woods et al. (2014) also observed *Phormidium* blooms at DRP concentrations >0.01 mg/L at two sites downstream of treated wastewater discharges in the Manawatu Region (Manawatu River downstream of the Palmerston North City Council's wastewater treatment plant discharge (WWTP) and Oroua River downstream of the Fielding WWTP discharge).

Similar to Canterbury rivers, blooms in Wellington's rivers occur over a wide range of DIN concentrations, including concentrations well below 0.1 mg/L.

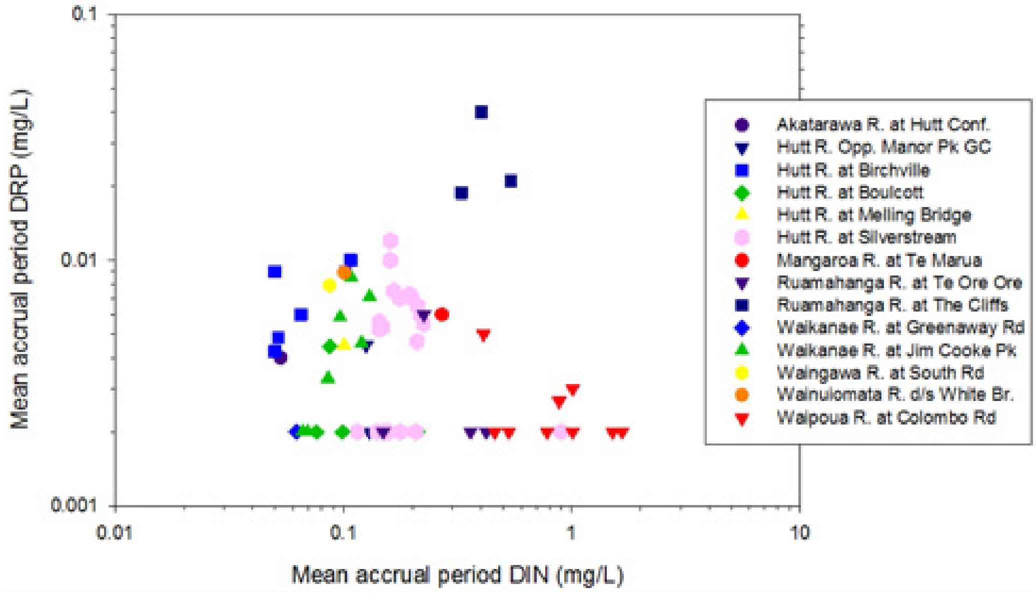

Figure 3.11: Mean DIN and DRP concentrations measured during the accrual period (based on 9x median flushing flow) associated with *Phormidium* blooms (>20% cover) recorded at RWQ and RSoE monitoring sites between 2005 and 2015. Note the log scale on both axes

To assess whether differences in DIN concentration explain year to year variation in *Phormidium* cover, maximum *Phormidium* cover recorded at RWQ monitoring sites (Figures 3.3 and 3.4) was compared to median summer-time DIN concentrations at nearby RSoE sites. Data from four RSoE sites were used, one each on the Hutt and Waipoua rivers, and two on the Ruamahanga River. The median summer-time DIN concentration was calculated for each site based on data collected between November and March from 2005/06 to 2014/15.

In the Hutt River opposite Manor Park Golf Club median summer-time DIN concentrations were highest during 2010/11 and lowest during 2009/10 and 2013/14 (Figure 3.12). Although, maximum *Phormidium* cover (as shown in Figure 3.3) was relatively high at Hutt River at Silverstream (located a short distance upstream of Hutt River opposite Manor Park Golf Club) in 2010/11 and low in 2013/14, maximum cover was high during 2009/10 suggesting no clear link between year to year variability in DIN concentrations and *Phormidium* cover. Similarly, for Waipoua and Ruamahanga rivers there was no clear relationship between median DIN concentration and maximum *Phormidium* cover shown in Figure 3.4.

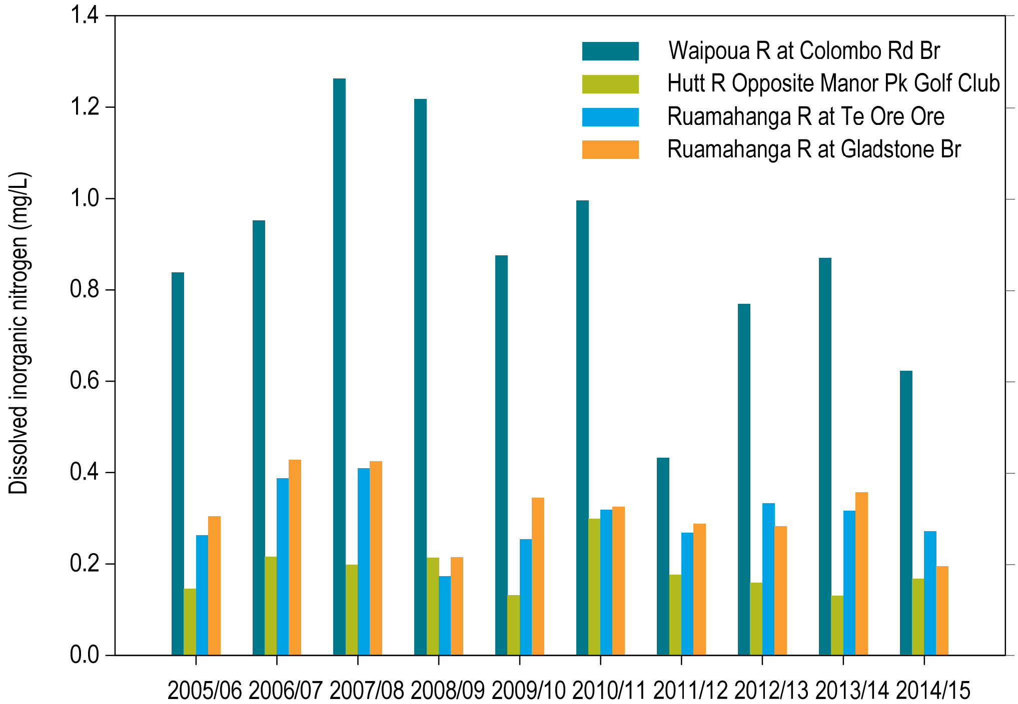

Figure 3.12: Median DIN concentrations measured during monthly sampling over the summer (November to March inclusive) at selected Hutt, Waipoua and Ruamahanga river RSoE sites between 2005/06 and 2014/15

3.4.2 Nutrients in deposited sediment

A feature of *Phormidium* mats in New Zealand rivers is a fine layer of sediment that is commonly observed on the underside of well-developed mats (Heath 2009). Fine sediment from the water column can become trapped to the sticky extracellular polymeric substances (EPS) surface of mats. Motile *Phormidium* filaments can quickly incorporate trapped particles into the mat matrix. Recent research has demonstrated that the biochemical conditions within *Phormidium* mats can be substantially altered during daily photosynthesis. These conditions include increased pH (>9) through the reduction of bicarbonate and reduced dissolved oxygen (<4 mg/L) through nightly respiration (Wood et al. 2015). Such conditions are known to be conducive to the release of phosphorus bound to fine sediment trapped in the mat matrix (Heath 2015). In the Mangatainoka River in Manawatu, water collected from within well-developed *Phormidium* mats had a DRP concentration 320-fold higher than the overlying water column (Wood et al. 2015a). Thus, the ability to facilitate phosphorus release from fine sediment is believed to be a key reason why *Phormidium* can bloom and out-compete other algal species when water column phosphorus concentrations are low. Green algal species, such as *Cladophora*, are also capable of creating conditions conducive to the release of phosphorus bound to fine sediment trapped in the mat matrix (Hamill 2013). However, the growth form and physiology of *Phormidium* mats (leathery like mats, see Figure 2.1) means that they are likely to be more effective at using this mechanism to out-compete other algal species in low nutrient conditions.

Fine sediments trapped in well-developed mats do not explain how *Phormidium* acquires phosphorus before a mat has developed. Many cyanobacteria are able to store phosphates (Kromkamp 1987), which enable them to perform two to four cell divisions, comparable to a 4–32 fold increase in biomass (Mur et al. 1999). This storage capacity may enable *Phormidium* blooms to maximise 'luxury' phosphorus uptake (ie, phosphorus uptake beyond what is required for normal metabolism) during episodic pulses in bio-available phosphorus. The physiological ability to store phosphorus may enable enough growth for a mat to form and fine sediment to accumulate.

3.5 Summary

- A range of benthic cyanobacteria species are present in rivers in the Wellington Region but only *Phormidium* is associated with blooms – some of which are toxic. This is consistent with what has been observed in other parts of New Zealand.

- Cyanobacteria occur in virtually all rivers in the region but *Phormidium* blooms tend to be limited to larger, gravel-bed rivers in Kapiti, Hutt and central Wairarapa. No *Phormidium* blooms have been recorded in rivers along the eastern Wairarapa Coast.

- Based on the monitoring data available, the most frequent and expansive *Phormidium* blooms occur in the Hutt and Waipoua rivers. However, blooms do not occur every summer at monitoring sites in these rivers. For example, no blooms were recorded in the Hutt or Waipoua rivers in the 2013/14 or 2014/15 summers.

- Anatoxin has been detected in *Phormidium* mats in 11 rivers in the region. The highest anatoxin concentrations have been recorded in the Mangaroa, Hutt and Waipoua rivers. Most *Phormidium*-related dog deaths in the Wellington Region have occurred on the Hutt River (11) and one has occurred in the Waipoua River (an instance of human illness has also been recorded from a tributary of the Waipoua River). It's also likely that five dogs deaths on the Waikanae River in summer 1998/99 were due to *Phormidium* poisoning.

- The occurrence of flushing flows is undoubtedly the key variable that controls periphyton abundance in rivers. However, it is unclear how the length of the accrual period between flushing flows affects *Phormidium* abundance in the Wellington Region. Longer accrual periods between large freshes (in this case 9x median flow events) were associated with a greater magnitude of *Phormidium* abundance. However, there was no relationship between *Phormidium* cover and accrual period length for (smaller) 3x median flushing events. It is likely that the magnitude of flushing flow required to remove *Phormidium* growth varies greatly depending on the physical characteristics of each river.

- While flushing flow frequency is likely to be an important regulator of *Phormidium* abundance in rivers where it occurs, it does not appear to explain why some rivers in the Wellington Region experience *Phormidium* blooms and others do not.

- Based on work from the Hutt River, *Phormidium* appears to prefer the water velocities associated with run or riffle habitat during stable flow conditions.

- Assessment of both annual and bloom-specific water column nutrient data suggest that *Phormidium* blooms in rivers in the Wellington Region occur under a range of nitrogen concentrations (0.05 to 1.7 mg/L) but generally occur in rivers with low phosphorus concentrations. This is consistent with what has been recorded in other parts of New Zealand.

- Water column nutrient availability appears to be a strong driver of why *Phormidium* blooms occur in some rivers in the region and not others. However, based on the data available, it does not explain why *Phormidium* blooms occur in some rivers in one year but not the next. For example, nutrient concentrations did not explain why blooms did not occur in the Hutt and Waipoua rivers in 2013/14 and 2014/15. Analysis of water column nutrient data may be misleading as periphyton uptake reduces water column nutrient concentrations. In addition, the fortnightly or monthly measurements of nutrient concentrations used in this assessment may not be sufficient to adequately assess the relationship between water column nutrients and *Phormidium* growth.

- Nutrients associated with sediment particles, in particular phosphorus, appear to be a key driver of *Phormidium* growth. The effect of sediment-associated nutrients on *Phormidium* blooms in the Wellington Region requires further investigation.

4. Hutt River catchment *Phormidium* investigations

As demonstrated in Section 3, benthic *Phormidium* blooms over the last decade have occurred frequently in the middle and lower reaches of the Hutt River. Riverbed cover of *Phormidium* in the Hutt River regularly breaches the interim New Zealand guidelines for benthic cyanobacteria in recreational fresh waters (MfE/MoH 2009), resulting in large reaches of the Hutt River being subject to health warnings during summer. Furthermore, toxin-producing *Phormidium* have been linked to at least 11 dog deaths in the Hutt River over the last decade (see Table 3.5).

The Hutt River, which flows past the urban areas of Upper Hutt and Lower Hutt, has over 1 million recreational users each year (GWRC Flood Protection, unpub. data). Because of the Hutt River's popularity for recreation and proximity to two major population bases, the risk of an animal or human health incident from toxin-producing *Phormidium* blooms is elevated compared to other rivers in the region (and nationally). As a result, a large amount of research by GWRC as well as Victoria University of Wellington and the Cawthron Institute has focused on understanding the environmental drivers of *Phormidium* blooms in the Hutt River. In this section, the research conducted by GWRC investigating the key drivers – river flow and nutrients – of Hutt River *Phormidium* blooms is presented. First a brief overview of the catchment is provided. Long-term hydrological patterns are then analysed followed by an assessment of the physical factors that drive *Phormidium* blooms in the Hutt River. The current state and temporal trends in nutrient (nitrogen and phosphorus) concentrations in the Hutt River catchment are summarised. Lastly, targeted investigations examining nutrient sources to the Hutt River are presented.

4.1 Catchment characteristics and values

The Hutt River has its headwaters in the southern end of the Tararua Range and traverses the length of the Hutt Valley before discharging into Wellington Harbour. The river receives flow inputs from four major tributaries; the Pakuratahi, Mangaroa, Akatarawa and Whakatikei rivers (Figure 4.1). The catchment is 655 km^2 in area and is dominated by greywacke geology with alluvial gravel deposits occurring in valley areas.

Indigenous forest and scrub is the dominant land cover type within the Hutt River catchment, making up approximately 70% of the catchment area (MfE 2010). Exotic forestry is common in hill country areas of the catchment and significant areas of agricultural land use (mostly dry stock) occur in lowland areas of the Pakuratahi and Mangaroa river catchments. In its mid and lower reaches, the Hutt River flows through a large urbanised floodplain encompassing the cities of Upper Hutt and Lower Hutt.

The alluvial gravel sediments of the Hutt Valley are associated with two groundwater basins, the Upper Hutt basin and the Lower Hutt basin. These groundwater basins include shallow, unconfined aquifers and deeper semi-confined to confined aquifers (Gyopari 2015).

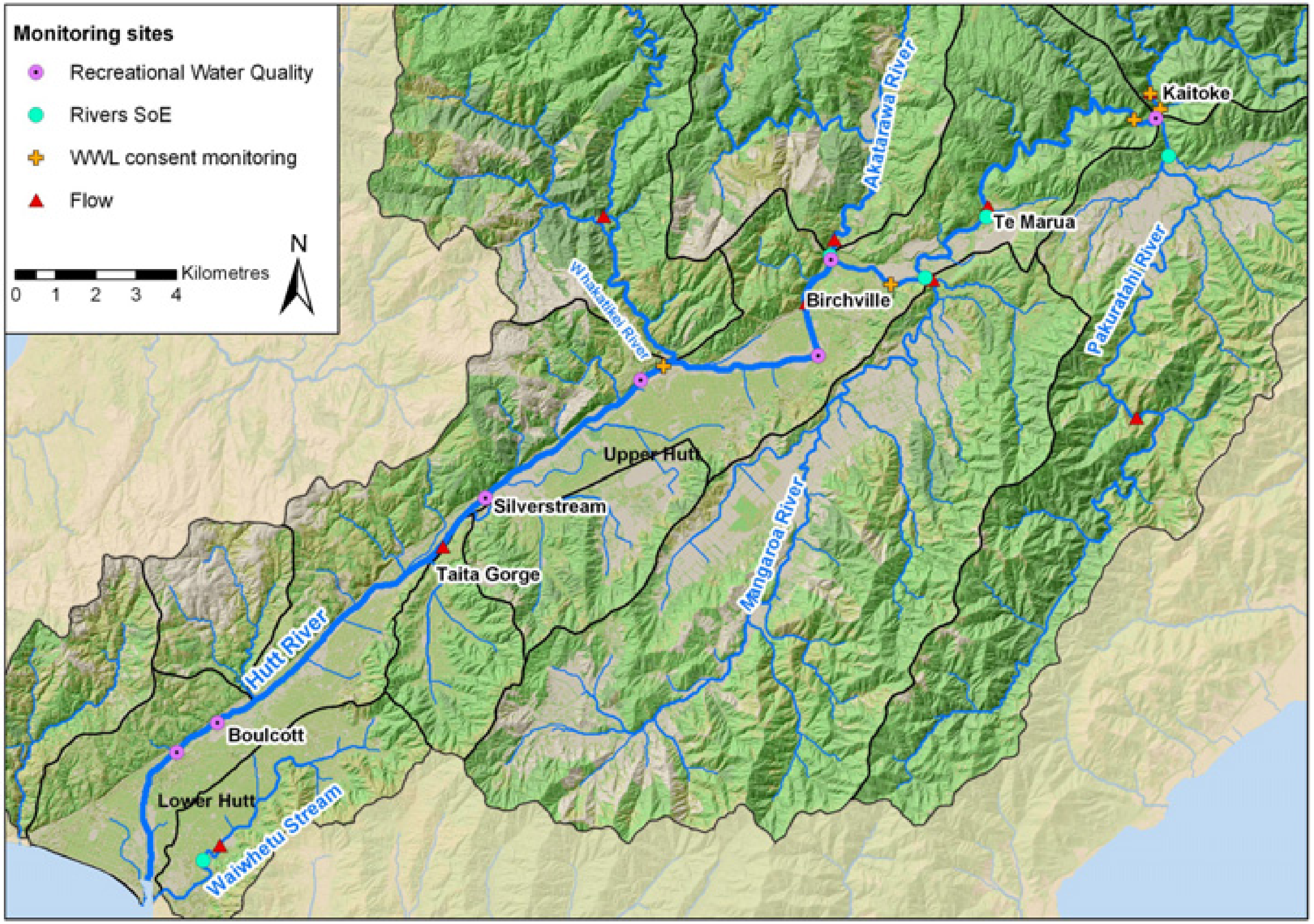

Figure 4.1: Hutt River catchment and location of key monitoring sites

As the Hutt River flows through the Hutt Valley there is a significant degree of interaction with the shallow, unconfined aquifers of the Upper Hutt and Lower Hutt basins. Concurrent river flow gaugings suggest flow loss from the river to groundwater in the reaches between Birchville and the Whakatikei River, and between Taita Gorge and Kennedy Good Bridge. The Hutt River gains flow from groundwater between the Moonshine Bridge and Taita Gorge and again from downstream of Kennedy Good Bridge to the river mouth (Figure 4.2; Gyopari 2015).

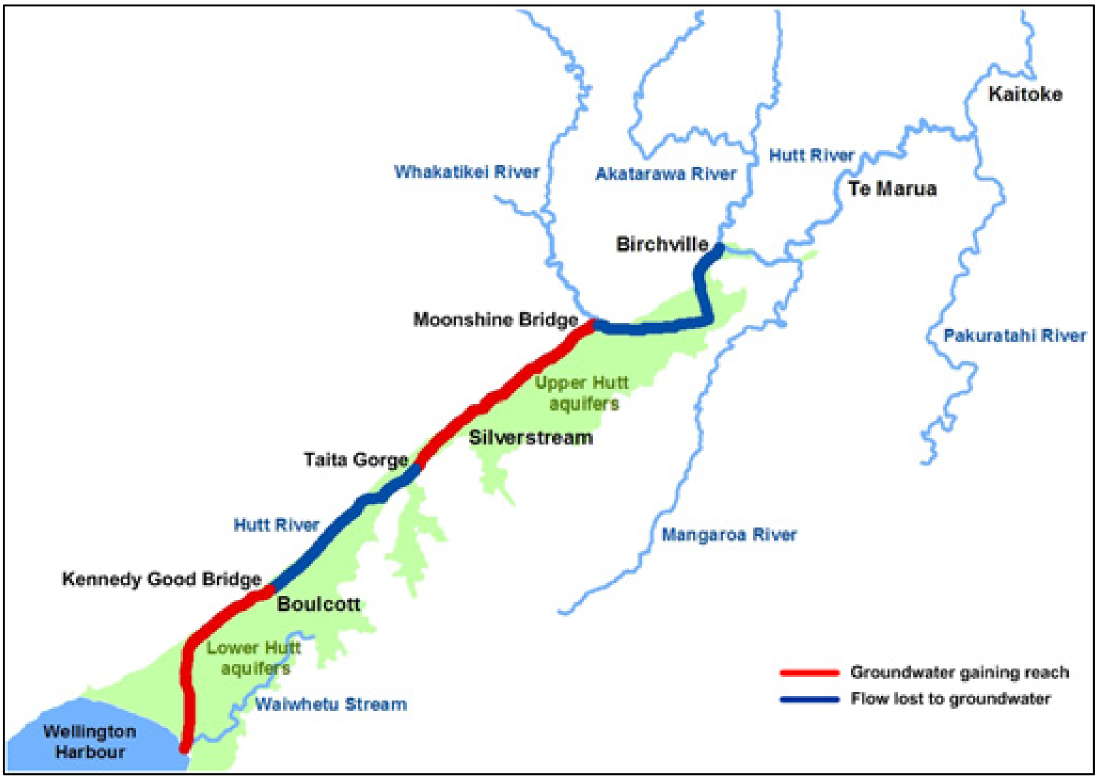

Figure 4.2: Schematic diagram of the Hutt River catchment illustrating groundwater gaining and losing reaches

The Hutt River at Taita Gorge has a median flow of 14,270 L/s and a 1-day mean annual low flow (MALF) of 3,380 L/s (Gordon 2012). Based on a flushing flow of three times median, the annual average accrual period ranges from 15 days at Te Marua to 20 days at Boulcott. The average annual maximum accrual period ranges from 51 days at Te Marua to 67 days at Boulcott (Thompson & Gordon 2011; Appendix 3).

The Hutt River is highly valued for recreational use, including swimming, kayaking and trout fishing, and due to the extensive network of walkways and tracks along its middle and lower reaches, the river margins are heavily used for walking, running and cycling. The ecological values of the Hutt River are also well recognised as reflected in its inclusion in the Regional Policy Statement (GWRC 2013) as a river with significant indigenous biodiversity values. The Hutt River and its tributaries are also recognised as a significant indigenous ecosystem in the Proposed Natural Resources Plan (PNRP) for the Wellington Region (GWRC 2015).

Both surface and ground waters of the Hutt River catchment are used extensively for municipal water supply for the Hutt Valley, Porirua and Wellington City. GWRC (managed by Wellington Water) holds resource consents to abstract surface water from the Hutt River at Kaitoke and groundwater from the Upper Hutt and Lower Hutt aquifers. The middle and lower reaches of the river are also managed by GWRC to reduce the risk of flooding to the urban areas of Upper and Lower Hutt, as outlined in GWRC's Hutt River Floodplain Management Plan and associated Environmental Strategy (currently being reviewed). GWRC holds resource consents for these flood protection activities and is currently in the process of renewing these consents.

4.2 Cyanobacteria *(Phormidium)* presence and abundance

Results from assessments of benthic cyanobacteria[8] cover at Hutt River RWQ monitoring sites indicate that *Phormidium* can be widespread at all sites from Birchville (in the middle reaches of the river) downstream (see Section 3.1; Figure 4.3). *Phormidium* cover of up to 70% has been recorded on at least one occasion at all recreational monitoring sites apart from Melling since monitoring begun in the 2009/10 summer (Figure 4.3). The Hutt River at Silverstream had the greatest number of exceedances of the MfE/MoH (2009) action threshold of any river site monitored in the Wellington Region. *Phormidium* cover was >50% of the riverbed on five occasions at this site between December 2009 and March 2015.

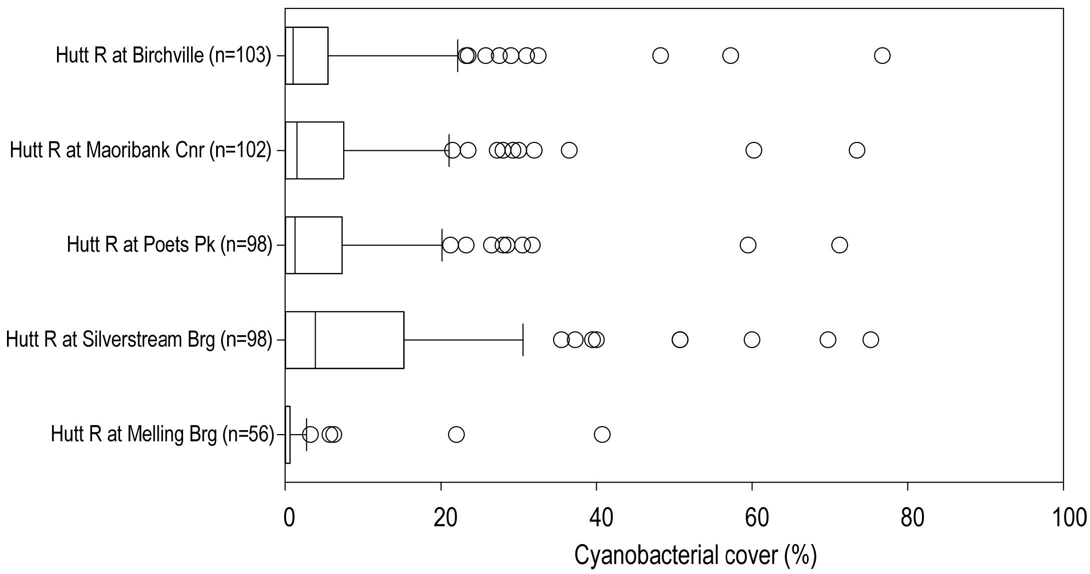

Figure 4.3: Box plots of weekly assessments of *Phormidium* cover at Hutt River RWQ river sites during summer months between December 2009 and March 2015 where cyanobacteria was present. *n* = number of different assessments. Line inside box shows the median, box edges show 25th and 75th percentiles, whiskers extend to the last data point within the 90th percentile, and open circles are outliers

8 As noted in Section 3.1, cyanobacterial blooms in rivers in the Wellington Region are dominated by *Phormidium*, hence cyanobacteria and *Phormidium* are used inter-changeably throughout the rest of this report.

4.3 Hydrological conditions and *Phormidium*

As outlined in Section 3.3.1, *Phormidium* blooms usually occur in stable base flows conditions (Milne & Watts 2007; Heath et al. 2010a; Heath et al. 2011). When a flushing flow occurs it removes *Phormidium* mats from the riverbed through abrasion by mobilised sediments and hydraulic action (Biggs et al. 1999; see Section 3.3). In 2008, a year-long Victoria University study of the Hutt and Wainuiomata rivers demonstrated decreasing river flows increased the probability of *Phormidium* mats being present (Heath et al. 2011). To examine the relationship between *Phormidium* and flow further, in 2012 GWRC commissioned a hydraulic habitat modelling analysis and in 2014 analysed Hutt River flushing flow frequency, accrual periods and hydrological river recession curves. These investigations are summarised below.

4.3.1 Flushing flow and accrual period analysis

The aim of this investigation was to assess whether the frequency of flushing flows and accrual period (time between flushing flow events) had changed through time. Reduced flushing flow frequency and increased accrual periods would indicate conditions more favourable for *Phormidium* bloom development. To assess changes in flushing flow frequency and accrual period over time, river flow data (at Taita Gorge) for the period 1 July 1979 to 30 June 2013 were examined.

In this analysis a flushing flow was considered to be a flow >3x the median. This flow statistic has been widely used as an indicator of biological disturbance and has been generally considered capable of removing riverbed periphyton (Biggs & Close 1989; Clausen & Biggs 1997; Hudson 2010).

The accrual period is defined as the time between flushing flows. A five-day filter period was used to assess the frequency of flushing flows. After the flow recedes from a flushing flow event the accrual phase is not considered to have begun until the flow remains below the flushing flow for five consecutive days. If a flow event exceeds the flushing flow magnitude within the five-day period, the start date is reset from the most recent event.

The median river flow recorded at Taita Gorge between 1 July 1979 and 30 June 2013 was 14,180 L/s. Thus, the 3x median flow was 42,500 L/s.

The number of flushing flow events ranged between 14 and 25 per year, while the annual average accrual period across the entire length of the flow record was 15 days (Figure 4.4a and b). In addition to investigating hydrological years, the same analysis was repeated examining summer months only (November to March, inclusive). The number of flushing flow events in the summer period ranged between 4 and 11 (Figure 4.4c). The frequency of >3x median flushing flow events showed no overall increasing or decreasing trend over time; however, the plot of average accrual period for November to March (Figure 4.4d) does show a slight increase over time, with relatively long average accrual periods having occurred in summer 2000/01, 2005/06, 2007/08 and 2010/11. All other summer periods since 2000/01 have had average accrual periods below the 18-day long term average for this 'summer' period.

