Trends and State of Nutrients in Lake Rotorua Streams 2002-2016

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Executive summary

Lake Rotorua is the largest lake by area in the Ōkataina Volcanic complex, and is home to numerous ecological, cultural, and recreational values. The lake has been vigorously studied since the mid 1960's, with results showing a steady decline in water quality that coincides with urban and agricultural development with the catchment. As a consequence, phytoplankton blooms, particularly those involving toxic cyanobacteria, have become more common over time, affecting the ability for residents and tourists alike to recreate in some parts of the lake.

Attempts have been made to slow or halt the decline, including: diverting the Rotorua City wastewater treatment plant effluent away from the Puarenga Stream, and applying it in a forestry block at the top of the catchment, as well as 'catchment control schemes' that encouraged stream fencing and the retirement of erosion prone land. These mitigations were effective for a short period of time, however, lake water quality continued to decline from 1995, driven, at least partly, by increases in baseflow nutrient concentrations in eight of the nine major inflows.

Bay of Plenty Regional Council (BOPRC), Rotorua Lakes Council, (RLC), Rotorua District Council (RDC), and the Te Arawa Lakes Trust (TALT) have collaborated on a Lakes Management Strategy (2000) and Action Plan (2009), to protect the values associated with Lake Rotorua, especially those impacted by declining water quality. These documents have led to the development of the recently notified Plan Change 10 (PC10), which is intended to provide a statutory framework to meet the proposed sustainable Lake Rotorua load target of 435 T of nitrogen per annum, by 2032. Monitoring of Lake Rotorua's nine major inflows is intended to support the Lakes Management Strategy, Action Plan and Plan Change 10, by providing monthly nutrient concentration and flow data, to be used for trend analysis and estimation of nutrient loads.

This report is the second to summarise nutrient trends and estimate loads for Lake Rotorua's inflows, and supersedes the 2013 report by Scholes entitled 'Trends and State of Nutrients in Lake Rotorua Streams 2013'. The current report also explores an additional method of trend analysis developed by the United States Geological Survey (USGS) called 'Weighted Regressions on Time Discharge and Season' (WRTDS), and two additional load estimation methods: WRTDS, and USGS' load estimation model (LOADEST). The WRTDS Model is part of the Exploration and Graphics for RivEr Trends (EGRET) R package, which has been developed to enable resource managers to extract more information from long term water quality datasets.

Trend analysis results

Trend analysis was carried out over four time periods; two of which were intended to provide insight into long (2002-2016) and short (2012-2016) term trends, and the other two were to avoid complications associated with the lab methodology change that occurred between July 2008 and July 2009 (pre-change = 2002-July 2008; post change = July 2009–2016).

Trend analysis for nitrogen constituents revealed:

- Deteriorating total nitrogen (TN) trends at 33.3% of sites between 2002 and 2016, while 11.1% showed significant improvement.
- More deteriorating TN trends after July 2009 (22.2% of sites) than before July 2008 (11.1% of sites), with the greatest number of deteriorating sites identified between 2012 and 2016 (44.4%).
- Nitrate-nitrite-nitrogen concentrations improved at 44.4% sites after July 2009, compared to 22.2% of sites before July 2008. In addition, no deteriorating trends were found between 2012 and 2016. However, 56.6% of sites were shown to have deteriorated over the long-term dataset.
- Total ammoniacal nitrogen (NH4-N) concentrations improved at 44.4% of sites between 2002 and 2016. However, further analysis showed that 44.4% of sites deteriorated between July 2009 and 2016, and 55.6% of sites deteriorated between 2012 and 2016.

These results depict an overall improvement in instream nitrate-nitrite nitrogen (NNN) concentrations, which were found to be steady or decreasing in most catchments after 2009. In contrast, trend analysis after July 2009 reveals a pattern of deteriorating NH4-N trends in many catchments, with the WRTDS model showing that elevated concentrations typically coincided with elevated flows, and that high flow NH4-N concentrations were increasing over time at some sites. However, the contribution of NH4-N to TN in most catchments is currently minor, with only the Puarenga and Waiohewa breaching 10%. Therefore, any increases in NH4-N are unlikely to be solely responsible for increasing TN trends, which suggests that particulate organic nitrogen is also a contributor. The source of NH4-N is debatable, with possible contributors including: animal effluents, stormwater discharge, leaking septic tanks, and geothermal inputs. Therefore, further investigation is recommended to identify specific sources, particularly in catchments that show large annual increases and concentrations that could potentially impact the local ecosystem, for example the Puarenga.

Trend results for phosphorus constituents revealed:

- Deteriorating total phosphorus (TP) trends at 66.7% of sites between 2002 and 2016, while 11.1% showed improvement. Further analysis revealed that a greater percentage of sites revealed deteriorating trends after July 2009 (88.9%) and between 2012 and 2016 (66.7%), compared with before July 2008 (11.1%).
- Deteriorating dissolved reactive phosphorus (DRP) trends were identified at 33.3% of sites between 2002 and 2016, with 77.8% of sites deteriorating after July 2009, and 66.7% between 2012 and 2016.
- No improving TP or DRP trends were identified at any site after July 2009.

Increasing DRP concentrations contributed to the number of deteriorating TP trends identified, particularly after July 2009. Although, load ratios and the increasing divide between DRP and TP concentrations at many sites emphasises the increasing prevalence of particulate phosphorus in recent years. Particulate phosphorus is typically mobilised via overland flow pathways caused by high intensity rainfall events. However, aside from a wet period between 2010 and 2012, annual rainfall accumulation and the number of high intensity rainfall events in the Lake Rotorua Catchment is comparable across years. This suggests that other factors may be exacerbating the supply of particulate phosphorus to Lake Rotorua in recent years.

Load results

Load estimates were similar between methods for all analytes, although the LOADEST and WRTDS methods were less affected by inter-annual variability. The combined TN load from all inflows fluctuated around 400 T/yr for the entire dataset, with the estimate for 2016 equating to between 410 and 415 T, as estimated by the numeric integration and LOADEST methods, respectively. This value is not comparable to the 435 T/yr limit stated in PC10 because it only accounts for base-mid flow loads from the nine major inflows. Further estimates of ungauged inflows, rainfall contribution, and sewage discharges from septic tanks need to be included before direct comparison can be made.

The TN load calculated for Lake Rotorua’s outflow, the Ōhau Channel, remained consistently low relative to inflow loads, implying that a large proportion of TN is transformed or denitrified within the lake. Total Nitrogen export was primarily in the form of organic nitrogen, which suggests that a large amount of bioavailable nitrogen is taken up by free floating algae and exported as algal biomass. The impact of nutrient export from Lake Rotorua and Lake Rotoiti on water quality in the lower Kaituna Catchment is suggested to be low, as the concentration of all analytes, except NH4-N, at Maungarangi Road (lower catchment site) exceeded that measured at either lake outflow. Nutrient characteristics at this site were found to be dominated by inorganic forms of nitrogen and phosphorus, likely to originate from surrounding land use.

Combined TP loads fluctuated around 23 T/yr between 2002 and 2010, before increasing to around 32 T/yr after this date. Loads for the 2016 calendar year equated to between 34 and 36 T, as estimated by numeric integration and LOADEST methods, respectively.

Inflow to outflow load ratios show that an increasingly smaller proportion of inflow TP has been exported from the lake after 2009, which aligns with the increased supply of particulate phosphorus found at many of the inflow sites, and the decreased algal biomass through alum dosing of the Utuhina and Puarenga streams. It’s likely that particulate phosphorus is deposited in lake sediments, which will be subsequently reduced and made soluble under anoxic conditions.

A comparison of load contributions from each site revealed that proportional TN and NNN load contributions have been relatively constant over time, and are dominated by the: Waitetī, Hamurana, Awahou and Puarenga catchments. Nearly 75% of the total NH4-N load is sourced from the Waiohewa Catchment, reflecting geothermal contribution, and justifying the upgrade of the Tikitere water treatment plant that is currently in progress. The next greatest contributor of NH4-N is the Puarenga Catchment, where the NH4-N load and proportional NH4-N load contribution, has been steadily increasing since 2010. Concentration-discharge signatures allude to a high flow source, consistent with overland flow, or shallow aquifer pathways.

Over 50% of the DRP load can be attributed to the Hamurana and Awahou catchments alone, reflecting the extended groundwater residence times in these catchments. Other major contributors include the Puarenga and Utuhina catchments, the latter of which contributes a visibly smaller proportion of total DRP load after 2006, coinciding with the start of the alum dosing programme. The Hamurana Catchment was also found to be the major TP load contributor, making up close to 25% of the overall load. However, the Puarenga, Utuhina, and Ngongotahā catchments all contribute proportionally more to the overall TP load than to the DRP load, highlighting the prevalence of particulate phosphorus in these catchments.

Recommendations

It is recommended that the following points are addressed to improve the data and information available for future analyses:

Improvement of scientific data

Increase high flow sampling events to provide more robust load estimates and inform concentration-discharge analyses (such as WRTDS). Results indicate contaminants may be responding differently at different parts of the hydrograph (e.g. baseflow versus. high flow). Accurate high flow measurements would provide more certainty around high flow WRTDS predictions, while also benefiting regression load estimates.

Improve continuous flow measurements. Continuous flow records can provide useful data for analysis, such as that employed by the EGRET package. Installation of water level loggers is a relatively simple task, enabling flow-water level relationships to be developed for non-hydrology sites. This data could also increase certainty around some of the spot gauging data which appears to be biased towards low flows in recent years.

Additional investigations

Investigate the increasing trend of high-flow source of NH4-N the Puarenga Catchment. Results show the NH4-N concentrations have increased in this catchment, particularly after 2009. A small scale investigation may provide answers about the source of this contamination and enable it to be minimised.

Identify hydrochemical or isotope signatures to clarify contaminant sources and pathways. The identification of discrete hydrochemical or isotope signatures could provide information about the source and pathway of contamination, allowing for targeted mitigation methods to be applied.

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Part 1:

Introduction

Background

Lake Rotorua is prized by residents and tourists alike for its numerous ecological, cultural and recreational values, including: a world class trout fishery, the iconic Mokoia Island, and being the setting of the well known Māori legend of Hinemoa and Tutanekai. The lake itself is the largest in the Bay of Plenty region by spatial extent, with a surface area of approximately 80.60 km^2, however, it is exceeded in volume by nearby Lake Tarawera, which has a volume of between 2,249 to 2,311 m^3 x 106 (depending on lake level), compared with 725 and 842 m^3 x 106 in Lake Rotorua (Ellery, 2004). These lakes, along with ten other major lakes within the Rotorua lakes district, are situated in caldera basins and explosion craters of the Ōkataina Volcanic Complex (McBride, Verburg, Bloor, & Hamilton, 2015). Each has a unique history, ranging from the youngest, Lake Rotomahana, which was formed during the eruption of Mt Tarawera in 1886, to the oldest, Lake Rotorua, which is thought to have formed shortly after the Mamaku Ignimbrite eruption, about 140,000 years ago.

Water quality within Lake Rotorua and its surrounding catchment, has been studied since the mid 1960's providing a useful comparison with current monitoring results (e.g. Fish, 1969). Such comparison reveals that water quality within Lake Rotorua has declined significantly since this time, which is coincident with urbanisation and agricultural development within its catchment (Hamilton, McBride, & Jones, 2014). A major symptom this decline has been the increase in phytoplankton productivity (algal blooms), particularly cyanobacteria, which is principally driven by increased levels of phosphorus and nitrogen (Scholes, 2013).

The source of increasing nutrients to Lake Rotorua has been the subject of a number of reports, with many authors emphasising the importance of discharge from the Rotorua sewage treatment plant (e.g. Rutherford, 2003). This activity persisted from 1973 to 1991, during which time Lake Rotorua experienced its greatest annual nutrient input, which has been jointly attributed to sewage input, leaking septic tanks, urban stormwater, increases in horticulture and pastoral farming, and other miscellaneous sources (Scholes, 2013).

The discharge from the Rotorua sewage treatment plant was diverted to a land-based effluent polishing system in 1991, where effluent is dispersed in specified blocks within the Whakarewarewa Forest (Hamilton et al., 2014; Scholes, 2013). This diversion, in conjunction with the Kaituna Catchment Control Scheme, which is aimed at fencing stream margins and retiring erosion prone land, resulted in significant short-term improvements in lake water clarity, nutrient and chlorophyll concentrations. However, since 1995 lake water quality has continued to deteriorate, with eight of the nine major stream inflows exhibiting increasing base-flow nitrate concentrations (Hamilton et al., 2014; Rutherford, 2003). This trend has been attributed to gradual nitrate enrichment of groundwater aquifers draining agricultural land, with changes in nitrate concentration reflecting the history of agricultural development and intensification (Hamilton et al., 2014).

Policy and strategy

Bay of Plenty Regional Council monitors the nine major inflows that feed into Lake Rotorua, and the lake itself, as part of the Council's wider integrated catchment management activities. Results also support the Rotorua Te Arawa Lakes Programme, which is a partnership between the RDC, BOPRC and Te Arawa Lakes Trust.

The objectives of these monitoring programmes were defined as part of the Lakes Management Strategy (2000) under the key element of 'Lake Protection'. Key goals included:

- addressing the causes of water pollution,
- determining the extent of pollution from stormwater, and
- defining and refining water quality standards.

The strategy also identified a number of tasks to be addressed as part of the long term management of Te Arawa/Rotorua lakes. Task 1 required BOPRC and RDC to reach agreement on the relative sources of water quality degradation for each lake. Task 2 was to refine water quality standards, and Task 3 was to report on current and future, lake, stream, and river buffer areas that are, or will be, retired from grazing.

In July 2009, the Lakes Rotorua and Rotoiti Action Plan was released. This was a joint, non-statutory document produced by BOPRC, RDC, and the Te Arawa Lakes Trust that identified actions to reduce nutrient loss from surrounding land use, to restore and protect the quality of Lakes Rotorua and Rotoiti. The document outlined a number of actions to progress towards a community derived target trophic level index (TLI) of 4.2. This objective is now established in the Regional Water and Land Plan under Objective 11.

Proposed actions included to meet this objective include:

- trialling sediment capping methods to prevent internal loading,
- harvesting aquatic macrophytes to allow new growth to take up more nutrients,
- continuing to improve the Rotorua WWTP via upgrades to infrastructure and new treatment methods,
- exploring the use of chemical flocculants to remove phosphorus from major inflows,
- reducing diffuse losses from land use by encouraging best management practices, adoption of new technology, assessing existing regulatory intervention, exploring non-regulatory intervention, and carrying out an economic analysis of the costs and benefits of different regulatory and non-regulatory interventions,
- treating geothermal water enriched with ammonium with zeolite material before it reaches the lake,
- diverting the Hamurana Stream to the Ōhau Channel, and
- establishing wetlands to attenuate excess nutrients.

The protection of Rotorua's Lakes was later incorporated into the Regional Policy Statement under the following policies:

- **Policy WL 3B** – which discusses the requirement to establish limits for the total amount of specified contaminants that enter the receiving waters of a catchment at risk. This includes contaminants that compromise public health, ecological values, mauri, fishability, swimmability and aesthetics.
- **Policy WL 5B** – outlines the allocation of land use activities to assimilate contaminants within the limits established in accordance of Policy WL 3B. This takes into account fairness/equity, public and private benefits, cultural values, resource use efficiency, exiting land use, existing capital investment, among other considerations.
- **Policy WL 6B** – requires rules that provide for the managed reduction of any nutrient losses that are in excess of the limits established in Policy WL 3B.

Finally, in 2017 the BOPRC notified Plan Change 10 (PC10) which outlines proposed changes to land use within the rural area in the Lake Rotorua groundwater catchment. The overarching objective of PC10 is to meet the sustainable lake load of 435 T of nitrogen per annum by 2032, which is set to maintain the trophic level index at 4.2 TLI units. This target is 320 T lower than the current estimate of nitrogen entering the lake, which has been estimated by the ROTAN catchment model (Rutherford, 2016).

Monitoring and reporting

Reporting of the state and trend of inflows to Lake Rotorua aligns with Task 1 and 2 of Lakes Management Strategy, and informs about the progress of actions listed in the Lakes Rotorua and Rotoiti Action Plan, while also providing justification for further intervention. In addition, flow-concentration data can be used to estimate load contributions from each of the inflows, which can be extrapolated and compared with limits set in PC10, or used to validate or calibrate more complex catchment models (e.g. ROTAN).

Water quality monitoring is carried out monthly on the nine major inflows to Lake Rotorua: the Awahou, Hamurana, Ngongotahā, Puarenga, Utuhina, Waingaehe, Waiohewa, Waiowhero, and Waitetī streams. In addition, one site in the upper Waitetī Catchment, 'Waitetī at Oturoa Road' is also monitored as it has previously been identified as a disproportionate source of particulate nutrients. Monitoring consists of water quality analysis and flow gauging, with the intention of providing a long term dataset for nutrient trend analysis. The associated flow measurement allows for the calculation of loads, although the monitoring programme was originally established to understand baseflow contributions, so estimates are inherently biased towards periods when relative load contribution is low.

Historical reporting has been in the form of traditional nutrient trend analysis, and load estimates calculated by multiplying nutrient concentrations and spot flow gaugings (see Scholes, 2013). However, a new method called Weighted Regression on Time, Discharge, and Season (WRTDS), part of the Exploration and Graphics for RivEr Trends (EGRET) R package, has been developed by the United States Geological Survey (USGS) and allows for higher resolution of flow-weighted trend information to be extracted from long term water quality datasets. Such information is useful for determining where on the hydrograph elevated concentrations are occurring, narrowing possible sources and informing the user if flow-specific concentrations are changing over time. This type of analysis has not previously been used for water quality reporting at BOPRC, but the results could prove useful for: supporting traditional trend analysis and load calculations, alluding to potential sources, and providing discussion pieces for community consultation. Therefore, this report will explore the WRTDS method and the EGRET package to determine how useful it is for routine Regional Council water quality reporting. Furthermore, an alternative load estimation method called LOADEST, also developed by USGS, will be compared to estimates calculated using traditional methods, and the WRTDS method, to see how calculated loads vary. Further information on both of these methods is provided in the methods section.

Report structure and objectives

The main results of this report are structured by catchment to enable information to easily be extracted and passed on to relevant community groups. Each catchment section provides a brief background of land use, and catchment specific discussion of the results. A summary discussion is included at the end to summarise the overall implications for Lake Rotorua.

Additional sections provide a between-site comparison of: flow, mean annual nutrient concentrations, and load.

The objectives of this report are threefold:

1 To report on nutrient trends and load estimates for the nine freshwater inputs that contribute to Lake Rotorua.

2 To provide a comparison between traditional trend analysis and flow weighted regression using USGS' Exploration and Graphics for RivEr Trends (EGRET) package developed in R, in an attempt to improve the information that can be derived from long term water quality datasets.

3 To compare the load estimate method used in the previous 'Trends and State Of Nutrients In Lake Rotorua Streams' Report (Scholes, 2013) with two other methods of load estimation, rLoadest, and EGRET, to determine if results are consistent across methods.

Part 2:

Methods

Data extraction and preening

Water quality data and discrete flow

Total nitrogen (TN), nitrate nitrite nitrogen (NNN), total ammoniacal nitrogen (NH4-N), total phosphorus (TP), and dissolved reactive phosphorus (DRP) were extracted from the Bay of Plenty Regional Council data archive, for ten sites across nine different inflows to Lake Rotorua, for the period of 1 January 2002–31 December 2016. Nine of these sites were located in the main stem in the lower part of their catchment, and became the primary focus for this report. These sites were: Awahou at SH 36, Hamurana at Hamurana Road, Ngongotahā at SH 36, Puarenga at FRI, Utuhina at Lake Road, Waingaehe at SH 30, Waiohewa at Rangiteaorere Road, Waiowhiro at Bonningtons Farm, and Waitetī at SH 36. The tenth site, Waitetī at Oturoa Road, has been identified as a high risk sub-catchment of the Waitetī, and was used to provide context to the Waitetī Catchment discussion.

The total number of samples amounted to 1577, the majority of which included discrete flow data that was measured on the same day as the sampling event. A total of 285 samples (18.0%) across all sites did not have a paired flow measurement. These sample events were matched to mean daily flow values calculated from continuous flow records that were present at 7 of the 10 sites. A total of 74 flow values were added in this step, however, 211 samples (13.3%) were still outstanding. Flows for the remaining sample events were synthesised using NIWA's TopNet hydrological model (see Clark et al., 2008). TopNet is based on historic rainfall events and soil permeability data and therefore provides a good representation of relative flow. However, the majority of reaches sampled were not calibrated to measured flow data and had to be adjusted so that the median of the synthesised dataset matched the median of the measured flow dataset. An additional 154 flow values were added using this method, leaving 57 sampling events (3.6%) lacking flow data. These data were kept in the dataset for trend analysis, but were removed prior to any load estimation.

Lab methodology changes

Bay of Plenty Regional Council's laboratory changed their analytical methods for analysing TN, TP and DRP in late 2008 and 2009. This resulted in less variability, but caused a step change in long-term data records (Scholes & Hamill, 2016). Ideally, this change would have been subject to a period of cross validation, where samples were processed using both methods until a robust relationship was developed; however, this did not occur which has caused problems for the calculation of trends that span this period. Previous trend analysis reports (e.g. Scholes, 2013; Scholes & Hamill, 2016) addressed this problem by carrying out minor investigations using sites that had few pressures and relatively stable water quality. Comparisons of data before and after the lab methodology change found that TN and DRP concentrations post-change were typically lower than pre-change, while TP was higher post-change compared with pre-change. The relationship between pre and post-change data allowed for development of adjustment equations to enable analysis that spans the two periods.

The current study employs TN and TP equations developed by Scholes and Hamill (2016), and a DRP equation developed by Scholes (2013). These are as follows:

$$TN_{Adj} = TN_{PC} + 0.0507$$

$$TP_{Adj} = TP_{PC} * 0.829$$

$$DRP_{Adj} = DRP_{PC} * 0.946 + 0.012$$

Where TN_{Adj}, TP_{Adj}, and DRP_{Adj} represent adjusted TN, TP and DRP values, while TN_{PC}, TP_{PC}, and DRP_{PC} are post lab methodology change concentrations in milligrams per litre.

More information on these equations can be found by referring to Appendix 2 in Scholes and Hamill (2016) for TN and TP, or in Appendix 3 of the current report. Appendix 3 also contains plots of adjusted versus unadjusted values for each site.

Outliers

Outliers were identified by plotting time series of any given analyte, separated by site, and noting any values that appeared to be out of place with regard to the rest of the dataset. These values were explored in detail by viewing other analyte values from the same sample, and a final decision was made whether to discard or not.

Contextual Data

Additional data was extracted on an as needed basis to provide context to the nutrient trend analysis and load results. This included: rainfall accumulation (mm) from five rainfall sites within the Lake Rotorua Catchment; outflow nutrient concentrations and flow from the Ōhau Channel at SH 33 site; and nutrient concentrations from Kaituna at Rotoiti Outlet, and Kaituna at Maungarangi Road, for downstream impact comparisons. Specific analytical methods are discussed in detail within each section.

Analysis

All analyses, except trend analysis, were carried out in R: A language and environment for statistical computing (R Core Team, 2017). Traditional trend analysis was performed using Time Trends v 6.01: Trend and Equivalence Analysis (Jowett, 2016).

Trend analysis

Traditional method

Trend analysis was carried out for every site except Waitetī at Oturoa Road, which did not have enough data to provide meaningful results. All other sites had long term datasets, enabling analysis to be carried out over the following periods:

- *Long term* - all available data between 1 January 2002 and 31 December 2016.
- *Pre-change* - all data analysed prior to the lab methodology change (January 2002 to July 2008).
- *Post-change* - all data analysed after the lab methodology change (July 2009 to 31 December 2016).
- *Short term* - all data collected between 1 January 2012 and 31 December 2016.

Trend analysis was also carried out on adjusted TN, TP, and DRP values over the long term dataset. It was assumed that these results are more accurate than non-adjusted values; hence any discussion referring to long term trends is based on adjusted values.

Preened data was screened to determine if chemical constituents changed with variation in flow. If variation was detected, these data were processed using a Mann-Kendall or Seasonal-Kendall trend test, depending on whether seasonal variation was detected, with flow as a covariate (see Helsel & Hirsch, 1992; Vant & Smith, 2004). Covariate adjustment used the LOWESS method with a 30% span, on monthly median values. If flow variation was not detected, the same method was used without applying flow as a covariate.

The Sen Slope Estimator (SEN) was used to represent the direction and magnitude of trends in data. Positive slopes indicate an increase in the concentration of a given constituent at that site over time (degradation of water quality), and negative slopes indicate a decrease in concentration over time (improvement of water quality). Trends were considered statistically significant if the $p<0.05$ (95% confidence), and the 95% SEN confidence interval did not contain zero. The percent annual change (PAC) value was also reported, although no attempt was made to define how meaningful each trend is for environmental management purposes. Previous studies (e.g. Ballantine & Davies-Colley, 2010; Scarsbrook, 2006; Scholes, 2013) have used a PAC value of 1% to define meaningful trends, although this value is arbitrary and the decision to use it is at the discretion of the reader.

Trend tables in the main body of text only show the direction of any significant trends for each period, and the associated PAC value. Tables in Appendix 1 contain the full statistical output.

Exploration and Graphics for RivEr Trends (EGRET)

Exploration and Graphics for RivEr Trends (EGRET) is an analysis package developed by USGS for evaluating long term changes in river conditions. The underlying objective of the package is to enable environmental scientists and catchment managers to explore river data for variations in discharge, analyte concentrations (such as a major ion, nutrient, or suspended sediment), and fluxes, and describe, quantify, and visualise their behaviour (Hirsch & De Cicco, 2015). Analysis uses the Weighted Regressions on Time, Discharge, and Season (WRTDS) method to describe long term trends in both concentration and flux (Hirsch & De Cicco, 2015). Such analyses can help communicate water quality changes that are taking place with more insight than traditional time-series trend analysis, providing the best information possible for guiding decisions about future efforts to protect and restore water quality (Hirsch et al., 2010).

The WRTDS method is suited to datasets with the following characteristics:

1 The number of samples collected at the sampling site is in excess of 60, although the method was originally designed for 200 or more.

2 The dataset spans a decade or more.

3 There exists a complete record of daily discharge values for the site over the period being analysed.

4 Samples should be representative of the entire cross section of the river, such that multiplying the measured concertation and discharge results in an unbiased estimate of flux.

5 River discharge should be adequately represented by the average daily discharge (i.e. flashy catchments should be avoided).

The WRTDS model requires daily mean flow values for the duration of the water quality sample record. This type of data is limited to rated hydrological sites with continuous stage measurement, meaning that only certain sites could be analysed (Hirsch & De Cicco, 2015). Sites selected for analysis using the EGRET package were:

- Ngongotahā at SH 36
- Puarenga at FRI
- Utuhina at Lake Road
- Waingaehe at SH 30

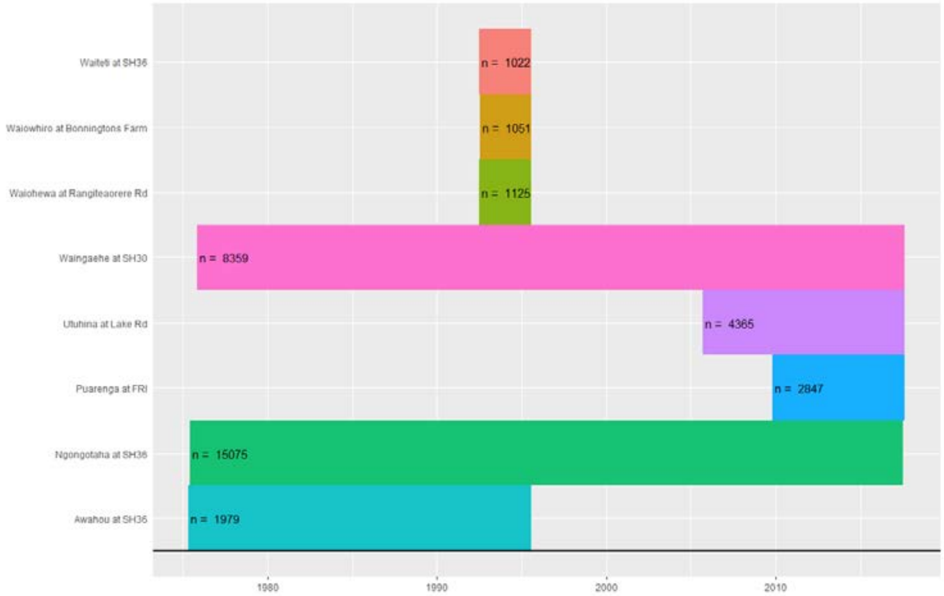


Figure 1 *Timeline of continuous flow records for Rotorua Inflow sites. Note that only sites with a continuous flow record have been shown.*

To avoid complications associated with lab methodology changes, EGRET analysis was limited to data collected after July 2009. Continuous flow data was extracted from BOPRC's data archive for the post-change period and averaged to daily mean values. This was combined with monthly water quality samples and site metadata using functions associated with the EGRET package, before being passed to the WRTDS model.

Standardised output was produced by the EGRET package for each analyte-site combination. This included:

1 Diagnostic plots to assess model rigor.

2 Modelled mean concentration and flow normalised concentration over the period of analysis.

3 Modelled flux estimates and flow normalised flux estimates over the period of analysis.

4 Modelled concentration at three discharges (lower, middle, upper) over the period of the analysis.

5 Modelled concentration versus discharge centred on 1 July (typically the peak for nutrient concentrations) for three years (beginning of record, middle of record, end of record) to explore how the concentration-discharge relationship had changed time.

6 Calculations of the trend in concentration and flux over time.

7 Calculations of discharge, concentration, flux, and flow normalised flux for each year of analysis.

8 Contour plots depicting the modelled concentration versus flow over the period of analysis.

All diagnostic plots were checked for each nutrient constituent-site combination, and model runs were only reported if they satisfied relevant validity metrics.

Additional information about the EGRET package and underlying statistical models can be found in the User guide to Exploration and Graphics for RivEr Trends (EGRET) and dataRetrieval: R packages for hydrologic data (Hirsch & De Cicco, 2015).

Load estimates

Traditional method

Scholes (2013) calculated nutrient loads for each of the nine Rotorua Inflows by multiplying discrete monthly water quality values by flow measurements taken as close to the sampling time as possible (usually within a few hours). Results in mg s-1 were converted to kg d-1 and averaged across each year to provide an average hourly load, which could then be extrapolated to an annual load by multiplying this value by 8,760 (number of hours per year). This method is a form of numeric integration where the instantaneous flux calculated at the time of sampling is assumed to represent the entire period up to when the next sample is taken (Meals, Richards, & Dressing, 2013). The annual load is simply the sum of the calculated interval (monthly) loads for that year.

This method has been repeated in the current report for comparative purposes. However, Meals et al. (2013) suggest that numeric integration is only satisfactory if the sampling frequency is high (in the order of 100 samples per year) otherwise load variability associated with discharge events may be missed, resulting in inaccuracies. This has prompted the inclusion of two additional methods of load estimation, LOAD ESTimator (LOADEST), and WRTDS (detailed below).

LOADEST and WRTDS

Both LOADEST and WRTDS are regression methods based on the relationship between flow and concentration for the period when concentration data exist (Meals et al., 2013). For specific information on how LOADEST (Runkel, Crawford, & Cohn, 2004) or WRTDS (Hirsch & De Cicco, 2015) calculate loads, refer to the referenced user guides.

Monthly analyte data and flow measurements were used to build and calibrate the LOADEST model in R for each site-analyte combination, over the period between 1 January 2002 and 31 December 2016. Models were built using the in-built 'best model' function, which uses the Akaike Information Criterion (AIC) to determine which of the nine in-built models fit the observation data the best. The 'best fit' model diagnostics were assessed, and models were only included if relevant validity metrics were satisfied. Finally, loads were calculated by using the established calibration relationship to evaluate the loads for the original dataset, providing results that are comparative to, but less variable than, the numeric integration method.

Load estimates for using the WRTDS method were calculated for the four continuous flow sites described above, using the same methodology as for EGRET analysis. The difference between the LOADEST method and WRTDS is that LOADEST uses a single set of parameters to describe the relationship of concentration to discharge, time, and season, rather than using locally weighted regression like WRTDS (Hirsch & De Cicco, 2015; Hirsch, Moyer, & Archfield, 2010). Load estimates are compared and discussed in the results section.