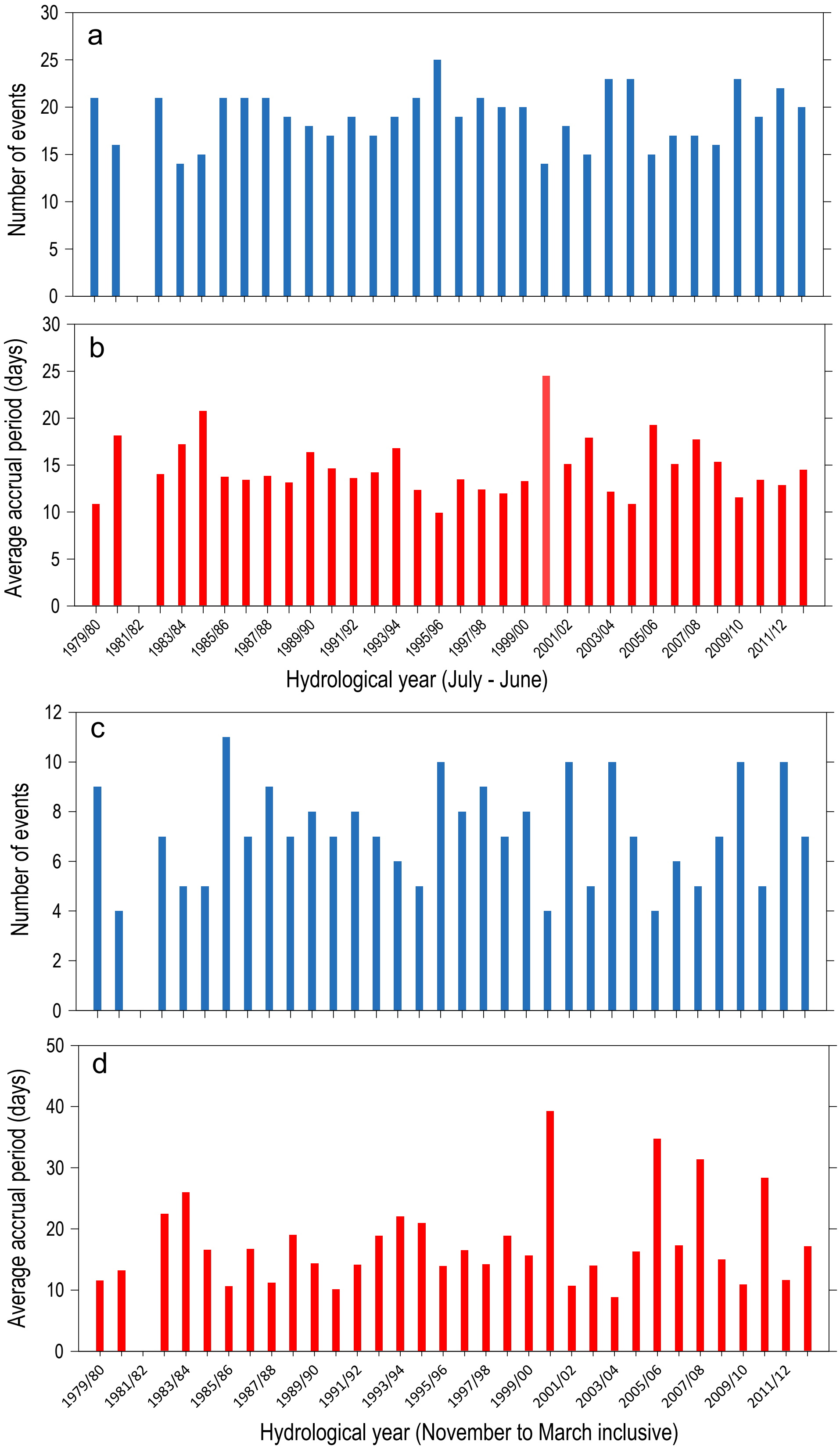

Figure 4.4: (a) Annual frequency of flushing flows (flow >3x the median). (b) Annual average accrual period based on a flushing flow of >3x median. (c) Annual frequency of flushing flows for November to March inclusive. (d) Average annual accrual period for November to March inclusive. The data hydrological data presented is for each year from 1979 to 2013

4.3.2 Hydrological recession characteristics

In addition to the flushing flow frequency analysis, a preliminary investigation of the flow record for Hutt River at Taita Gorge was also undertaken to assess if river recession characteristics (the rate at which the flow declines following a flushing event) had changed over time. A more rapid river recession following a flushing flow may favour cyanobacterial bloom development by increasing the accrual period available for growth and providing favourable physical habitat (depth, velocity and substrate stability) more quickly.

Nine recession events with extended periods of decreasing river flow from the Hutt River at Taita Gorge flow record (1 July 1979 and 30 June 2013) were compared (Harkness 2014). Individual flow recessions were converted to dimensionless flow units for comparison. With the exception of an event in April 1997, all recession events had very similar base-flow recession slopes (Appendix 4; Harkness 2014). Thus, there appears to have been no discernible change to the flow recession characteristics of the Hutt River in the last 30+ years, as measured at Taita Gorge.

4.3.3 *Phormidium* hydraulic habitat model assessment

In order to examine the effect of decreasing flow on *Phormidium* growth during an accrual period, a hydraulic habitat model was developed for *Phormidium* in the Hutt River (Heath et al. 2012). Traditionally, hydraulic habitat models have been used to describe how in-stream habitat (depth, velocity and substrate type) for macroinvertebrates and fish change with flow (Jowett et al. 1991, 2008; Hayes & Jowett 1994). Hydraulic habitat models predict changes in available instream physical habitat with river flow. These models consist of a hydraulic model coupled with habitat suitability criteria for target species (Hayes et al. 2002; Jowett et al. 2008). The hydraulic model predicts river velocity and depth at a given flow for fixed points, which represent cells in a grid covering the river area under consideration. Habitat suitability criteria are developed from observations of the physical habitat (velocity, substrate and depth) that is occupied by the study organism – ie, the relative abundance (coverage or numbers of individuals in specific habitats). Combined, these two models predict the amounts of physical habitat available for target species under different flows for a given river reach. The aim of this study was to establish if decreased flow in the Hutt River during a summer time accrual period results in increased *Phormidium* habitat and, therefore, riverbed coverage.

In this study, over 650 observations were taken from seven Hutt River sites in summer low flows during February 2012. Each observation included measurements of velocity (up to 2 m/s), depth (up to 0.70 m) and substrate type as well as *Phormidium* coverage. Once this raw data were collected, both forage ratio and quantile regression methodologies were used to derive *Phormidium* habitat preference curves for velocity, depth and substrate type (refer Heath et al. 2012 & 2015 for further details).

Together, the habitat preference curves formed the site-specific habitat suitability criteria (HSC) for hydraulic habitat modelling to determine the relationship between flow and potential *Phormidium* habitat availability using

RHYHABSIM software (Jowett 2006). The hydraulic habitat modelling utilised three existing Hutt River hydraulically modelled reaches; Birchville, Taita and Silverstream (Harkness 2002).

Phormidium mat cover, across all sites, was greatest in velocities between 0.7 and 1.1 m/s; however, *Phormidium* was observed in velocities up to 2.1 m/s. This velocity was much greater than previously used to model *Phormidium* coverage in the Hutt River (Hudson 2010). The optimum velocity varied among sites, decreasing from upstream to downstream indicating that the optimum velocity is site dependant. The lower optimum velocities downstream may result from higher downstream nutrient concentrations. The optimum velocity required for *Phormidium* mats to diffuse/uptake nutrients to support growth varies depending on the nutrient concentration – the higher the nutrient concentration the lower the velocity needed to support growth (King et al. 2014). *Phormidium* mat cover increased with substrate size; however, this trend was only marginal using quantile regression from the upper response distribution (0.90 quantile). Small substrates may have had insufficient time since the last flushing flow for colonisation and growth to occur. Growth on larger substrates may be faster than small substrates due to the larger amount of cracks and crevices that provides refuge during large flow events and sites from which colonisation of the substrate can occur. *Phormidium* mat cover had a slight negative relationship with depth. However, depth could only be measured safely up to 0.70 m.

After instream habitat modelling, using both quantile regression and forage generated HSC, only negligible changes in *Phormidium* habitat were predicted for the three hydraulically modelled reaches (Birchville, Silverstream and Taita) in low flows. Although there were differences in magnitude between quantile regression and forage ratio generated responses, both methods' curves shared similar tendencies; they did not alter greatly with changes in depth, substrate type or velocity (Heath et al. 2012). This reflects the ability of *Phormidium* to colonise and grow in a wide range of velocities, depths and on all substrate sizes during stable river flows. This indicates that during an accrual period, decreasing flow is not a key driver of *Phormidium* growth.

4.4 Nutrients and *Phormidium*

Nutrients, in particular nitrogen and phosphorus, are the key building blocks of algal growth. Research undertaken in multiple rivers around New Zealand, including in the Wellington Region, has revealed that water column nitrogen and phosphorus concentrations are important parameters driving the occurrence and development of *Phormidium* blooms (see Section 3.4; Wood & Young 2011; Heath et al. 2012; McAllister 2015). As a result, in the Hutt River there has been a large focus on understanding the dynamics between nitrogen and phosphorus, and *Phormidium* blooms. In this section the large body of work examining nutrient concentrations and their relationship with *Phormidium* blooms in the Hutt River is presented. Note that extensive use of acronyms is made in the text of this section for dissolved inorganic nitrogen (DIN), ammoniacal nitrogen (Amm. N), total nitrogen (TN), dissolved reactive phosphorus (DRP) and total phosphorus (TP).

4.4.1 Nutrient concentrations

As part of GWRC's Rivers State of the Environment (RSoE) monitoring programme, water quality variables, including instream nutrients, are assessed monthly (on the same day) at eight monitoring sites in the Hutt River catchment[9] (Table 4.1, Appendix 1). Since 2011, GWRC's Water Supply Department (now part of Wellington Water Ltd (WWL)) has also undertaken fortnightly summer nutrient monitoring at seven main-stem Hutt River sites between 1 November and 30 April, inclusive (Appendix 1).

Before calculating site median concentrations, RSoE data were screened for outliers and where there was a cause for concern around the quality of a data value (eg, dissolved nutrient concentrations were greater than total nutrient counterparts), these values were removed. During data processing, any results reported less than the detection limit (ie, censored data) were replaced by values one half of the detection limit (eg, a value of <2 became 1).

RSoE monitoring data indicate that median DIN concentrations in the Hutt River increase from 0.076 mg/L at Te Marua to 0.198 mg/L at Manor Park (Table 4.1). In contrast, median DRP concentrations are low at all three Hutt River RSoE sites (<0.005 mg/L). Although results from the Waiwhetu Stream are summarised here for completeness (and show the highest nutrient concentrations of all the Hutt River tributaries), this stream drains to the mouth of the Hutt River meaning that nutrient inputs from the Waiwhetu Stream are unlikely to affect the occurrence of *Phormidium* blooms in the Hutt River. The Mangaroa and Pakuratahi rivers have the highest median nitrogen concentrations of the Hutt River's four major tributaries (Table 4.1).

Table 4.1: Median nutrient concentrations at eight Hutt River catchment RSoE monitoring sites based on monthly sample results collected between 1 July 2012 and 30 June 2015 (*n*=~36). Minimum and maximum values are presented within the brackets

Site No.	Site name	DIN (mg/L)	TN (mg/L)	DRP (mg/L)	TP (mg/L)
RS20	Hutt R at Te Marua Intake Site	0.076 (0.034–0.17)	0.16 (<0.11–0.42)	0.004 (<0.004–0.006)	0.007 (<0.004–0.032)
RS21	Hutt R opposite Manor Park Golf Club	0.198 (0.085–0.39)	0.32 (0.19–1.96)	0.005 (0.005–0.008)	0.012 (<0.004–0.38)
RS22	Hutt R at Boulcott	0.178 (0.083–0.33)	0.32 (0.15–1.83)	0.005 (<0.004–0.008)	0.010 (<0.004–0.39)
RS23	Pakuratahi R 50m below Farm Crk	0.199 (0.059–0.30)	0.29 (0.26–0.44)	0.005 (<0.004–0.011)	0.010 (<0.004–0.036)
RS24	Mangaroa R at Te Marua	0.410 (0.166–0.64)	0.59 (0.34–0.97)	0.010 (<0.004–0.018)	0.019 (<0.004–0.046)
RS25	Akatarawa R at Hutt confluence	0.092 (<0.011–0.63)	0.19 (<0.11–1.38)	0.004 (<0.004–0.008)	0.007 (<0.004–0.30)
RS26	Whakatikei R at Riverstone	0.129 (0.210–0.68)	0.21 (<0.11–0.73)	0.008 (<0.004–0.012)	0.012 (<0.004–0.85)
RS27	Waiwhetu S at Wainui Hill Br	0.575 (0.017–1.46)	0.84 (0.30–1.65)	0.025 (0.008–0.052)	0.048 (0.015–0.20)

9 Waiwhetu Stream is sampled on a different day to the rest of the Hutt River catchment RSoE sites.

Fortnightly summer-time water quality monitoring at seven Hutt River sites by WWL shows that nitrogen concentrations generally increase down the Hutt River between Kaitoke and Silverstream (Figure 4.5). In particular, the greatest nitrogen increases occur downstream of the Pakuratahi and Mangaroa River confluences, and between the Whakatikei River confluence and Silverstream Bridge. In the reach between Whakatikei River confluence and Silverstream Bridge the median DIN concentration increases approximately 3-fold from 0.07 mg/L to 0.22 mg/L. The decrease in DIN concentrations downstream of the Akatarawa and Whakatikei confluences is the result of lower DIN concentrations in these tributaries (Table 4.1). Total phosphorus and DRP concentrations are consistently low across all sites.

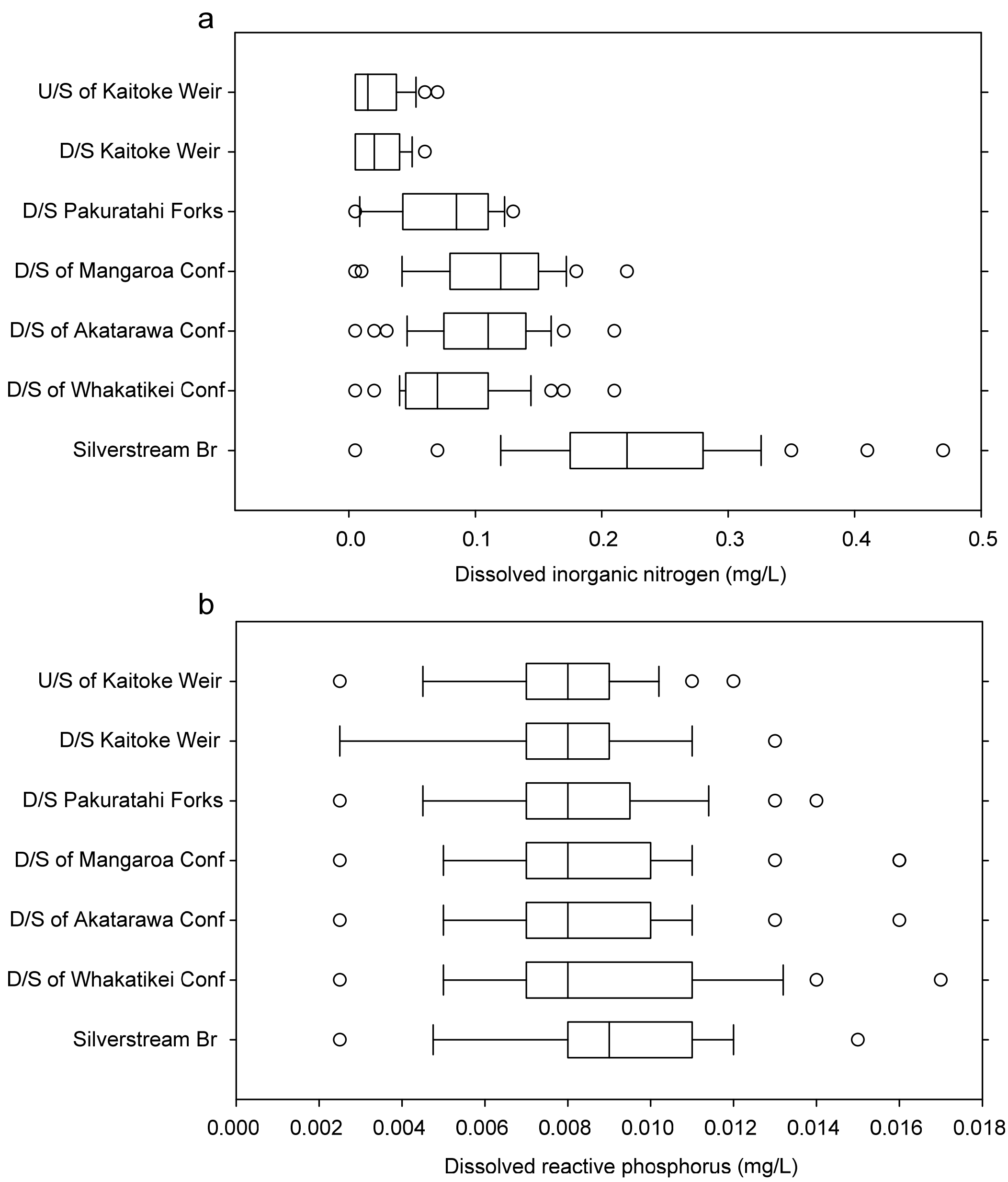

Figure 4.5: Box-plot of (a) dissolved inorganic nitrogen and (b) dissolved reactive phosphorus concentrations for the seven WWL Hutt River monitoring sites (*n*=35–37) sampled between November and April over 2012/13 to 2014/15 inclusive. Line inside box shows the median, box edges indicate 25th and 75th percentiles, whiskers extend to the last data point within the 10th and 90th percentiles, and open circles are outliers

4.4.2 Temporal trends in nutrient concentrations

To assess temporal trends in nitrogen and phosphorus concentrations in the Hutt River and its tributaries, monthly data from seven of GWRC's Hutt River catchment RSoE sites collected between 1 July 2006 and 1 June 2015 inclusive were analysed (the Waiwhetu Stream was excluded from this analysis). Only data collected post-July 2006 was used in this analysis as a change in GWRC analytical laboratory (including the detection limits for some variables eg, DRP) at this time was deemed to have produced 'step changes' in some water quality variables (Perrie et al. 2012), confounding trend assessments.

Consistent with previous GWRC SoE reporting (Perrie et al. 2012), trends were examined using the Seasonal Kendall trend test in NIWA's Time Trends software (Version 3.20). This is a non-parametric statistical method widely used in the analysis of trends in water quality in New Zealand (eg, Scarsbrook et al. 2003). The magnitude of the trend is determined by the Seasonal Kendall slope estimator (SKNE); the greater the slope, irrespective if the slope is negative or positive, the greater the magnitude of the trend. Seasonal Kendall trend tests were undertaken using 12 'seasons' (ie, reflecting monthly water sampling) and flow-adjustment was performed in the time trends software using LOWESS (Locally Weighted Scatterplot Smoothing) with a 30% span.

In rivers and streams, flow at the time of sampling has a significant effect on water quality (eg, TP concentrations may be elevated in high flows following rainfall). The effect of changes in flow may obscure trends due to factors directly related to human activities such as changes in land use. It is therefore preferable to 'flow-adjust' water quality records prior to trend analysis and report both raw and flow-adjusted data.

Prior to analysis, the nutrient data sets, which often contain a high proportion of censored values (ie, concentrations reported as below the analytical detection limit), were processed as follows:

- If a data set contained less than 25% censored data, the censored values were halved; and
- For data sets containing greater than 25% censored data, trend analysis was not performed.

In this report a trend was deemed to be significant if the *p*-value was less than 0.05 (ie, statistically significant) and if the rate of change was >1% per year.

Since 1989 NIWA have also monitored water quality monthly at two Hutt River sites, Kaitoke and Boulcott, as part of their national river water quality network (NRWQN). Trend assessment outputs for the NIWA sites from Larned et al. (2015)[10] are briefly examined (although note that a different time period (2004 to 2013) was analysed and slightly different trend analysis methods were used).

[10] Trend assessment data outputs were accessed from the following MfE webpage in May 2016: https://data.mfe.govt.nz/table/2531-river-water-quality-trends-by-monitoring-site-1989-2013/data/

Table 4.2: Trends in nitrogen and phosphorus concentrations for seven of GWRC's RSoE Hutt River catchment sites between July 2006 and June 2015. MASS=median annual Sen slope (mg/L/yr) calculated using the Seasonal Kendall test. Significant trends (*p<0.05* and a rate of change >1% per year) are highlighted in green (decreasing) and red (increasing)

Dissolved inorganic nitrogen (DIN)									
Site	Median	Raw data				Flow-adjusted data			
		n	MASS	Rate of change (%/year)	*p*-value	*n*	MASS	Rate of change (%/year)	*p*-value
Pakuratahi R 50m below Farm Ck	0.210	107	-0.0079	-3.78	0.003	103	-0.0090	-4.28	<0.001
Mangaroa R at Te Marua	0.450	107	-0.0261	-5.81	<0.001	107	-0.0237	-5.27	<0.001
Akatarawa R at Hutt Confluence	0.100	108	-0.0022	-2.23	0.148	108	-0.0005	-0.48	0.741
Whakatikei R at Riverstone	0.122	108	-0.0011	-0.92	0.740	108	0.0024	1.98	0.140
Hutt R at Te Marua Intake Site	0.086	108	-0.0030	-3.49	0.015	107	-0.0029	-3.41	0.011
Hutt R opposite Manor Park	0.220	108	-0.0050	-2.29	0.025	107	-0.0054	-2.46	0.041
Hutt R at Boulcott	0.198	107	-0.0067	-3.44	0.035	106	-0.0051	-2.57	0.131
Total nitrogen (TN)									
Site	Median	Raw data				Flow-adjusted data			
		n	MASS	Rate of change (%/year)	*p*-value	*n*	MASS	Rate of change (%/year)	*p*-value
Pakuratahi R 50m below Farm Ck	0.310	107	-0.0099	-3.20	0.017	103	-0.007	-2.44	0.030
Mangaroa R at Te Marua	0.630	107	-0.0219	-3.48	0.000	107	-0.0236	-3.74	0.000
Akatarawa R at Hutt Confluence	0.155	108	0.0000	0.00	1.000	108	0.0028	1.80	0.196
Whakatikei R at Riverstone	0.200	107	0.0010	0.50	0.210	108	0.0072	3.58	0.008
Hutt R at Te Marua Intake Site	0.160	108	-0.0002	-0.12	0.503	107	0.0003	0.17	0.976
Hutt R opposite Manor Park	0.350	108	-0.0050	-1.44	0.069	107	-0.0062	-1.71	0.120
Hutt R at Boulcott	0.300	107	-0.0027	-0.89	0.356	106	-0.0015	-0.50	0.558
Dissolved reactive phosphorus (DRP)									
Site	Median	Raw data				Flow-adjusted data			
		n	MASS	Rate of change (%/year)	*p*-value	*n*	MASS	Rate of change (%/year)	*p*-value
Pakuratahi R 50m below Farm Ck	0.005	108	0.0000	0.00	0.731	104	0.0000	-0.09	0.900
Mangaroa R at Te Marua	0.010	108	0.0001	0.562	0.393	108	0.0001	1.00	0.321
Akatarawa R at Hutt Confluence	0.002	108	Trend analysis not performed (59% data set contains censored values)						
Whakatikei R at Riverstone	0.007	108	0.0002	2.75	0.014	108	0.0002	0.28	0.058
Hutt R at Te Marua Intake Site	0.002	108	Trend analysis not performed (48% data set contains censored values)						
Hutt R opposite Manor Park	0.005	108	Trend analysis not performed (39% data set contains censored values)						
Hutt R at Boulcott	0.004	108	Trend analysis not performed (45% data set contains censored values)						
Total phosphorus (TP)									
Site	Median	Raw data				Flow-adjusted data			
		n	MASS	Rate of change (%/year)	*p*-value	*n*	MASS	Rate of change (%/year)	*p*-value
Pakuratahi R 50m below Farm Ck	0.009	108	0.0000	0.00	0.669	104	0.0000	-0.13	1.000
Mangaroa R at Te Marua	0.019	108	0.0000	0.00	0.692	108	-0.0001	-0.64	0.452
Akatarawa R at Hutt Confluence	0.006	108	0.0000	0.00	0.580	108	0.0001	1.70	0.383
Whakatikei R at Riverstone	0.011	108	-0.0003	-2.60	0.160	108	-0.0002	-1.94	0.125
Hutt R at Te Marua Intake Site	0.007	108	-0.0001	-1.43	0.257	107	-0.0001	-1.93	0.213
Hutt R opposite Manor Park	0.012	108	-0.0005	-4.33	0.155	107	-0.0003	-2.16	0.072
Hutt R at Boulcott	0.010	108	-0.0001	-0.94	0.638	107	-0.0001	-1.25	0.484

Significant decreasing (ie, improving) trends in DIN concentrations were observed at four Hutt River catchment RSoE sites (flow-adjusted data) between July 2006 and June 2015 inclusive (Table 4.2). Decreases in DIN ranged between 2.5% (Hutt River opposite Manor Park) and 5.3% (Mangaroa River at Te Marua; Figure 4.6a) per year. For TN, the Pakuratahi River below Farm Creek and Mangaora River at Te Marua had significant decreasing trends (2.4 and 3.7% per year respectively, flow-adjusted data), while the Whakatikei River at Riverstone, recorded a significant increasing (ie, deteriorating) trend of 3.6% per year over the reporting period (flow-adjusted data; Figure 4.6b). Overall, nitrogen concentrations in the Hutt River catchment were generally trending downwards (ie, improving) with the exception of the Whakatikei River at Riverstone. The reasons for the observed trends are unclear but they are generally consistent with those reported by NIWA for their long-term Hutt River water quality monitoring sites at Kaitoke and Boulcott. At NIWA's Boulcott site, both nitrate nitrogen and TN concentrations decreased significantly (0.0066 and 0.0070 mg/L/yr) between 2004 and 2013 (flow-adjusted data). In contrast, no significant trends in nitrate nitrogen or TN concentrations were observed in flow-adjusted data at the pristine (reference site) Hutt River at Kaitoke (Larned et al. 2015).

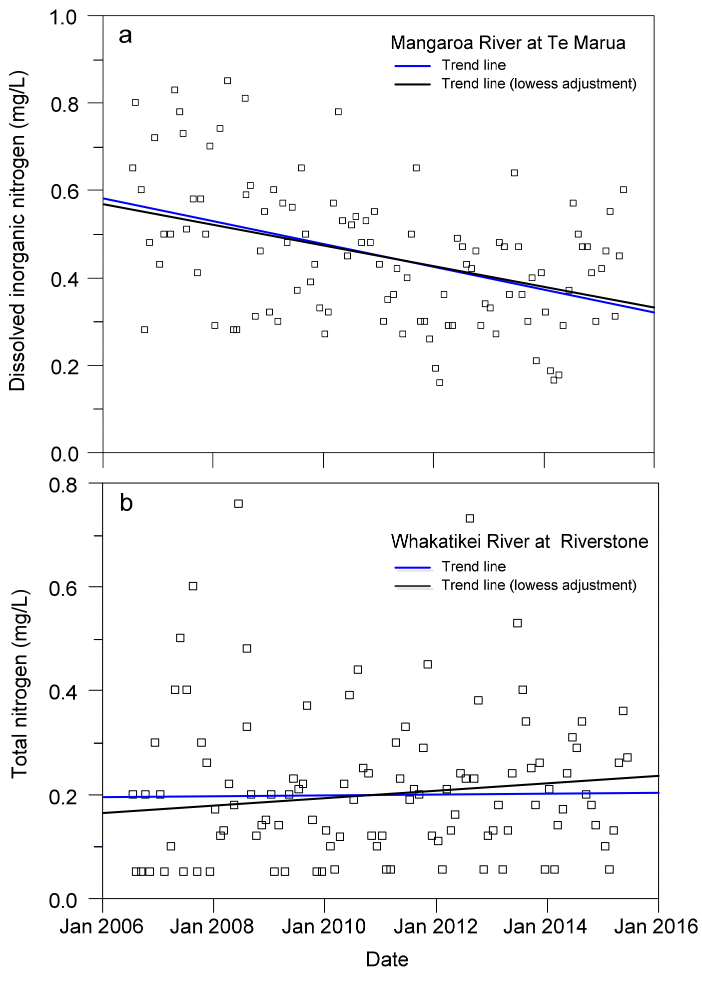

Figure 4.6: Trends (both raw and flow-adjusted) in concentrations of a) dissolved inorganic nitrogen in the Mangaroa River at Te Marua and b), total nitrogen in the Whakatikei River at Riverstone, based on monthly water sampling by GWRC between July 2006 and June 2015 inclusive

Very few trends were evident in phosphorus concentrations in the Hutt River and its tributaries. Overall, phosphorus concentrations at all Hutt River catchment sites are generally low and often below analytical detection, making meaningful temporal trend assessments difficult. Analysis undertaken on flow-adjusted data for NIWA's site at Boulcott found no significant trends in DRP or TP concentrations between 2004 and 2013. In contrast, a small, but statistically significant, increasing trend in DRP of <0.0001 mg/L per year was reported for the Hutt River at Kaitoke (flow-adjusted data; Larned et al. 2015).

4.4.3 Nutrient load estimates

In 2012, nutrient loads in the Hutt River and the contribution of the four main tributaries were estimated using data from GWRC's eight RSoE monitoring sites in the Hutt River catchment (Table 4.3). Nutrient loads were estimated using flow and nutrient concentration data collected between July 2006 and June 2012 inclusive.

Table 4.3: RSoE sites in the Hutt River catchment –all sites except site RS27 are sampled on the same day each month

Site no.	Site name	Flow data available (confidence in estimate)
RS20	Hutt R at Te Marua Intake Site	Actual (high)
RS21	Hutt R opposite Manor Park Golf Club	Estimate (high)
RS22	Hutt R at Boulcott	Estimate (high)
RS23	Pakuratahi R 50 m below Farm Crk	Estimate (moderate)
RS24	Mangaroa R at Te Marua	Actual (high)
RS25	Akatarawa R at Hutt confluence	Estimate (high)
RS26	Whakatikei R at Riverstone	Estimate (moderate)
RS27	Waiwhetu S at Wainuiomata Hill Br	Estimate (high)

Flow data were available as continuous (15-minute interval) records for two RSoE sites (Table 4.3) and as synthetic flow records at six sites. The synthetic flow records were derived from continuous flow monitoring sites upstream. Confidence in these estimated flow records ranged from 'moderate' to 'high' (Table 4.3). Due to equipment failure there were gaps in the flow record at some sites resulting in flow statistics not being able to be calculated for some months.

Monthly nutrient concentration data for DRP, DIN, TP and TN were available for all eight sites. All results reported as below the analytical detection limit were replaced by values one half of the detection limit. Nutrient load estimates for Waiwhetu Stream are included here for completeness but, as noted in Section 4.4.1, due to the location of its confluence with the Hutt River, Waiwhetu Stream nutrient inputs are unlikely to affect cyanobacteria growth in the Hutt River. Nutrient loads could not be estimated for the Waiwhetu Stream at Wainuiomata Hill Bridge for the 2011/12 year as monitoring ceased at this site in December 2011.

(a) Methods

Daily nutrient loads at Hutt River catchment RSoE sites were estimated by multiplying the nutrient concentration from the spot sample for that day by the mean daily flow and a time factor. To estimate annual and seasonal nutrient loads two methods were used; the averaging approach and the Beale ratio estimator. At Hutt River opposite Manor Park Golf Club (RS21), where *Phormidium* blooms are frequent, daily nutrient loads under different flow conditions were also examined.

Averaging approach

This method uses the monthly mean river flow and the monthly average contaminant (nutrient) concentration to estimate monthly loads. The annual load is then calculated by summing up the monthly loads (see Appendix 5).

This method is particularly applicable when the contaminant concentration and river flow are independent variables (Richards 1998). Regression analysis of nutrient and flow data from the eight RSoE Hutt River catchment sites showed that at all sites there was little or no relationship between nutrient concentrations and flows (r^2<0.5 in all cases). Monthly average flow estimates were not calculated at sites where flow data were missing for more than 10 days during the month.

Beale ratio estimator

Based on the assumption that the ratio of load to flow for the entire year equals that for load to flow on the days on which concentrations were measured, the Beale ratio estimator uses the year's data to calculate a mean daily load, then uses the mean flow from days lacking concentration data to adjust the mean daily load. However, as daily load and daily flow are correlated variables, this ratio estimator is biased and a bias correction factor must be used (see Appendix 5 for formula). The annual nutrient load can then be estimated by multiplying the adjusted daily load by 365 (or 366 for leap years) (Richards (1998).

(b) Load results

Estimates of annual nutrient loads for the eight sites in the Hutt River catchment for the period July 2006 to June 2012 are shown in Figure 4.7 and tabulated in Appendix 6. Load estimates from the two methods used (ie, averaging and the Beale ratio estimator) were largely consistent and for ease of interpretation only the averaging method results are presented here.

Between Hutt River at Te Marua Intake (site RS20) and Hutt River at Manor Park Golf Club (site RS21) nutrient loads increased by between three (for DRP) and six (for DIN) times. However, for all but one nutrient species (TP) annual loads decreased slightly between Hutt River opposite Manor Park Golf Club and Hutt River at Boulcott (RS22). It is likely that this is largely related to the decrease in flow between these two sites as a result of loss to groundwater (refer Section 4.1).

Of the four main Hutt River tributary monitoring sites, Mangaroa River at Te Marua and Pakuratahi River below Farm Creek had the highest annual nutrient loads while the Whakatikei River at Riverstone had the lowest. No RSoE site exists to enable a direct estimate of nutrient loads from the Hutt River catchment above the Pakuratahi River confluence.[11] However, subtracting the annual load estimates for each nutrient species at Pakuratahi River below Farm Creek (site RS23) from those at Hutt River at Te Marua (site RS20) suggests that nutrient loads from the upper reaches of the Hutt River are minimal.

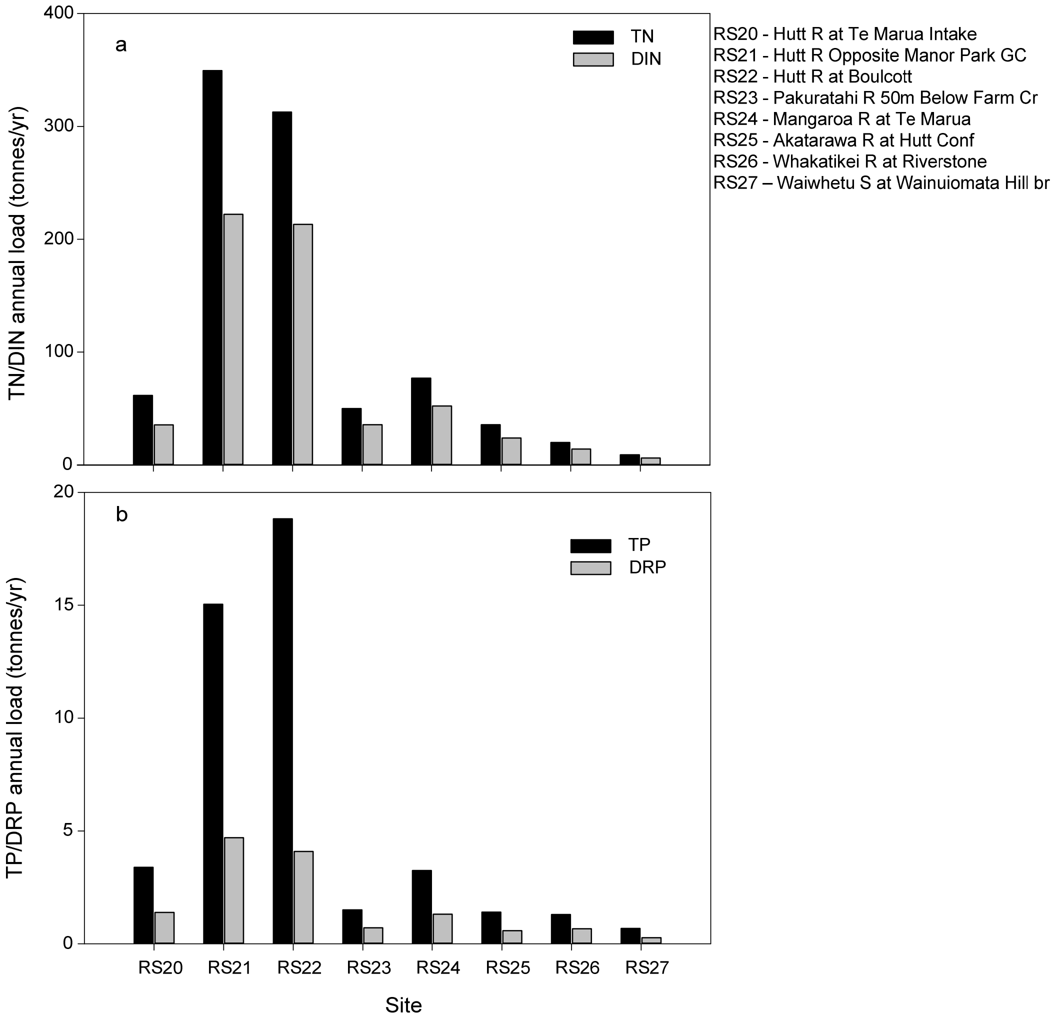

Figure 4.7: Estimated mean annual load of a) TN and DIN, and b) TP and DRP, using the averaging method for RSoE sites within the Hutt River catchment for the period July 2006 to June 2012. TN = total nitrogen, DIN = dissolved inorganic nitrogen, TP = total phosphorus and DRP = dissolved reactive phosphorus

The Mangaroa River was the largest tributary contributor to annual nutrient loads at Hutt River opposite Manor Park (site RS21 where *Phormidium* blooms are frequent), with an estimated contribution of 21–27% depending on the nutrient species (Figure 4.8). The Pakuratahi River was the second largest contributor followed by the Akatarawa and Whakatikei rivers. When load estimates were constrained to the summer period only (defined as November to April inclusive), the proportion of the load at site RS21 contributed by the four tributaries was very similar to annual load estimates (Figure 4.8).

[11] NIWA monitors the Hutt River at Kaitoke upstream of the Pakuratahi River confluence but historically has carried out monthly monitoring on a different day.

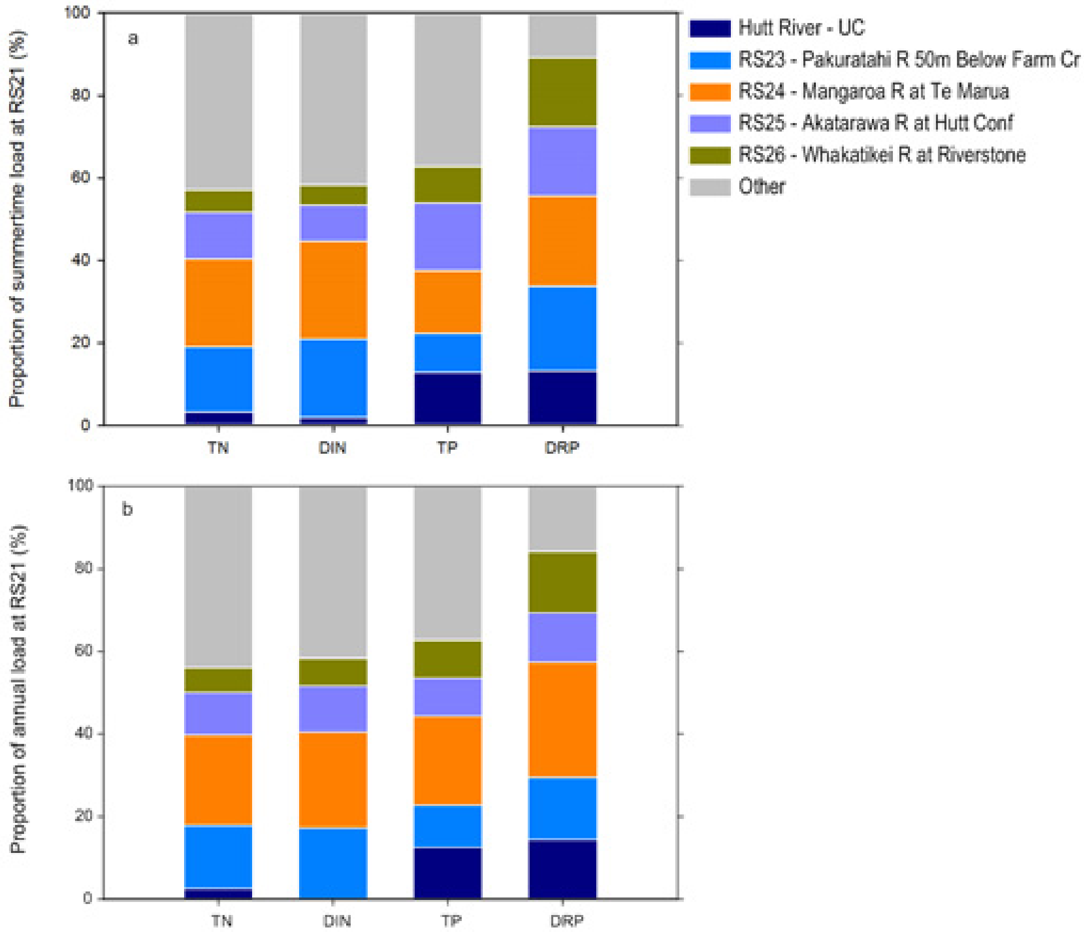

Figure 4.8: Estimated contribution to a) annual and b) summer-time nutrient load at Hutt River opposite Manor Park Golf Club (site RS21) of the four upstream RSoE tributary sites. Note that the proportion of nutrient load from the upper catchment (UC) of the Hutt River has been estimated by subtracting Pakuratahi River nutrient loads from those at Hutt River at Te Marua (RS20). TN = total nitrogen, DIN = dissolved inorganic nitrogen, TP = total phosphorus and DRP = dissolved reactive phosphorus

The total contribution to annual nutrient load of the Hutt River (at Manor Park) by the four main tributaries ranged from 50% (TP) to 70% (DRP) suggesting that, depending on the nutrient species, up to 50% of the nutrient load to the Hutt River is from other sources. Other potential sources of nutrients to the Hutt River include direct runoff from land adjacent to the main-stem of the Hutt River, small tributaries for which little/no monitoring data are available (eg, Hulls Creek, Mawaihakona Stream) and groundwater inputs.

<u>Flow-based variation in nutrient load at Manor Park (site RS21)</u>

The proportion of the DIN and TN load contributed by each upstream tributary was relatively stable under different flow conditions (Figure 4.9). However, there is some suggestion that DIN inputs from the Pakuratahi and Mangaroa rivers may make up a greater proportion of the overall nutrient load at site RS21 during 1-day MALF conditions than during higher flows.

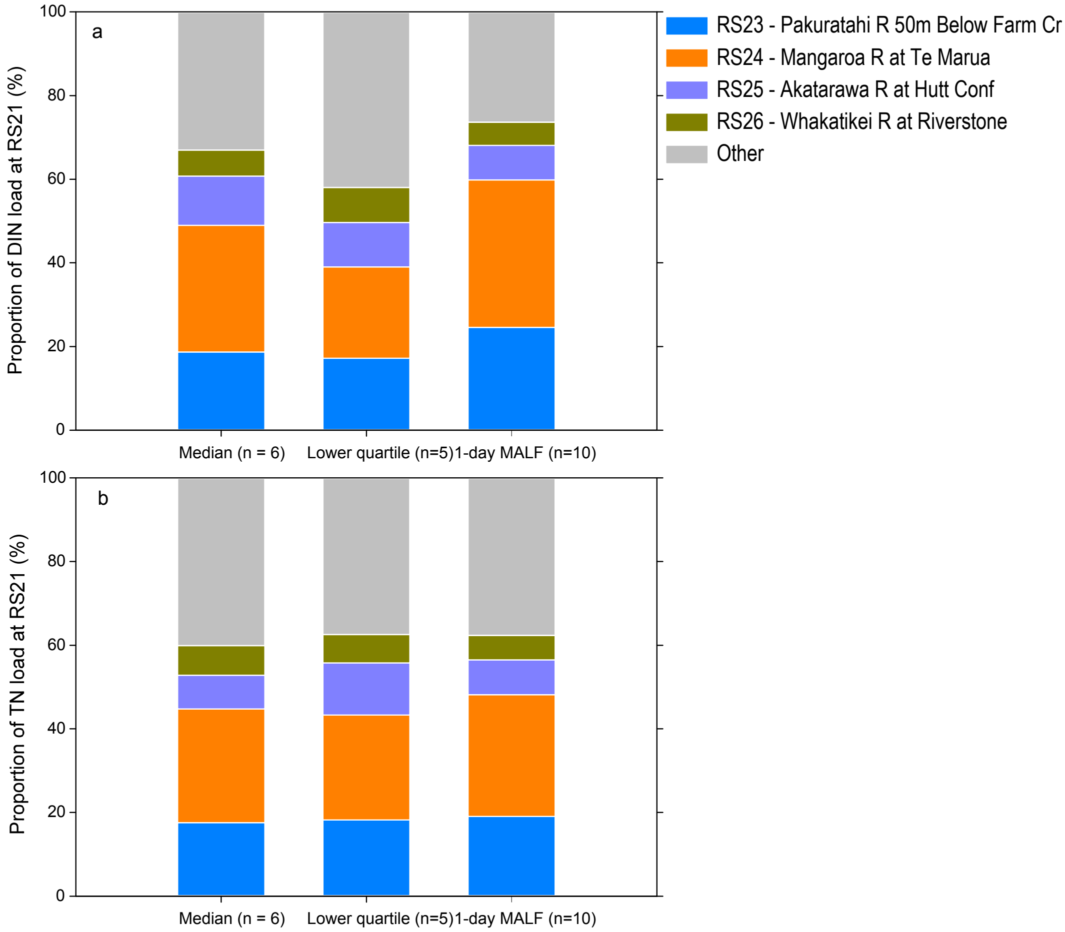

Figure 4.9: Estimated contribution of a) DIN and b) TN load at Hutt River opposite Manor Park Golf Club (site RS21) from the four upstream RSoE tributary sites under median, lower quartile and 1-day MALF flow conditions. The Pakuratahi and Mangaroa site contributions are coloured blue and orange, respectively. Note that these graphs omit inputs from the upper catchment of the Hutt River as these are considered to be minimal

The sum of the total DRP and TP load from the tributaries was greater than the load at site RS21, particularly during MALF conditions, suggesting that phosphorus is lost from the system during low flows. This is likely to be the result of phosphorus uptake by periphyton; the Hutt River is generally considered to be phosphorus-limited (Ausseil et al. 2013).

4.4.4 Flow and nutrient inputs in the Whakatikei-Taita Gorge reach

As identified in Sections 4.4.1 and 4.4.3, there is a marked increase in nitrogen concentrations in the Hutt River reach between the Whakatikei River confluence and Taita Gorge (Figure 4.5a). Gyopari (2014) identified a consistent flow gain of 1,000–1,700 L/s attributable to groundwater inputs in this reach. This section details the investigations undertaken to identify nutrient inputs in the Whakatikei-Taita Gorge reach (7.3 km), in particular inputs from groundwater.

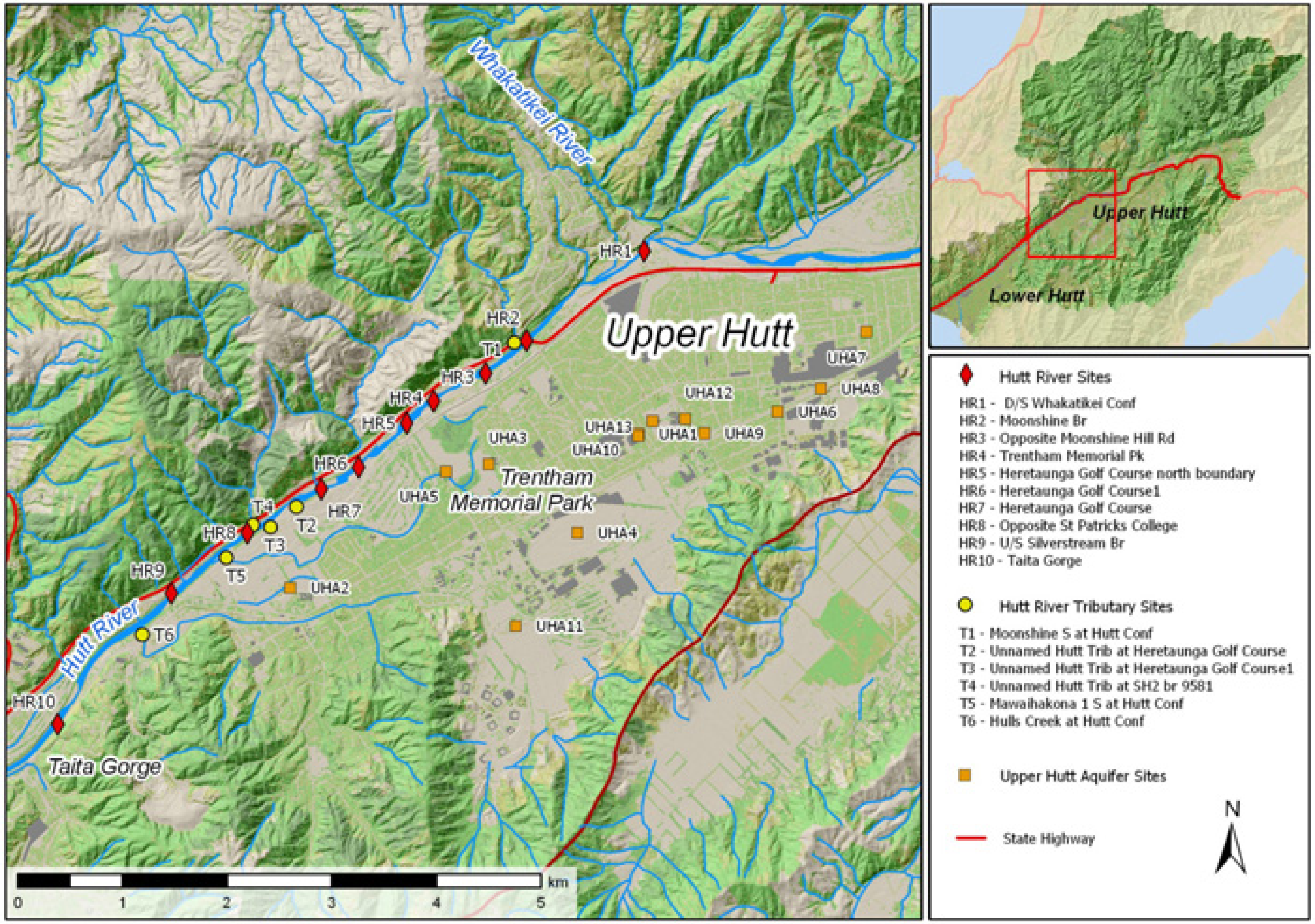

Figure 4.10: Map of sampling sites in the Whakatikei-Taita Gorge reach and the Upper Hutt unconfined groundwater zone

The Whakatikei-Taita Gorge reach was investigated by GWRC on five separate low-flow sampling occasions between February 2013 and March 2015. Instantaneous nutrient loads for DIN, TN, DRP and TP were derived from concurrent water sampling and flow gauging at multiple main-stem and all flowing tributary sites on three occasions; 28 February 2013, 18 February 2015 and 12 March 2015 (Table 4.4, Appendix 1) In addition, water samples for nutrient analysis were also collected from multiple main-stem and tributary sites in the Whakatikei-Taita Gorge reach on 2 December 2013 and 27 February 2014 (Table 4.4) as well as the Upper Hutt unconfined groundwater zone. Further groundwater samples were taken directly from the riverbed using a pneumatic pump at selected main-stem sites during sampling on 18 February and 12 March 2015. Groundwater samples were collected for nutrient analysis and to estimate the relative contribution of groundwater to Hutt River nutrient concentrations in the Whakatikei-Taita Gorge reach. Selected groundwater samples from 18 February and 12 March 2015 also underwent age dating and stable isotope analysis to determine groundwater age and possible nutrient sources. All raw data from the Whakatikei-Taita Gorge reach can be found in Appendix 7.

Table 4.4: Details of samples taken from the Hutt River and its tributaries in the Whakatikei/Taita Gorge on five occasions between February 2013 and March 2015

Sampling date	Flow at Taita Gorge (L/s) and (flow percentile)	No. of sites	Sampling undertaken
28/02/2013	5,208 (12%)	Hutt River sites - 5 Tributary sites - 5	Concurrent flow gauging and water sampling
02/12/2013	13,796* (49%)	Hutt River sites - 5 Tributary sites - 3	Water sampling only
27/02/2014	3,632* (5%)	Hutt River sites - 6 Tributary sites - 3	Water sampling only
18/02/2015	2,763 (2%)	Hutt River sites - 9 Tributary sites - 6	Concurrent flow gauging and water sampling
12/03/2015	3,107 (3%)	Hutt River sites - 9 Tributary sites - 6	Concurrent flow gauging and water sampling

* Flow as measured at 12.00pm NZST from the Hutt River at Taita Gorge.

(a) Flow

On all but one sampling occasion river flow at Taita Gorge was in the lowest 15 percentile (<5,300 L/s) of flows for this site (Table 4.4). The exception was on 2 December 2013 when flow at Taita Gorge was close to median.

On 28 February 2013 (the initial sampling round), flow increased 46% or 1,629 L/s in the Whakatikei-Taita Gorge reach (Figure 4.11). Similarly, flow increased 28 (615 L/s) and 47% (992 L/s) in the Whakatikei-Taita Gorge reach on 18 February and 12 March 2015, respectively (Figure 4.11). However, the increase in flow was not consistent among sampling occasions. On 18 February 2015, river flow decreased from 2,756 L/s at upstream site Moonshine Bridge (site HR1) to 2,181 L/s at Heretaunga Golf Course north boundary (site HR5) before increasing to 2,796 L/s at St Patricks College (site HR8). In contrast, the river flow on 28 February 2013 and 12 March 2015 increased consistently down the Whakatikei-Taita Gorge reach. The variation in river flows across sampling rounds may be due to precipitation in the catchment before sampling. Four days before sampling on 12 March 2015 a minor rainfall event resulted in a peak flow of 32,000 L/s, as measured at Taita Gorge, which is likely to have resulted in changes to groundwater/surface water interactions in this reach. The relationship between Hutt River catchment rainfall and variation in groundwater gaining and losing in the Whakatikei-Taita Gorge reach requires further investigation.

The contribution from all flowing tributaries to the Hutt River in the Whakatikei-Taita Gorge reach ranged between 124 (18 February 2015) to 162 L/s (28 February 2013), accounting for less than 20% of the increase in flow on each of the three sampling occasions where flow gaugings were conducted (data not shown). This indicates that approximately 80% of flow increase in the Whakatikei-Taita Gorge reach is from groundwater inputs. The Mawaihakona Stream had the largest flow of all the measured tributaries on each of the three sampling occasions, ranging between 69 and 100 L/s.

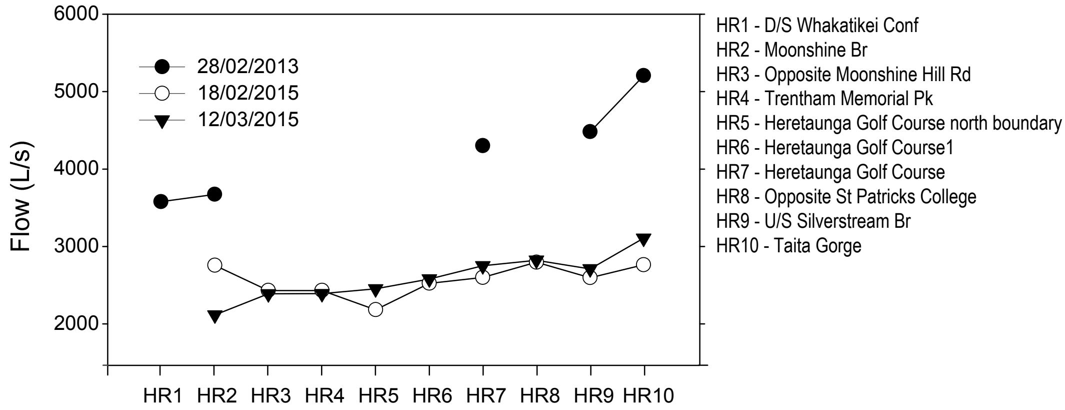

Figure 4.11: Instantaneous river flow at multiple main-stem Hutt River sites in Whakatikei-Taita Gorge reach on 28 February 2013, 18 February 2015 and 12 March 2015

(b) Surface water nutrient concentrations

Nitrogen concentrations in the Hutt River reach between the Whakatikei River confluence and Taita Gorge exhibited similar spatial patterns on all five sampling occasions (Figure 4.12). On each sampling occasion DIN concentrations increased at least two-fold in the Whakatikei-Taita Gorge reach. The majority of this increase occurred between Moonshine Bridge (site HR2) and Heretaunga Golf Course (site HR7; Figure 4.12). Total nitrogen concentrations also increased substantially over the Whakatikei-Taita Gorge reach, although this increase was more spatially and temporally variable (Figure 4.12). The six small Hutt River tributaries in the Moonshine-Taita Gorge reach had DIN concentrations that ranged between <0.011 mg/L (Hulls Creek; 28/02/2013) and 0.59 mg/L (Mawaihakona Stream; 12/03/2015; data not shown). The concentrations of both DRP and TP were close to or below detection at all Hutt River sites (data presented in Appendix 7).