Part 3:

Results and discussion

Rainfall

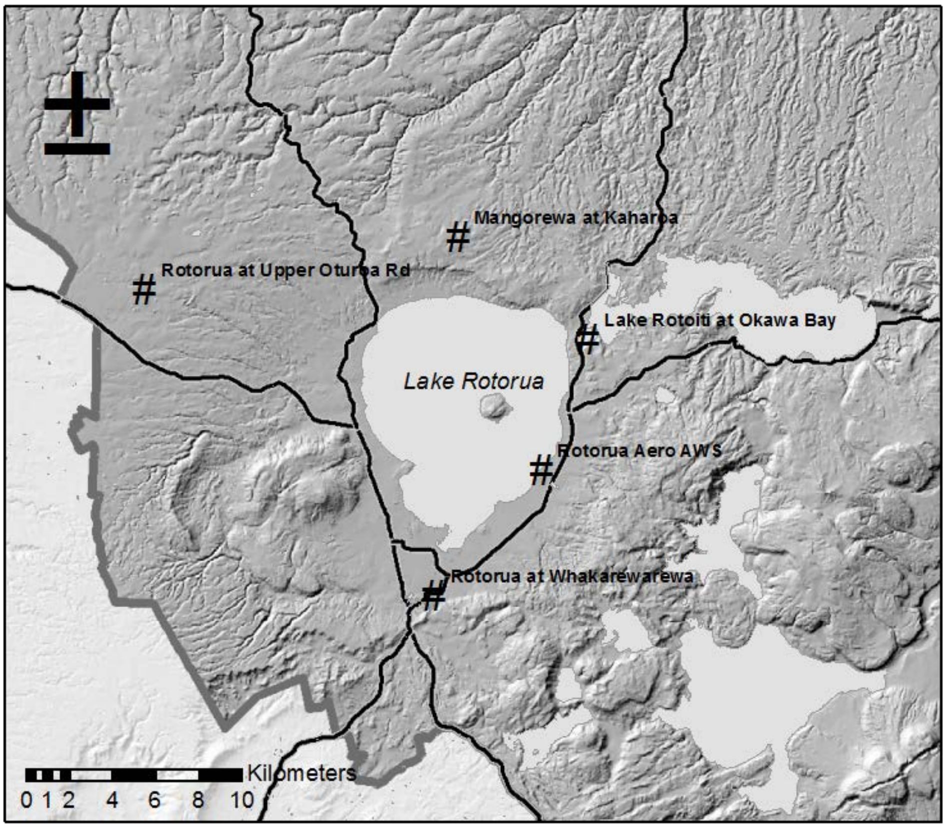


Figure 2 *Rainfall monitoring sites around Lake Rotorua.*

Background

Rainfall is a key driver of nutrient flushing and erosion processes, therefore it is important factor to consider when interpreting catchment nutrient loading. There are five rainfall monitoring sites within the Lake Rotorua Catchment (Figure 2), three of which have data records that span back to 2002. This information can be used to provide some context about environmental conditions coinciding with annual nutrient loads.

Analysis and results

Rainfall data is collected at 15 minute intervals at all sites except 'Rotorua Aero AWS', where it is logged once every hour. Rainfall depth was summed per year, for each site, and analysed to determine if there were spatial differences. Results show that mean annual rainfall varied between sites ($p<0.001$), with 'Mangorewa at Kaharoa' and 'Rotorua at Upper Oturoa Road' having significantly higher mean annual rainfall than the other three sites (Figure 3; all $p<0.05$). These two sites are situated at the northern end of the lake, implying that northern and north-western catchments may receive more rainfall on average than eastern and southern catchments. However, these two sites are also located at higher elevations than the three other sites, suggesting that localised rainfall patterns within the Lake Rotorua Catchment are, at least partly, influenced by elevation.

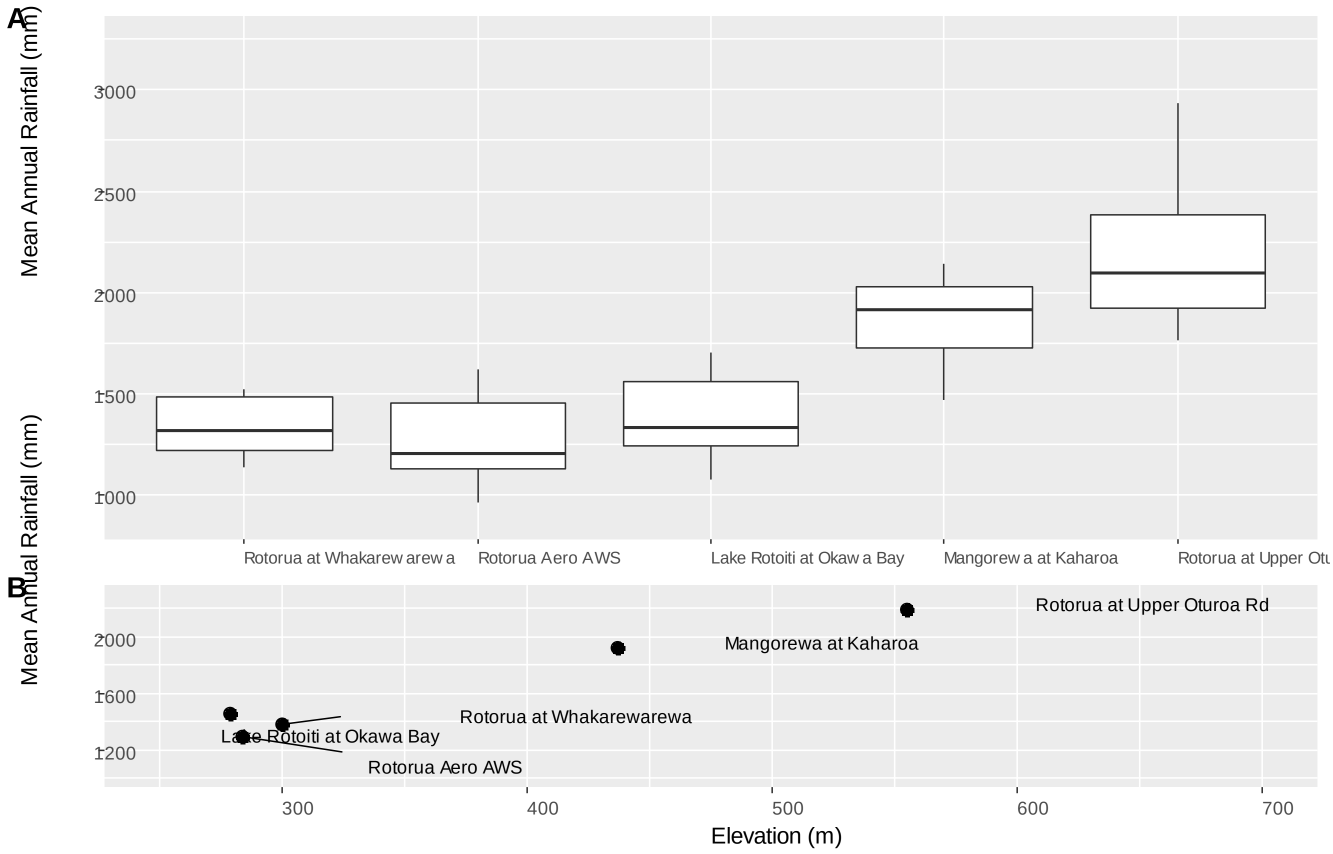


Figure 3 *(A) Mean annual rainfall for each of the five rainfall monitoring stations around Lake Rotorua, 2002-2016. (B) Mean annual rainfall versus elevation for each monitoring station.*

Inter-annual rainfall patterns between 2002 and 2016 are summarised in Figure 4, which reveals notable consistency in rainfall patterns between sites. All three sites with data records extending back to 2002 experienced less than normal rainfall in 2002, before fluctuating between 80% and 120% of normal in the years leading up to 2008. The exception to this pattern was Mangorewa at Kaharoa, which recorded greater than normal rainfall for each of these years except 2002.

All sites were operational from 2009, and each showed that 2011 was the wettest year over the duration of the study, with close to 170% of normal rainfall registered at the Mangorewa at Kaharoa site. Mangorewa at Kaharoa and Rotorua at Upper Oturoa Road also experienced greater than normal rainfall during 2012, while lower elevation, eastern sites experienced less than normal rainfall in that year. Total rainfall accumulation was below normal at all sites between 2013 and 2015, and increased to above normal in 2016 for all sites except Rotorua Aero AWS, which recorded 97% of normal rainfall. None of the rainfall records appear to show any obvious trends over time, although official trend analysis was not carried out.

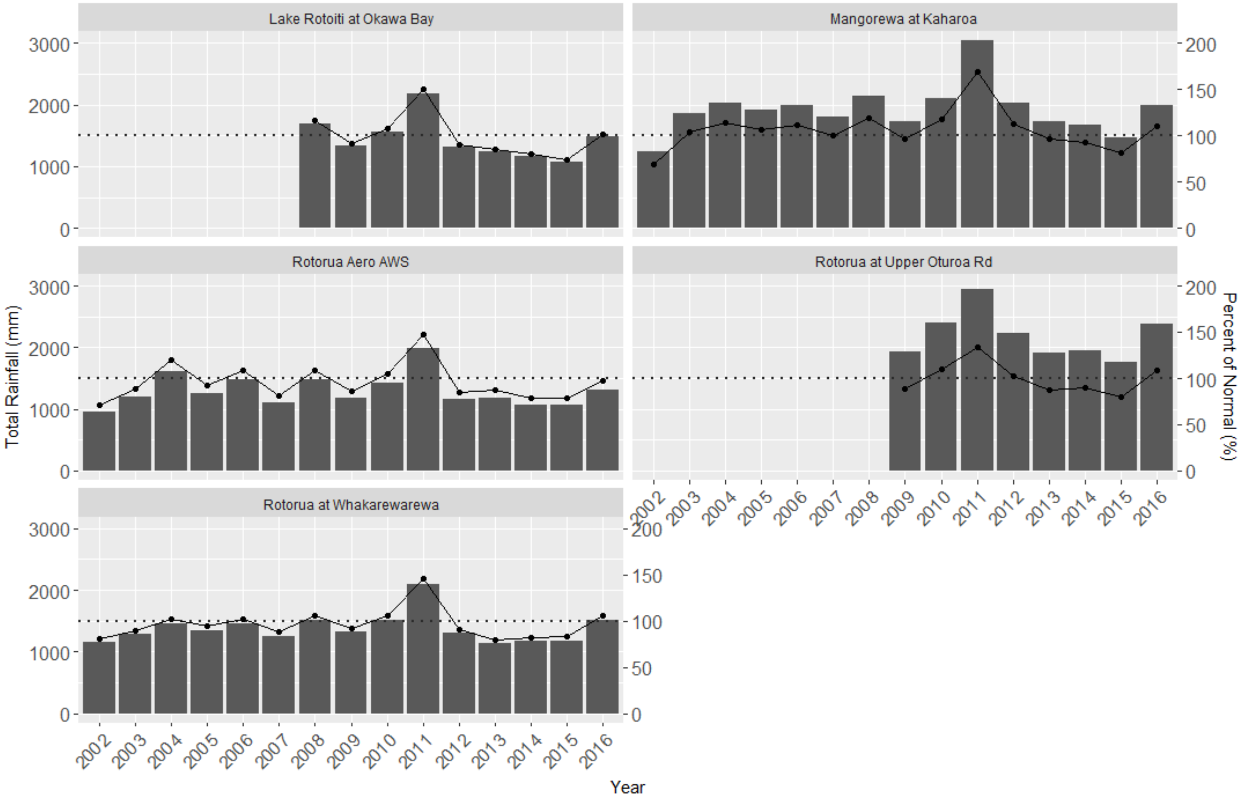


Figure 4 *Total annual rainfall between 2002 and 2016, for each rainfall monitoring site. The black dotted line represents normalised rainfall, and is read according to the secondary Y axis. 'Normal' rainfall was interpreted as the mean annual rainfall across the length of the available data record.*

Data records were also analysed for the frequency of high intensity rainfall events of different sizes. This was carried out to ensure that total annual rainfall was reflective of the number of high intensity rainfall events. This is important because the number of high intensity events could theoretically increase between years while total annual rainfall remains constant, i.e. the volume of rainfall remains constant but occurs in more intense, less frequent events. Such events are responsible for significant nutrient and sediment mobilisation, and the resulting event loads can be disproportionate contributors to the overall nutrient pool (Abell, 2013).

For the sake of this analysis, the minimum inter-event time, i.e. the minimum dry period between rainfall events, was set at 60 minutes. This means that any rainfall accumulation that was recorded within 60 minutes of the last, was counted as the same rainfall event. Event size was calculated, and the number of events exceeding 30 mm and 50 mm accumulation, per year, are shown in Figure 5.

Both 30 mm and 50 mm event frequency broadly reflect the total annual rainfall findings above, where a greater number of high intensity rainfall events occurred in 2011 than in other years. 2008 and 2012 also experienced a small increase in the number of 30 mm and 50 mm rainfall events, at most sites. Mean event size for each site peaked in 2011, although this was less pronounced at 'Rotorua at Upper Oturoa Road' where 2010 and 2012 mean event sizes were similar.

Further analysis showed that the higher altitude, northern rainfall sites (Mangorewa at Kaharoa, and Rotorua at Upper Oturoa Road) had a greater number of 30 mm and 50 mm rainfall events than were recorded at the Rotorua at Aero AWS and Rotorua at Whakarewarewa rainfall sites (all $p<0.05$).

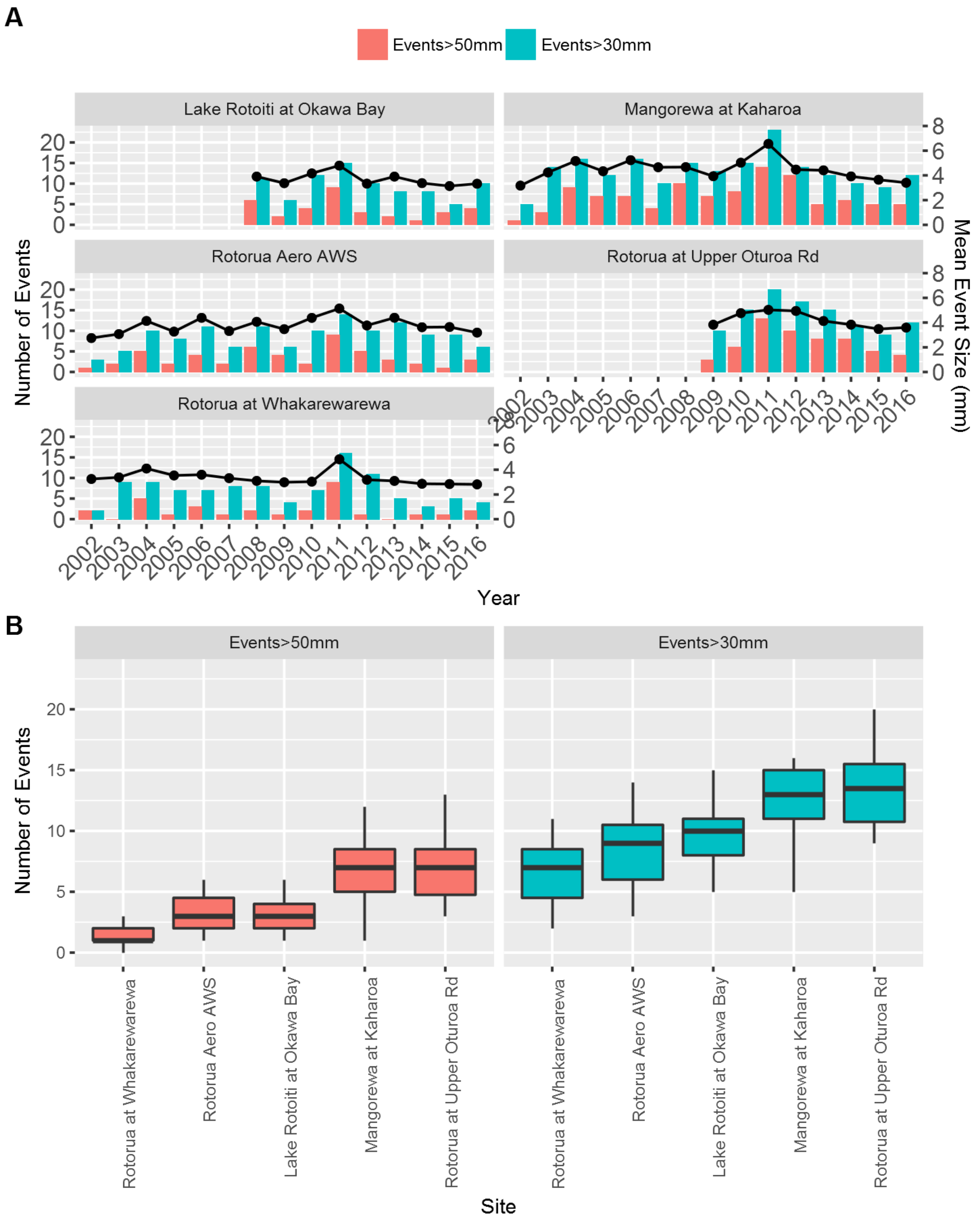


Figure 5 *(A)The number of 50 mm or greater (orange) and 30 mm or greater (blue) rainfall events that occurred at each site, between 2002 and 2016. Mean event size per year is included on a secondary y axis. (B) The mean annual number of 50 mm or greater, and 30 mm or greater, rainfall events that occur at each Lake Rotorua rainfall site.*

Rainfall summary

In summary, rainfall in the Lake Rotorua Catchment varies spatially, with the two northern/north-western sites receiving more annual rainfall, and a greater number of high intensity rainfall events per year. However, these sites are located at a higher altitude, which suggests that topography may play a key role in localised rainfall patterns. Total rainfall, the number of high intensity events, and event size seem to follow a similar pattern, where some years, e.g. 2011, 2008, stand out as being particularly wet. In addition, records for the period between 2012 and 2015 indicate less than normal rainfall accumulations, and less high intensity rainfall events than in other years, suggesting a period of drier than normal weather. Finally, there were no visible trends in: total rainfall accumulation, the frequency of high intensity events, or mean rainfall event size.

Flow

The Hamurana Stream had the largest median flow over the entire data period, followed by the Puarenga, Awahou, Utuhina, and Ngongotahā Streams (Figure 6). These streams all had median flows greater than1.5 m^3/s, in contrast to the Waiohewa, Waiowhiro, and Waingaehe streams that had flows less than 0.5 m^3/s. The Ngongotahā, Puarenga, and Utuhina Streams are all more variable than other sites, which may indicate a larger surface water to groundwater input ratio.

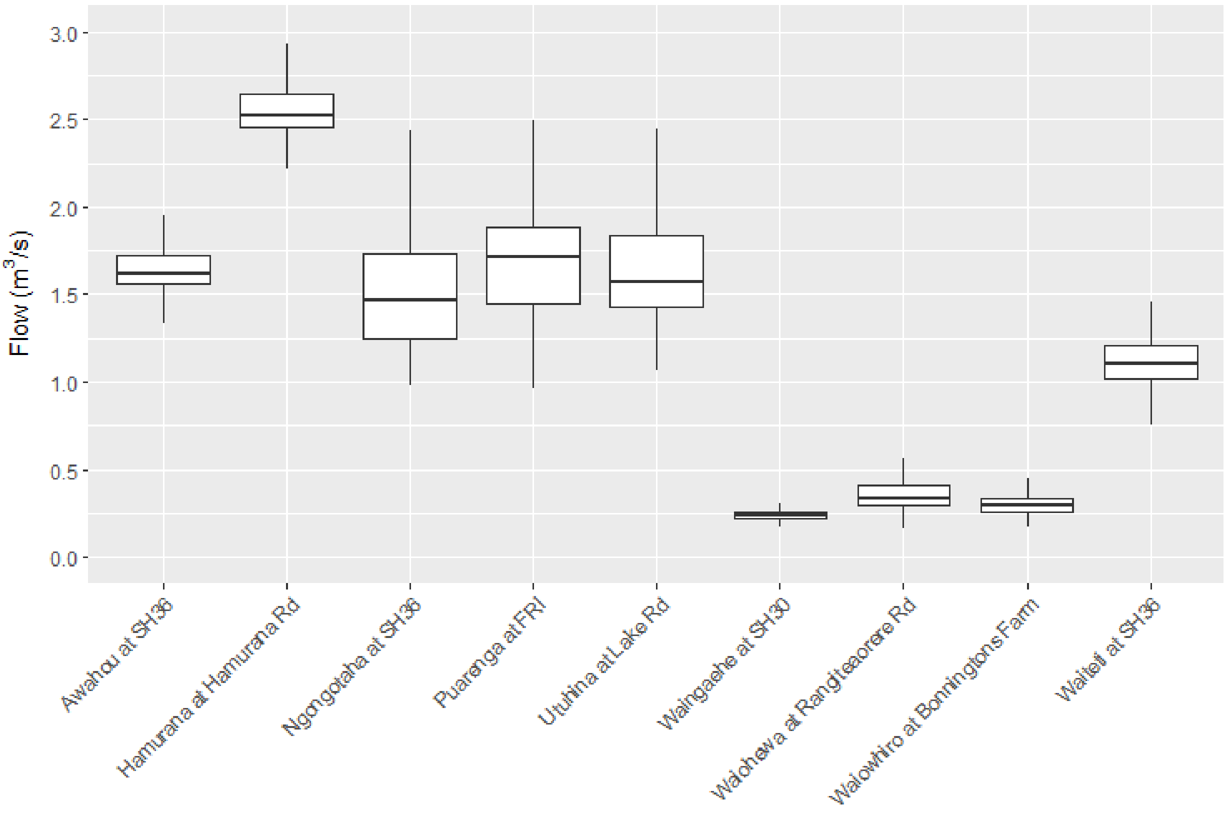


Figure 6 Box-whisker plot of flow values for each site between 2002 and 2016.

Mean flow data collected from each of site, over time, are shown in Table 1 , with trend analysis results presented in Table 2. Results show that flow increased between 2002 and 2016 in the Awahou, Ngongotahā, and Hamurana streams by 0.48%, 0.53%, and 1.02% per annum, respectively. Waiowhiro at Bonningtons Farm was the only site to show a significant declining trend over the 15 year dataset, with a reduction in flow by 0.86% per annum.

Flow was stable at most sites before the lab methodology change (July 2008), with only Waingaehe at SH 30 and Waitetī at SH 36 expressing significant trends (both increasing by 3.21% and 4.22% per annum, respectively). However, significant trends were found for all sites except Puarenga at FRI, post method change. Of these, flow declined at all sites except Hamurana at Hamurana Road which increased at 0.97% per annum. The time series flow plot for this site (shown in the site catchment specific analysis section), depicts a step change which occurred in, and has persisted since, 2012. The BOPRC Environmental Data Services (EDS) team cannot currently explain exactly why this has occurred, but are looking into the cause. Regardless, the step change is undoubtedly a driver in the increasing loads seen in this catchment post July 2009.

For all sites where flow was declining, this declining trend persisted and increased in magnitude in the 2012-2016 dataset for all sites but Utuhina at Lake Road (six sites in total). These results seem to reflect the rainfall pattern for these years, where total rainfall accumulation was at or close to normal in 2012, proceeded by a period of three drier years, although rainfall accumulations increased again in 2016. The declining rainfall pattern was more pronounced in northern, high elevation rainfall sites which experienced a comparatively wetter 2012 (relative to normal rainfall) than other sites. The medium-large rainfall accumulation in 2012 followed by a prolonged dry period may be predominant driver behind declining trend for flow at some sites.

These results differ from that of Scholes (2013) who found that steam flow was increasing in seven of the nine Rotorua Lake catchments, and attributed this to recent high rainfall events. The main reason for the difference between Scholes' analysis and the current investigation is that Scholes' dataset ended during the wet 2009-2012 period, while the two datasets showing declining flow in the current investigation began during this period and ended just after an extended dry period. This emphasises how short term trend analysis can be influenced by periods of environmental abnormality, and suggests that long term trend analysis provides a more robust indication of meaningful changes at a site.

Table 1 *Annual average flow for nine Rotorua Streams (m^3/s).*

Name	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Awahou at SH 36	1.83	1.54	1.51	1.53	1.67	1.97	1.59	1.65	1.71	1.87	1.94	1.65	2.12	1.60	1.61
Hamurana at Hamurana Road	2.61	2.41	2.48	2.51	2.67	2.46	2.43	2.42	2.53	2.67	2.65	2.60	2.63	2.66	2.69
Ngongotahā at SH 36	1.31	1.16	1.58	1.57	1.66	1.32	2.18	1.69	1.62	1.92	2.24	1.73	1.46	1.25	1.63
Puarenga at FRI	1.59	1.51	1.91	1.78	1.72	1.52	1.70	1.56	1.48	2.29	2.16	1.89	2.02	1.58	2.35
Utuhina at Lake Road	1.54	1.45	1.81	1.59	1.84	1.53	1.67	1.77	1.90	1.91	2.04	1.45	1.63	1.31	1.58
Waingaehe at SH 30	0.25	0.21	0.22	0.25	0.28	0.25	0.25	0.25	0.24	0.28	0.29	0.26	0.24	0.21	0.20
Waiohewa at Rangiteaorere Road	0.34	0.30	0.33	0.35	0.42	0.63	0.43	0.35	0.48	0.51	0.45	0.38	0.99	0.25	0.29
Waiowhiro at Bonningtons Farm	0.32	0.30	0.32	0.29	0.34	0.31	0.32	0.29	0.36	0.34	0.35	0.30	0.31	0.23	0.29
Waiteti at SH 36	1.41	0.89	1.11	1.15	1.33	2.16	1.06	1.18	1.31	2.46	1.65	1.19	1.77	1.07	1.11
Total	**11.19**	**9.77**	**11.28**	**11.01**	**11.92**	**12.16**	**11.62**	**11.15**	**11.63**	**14.25**	**13.78**	**11.45**	**13.18**	**10.17**	**11.75**

Table 2 *Results of a Seasonal or Mann-Kendall test (depending on seasonality) on flow, for four different periods: All (2002-end of 2016), Pre Change (2002-July 2008), Post Change (July 2009-end of 2016), and 2012-2016. The direction of significant trends ($p<0.05$) are represented by increasing (⇗) or decreasing (⇘) arrows, while a blank rectangle (□) depicts no trend. PAC stands for percentage annual change. Full trend statistics can be found in Appendix 1.*

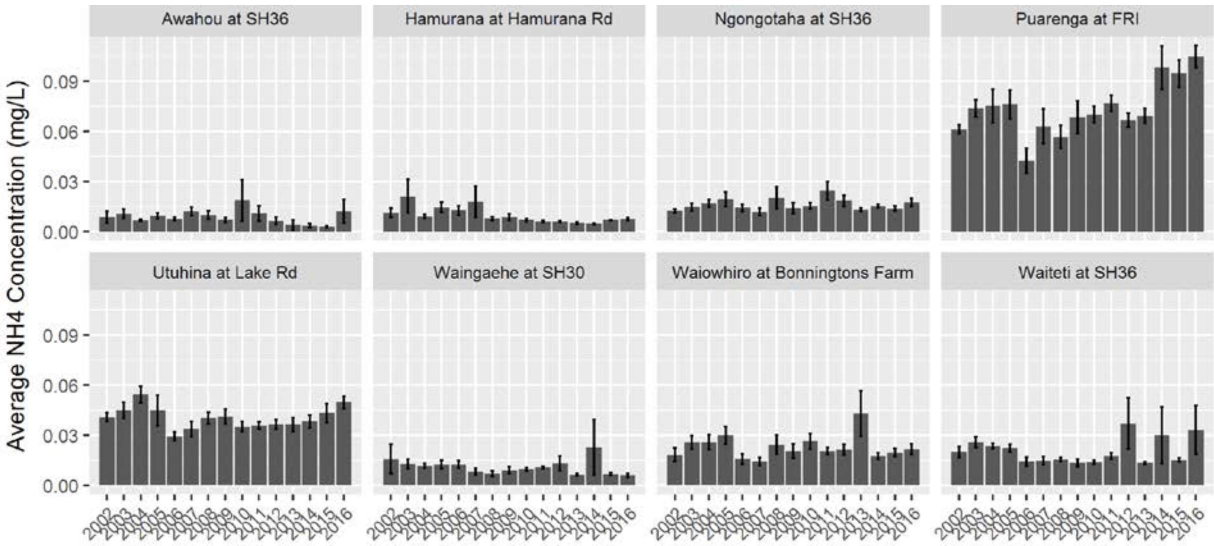
	All		Pre-Change		Post-Change		2012-2016	
Site	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**
Awahou at SH 36	⇗	0.48	□		⇘	-0.98	⇘	-3.38
Hamurana at Hamurana Road	⇗	0.53	□		⇗	0.97	□	
Ngongotahā at SH 36	⇗	1.02	□		⇘	-3.78	⇘	-8.36
Puarenga at FRI	□		□		□		□	
Utuhina at Lake Road	□		□		⇘	-4.73	□	
Waingaehe at SH 30	□		⇗	3.21	⇘	-4.03	⇘	-8.39
Waiohewa at Rangiteaorere Road	□		□		⇘	-3.95	⇘	-8.46
Waiowhiro at Bonningtons Farm	⇘	-0.86	□		⇘	-3.94	⇘	-4.45
Waiteti at SH 36	□		⇗	4.22	⇘	-2.09	⇘	-5.28

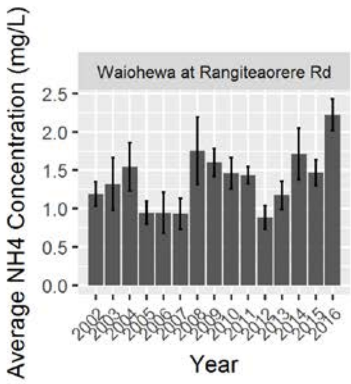
Comparative concentrations

Mean annual TN concentrations for most sites fluctuated between 0.8 mg/L and 2.0 mg/L for the duration of the study (Figure 7). The Hamurana Stream had the lowest TN concentrations of all sites, with annual mean values below 1.0 mg/L, and had the lowest mean TN concentration (0.75 mg/L) of all sites in 2016. The geothermally fed Waiohewa Stream consistently had the largest mean TN concentration, with all years exceeding 2.0 mg/L.

NNN concentrations were greatest in the Awahou, Waingaehe, and Waitetī catchments and lowest in the Utuhina Catchment (Figure 8). NH4-N concentrations were the greatest by far in the geothermally fed Waiohewa Stream, which had concentrations nearly 20 times greater than the next highest site (Puarenga at FRI) (Figure 9). The Hamurana and Awahou streams contained the lowest mean annual NH4-N concentrations with values consistently below 0.015 mg/L.

Mean annual TP concentrations varied between sites, ranging from around 0.05 mg/L in Waitetī and Waiowhiro streams, to nearly 0.15 mg/L in the Waingaehe Stream (Figure 10). DRP was highest in Waingaehe and Hamurana streams, followed closely by the Awahou, with mean annual concentrations regularly exceeding 0.06 mg/L over the monitored period (Figure 11).


Awahou at SH36
Hamurana at Hamurana Rd
Ngongotaha at SH36
Puarenga at FRI
Utuhina at Lake Rd
Waingaehe at SH30
Waiowhiro at Bonningtons Farm
Waiteti at SH36
Average NH4 Concentration (mg/L)
0.00
0.03
0.06
0.09
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016


Waiohewa at Rangiteaorere Rd
Average NH4 Concentration (mg/L)
0.0
0.5
1.0
1.5
2.0
2.5
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
Year

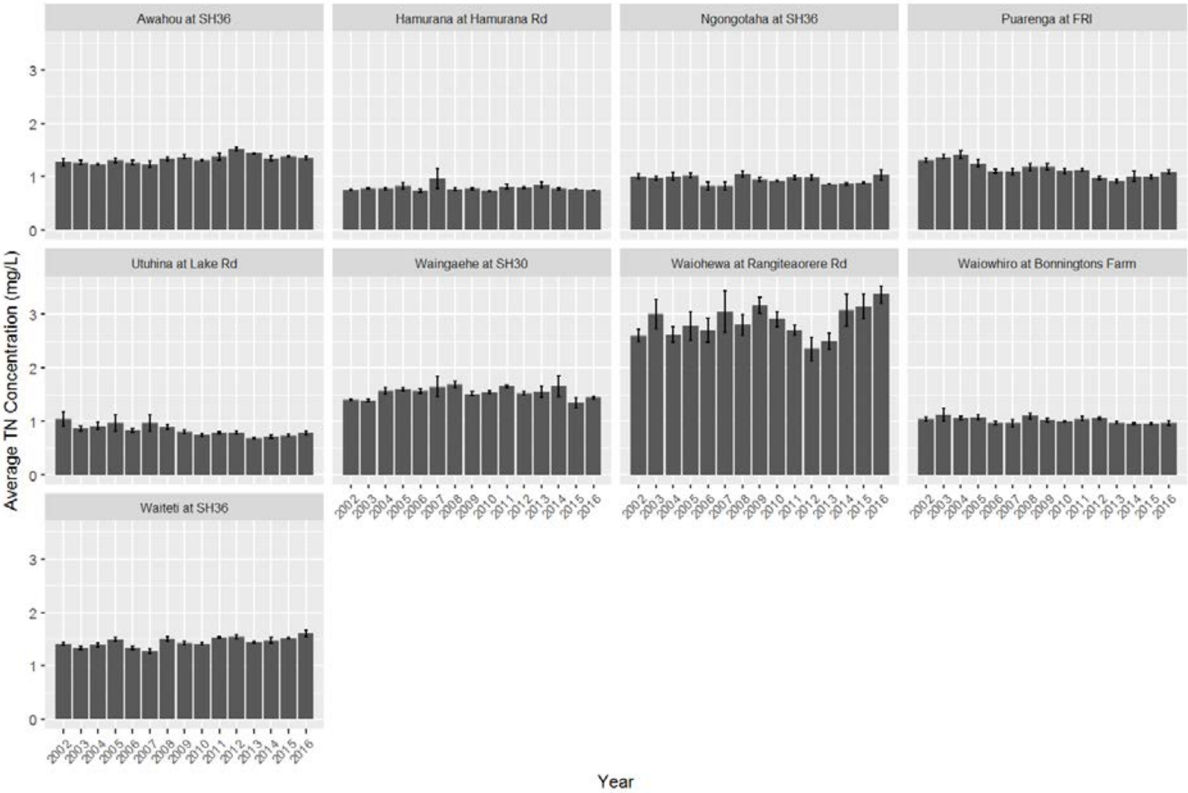


Figure 7 *Mean TN concentrations at each of the ten monitored sites over time. Error bars represent ± one standard error.*

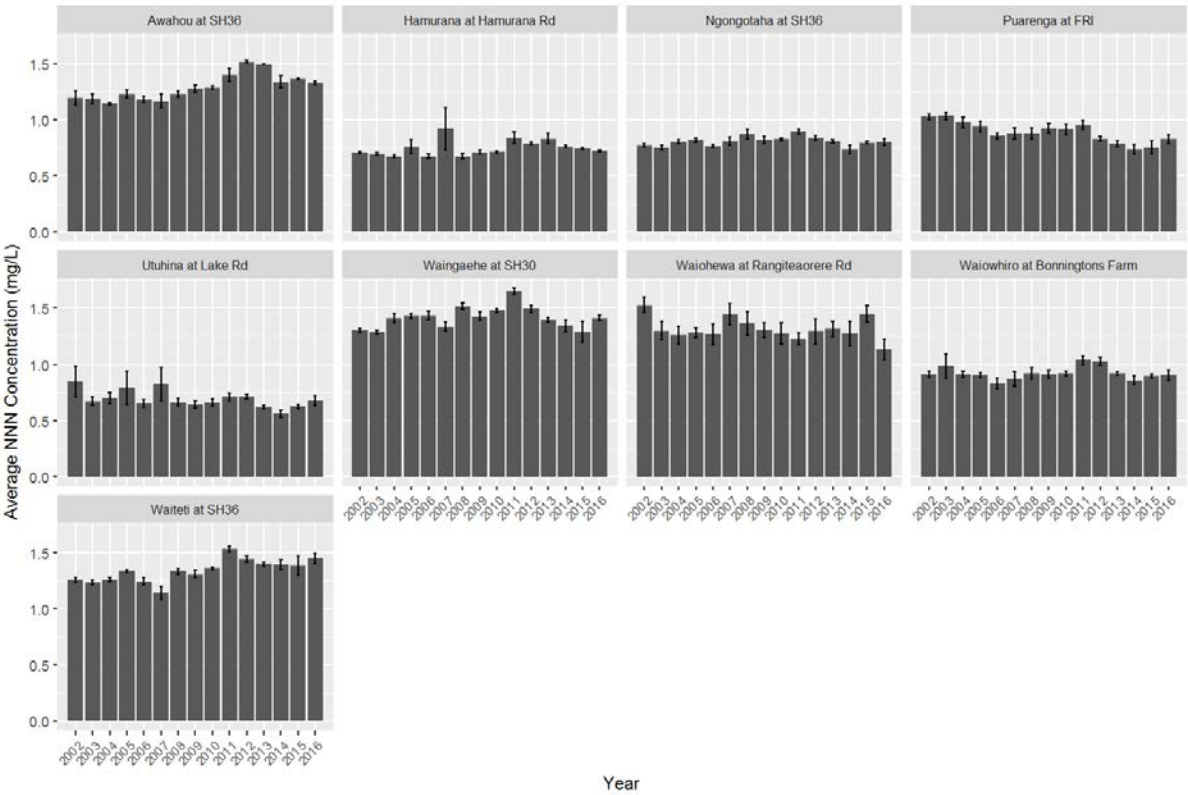
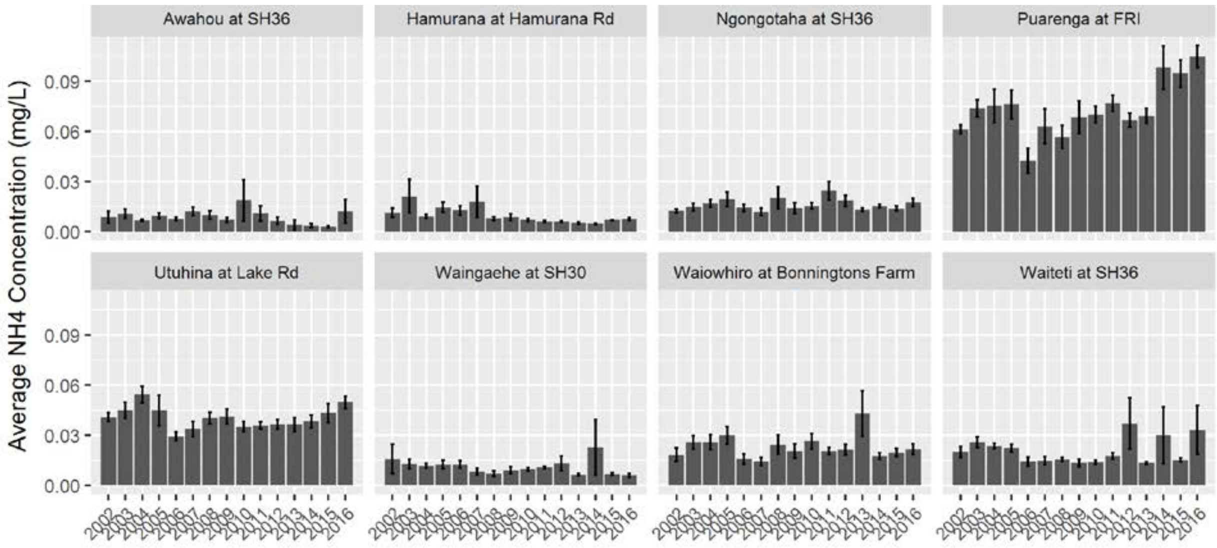


Figure 8 *Mean NNN concentrations at each of the ten monitored sites over time. Error bars represent ± one standard error.*



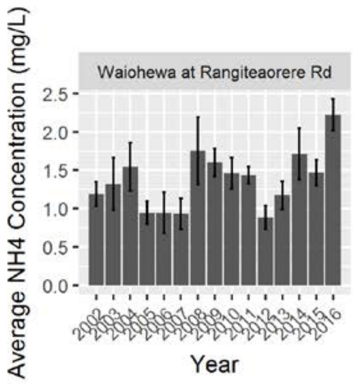


Figure 9 *Mean NH4-N concentrations at eight of the nine main monitoring sites over time (top). Waiohewa at Rangiteaorere Road has been included as a separate plot (bottom) due to the relative concentration difference with other sites. Error bars represent ± one standard error.*

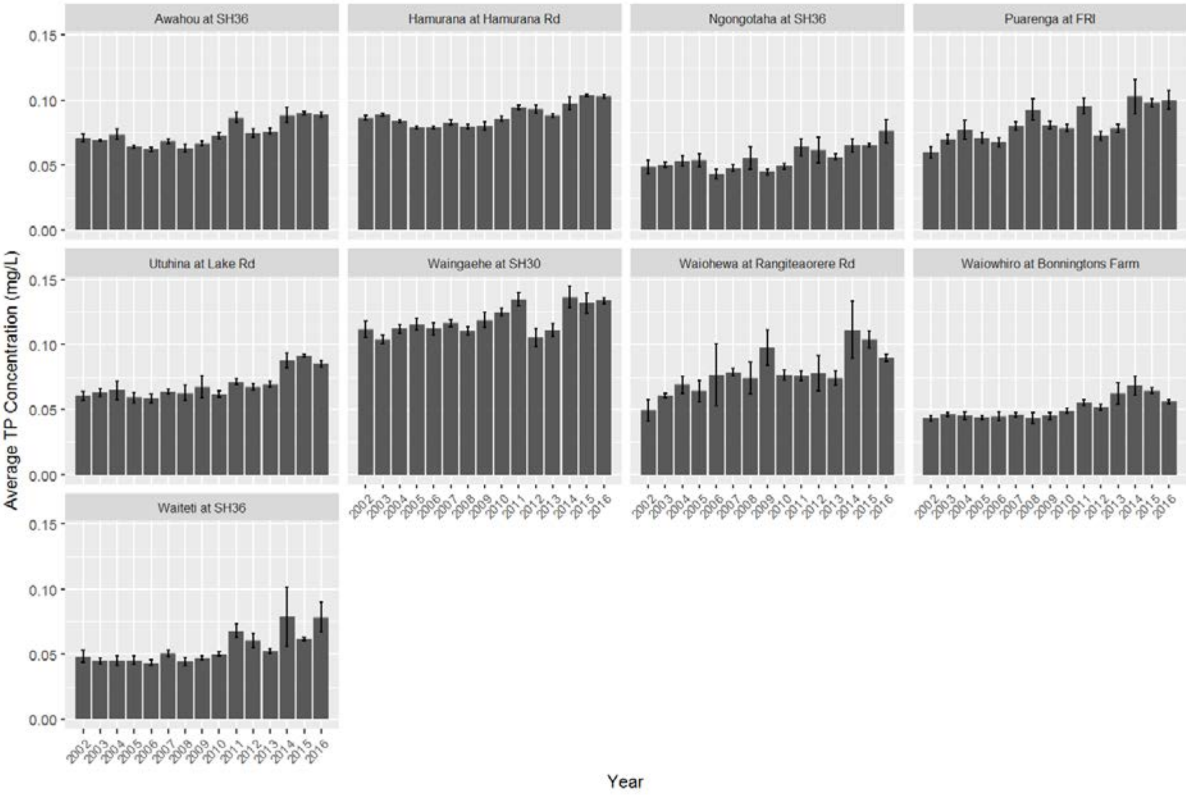


Figure 10 *Mean TP concentrations at each of the nine main monitored sites over time. Error bars represent ± one standard error.*

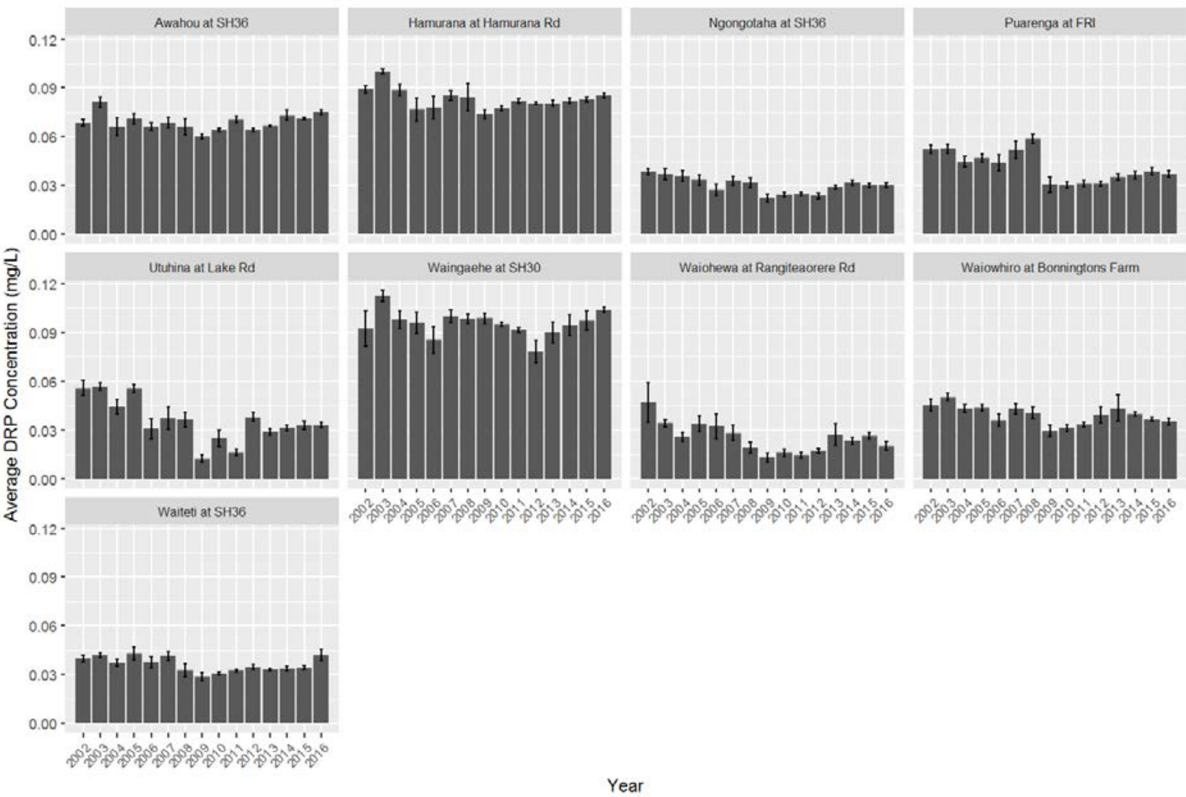


Figure 11 *Mean DRP concentrations at each of the ten monitored sites over time. Error bars represent ± one standard error.*

Catchment specific analysis

Awahou Catchment

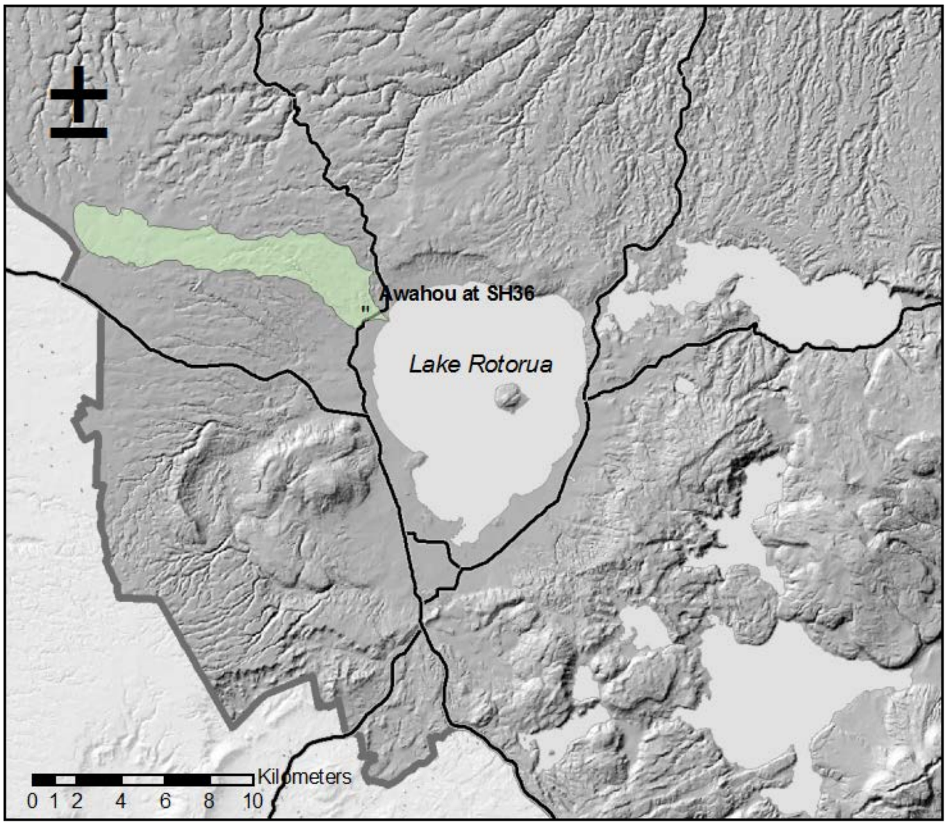


Figure 12 Location of the Awahou Catchment and the Awahou at SH 36 monitoring site.

Background

The Awahou Catchment is located on Lake Rotorua's North West shore and drains to Lake Rotorua via the Awahou Stream (Figure 12). The catchment covers approximately 2,842 ha and is dominated by pasture and arable land (56%), lifestyle blocks and mixed land use (14%), exotic forest (12%), and indigenous forest (10%). Dairy has become more prevalent in this catchment over time, with the greatest increase in this land use occurring in the late 1970's and 1980's (Rutherford, Palliser, & Wadhwa, 2011).

Previous studies state that groundwater is a significant contributor to the Awahou Stream and estimate the mean residence time to be 75 years (Morgenstern et al., 2015). This is the third longest residence time of all Lake Rotorua catchments.

Trend analysis

The Awahou Stream is monitored where it intersects SH 36 at the lower end of the catchment. Trend analysis results show that TN (adjusted), NNN, TP (adjusted), and DRP (adjusted) concentrations increased between 2002 and 2016, by 0.89%, 1.06%, 0.42%, and 1.00% respectively, while NH4-N decreased by 4.76% (Figure 13; Table 3).

Nitrogen species revealed no significant trend post the lab methodology change. However, decreasing trends were shown for TN (0.82% p.a.) and NNN (1.01% p.a.) in the last five years of the dataset (2012-2016), while NH4-N increased by 12.23% per annum. Both TP and DRP expressed increasing trends post lab method change (3.36% p.a., 2.11% p.a.), and also in the last five years of the dataset (2.79% p.a., 2.24% p.a.).

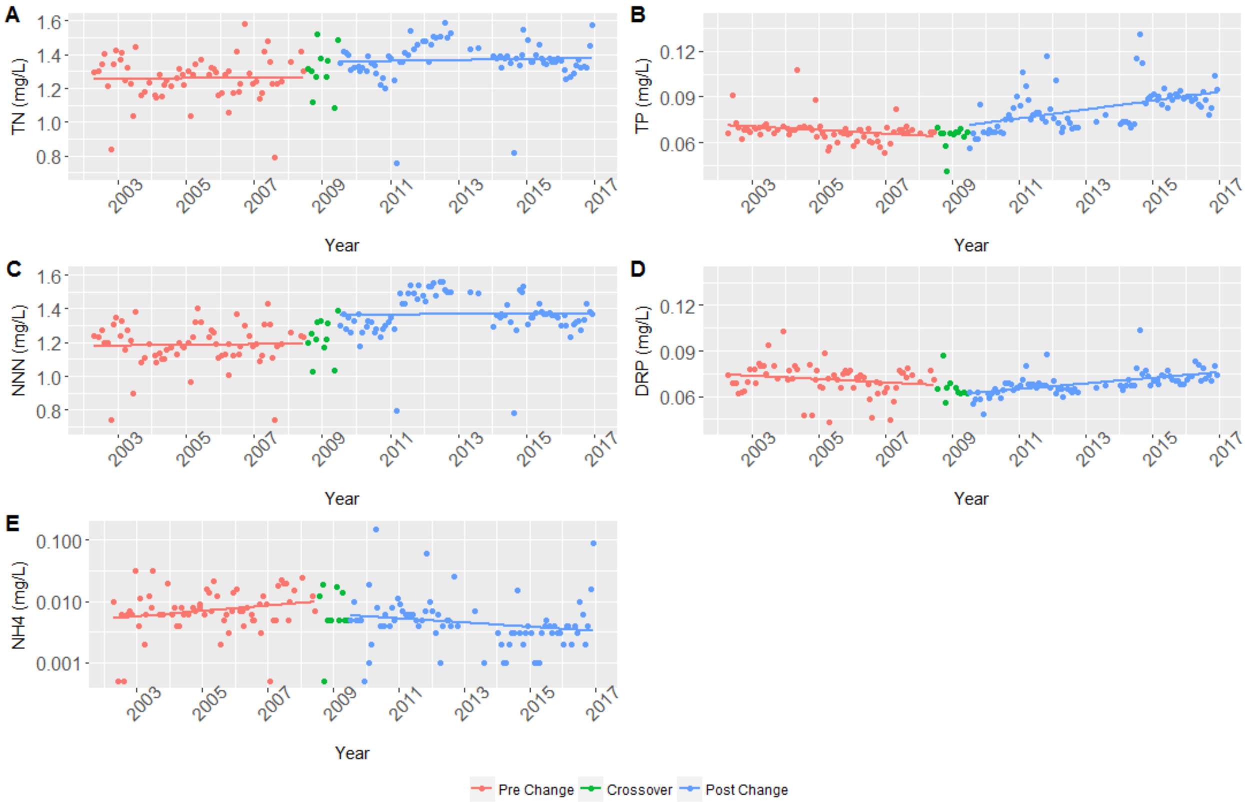


Figure 13 *Trend plots for TN, TP, NNN, DRP, and NH4-N (A-E) at the Awahou at SH 36 water quality site, for the period of 1 January 2002 to 31 December 2016. Plots are based on unadjusted data, split into pre (red) and post (blue) lab method change groups, with a one year crossover period (green). Pre and post lab method groups include a fitted linear regression model. NH4-N is plotted on a log transformed axis.*

Table 3 *Trend analysis results for analyte concentrations at the Awahou at SH 36 water quality monitoring site. Trend analysis was carried out on unadjusted (All) and adjusted (All Adjusted) data for the period of 2002-2016, as well as pre and post lab methodology periods, and last five years of the dataset (2012-2016). The direction of significant trends ($p<0.05$) are represented by increasing (↗) or decreasing (↘) arrows, while a blank rectangle (□) depicts no trend. PAC stands for percentage annual change. Full trend statistics can be found in Appendix 1.*

	All		All Adjusted		Pre-Change		Post-Change		2012-2016	
Site	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Site**	**Trend**
TN	↗	0.60	↗	0.89	□		□		↘	-0.82
NNN	↗	1.06	-	-	□		□		↘	-1.01
NH4	↘	-4.76	-	-	□		□		↗	12.23
TP	↗	2.03	↗	0.42	□		↗	3.36	↗	2.79
DRP	□		↗	1.00	□		↗	2.11	↗	2.24

Load estimates

Method comparison and patterns

Load estimates were relatively consistent across the two methods, for most analytes. However, estimates of NH4-N using the LOADEST method were slightly less variable than those calculated using numeric integration (Figure 14). Results show a gradual increasing load over time for all analytes except NH4-N, which is consistent with the long-term trend analysis results (with the exception of DRP). The load trajectory for DRP is likely to be buffered by the lab methodology change, i.e. DRP values post-change are lower than pre-change, reducing the slope of temporal increases.

All analytes show variation in average annual load over time, and general load peaks in 2007, 2012, and 2014, although the relative magnitude differs between nitrogen and phosphorus species. This pattern coincides with elevated values in the flow record, which are likely to disproportionately influence annual load estimates. The TN and NNN temporal load pattern also appears to follow rainfall and stream flow patterns, peaking in the wet 2011-2012 period and declining towards 2006.

2016 Calendar Year

It was estimated that between 68 and 71 T of TN was contributed to Lake Rotorua via the Awahou Stream during the 2016 calendar year, depending on the calculation method used. This was comprised of between 67 and 71 T of NNN, and 0.3 to 0.6 T of NH4-N. TP loads were estimated to be between 4.5 and 4.8 T, which is comprised of between 3.8 to 3.9 T of DRP.

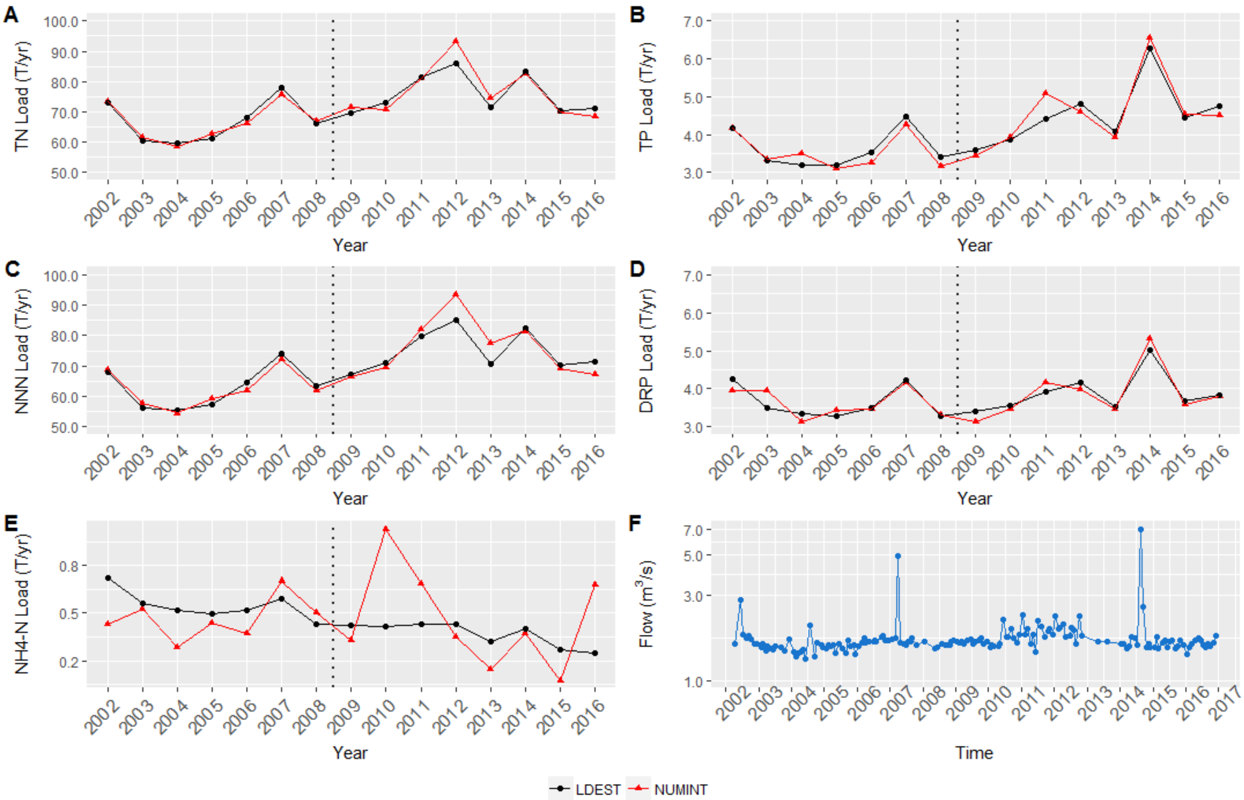


Figure 14 *(A-E) Load estimates for each analyte at the Awahou at SH 36 water quality monitoring site, using two different estimation methods: numeric integration (red) and LOADEST (black). The vertical dotted line represents the lab method change (July 2008). (F) The discrete flow record used to calculate loads.*

Load ratios

Comparison of NNN load to TN load over the duration of the study shows that NNN comprises at least 90% of the TN load in all years since 2002, with numbers exceeding 98% since 2012 (Figure 15). DRP also made up a significant percentage of TP with all annual values remaining above 80%. NH4-N made up anywhere between 0.3% and 0.9% of TN, depending on the year.

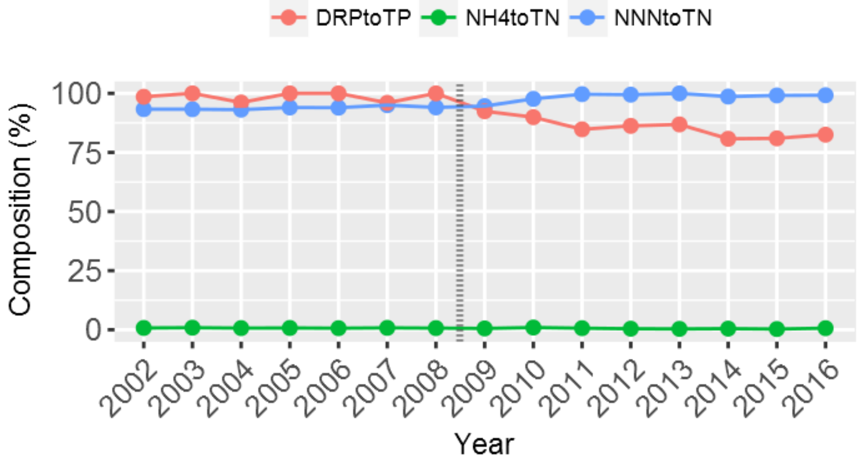


Figure 15 *The overall composition of TN that is attributed to NNN (blue) and NH4-N (green), and TP attributed to DRP (red) for the Awahou at SH 36 site. Composition is calculated from the average of all load estimation methods.*

Catchment summary

Scholes (2013) found that TN was increasing in the Awahou Stream by 0.67% per year for the period of 2002-2012, and attributed this to increases in NNN losses caused by development or conversion of land to intensive land use. The current study has found a continuation of the same pattern, and supports the idea that increasing NNN concentrations are driving increases in TN based on the fact that the contribution of NNN to TN has been increasing over time and now comprises over 98% of the total nitrogen pool. However, results since 2012 show that both NNN and TN concentrations are decreasing, which is reflected in load estimates for that period.

TP concentrations were found to be increasing across all timeframes except the pre-lab change, with larger PAC values post-method change and between 2012-2016, compared with the full 15 year period. Load estimates show a similar pattern, where calculations increase post 2009, highlighting a potentially significant change in the catchment.

Morgenstern et al. (2005) point out that increased loading over time of naturally leached P from volcanic aquifer material is not expected, but P losses from land use could break through the soil as DRP potentially enriching aquifers, resulting in an increased load. Given that over 75% of the TP pool is made up by DRP, this may explain why TP and DRP concentrations have increased over time, in addition to minor supplementary sources of particulate P through overland flow or erosion events. Possible contributors include land uses such as intensive agriculture or forestry, although further investigation is needed to determine specific sources.

NH4-N is shown to be decreasing overall within this catchment, although trend analysis over the final five year period suggests otherwise. This result appears to be influenced by four elevated samples in 2016 which collectively have increased the trajectory of the trend slope. Despite this finding, load estimates continue to decrease which suggests that this is of little ecological concern.

Hamurana Catchment

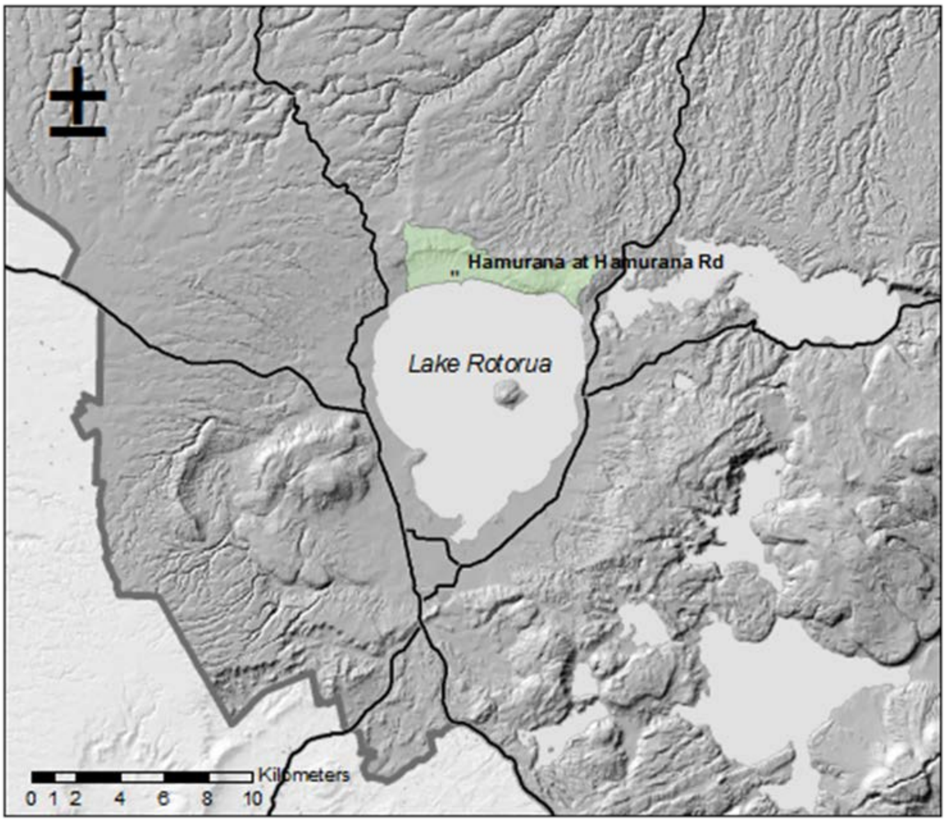


Figure 16 Location of the Hamurana Catchment.

Background

The Hamurana Catchment is located on the northern most shore of Lake Rotorua (Figure 16) and is one of the smaller Lake Rotorua sub-catchments with an approximate area of 1,522 ha. Land use is dominated by pasture and arable land (60%), lifestyle blocks and mixed land use (19%), and native forest (8%).The Hamurana Stream is the main surface water body feeding into Lake Rotorua from this catchment, a significant proportion of which comes from the Hamurana spring.

Morgenstern et al. (2015) suggest that the Hamurana spring has the second longest mean residence time of all Lake Rotorua sub-catchments, equating to approximately 125 years. Phosphorus concentrations in Rotorua groundwater are typically positively correlated with mean residence time, implying that natural concentrations in the Hamurana spring should be elevated above other catchments (Morgenstern, Reeves, Daughney, Cameron, & Gordon, 2005). Given that this stream also has the greatest mean flow of all of the other sub-catchments, we can expect that TP and DRP from this catchment will be significant in the context of overall loading to Lake Rotorua.

Trend analysis

Trend analysis of water quality concentration data from the Hamurana at Hamurana Road site, for the 2002-2016 dataset, shows an increasing trend for TN (adjusted) and NNN of 0.58% per annum for both analytes, while NH4-N and TP (adjusted) decreased by 3.60% and 0.49% p.a., respectively (Figure 17; Table 4).

Prior to the lab methodology change, TP and DRP express significant declining trends of 1.47% and 1.86% p.a., respectively. However, the direction of both of these reverses post method change, with TP increasing at 2.13% p.a. and DRP at 0.78% p.a. In addition, NNN concentrations were shown to have declined by 0.55% p.a. over this period. Trends for NNN and TP continue their trajectory, and increase in magnitude, for the last five years of the dataset, with NNN reducing by1.86% p.a. and TP increasing by 2.95%. TN was also found to reduce by 0.99% p.a. over the final five years of the dataset.