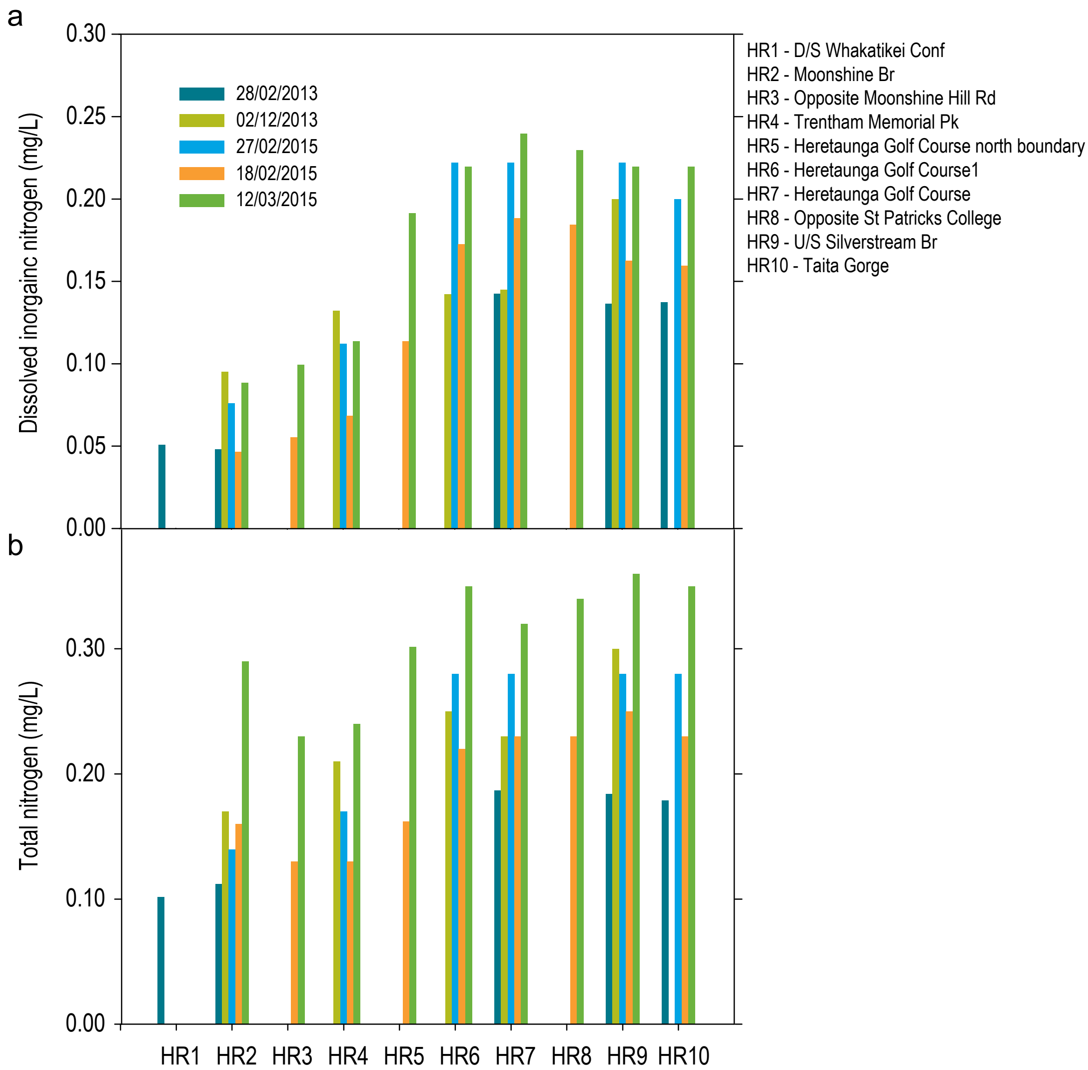

Figure 4.12: a) Dissolved inorganic nitrogen and b) total nitrogen concentrations in the Whakatikei-Taita Gorge reach of the Hutt River as measured on five separate occasions between 28 February 2013 and 12 March 2015

(c) Surface water nutrient loads

The instantaneous DIN load increased 3.5 (437 mg/s), 3.8 (362 mg/s) and 3.5 (471 mg/s) fold on the 28 February 2013, 18 February 2015 and 12 March 2015 sampling rounds, respectively, in the 2.5 km reach between Moonshine Bridge (site HR2) and Heretaunga Golf Course (site HR7; Figure 4.13). On 18 February 2015 and 12 March 2015, when sampling was undertaken at a finer spatial resolution, the largest gains in instantaneous DIN load were observed between Trentham Memorial Park (site HR4) and Heretaunga Golf Course1 (site HR6), a 950 m reach where DIN load increased 2.6 and 2.1 fold, respectively (Figure 4.13). Similarly, the TN load increased 1.8 and 1.6 fold between these two sites on 18 February and 12 March 2015, respectively (Figure 4.13). Between Moonshine Bridge (site HR2) and the Heretaunga Golf Course (site HR7) there was only one flowing tributary; Moonshine Stream, which contributed <1% to the increase in DIN load on all three sampling rounds. Thus, the increase in nitrogen load in this reach is a result of groundwater inputs.

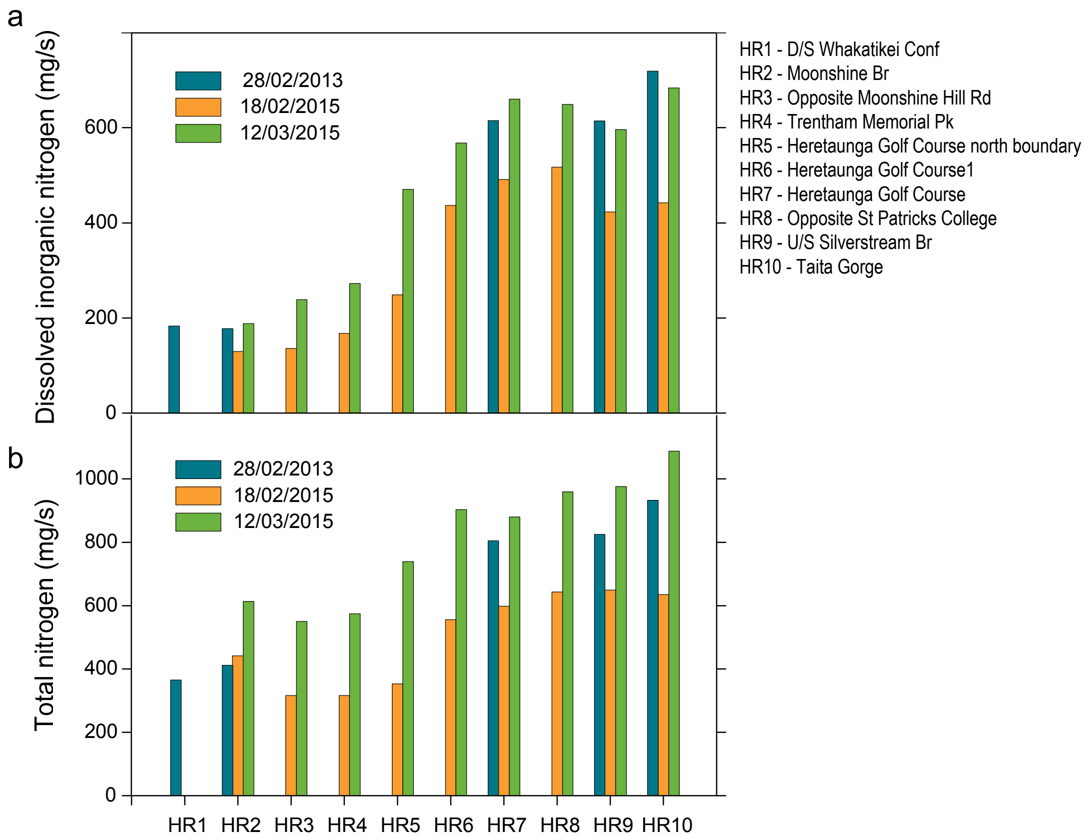

Figure 4.13: Instantaneous nitrogen loads at multiple main-stem Hutt River sites in the Whakatikei-Taita Gorge reach on 28 February 2013, 18 February 2015 and 12 March 2015

(d) Groundwater nutrient concentrations

Based on calculation, an increase in flow of 629 L/s and an increase in DIN nutrient load of 437 mg/s from Moonshine Bridge (site HR2) to Heretaunga Golf Course (site HR7) on 28 February 2013 requires a groundwater DIN concentration of 0.69 mg/L. Similarly, groundwater concentrations of 0.58 and 0.74 mg/L would have been required on 18 February and 12 March 2015, respectively. Water samples collected from bores in the unconfined Upper Hutt aquifer had concentrations ranging between 0.41 and 2.0 mg/L (Table 4.5). Thus, groundwater DIN concentrations are sufficient to account for the increase in DIN load in the Hutt River between Moonshine Bridge (site HR2) and Heretaunga Golf Course (site HR7; Table 4.5).

The interaction between the unconfined aquifer in the Upper Hutt groundwater zone and the Hutt River has also been demonstrated by Daughney (2010) in an assessment of hydrochemical signatures[12]. The hydrochemistry of groundwater at the South Pacific Tyres bore in Upper Hutt was similar to that of GWRC's RSoE site 'Hutt River at Manor Park (site RS21)', particularly during the summer months.

[12] Groundwater can be assigned to hydrochemical facies or water types based on the unique hydrochemical composition of the groundwater in individual bores. Assignment of groundwater to a particular water type can indicate environmental factors (such as origin of recharge, land use, lithology and confinement) which may influence the hydrochemical composition of groundwater in each bore (Daughney 2010).

Table 4.5: Dissolved inorganic nitrogen (DIN) concentrations in water samples from the unconfined Upper Hutt aquifer. Five bores were sampled as part of a GWRC investigation in 2013/14. The bore at South Pacific Tyres was sampled on a quarterly basis under GWRC's Groundwater Quality SoE monitoring programme up until September 2010 while the remainder of the historic bores were sampled as part of a GWRC Water Supply investigation (MWH 2006 & 2008)

2013/14 groundwater sampling			
Site name	**Map no. (Fig 4.10)**	**DIN (mg/L)**	**Result type**
Coca Cola	UHA1	0.671	Mean of two samples, 2013/14 summer
St Pats	UHA2	1.996	Mean of two samples, 2013/14 summer
Trentham Memorial Park (GWRC bore)	UHA3	0.596	Mean of two samples, 2013/14 summer
Trentham Race Course	UHA4	1.776	One-off sample, February 2014
Trentham Memorial Park (UHCC bore)	UHA5	1.026	One-off sample, March 2014
Historic groundwater sampling			
South Pacific Tyres	UHA6	1.04	Median from regular quarterly sampling from August 2005 to July 2010
Upper Hutt Bowling Club	UHA7	0.62	Mean of two samples, July 2006
On Track	UHA8	0.63	One-off sample, July 2007
MacLean St	UHA9	0.83	Mean of two samples, July 2007
Uni Bag	UHA10	0.59	Mean of two samples, July 2006
Trentham Race Course	UHA4	1.45	Mean of two samples, July 2006
Trentham Golf Course	UHA11	0.41	Mean of two samples, July 2006
Heretaunga College	UHA12	0.57	Mean of two samples, July 2007
Blockhouse Lane	UHA13	0.59	One-off sample, July 2007

No bores exist in the area adjacent to the river in the Whakatikei-Taita Gorge reach making it difficult to assess the nutrient concentration of groundwater entering the Hutt River in this reach. For this reason, on the 18 February and 12 March 2015 sampling rounds a pneumatic pump was used to extract water directly from the riverbed (Figure 4.10). It is assumed that groundwater entering the Hutt River in the Whakatikei-Taita Gorge reach will do so via the riverbed. To confirm this, Radon (Rn; an indicator of the presence of groundwater) concentrations were measured (Table 4.6).[13] Radon concentrations of ca. >0.5 Bq/L are indicative of groundwater input, while concentrations ca. >30 Bq/L are considered to be pure groundwater (Morgenstern[14], pers. comm. 2015). In total, nine samples were collected from the riverbed, four on 18 February 2015 and five on 12 March 2015 (Table 4.6).

[13] Radon is a gas found in groundwater which is lost to the atmosphere through degassing, resulting in low concentrations of radon in surface water. This contrast of high radon concentration in groundwater and low concentration in river, stream, and lake water enables identification of groundwater discharges to surface water and recharge of surface water to groundwater.

[14] Dr Uwe Morgenstern, Team Leader Isotope Hydrology & Water Dating, GNS Science.

Table 4.6: Results of water samples from the bed of the Hutt River taken on 18 February and 12 March 2015. Rn = Radon, DO = dissolved oxygen, DIN = dissolved inorganic nitrogen, Amm. N = ammoniacal nitrogen, TN = total nitrogen, DRP = dissolved reactive phosphorus and TP = total phosphorus

Samples		Rn (Bq/L)	DO (mg/L)	DIN (mg/L)	Amm. N (mg/L)	TN (mg/L)	DRP (mg/L)	TP (mg/L)
February	RB3	2.6	9.6	<0.005	0.109	0.17	0.0027	0.006
	RB5	28.0	5.0	<0.005	1.11	1.12	0.0077	0.012
	RB7	15.1	1.0	<0.005	0.044	<0.11	0.0170	0.019
	RB8	4.7	9.1	0.018	0.31	0.40	0.0037	0.007
March	RB5	35.1	4.15	< 0.005	1.21	1.25	0.0095	0.008
	RB5a	5.0	7.92	0.011	0.33	0.43	0.0021	0.008
	RB6	5.6	3.71	0.077	0.38	0.52	< 0.001	0.014
	RB6a	11.3	4.87	< 0.005	1.09	1.17	0.0071	0.005
	RB7	16.3	1.79	< 0.005	0.61	0.68	0.0082	0.007

The riverbed sample RB5 (Hutt River at Heretaunga Golf Course north boundary) was collected from a side channel of the Hutt River, which ran parallel to the river on the true left bank (TLB). Water in this channel appeared to be upwelling directly out of the riverbed before entering the main-stem of the Hutt River just upstream of site HR6. Furthermore, sample RB6a (collected on the 12 March 2015 sampling round) was from a groundwater seep located on the TLB of the river that was draining through a large boulder retaining wall.

Radon concentrations on the 18 February 2015 and 12 March 2015 sampling rounds ranged between 2.6 (RB3; 18 February 2015) and 35.1 Bq/L (RB5; 12 March 2015 sampling round) indicating there was at least some groundwater input at each site sampled. Riverbed samples collected from site RB5 had radon concentrations of 28.0 and 35.1 Bq/L on 18 February 2015 and 12 March 2015, respectively; this indicates that water pumped from the riverbed at this site was pure groundwater. Dissolved inorganic nitrogen concentrations varied among the different riverbed samples collected, ranging between 0.044 mg/L at site RB7 (18 February 2015) and 1.21 mg/L at site RB5 (12 March 2015; Table 4.6). Similarly, TN concentrations were also variable ranging between <0.11 mg/L at site RB7 (18 February 2015) and 1.25 mg/L at RB5 (12 March 2015). Generally, DIN and TN riverbed concentrations were elevated compared to their surface water equivalents (Figure 4.12), with the exception of site RB7 sampled on 18 February 2015 which is discussed below. Furthermore, there appears to be a relationship between nitrogen and Rn concentrations; ie, the greater the groundwater input, as measured by Rn, the greater the nitrogen (DIN and TN) concentration.

Site RB5 had the highest DIN and TN concentrations on both sampling rounds and also had the highest Rn concentrations (Table 4.6). Furthermore, the reach between HR4 and HR6 had the largest increase in instantaneous DIN load, 2.6 and 2.1 fold on 18 February 2015 and 12 March 2015, respectively (refer Figure 4.13). As mentioned above, sample RB5 is from a side channel and enters the Hutt River just upstream of site HR6. This channel had a flow of 120 and 121 L/s and a surface water DIN concentration of 0.87 and 0.98 mg/L on 18 February 2015 and 12 March 2015, respectively (data not shown). This equates to 39 and 40% of the DIN load increase between sites HR3 and HR5 on the 18 February 2015 and 12 March 2015 respectively, with the remainder likely to be from nitrogen-rich groundwater upwelling in the main Hutt River stem.

Site RB7 had similar Rn concentrations, 15.1 and 16.3 Bq/L, on 18 February 2015 and 12 March 2015, respectively. In contrast, DIN concentrations were substantially lower on 18 February 2015 (0.044 mg/L) than on 12 March 2015 (0.61 mg/L). Similar trends were also observed for TN. The reason for this large difference in nitrogen concentrations is unclear, but may indicate different groundwater sources. This may be linked to the very low flow conditions observed in the February sampling round and the heterogeneous nature of the aquifer under different recharge conditions (Gyopari[15], pers. comm. 2015).

Site RB6a, sampled directly from a seep on the true left bank of the Hutt River, had elevated radon (11.3 Bq/L; note, exposure of the water exiting the seep to the air may have reduced the radon concentration) and DIN (1.09 mg/L) concentrations. This seep was flowing with large quantities of water over a 5 m length indicating it may be a paleo-channel (ie, historic flow path).

(e) Groundwater age and nutrient sources

In collaboration with GNS Science, additional samples were taken to examine the age of the groundwater and determine possible nitrogen sources. Samples were taken at sites RB5 (12 March 2015), RB6a (18 February 2015) and RB7 (12 March 2015) as well as a surface water control sample (site HR8; 18 February 2015).

Stable isotope analyses of groundwater samples taken from the hyporheic zone of the river were unable to identify a clear nitrogen source (Baisden[16], pers. comm. 2015). Age dating of selected riverbed/groundwater samples, using a combination of Tritium, SF6 (sulfur hexafluoride) and CFCs (chlorofluorocarbons), revealed that the groundwater was relatively young. The surface water control (HR8) was estimated to have a mean age of 1.3 years, while the three riverbed samples had an estimated age between 2.3 (RB5 and RB7) and 2.8 (RB6a) years (Morgenstern[17], pers. comm. 2015). The young age of the groundwater entering the Hutt River indicates that water moves quickly through the unconfined Upper Hutt aquifer and, subsequently, historic land use is unlikely to have a significant effect on water quality.

4.4.5 Upper Hutt nutrient investigations

In the 2014/15 summer, two Victoria University of Wellington summer scholarship students supported by Upper Hutt City Council (UHCC) and GWRC undertook investigations attempting to further elucidate the sources of nitrogen to the Hutt River. The first investigation examined nutrient concentrations in the Upper Hutt stormwater network during summer low flows (Wild 2015). The second research project consisted of literature reviews, GIS mapping and calculations to build a model of nitrogen inputs to

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[15] Dr Mark Gyopari, Director and Principal Scientist, Earth in Mind Ltd.

[16] Dr Troy Baisden, Environmental Scientist – Isotope Biochemistry, GNS Science.

[17] Dr Uwe Morgenstern, Team Leader Isotope Hydrology & Water Dating, GNS Science.

groundwater in Upper Hutt (Kelly 2015). The key findings from these two investigations are summarised below.

(a) Stormwater investigation

Wild (2015) examined nutrient concentrations in Upper Hutt stormwater network 'discharges' during summer low flows. The stormwater network was identified as a possible source of nitrogen to the Hutt River during summer low flows with groundwater infiltration and sewer leaks as potential contaminant sources.

Water samples were collected for nutrient analysis from nine stormwater catchments at their Hutt River outlets (Figure 4.14) on three separate occasions (18 December 2014, 22 February 2015 and 17 March 2015) in 2014/15 summer base flow conditions, with the assistance of Wellington Water Ltd (WWL). Sampling on 17 March 2015 was targeted as a wet weather event but the forecasted rain did not arrive before the pre-scheduled sampling run. The sampling coincided with WWL's monthly microbiological water quality monitoring programme.

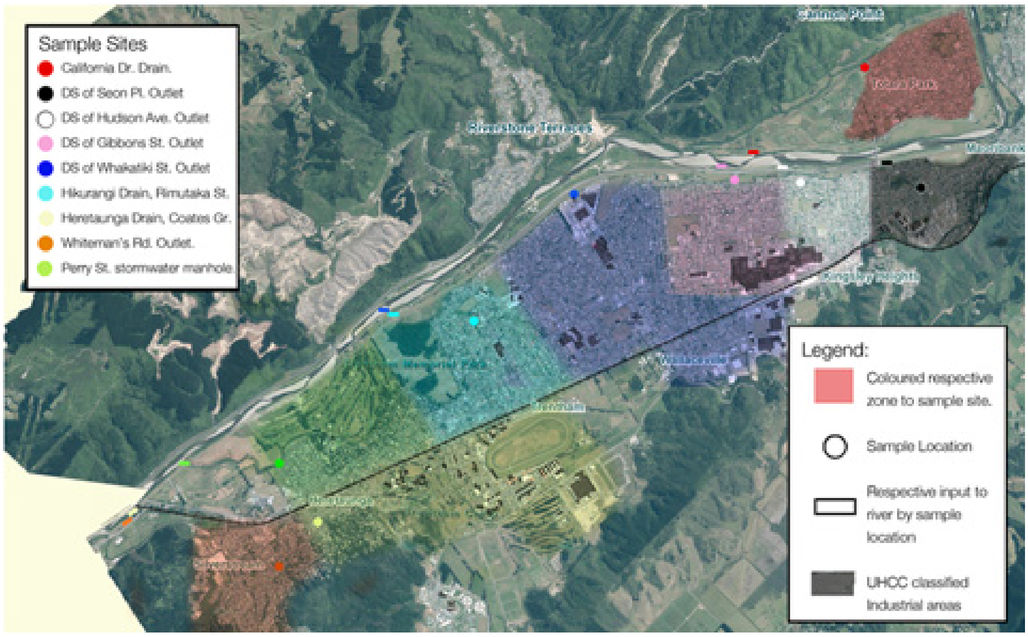

Figure 4.14: Upper Hutt stormwater catchments and monitoring sites sampled by Wild (2015) in summer 2014/15

Nitrogen concentrations were relatively low in all eight flowing stormwater outlets. Concentrations of DIN ranged between 0.019 mg/L in the Hikurangi Drain at Rimutaka Street to 2.07 mg/L downstream of the California Drive outlet (Table 4.7), with the exception of California Drive outlet which drains the suburb of Totara Park. California Drive had a dry weather median TN concentration of 2.3 mg/L, substantially higher than samples taken from the other stormwater zones. WWL is currently investigating the source of this nitrogen at California Drive, although the flow was very low (not measured), meaning the contribution to Hutt River nitrogen loads during summer low flow is likely to be minimal. Similarly, the flow from all the nine stormwater outlets was minor, and in some cases, there was no flow (eg, downstream of the

Whakatikei Street outlet). Phosphorus concentrations were also low (DRP ≤ 0.054) at the eight flowing stormwater outlets.

Table 4.7: Nitrogen and phosphorus concentrations in water samples taken from eight stormwater outlets in Upper Hutt over three low flow sampling rounds during summer 2014/15. Median, minimum and maximum results are presented. DIN = dissolved inorganic nitrogen, TN = total nitrogen, DRP = dissolved reactive phosphorus and TP = total phosphorus. Downstream (D/S) of Hudson Avenue outlet has been excluded as it had no flow on all three sampling occasions while D/S of Whakatikei St outlet was only flowing on one occasion

Site		DIN (mg/L)	TN (mg/L)	DRP (mg/L)	TP (mg/L)
Whitemans Rd	Med	0.090	0.23	0.025	0.04
	Min	0.065	0.21	0.021	0.03
	Max	0.246	0.45	0.027	0.05
Heretaunga Drain at Coates Gr	Med	0.102	0.64	0.031	0.09
	Min	0.072	0.39	0.028	0.07
	Max	0.467	0.97	0.031	0.10
Perry St stormwater PS	Med	0.604	0.69	0.042	0.08
	Min	0.351	0.44	0.004	0.07
	Max	0.616	1.01	0.046	0.13
Hikurangi Drain at Rimutaka St	Med	0.141	0.39	0.035	0.06
	Min	0.019	0.38	0.026	0.04
	Max	0.255	0.74	0.044	0.11
D/S of Gibbons St outlet	Med	0.154	0.64	0.041	0.10
	Min	0.068	0.46	0.024	0.09
	Max	0.391	0.72	0.054	0.12
D/S of Whakatikei St outlet	Med	0.037	0.31	0.026	0.05
	Min	NA	NA	NA	NA
	Max	NA	NA	NA	NA
D/S of California Dr outlet	Med	1.873	1.96	0.012	0.01
	Min	1.708	1.94	0.012	0.01
	Max	2.103	2.30	0.013	0.02
D/S of Seon Pl outlet	Med	0.092	0.52	0.017	0.05
	Min	0.027	0.40	0.012	0.03
	Max	0.167	1.01	0.031	0.12

Overall, the investigation suggested that nutrient inputs to the Hutt River from Upper Hutt stormwater outlets during summer base flow are low. However, further investigation is needed to assess if there is any nutrient inputs from stormwater or sewer infrastructure directly to groundwater in the Upper Hutt area. Modelling undertaken by WWL suggests infrastructure is in 'good shape' and there is likely to be a minimal loss to groundwater (Gunaratna[18], pers. comm. 2015).

[18] Bandula Gunaratna, Engineer, Wellington Water Ltd.

(b) Land use investigation

This research project consisted of literature reviews, GIS mapping and calculations to build a model of nitrogen inputs to groundwater in Upper Hutt (Kelly 2015) for the purpose of identifying dominant sources of nitrogen to the unconfined groundwater.

The New Zealand Land Cover Database (LCDB, v4, MfE 2012) and UHCC land zones were used to identify land uses in Upper Hutt. For each identified land use, nitrogen application rates were assigned. Application rates were based on values from international studies and actual fertilisation data for Trentham Race Course, the Royal Wellington Golf Course and the UHCC (for managed parks). Nitrogen leaching rates were also calculated, based on the different land uses and aquifer characteristics. From these data, the total amount of nitrogen entering the unconfined Upper Hutt aquifer was calculated. Combined with flow for groundwater upwelling in the Whakatikei–Taita Gorge reach, a mean groundwater nitrogen concentration of 0.83 mg/L was estimated. Coincidently, this corroborates with the TN concentrations from the riverbed/groundwater samples collected in the groundwater nutrient section (see Section 4.4.4d).

Based on model outputs parks, Trentham Race Course and golf courses are the land uses with the highest loss of nitrogen to groundwater per unit area. These land uses are potential targets for nitrogen management. A number of recommendations were made to improve the assessment, including determining actual fertilisation rates for residential lawns and vegetable gardens in Upper Hutt.

4.4.6 Mangaroa and Pakuratahi river investigations

The assessment of nutrient loads to the Hutt River from its four main tributaries in Section 4.4.3 identified the Pakuratahi and Mangaroa rivers as the largest contributors of plant available nitrogen (ie, DIN). On 29 January 2015 (during stable summer low flow conditions) and 30 June 2015 (during winter base flows) concurrent flow gauging and water sampling was undertaken at multiple Pakuratahi and Mangaroa river catchment sites to investigate potential nutrient (principally nitrogen) sources.

(a) Pakuratahi River catchment investigation

To examine nutrient inputs to the Pakuratahi River eight sites were examined[19], including four sites on the main stem of the river and one on each of the four major tributaries; Rimutaka Stream (site P-3), Puffer Stream (site P-4), Kaitoke Stream (site P-5) and Farm Creek (site P-6; Figure 4.15). The four major Pakuratahi River tributaries were all located in a ~2.8 km reach between Pakuratahi River at SH2 (site P-2) and the most downstream site, Pakuratahi River at 50 m below Farm Creek (site P-7). The Pakuratahi at River at Truss Bridge (site P-1) was selected as an upstream reference site.