Figure 17 *Trend plots for TN, TP, NNN, DRP, and NH4-N (A-E) at the Hamurana at Hamurana Road water quality site, for the period of 1 January 2002 to 31 December 2016. Plots are based on unadjusted data, split into pre (red) and post (blue) lab method change groups, with a one year crossover period (green). Pre and post -ab method groups include a fitted linear regression model. TN, NNN, and NH4-N are plotted on log transformed axes.*

Table 4 *Trend analysis results for analyte concentrations at the Hamurana at Hamurana Road water quality monitoring site. Trend analysis was carried out on unadjusted (All) and adjusted (All Adjusted) data for the period of 2002-2016, as well as pre and post-lab methodology periods, and last five years of the dataset (2012-2016). The direction of significant trends (p<0.05) are represented by increasing (⬀) or decreasing (⬂) arrows, while a blank rectangle (▭) depicts no trend.* PAC stands for percentage annual change. *Full trend statistics can be found in Appendix 1.*

	All		All Adjusted		Pre-Change		Post-Change		2012-2016	
Variable	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**
TN	▭		⬀	0.58	▭		▭		⬂	-0.99
NNN	⬀	0.58	-	-	▭		⬂	-0.55	⬂	-1.86
NH4	⬂	-3.60	-	-	▭		▭		▭	
TP	⬀	1.12	⬂	-0.49	⬂	-1.47	⬀	2.13	⬀	2.95
DRP	⬂	-0.49	▭		⬂	-1.86	⬀	0.78	▭	

Load estimates

Method comparison and patterns

Load estimation results differed slightly between methods, with the LOADEST method being less influenced by annual variation; however, both methods provided similar overall load trajectories (Figure 18). TN, NNN, TP and DRP all show an increasing load over time, particularly after the lab methodology change, whereas NH4-N can be seen to decline throughout the entire dataset.

2016 Calendar Year

Approximately 64 to 66 T of TN are estimated to have been transported from the Hamurana Catchment to Lake Rotorua during the 2016 calendar year. This was comprised of between 61 and 67 T of NNN, and 0.52 to 0.63 T of NH4-N. The TP load was estimated to be between 8.8 and 9.1 T, of which 7.1 to 7.3 T were made up of DRP.

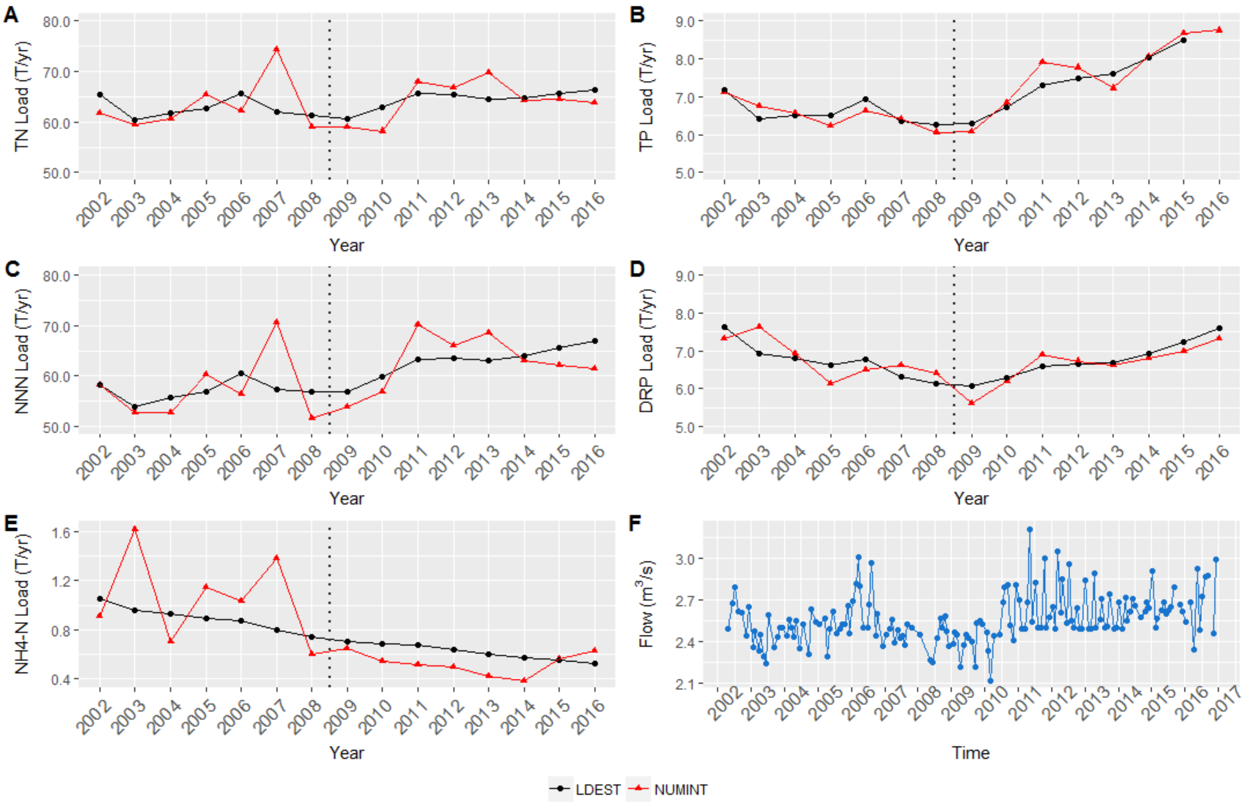


Figure 18 (A-E) Load estimates for each analyte at the Hamurana at Hamurana Road water quality monitoring site, using two different estimation methods: numeric integration (red) and LOADEST (black). The vertical dotted line represents the lab method change (July 2008). (F) The discrete flow record used to calculate loads.

Load ratios

As with the Awahou Catchment, the percentage of TN made up of inorganic NNN is extremely high, exceeding 88% since 2002, and tracking towards 100% in 2016 (Figure 19). The percentage of TP that is comprised of DRP has reduced since 2009, but exceeds 82% for the duration of the study period.

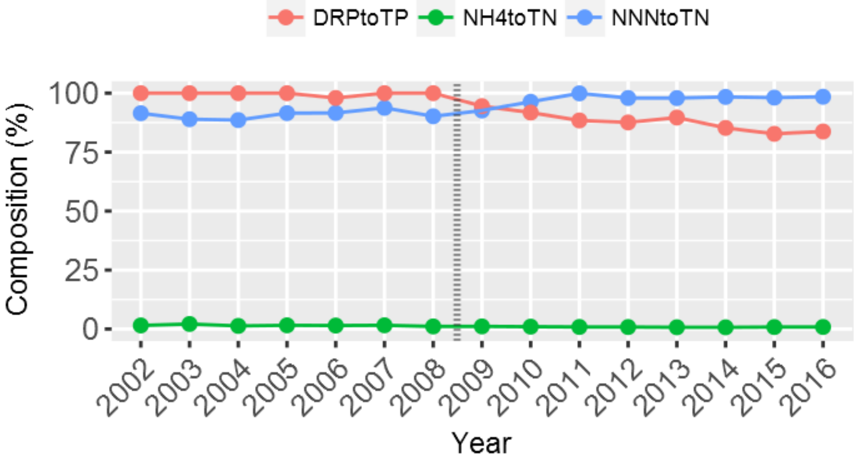


Figure 19 The overall composition of TN that is attributed to NNN (blue) and NH4-N (green), and TP attributed to DRP (red) for the Hamurana at Hamurana Road site. Composition is calculated from the average of all load estimation methods.

Catchment summary

TN and NNN concentrations in the Hamurana Stream increased throughout the fifteen year dataset, although declining trends were found for datasets post the lab methodology change (2009). This result seems to indicate that there was either a physical or behavioural change in the catchment around this time which, resulted in a reduction in inorganic N losses, and reduced TN concentrations. However it's worth noting that the pre-change TN and NNN data record has at least five potential outliers that may have caused neutral trends to become positive for these analytes. TP and DRP, on the other hand showed declining concentration trends prior to, and increasing trends after, the lab methodology change, with the PAC for TP increasing in the last five years of the dataset.

Load estimates have increased throughout time for all analytes except NH4-N. However, the reason for this can be seen through examination of Figure 18 (F), where there is a step change in measured flow after 2010. This is most likely an artefact of a change in the sampling method, or an error in the flow record rather than increased discharge from the catchment itself. This may be due to a rating shift from flood activity, or a result of high lake levels influencing flow gauging. However, the Environmental Data Team could find no obvious reason for this change and suggested that the record should be treated as 'true'. Regardless, this explains why TN and NNN loads show a step around 2010, but concentrations are actually declining. This also raises questions about the magnitude of TP and DRP load increases over this period.

Despite uncertainty of magnitude, we know from trend analysis that TP and DRP have increased in concentration since the lab methodology change, albeit at different rates. The difference between the rate of increase in DRP and TP shows that non-DRP forms of phosphorus, i.e. particulate phosphorus, are becoming more important to the TP pool in this catchment, although a significant amount (> 75%) is still derived from DRP. Particulate phosphorus is mobilised through overland flow caused by high rainfall, implying that this pathway could be becoming more active in the Hamurana Catchment. Possible reasons include: modification of soil structure due to increased agriculture, changes to the vegetative landscape to make way for pasture, or simply increased localised intensive rainfall. However, further investigation is needed to accurately determine a source.

Ngongotahā Catchment

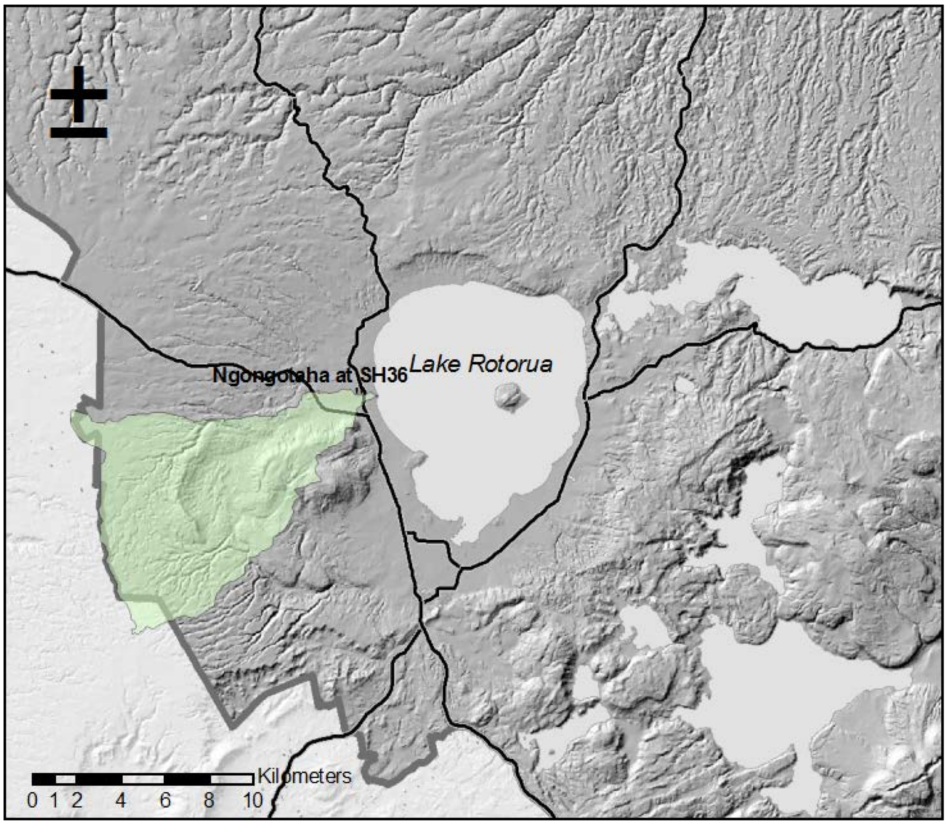


Figure 20 Location of the Ngongotahā Catchment.

Background

The 7,841 ha Ngongotahā Catchment, one of the largest in the Lake Rotorua Catchment, is located on the west side of Lake Rotorua and drains via the Ngongotahā Stream (Figure 20). The catchment is composed primarily of pasture and arable land (43%), native forest or scrub (33%), and exotic forest (13%). Approximately 1% of the catchment is occupied by the urban township of Ngongotahā which has a population of approximately 4,000 people. Flow results show that Ngongotahā Stream is one of the more variable streams with regard to flow, suggesting that surface water input is likely to be an important contributor. The mean residence time for groundwater in this catchment is 30 years which is the youngest of all Lake Rotorua's sub-catchments (Morgenstern et al., 2015).

Trend analysis

The Ngongotahā Stream is monitored where it crosses SH 36, near the township of Ngongotahā. Trend analysis revealed increasing trends for TP (adjusted) and DRP (adjusted) of 0.73% and 0.89% p.a., respectively, over the 15 year dataset (Figure 21; Table 5).

Significant trends for the pre-change dataset were absent, however, TN and NNN were found to be decreasing post-change by 0.55% p.a., and 0.65% p.a., respectively. TP and DRP also increased post-change by 3.85% p.a. and 3.05% p.a., respectively, while the increasing trend for TP was also found in the final five years of the dataset (3.63% p.a.), but was absent for all other analytes.

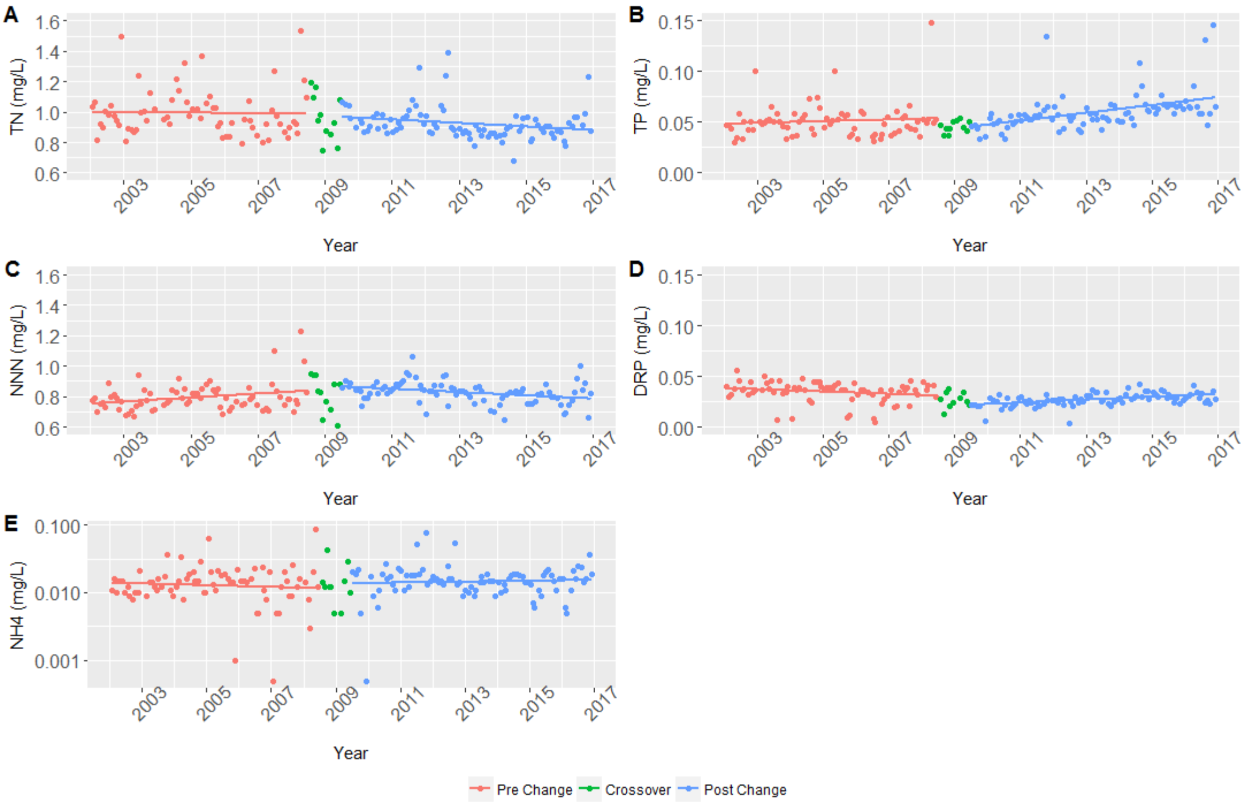


Figure 21 *Trend plots for TN, TP, NNN, DRP, and NH4-N (A-E) at the Ngongotahā at SH 36 water quality site, for the period of 1 January 2002 to 31 December 2016. Plots are based on unadjusted data, split into pre (red) and post (blue) lab method change groups, with a one year crossover period (green). Pre and post lab method groups include a fitted linear regression model. NH4-N is plotted on a log transformed axis.*

Table 5 *Trend analysis results for analyte concentrations at the Ngongotahā at SH 36 water quality monitoring site. Trend analysis was carried out on unadjusted (All) and adjusted (All Adjusted) data for the period of 2002-2016, as well as pre and post lab methodology periods, and last five years of the dataset (2012-2016). The direction of significant trends (p<0.05) are represented by increasing (⬀) or decreasing (⬂) arrows, while a blank rectangle (□) depicts no trend.* PAC stands for percentage annual change. *Full trend statistics can be found in Appendix 1.*

	All		All Adjusted		Pre Change		Post Change		2012-2016	
Variable	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**
TN	⬂	-0.76	□		□		⬂	-0.55	□	
NNN	□		-	-	□		⬂	-0.65	□	
NH4	□		-	-	□		□		□	
TP	⬀	2.19	⬀	0.73	□		⬀	3.85	⬀	3.63
DRP	⬂	-1.58	⬀	0.89	□		⬀	3.05	□	

EGRET trend analysis

The Ngongotahā Stream contains a NIWA operated, continuous flow site located approximately 500 m upstream of the water quality monitoring site. This flow record, when combined with monthly water quality samples, provided enough data to run the WRTDS model using the EGRET R package in an attempt to derive more information from the long term monitoring dataset. All EGRET analyses were carried out on the post-change dataset only.

Results show that TN concentrations were greater at higher flows (2 m^3/s and above) occurring during the winter period, and the magnitude of TN peaks have reduced very slightly between 2009 and 2016 (Figure 22). NNN concentrations were slightly different from the TN signature, showing winter peaks dominated by low flow contribution, reducing in magnitude over time. NH4-N concentrations were highest at elevated flows, and show a pattern of increasing concentration over time, although the magnitude (0.02 mg/L-0.03 mg/L) is minor compared to other sites.

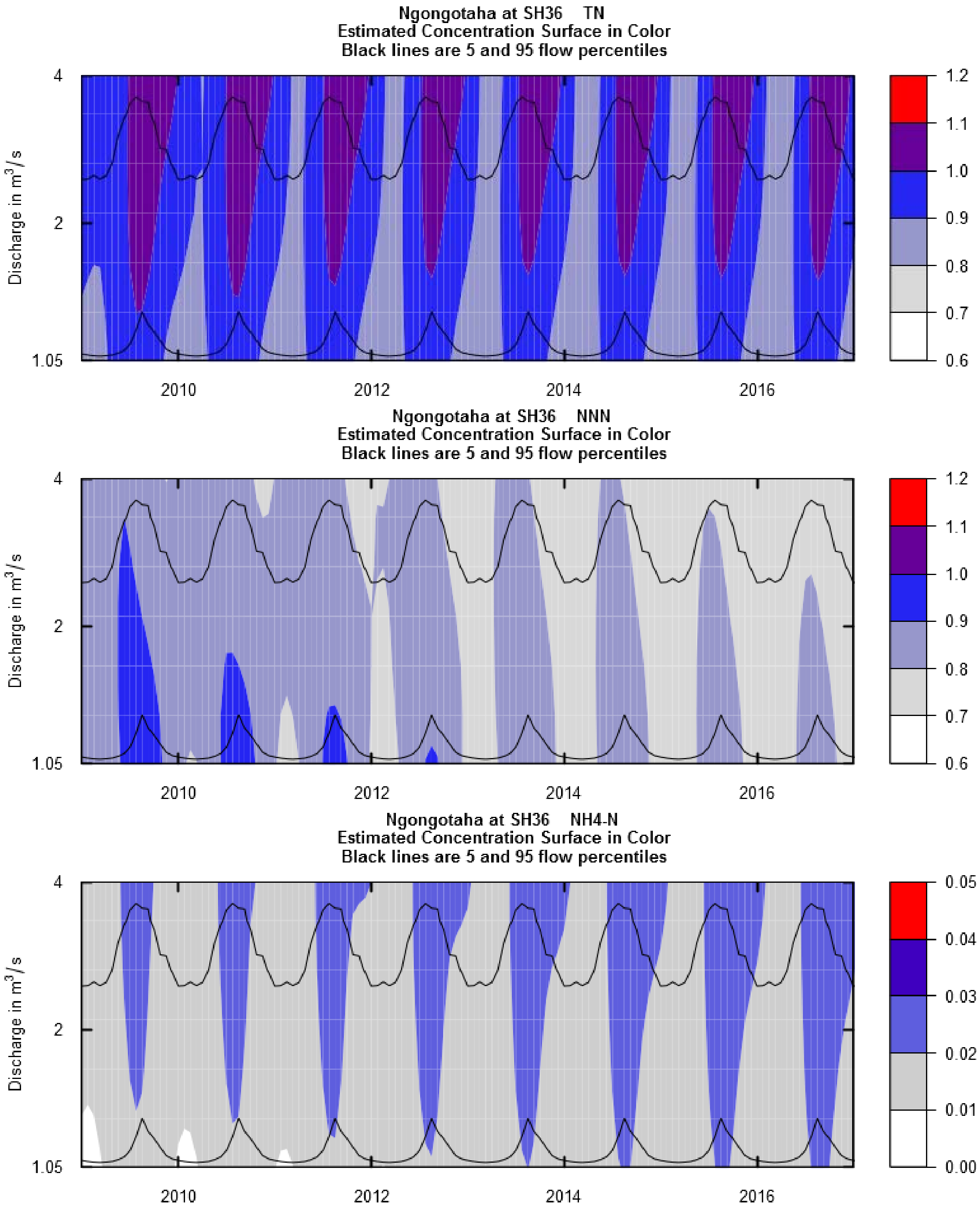


Figure 22 *Modelled concentration versus discharge for the Ngongotahā at SH 36 site, between 2002 and 2016 for nitrogen species. Analytes from the top are: TN, NNN, NH4-N. The panel on the right hand side of the plot shows the concentration of the analyte in mg/L.*

TP shows an obvious dominance at high flows (2 m^3/s and above), which has increased in magnitude since 2011 (Figure 23). Peak high flow TP concentrations are predicted to occur during the spring period when 95th and 5th flow percentiles are declining. DRP contribution shows a similar signature, but the magnitude is much less than TP (0.03 mg/L vs. 0.10 mg/L).

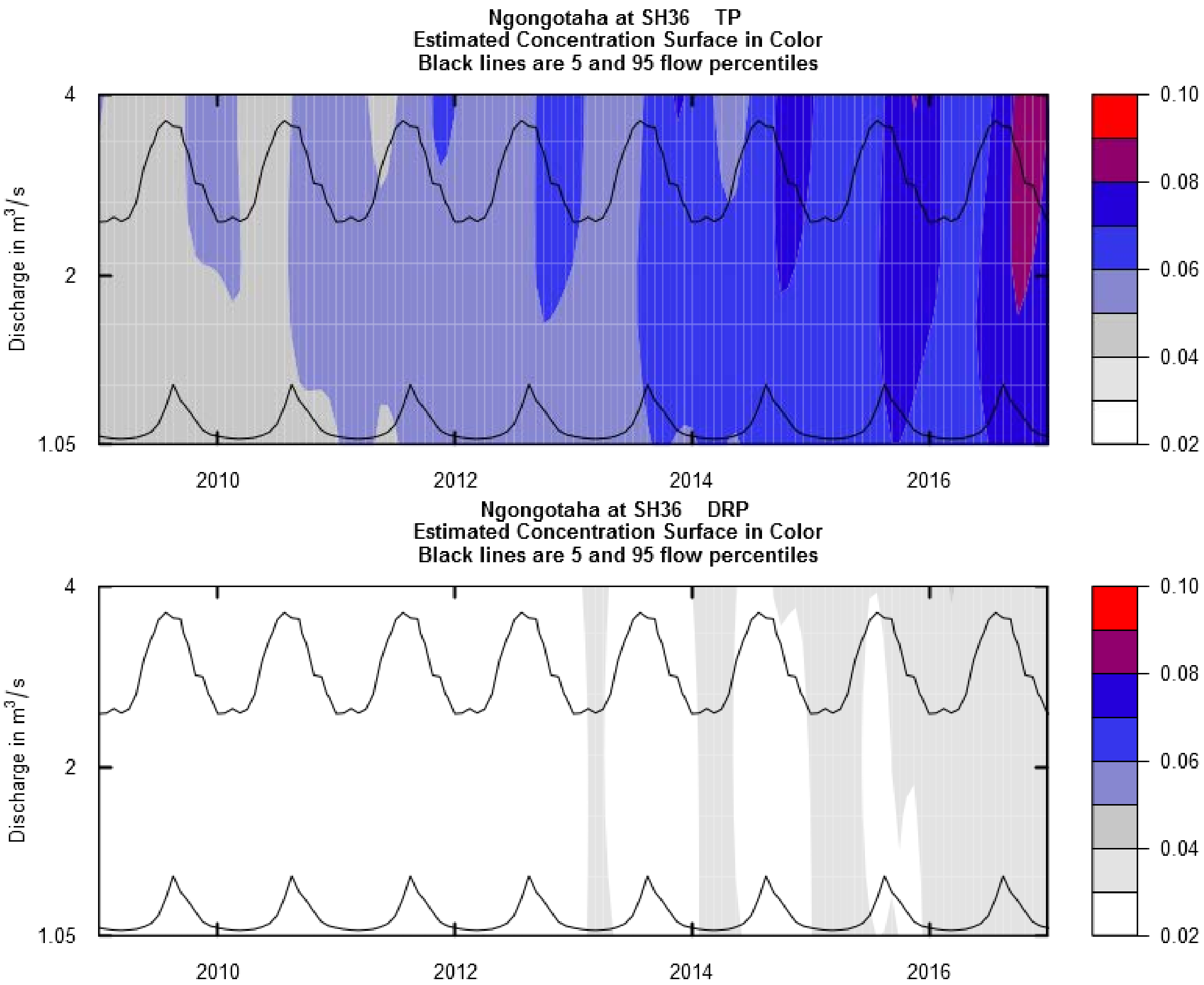


Figure 23 Modelled concentration versus discharge for the Ngongotahā at SH 36 site, between 2002 and 2016 for phosphorus species. Analytes from the top are: TP, and DRP. The panel on the right hand side of the plot shows the concentration of the analyte in mg/L.

Load estimates

Method comparison and patterns

Load estimates were consistent between numeric integration and LOADEST leading up to 2010, and between all three methods post 2010 (Figure 24). All analytes show a similar peak in 2008, caused by elevated flow measurements, and 2010 to 2013, coinciding with the 'wet period' defined in the rainfall section. Overall load patterns for all analytes except DRP follow general rainfall patterns, where loads since 2013 reduced until 2015, and then increased again in 2016. TP concentrations appear to be increasing with time, and NH4-N shows the most variable load estimates between years.

2016 Calendar Year

Load estimates for the 2016 calendar year ranged from 49.0 to 53.2 T of TN, 40.2 to 42.2 T of NNN, 0.87 to 1.03 T of NH4-N, 3.85 to 3.90 T of TP, and 1.53 to 1.78 T of DRP.

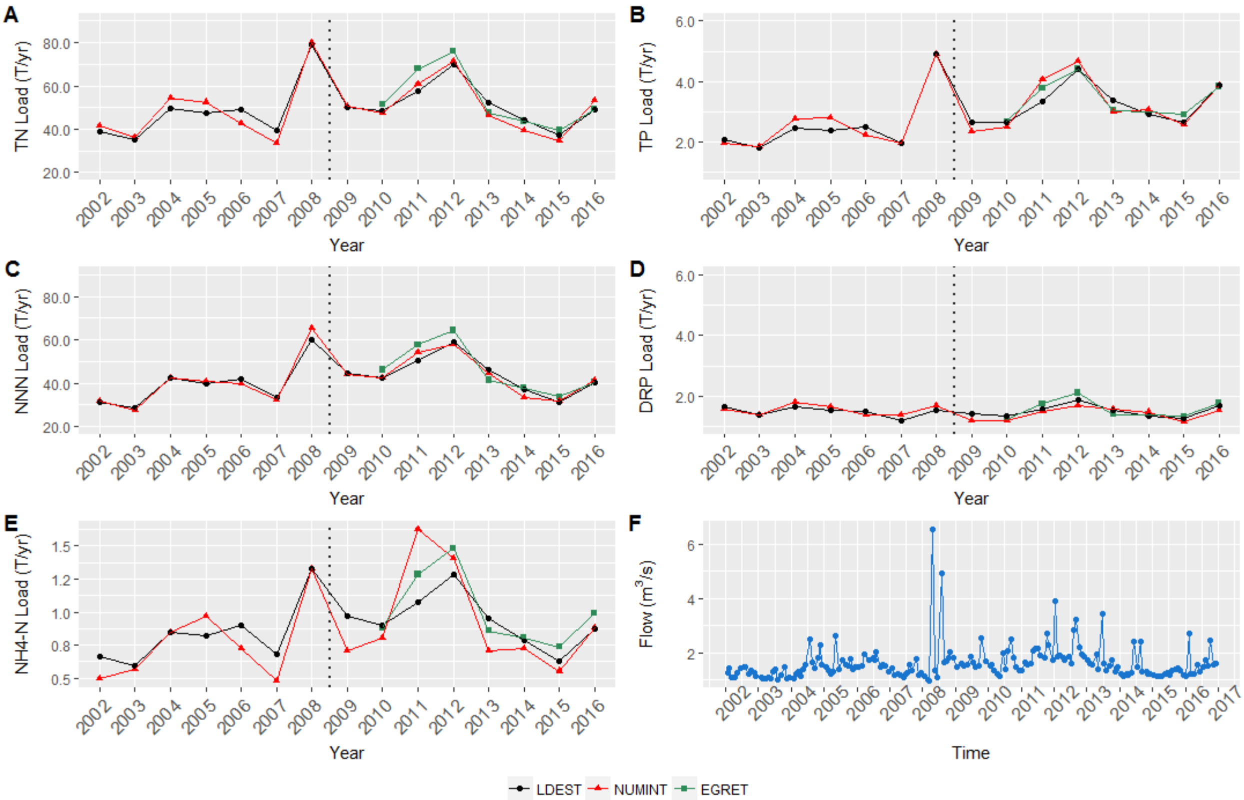


Figure 24 *(A-E) Load estimates for each analyte at the Ngongotahā at SH 36 water quality monitoring site, using two different estimation methods: numeric integration (red) and LOADEST (black). The vertical dotted line represents the lab method change (July 2008). (F) The discrete flow record used to calculate loads.*

Load ratios

Load ratios show that the percentage of TN as NNN is above 75% and increased over time to 2013, where it began to decline again (Figure 25). DRP, on the other hand, made up around 80% of the TP load in 2002 but has reduced steadily to around 40% in 2016. NH4-N contribution is relatively constant throughout time and below 2% of the TN pool.

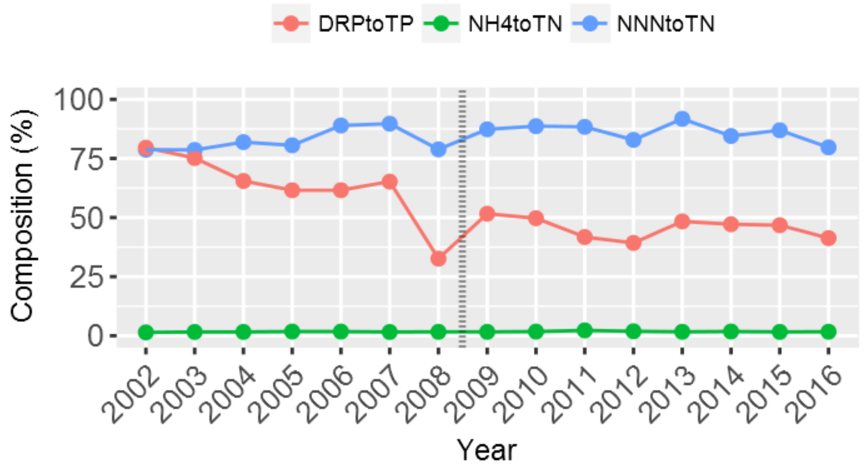


Figure 25 *The overall composition of TN that is attributed to NNN (blue) and NH4-N (green), and TP attributed to DRP (red) for the Ngongotahā at SH 36 site. Composition is calculated from the average of numeric integration and LOADEST load estimation methods.*

Catchment summary

All measured analytes express elevated concentrations during winter periods of high flow in the Ngongotahā Stream. Furthermore, load estimates for all analytes except DRP, show a similar pattern to that of total rainfall and high intensity rainfall events, suggesting that the load signature is at least partly driven by localised rainfall patterns.

Trend analysis results show that there has been no change in the concentration of nitrogen species over the fifteen year dataset; however, both TN and NNN have reduced slightly since 2009. EGRET analysis suggests that the high flow contribution of NH4-N has increased in recent years, although concentrations are below 0.03 mg/L and the percent contribution to the TN pool is less than 2% meaning there is likely to be little ecological significance at this stage.

Similar to other catchments, phosphorus concentrations increased over the duration of the study, with evidence suggesting that the majority of P is sourced during high flows in particulate form. This supports the work of Abell (2013) who found that TP in the Ngongotahā Stream was positively correlated to flow during storm events, and claimed that particulate phosphorus was responsible for the majority of the high-flow, and thus overall, load. The other side of this finding is that the contribution of DRP, sourced predominantly from superphosphate, animal effluent, or groundwater input, is diminishing relative to the overall phosphorus pool, although concentrations post lab methodology change have increased by around 3% per annum. These results suggest that appropriate mitigations to intersect and store overland flow, or to avoid stock interaction with erodible waterways, may reduce the overall phosphorus load contribution from this catchment.