19 Pakuratahi 50 m d/s of Water Works Road (site P-4a) was only sampled on 30 June 2015.

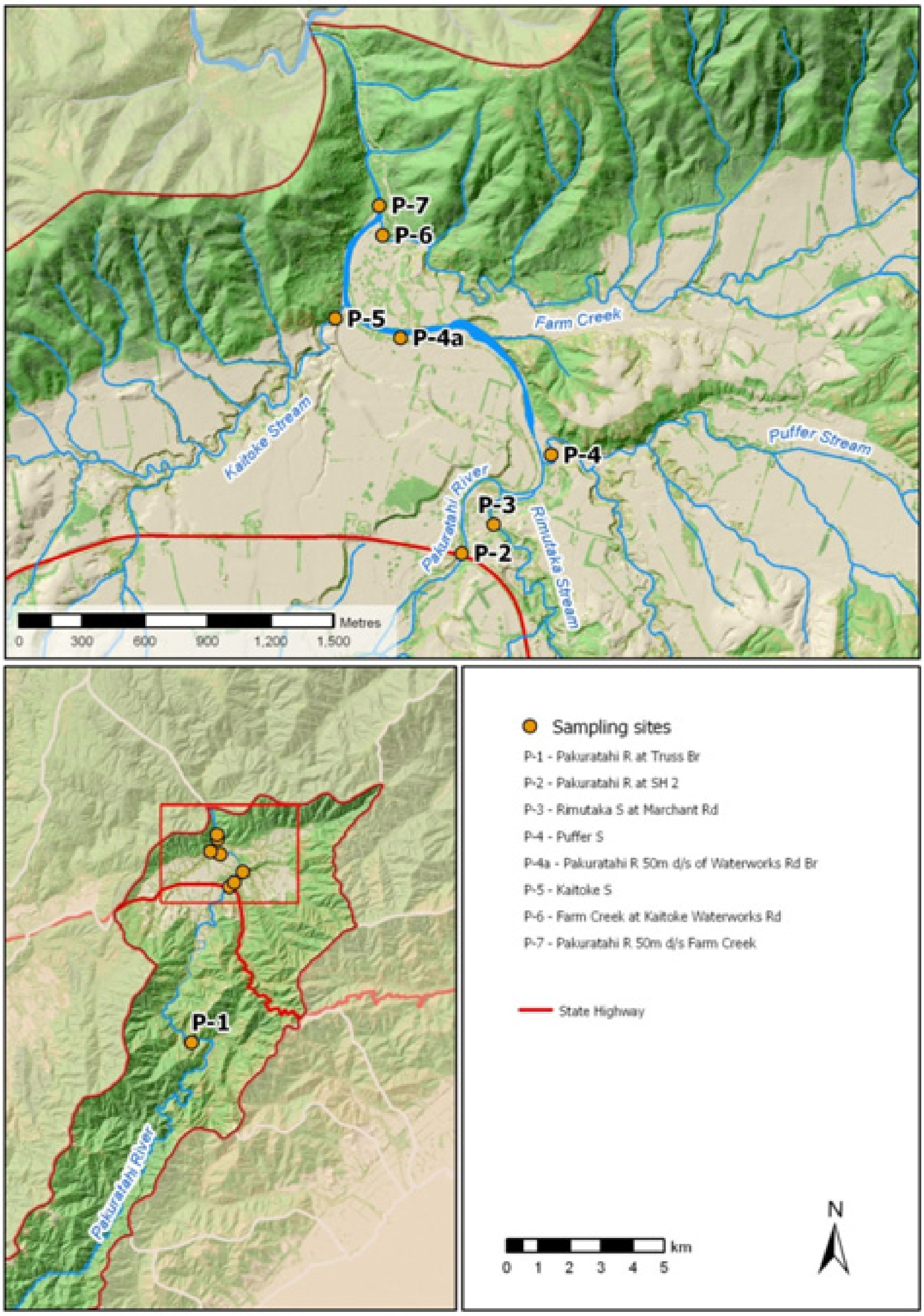

Figure 4.15: Map of Pakuratahi River catchment monitoring sites sampled in summer and winter 2015

Pakuratahi River DIN concentrations in the ranged between 0.005 mg/L at Truss Bridge (site P-1) in summer and 0.34 mg/L 50m below Farm Creek (Site P-7) in winter (Table 4.8). Of the tributaries sampled, DIN concentrations ranged between 0.039 mg/L in the Rimutaka Stream in summer and 0.62 mg/L in the Kaitoke Stream in summer. Concentrations of TN followed a similar pattern. Both DRP and TP concentrations were below 0.009 mg/L at all sites apart from the sample taken from Farm Creek during winter which had a TP concentration of 0.011 mg/L.

Table 4.8: Flow and nutrient concentrations in the Pakuratahi River catchment during one-off sampling in summer (29 January) and winter (30 June) 2015. DIN = dissolved inorganic nitrogen, TN = total nitrogen, DRP = dissolved reactive phosphorus and TP = total phosphorus

Site name and no.	Flow (L/s)	DIN (mg/L)	TN (mg/L)	DRP (mg/L)	TP (mg/L)
Summer sampling round					
Pakuratahi R at Truss Br (P-1)	151	0.005	0.06	0.002	0.002
Pakuratahi R at SH 2 (P-2)	166	0.067	0.17	0.004	0.002
Rimutaka S at Marchant Rd (P-3)	8	0.039	0.11	0.006	0.006
Puffer S (P-4)	7	0.220	0.31	0.009	0.008
Kaitoke S (P-5)	21	0.570	0.72	0.001	0.008
Farm S at Kaitoke Waterworks Rd (P-6)	37	0.173	0.23	0.009	0.008
Pakuratahi R 50m d/s Farm Crk (P-7)	299	0.330	0.43	0.004	0.002
Winter sampling round					
Pakuratahi R at Truss Br (P-1)	758	0.026	0.06	0.003	0.005
Pakuratahi R at SH 2 (P-2)	907	0.120	0.15	0.003	0.004
Rimutaka S at Marchant Rd (P-3)	155	0.290	0.36	0.004	0.006
Puffer S (P-4)	213	0.310	0.39	0.004	0.006
Pakuratahi R 50m d/s of Waterworks Rd Br (P-4a)	1,638	0.230	0.30	0.003	0.006
Kaitoke S (P-5)	211	0.620	0.74	0.005	0.009
Farm Crk at Kaitoke Waterworks Rd (P-6)	236	0.280	0.34	0.009	0.011
Pakuratahi R 50m d/s Farm Crk (P-7)	2,545	0.340	0.40	0.004	0.006

The instantaneous DIN and TN loads in the main-stem of the Pakuratahi River increased substantially from the most upstream site at Truss Bridge (site P-1) to the most downstream site 50 m below Farm Creek (site P-7) in both the summer and winter base flow sampling rounds (Figure 4.16). The majority of this increase in load occurred in a 2.8 km reach between SH2 (site P-2) and 50 m below Farm Creek (site P-7). In this reach, the instantaneous DIN load increased from 11 and 19 mg/s to 99 and 865 mg/s in the summer and winter sampling rounds, respectively (Figure 4.16). Together the four major tributaries and upstream Pakuratahi River site (site P-2) only contributed 32% (31.4 mg/s) and 48% (307.9 mg/s) of the DIN load as measured below Farm Creek (site P-7) for the summer and winter sampling rounds, respectively (Figure 4.17). Thus, 68% (67 mg/s) and 52% (449 mg/s) of the DIN load at 50 m below Farm Creek (site P-7) was unaccounted for in the summer and winter sampling rounds, respectively. Similarly, over 50 and 57% of the TN load as measured at 50 m below Farm Creek (site P-7) could not be accounted for by tributary inputs in the summer and winter sampling rounds, respectively (Figure 4.17).

In the Pakuratahi River reach between SH2 (site P-2) and 50 m below Farm Creek (site P-7) there was a 133 L/s and 1,638 L/s increase in flow in the summer and winter sampling rounds, respectively (Figure 4.16). In the summer sampling round 73 L/s (55%) of this increase in flow was unaccounted for (ie, it could not be attributed to the four measured tributaries in this reach).

Similarly, in the winter sampling round 823 L/s (50%) of the flow increase was unaccounted for. Small ungauged tributaries in this reach may be contributing to this flow and nitrogen load increase but any flow and nitrogen inputs attributable to these would only be minor; the largest Pakuratahi tributary, Farm Creek (site P-6), in the summer sampling round only had a flow of 37 L/s. Thus, the source of the unaccounted flow and nitrogen in the lower Pakuratahi River (below SH2) is most likely groundwater.

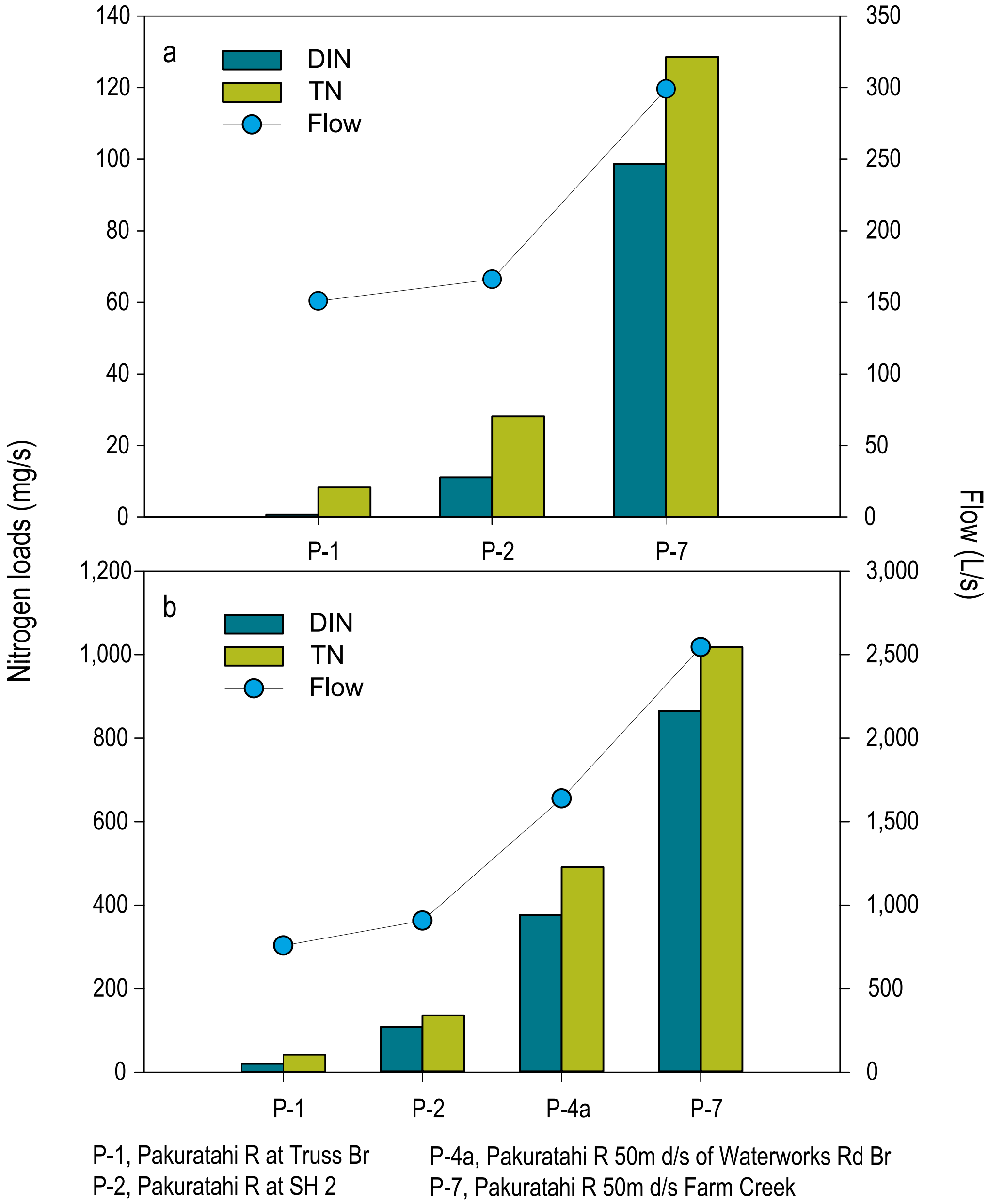

Figure 4.16: River flow and nitrogen loads for the Pakuratahi River as measured on (a) 29 January 2015 and (b) 30 June 2015. DIN = dissolved inorganic nitrogen and TN = total nitrogen. Note the different scales of the *y*-axes

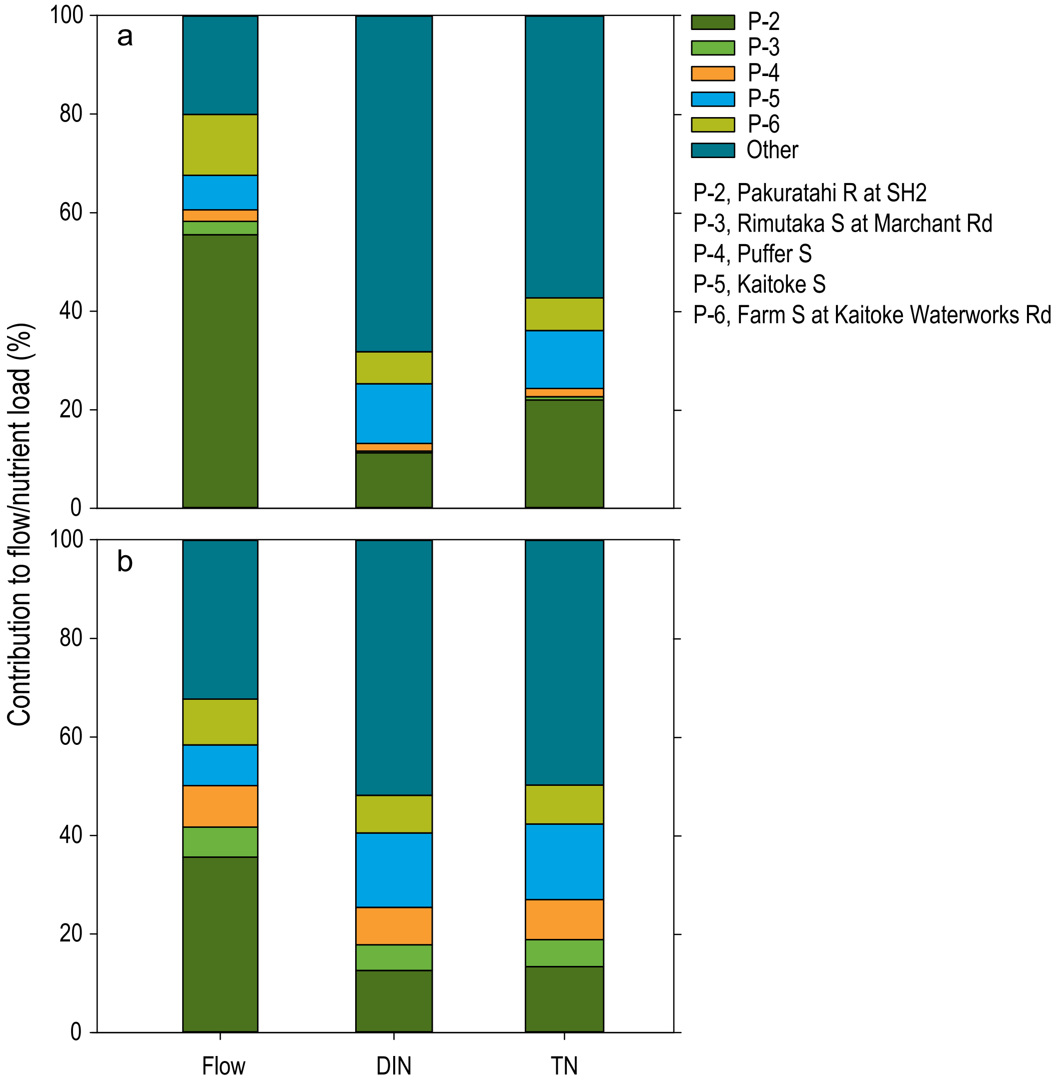

Figure 4.17: Flow and contribution of the four main tributaries and Pakuratahi River at SH2 to the instantaneous dissolved inorganic (DIN) and total nitrogen (TN) loads at downstream Pakuratahi River at 50 m d/s Farm Creek on (a) 29 January 2015, and (b) 30 June 2015

All four main tributaries of the lower reaches of the Pakuratahi River have significant agricultural land use in their catchments. According to the LCDB (v5, MfE 2014b), high producing pastoral land cover accounts for 43% of the Kaitoke Stream catchment, 25% for the Puffer Stream catchment, 18% of Farm Creek catchment and 9% of Rimutaka catchment. Nitrogen leaching in these areas may be contributing to groundwater nitrogen concentrations and, thus, nitrogen loads in the lower Pakuratahi River. Further investigation is required to identify groundwater gaining reaches in the lower reaches of the Pakuratahi River and the sources of nitrogen to groundwater.

Instantaneous phosphorus (DRP and TP) loads and concentrations were relatively low across all sites (Table 4.8). The DRP load was highest (10.2 mg/s) in the winter sampling round at 50m d/s of Farm Creek (P-7); the corresponding DRP concentration was only 0.004 mg/L. Of the four Pakuratahi tributaries, Farm Creek (P-6) had the highest DRP concentration (0.009 mg/L, summer sampling round) and Kaitoke Stream (P-5) the lowest (0.0014 mg/L, summer sampling round; Table 4.8). Instantaneous DRP loads increased by ~five-fold in both the summer and winter sampling round, respectively (phosphorus load data not presented).

(b) Mangaroa River investigation

To investigate nutrient inputs to the Mangaroa River eight sites were examined, including six sites on the Mangaroa River itself and the two tributary sites; Black Stream (M-3) and Blaikie Stream (M-7; Figure 4.18). Black Stream was selected because it drains the Waipango Swamp which is rich in organic material and tannins, while Blaikie Stream was selected because the former Gabities Piggery is located in the catchment and previously has been identified as a possible contributing factor to poor water quality in the Mangaroa River (eg, Milne & Perrie 2005). The Mangaroa River main-stem sites were spread across the length of the river with the greatest focus on the middle and lower reaches.

Concentrations of DIN in the main-stem of the Mangaroa River ranged between 0.08 mg/L at Mangaroa Valley Road (site M-2) in summer and 0.72 mg/L at Russell Road (site M-1) in winter (Table 4.9). Of the two tributaries sampled, DIN concentrations ranged between 0.02 mg/L in Blaikie Stream (M-7) in summer and 0.62 mg/L in Blaikie Stream in winter. Concentrations of TN followed a similar pattern. Both DRP and TP concentrations were below 0.04 mg/L at all main-stem sites. Black Stream (site M-3) had the highest TP concentration (0.27 mg/L; summer sampling round).

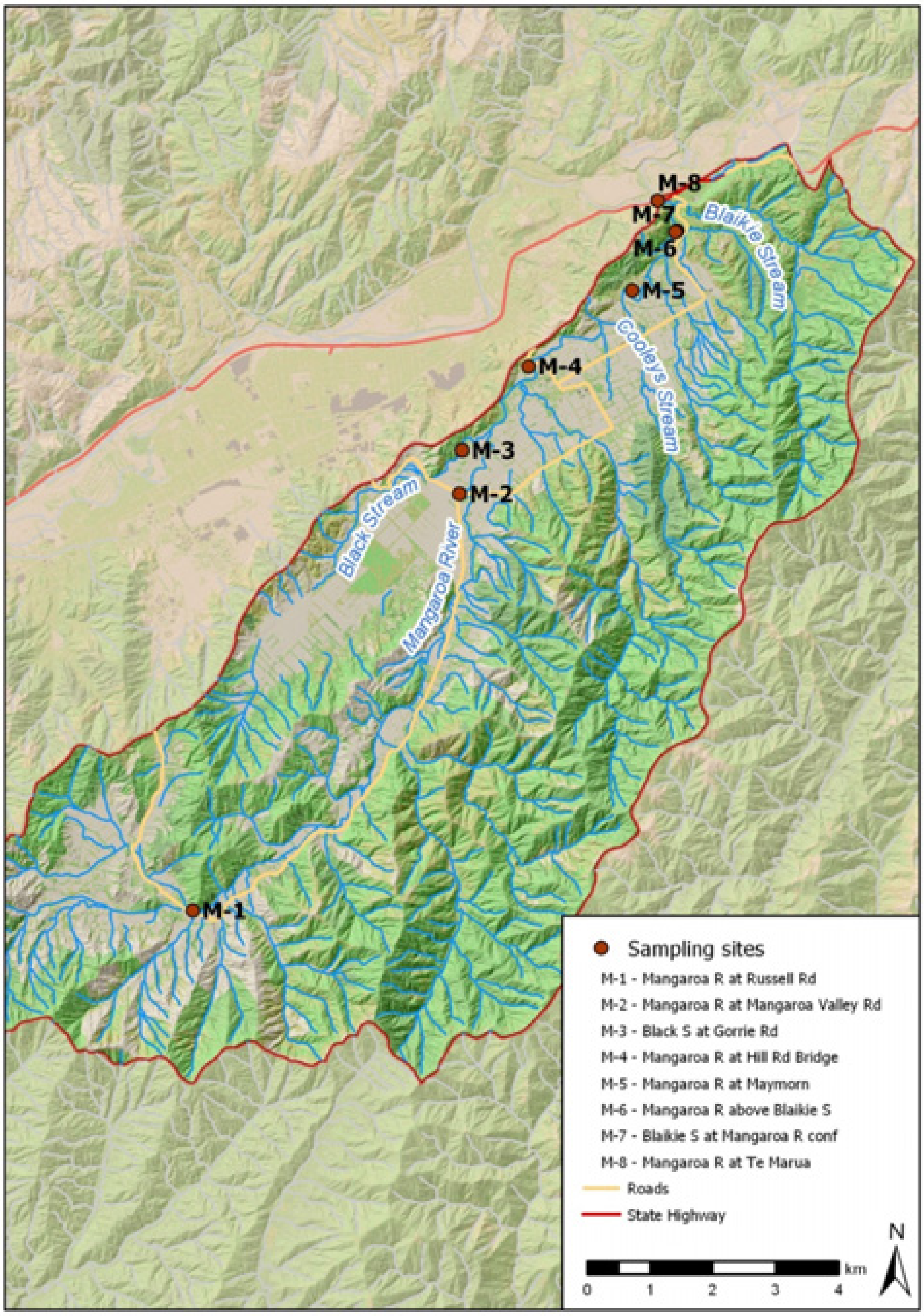

Figure 4.18: Map of Mangaroa River catchment monitoring sites sampled in summer and winter 2015

Table 4.9: Flow and nutrient concentrations in the Mangaroa River catchment during one-off sampling in summer (29 January) and winter (30 June) 2015. DIN = dissolved inorganic nitrogen, TKN = total Kjeldahl nitrogen, TN = total nitrogen, DRP = dissolved reactive phosphorus, TP = total phosphorus and TOC = total organic carbon

Site name and no.	Flow (L/s)	DIN (mg/L)	TKN (mg/L)	TN (mg/L)	DRP (mg/L)	TP (mg/L)	TOC (mg/L)
Summer sampling round							
Mangaroa R at Russell Rd (M-1)	42	0.20	0.23	0.42	0.014	0.038	4.5
Mangaroa R at Mangaroa Valley Rd (M-2)	103	0.08	0.17	0.24	0.004	0.012	2.7
Black S at Gorrie Rd (M-3)	12	0.60	1.39	1.51	0.115	0.270	46
Mangaroa R at Hill Rd Bridge (M-4)	98	0.49	0.16	0.65	0.013	0.022	4.8
Mangaroa R at Maymorn (M-5)	185	0.64	0.18	0.82	0.004	0.010	2.6
Mangaroa R above Blaikie S (M-6)	249	0.55	0.13	0.68	0.005	0.012	2.4
Blaikie S at Mangaroa R conf (M-7)	2	0.02	0.38	0.39	0.050	0.078	7.1
Mangaroa R at Te Marua (M-8)	298	0.40	0.14	0.54	0.005	0.010	2.2
Winter sampling round							
Mangaroa R at Russell Rd (M-1)	329	0.72	0.22	0.91	0.007	0.024	3.6
Mangaroa R at Mangaroa Valley Rd (M-2)	1,237	0.38	0.10	0.48	0.005	0.011	2.1
Black S at Gorrie Rd (M-3)	178	0.45	1.10	1.26	0.086	0.111	41
Mangaroa R at Hill Rd Bridge (M-4)	1,678	0.43	0.18	0.58	0.013	0.018	6.8
Mangaroa R at Maymorn (M-5)	2,305	0.25	0.16	0.40	0.013	0.027	4.4
Mangaroa R above Blaikie S (M-6)	2,377	0.70	0.18	0.87	0.012	0.017	5.0
Blaikie S at Mangaroa R conf. (M-7)	37	0.68	0.16	0.84	0.012	0.018	4.9
Mangaroa R at Te Marua (M-8)	2,533	0.67	0.16	0.83	0.012	0.018	4.0

Instantaneous DIN loads increased 14 and 7-fold from the most upstream site Russell Road (M-1) to the most downstream site at Te Marua (M-8) for the summer (29 January 2015) and winter (30 June 2015) base flow sampling rounds, respectively (Figure 4.19). This increase in instantaneous DIN load corresponded with a ~7-fold increase in flow on both sampling occasions. In the summer sampling round the largest increase in DIN load occurred in the middle to lower reaches of the Mangaroa River between the Mangaroa Valley Road Bridge (site M-2) and Maymorn (site M-5); in this 6.8 km long reach DIN load increased 110 mg/s (Figure 4.19). Most of this DIN load increase (70 mg/s) occurred between Hill Road Bridge (site M-4) and Maymorn (site M-5). In contrast, the largest increase in DIN load in the winter sampling round occurred in the lower Mangaroa River between Maymorn (site M-5) and Mangaroa River above Blaikie Stream (site M-6; Figure 4.19). In this small ~1.5 km reach the DIN load increased 1,088 mg/s with only a small increase in flow (72 L/s). Instantaneous TN loads followed a similar spatial trend as DIN loads for both sampling rounds.

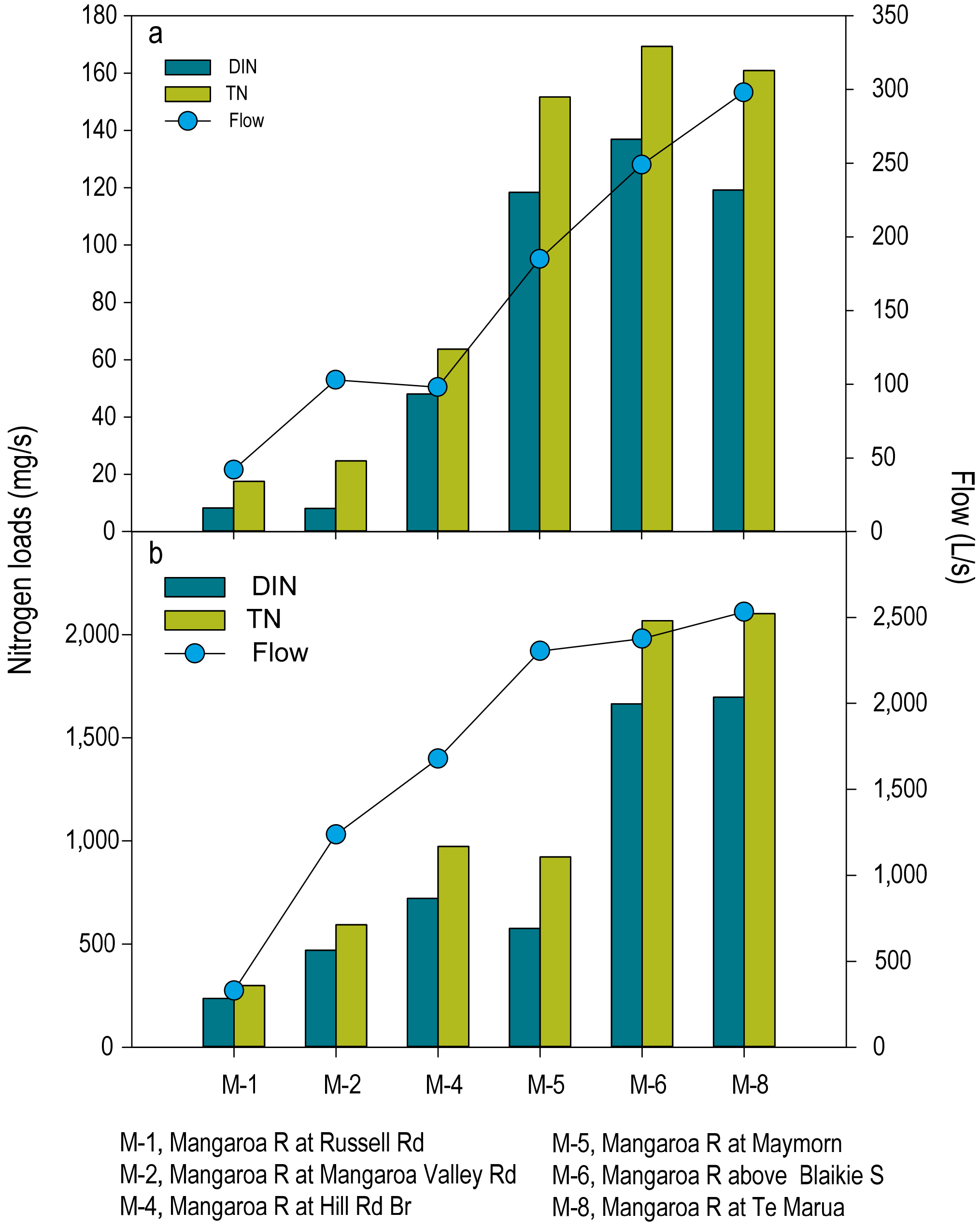

Figure 4.19: River flow and instantaneous dissolved inorganic nitrogen (DIN) and total nitrogen (TN) loads for six main-stem Mangaroa River sites on (a) 29 January 2015, and (b) 30 June 2015

Blaikie Stream, which contains the former Gabities piggery in its catchment, had instantaneous DIN loads of 0.04 and 25.2 mg/s for the summer and winter sampling rounds, respectively. These equate to 0.03 and 1.5% of the instantaneous DIN loads as measured at the Mangaroa River at Te Marua (site M-8) for the summer and winter sampling rounds, respectively. Similarly, Blaikie Stream made up only a small proportion of the TN load as measured at Mangaroa River at Te Marua. Thus, Blaikie Stream is not a large contributor of nitrogen load to the Mangaroa and Hutt rivers. Instantaneous DRP load at Blaikie Stream was 0.1 and 0.45 mg/s for the summer and winter sampling rounds, respectively. These equate to 7.1 and 1.5% of the instantaneous DRP loads as measured at the Mangaroa River at Te Marua for the summer and winter sampling rounds, respectively.

Black Stream, which drains the Waipango Swamp, had instantaneous DIN loads of 7.2 and 25 mg/s for the summer and winter sampling rounds, respectively. These equate to 15 and 4.8% of the instantaneous DIN loads as measured at the immediate downstream site Mangaroa River at Hill Road Bridge (site M-4) for the summer and winter sampling rounds, respectively. Instantaneous DRP loads were 1.4 and 15.3 mg/s for the summer and winter sampling rounds, respectively. These equate to 106.7 and 49.5% of the instantaneous DRP loads as measured at Mangaroa River at Hill Road Bridge for the summer and winter sampling rounds, respectively. Phosphorus from Black Stream is likely to be lost from the Mangaroa River through biogeochemical processes, including algal uptake and explains why the Black Stream DRP load was greater than that from the Mangaroa River at Hill Road Bridge in the summer sampling round.

In the summer sampling round (29 January 2015), the reasons for the large increase in nitrogen load between Mangaroa Valley Road (site M-2) and above Blaikie Stream (site M-5) are unclear. However, the following factors may be contributing to the observed increase in nitrogen loads (and will require further investigation):

- Nitrogen inputs from ungauged tributaries – larger Mangaroa River tributaries such as Cooleys and Colletts streams may be contributing to the large increase in nitrogen loads between sites M-4 and M-5. However, four sets of water samples collected by Victoria University students in 2014 from Cooleys Stream had a median DIN concentration of 0.07 mg/L and a maximum of 0.29 mg/L, indicating that loads from Cooleys Stream are unlikely to cause significant increases in Mangaroa River nitrogen loads (Spence et al. 2014).

- Nitrogen inputs from groundwater – further concurrent flow gauging and water sampling is required to elucidate the relative contributions from groundwater and tributaries in this reach. A radon survey could be used initially to identify groundwater upwelling reaches in the Mangaroa River.

- Nitrogen inputs from Black Stream and the Waipango Swamp/Peatland – Black Stream which drains the Waipango Swamp was found to have elevated organic nitrogen (inferred from TKN; Table 4.9). Nitrification, the biological process of converting (non-plant available) organic nitrogen to (plant available) inorganic nitrogen may be contributing to the increase in DIN loads in the Mangaroa River between Mangaroa Valley Road (site M-2) and Hill Road Bridge (site M-4). In addition, the Waipango Swamp may be contributing to groundwater nitrogen concentrations and therefore downstream Mangaroa River nitrogen loads.

On the winter base-flow sampling round instantaneous nitrogen loads increased substantially in the ~1.5 km reach between Maymorn (site M-5) and the Blaikie Stream confluence (site M-6). To achieve an increase of 1,088 mg/s DIN load with a 72 L/s gain in flow between Maymorn and Blaikie Stream, a

DIN concentration of 15 mg/L would be required. This is an extremely high nitrogen concentration. It seems unlikely that this increase is the result of groundwater inputs given the small increase in flow and the large groundwater nitrogen concentration required. Bore R27/6833 (Mangaroa School) sampled as part of the GWRC's Groundwater Quality SoE programme has never had a DIN concentration >5 mg/L since monitoring at this site began in 1996. Further investigation is needed to understand the increased instantaneous nitrogen load in the Mangaroa River between Maymorn (site M-5) and Blaikie Stream (site M-6) in winter.

Instantaneous phosphorus loads in the Mangaroa River were relatively low when compared to their instantaneous nitrogen load counterparts. In both the summer and winter sampling rounds, the largest increase in instantaneous phosphorus loads occurred between Mangaroa Valley Road (site M-2) and Hill Road Bridge (site M-4). In this reach, instantaneous DRP loads increased 3.6 and 3.3-fold for the summer and winter sampling rounds, respectively. This increase can be largely attributed to Black Stream (site M-3) that had elevated DRP concentrations (0.115 mg/L in summer; 0.086 mg/L in winter) compared to the other seven Mangaroa River catchment sites (Table 4.9). Blaikie Stream (site M-7), the only other tributary sampled, also had elevated phosphorus concentrations. However, this stream had a very low flow; 2 and 37 L/s in the summer and winter sampling rounds, respectively. Thus, Blaikie Stream is only a minor contributor to the overall Mangaroa River phosphorus load (data not presented).

4.4.7 Kaitoke Weir nutrient dilution investigation

Greater Wellington Regional Council currently has resource consent to take water from the Hutt River at the Kaitoke Weir down to 600 L/s for potable water supply. The hydraulic habitat assessment detailed in Section 4.3.3 demonstrated that reduced flow is unlikely to result in an increase in *Phormidium* growth; however, another possible effect of water abstraction at Kaitoke Weir is a reduction in the capacity of the river to dilute downstream nutrient inputs, particularly in the reaches downstream of the Pakuratahi and Mangaroa river confluences.

To investigate the potential effects of water abstraction from Kaitoke Weir on downstream nutrient concentrations (primarily nitrogen), a preliminary desktop assessment was undertaken utilising data from a variety of sources (Table 4.10). In this desktop assessment, calculations are based on summer-time flow and nutrient data presented for the Pakuratahi and Mangaroa rivers in Section 4.4.6, median nutrient values from the Hutt River at Kaitoke (GWRC/WWL consent monitoring) and NIWA flow data from Kaitoke Weir. Two scenarios are examined; 1, no water abstraction and 2, water abstraction down to 600 L/s. Both these scenarios and their results are presented in Table 4.11.

Table 4.10: Data sources, sites and variables used to estimate the effects of water abstraction from Kaitoke Weir on downstream Hutt River nutrient concentrations. DIN = dissolved inorganic nitrogen, TN = total nitrogen, DRP = dissolved reactive phosphorus and TP = total phosphorus

Data source	Period	Site(s)	Variables used
GWRC/WWL consent monitoring data	Fortnightly summer monitoring data (1 Nov to 30 Mar inclusive) from 2010/11 to 2013/14	• Hutt R at Kaitoke	• DIN • TN • DRP • TP
GWRC Rivers State of the Environment (RSoE) nutrient data	Monthly summer monitoring data (1 Nov to 30 Apr inclusive) from 1 Jan 2005 to 30 Apr 2014	• RS23, Pakuratahi R50m below Farm Creek • RS24, Mangaroa R at Te Marua	• DIN • TN • DRP • TP
GWRC Pakuratahi and Mangaroa River targeted Investigation data (see Section 4.3.5)	Summer low flow nutrient and flow data from 29 Jan 2015	• RS23, Pakuratahi R50m below Farm Creek RS24, Mangaroa R at Te Marua	• DIN • TN • DRP • TP • Flow
NIWA continuous flow site	1500hrs, 29 Jan 2015	• Kaitoke Weir	• Flow

Table 4.11: Predicted median Hutt River nutrient concentrations under two different water abstraction scenarios. Shaded boxes represent where flow and nutrient concentration estimates were calculated. Flow estimates were derived by summing all upstream flow sources, while nutrient estimates are the sum of the proportion contributions (based on flow) from each upstream source. Nutrient concentrations are in mg/L and flow in L/s. DIN = dissolved inorganic nitrogen, TN = total nitrogen, DRP = dissolved reactive phosphorus, TP = total phosphorus

	Scenario 1: No abstraction					Scenario 2: Abstraction down to 600 L/s				
Site	**Flow**	**DIN**	**TN**	**DRP**	**TP**	**Flow**	**DIN**	**TN**	**DRP**	**TP**
Hutt R at Kaitoke	1,165	0.020	0.075	0.005	0.009	600	0.020	0.075	0.005	0.009
Pakuratahi R	300	0.330	0.430	0.004	0.004	300	0.330	0.430	0.004	0.004
Hutt R D/S of Pakuratahi – flow and nutrient estimates	1,465	**0.083**	0.148	0.005	0.008	900	**0.123**	0.193	0.005	0.007
Mangaroa R	300	0.400	0.540	0.005	0.01	300	0.400	0.540	0.005	0.010
Hutt R D/S of Mangaroa – flow and nutrient estimates	1,765	**0.137**	0.214	0.005	0.008	1,200	**0.193**	0.280	0.005	0.008

Under scenario 1 (no water abstraction), median DIN concentrations are estimated to increase from 0.020 mg/L at Kaitoke to 0.083 mg/L downstream of the Pakuratahi River confluence, reaching 0.137 mg/L downstream of the Mangaroa River confluence. In contrast, when Hutt River flow is reduced to 600 L/s median DIN concentrations increased from 0.020 to 0.123 mg/L, reaching 0.193 mg/L downstream of the Pakuratahi and Mangaroa rivers, respectively. This equates to a 1.48-fold increase DIN concentration downstream of the Pakuratahi River and 1.41-fold DIN increase downstream of the Mangaroa River. Similar magnitudes of increase were also observed for TN (Table 4.11). Both DRP and TP exhibited only minor changes in median concentrations with distance downstream (Table 4.11).

The Pakuratahi and Mangaroa rivers are the two largest contributors of nitrogen load to the Hutt River of the four major Hutt River tributaries (see Sections 4.4.3 and 4.4.6). In this desktop assessment, Hutt River water abstraction down to 600 L/s at Kaitoke Weir is predicted to increase nitrogen concentrations downstream of both the Pakuratahi and Mangaroa river confluences. Hutt River DIN and TN concentrations were predicted to increase from 0.020 and 0.075 mg/L at Kaitoke Weir to 0.193 and 0.28 mg/L downstream of the Mangaroa river confluence, respectively. These concentrations are consistent with WWL's summer consent monitoring data where median DIN and TN concentrations downstream of the Mangaroa River confluence were 0.15 and 0.23 mg/L, respectively (see Section 4.4.1).

In the desktop assessment water abstraction increased the Hutt River DIN concentrations downstream of the Pakuratahi and Mangaroa rivers by over 1.4-fold. Below the Mangaroa River this resulted in DIN concentration estimate of 0.193. Thus, water abstraction at Kaitoke Weir may be resulting in modest increases in Hutt River DIN and TN concentrations downstream of both the Pakuratahi and Mangaroa rivers. This increase in nitrogen concentrations may be helping to facilitate *Phormidium* blooms downstream. Groundwater inputs and upwelling are not known to occur upstream of the Mangaroa River confluence; therefore, groundwater is not believed to be contributing to increased nitrogen concentrations. However, a detailed investigation is needed to examine what the effect of water abstraction is on downstream nutrient concentrations. These two assessments are limited by nutrient and flow data that have not been collected at the same time.

4.5 Summary

- Analysis of Hutt River flow records revealed that there has been no significant change in the annual frequency of flushing flows (defined as three times the median flow) and annual periphyton/cyanobacteria accrual periods from 1979 to 2013 inclusive.

- Physical habitat suitability analysis revealed that *Phormidium* has a broad physical habitat preference, persisting in a wide range of velocities, depths and substrate types. Hutt River hydraulic habitat modelling revealed only negligible changes in available *Phormidium* physical habitat and abundance with flow. The results of this modelling suggest that during an accrual period, decreasing flow is not likely to be a key driver of *Phormidium* growth.

- Analysis of fortnightly GWRC/Wellington Water Ltd summer consent monitoring data indicates that dissolved inorganic nitrogen (DIN) concentrations in the Hutt River increase over 10-fold between Kaitoke weir (median 0.015 mg/L) and Silverstream Bridge (median 0.22 mg/L).

In contrast, dissolved reactive phosphorus (DRP) concentrations remain relatively low along the entire length of the Hutt River.

- Temporal trend analysis performed on GWRC's Hutt River catchment RSoE data for the period July 2006 to June 2015 revealed that water column nitrogen concentrations decreased at most monitoring sites. For the Pakuratahi and Mangaroa rivers, DIN decreased by 0.009 (4.4%) and 0.023 (5.1%) mg/L/year (flow adjusted data), respectively.

- Annual nutrient load estimates, based on RSoE monthly monitoring data for the period July 2006 to June 2012, identified the Pakuratahi and Mangaroa tributaries as the biggest surface water contributors of nitrogen to the Hutt River, as measured at Manor Park. However, the four major tributaries as well as the Hutt River headwaters were only estimated to contribute approximately 60% of the DIN load to the Hutt River at this point.

- Concurrent flow gauging and water sampling in summer low flows demonstrated significant nitrogen input from groundwater to the Hutt River between the Whakatikei River confluence and Taita Gorge. In the 950 m stretch between Trentham Memorial Park and Heretaunga Golf Course DIN load in the Hutt River increased approximately 2-fold. Radon testing of riverbed water samples confirmed the presence of groundwater upwelling. Hyporheic riverbed/groundwater samples had elevated nitrogen concentrations compared to their surface water equivalents. In a sample taken from the riverbed at the boundary between Trentham Memorial Park and Heretaunga Golf Course on 18 February 2015 the DIN concentration was approximately 10-fold higher than the surface water sample taken at the same site (1.11 mg/L in the riverbed sample compared with 0.07 mg/L). These results indicate that groundwater inputs are responsible for the large increases in instream nitrogen concentrations in the Whakatikei-Taita Gorge reach.

- The sources of nitrogen to the unconfined Upper Hutt aquifer remain unclear. Stable isotope analysis of groundwater samples taken from the hyporheic zone of the river was unable to identify a clear nitrogen source. Age dating of selected riverbed/groundwater samples revealed that the groundwater was relatively young (between 1.8 and 2.8 years).

- Desktop analysis identified parks, golf courses and racecourses as potentially significant sources of nitrogen to groundwater in Upper Hutt. However, it is important to note that nitrate nitrogen concentrations in the unconfined aquifer are relatively low (~1 mg/L) and are well below the Drinking-water Standards for New Zealand maximum acceptable value of 11.3 mg/L (MoH 2008).

- There appears to be no significant contribution of nutrients to the Hutt River from 'stormwater' discharges in the Upper Hutt area during dry weather. However, the contribution of nutrients from wastewater infrastructure in Upper Hutt groundwater is unclear and requires further investigation.

- In the Pakuratahi River catchment, groundwater inputs downstream of SH2 were identified as the likely reason for a 6-fold increase in DIN concentrations observed in a 2.8 km reach between SH2 and below the Farm Creek confluence. Less than half of the DIN load in the lower reaches of the river could be attributed to inputs from the four major tributaries. More work is needed to quantify groundwater inputs of nutrients to the Pakuratahi River.

- Concurrent flow gauging and water sampling revealed nitrogen (DIN and TN) loads increase over 12-fold along the Mangaroa River between Russell Road and Te Marua. In both summer and winter sampling events, the majority of this increase occurred in the lower Mangaroa River catchment. Ungauged tributaries such as Cooleys and Colletts streams, the Waipango Swamp/Peatland and groundwater inputs may all be contributing to this nitrogen load increase. However, further investigation is required to ascertain what their relative contributions are. The large increase in DIN load (1,088 mg/s) over a 1.5 km reach recorded in the lower reaches of the Mangaroa on one sampling occasion in winter also requires further investigation.

- A preliminary assessment of the effect of water abstraction from the Hutt River at Kaitoke Weir on downstream nutrient concentrations demonstrated that abstraction has the potential to cause moderate increases (approximately 1.4-fold) in river nitrogen concentration downstream of the Pakuratahi and Mangaroa rivers. Further work is needed to thoroughly assess the effects of water abstraction on Hutt River nutrient concentrations over a wide range of flow conditions.

5. Discussion

This section synthesises the findings from Sections 2, 3 and 4 and discusses *Phormidium* bloom management. This section also sets out future research priorities that will further our understanding of *Phormidium* blooms in the Wellington Region.

5.1 Cyanobacteria abundance and toxicity in the Wellington Region

A diverse range of benthic cyanobacterial species persist naturally in low abundance (<10% cover of the riverbed) in rivers and streams throughout the Wellington Region. However, in stable conditions species from the *Phormidium* genera can form expansive blooms (>20% riverbed cover) in the larger gravel-bed rivers in Kapiti, Hutt Valley and central Wairarapa. This is of considerable concern to recreational users and managers of potable water supply takes because *Phormidium* can produce a range of powerful neurotoxins (specifically anatoxin) which have already been linked to at least 17 dog deaths as well as a suspected human illness in the Wellington Region Wood et al. 2007; Heath et al. 2010a; Quiblier et al. 2014). Across New Zealand there has now been over 100 dog deaths linked to anatoxin-producing *Phormidium* blooms (Wood/Heath unpub. data). In the Hutt River *Phormidium* blooms have been responsible for 11 dog deaths – most likely reflecting the river's popularity for recreation, its proximity to two large urban centres and its easy accessibility (via the Hutt River Trail). No *Phormidium* blooms have been recorded or reported in rivers along the eastern Wairarapa Coast or in the smaller urban streams in the region. However, there have been reports of benthic cyanobacteria in a number of small streams in the region, including the Wharemauku Stream (Kapiti Coast) and Hulls Creek (Upper Hutt).

Based on monitoring data available, the most frequent and expansive *Phormidium* blooms occur in the Hutt and Waipoua rivers. In these two rivers, *Phormidium* blooms can cover in excess of 80% of the riverbed at some monitoring sites. However, blooms do not occur every summer in these two rivers. For example, no blooms were recorded in the Hutt or Waipoua rivers over the 2013/14 or 2014/15 summers. Similar temporal variation has been observed in a number of river and stream sites across the region. The reasons for this temporal variation are not entirely clear, highlighting the need for further research investigating the factors driving *Phormidium* bloom occurrence.

It is not possible to assess long term trends in the occurrence of *Phormidium* blooms as cyanobacteria specific monitoring only began in 2005/06 following the initial Hutt River dog deaths (Milne & Watts 2007). As a result it is unclear whether the large number of dog deaths associated with *Phormidium* blooms in recent years is the result of an increase in the frequency and/or toxicity of blooms or whether *Phormidium*-related dog deaths occurred previously but went unreported and bloom occurrence has remained constant. It is possible that a combination of both scenarios has occurred. There are no clear trends in *Phormidium* bloom occurrence based on monitoring data collected between 2005/06 and 2014/15.

Anatoxins are the only cyanotoxins to have been detected in benthic cyanobacteria in the Wellington Region. In each instance where anatoxins were detected, *Phormidium* was either formally identified or believed to be the causative cyanobacterium. This is consistent with sampling across New Zealand where *Phormidium* remains the only known anatoxin-producing benthic cyanobacterium (Heath et al. 2010a; Quibler et al. 2013). Testing for cyanotoxins has generally been in response to *Phormidium* blooms because of their known ability to produce anatoxins; it's likely that testing of other benthic cyanobacteria species, which are widespread in the Wellington Region, will identify further cyanotoxin-producing species as well as cyanotoxins. However, given their low abundance, and therefore the low risk of exposure, other toxin-producing cyanobacteria are likely to present only a minor health risk to river users.

Testing of *Phormidium* mats from both the environment and in laboratory conditions has generally demonstrated that the majority of anatoxins remain intracellular (ie, are not released into the water column; Heath et al. 2014, 2016). However, a one-off water sample collected from the Waipoua River in 2009 was shown to contain elevated anatoxin concentrations (Wood et al. 2010). This suggests that, during periods of high *Phormidium* coverage, further investigation should be conducted to assess the risk posed from extracellular anatoxins to drinking water supplies and recreational users.

Recent research investigating anatoxin production has shown that not all strains of *Phormidium* are capable of producing anatoxins and that both non-toxic and toxic strains can co-exist (Heath et al. 2010a; Wood et al. 2010b; Wood et al. 2012a). Furthermore, different toxic genotypes can produce different concentrations and variants of anatoxins (Wood et al. 2012a). The proportions of toxic and non-toxic strains within a *Phormidium* mat as well as anatoxin concentrations are very dynamic and are currently not able to be predicted. This is apparent in the Wellington Region where anatoxin production and concentration are spatially and temporally variable among sites (refer Section 3.2). Advancements in understanding anatoxin production and what causes the dominance of toxin-producing strains is challenging because toxic and non-toxic strains are indistinguishable using morphological techniques (Heath et al. 2010a). Because of this complex spatial and temporal variability, *Phormidium* bloom research has tended to focus on the drivers leading to *Phormidium* bloom development rather than elucidating the drivers of anatoxin production and the dominance of toxin-producing strains.

5.2 *Phormidium* bloom drivers

As presented in detail in Sections 3 and 4, river flow (and associated physical drivers) and nutrients are two of the key drivers of *Phormidium* blooms.

5.2.1 River flow and physical drivers

The occurrence of 'flushing flows' is undoubtedly the key variable that regulates *Phormidium* (and all periphyton) abundance in rivers and streams. However, the magnitude of flow that actually generates flushing of *Phormidium* from the riverbed is not entirely clear. It is likely that the magnitude of flushing flow required varies greatly depending on the physical characteristics of the river (such as substrate size and stability) and *Phormidium* mat life-stage (Wood et al. 2014). This makes it difficult to assess the relationship between flushing flow and *Phormidium* using generic flushing flows such as the commonly used three times median flow.

Analysis of periphyton accrual (growth) periods between flushing flows showed that it is unclear how the length of time between flushing flows affects *Phormidium* growth in the Wellington Region. Longer accrual periods between large flushes (in this case >9x median flow events) were associated with a greater magnitude of *Phormidium* growth. However, there was no relationship between *Phormidium* growth and accrual period length for (smaller) >3x median flushing events. In addition, the difference in annual accrual statistics estimated for rivers across the region did not explain why some rivers in the Wellington Region experience *Phormidium* blooms and others do not. This suggests that factors other than frequency of flushing flows are potentially more important in determining where and when *Phormidium* blooms occur. Work from the across New Zealand supports this assertion with *Phormidium* growth having been correlated with particular nutrient concentration thresholds regardless of accrual period length (Wood & Young 2012; Wood et al. 2014). Further analysis of the relationship between accrual period and cyanobacterial abundance in the Wellington Region should involve identification of river or site specific flushing flow magnitudes. These can then be used to more thoroughly assess the effect of flushing flow frequency/accrual period on cyanobacteria abundance.

Additional physical variables not investigated in this report, such as climatic factors, may help to explain the observed year to year variability in *Phormidium* abundance. For example, year to year variation in ultraviolet (UV) radiation may have an effect on cyanobacteria growth. Many cyanobacteria possess two pigments (scytonemin and mycosporine-like amino acids) which help to protect them against UV radiation, providing *Phormidium* with a possible competitive advantage over other algal species in years with high solar radiation (Garcia-Pichel & Castenholz 1993; Bhandari & Sharma 2011). Furthermore, water temperature, which affects *Phormidium* growth rates (Tang & Vincent 1999), may be more optimal in some years than others. The timing and magnitude of rainfall events may also facilitate *Phormidium* bloom development. Overall, it is likely that a multitude of physical/climatic factors influence the variability in abundance of *Phormidium* among years and that the relationships between these are dynamic and complex.

Analysis of Hutt River flow data revealed that there had been no significant change in the annual frequency of flushing flows (>3x median flow) and average accrual periods from 1979 to 2013 inclusive. This indicates that the climatic factors that can affect precipitation and the frequency of flushing flows in the Hutt River have not altered greatly over this time period. In addition, a preliminary analysis of Hutt River hydrological recession curves indicated that natural and/or unnatural river channel modifications over the last 20 years has not resulted in increased Hutt River accrual period times.

Hydraulic habitat modelling, which assesses the physical habitat (depth, velocity and substrate type) that flora and fauna can occupy under different low flow conditions, revealed only negligible changes in available *Phormidium* physical habitat and abundance with flow in the Hutt River (Heath et al. 2012, 2015). The modelling showed *Phormidium* had a broad physical habitat preference persisting in a wide range of velocities, depths and substrate types. These modelling results suggest that factors other than flow are responsible for regulating abundance. This shows that water abstraction from rivers is unlikely to result in more suitable habitat for *Phormidium* growth. However, a preliminary assessment of the effect of abstraction from the Hutt River at Kaitoke Weir suggests that water abstraction during dry weather could be indirectly linked to increased *Phormidium* blooms by reducing the dilution capacity of the river and increasing water column nutrient concentrations.

5.2.2 Nutrients

Assessment of both annual and bloom-specific water column nutrient data suggests that *Phormidium* blooms in rivers in the Wellington Region occur under a wide range of nitrogen concentrations, but only occur in rivers with low soluble phosphorus concentrations (<0.01 mg/L). The ability to bloom in low phosphorus concentrations appears to give *Phormidium* a competitive advantage over other algal species. Similarly, *Phormidium* blooms in the Manawatu, Tasman and Canterbury regions also occur in low phosphorus concentrations (Wood and Young 2011, 2012; Wood et al. 2014; McAllister 2015). Thus, water column nutrient concentrations appear to be a strong driver of why *Phormidium* blooms occur at some river and stream sites across the region but not at others.

The occurrence of *Phormidium* blooms in low nutrient concentrations suggests that regulating the occurrence of *Phormidium* proliferations through nutrient control measures will be difficult. For example, in the Hutt River, GWRC's monitoring site opposite Manor Park Golf Club has the highest instream nutrient concentrations but, compared with similar rivers and streams across New Zealand, the median soluble phosphorus concentration is in the lowest quartile nationally, with concentrations often below analytical detection. While the median soluble nitrogen concentration is higher (around 0.2 mg/L), this is also still well below the national median.[20] Further, trend analysis for the period June 2006 to July 2015 also indicates that DIN concentrations in the Hutt River are generally declining.

Phormidium blooms do tend to be more frequent and of greater magnitude where DIN concentrations are highest in the middle reaches of the river, such as at Manor Park. Nitrogen inputs to the Hutt River have been identified to come from a wide range of sources based on data collected via long term monitoring programmes and specific investigations. The largest contributions of nitrogen have been identified as coming from the Pakuratahi and Mangaroa rivers, and unconfined groundwater entering the river in the reach between the Whakatikei River confluence and Taita Gorge (Figure 5.1).

[20] Based on information on the Land Air Water Aotearoa (LAWA) website (accessed April 2016) which presents river and stream water quality data from all regions of New Zealand. (http://www.lawa.org.nz/explore-data/wellington-region/river-quality/hutt/hutt-river-opposite-manor-park-golf-club/)

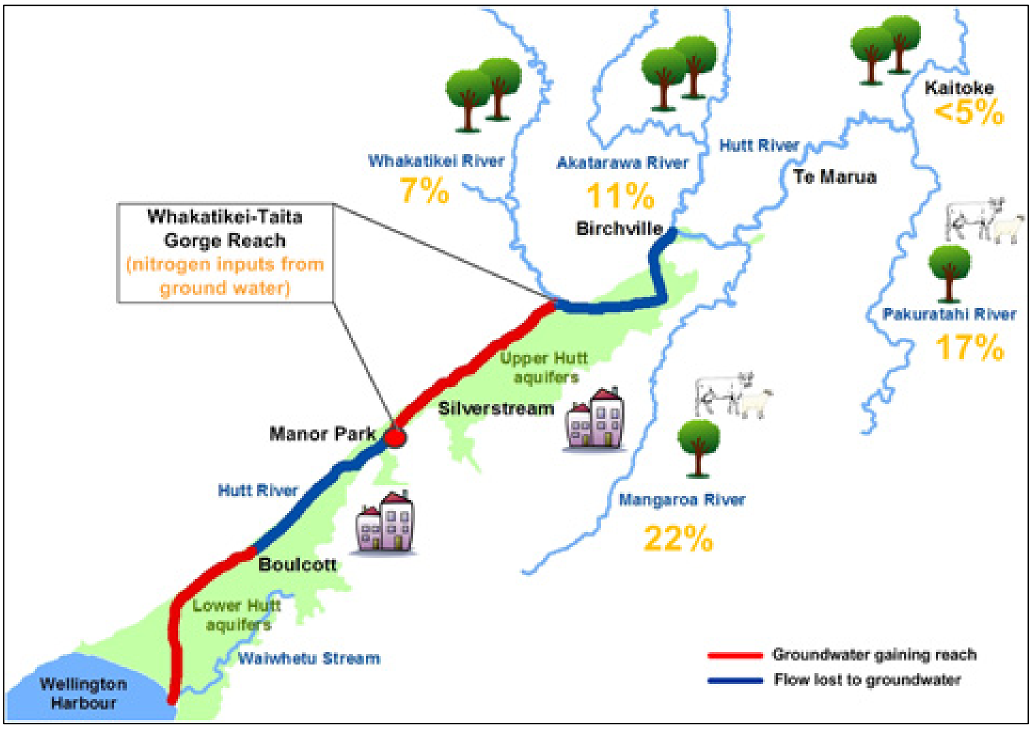

Figure 5.1: Schematic diagram of the Hutt River catchment highlighting the major surface and ground water nitrogen sources to the Hutt River Manor Park Golf Club (red dot) Where *Phormidium* cover tends to be highest

The Pakuratahi and Mangaroa rivers were identified to contribute approximately 17 and 22% of the nitrogen load as measured at Manor Park, respectively. In the Pakuratahi River catchment, groundwater inputs are likely to be responsible for a six-fold increase in DIN concentrations observed over a 2.8 km reach between State Highway 2 and below the confluence with Farm Creek. In the Mangaroa River catchment, nitrogen loads increase approximately 10 times in the lower reaches of the Mangaroa River, between Hill Road Bridge and upstream of Blaikie Stream; further research is needed to elucidate the contribution of groundwater, the Waipango peatland, tributaries such as Cooley and Colletts streams and potential point sources to the total nitrogen load. Encouragingly, analysis of trends in DIN concentrations in the lower Pakuratahi and Mangaroa rivers over the period July 2006 to June 2015 found significant decreases in concentrations (0.009 mg/L/year and 0.023 mg/L/y, respectively).