Abell also calculated TP and TN loads for the Ngongotahā Stream between 2010 and 2012. These equated to the equivalent of 102.6 T of TN, and 8.14 T of TP; approximately 240% and 208% greater than the largest estimate for 2016 in the current study. However, calculated loads in the current study are comparable to those calculated by Scholes (2013) for the 2011 calendar year, who used a similar dataset in his analysis. This demonstrates the disparity between load analyses carried out on datasets with different sampling objectives, and reinforces the importance of obtaining samples during storm flow events if accurate load information is required. Abell emphasises temporal load inequality with his finding that 50% of the TN and TP load on the Ngongotahā was delivered in 28% and 10% of the time, respectively. Bay of Plenty Regional Council's current monitoring plan is likely to miss these events, unless they coincide with scheduled monitoring runs, resulting in significant underestimation of the true load.

Puarenga Catchment

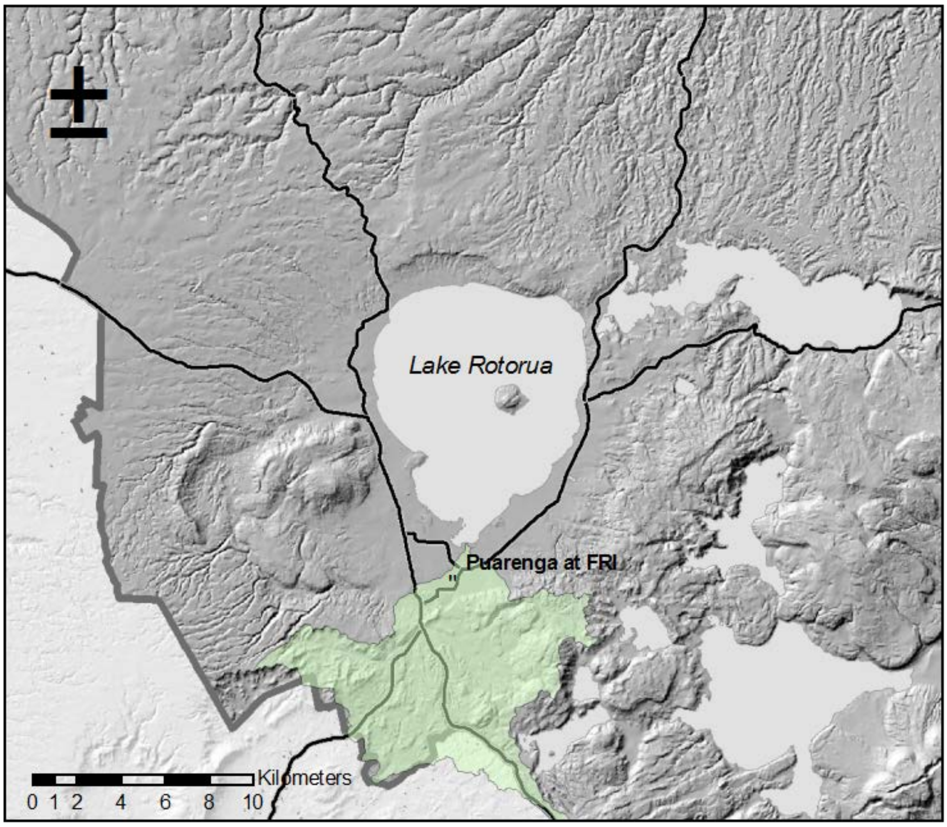


Figure 26 Location of the Puarenga Catchment.

Background

The Puarenga Catchment covers approximately 8,137 ha, including much of Rotorua City (Figure 26). The catchment is primarily composed of exotic forest (49%), pasture and arable land (28%), and native forest (10%). Groundwater in this catchment is relatively young with a mean residence time of approximately 40 years (Morgenstern et al., 2015).

Trend analysis

Water quality is measured at the Puarenga at FRI (Forestry Research Institute now known as Scion) site, located near SH 30 on the south-eastern side of Rotorua City. Puarenga at FRI is also a rated flow site, with continuous flow data dating back to 2010.

Trend analysis revealed an improving trend for TN (adjusted) (1.91% p.a.), and NNN (1.97% p.a.), over the 15 year study period (Figure 27; Table 6). However, deteriorating trends were found for TP (0.73% p.a.) and NH4-N (2.34%) over the same period.

Analysis of the pre-change dataset revealed improving trends for TN and NNN of 2.82% p.a. and 2.41% p.a. respectively, while TP concentrations increased by 3.12% p.a. Four analytes showed significant trends over the post-change dataset, with NNN concentrations continuing to decrease by 3.65% p.a., while TP, NH4-N, and DRP concentrations increased by 3.28% p.a., 3.88% p.a. and 4.99% p.a., respectively. Significant deteriorating trends were also found for TP and NH4 in the final five year dataset, both of which increased at comparatively high rates of 4.91% and 13.36% p.a. TN concentrations also increased over the final five years by 3.61% p.a.

Figure 27 Trend plots for TN, TP, NNN, DRP, and NH4-N (A-E) at the Puarenga at FRI water quality site, for the period of 1 January 2002 to 31 December 2016. Plots are based on unadjusted data, split into pre (red) and post (blue) lab method change groups, with a one year crossover period (green). Pre and post lab method groups include a fitted linear regression model. TN, NNN, TP, and DRP are plotted on log transformed axes.

Table 6 Trend analysis results for analyte concentrations at the Puarenga at FRI water quality monitoring site. Trend analysis was carried out on unadjusted (All) and adjusted (All Adjusted) data for the period of 2002-2016, as well as pre and post-lab methodology periods, and last five years of the dataset (2012-2016). The direction of significant trends (p<0.05) are represented by increasing (↗) or decreasing (↘) arrows, while a blank rectangle (□) depicts no trend. PAC stands for percentage annual change. *Full trend statistics can be found in Appendix 1.*

	All		All Adjusted		Pre-Change		Post-Change		2012-2016	
Variable	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**
TN	↘	-2.40	↘	-1.91	↘	-2.82	□		↗	3.61
NNN	↘	-1.97	-	-	↘	-2.41	↘	-3.65	□	
NH4	↗	2.34	-	-	□		↗	3.88	↗	13.36
TP	↗	2.36	↗	0.73	↗	3.12	↗	3.28	↗	4.91
DRP	↘	-2.69	□		□		↗	4.99	□	

EGRET trend analysis

Figure 28 shows elevated concentrations of all nitrogen species during high flow. Peak concentrations of TN have remained between 1.2 and 1.4 mg/L during elevated winter flow periods, throughout the analysed time frame (2010-2016). However, the relative contribution of NNN and NH4-N has changed over time with high flow NNN concentrations reducing, and NH4-N concentrations increasing, over time.

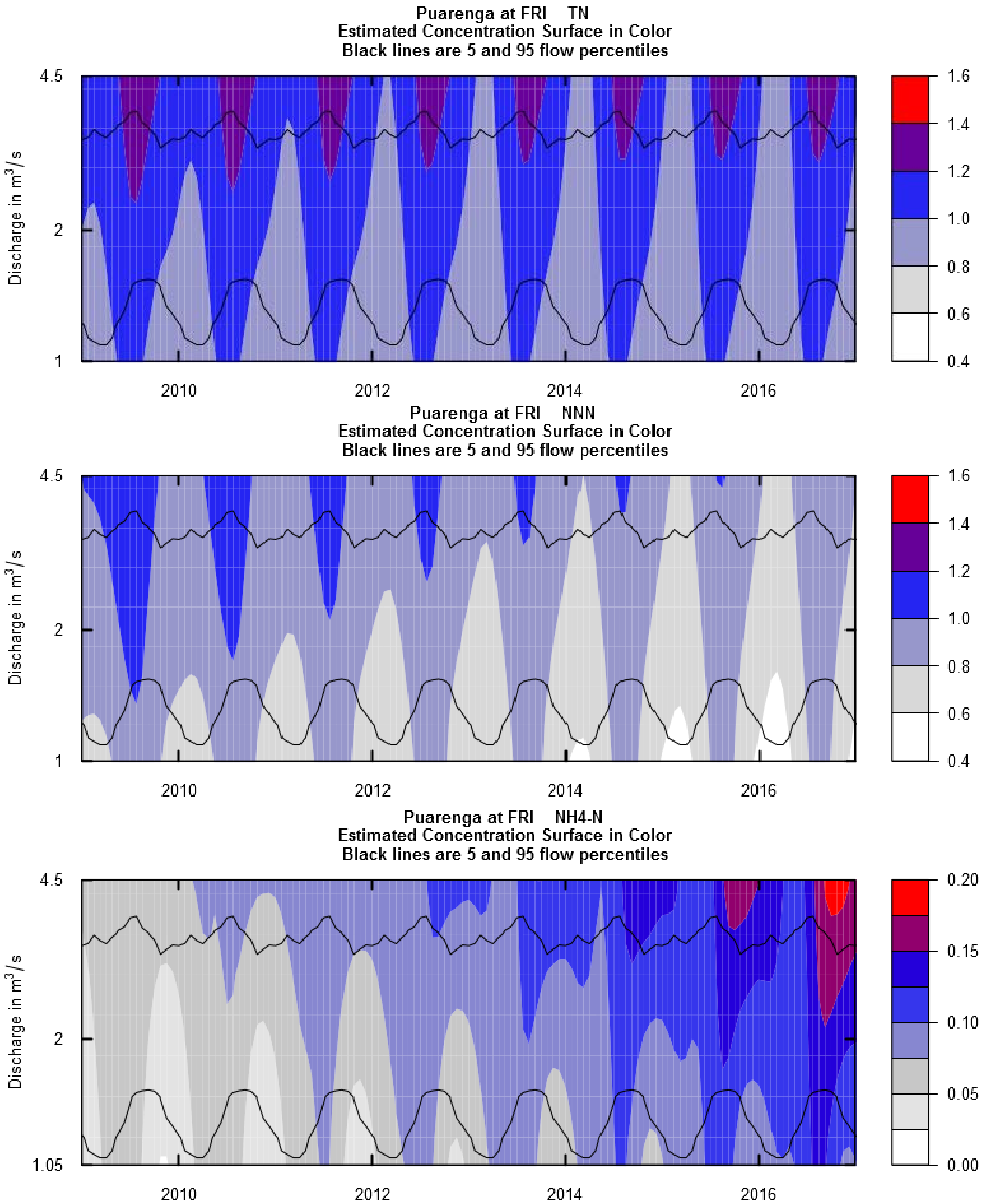


Figure 28 *Modelled concentration versus discharge for the Puarenga at FRI site between 2010 and 2016, for nitrogen species. Analytes from the top are: TN, NNN, and NH4-N.*

Similar to N species, TP concentrations have increased since 2010, with the highest occurring in summer at low flows, although in recent years there has very little difference between concentrations predicted for high and low flows (Figure 29). DRP shows a more typical baseflow signature, where concentrations have been increasing at lower flows throughout the data record; however, predicted DRP concentrations are only half of TP, implying that particulate sources must be contributing to the TP pool.

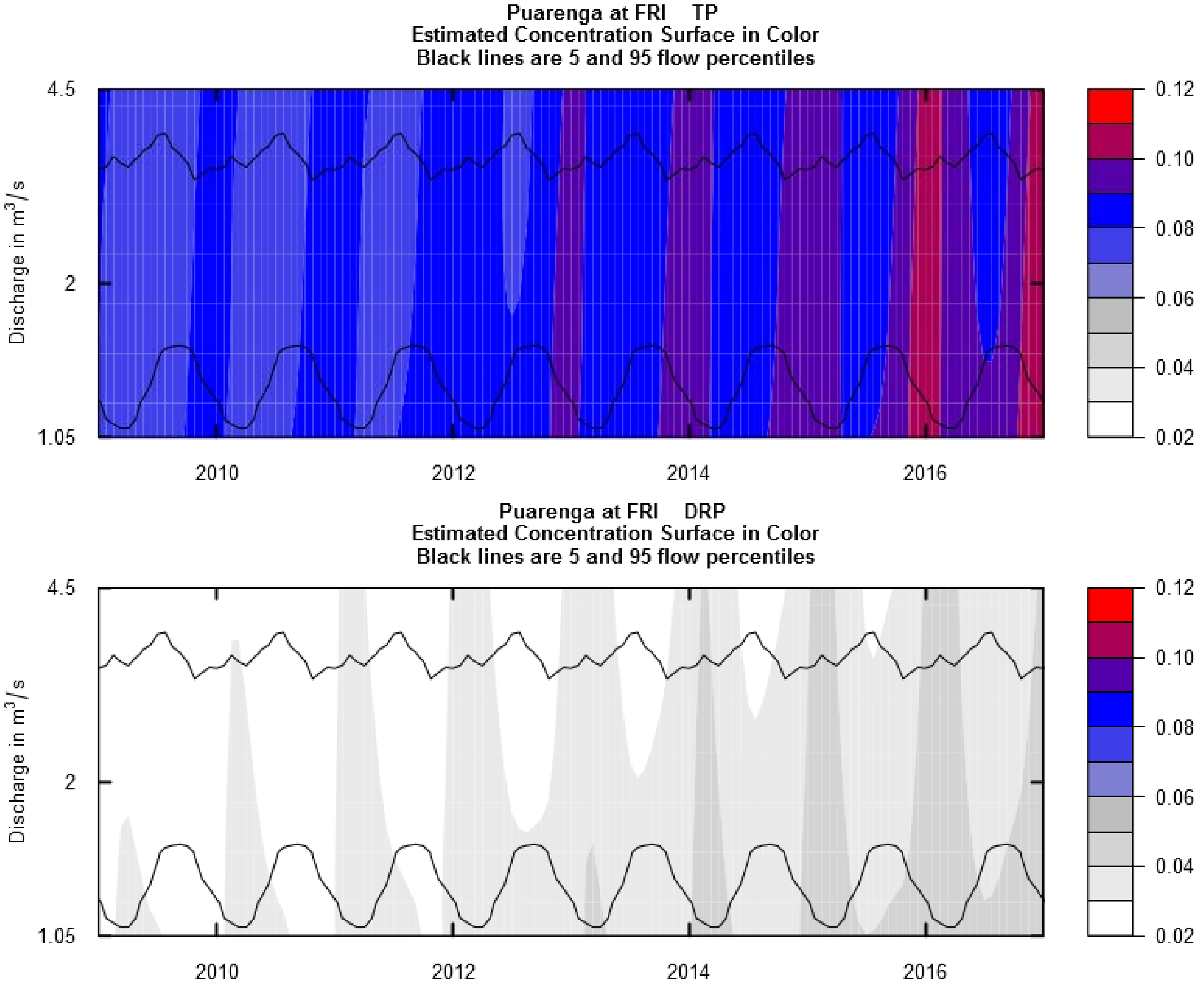


Figure 29 Modelled concentration versus discharge for the Puarenga at FRI site between 2010 and 2016, for phosphorus species. Analytes from the top are: TP, and DRP.

Load estimates

Method comparison and patterns

Load estimates share a relatively consistent pattern between methods for all analytes (Figure 30). All analytes except DRP show load peaks in 2004 and 2011, which correspond with increased stream flow measurements and higher than normal rainfall totals. TN and NNN show a similar pattern with no real discernible trend, although TN shows increased load variability since 2011. NH4-N loads have been increasing steadily since 2011, suggesting a significant shift in the catchment.

TP loads have increased from around 3 T per year in 2002 to close to 7 T in 2016, although the DRP contribution has remained consistent around 2.5 T per year.

2016 Calendar Year

Estimates of nutrient loads for Puarenga at FRI for the calendar year of 2016 are as follows: between 60.2 and 85.5 T of TN, 48.9 to 61.5 T of NNN, 7.8 to 11.1 T of NH4-N; 6.3 to 8.5 T of TP, and 2.5 to 2.7 T of DRP.

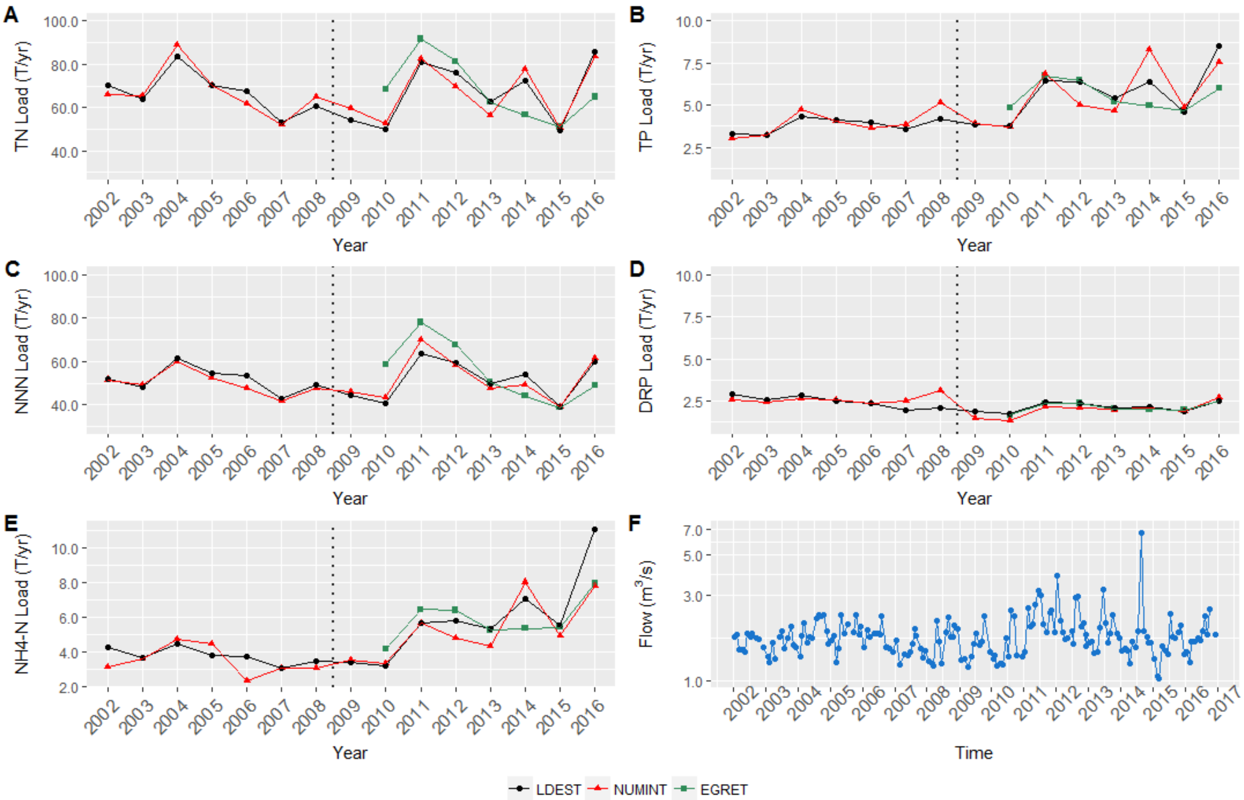


Figure 30 *(A-E) Load estimates for each analyte at the Puarenga at FRI water quality monitoring site, using two different estimation methods: numeric integration (red) and LOADEST (black). The vertical dotted line represents the lab method change (July 2008). (F) The discrete flow record used to calculate loads.*

Load ratios

The ratio of NNN to TN at this site has fluctuated around 75% since 2002, but has decreased slightly since 2013, while the proportion of TP made up by DRP has decreased steadily from above 85% in 2002 to below 35% in 2016. The NH4-N contribution to TN remained between 4% and 6% until 2009. After this date the contribution steadily increased to above 11% in 2016.

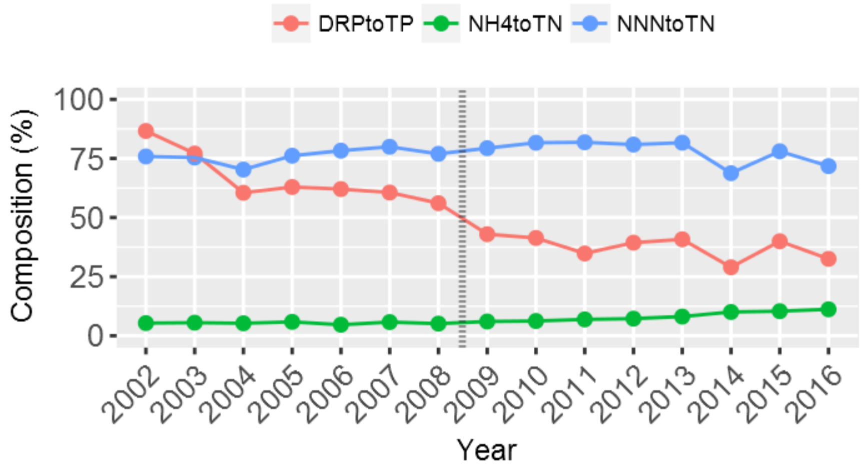


Figure 31 *The overall composition of TN that is attributed to NNN (blue) and NH4-N (green), and TP attributed to DRP (red) for the Puarenga at FRI site. Composition is calculated from the average of numeric integration and LOADEST load estimation methods.*

Catchment summary

The Puarenga Catchment shows an overall reduction in TN and NNN concentrations across the 15 year dataset, although TN was found to have increased over the final five years of the dataset. The concentration-discharge relationship shows that elevated concentrations of all nitrogen species predominantly occur during high flows, implying that pathways associated with rainfall and flow (e.g. diffuse runoff, stormwater flushing) are a major source. Of particular concern is the emerging pattern of NH4-N, which is primarily sourced from decomposing organic material, animal urine (in the form of urea), or effluent. Mean annual concentrations of NH4-N in the Puarenga Stream are among the highest of all sites included in this study, with the exception of the geothermally influenced Waiohewa Catchment. Unlike the Waiohewa, the source is likely to be losses from agricultural land use in the upper catchment, contributions from the landfill site, or potential run off or stormwater overflow in the urban part of the catchment.

Scholes (2013) also found that NNN concentrations in the Puarenga Stream were decreasing, and implied that the response was due to changes to the wastewater treatment facility that took place in 2002. Historically this point-source was seen as a significant contributor to the degradation of Lake Rotorua, and since 2002 treated wastewater has been spray irrigated to a nearby forest rather than discharged directly into the Puarenga Stream. The results from Scholes (2013) are supported by the current study and suggest that this mitigation has been effective in reducing TN concentrations in the Puarenga Stream. However, Burns, McIntosh, and Scholes (2009) state that much of the nitrate applied to the forest is no longer absorbed and now enters the lake via the Puarenga Stream. Our results do not provide enough direct evidence to support this statement, as there was a decreasing trend in NNN concentrations over the period of the study, and no evidence to suggest an increase in concentration over the most recent five year period. However, closer inspection of the data shows marked seasonality of NNN concentrations in recent years, with peaks occurring each winter since 2013. The seasonal variability and relationship with flow may have masked the increasing short-term trend of NNN, which is visible through observation of time series data. This forms a logical explanation for the recent increasing TN trend, especially when combined with increasing NH4-N concentrations.

The results in the current study support that of Abell (2013) who found that TN concentrations were positively correlated with flow in the Puarenga Stream. Although Abell also found that high flow nitrate (NO3-N) concentrations were diluted to levels below that found in baseflow conditions, which is in contrast to our results. The reason for the difference is most likely to come down to sampling regime. Abell targeted flow peaks and sampled at 1-2 hour intervals, where the WRTDS modelling component of our study was run using monthly monitoring data that was originally initiated with the objective of identifying long term changes in water quality under median-baseflow conditions. Results may have been closer if the WRTDS model was provided with a representative proportion of targeted high flow samples.

Trend analysis results show that TP concentrations in the Puarenga Stream are increasing with time, and the rate of increase has been greater in the last five years than over the duration of the entire dataset. Modelling results support this finding and show that elevated TP concentrations are present at all flows, while DRP concentrations are greatest at low flows. This implies multiple sources, where there is a greater contribution of DRP at lower flows, while particulate phosphorus dominates at higher flows. Given the difference in trajectory between TP and DRP loads since 2010, we can be confident that the latter is the reason TP loads are increasing in the Puarenga Stream. These results are consistent with those found by Abell (2013), who found a correlation between flow and TP concentration on both the Puarenga and Ngongotahā Streams.

Load estimates for the Puarenga Stream by Abell (2013) were equivalent to 102.44 T of N per year, and 10.8 T of phosphorus, based on monitoring between 2010 and 2012. As for the Ngongotahā, these results are significantly higher than the estimated 2016 loads in the current study, which may be jointly explained by: unusually high rainfall over the 2010-2012 period (as seen in Figure 30), and the resolution of data collected during periods of high flow.

Utuhina Catchment

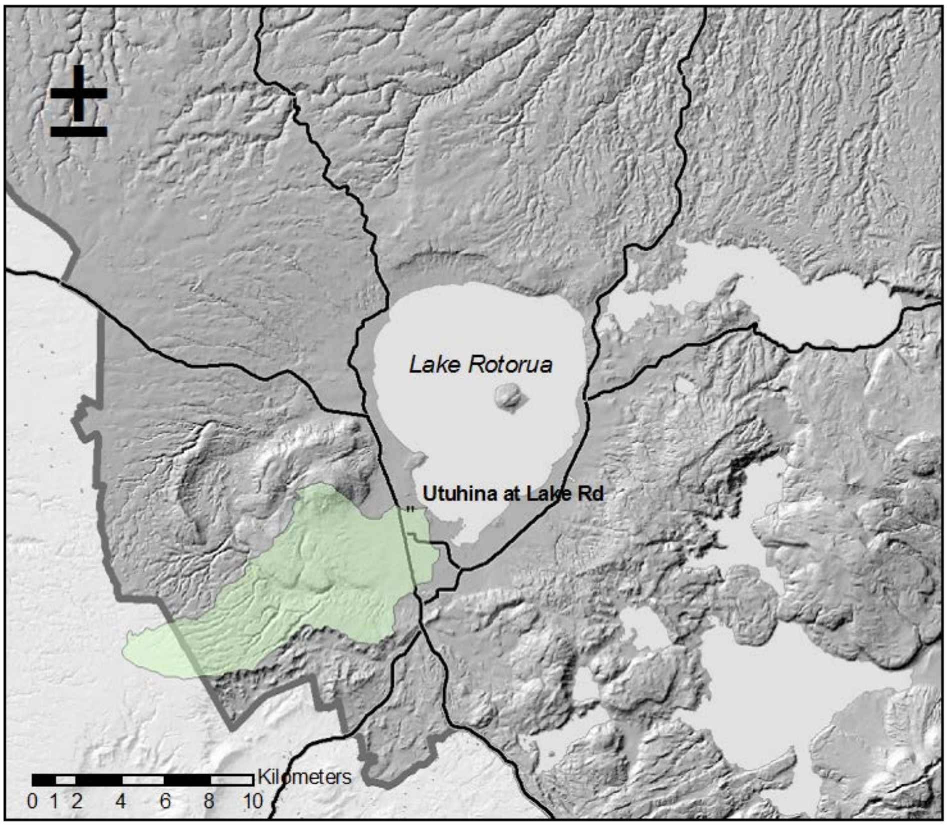


Figure 32 Location of the Utuhina Catchment.

Background

The Utuhina Catchment covers approximately 5,955 ha and is situated in the south western corner of the Lake Rotorua Catchment, between the Puarenga and Ngongotahā catchments (Figure 32). Non-urbanised land use is comprised of native forest and scrub (27%), pasture and arable land (22%), and exotic forest (18%). In addition, the catchment encompasses 1,284 ha of a Rotorua City, equating to 22% of the overall catchment area. Groundwater inputs to the Utuhina Stream have a mean residence time of 60 years, which is of intermediate age relative to the other Lake Rotorua sub-catchments.

Trend analysis

The Utuhina Catchment is drained by the Utuhina Stream, which is monitored monthly where it intersects Lake Road, approximately 800 m upstream of Lake Rotorua. This site has been a rated flow site since 2006, providing enough data for WRTDS analysis.

Trend analysis showed that TP (adjusted) increased at a rate of 1.08% p.a. while DRP (adjusted) decreased by 1.74% p.a. over the 15 year dataset (Figure 33; Table 7).

Significant pre-change trends were found for NH4-N and DRP of 6.60% and 4.36% p.a., respectively. However, all analytes except NNN increased post-change, varying in the rate of change from 0.98% p.a. for TN, to 4.90% p.a. for DRP. TN (1.62% p.a.), NH4-N (7.99% p.a.), and TP (4.41% p.a.) all expressed increasing trends for the last five years of the dataset.

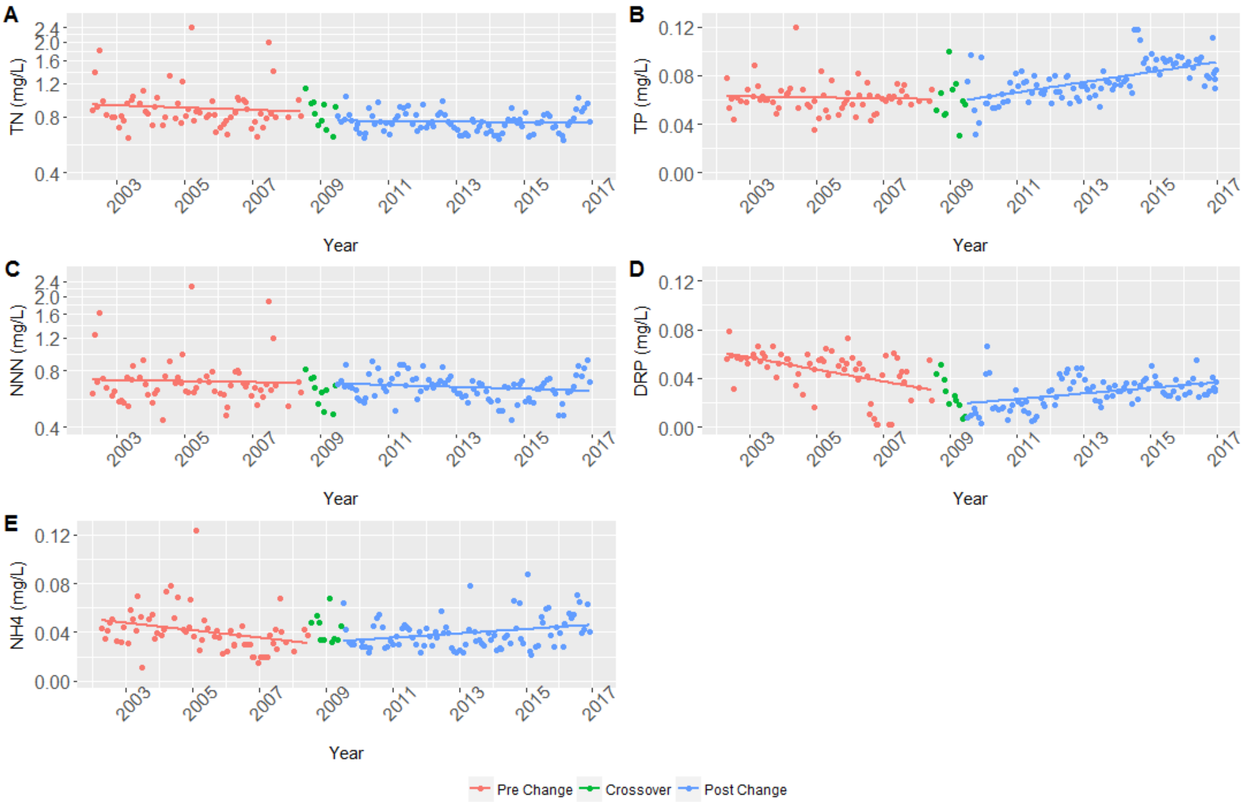


Figure 33 *Trend plots for TN, TP, NNN, DRP, and NH4-N (A-E) at the Utuhina at Lake Road water quality site, for the period of 1 January 2002 to 31 December 2016. Plots are based on unadjusted data, split into pre (red) and post (blue) lab method change groups, with a one year crossover period (green). Pre and post lab method groups include a fitted linear regression model. TN and NNN are plotted on log transformed axes.*

Table 7 *Trend analysis results for analyte concentrations at the Utuhina at Lake Road water quality monitoring site. Trend analysis was carried out on unadjusted (All) and adjusted (All Adjusted) data for the period of 2002-2016, as well as pre and post lab methodology periods, and last five years of the dataset (2012-2016). The direction of significant trends (p<0.05) are represented by increasing (⬀) or decreasing (⬂) arrows, while a blank rectangle (▭) depicts no trend.* PAC stands for percentage annual change. *Full trend statistics can be found in Appendix 1.*

	All		All Adjusted		Pre-Change		Post-Change		2012-2016	
Variable	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**
TN	⬂	-1.13	▭	-0.41	▭		⬀	0.98	⬀	1.62
NNN	▭		-	-	▭		▭		▭	
NH4	▭		-	-	⬂	-6.60	⬀	4.84	⬀	7.99
TP	⬀	2.74	⬀	1.08	▭		⬀	3.60	⬀	4.41
DRP	⬂	-4.58	⬂	-1.74	⬂	-4.36	⬀	4.90	▭	

EGRET trend analysis

Flow-concentrations signatures show that TN and NNN concentrations are elevated at high flows, and that peak concentrations occur during winter when the 95% flows are the highest (Figure 34). In addition, peak high-flow concentrations for both analytes have remained relatively constant since 2009, although the low-flow extent of peak NNN concentrations has reduced in recent years. NH4-N concentrations also show high-flow dominance, and an increasing peak concentration post 2013. Both TP and DRP have peak concentrations occurring at lower flows, which increase in magnitude after 2011 (Figure 35). However, DRP peaks only compose about half of the predicted TP peak concentration.