Groundwater upwelling in the Whakatikei–Taita Gorge reach of the Hutt River during summer low flows was found to increase the instream nitrogen load over 3-fold on three separate sampling occasions. Most of this increase occurred in a 950 m reach between Trentham Memorial Park and the Heretaunga Golf Course. Groundwater upwelling in this reach is likely to account for the majority of nitrogen load (as measured at the Hutt River at Manor Park) that cannot be attributed to the four major tributaries (Figure 5.1). Groundwater nitrogen concentrations, whilst low in a national context[21], were

[21] Nitrate nitrogen concentrations in the shallow unconfined aquifer are in the order of 1 mg/L (Tidswell et al. 2012), which is well below the national average of 1.7 mg/L reported by Daughney and Randall (2009). The national drinking water standard is 11.3 mg/L.

up to 10-fold higher than concentrations measured in the river in this reach. The sources of nitrogen to the unconfined Upper Hutt aquifer in are unclear. Stable isotope analysis of groundwater samples taken from the hyporheic zone of the river was unable to identify a clear nitrogen source. Desktop analysis of nutrient inputs from land use in the Upper Hutt area suggests that parks, golf courses and race courses are the biggest nitrogen contributors (Kelly 2015). The contribution of nutrients from Upper Hutt stormwater and wastewater infrastructure to groundwater is unclear and requires further investigation.

While instream nutrient concentrations are important, water column nutrient concentrations do not explain why *Phormidium* blooms occur at some river sites in one year but not in the next. For example, nutrient concentrations did not explain why *Phormidium* bloomed in the Hutt or Waipoua rivers in the 2013/14 and 2014/15 summers. Recent research supports our observations that *Phormidium* bloom development is considerably more complicated than simply being dependent on DIN and DRP concentrations. A myriad of interacting factors are now hypothesised to contribute to the variability of *Phormidium* abundance and that these can be extremely dynamic (Heath 2015; Quibler et al. 2013).

Sediment-bound nutrients may be an important driver of *Phormidium* growth. Recent research has shown that well developed *Phormidium* mats are capable of creating conditions that facilitate the release of nutrients, in particular phosphorus, bound to sediment that can become trapped and incorporated into the mat matrix (Wood et al. 2015a, b). This means well developed *Phormidium* may not be reliant on the water column for nutrients and can essentially self-regulate its access to nutrients. This may in part help explain why *Phormidium* mats/blooms are found in low water column phosphorus concentrations yet can still form expansive blooms. However, this does not explain how *Phormidium* mats establish in the first place when sediment has not had a chance to become trapped within the mat matrix. A recent investigation conducted in the Hutt River proposed bacterial pre-conditioning and mat formation on suitable riverbed substrate may facilitate *Phormidium* colonisation (Brasell et al. 2014). It is possible that sediment has already begun to be trapped in the extracellular polymeric substances matrix of a bacterial mat before *Phormidium* establishment. Variation in levels of deposited sediment or sediment bound nutrients may help explain why *Phormidium* blooms in some years but not others. If this is the case, then management of fine sediment and/or sediment-bound phosphorus entering large gravel-bed rivers in the Wellington Region may help to prevent bloom development.

It is possible that, in addition to nitrogen and phosphorus, other micronutrients such as iron, potassium and sodium may also be important drivers of *Phormidium* growth and abundance. In a study of the *Phormidium* mats in the Mangatainoka River (Manawatu), concentrations of iron, potassium, nickel, boron and aluminium were all higher (21, 13, 11, 8 and 5-fold, respectively) within the *Phormidium* mat water than the overlying bulk river water (Wood et al. 2015). These micronutrients may be associated with inputs of sediment, organic material (eg, from wetlands and wastewater treatment plants), surface water or groundwater. Hardland et al. (2013) showed that low (0.04 mg/L) and high (4.0 mg/L) iron concentrations inhibited *Phormidium* growth in batch culture experiments. Additionally, at high iron concentrations *Phormidium* no longer adhered to the culture container walls. This is an area requiring further research in the form of both laboratory and field studies.

5.3 *Phormidium* bloom management

It is very clear that there are multiple factors that contribute to *Phormidium* blooms in rivers in the Wellington Region and that the relationships between these factors are extremely dynamic and complex. Nonetheless, we do know that both river flow and nutrients are key factors and some aspects of these may be possible to manage.

In terms of flow, given flushing flows are the key regulators/removers of periphyton a future management option to control *Phormidium* blooms in troublesome rivers, such as the Hutt River, could be to utilise water storage in the upper river catchments to create an artificial flushing flow when *Phormidium* blooms are at dangerous levels. The duration and intensity of flow required to reduce *Phormidium* blooms to acceptable level and the volume of storage required to achieve this would have to be identified for each individual catchment. However, the abstraction or damming required to create artificial flushing flows of sufficient magnitude may also have significant negative impacts on instream fauna and flora and these would need to be considered in detail. Furthermore, the health and safety aspects of creating flushing flows would have to be carefully considered to protect recreational users.

Modelling of changes in the availability of suitable habitat for *Phormidium* growth with decreasing flow suggests that water abstraction from rivers is unlikely to result in more suitable habitat for *Phormidium* growth. However, increased water abstraction from rivers and streams and/or connected groundwater systems could indirectly result in increased occurrence of *Phormidium* blooms by reducing the capacity of water bodies to dilute nutrient inputs.

In terms of nutrients, management of catchment nitrogen sources in rivers, such as the Hutt River, may help reduce the incidence and magnitude of *Phormidium* blooms. In the Hutt River catchment, efforts should focus on:

- Nitrogen inputs on land in the recharge area for the unconfined Upper Hutt aquifer that discharges to the Hutt River in the Whakatikei–Taita Gorge reach, particularly intensively managed areas such as parks, golf courses and the Trentham Race Course. The contribution of leaking and/or cross connected wastewater and stormwater infrastructure to groundwater nutrient concentrations in this area is largely unknown and should also be investigated.

- Management of nitrogen inputs from agricultural and lifestyle blocks in the Pakuratahi River and Mangaroa River sub catchments.

Nitrogen is difficult to manage, being highly soluble (and hence easily leached from soils), and significant reductions may prove to be a challenge given nitrogen concentrations are already relatively low in both the Hutt River and the unconfined Upper Hutt aquifer. However, age-dating of selected riverbed/

groundwater revealed that the unconfined groundwater was between 2.3 and 2.8 years old. This suggests that the results from any management actions to reduce groundwater nutrient inputs are likely to be realised within a relatively short time period.

The role of nitrogen in driving *Phormidium* growth has implications for land use change in the Wellington Region. There are a number of rivers in the region that have water column phosphorus concentrations suitable for *Phormidium* growth (<0.01 mg/L soluble reactive phosphorus). However, many of these rivers currently have low DIN concentrations that are likely to be limiting bloom occurrence. The potential for increases in *Phormidium* bloom frequency needs to be considered when assessing effects of changing land use in the region. For example, an increase in nitrogen leaching could result in increased occurrence of *Phormidium* blooms in a number of rivers in the region including the Otaki River, several tributaries of the Hutt and Ruamahanga rivers, and rivers draining to the eastern Wairarapa coast (Figure 5.2).

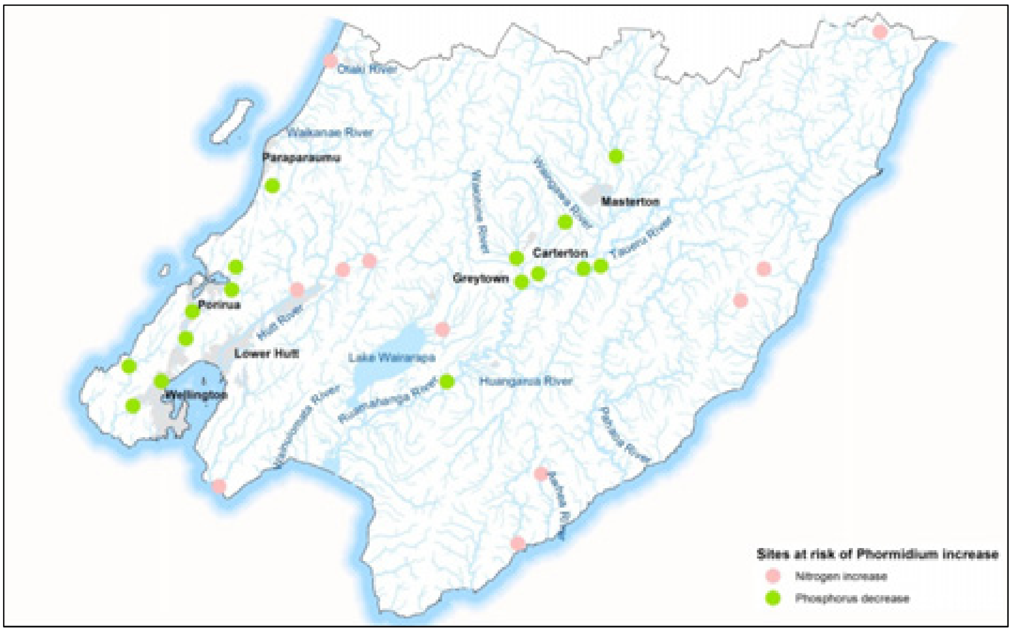

Figure 5.2: RSoE sites where there may be a potential risk of increased *Phormidium* bloom occurrence with change in land use or discharges resulting from either an increase in soluble nitrogen or a decrease in phosphorus inputs

With regard to phosphorus, *Phormidium* blooms occur in low water column phosphorus concentrations meaning that management actions taken to reduce dissolved phosphorus concentrations are unlikely to result in a decrease in *Phormidium* bloom occurrence. In contrast, it has been suggested that reducing DRP concentrations in rivers which currently have moderate to high nitrogen concentrations could also result in an increase in *Phormidium* blooms (Uytendaal & Ausseil 2013). This theory is untested and requires laboratory and field studies to substantiate it. However, if proven correct, a decrease in water column phosphorus concentrations could potentially result in more suitable conditions for *Phormidium* blooms in the Ruamahanga River and its tributaries as treated municipal wastewater discharges in the Wairarapa are progressively moved to land. Improvements in stormwater and wastewater discharges to Wellington and Porirua urban streams could also potentially result in increased *Phormidium* growth, although very large reductions to existing instream DRP concentrations would be needed to reach <0.01 mg/L.

Although reducing water column phosphorus concentrations is unlikely to result in a reduction in *Phormidium* bloom occurrence, it is possible that a reduction in sediment associated phosphorus would assist. Scientific evidence is building that associates fine instream suspended sediment with *Phormidium* bloom development in rivers and streams (Wood et al. 2014; Wood et al. 2016). Identification of the sources of fine sediment, especially sediment with high concentration of biologically available phosphorus content, may be an important step towards managing *Phormidium* bloom development. Potential sources of fine sediment to rivers and streams include agriculture, forestry and urban land. The role of sediment resuspension from instream channel maintenance, erosion and flood protection work in increasing the availability of sediment associated phosphorus to *Phormidium* also needs further investigation.

5.4 *Phormidium* blooms

With regard to managing health risk from *Phormidium* blooms in the Wellington Region, monitoring is currently focussed on assessment of *Phormidium* cover rather than toxin concentration. Because toxin production in *Phormidium* is spatially and temporally variable and can be very dynamic, with mats having been observed to go from non-toxic to toxic in short periods of time (Heath et al., 2011; Wood & Young 2011, 2012), it should be assumed that all *Phormidium* mats contain toxins. In addition, although toxin production is not necessarily related to *Phormidium* cover it is considered that the likelihood of contact with toxic *Phormidium* mats is likely to increase with increasing cover. For these reasons cyanobacteria cover is used as the basis for the interim guidelines for cyanobacteria in recreational fresh waters (MfE/MoH 2009).

The spatial and temporal variability in both *Phormidium* growth and toxicity highlighted in this report supports the need for a (continued) strong focus on communicating known risk at monitored sites and educating river users to identify *Phormidium* blooms wherever they may be. *Phormidium* or ‘toxic algae’ risk communication at freshwater recreation sites in the Wellington Region is a joint effort between GWRC, local councils and Regional Public Health and over the last 10 years a wide range of communication and education tools have been utilised. These include health warning and information signs, media releases, fact sheets, public seminars and a webpage dedicated to toxic algae warnings, photos and other information. More recently toxic algae information has been publicised using radio advertising and social media (Milne et al. 2014; Greenfield et al. 2015). In partnership with Victoria University, another initiative investigated in recent years has been the development of novel monitoring techniques such as Unmanned Aerial Vehicles (UAV; Hempel 2014). The use of UAVs has the potential to provide data over large stretches of rivers which will improve knowledge on bloom formation and real time risk.

5.5 Knowledge gaps and research priorities

A significant amount of knowledge has been gained on toxic *Phormidium* blooms in the Wellington Region over the last decade since the release of GWRC's technical report (Milne & Watts 2007) that documented the initial Hutt River 2005/06 summer dog deaths. However, there are also a number of knowledge gaps that remain. These are outlined below.

- There is a paucity of information on the spatial and temporal variability of *Phormidium* blooms in rivers and streams outside of the Hutt River as well as the environmental factors driving blooms. For example, no catchment wide nutrient input or flow information have been collated for the Waipoua River, which experiences regular *Phormidium* blooms. Targeted investigations in these other rivers and streams known to be affected by *Phormidium* growth may further help to elucidate the factors driving *Phormidium* blooms.

- There is a limited understanding of the effect of sediment deposition on the growth of *Phormidium* in New Zealand's rivers. This understanding will likely be improved by a Victoria University MSc project currently underway in the Wellington Region. However, further studies will be needed including assessment of sediment deposition rates and sources in Wellington rivers and streams, identification of sediment nutrient content (including iron, aluminium, calcium and manganese) and assessment of the correlation between bloom occurrence and sediment generated by flood events or instream works.

- Further work is needed to identify river/site specific flow magnitudes needed to remove cyanobacteria blooms in the Wellington Region. Once these are identified the effect of flushing flow frequency on cyanobacteria abundance can be more thoroughly assessed.

- A thorough assessment of the effects of water abstraction from Kaitoke Weir on Hutt River nutrient concentrations over a wide range of flow conditions is needed.

- While nutrient concentrations appear to explain, at least in part, why *Phormidium* blooms occur in some rivers but not others in the Wellington Region it is not clear what controls year to year variability in bloom occurrence. More frequency assessment of nutrient concentrations may be needed (eg, weekly or through the use of continuous nitrate sensors). Moreover, climatic factors (including changes in these as a result of global warming) such as UV radiation (linked to cloud cover), temperature and timing and magnitude of rainfall events have not been fully assessed in terms of the effects they have on year to year variability in *Phormidium* bloom occurrence.

- It is clear that nitrogen and phosphorus are key nutrients driving the occurrence of *Phormidium* blooms. However, little is known of the role of other nutrients such as iron, potassium and zinc in *Phormidium* growth. It is possible that these nutrients and their occurrence in groundwater, sediment and organic-rich discharges may play an important role in the occurrence of *Phormidium* blooms. This could be investigated further through laboratory studies, stream mesocosm experiments and field studies.

- The sources of nitrogen in the unconfined Upper Hutt aquifer are not clear. Further work is required to assess the inputs from different land uses and stormwater and wastewater infrastructure to help identify where management intervention is best targeted. Particular focus should be placed on identifying the source of groundwater nutrients entering the Hutt River between Trentham Memorial Park and Heretaunga Golf Course.

- Further investigation of nitrogen inputs from groundwater in the Pakuratahi River catchment and inputs from both tributaries and groundwater in Mangaroa River catchment is needed.

- There is a limited understanding of extracellular anatoxin concentrations (ie, toxin released by cells into water column) in the water column during expansive *Phormidium* blooms and more information is required to fully assess the potential health risks to river users.

- The factors that regulate toxin production and/or cause shifts in the relative abundance of toxic and non-toxic genotypes require further research. The ability to monitor/detect shifts in the relative abundance of toxic and non-toxic genotypes will be improved with the development of anatoxin specific real-time polymerase chain reaction (PCR) analysis currently being developed by as part of a Victoria University PhD project supported by GWRC.

- There is limited understanding of the effects of toxin-producing *Phormidium* blooms on the wider ecosystem. Preliminary research has indicated that macroinvertebrate community composition can be altered due to *Phormidium* mats (Heath unpub. data). Furthermore, an international investigation has shown that trout metabolism can become elevated when exposed to anatoxins (Osswald et al. 2013). The effects of anatoxin on macroinvertebrates are being explored further as part of a Victoria University PhD project supported by GWRC.

- The role other microorganisms (such as bacteria, fungi and archaea) from many functional groups and varying metabolic activities play in *Phormidium* bloom development and establishment needs investigation.

6. Conclusions

Toxic *Phormidium* blooms are widespread in large gravel-bed rivers in the Wellington Region and throughout New Zealand. They have been linked to 17 dog deaths in the Wellington Region and well over 100 across the country. The drivers that lead to spatial and temporal variability in anatoxin production are poorly understood. Thus, currently the best way of managing the risk from blooms is to reduce the abundance of *Phormidium* itself and to provide river users with resources that provide information on how to reduce exposure to blooms where they occur. Over the last 10 years knowledge of the environmental drivers of *Phormidium* blooms has progressed markedly. In the Hutt River and other rivers that experience frequent blooms, reductions in nitrogen, as well as fine sediment, may help to reduce *Phormidium* bloom occurrence and magnitude. Nevertheless, the multitude of physicochemical and biotic factors that regulate *Phormidium* bloom development are not fully understood and appear to be complex, dynamic and spatially and temporally variable. This highlights the need for further monitoring and investigation examining the environmental drivers of *Phormidium* bloom development as well as anatoxin production. Furthermore, management practices specifically designed to reduce *Phormidium* bloom development should continue to be explored and trialled.

6.1 Recommendations

We recommend:

- Increased assessment/monitoring of *Phormidium* blooms in rivers and streams outside of the Hutt River, such as the Waipoua River;
- Further examination of river/site specific flow magnitudes needed to remove cyanobacteria blooms to better identify the effect of flushing flow frequency on *Phormidium* abundance;
- Furthering our understanding of the relationship between fine sediment, phosphorus and *Phormidium* bloom development;
- Elucidating the sources of fine sediment, fine sediment nutrient content and instream fine sediment deposition rates, in particular in the Hutt and Ruamahanga River catchments;
- Investigating the sources of nutrients during initial *Phormidium* colonisation and establishment as well as the role bacterial facilitation plays in this process;
- Further examination of the effects of water abstraction from Kaitoke Weir on Hutt River nutrient concentrations over a wide range of flow conditions;
- Exploring in more detail the effects of climatic factors on *Phormidium* bloom development and year to year variability;

- Further investigation into the role micronutrients such as iron, potassium and zinc play in *Phormidium* bloom development;
- Further investigations of Hutt River nitrogen sources, in particular:
  - nitrogen inputs from tributaries and groundwater in the Pakuratahi and Mangaroa river catchments,
  - nitrogen inputs to the shallow unconfined Upper Hutt aquifer;
- More frequent assessment of water column nutrient concentrations to fully understand the relationship with *Phormidium* bloom development and anatoxin production; and
- Continued investment in risk communication and education initiatives about *Phormidium* blooms to improve public awareness and river user safety.

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Appendix 1: Monitoring and investigation site locations

GWRC Rivers State of the Environment (RSoE), Recreational Water Quality (RWQ) and Hutt River catchment targeted investigation sampling site coordinates (NZTM).

Site No.	Site name	Easting	Northing
River State of the Environment sites (RSoE)			
RS03	Waitohu Stream at Forest Pk	1787593	5483689
RS05	Otaki River at Pukehinau	1785426	5478749
RS06	Otaki River at Mouth	1777982	5485886
RS09	Waikanae River at Mangaone Walkway	1779974	5473638
RS10	Waikanae River at Greenaway Rd	1771223	5472915
RS11	Whareroa Stream at Waterfall Rd	1768074	5464532
RS13	Horokiri Stream at Snodgrass	1761804	5450652
RS14	Pauatahanui Stream at Elmwood Br	1761097	5446783
RS15	Porirua Stream at Glenside	1753289	5438364
RS16	Porirua Stream at Wall Park	1754366	5443031
RS17	Makara Stream at Kennels	1743530	5433635
RS18	Karori Stream at Makara Peak M.B. Park	1744213	5426874
RS19	Kaiwharawhara Stream at Ngaio Gorge	1749069	5431077
RS20	Hutt River at Te Marua Intake Site	1780071	5450158
RS21	Hutt River Opposite Manor Park Golf Club	1766679	5442285
RS23	Pakuratahi River 50m Below Farm Creek	1784607	5451677
RS24	Mangaroa River at Te Marua	1778543	5448643
RS25	Akatarawa River at Hutt Confluence	1776183	5449184
RS26	Whakatikei River at Riverstone	1772256	5446748
RS28	Wainuiomata River at Manuka Track	1768242	5430634
RS29	Wainuiomata River d/s of White Bridge	1757316	5415724
RS30	Orongorongo River at Orongorongo Station	1758930	5413094
RS31	Ruamahanga River at McLays	1818149	5485809
RS33	Ruamahanga River at Gladstone Bridge	1821208	5450327
RS34	Ruamahanga River at Pukio	1797832	5431010
RS35	Mataikona Trib at Sugar Loaf Rd	1871844	5490906
RS37	Taueru River at Gladstone	1824148	5450815
RS38	Kopuaranga River at Stewarts	1826760	5469569
RS41	Waingawa River at South Rd	1820716	5460649
RS43	Motuwaireka Stream at Headwaters	1852018	5450302
RS44	Totara Stream at Stronvar	1848025	5444916
RS45	Parkvale Trib at Lowes Res.	1818094	5458352
RS46	Parkvale Stream at Weir	1813515	5449469
RS47	Waiohine River at Gorge	1801889	5455995
RS48	Waiohine River at Bicknells	1810615	5448099
RS49	Beef Creek at Headwaters	1803963	5456398
RS50	Mangatarere Stream at SH 2	1809768	5452160
RS51	Huangarua River at Ponatahi Bridge	1807009	5435213

Site No.	Site name	Easting	Northing
RS52	Tauanui River at Whakatomotomo Rd	1790648	5414515
RS53	Awhea River at Tora Rd	1809951	5403289
RS54	Coles Creek Trib at Lagoon Hill Rd	1814020	5415217
RS55	Tauherenikau River at Websters	1797082	5439942
RS56	Waiorongomai River at Forest Pk	1779604	5430559
Recreational Water Quality sites (RWQ)			
	Otaki River at State Highway 1	1781059	5484512
	Waikanae River at State Highway 1	1773782	5472285
	Waikanae River at Jim Cooke Park	1772025	5472375
	Hutt River at Birchville	1775575	5448016
	Hutt River at Maoribank Corner	1775394	5446566
	Hutt River at Poets Park	1771462	5446092
	Hutt River at Silverstream Bridge	1767616	5443211
	Hutt River at Boulcott	1761038	5437628
	Hutt River at Melling Bridge	1759894	5436822
	Wainuiomata River at Richard Prouse Park	1764536	5429141
	Ruamahanga River at Double Bridges	1824287	5471781
	Ruamahanga River at Te Ore Ore	1825574	5463019
	Ruamahanga River at The Cliffs	1821476	5452180
	Ruamahanga River at Kokotau	1815756	5447191
	Ruamahanga River at Morrisons Bush	1808918	5441108
	Ruamahanga River at Waihenga Bridge	1804604	5436519
	Waipoua River at Colombo Rd Bridge	1825018	5462890
	Waingawa River at Kaituna	1812555	5470757
	Waiohine River at State Highway 2	1809662	5451705
Hutt River catchment investigation sampling sites			
HR1	D/S Whakatikei conf	1772135	5446480
HR2	Moonshine Br	1771010	5445624
HR3& RB4	Opposite Moonshine Hill Rd	1770619	5445312
HR4	Trentham Memorial Pk	1770123	5445046
HR5& RB5	Heretaunga Golf Course north boundary	1769865	5444836
HR6& RB6	Heretaunga Golf Course1	1769406	5444415
HR7& RB7	Heretaunga Golf Course	1769049	5444207
HR8& RB8	Opposite St Patricks College	1768343	5443787
HR9	U/S Silverstream Br	1767616	5443211
HR10	Taita Gorge	1766532	5441959
RB5a	Heretaunga Golf Course north boundary – 100m d/s	1769363	5444390
RB6b	Heretaunga Golf Course1 – 100m downstream	1769191	5444239
T1	Moonshine S at Hutt Conf	1770893	5445605
T2	Unnamed Hutt Trib at Heretaunga Golf Course	1768812	5444036
T3	Unnamed Hutt Trib at Heretaunga Golf Course1	1768565	5443842
T4	Unnamed Hutt Trib at SH2 bridge 9581	1768397	5443864
T5	Mawaihakona 1 S at Hutt conf	1768141	5443550
T6	Hulls Creek at Hutt conf	1767339	5442815

Site No.	Site name	Easting	Northing
UHA1	R27/6978 Coca Cola	1772082	5444731
UHA2	R27/7021 St Patricks	1768753	5443262
UHA3	R27/7004 GWRC - Tentham Memorial Park	1770649	5444445
UHA4	R27/7041 Trentham Race Course	1771497	5443787
UHA5	R27/7335 UHCC - Trentham Memorial Park	1770239	5444374
UHA6	South Pacific Tyres	1773410	5444945
UHA7	Upper Hutt Bowling Club	1774256	5445709
UHA8	On Track	1773824	5445164
UHA9	MacLean St	1772710	5444737
UHA10	Uni Bag	1772079	5444712
UHA11	Trentham Golf Course	1770908	5442897
UHA12	Heretaunga College	1772527	5444877
UHA13	Blockhouse Lane	1772217	5444854
P-1	Pakuratahi R at Truss Br	1783788	5445190
P-2	Pakuratahi R at SH 2	1784991	5450147
P-3	Rimutaka S at Marchant Rd	1785144	5450285
P-4	Puffer S	1785418	5450618
P-4a	Pakuratahi R 50m d/s of Waterworks Rd Br	1784699	5451176
P-5	Kaitoke S	1784388	5451269
P-6	Farm Creek at Kaitoke Waterworks Rd	1784613	5451666
P-7	Pakuratahi R 50m d/s Farm Creek	1784597	5451808
M-1	Mangaroa R at Russell Rd	1771172	5437314
M-2	Mangaroa R at Mangaroa Valley Rd	1775415	5443937
M-3	Black S at Gorrie Rd	1775455	5444629
M-4	Mangaroa R at Hill Rd Bridge	1776514	5445964
M-5	Mangaroa R at Maymorn	1778161	5447177
M-6	Mangaroa R above Blaikie S	1778873	5448124
M-7	Blaikie S at Mangaroa R conf	1778850	5448107
M-8	Mangaroa R at Te Marua	1778565	5448605

Appendix 2: Cyanobacteria blooms recorded by GWRC between 2004 and 2015

List of cyanobacteria bloom events (ie, >20% riverbed cover) recorded at GWRC Rivers State of the Environment (RSoE) and Recreational Water Quality monitoring sites between 2004 and 2015.

Site name	Site type	Date	Cyanobacteria cover (%)
Akatarawa River at Hutt Confluence	RSoE	12/12/2013	20
Huangarua River at Ponatahi Bridge	RSoE	26/08/2013	30
Hutt River at Birchville	RWQ	07/02/2012	28
Hutt River at Birchville	RWQ	13/02/2012	57
Hutt River at Birchville	RWQ	21/02/2012	77
Hutt River at Birchville	RWQ	27/11/2012	21
Hutt River at Birchville	RWQ	04/12/2012	31
Hutt River at Birchville	RWQ	04/02/2013	23
Hutt River at Boulcott	RWQ and RSoE	16/01/2007	68
Hutt River at Boulcott	RWQ and RSoE	23/01/2007	74
Hutt River at Boulcott	RWQ and RSoE	09/02/2010	44
Hutt River at Boulcott	RWQ and RSoE	16/02/2010	49
Hutt River at Boulcott	RWQ and RSoE	09/03/2010	29
Hutt River at Boulcott	RWQ and RSoE	16/03/2010	50
Hutt River at Boulcott	RWQ and RSoE	15/03/2011	39
Hutt River at Boulcott	RWQ and RSoE	22/03/2011	68
Hutt River at Maoribank Corner	RWQ	07/02/2012	30
Hutt River at Maoribank Corner	RWQ	13/02/2012	60
Hutt River at Maoribank Corner	RWQ	21/02/2012	74
Hutt River at Maoribank Corner	RWQ	27/11/2012	28
Hutt River at Maoribank Corner	RWQ	04/12/2012	24
Hutt River at Maoribank Corner	RWQ	04/02/2013	29
Hutt River at Maoribank Corner	RWQ	11/03/2013	27
Hutt River at Melling Bridge	RWQ	07/02/2012	22
Hutt River at Melling Bridge	RWQ	13/02/2012	41
Hutt River at Poets Park	RWQ	30/01/2012	21
Hutt River at Poets Park	RWQ	07/02/2012	31
Hutt River at Poets Park	RWQ	13/02/2012	60
Hutt River at Poets Park	RWQ	21/02/2012	71
Hutt River at Poets Park	RWQ	04/02/2013	23
Hutt River at Silverstream Bridge	RWQ	16/01/2007	33
Hutt River at Silverstream Bridge	RWQ	23/01/2007	51
Hutt River at Silverstream Bridge	RWQ	20/02/2007	22
Hutt River at Silverstream Bridge	RWQ	27/02/2007	53
Hutt River at Silverstream Bridge	RWQ	18/12/2007	20
Hutt River at Silverstream Bridge	RWQ	05/02/2008	51
Hutt River at Silverstream Bridge	RWQ	12/02/2008	77

Site name	Site type	Date	Cyanobacteria cover (%)
Hutt River at Silverstream Bridge	RWQ	19/02/2008	72
Hutt River at Silverstream Bridge	RWQ	26/02/2008	78
Hutt River at Silverstream Bridge	RWQ	18/03/2008	33
Hutt River at Silverstream Bridge	RWQ	25/03/2008	51
Hutt River at Silverstream Bridge	RWQ	27/01/2009	23
Hutt River at Silverstream Bridge	RWQ	09/03/2010	40
Hutt River at Silverstream Bridge	RWQ	16/03/2010	60
Hutt River at Silverstream Bridge	RWQ	07/12/2010	20
Hutt River at Silverstream Bridge	RWQ	15/03/2011	37
Hutt River at Silverstream Bridge	RWQ	22/03/2011	51
Hutt River at Silverstream Bridge	RWQ	24/01/2012	24
Hutt River at Silverstream Bridge	RWQ	30/01/2012	27
Hutt River at Silverstream Bridge	RWQ	07/02/2012	51
Hutt River at Silverstream Bridge	RWQ	13/02/2012	70
Hutt River at Silverstream Bridge	RWQ	21/02/2012	75
Hutt River at Silverstream Bridge	RWQ	27/11/2012	25
Hutt River at Silverstream Bridge	RWQ	04/12/2012	25
Hutt River at Silverstream Bridge	RWQ	28/01/2013	24
Hutt River at Silverstream Bridge	RWQ	04/02/2013	36
Hutt River at Silverstream Bridge	RWQ	06/03/2013	29
Hutt River at Silverstream Bridge	RWQ	11/03/2013	40
Hutt River at Silverstream Bridge	RWQ	24/02/2015	20
Hutt River Opposite Manor Park Golf Club	RSoE	08/03/2010	Unknown*
Hutt River Opposite Manor Park Golf Club	RSoE	16/02/2012	46
Mangaroa River at Te Marua	RSoE	28/02/2013	37
Ruamahanga River at Kokotau	RWQ	20/02/2007	26
Ruamahanga River at Kokotau	RWQ	27/02/2007	22
Ruamahanga River at Kokotau	RWQ	06/03/2007	83
Ruamahanga River at Kokotau	RWQ	13/03/2007	26
Ruamahanga River at Kokotau	RWQ	23/01/2013	24
Ruamahanga River at Kokotau	RWQ	29/01/2013	56
Ruamahanga River at Kokotau	RWQ	19/02/2013	70
Ruamahanga River at Kokotau	RWQ	05/03/2013	42
Ruamahanga River at Kokotau	RWQ	13/03/2013	69
Ruamahanga River at Kokotau	RWQ	26/01/2015	70
Ruamahanga River at Te Ore Ore	RWQ and RSoE	27/02/2007	24
Ruamahanga River at Te Ore Ore	RWQ and RSoE	01/03/2011	26
Ruamahanga River at Te Ore Ore	RWQ and RSoE	15/03/2011	33
Ruamahanga River at Te Ore Ore	RWQ and RSoE	22/03/2011	30
Ruamahanga River at Te Ore Ore	RWQ and RSoE	29/03/2011	23
Ruamahanga River at Te Ore Ore	RWQ and RSoE	13/03/2013	25
Ruamahanga River at The Cliffs	RWQ	09/01/2007	31
Ruamahanga River at The Cliffs	RWQ	16/01/2007	31

Site name	Site type	Date	Cyanobacteria cover (%)
Ruamahanga River at The Cliffs	RWQ	27/02/2007	37
Ruamahanga River at The Cliffs	RWQ	06/03/2007	48
Ruamahanga River at The Cliffs	RWQ	13/03/2007	57
Ruamahanga River at The Cliffs	RWQ	05/03/2013	30
Ruamahanga River at The Cliffs	RWQ	13/03/2013	69
Waikanae River at Greenaway Rd	RSoE	27/01/2012	47
Waikanae River at Jim Cooke Park	RWQ	21/01/2009	22
Waikanae River at Jim Cooke Park	RWQ	27/01/2009	24
Waikanae River at Jim Cooke Park	RWQ	03/02/2009	35
Waikanae River at Jim Cooke Park	RWQ	11/02/2009	39
Waikanae River at Jim Cooke Park	RWQ	27/01/2010	20
Waikanae River at Jim Cooke Park	RWQ	09/02/2010	24
Waikanae River at Jim Cooke Park	RWQ	23/11/2010	20
Waikanae River at Jim Cooke Park	RWQ	15/03/2011	20
Waikanae River at Jim Cooke Park	RWQ	22/02/2012	22
Waingawa River at South Rd	RWQ and RSoE	10/02/2009	26
Wainuiomata River d/s of White Bridge	RSoE	15/02/2010	57
Waipoua River at Colombo Rd Bridge	RWQ and RSoE	14/01/2008	29
Waipoua River at Colombo Rd Bridge	RWQ and RSoE	22/01/2008	34
Waipoua River at Colombo Rd Bridge	RWQ and RSoE	08/12/2008	30
Waipoua River at Colombo Rd Bridge	RWQ and RSoE	15/12/2008	40
Waipoua River at Colombo Rd Bridge	RWQ and RSoE	08/02/2010	47
Waipoua River at Colombo Rd Bridge	RWQ and RSoE	16/02/2010	39
Waipoua River at Colombo Rd Bridge	RWQ and RSoE	23/02/2010	39
Waipoua River at Colombo Rd Bridge	RWQ and RSoE	22/03/2010	22
Waipoua River at Colombo Rd Bridge	RWQ and RSoE	22/02/2011	25
Waipoua River at Colombo Rd Bridge	RWQ and RSoE	01/03/2011	25
Waipoua River at Colombo Rd Bridge	RWQ and RSoE	29/12/2011	80
Waipoua River at Colombo Rd Bridge	RWQ and RSoE	25/01/2012	45
Waipoua River at Colombo Rd Bridge	RWQ and RSoE	03/01/2013	23
Waipoua River at Colombo Rd Bridge	RWQ and RSoE	08/01/2013	38
Waipoua River at Colombo Rd Bridge	RWQ and RSoE	15/01/2013	30
Waipoua River at Colombo Rd Bridge	RWQ and RSoE	23/01/2013	52
Waipoua River at Colombo Rd Bridge	RWQ and RSoE	29/01/2013	54

* High biomass (59.8 mg/m^2) recorded and *Phormidium* identified as dominant taxon.

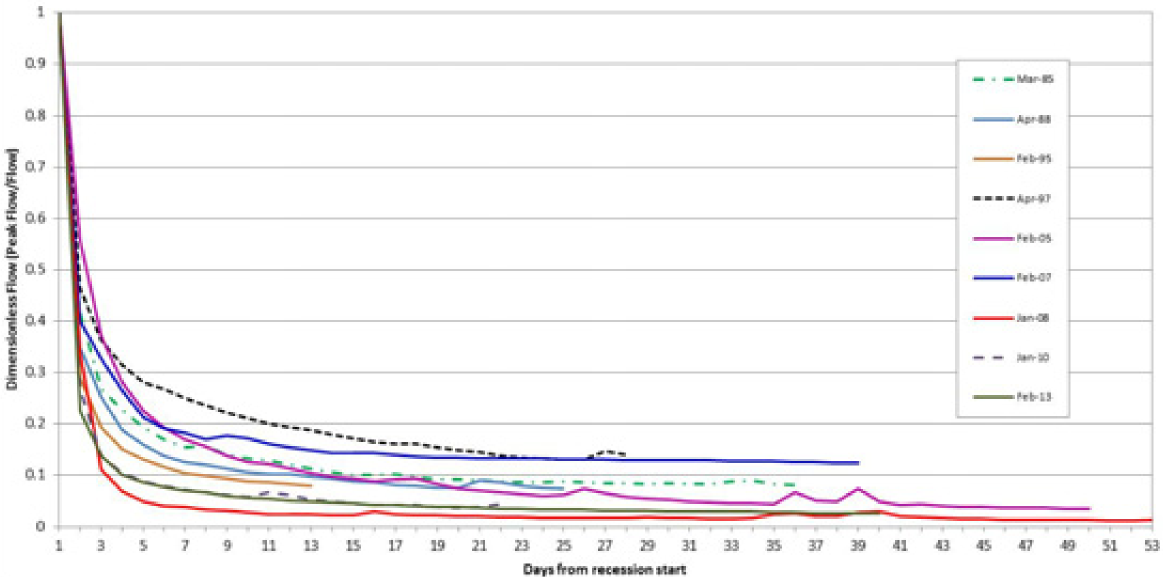
Appendix 3: Periphyton accrual statistics

Annual average accrual and annual maximum accrual days for RSoE periphyton monitoring sites from Thompson and Gordon (2011).

Site code	Site name	Average accrual (days)	Average maximum accrual (days)
RS03	Waitohu Stream at Forest Park	19	58
RS05	Otaki River at Pukehinau	16	47
RS06	Otaki River at Mouth	17	52
RS09	Waikanae River at Mangaone Walkway	30	97
RS10	Waikanae River at Greenaway Rd	28	93
RS11	Whareroa Stream at Waterfall Rd	26	95
RS13	Horokiri Stream at Snodgrass	33	111
RS14	Pauatahanui Stream at Elmwood Bridge	30	94
RS15	Porirua Stream at Glenside O. Cable	21	73
RS16	Porirua Stream at Wall Park	21	72
RS17	Makara Stream at Kennels	25	85
RS18	Karori Stream at Makara Peak	21	73
RS19	Kaiwharawhara Stream at Ngaio Gorge	26	91
RS20	Hutt River at Te Marua Intake Site	15	51
RS21	Hutt River opposite Manor Park Golf Club	20	64
RS22	Hutt River at Boulcott	20	67
RS23	Pakuratahi River 50m below Farm Creek	15	47
RS24	Mangaroa River at Te Marua	24	89
RS25	Akatarawa River at Hutt Confluence	20	63
RS26	Whakatikei River at Riverstone	26	86
RS28	Wainuiomata River at Manuka Track	27	96
RS29	Wainuiomata River d/s White Bridge	27	80
RS30	Orongorongo River at Orongorongo Stn	17	49
RS31	Ruamahanga River at McLays	13	38
RS32	Ruamahanga River at Te Ore Ore	16	40
RS33	Ruamahanga River at Gladstone Bridge	14	39
RS34	Ruamahanga River at Pukio	20	69
RS35	Mataikona tributary at Sugar Loaf Rd	28	100
RS37	Taueru River at Gladstone	45	180
RS38	Kopuaranga River at Stewarts	28	113
RS40	Waipoua River at Colombo Rd Bridge	22	96
RS41	Waingawa River at South Rd	15	44
RS43	Motuwaireka Stream at headwaters	30	110
RS44	Totara Stream at Stronvar	32	100
RS45	Parkvale tributary at Lowes Reserve	49	165
RS46	Parkvale Stream at Weir	49	165
RS47	Waiohine River at Gorge	15	44
RS48	Waiohine River at Bicknells	14	41
RS49	Beef Creek at headwaters	19	64
RS50	Mangatarere Stream at State Highway 2	21	63
RS51	Huangarua River at Ponatahi Bridge	29	105
RS52	Tauanui River at Whakatomotomo Rd	24	85
RS53	Awhea River at Tora Rd	27	105
RS54	Coles Creek tributary at Lagoon Hill Rd	27	105
RS55	Tauherenikau River at Websters	15	43
RS56	Waiorongomai River at Forest Park	16	52

Appendix 4: Hutt River hydrological recession curves

Nine recession events, where there had been extended periods of decreasing river flow from the Hutt River at Taita Gorge flow record (1 July 1979 and 30 June 2013).



Appendix 5: Formulae for estimating nutrient loads

Averaging method:

Monthly load:

$$Load(month_i) = [Pollut](month_i) \cdot \int_{01/month_i}^{31/month_i} Flow(t) \cdot dt$$

Annual load:

$$Load(year_i) = \sum_{i=1}^{12} Load(month_i)$$

Beale ratio estimator:

$$Average\_daily\_load_{year} = Average\_daily\_load_o \cdot \frac{Average\_daily\_flow_{year}}{Average\_daily\_flow_o} \left[\frac{1 + \left(\frac{1}{n} - \frac{1}{N}\right)\frac{s_{lq}}{l_o q_o}}{1 + \left(\frac{1}{n} - \frac{1}{N}\right)\frac{s_{qq}}{q_o^2}} \right]$$

$_{year}$ = an average for the year

$_o$ = an average over the days on which concentrations was observed

S_{lq} = covariance between flow and pollutant flux

S_{qq} = variance of the flow based on the days on which concentrations was measured

N = the expected population size (365)

n = the number of concentration measures (generally 12)

l_o = average daily flux on days concentration was measured

q_o = average daily flow on days concentration was measured

Appendix 6: Estimated annual nutrient loads for RSoE sites in the Hutt River catchment

Site	Annual Total Nitrogen load (tonnes/yr)							
	Method	2006/07	2007/08	2008/09	2009/10	2010/11	2011/12	Annual mean
Hutt @ Te Marua	Averaging	70.84	43.83	75.12	59.66	69.02	49.62	61.35
	Beale ratio estimator	81.24	27.44	86.86	64.95	77.65	49.54	64.61
Hutt River opposite Manor Park Golf Club	Averaging	392.08	229.44	491.35	292.40	459.54	253.69	353.08
	Beale ratio estimator	346.73	213.18	622.95	388.78	490.49	285.02	391.19
Hutt @ Boulcott	Averaging	333.02	211.82	481.26	247.36	380.49	224.16	313.02
	Beale ratio estimator	333.40	211.59	539.01	294.60	399.99	214.16	332.12
Pakuratahi River 50m d/s of Farm Creek	Averaging	52.23	67.01	57.29	38.97	48.44	35.44	49.90
	Beale ratio estimator	54.30	42.64	69.80	42.57	49.45	35.04	48.96
Mangaroa River @ Te Marua	Averaging	100.74	49.48	111.28	60.76	80.01	58.21	76.74
	Beale ratio estimator	97.46	51.18	137.61	74.21	85.43	56.42	83.72
Akatarawa River at Hutt confluence	Averaging	42.31	34.95	37.58	25.65	54.76	19.80	35.84
	Beale ratio estimator	41.85	39.38	49.24	37.86	61.80	20.49	41.77
Whakatikei River at Riverstone	Averaging	14.92	22.83	26.33	16.13	24.11	15.97	20.05
	Beale ratio estimator	16.59	18.32	37.44	21.02	27.64	15.98	22.83
Waiwhetu Stream at Wainuiomata Hill Bridge	Averaging	12.48	6.25	11.62	7.77	6.95	-	9.01
	Beale ratio estimator	13.25	5.65	12.07	7.50	7.01	-	9.10

Site	Annual Dissolved Inorganic Nitrogen load (tonnes/yr)							
	Method	2006/07	2007/08	2008/09	2009/10	2010/11	2011/12	Annual mean
Hutt @ Te Marua	Averaging	45.71	32.77	42.16	24.96	36.39	30.17	35.36
	Beale ratio estimator	41.26	28.43	42.02	29.01	29.73	25.43	32.65
Hutt River opposite Manor Park Golf Club	Averaging	279.41	153.23	338.91	170.86	244.10	154.27	223.46
	Beale ratio estimator	258.83	134.83	389.32	216.52	247.97	134.83	230.38
Hutt @ Boulcott	Averaging	246.08	132.77	364.39	149.56	241.31	155.80	214.98
	Beale ratio estimator	212.80	130.36	366.59	173.92	214.65	132.91	205.20
Pakuratahi River 50m d/s of Farm Creek	Averaging	37.74	54.49	41.44	23.58	31.38	24.38	35.50
	Beale ratio estimator	33.59	30.46	49.05	23.89	24.78	21.72	30.58
Mangaroa River @ Te Marua	Averaging	74.35	32.83	76.14	41.43	49.44	37.40	51.93
	Beale ratio estimator	72.82	33.52	89.17	43.47	46.38	32.43	52.97
Akatarawa River at Hutt confluence	Averaging	30.55	24.76	25.90	14.50	36.18	13.83	24.29
	Beale ratio estimator	30.94	35.01	33.64	20.86	37.34	12.12	28.32
Whakatikei River at Riverstone	Averaging	15.59	16.56	17.78	10.58	15.72	9.12	14.22
	Beale ratio estimator	18.97	11.94	25.61	13.95	17.44	8.38	16.05
Waiwhetu Stream at Wainuiomata Hill Bridge	Averaging	7.93	3.97	8.58	5.23	4.82	-	6.11
	Beale ratio estimator	8.58	3.49	9.19	4.41	4.50	-	6.03

Site	Annual Total Phosphorus load (tonnes/yr)							
	Method	2006/07	2007/08	2008/09	2009/10	2010/11	2011/12	Annual mean
Hutt @ Te Marua	Averaging	5.29	2.63	4.47	2.69	2.97	1.93	3.33
	Beale ratio estimator	5.91	3.20	7.03	3.88	3.55	2.07	4.27
Hutt River opposite Manor Park Golf Club	Averaging	20.57	9.14	20.61	12.19	16.71	9.31	14.76
	Beale ratio estimator	22.49	14.19	31.76	18.61	21.20	10.44	19.78
Hutt @ Boulcott	Averaging	30.01	15.57	26.96	14.14	17.14	7.74	18.59
	Beale ratio estimator	33.39	22.13	49.21	21.25	21.60	7.82	25.90
Pakuratahi River 50m d/s of Farm Creek	Averaging	2.05	1.11	1.53	1.49	1.67	0.92	1.46
	Beale ratio estimator	2.16	1.20	2.46	1.95	2.15	1.07	1.83
Mangaroa River @ Te Marua	Averaging	3.67	1.63	5.38	2.81	3.53	2.18	3.20
	Beale ratio estimator	3.85	1.91	8.64	4.80	5.08	2.58	4.48
Akatarawa River at Hutt confluence	Averaging	2.04	0.94	1.31	1.08	1.49	1.02	1.31
	Beale ratio estimator	3.02	1.19	1.67	1.45	1.81	1.11	1.71
Whakatikei River at Riverstone	Averaging	2.04	0.96	1.18	1.05	1.32	1.18	1.29
	Beale ratio estimator	2.14	1.07	1.38	1.23	1.38	1.25	1.41
Waiwhetu Stream at Wainuiomata Hill Bridge	Averaging	0.91	0.54	0.91	0.56	0.47	-	0.68
	Beale ratio estimator	0.99	0.52	0.67	0.75	0.51	-	0.69

Site	Annual Dissolved Reactive Phosphorus load (tonnes/yr)							
	Method	2006/07	2007/08	2008/09	2009/10	2010/11	2011/12	Annual mean
Hutt @ Te Marua	Averaging	1.77	0.75	1.45	1.58	1.44	1.05	1.34
	Beale ratio estimator	1.82	1.07	1.18	1.91	1.38	1.19	1.42
Hutt River opposite Manor Park Golf Club	Averaging	4.20	2.49	5.73	5.70	5.82	3.92	4.64
	Beale ratio estimator	4.00	3.01	4.58	6.44	6.23	3.72	4.66
Hutt @ Boulcott	Averaging	4.16	2.46	4.32	4.73	5.47	2.80	3.99
	Beale ratio estimator	4.26	3.20	4.83	6.16	5.90	2.87	4.54
Pakuratahi River 50m d/s of Farm Creek	Averaging	0.56	0.43	0.71	1.00	0.81	0.63	0.69
	Beale ratio estimator	0.47	0.26	0.73	1.09	0.86	0.70	0.69
Mangaroa River @ Te Marua	Averaging	1.53	0.60	1.48	1.49	1.59	1.07	1.30
	Beale ratio estimator	1.50	0.73	1.62	1.73	1.79	1.17	1.42
Akatarawa River at Hutt confluence	Averaging	0.46	0.32	0.56	0.66	0.91	0.43	0.56
	Beale ratio estimator	0.45	0.43	0.49	0.82	0.88	0.43	0.58
Whakatikei River at Riverstone	Averaging	0.79	0.48	0.57	0.77	0.79	0.55	0.66
	Beale ratio estimator	0.72	0.39	0.60	0.82	0.79	0.55	0.64
Waiwhetu Stream at Wainuiomata Hill Bridge	Averaging	0.25	0.24	0.37	0.28	0.20	-	0.27
	Beale ratio estimator	0.29	0.25	0.28	0.28	0.20	-	0.26

Appendix 7: Whakatikei-Taita Gorge investigation flow and nutrient data

DIN = dissolved inorganic nitrogen, TN = total nitrogen, DRP = dissolved reactive phosphorus and TP = total phosphorus

Sampling site and no.	28/02/2013					02/12/2013				
	Flow (L/s)	DIN (mg/L)	TN (mg/L)	DRP (mg/L)	TP (mg/L)	Flow (L/s)	DIN (mg/L)	TN (mg/L)	DRP (mg/L)	TP (mg/L)
Whakatikei Conf (HR1)	3,579	0.051	0.102	<0.004	0.008	NA	NA	NA	NA	NA
Moonshine Br (HR2)	3,672	0.049	0.112	<0.004	0.006	NA	0.096	0.170	0.005	0.007
Opposite Moonshine Hill Rd (HR3)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Trentham Memorial Pk (HR4)	NA	NA	NA	NA	NA	NA	0.133	0.210	<0.004	0.006
Heretaunga Golf Course north boundary (HR5)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Heretaunga Golf Course1 (HR6)	NA	NA	NA	NA	NA	NA	0.143	0.250	<0.004	0.008
Heretaunga Golf Course (HR7)	4,301	0.143	0.187	<0.004	0.004	NA	0.146	0.230	<0.004	0.005
Opposite St Patricks College (HR8)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
U/S of Silverstream Br (HR9)	4,482	0.137	0.184	<0.004	0.006	NA	0.201	0.300	<0.004	0.007
Taita Gorge (HR10)	5,208	0.138	0.179	<0.004	0.004	NA	NA	NA	NA	NA
Moonshine S at Hutt R conf (T1)	15	0.165	0.251	0.017	0.017	NA	NA	NA	NA	NA
Unnamed Hutt Triv at Heretaunga golf (T2)	13	0.058	0.195	<0.004	0.015	NA	0.195	0.370	<0.004	0.013
Unnamed Hutt Trib at Heretaunga golf Course1 (T3)	4	0.238	0.387	0.004	0.016	NA	1.066	1.26	0.007	0.013
Unnamed Hutt Trib at SH2 Br 9581 (T4)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Mawaihakona S at Hutt Conf (T5)	100	0.594	0.715	0.005	0.022	NA	1.185	1.330	0.01	0.017
Hulls Cr at Hutt Conf (T6)	31	<0.011	0.202	0.030	0.048	NA	NA	NA	NA	NA

Sampling site and no.	27/02/2014					18/02/2015				
	Flow (L/s)	DIN (mg/L)	TN (mg/L)	DRP (mg/L)	TP (mg/L)	Flow (L/s)	DIN (mg/L)	TN (mg/L)	DRP (mg/L)	TP (mg/L)
Whakatikei Conf (HR1)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Moonshine Br (HR2)	NA	0.077	0.140	<0.004	0.006	2,756	0.047	0.160	0.002	< 0.004
Opposite Moonshine Hill Rd (HR3)	NA	NA	NA	NA	NA	2,431	0.056	0.130	0.001	< 0.004
Trentham Memorial Pk (HR4)	NA	0.113	0.170	<0.004	<0.004	2,431	0.069	0.130	0.002	0.007
Heretaunga Golf Course north boundary (HR5)	NA	NA	NA	NA	NA	2,181	0.114	0.162	0.001	0.006
Heretaunga Golf Course1 (HR6)	NA	0.223	0.280	<0.004	<0.004	2,524	0.173	0.220	0.003	0.005
Heretaunga Golf Course (HR7)	NA	0.223	0.280	<0.004	0.005	2,600	0.189	0.230	0.003	0.010
Opposite St Patricks College (HR8)	NA	NA	NA	NA	NA	2,796	0.185	0.230	0.002	0.006
U/S of Silverstream Br (HR9)	NA	0.223	0.280	<0.004	<0.004	2,596	0.163	0.250	0.002	< 0.004
Taita Gorge (HR10)	NA	0.201	0.280	<0.004	<0.004	2,763	0.160	0.230	0.001	< 0.004
Moonshine S at Hutt R conf (T1)	NA	NA	NA	NA	NA	9	0.071	0.170	0.008	0.010
Unnamed Hutt Triv at Heretaunga golf (T2)	NA	0.261	0.500	<0.004	0.020	2	0.139	0.440	0.001	0.028
Unnamed Hutt Trib at Heretaunga golf Course1 (T3)	NA	0.635	0.750	<0.004	0.006	6	0.260	0.470	< 0.001	0.012
Unnamed Hutt Trib at SH2 Br 9581 (T4)	NA	NA	NA	NA	NA	16	0.540	0.900	0.006	0.010
Mawaihakona S at Hutt Conf (T5)	NA	0.355	0.460	0.007	0.009	75	0.530	0.710	0.010	0.016
Hulls Cr at Hutt Conf (T6)	NA	NA	NA	NA	NA	16	0.016	0.330	0.025	0.040

Sampling site and no.	12/03/2015				
	Flow (L/s)	**DIN (mg/L)**	**TN (mg/L)**	**DRP (mg/L)**	**TP (mg/L)**
Whakatikei Conf (HR1)	NA	NA	NA	NA	NA
Moonshine Br (HR2)	2,115	0.089	0.290	0.002	< 0.004
Opposite Moonshine Hill Rd (HR3)	2,389	0.100	0.230	0.001	< 0.004
Trentham Memorial Pk (HR4)	2,391	0.114	0.240	0.003	0.011
Heretaunga Golf Course north boundary (HR5)	2,451	0.1872	0.295	0.002	0.0041
Heretaunga Golf Course1 (HR6)	2,581	0.220	0.350	0.003	<0.004
Heretaunga Golf Course (HR7)	2,750	0.240	0.320	0.002	0.004
Opposite St Patricks College (HR8)	2,821	0.230	0.340	0.002	0.004
U/S of Silverstream Br (HR9)	2,710	0.220	0.360	0.002	< 0.004
Taita Gorge (HR10)	3,107	0.220	0.350	0.002	0.009
Moonshine S at Hutt R conf (T1)	15	0.091	0.230	0.009	0.012
Unnamed Hutt Triv at Heretaunga golf (T2)	9	0.370	0.610	< 0.001	0.031
Unnamed Hutt Trib at Heretaunga golf Course1 (T3)	7	0.230	0.370	< 0.001	0.005
Unnamed Hutt Trib at SH2 Br 9581 (T4)	10	0.500	0.640	0.009	0.015
Mawaihakona S at Hutt Conf (T5)	69	0.590	0.730	0.006	0.008
Hulls Cr at Hutt Conf (T6)	17	0.031	0.750	0.032	0.051

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