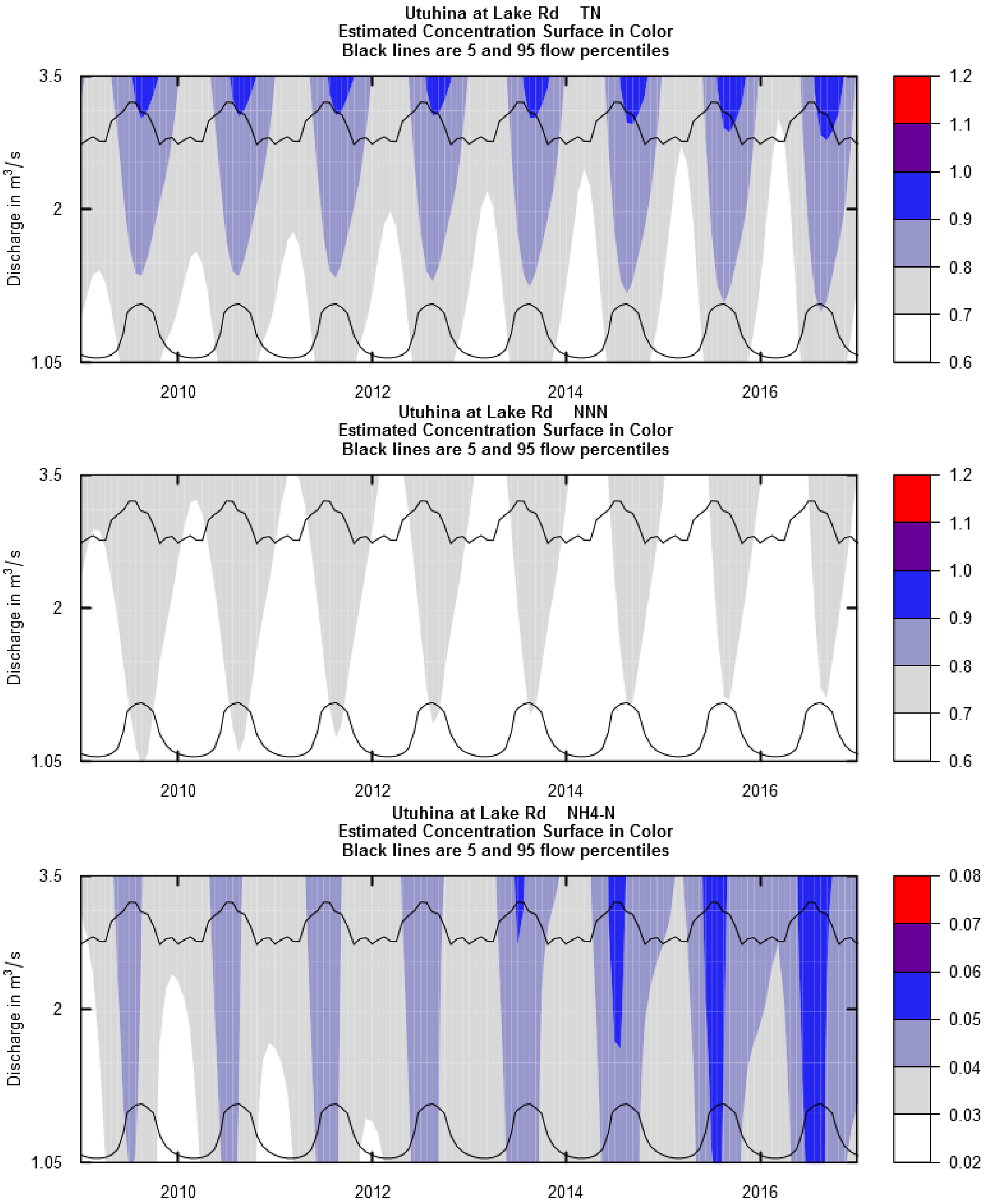


Figure 34 *Modelled concentration versus discharge for the Puarenga at FRI site between 2010 and 2016, for nitrogen species. Analytes from the top are: TN, NNN, and NH4-N.*

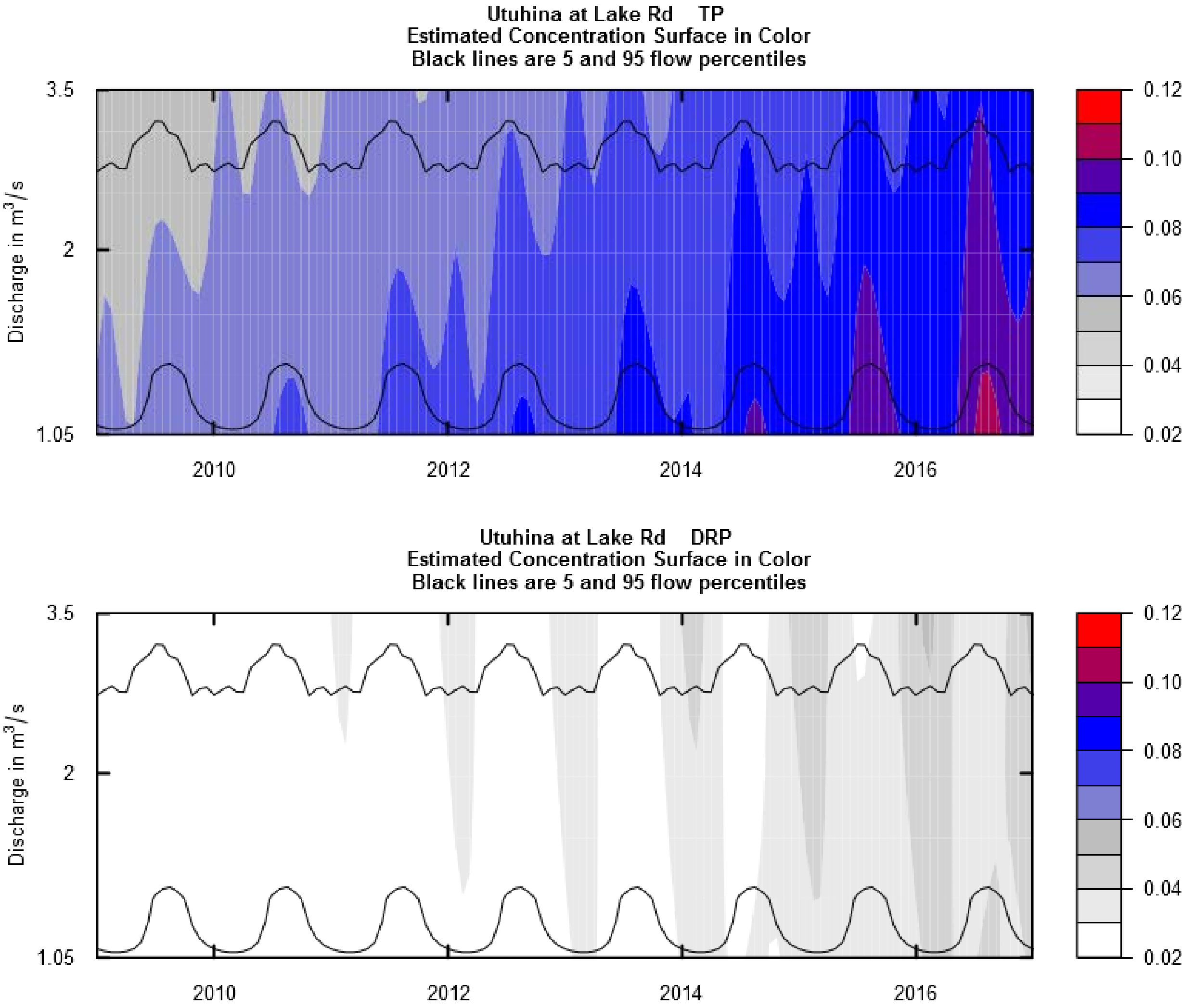


Figure 35 Modelled concentration versus discharge for the Utuhina at Lake Road site between 2010 and 2016, for phosphorus species. Analytes from the top are: TP, and DRP.

Load estimates

Method comparison and patterns

All load estimation methods show comparable patterns through the duration of the monitoring period, although EGRET predictions are larger in the 'wet' year of 2011 (Figure 36). A step change is observable for TN, NNN, and NH4-N between 2012 and 2013, where loads post 2013 are noticeably lower than those prior to this date. This pattern coincides with the wet 2010-2012 rainfall pattern, followed by the drier period in 2013-2015. NH4-N loading fluctuates more than TN or NNN, but follows a broadly similar overall pattern.

TP load estimates increased from 3.0 T per year in 2002 to around 4.5 T in 2015. However, DRP temporal loading differs, decreasing from around 3.0 T in 2002 to below 2.0 T in 2009, where it seems to have stabilised.

2016 Calendar Year

Estimated loads for all analytes during 2016 are as follows: between 38.5 and 40.3 T of TN, 32.3 to 34.9 T of NNN, 2.3 to 2.5 T of NH4-N, 4.2 to 4.6 T of TP, and 1.6 to 2.0 T of DRP.

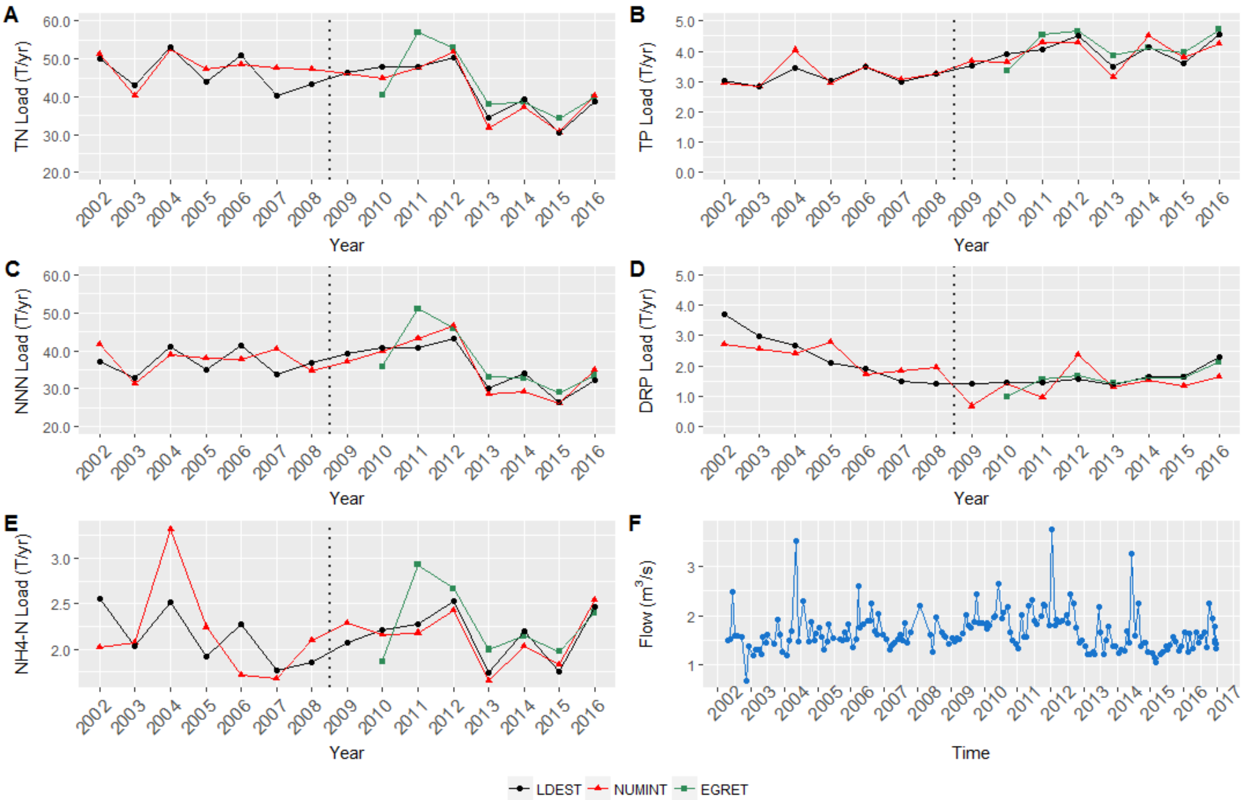


Figure 36 *(A-E) Load estimates for each analyte at the Utuhina at Lake Road water quality monitoring site, using two different estimation methods: numeric integration (red) and LOADEST (black). The vertical dotted line represents the lab method change (July 2008). (F) The discrete flow record used to calculate loads.*

Load ratios

The NNN to TN ratio has been relatively constant at this site since 2002, although this has increased slightly since 2010 (Figure 37). However, the DRP to TP ratio has changed significantly, particularly between 2002 and 2009 where it dropped from around 100% of TP to between 25 and 45% post 2009. NH4-N loads have increased from making up 4.5% of TN in 2002, to 6.3% in 2016.

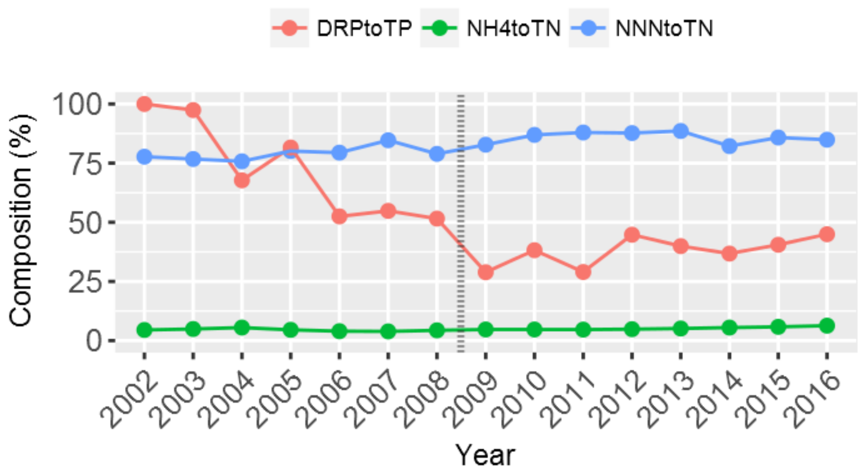


Figure 37 *The overall composition of TN that is attributed to NNN (blue) and NH4-N (green), and TP attributed to DRP (red) for the Utuhina at Lake Road site. Composition is calculated from the average of numeric integration and LOADEST load estimation methods.*

Catchment summary discussion

The Utuhina Catchment shows overall signs improvement for DRP across the fifteen year and pre-change datasets. Much of this can be attributed to the aluminium sulfate (alum) dosing programme that has taken place upstream of the Utuhina at Lake Road site since 2006 (Hamilton et al., 2014). However, a significant increasing trend was found in the post-change dataset, which may be due to changes in the alum treatment method, where treatment objectives changed from locking phosphorus within the riverine environs to targeting phosphorus in the stream and lake.

This result contrasts that of TP which increased across the fifteen year dataset, with an elevated PAC post-change and in the last five years of the dataset. TP load estimates have also increased by about a tonne over the fifteen year period. Ratios of DRP to TP, combined with load and concentration trajectories suggest that the contribution of DRP is reducing, while the contribution of particulate phosphorus is increasing. This result is consistent with the alum dosing schedule, and may also indicate increasing storm flow transport.

The modelled concentration-flow signature for TP shows a baseflow signature that is increasing in magnitude over time. This result is unexpected given the dominance of particulate phosphorus between 2009 and 2016, and the typical association with high flow. Hirsch and De Cicco (2015) suggest that such a signature is a possible sign of a point source. However, in this situation it's more likely that the WRTDS model has been affected by sudden TP and DRP changes caused by alum dosing treatment, such as the short term reduction observed in 2009 which coincided with one of the largest dosing events (600kg) (Hamilton et al., 2014). This event was followed by a short term increase before stabilising again, which may explain why the WRTDS model predicted increasing baseflow concentrations.

NH4-N concentrations were shown to decrease over the pre-change dataset, but reverse direction in the post-change, and final five year datasets. Modelling results suggest that NH4-N concentrations are highest at elevated flows, alluding to a number of possible sources such as: effluent from livestock, geothermal flushing, septic tanks, or storm water overflow. TN concentrations also increased over this period, which must be partly driven by increasing NH4-N concentrations. However NH4-N contributes a much smaller percentage to the TN pool than NNN, which means that any variation in the latter will potentially have more impact than the increasing NH4-N trend.

Waingaehe Catchment

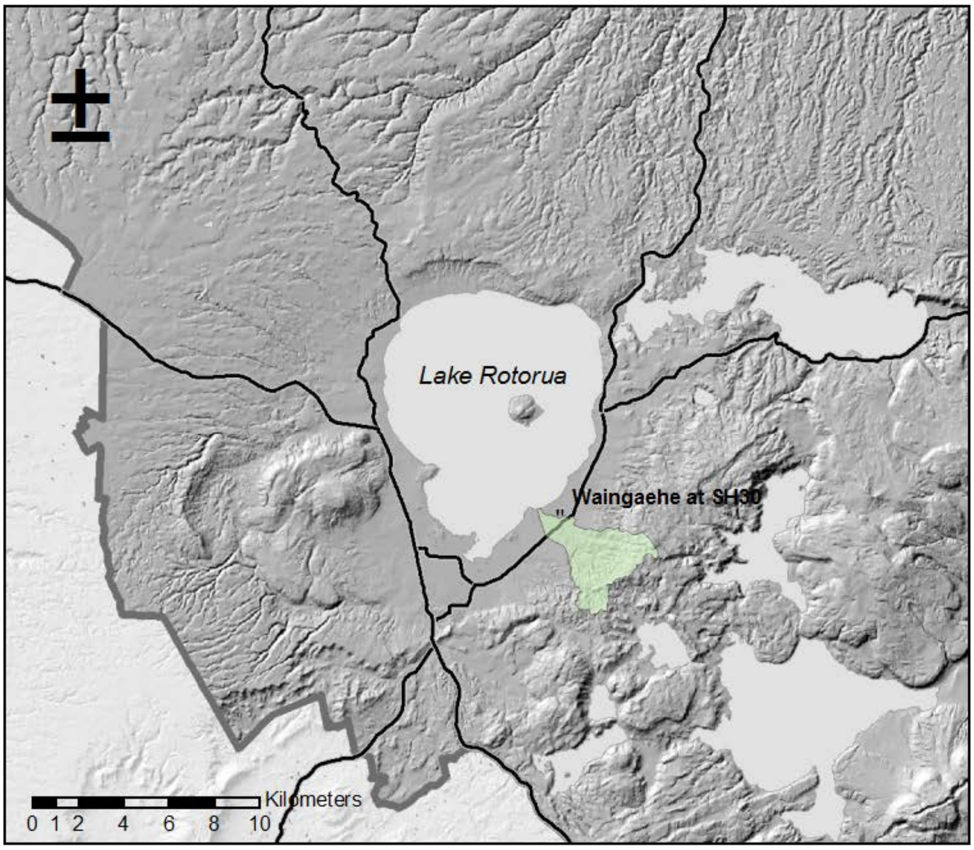


Figure 38 Location of the Waingaehe Catchment.

Background

The Waingaehe Catchment is a small 1,060 ha catchment located on the eastern side of Lake Rotorua (Figure 38). The catchment is dominated by pasture and arable land (59%) and exotic forest (28%), with minor contributions from other sources. The main surface water body in the Waingaehe Catchment is the Waingaehe Stream, which is monitored monthly where it intersects SH 30. Morgenstern et al. (2015) calculated an average mean residence time of 145 years for this catchment, older than any other Lake Rotorua sub-catchment.

Trend analysis

The Waingaehe has a continuous flow record associated with the water quality monitoring site, allowing for application of the WRTDS model.

Trend analysis revealed that NNN concentrations increased over the 15 year dataset by 0.37% p.a., while NH4-N decreased by 3.60% p.a. (Figure 39; Table 8).

TN was the only analyte to express an increasing trend for the pre-change dataset, with concentrations changing by 1.63% p.a. Both TN and NNN decreased significantly over the post-change dataset (0.71% and 0.88% p.a., respectively). No significant trends were found for the last five years of the dataset.

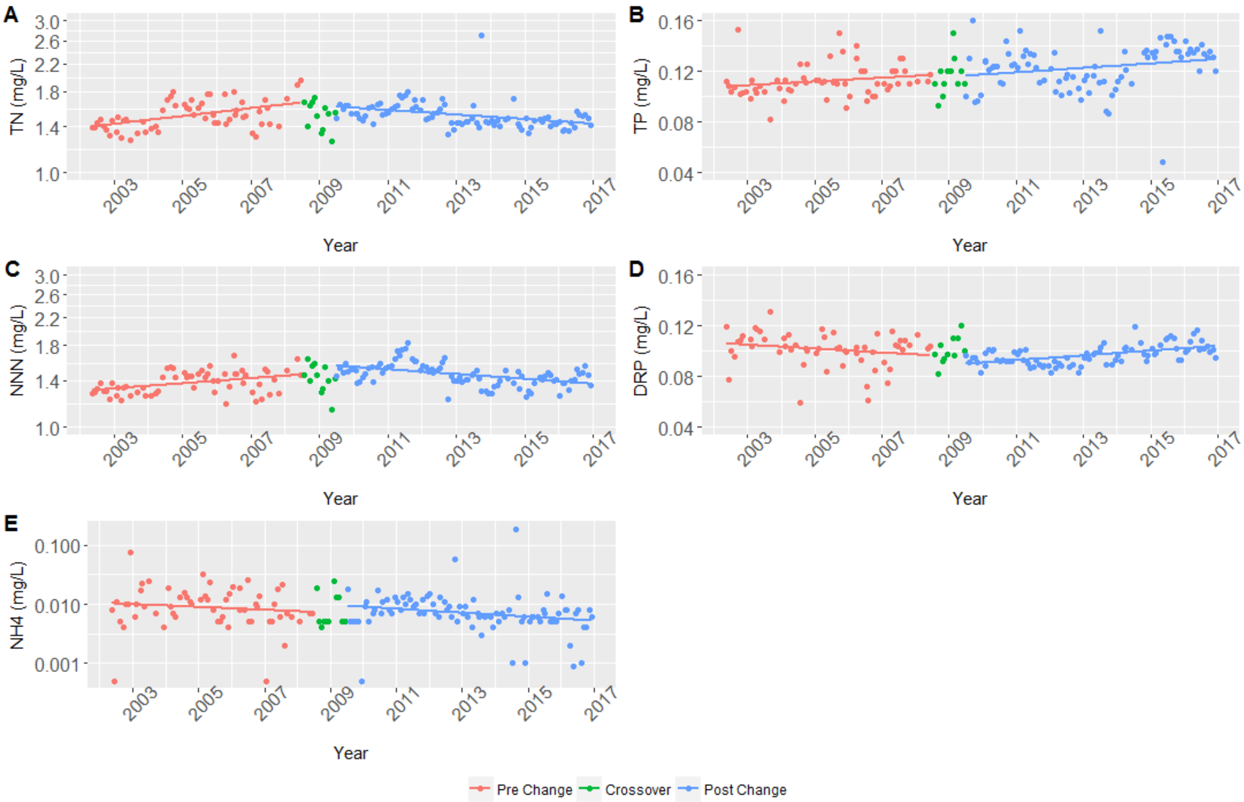


Figure 39 *Trend plots for TN, TP, NNN, DRP, and NH4-N (A-E) at the Waingaehe at SH 30 water quality site, for the period of 1 January 2002-31 December 2016. Plots are based on unadjusted data, split into pre (red) and post (blue) lab method change groups, with a one year crossover period (green). Pre and post lab method groups include a fitted linear regression model. TN, NNN and NH4-N are plotted on log transformed axes.*

Table 8 *Trend analysis results for analyte concentrations at the Waingaehe at SH 30 water quality monitoring site. Trend analysis was carried out on unadjusted (All) and adjusted (All Adjusted) data for the period of 2002-2016, as well as pre and post lab methodology periods, and last five years of the dataset (2012-2016). The direction of significant trends (p<0.05) are represented by increasing (⬀) or decreasing (⬂) arrows, while a blank rectangle (▭) depicts no trend. PAC stands for percentage annual change. Full trend statistics can be found in Appendix 1.*

	All		All Adjusted		Pre-Change		Post-Change		2012-2016	
Variable	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**
TN	▭		▭		⬀	1.63	⬂	-0.71	▭	
NNN	⬀	0.37	-	-	▭		⬂	-0.88	▭	
NH4	⬂	-3.60	-	-	▭		▭		▭	
TP	⬀	1.39	▭		▭		▭		▭	
DRP	⬂	-0.40	▭		▭		▭		▭	

EGRET trend analysis

Flow concentration signatures suggest that elevated concentrations of all nitrogen species occur during high flow winter periods (Figure 40). Furthermore, the magnitude of peak concentrations of these analytes has been decreasing steadily since 2009.

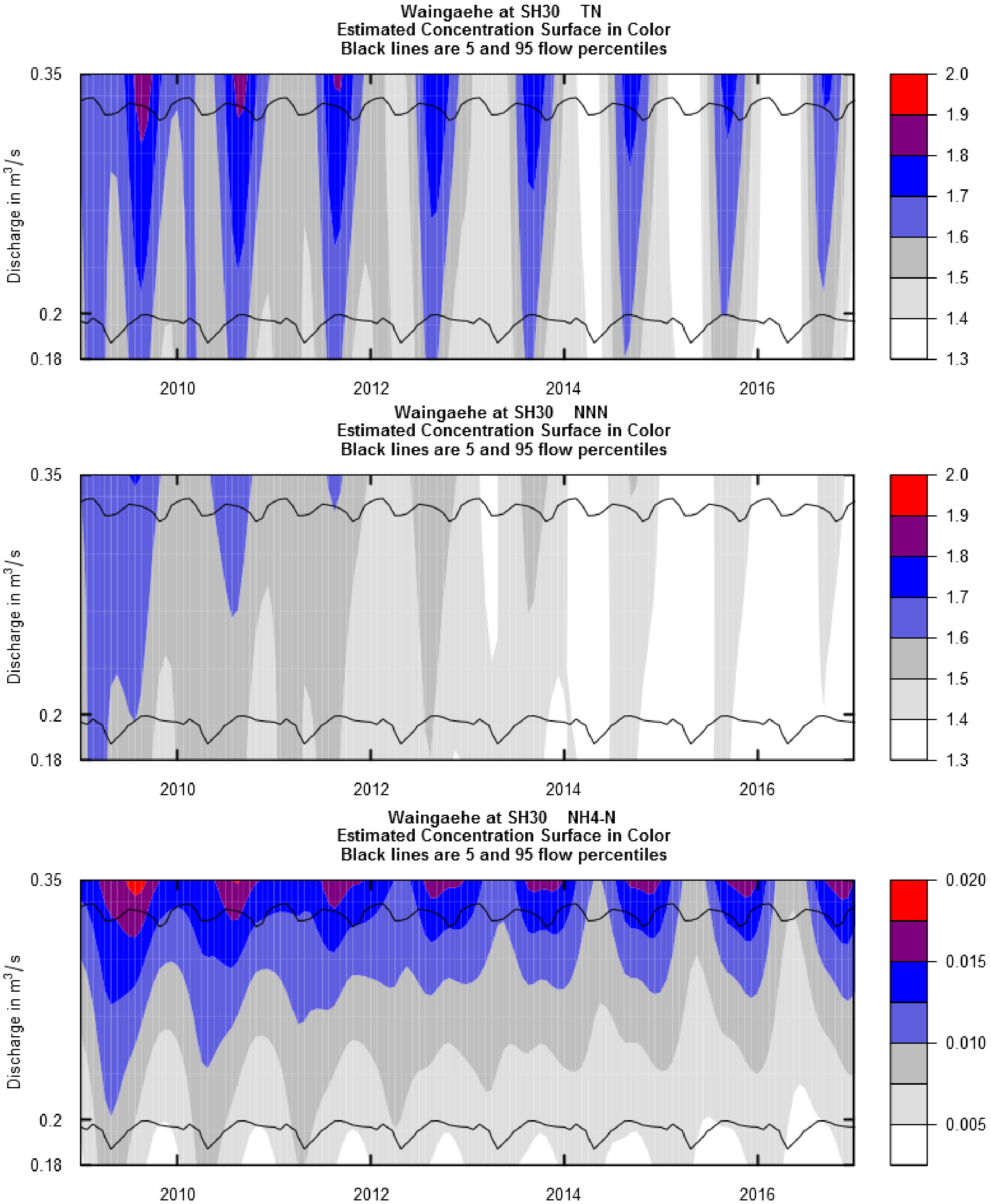


Figure 40 Modelled concentration versus discharge for the Waingaehe at SH 30 site between July 2009 and the end of 2016, for nitrogen species. Analytes from the top are: TN, NNN, and NH4-N.

Phosphorus depicts a different pattern to nitrogen, with higher concentrations occurring at low flows for both TP and DRP. Both of these analytes have two seasonal peaks, one in summer and one in winter. Summer TP peaks appear to be reasonably constant over time, while winter peaks show a slight increase in magnitude towards 2016. Both summer and winter DRP peaks have reduced slightly in concentration with time.

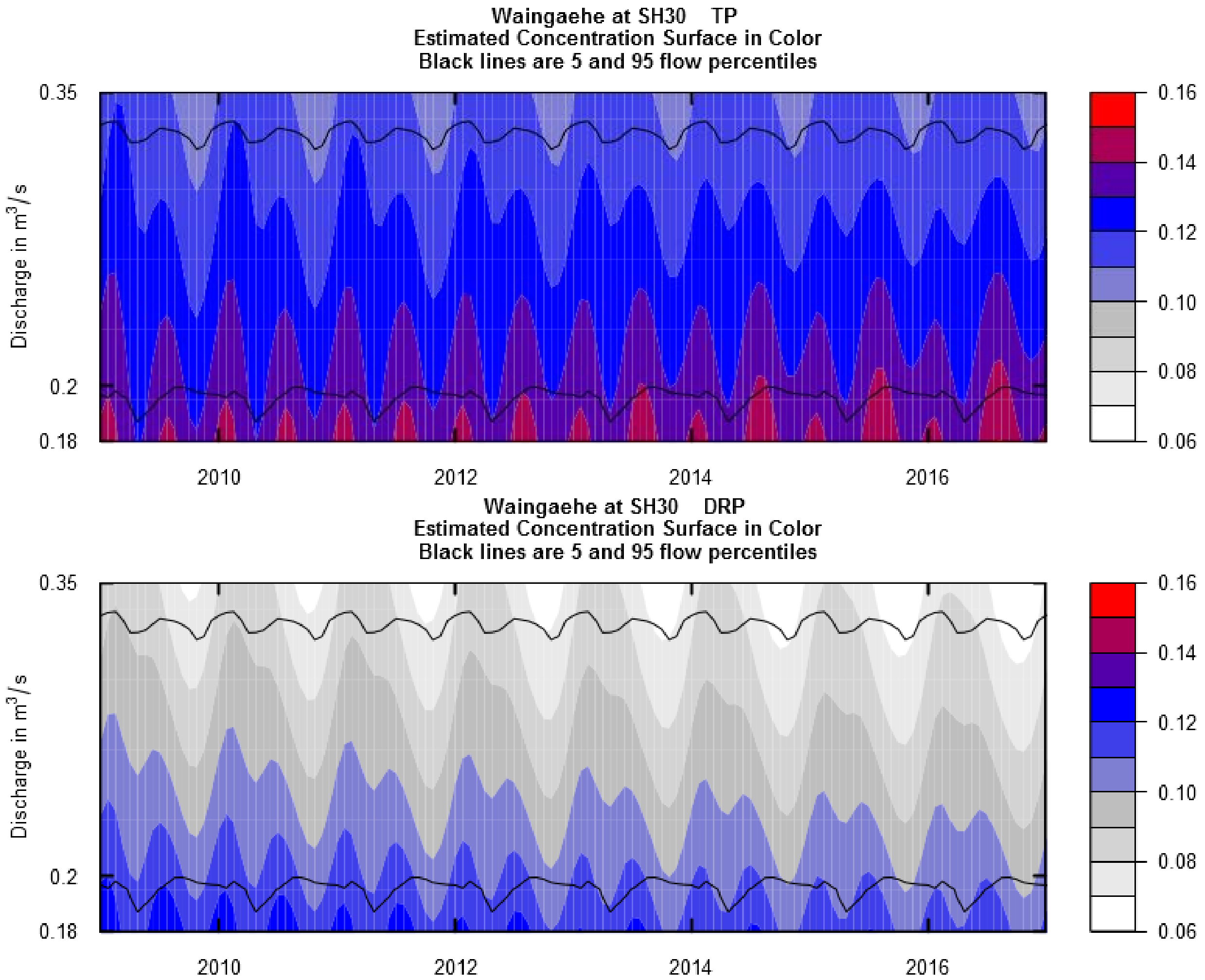


Figure 41 Modelled concentration versus discharge for the Waingaehe at SH 30 site between July 2009 and the end of 2016, for phosphorus species. Analytes from the top are: TP, and DRP.

Load estimates

Method comparison and patterns

All load estimation methods were relatively consistent for this site (Figure 40). TN, NNN, and TP show patterns of increasing loads up to 2012, before steadily decreasing towards 2016. This pattern is consistent with that of other catchments, and may be driven by local rainfall patterns. DRP loading has remained steady at about 0.8 T per year until 2012, and has decreased slightly since then. The NH4-N load estimate for 2014 is significantly higher for the numeric integration method, which is probably due to an elevated flow measurement in winter impacting this method more than smoothing (EGRET) and regression (LOADEST) methods.

2016 Calendar Year

Estimated loads for 2016 range from 8.8 to 9.6 T of TN, 8.4 to 9.1 T of NNN, 0.04 to 0.05 T of NH4-N, 0.83 to 0.89 T of TP, and 0.66 to 0.68 T of DRP.

Load ratios

Load ratios are reasonably constant over time, with NNN composing over 90% of TN for all but two years (2007, 2014), while DRP decreased from over 90% of TP in 2003 to 70% in 2011, increasing back up to 80% in 2016 (Figure 43). NH4-N has remained below 1% of TN for all years aside from 2014 where it reached 1.2%.

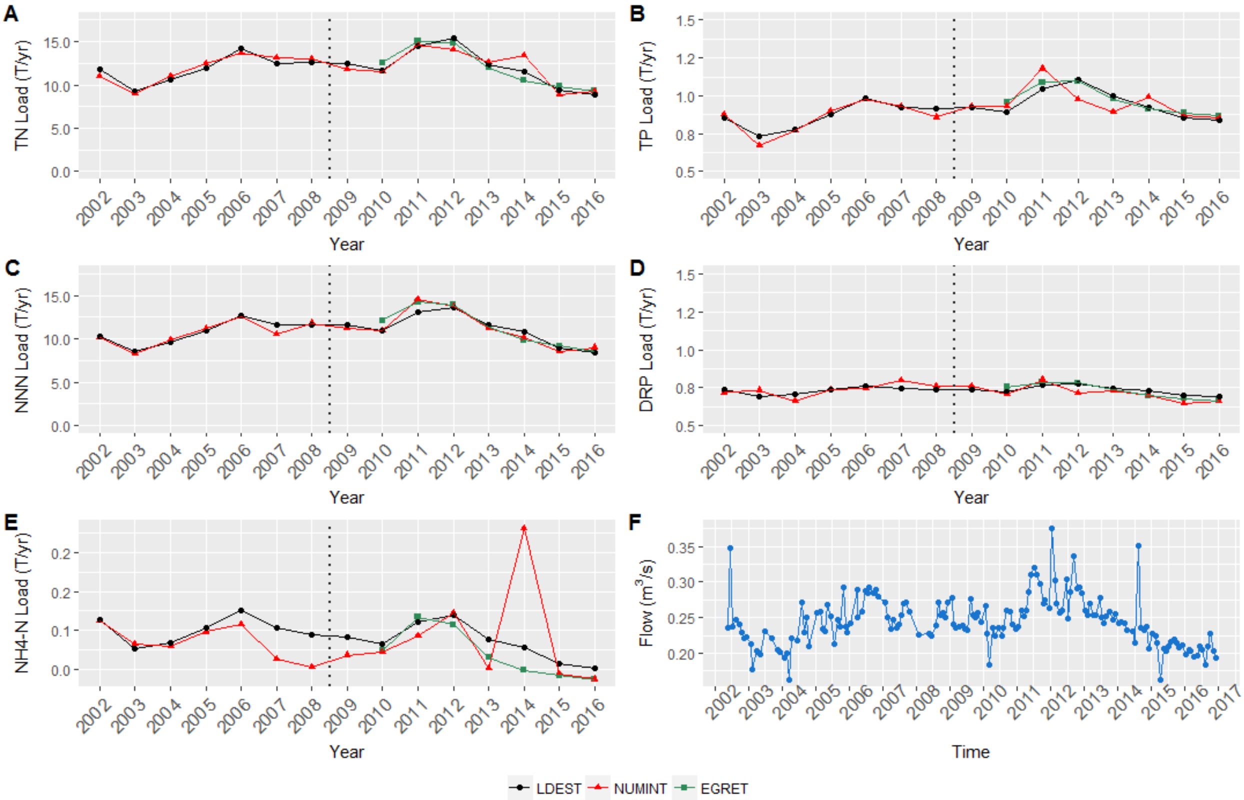


Figure 42 *(A-E) Load estimates for each analyte at the Waingaehe at SH 30 site water quality monitoring site, using two different estimation methods: numeric integration (red) and LOADEST (black). The vertical dotted line represents the lab method change (July 2008). (F) The discrete flow record used to calculate loads.*

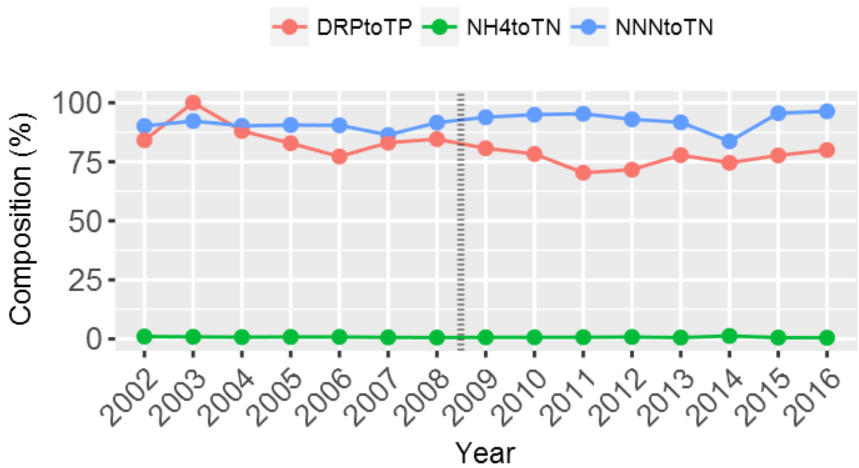


Figure 43 *The overall composition of TN that is attributed to NNN (blue), and TP attributed to DRP (orange) for the Waingaehe at SH 30 site. Composition is calculated from the average all load estimation methods.*

Catchment summary

The composition ratios of NNN to TN, and DRP to TP, at this site shows that TN and TP concentrations are driven by their major inorganic components. The concentration of NNN has increased over the long-term dataset, although declining trends were found for TN and NNN in the post-change dataset, and no significant trends were found in the final five years of the dataset. This suggests an overall improvement in nitrogen losses since 2009.

Modelling results show that the concentration of all nitrogen species were greater during periods of high flow, which is characteristic of catchment derived, diffuse sources. However, the elevated flow signature may also be caused by flushing of nitrate or ammonia enriched, shallow, unconfined aquifers. In contrast, TP and DRP are both elevated at lower flows, implying a baseflow source. Given the high DRP to TP ratio and the old age of groundwater, we can be reasonably confident that a significant proportion of phosphorus is supplied to the Waingaehe Stream in a dissolved form through groundwater enrichment.

The difference between TP and DRP loading suggests that particulate phosphorus is also an important contributor. Given that this contaminant pathway is activated in high intensity rainfall and flow events, the load contribution can be disproportionate to the amount of time the pathway is active (Abell, 2013). This is likely to be the reason why TP loads have varied, and show similar temporal pattern to total rainfall, while DRP loads have remained constant. This is also supported by the reduced ratio of DRP to TP that occurred during 2011, the wettest year of the study. Nitrogen loads also follow the broad rainfall/flow pattern, which explains why loads have shown a marked decline since 2011 while concentrations for these analytes were unchanged over the final five years.

Waiohewa Catchment

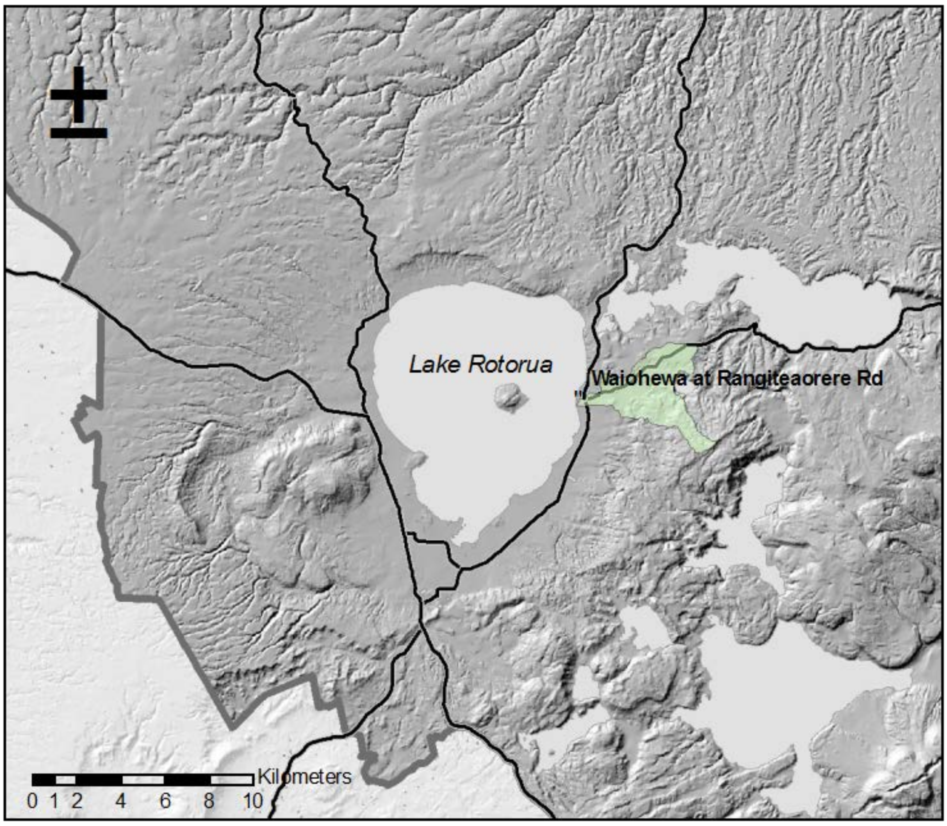


Figure 44 Location of the Waiohewa Catchment.

Background

The Waiohewa Catchment is another small (1,200ha) catchment draining from the eastern hills of Lake Rotorua (Figure 44). Previous studies (e.g. Williamson & Cooke, 1982) have recognised the disproportionate contribution of NH4-N coming from the Tikitere geothermal field near Hell's Gate. Land cover within this catchment is comprised primarily of pasture and arable land (30%), lifestyle blocks and mixed land use (19%), native forest and scrub (18%), 'other' land uses (16%), and exotic forest (12%).

Trend analysis

The Waiohewa Catchment drains into Lake Rotorua via the Waiohewa Stream, which is routinely monitored where it crosses Rangiteaorere Road, approximately 400 m upstream of Lake Rotorua.

Trend analysis revealed an increase in TP by 1.38% p.a. over the 15 year dataset (Figure 45; Table 9). NH4-N was the only analyte to show a significant trend over the pre-change dataset, declining by 7.71% p.a. However, NH4-N, TP, and DRP all increased over the post-change dataset by 4.13%, 2.37%, and 7.04% respectively, while TN and NH4-N increased in the last five years of the dataset by 5.98% and 11.98% p.a.

Figure 45 *Trend plots for TN, TP, NNN, DRP, and NH4-N (A-E) at the Waiohewa at Rangiteaorere Road water quality site, for the period of 1 January 2002 to 31 December 2016. Plots are based on unadjusted data, split into pre (red) and post (blue) lab method change groups, with a one year crossover period (green). Pre and post lab method groups include a fitted linear regression model.*

Table 9 *Trend analysis results for analyte concentrations at the Waiohewa at Rangiteaorere Road water quality monitoring site. Trend analysis was carried out on unadjusted (All) and adjusted (All Adjusted) data for the period of 2002-2016, as well as pre and post lab methodology periods, and last five years of the dataset (2012-2016). The direction of significant trends ($p<0.05$) are represented by increasing (⬀) or decreasing (⬂) arrows, while a blank rectangle (▭) depicts no trend. PAC stands for percentage annual change. Full trend statistics can be found in Appendix 1.*

	All		All Adjusted		Pre-Change		Post-Change		2012-2016	
Variable	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**
TN	▭		▭		▭		▭		⬀	5.98
NNN	▭		-	-	▭		▭		▭	
NH4	▭		-	-	⬂	-7.71	⬀	4.13	⬀	11.98
TP	⬀	3.14	⬀	1.38	▭		⬀	2.37	▭	
DRP	⬂	-3.50	▭		▭		⬀	7.04	▭	

Load estimates

Method comparison and patterns

Load estimates for this site are relatively consistent across methods for all analytes, although NH4-N estimates are consistently higher using the LOADEST method after 2004. This is possibly because the geothermal source of NH4-N is less related to flow than other parameters, making regression curve estimation less accurate for this analyte. The trajectory of the calculated load estimates for most analytes is variable, although typically there is a gradual increase to 2011, before decreasing towards the end of the dataset. The one exception to this pattern is DRP which has decreased from around 0.5 T in 2002 to 0.25 T in 2016. It's worth noting that trend results do not seem to reflect the increasing TN and NH4-N over the last five years of the dataset, suggesting that concentration increases are buffered by decreased flows over this period.

2016 Calendar Year

Estimated loads for this site during 2016 range from: 25.6 to 30.1 T of TN, 10.8 to 13.0 of NNN, 18.9 to 23.8 T of NH4-N, 0.82 to 0.90 T of TP, and 0.21 to 0.28 T of DRP.

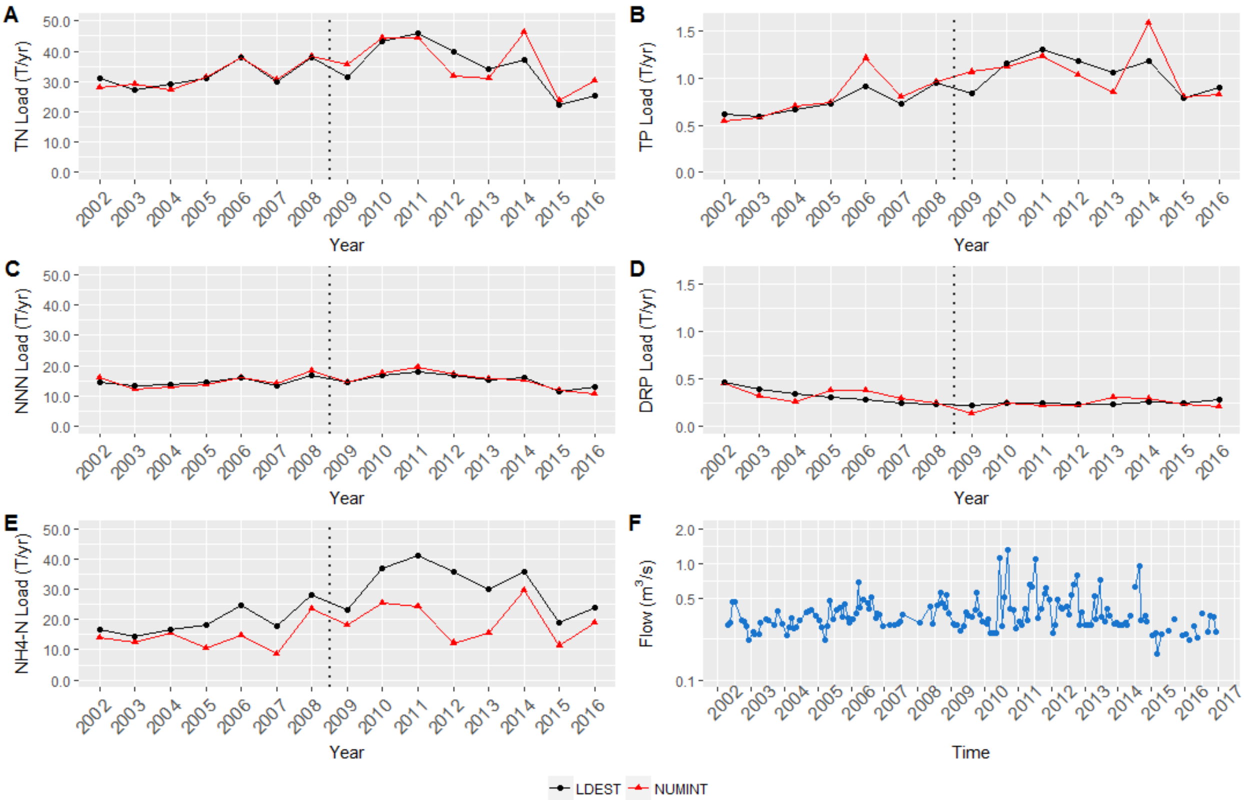


Figure 46 (A-E) Load estimates for each analyte at the Waiohewa at Rangiteaorere Road site water quality monitoring site, using two different estimation methods: numeric integration (red) and LOADEST (black). The vertical dotted line represents the lab method change (July 2008). (F) The discrete flow record used to calculate loads.

Load ratios

NNN has remained relatively constant over time, composing between 40% and 50% of TN since 2002, while DRP reduced steadily from 80% of TP in 2002 to 18% in 2009, increasing to around 30% in 2016 (Figure 47). NH4-N is the dominant component of TN at this site, making up around 50% between 2002 and 2007, before increasing to 77% in 2016.

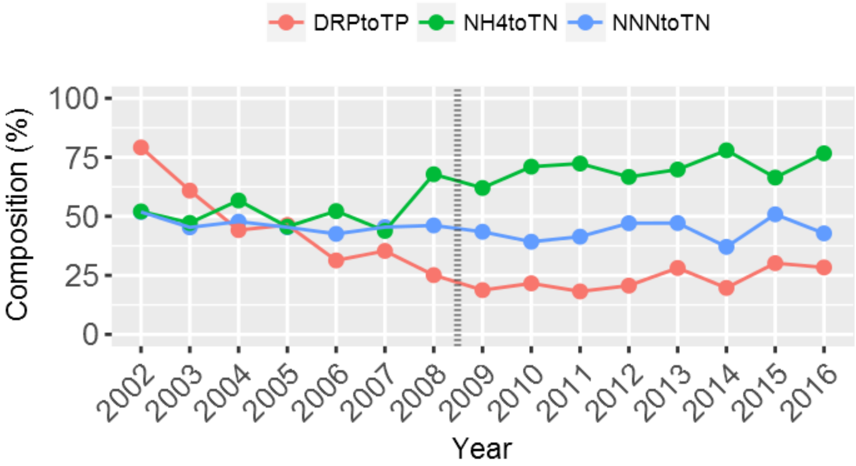


Figure 47 *The overall composition of TN that is attributed to NNN (blue) and NH4 (green), and TP attributed to DRP (red) for the Waiohewa at Rangiteaorere Road site. Composition is calculated from the average of numeric integration and LOADEST load estimation methods.*

Catchment summary

The Waiohewa Catchment is unusual in the supply of naturally sourced NH4-N from geothermal inputs, and the magnitude that this contributes to the overall nitrogen pool within the Waiohewa Stream. Trend analysis shows that TP concentrations increased over the long term dataset despite DRP remaining constant. The change from DRP dominated TP to particulate dominated TP occurred predominantly between 2002 and 2009. Since this date, the composition has remained constant while TP loads have continued to increase and DRP loads have reduced, which implies that particulate loads are probably associated with high flow events, as seen in other catchments. DRP is also known to be strongly adsorbed to alumininosilicates under low pH conditions (Ryden & Syers, 1975; as cited in Williamson & Cooke, 1982), therefore the binding and subsequent entrainment of P-bound geothermal muds may explain why DRP loads are comparatively low.

Given the high ratio of NH4-N to TN, especially since 2008, and the association of NH4-N to geothermal inputs within this catchment, it's safe to conclude that increases in TN are predominantly driven by geothermal inputs. The reason for the increasing trend post-change, and the accelerated PAC in the last five years of the dataset is unknown and may need further investigation. One possible explanation is that the localised climate has changed, affecting aquifer flushing dynamics, although rainfall patterns show that the 2012-2015 period was drier than normal. Alternatively, depletion of oxygen content in the geothermal aquifer could result in more NH4-N being released as a greater number of binding sites are dissolved. Another possibility is that the geothermal source is being supplemented with losses from surrounding land use, which aligns with the post-change increasing DRP trend. However, the sheer size of geothermal inputs relative to the agricultural catchment is likely to dwarf any such changes.

Regardless of the source, the mean annual TN concentration at this site is the highest of all monitored sites and is primarily driven by geothermally sourced NH4-N. This, in turn, manifests into a TN load that is disproportionate to the size of the inflow or catchment. Ratios between NNN and TN illustrate that NNN makes up the vast majority of the remaining fraction of nitrogen, which is inherently linked to NH4-N as geothermal water encounters oxygen and nitrification takes place. Williamson and Cooke (1982) suggest that nitrification could account for up to 55% of the decrease in NH4-N in this stream.

Waiowhiro Catchment

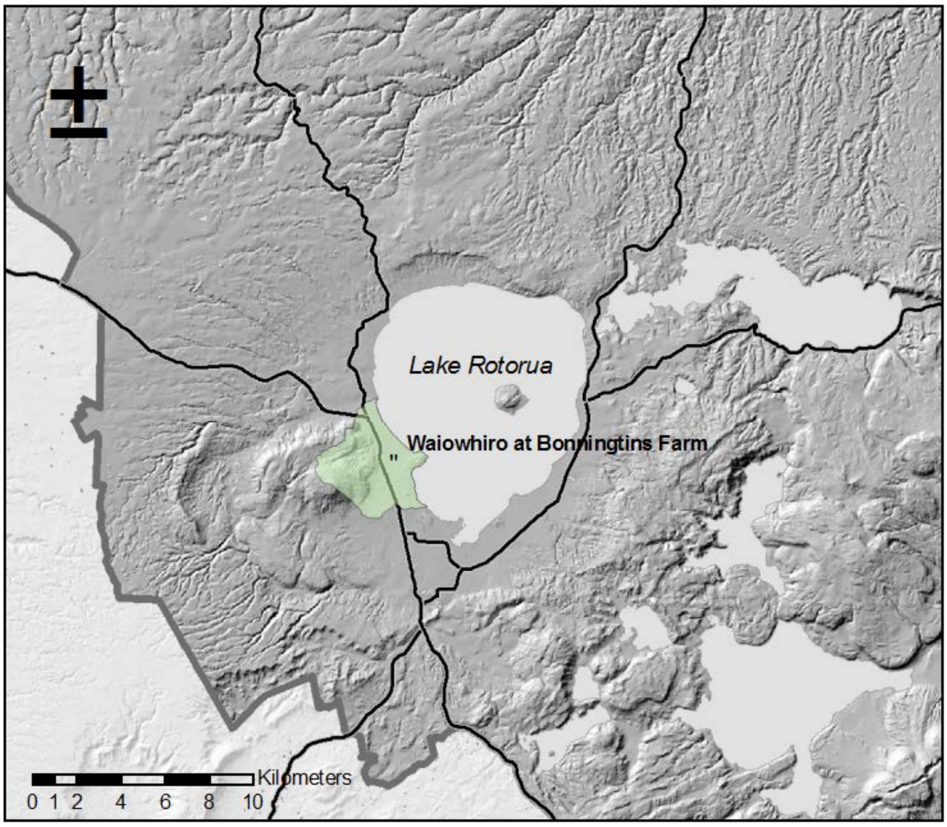


Figure 48 Location of the Waiowhiro Catchment.

Background

The Waiowhiro is a small (1,480 ha) catchment on the western shore of Lake Rotorua, situated between the Ngongotahā and Utuhina (Figure 48). This is the only catchment to be dominated by urban land use (40%), with native forest and scrub, and pasture and arable land both comprising 20% of the land use. The Waiowhiro Catchment drains into Lake Rotorua via the Waiowhiro Stream, which originates on the north eastern aspect of Mt Ngongotahā and includes the well known Fairy and Paradise springs.

Trend analysis

Water quality is monitored at Bonningtons Farm, approximately 900 m upstream of Lake Rotorua on Kawaha Point.

Trend analysis shows that NNN concentrations increased by 0.32% p.a. over the fifteen year dataset (Figure 49; Table 10). Both TN and NNN reduced over the pre-change dataset by 1.68% and 1.54%, respectively, while TP increased by 2.09% post-change. No significant trends were found over the last five years of the dataset.

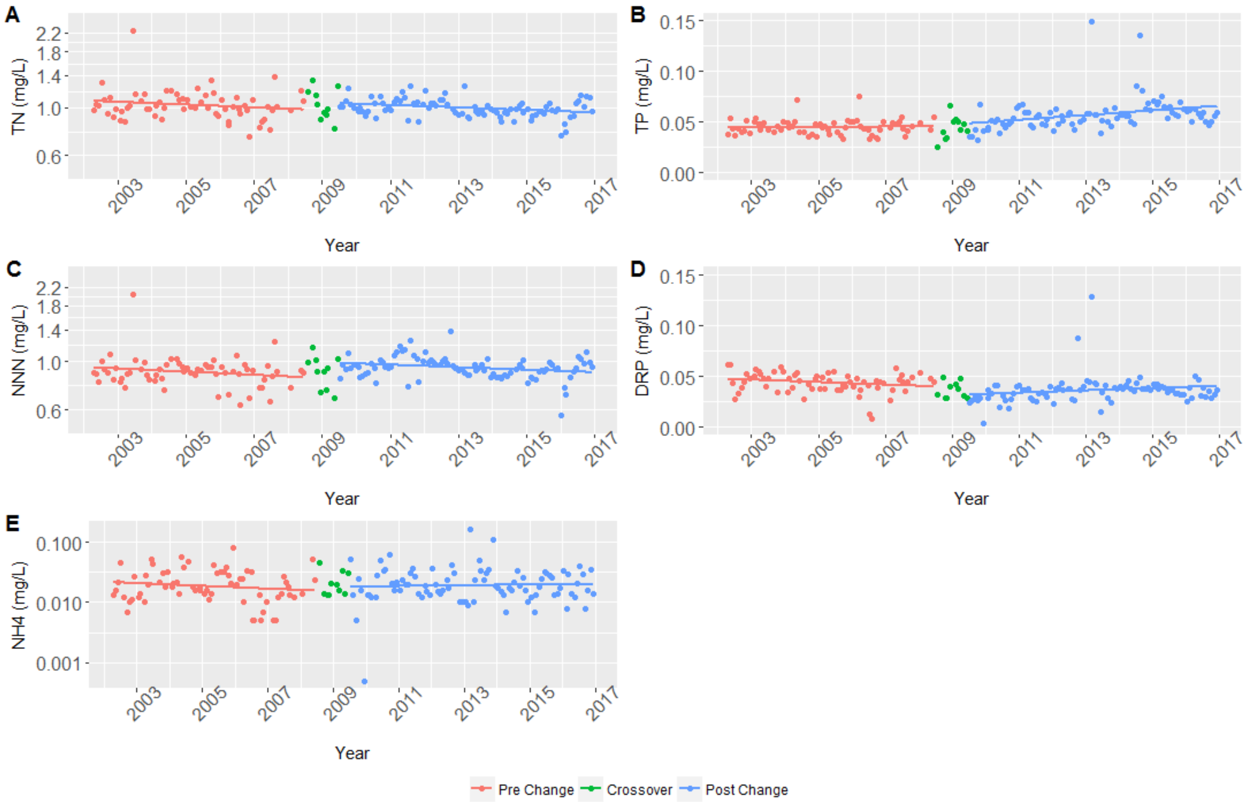


Figure 49 *Trend plots for TN, TP, NNN, DRP, and NH4-N (A-E) at the Waiowhiro at Bonningtons Farm water quality site, for the period of 1 January 2002-1 December 2016. Plots are based on unadjusted data, split into pre (red) and post (blue) lab method change groups, with a one year crossover period (green). Pre and post lab method groups include a fitted linear regression model. TN, NNN, and NH4-N are plotted on log transformed axes.*

Table 10 *Trend analysis results for analyte concentrations at the Waiowhiro at Bonningtons Farm water quality monitoring site. Trend analysis was carried out on unadjusted (All) and adjusted (All Adjusted) data for the period of 2002-2016, as well as pre and post-lab methodology periods, and last five years of the dataset (2012-2016). The direction of significant trends (p<0.05) are represented by increasing (⬀) or decreasing (⬂) arrows, while a blank rectangle (▭) depicts no trend. PAC stands for percentage annual change. Full trend statistics can be found in Appendix 1.*

	All		All Adjusted		Pre Change		Post Change		2012-2016	
Variable	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**
TN	▭		▭		⬂	-1.68	▭		▭	
NNN	⬀	0.32	-	-	⬂	-1.54	▭		▭	
NH4	▭		-	-	▭		▭		▭	
TP	⬀	2.07	▭		▭		⬀	2.09	▭	
DRP	⬂	-2.15	▭		▭		▭		▭	

Load estimates

Method comparison and patterns

Load estimates were consistent between the two estimation methods for TN, NNN, TP, and DRP, although they differed slightly for NH4-N, where the LOADEST method was less affected by inter-annual variability than numeric integration (Figure 50). Both TN and NNN expressed consistent annual loads of around 10 and 9 T, respectively, until 2012, when both declined noticeably. This period of decline is similar to that seen at other sites, and aligns with a comparatively dry period in the rainfall record. DRP load reduced from 0.5 T per annum in 2002 to around 0.3 T in 2016, while TP increased from 0.4 to 0.6 T per year after 2010, where it has remained since. NH4-N shows no discernible pattern, although loads drop post 2010 in a similar fashion to TN and NNN.

2016 Calendar Year

Loads for 2016 are as follows: between 8.7 and 8.9 T of TN, 8.2 and 8.5 T of NNN, 0.2 T of NH4, 0.5 and 0.6 T of TP, and 0.3 T of DRP.

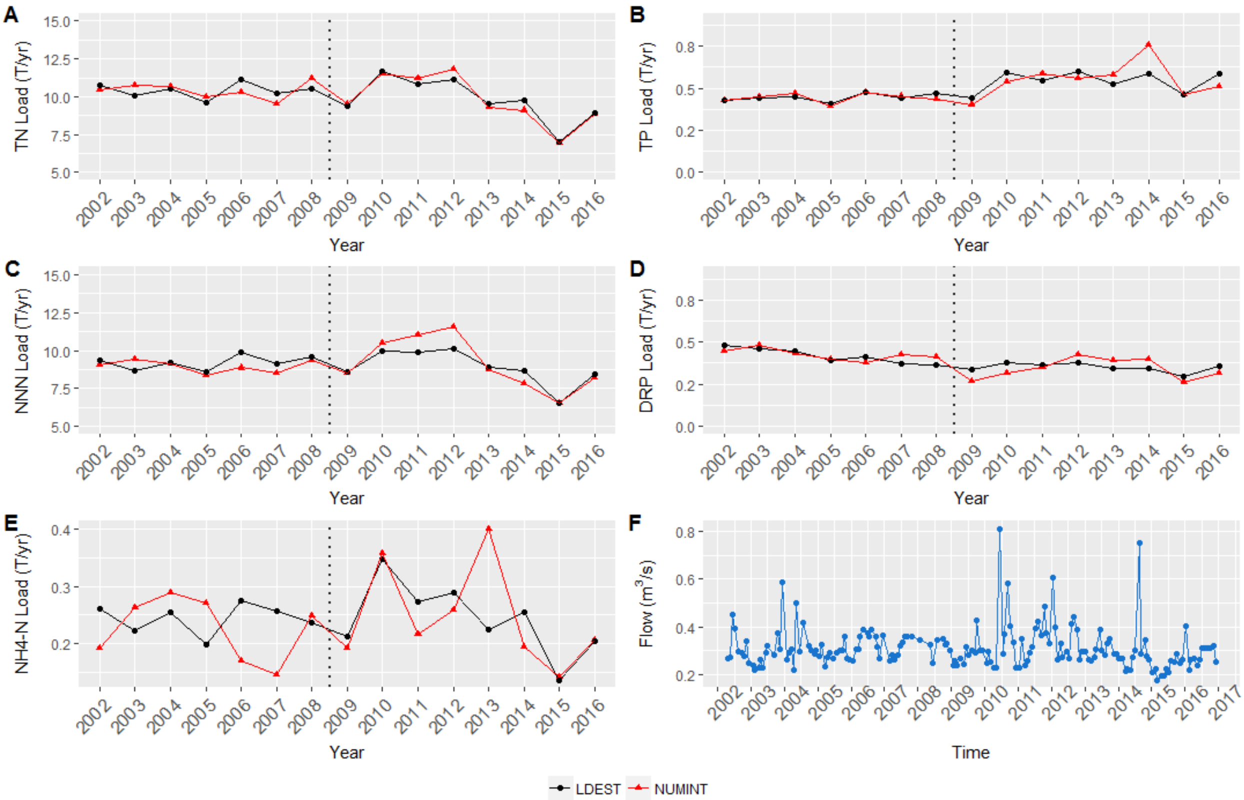


Figure 50 (A-E) Load estimates for each analyte at the *Waiowhiro at Bonningtons Farm* site water quality *monitoring* site, using two different estimation methods: numeric integration (red) and LOADEST (black). The vertical dotted line represents the lab method change (July 2008). (F) The discrete flow record used to calculate loads.

Load ratios

The relationship between NNN and TN has remained relatively constant since 2002, although there has been a slight increase from around 87% composition to 93% after 2010 (Figure 51). The percentage of TP that is comprised of DRP has steadily decreased, where DRP made up close to 100% of TP in 2002, but reduced to around 60% by the end of 2016. NH4-N contribution has remained around 2.5% of TN over the 15 year dataset.

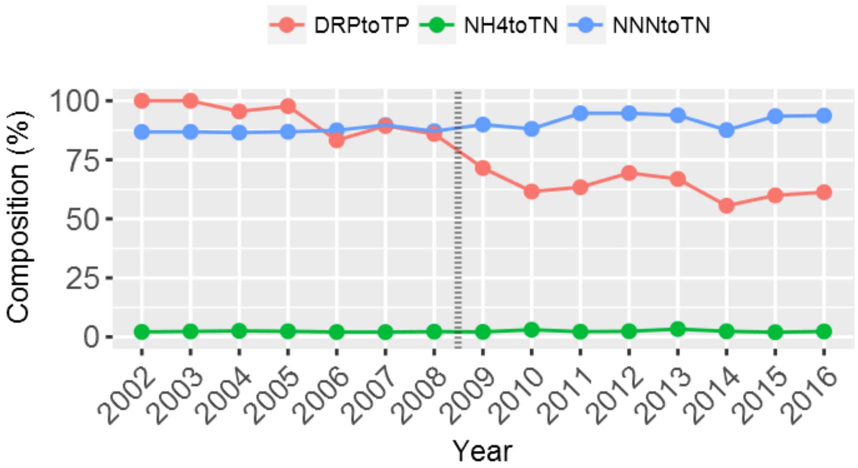


Figure 51 *The overall composition of TN that is attributed to NNN (blue) and NH4 (green), and TP attributed to DRP (red) for the Waiowhiro at Bonningtons Farm site. Composition is calculated from the average of numeric integration and LOADEST load estimation methods.*

Catchment summary

The Waiowhiro Catchment shows minimal signs of deterioration over the fifteen year dataset, with only NNN showing any sign of an increasing trend. Concentrations of both TN and NNN have reduced since 2009, which, when combined with the wet 2010-2012 period, and the dry 2013-2015 period, have resulted in a small load increase over the wet period followed by a reduction towards 2015. Although TN concentrations have been declining since 2009, load ratios show that this analyte is strongly driven by NNN, and shows similar loading patterns to local rainfall, suggesting that following rainfall-associated vectors may be important: flushing from aquifers, runoff from agricultural land, or stormwater overflow from the significant urban proportion of the catchment.

As with many other catchments, DRP concentrations have remained constant while TP has increased, particularly in recent years. This underlines an emerging pattern of particulate phosphorus mobilisation, most likely associated with overland flow events.

Waitetī Catchment

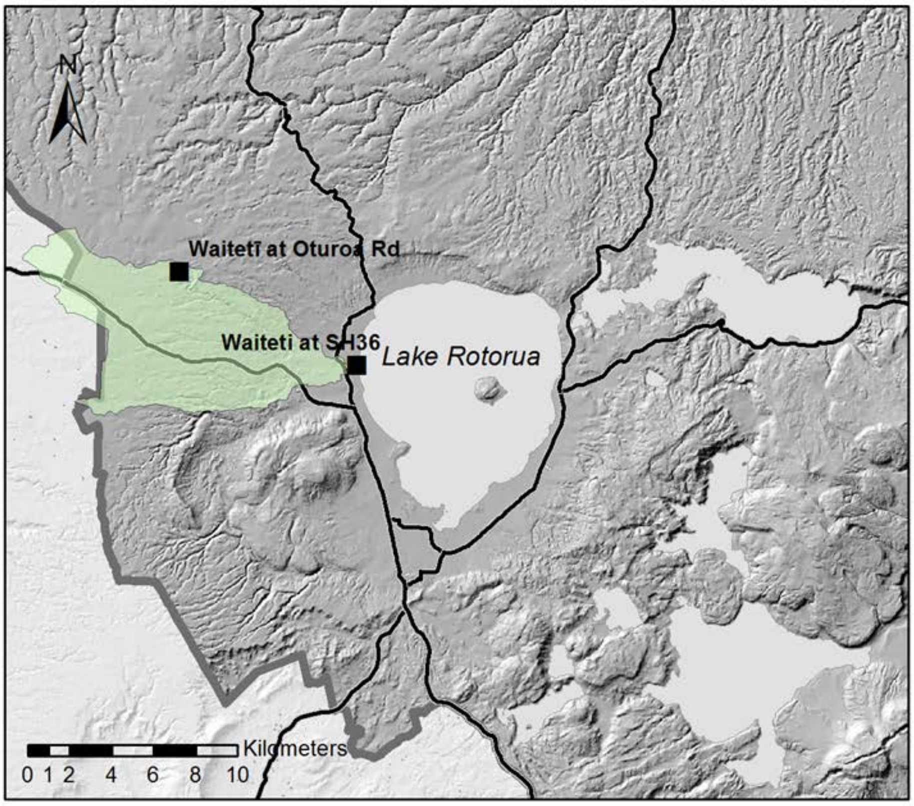


Figure 52 Location of the Waitetī Catchment and the Waitetī at SH 36 water quality monitoring site.

Background

The Waitetī Catchment covers an area of approximately 7,064 ha on the west shore of Lake Rotorua, and drains to the lake via the Waitetī Stream (Figure 52). The catchment is dominated by pasture and arable land (60%) and native forest and scrub (23%). The catchment has historically been monitored where SH 36 intersects the Waitetī Stream. However, an additional site, Waitetī at Oturoa Road, was added in 2015 to understand the nutrient flux coming from a sub-catchment perceived as being high risk. This site does not contain enough data to run trend analysis or form regression rating curves for the LOADEST method, so results are limited to observations of time-series data and numeric integration load estimates for 2016.

Trend analysis

Trend analysis showed significant trends for all analytes across the 15 year dataset. Of these, TN (adjusted), NNN, and TP (adjusted) increased by 1.00%, 1.13%, and 1.02% p.a., respectively. NH4-N and DRP (adjusted) both decreased by 2.39% and 1.18% p.a., respectively.

Interestingly, no analyte revealed a significant pre-change trend, yet all analytes were shown to be increasing post-change, with PAC ranging from 0.75% p.a. for NNN to 3.64% p.a. for TP. All analytes except NNN expressed significant increasing trends in the last five years of the dataset, ranging from PAC values of 1.23% for TN to 9.83% for NH4-N.

Figure 53 *Trend plots for TN, TP, NNN, DRP, and NH4-N (A-E) at the Waitetī at SH 36 water quality site, for the period of 1 January 2002 to 31 December 2016. Plots are based on unadjusted data, split into pre (red) and post (blue) lab method change groups, with a one year crossover period (green). Pre and post lab method groups include a fitted linear regression model. TN, NNN, NH4-N, TP, and DRP are plotted on log transformed axes.*

Table 11 *Trend analysis results for analyte concentrations at the Waitetī at SH 36 water quality monitoring site. Trend analysis was carried out on unadjusted (All) and adjusted (All Adjusted) data for the period of 2002-2016, as well as pre and post lab methodology periods, and last five years of the dataset (2012-2016). The direction of significant trends (p<0.05) are represented by increasing (⬀) or decreasing (⬂) arrows, while a blank rectangle (▭) depicts no trend. PAC stands for percentage annual change. Full trend statistics can be found in Appendix 1.*

	All		All Adjusted		Pre Change		Post Change		2012-2016	
Variable	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**
TN	⬀	0.74	⬀	1.00	▭		⬀	0.95	⬀	1.23
NNN	⬀	1.13	-	-	▭		⬀	0.75	▭	
NH4	⬂	-2.39	-	-	▭		⬀	3.51	⬀	9.83
TP	⬀	2.84	⬀	1.02	▭		⬀	3.64	⬀	3.66
DRP	⬂	-0.92	⬀	1.18	▭		⬀	2.72	⬀	2.35

Load estimates

Method comparison and patterns

Both load estimation methods provided very similar results for the Waitetī Catchment. All analytes increased gradually over time, with the exception of NH4-N which remained constant at around 0.7 T per year for the majority of the analysis period. TN, NNN, and TP expressed load patterns related to flow and rainfall, which peaked in the wet period of 2010-2012, and reduced from 2013-2015. DRP and NH4-N show a similar peak in 2012.

2016 Calendar Year

Loads for 2016 are as follows: between 55.6 and 57.3 T of TN, 49.9 and 50.6 T of NNN, 0.80 and 1.37 T of NH4, 2.5 and 3.0 T of TP, and 1.4 and 1.5 T of DRP.

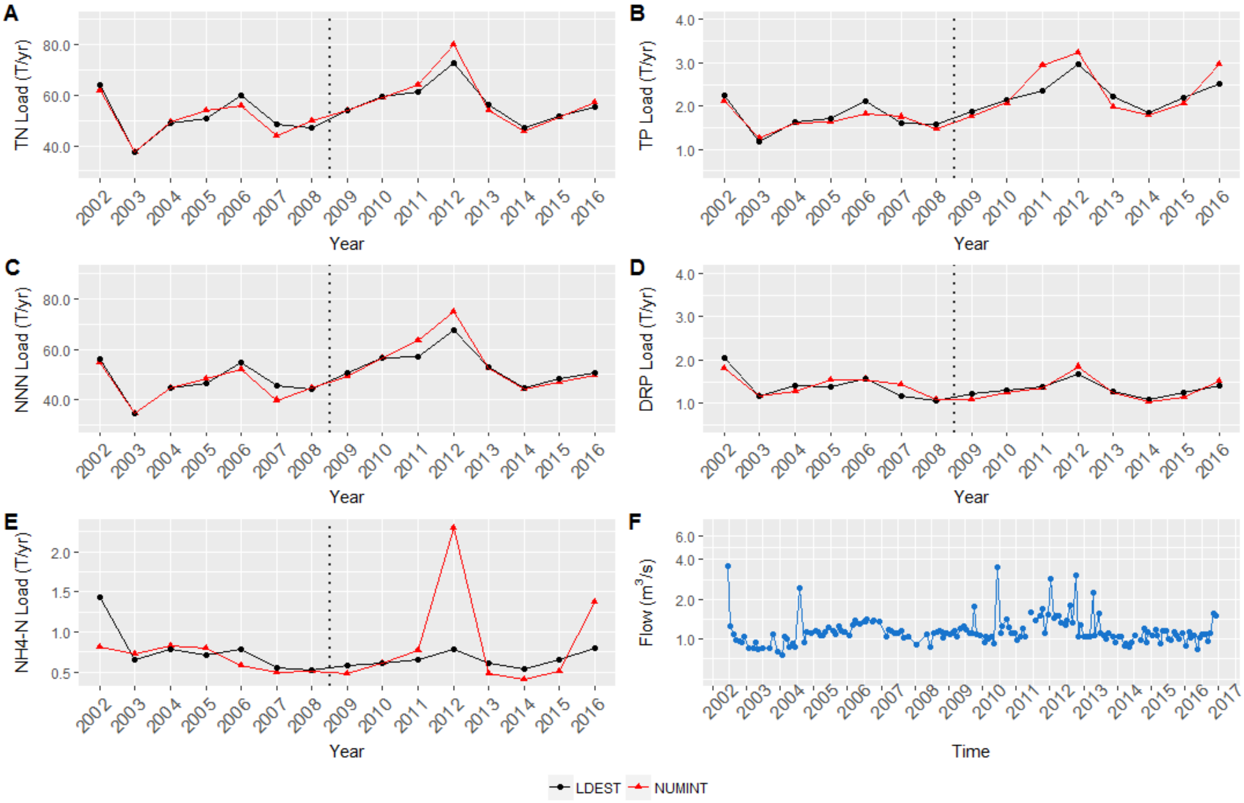


Figure 54 The overall composition of TN that is attributed to NNN (blue) and NH4 (green), and TP attributed to DRP (red) for the Waitetī at SH 36 site. Composition is calculated from the average of numeric integration and LOADEST load estimation methods.

Load ratios

NNN makes up around 90% of TN throughout the entire dataset, while DRP decreased from 90% of TP in 2002, to approximately 50% in 2016 (Figure 55). NH4-N contribution has remained consistently between 1% and 2% over the duration of the dataset.

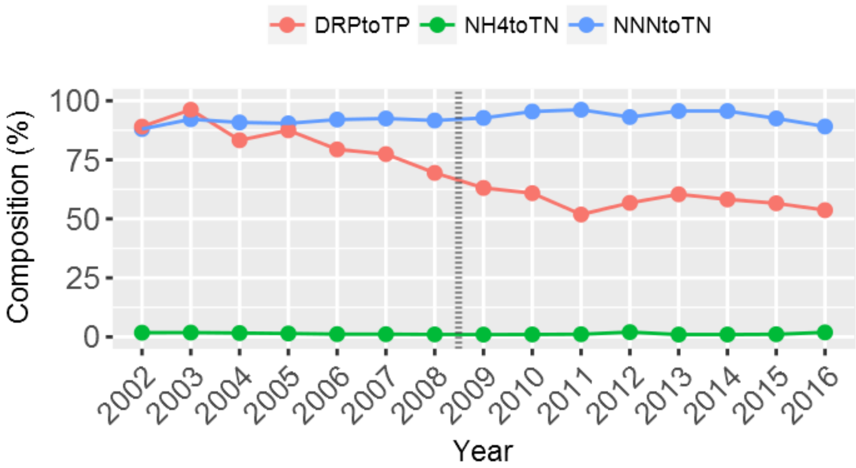


Figure 55 *The overall composition of TN that is attributed to NNN (blue), and TP attributed to DRP (orange) for the Waitetī at SH 36. Composition is calculated from the average all load estimation methods.*

Waitetī at Oturoa Road

Results for the Waitetī at Oturoa Road site are shown in Figure 56. The survey period runs from July 2015 to December 2016 which is too short for statistical trend analysis; however, concentrations can be seen to vary significantly at different times of the year, with all analytes expressing peaks in the winter of 2016. TP and DRP precede this period with elevated summer concentrations followed by decreased concentrations from April to August.

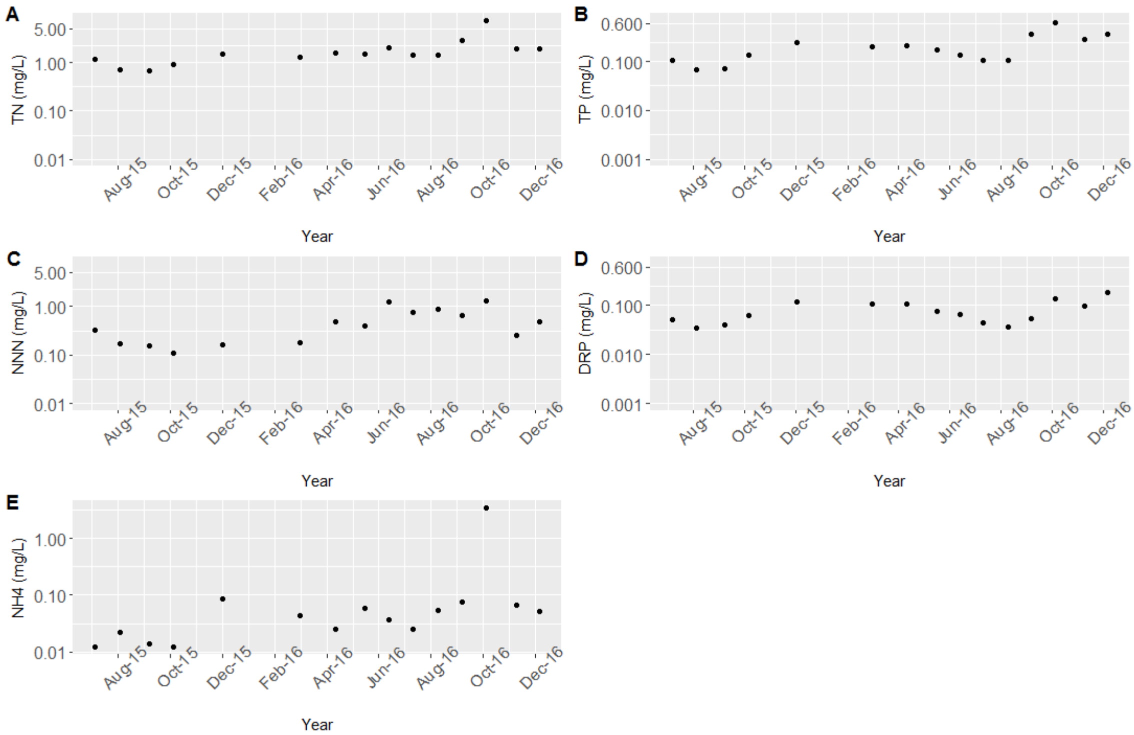


Figure 56 *Trend plots for TN, TP, NNN, DRP, NH4-N, TP, and DRP (A-E) at the Waitetī at Oturoa Road water quality site, for the period of 1 July 2015-31 December 2016. TN, NNN,NH4-N, TP, and DRP are plotted on log transformed axes.*

Waitetī at Oturoa Road - 2016 load estimates

Load calculation methods for the Waitetī at Oturoa Road site were limited to numeric integration due to a lack of data. During the calendar year of 2016, nutrient loads at this site equated to: 0.52 T of TN, 0.12 T of NNN, 0.02 T of NH4-N, 0.08 T of TP, and 0.03 T of DRP.

Waitetī at Oturoa Road - load ratios

The percentage of TN attributed to NNN during 2016 at this site is low at 22.6%, while DRP makes up only 40.5% of TP. NH4-N contributes 2.9% of the TN load.

Catchment summary

The Waiteti Catchment shows symptoms of deterioration, with all measured analytes increasing over post-change dataset. Furthermore, the annual rate of increase of TN, TP, and NH4-N accelerated over the last five years of the dataset.

Loads for all analytes appear to be linked to stream flow and rainfall, with peak loads occurring during the wet 2010-2012 period. Phosphorus loads and ratios show that particulate phosphorus had become the dominant contributor over time, emphasising the increasing contribution of sediment mobilisation through storm flow events.

Load ratios suggest that TN is strongly linked to NNN, and load patterns follow streamflow and rainfall patterns. This points to overland pathways as a major contributor; however the lack of ratio variability may indicate a constant inorganic nitrogen source such as enriched groundwater. Furthermore, for this ratio to remain constant while loads are increasing, any increases in NNN must also be met by either organic nitrogen or NH4-N, illustrating that there is also a minor contribution from these contaminants. NH4-N revealed the greatest rate of increase over the last five years of the dataset, and marked seasonality can be seen over this period in the time series plots where maximum concentrations occur in winter. This type of pattern is indicative of contamination through overland flow pathways.

The upper catchment monitoring site at Oturoa Road has concentrations of TN and NH4-N that are comparable only to the Waingaehe Catchment, and mean TP concentrations in 2016 that exceed that found at all other sites. Results from this site point to an obvious flow concentration relationship, which is indicative of a small, hydrologically flashy catchment. Measured nutrient concentrations are high for both nitrogen and phosphorus species, which shows a readily available nutrient source that is mobilised during high flows. However, current load estimates from this sub-catchment equate to only 0.9% of the overall SH 36 TN load, while TP contributes 3%. This implies that particulate TP mitigation, especially at high flows, should be the primary focus for this sub-catchment.

Combined load estimates

Load estimates

Combined load estimates to Lake Rotorua from all nine catchments are tabulated in Table 12, and shown in Figure 57. This figure has been created using the numeric integration and LOADEST methods only because EGRET could only be applied to four catchments, and the time period of application differed depending on the availability of continuous flow records. Results between the two load estimation methods are remarkably similar for TN, NNN, TP, and DRP; however, estimation methods for NH4-N differ, with greater LOADEST estimates for all years, and significant divergence between the two methods between 2010 and 2014. This pattern is similar to a number of the individual sites, particularly those with geothermal NH4-N inputs where concentration may not be directly linked to flow. In these cases, LOADEST fits the flow concentration-relationship resulting in elevated load predictions, when flow may in fact be diluting NH4-N concentrations and the true load may be significantly lower. For this reason, the numeric integration method is likely to be more accurate for NH4-N loads than the LOADEST method.

The load trajectory for TN and NNN are similar and seem to follow rainfall patterns. Estimates for both of these analytes increase gradually between 2002 and 2010, before expressing a peak period during 2011-2012 (wet period), followed by a reduction between 2013 and 2015. NH4-N is more variable year-to-year, but both estimation methods show an increase in loads after 2008. TP loads were constant between 2002 and 2010 at approximately 24 T, but increased after 2011 to 35 T. DRP showed a steady decline from approximately 22 T in 2002, to 18.5 T in 2011 where it remained until the end of 2016.

Our results show that approximately 470 T of TN and 32.5 T of TP were transported from the nine major inflows during 2011. This result is consistent with the 465 T of nitrogen and 35 T of phosphorus estimated by Scholes (2013), with slight differences that can partly be attributed to additional methods used to obtain flow values for samples that previously had no data (i.e. continuous flow extraction, or TOPDESK simulation with renovation factor). TN Loads have since reduced to approximately 412 T of nitrogen in 2016, while TP loads increased slightly to 35 T.

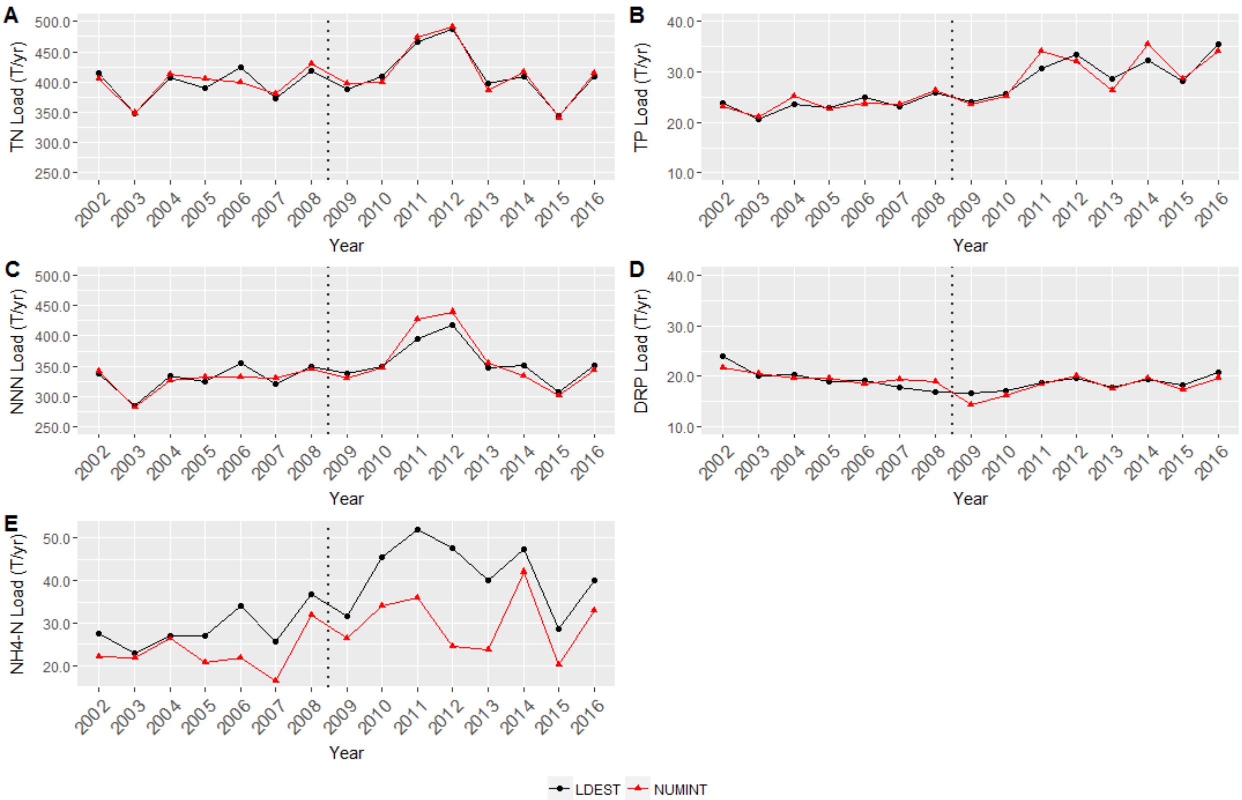


Figure 57 Combined loads to Lake Rotorua over the period of the study. NUMINT represents the numeric integration method, and LDEST represents LOADEST.

Table 12 Combined annual load estimates to Lake Rotorua from the nine monitored sub-catchments, using the numeric integration (Num Int) and LOADEST methods. Estimates are in T (t).

Analyte	Variable	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
TN	TN-LDEST	415.5	347.8	406.9	389.4	424.7	373.8	419.1	388.7	408.6	465.9	487.1	397.5	409.9	344.6	409.8
TN	TN-NUMINT	405.6	349.1	413.4	405.9	399.4	381.2	430.8	397.9	400.2	474.0	491.4	386.2	416.1	341.5	414.9
NNN	NNN-LDEST	337.0	284.9	333.5	324.2	355.5	321.1	348.8	337.9	349.5	395.9	418.5	347.7	351.7	308.1	351.1
NNN	NNN-NUMINT	342.4	283.2	325.6	332.7	332.9	330.2	345.5	331.0	347.2	428.2	439.8	355.4	333.5	302.1	344.3
NH4	NH4-LDEST	27.7	22.9	27.0	27.2	34.2	25.8	36.7	31.6	45.4	52.1	47.6	39.9	47.5	28.7	40.1
NH4	NH4-NUMINT	22.1	21.8	26.5	20.9	22.0	16.5	32.0	26.6	34.1	36.1	24.5	23.7	42.1	20.2	33.0
TP	TP-LDEST	24.0	20.6	23.5	23.0	24.9	23.1	26.0	24.1	25.7	30.8	33.5	28.7	32.3	28.1	35.6
TP	TP-NUMINT	23.2	21.0	25.2	22.8	23.7	23.5	26.3	23.7	25.3	34.2	32.2	26.3	35.6	28.7	34.1
DRP	DRP-LDEST	23.9	20.1	20.2	18.9	19.1	17.8	16.8	16.7	17.0	18.8	19.7	17.8	19.5	18.2	20.7
DRP	DRP-NUMINT	21.6	20.6	19.5	19.7	18.5	19.4	19.0	14.3	16.2	18.4	20.1	17.6	19.7	17.3	19.7

Outflow

The outflow of Lake Rotorua, called the Ōhau Channel, is situated at the north western end of the lake and drains to the Kaituna River via Lake Rotoiti. A comparison between combined inflow and outflow loads provides information about nutrient processes and retained loads within Lake Rotorua, hence annual comparisons of inflow to outflow TN (Figure 58) and TP (Figure 59) loads, averaged across estimation methods, are included below.

Inflow TN loads have been consistently greater than outflow loads throughout the entire dataset, and the percentage exported has reduced from above 50% between 2002 and 2012, to around 40% in 2016 (Figure 60). This implies that an increasingly large proportion of TN is either: denitrified, bound directly to sediment and deposited at the bottom of the lake, or taken up by autotrophs and deposited as organic nitrogen at the bottom of the lake. Outflow loads since 2012 have reduced slightly in response to a reduction in mean annual flow, which is tightly linked to local rainfall patterns. However, loads for these years are lower than loads estimated for 2002 and 2003 which had comparable flow, suggesting that the reduction in outflow TN load is driven by a combination of flow and other factors.

It is interesting to note that the 2013-2016 outflow load reduction coincides with a period where NNN concentrations were decreasing at two inflow sites, and showed no trend at any of the others. Load ratios from the outflow show that TN export is predominantly in the form of particulate organic nitrogen (Figure 61) implying that bioavailable forms of nitrogen are taken up and stored within the tissues of organic matter, most likely free floating phytoplankton. The link between NNN and TN loads for the outflow is therefore intuitive, while non-bioavailable forms of N from inflows may settle out in lake sediments and be mineralised at a slower rate, buffering the supply to the outflow.

TP loads in the Ohau Channel between 2002 and 2006 matched inflow loads which, according to Scholes (2013), coincides with a period of severe algal blooms which increased the export of phosphorus in the form of algal biomass (Figure 60). Load ratios show that organic phosphorus makes up more than 75% of TP for most years, and there was no noticeable shift to indicate that a greater proportion of phosphorus was being exported in organic forms during the 2004 algal bloom, i.e. the algal response was proportional to nutrient export. The divide between inflow and outflow TP load increased steadily from 2006 to 2017, reflecting the increasing contribution of particulate phosphorus from many of the major inflows, and potentially a reduction of easily transportable phosphorus fractions (i.e. DRP) through alum dosing of the Utuhina and Puarenga streams. A significant proportion of the particulate phosphorus load is likely to find its way to the bottom of the lake, and be released in bioavailable forms under stratified, anoxic conditions. However, the release of soluble phosphorus from bottom sediments is reliant on favourable conditions, which may affect the temporal alignment of the TP import versus export via the Ōhau Channel.

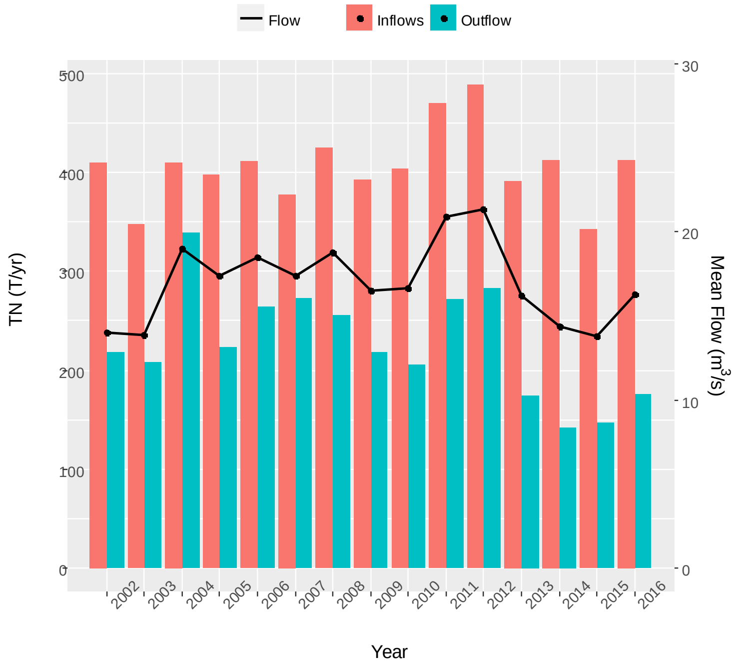


Figure 58 Comparison of major inflow and outflow TN loads throughout the duration of the study. The black line represents the mean annual flow for the Ōhau Channel (Lake Rotorua Outflow), as calculated from mean daily flows corresponding with each water quality sample.

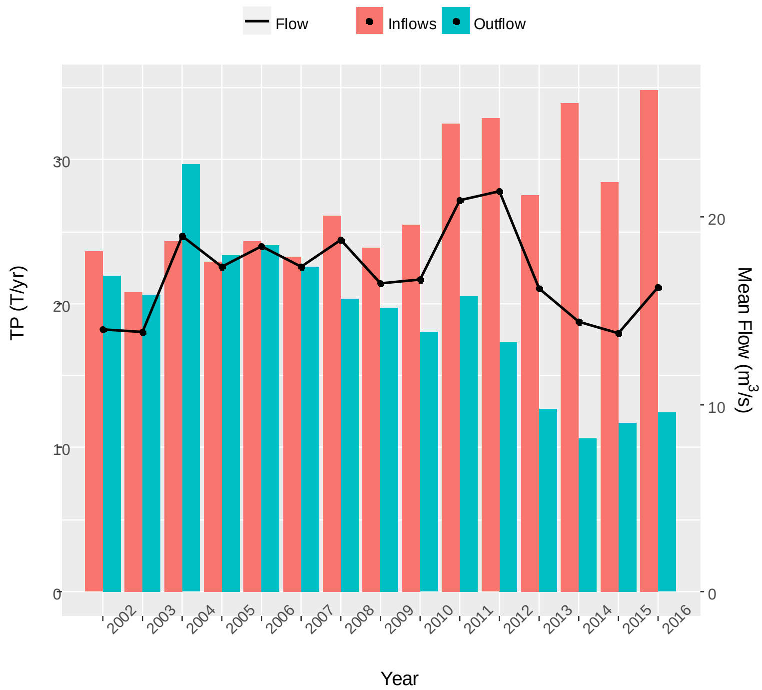


Figure 59 Comparison of major inflow and outflow TP loads throughout the duration of the study. The black line represents the mean annual flow for the Ōhau Channel (Lake Rotorua Outflow), as calculated from mean daily flows corresponding with each water quality sample.

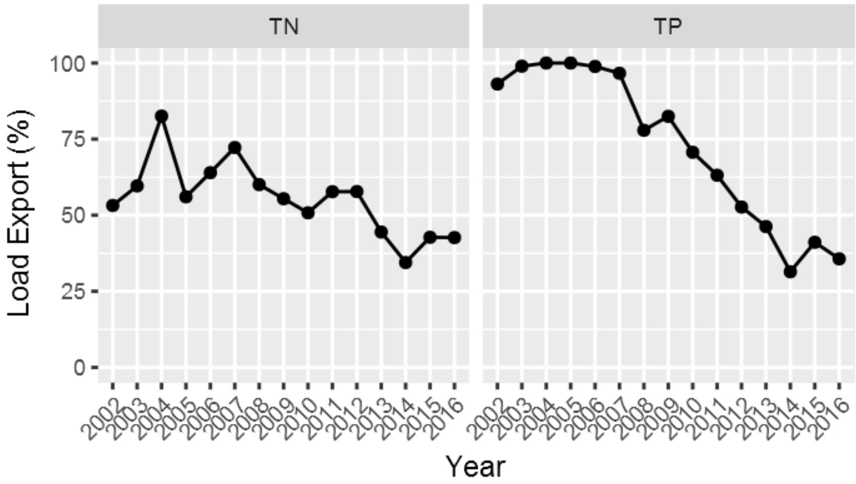


Figure 60 *The percentage of TN (left) and TP (right) loads calculated from major inflows, which are exported from the lake via the Ōhau Channel, over time.*

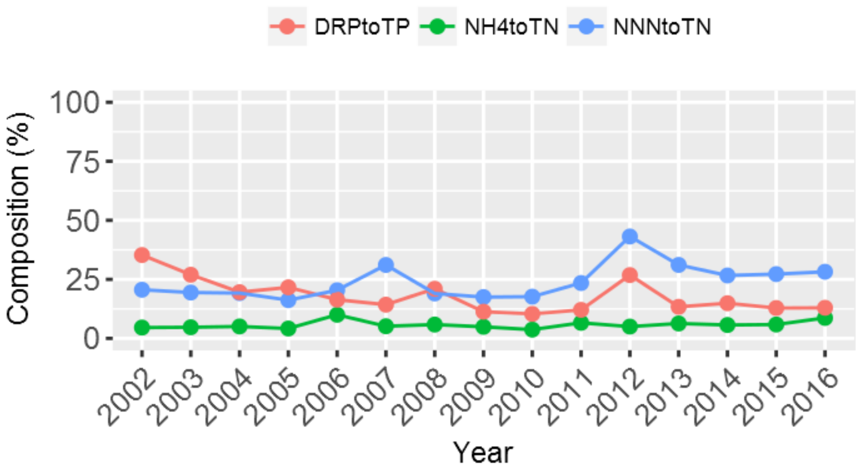


Figure 61 *The overall composition of TN that is attributed to NNN (blue) and NH4 (green), and TP attributed to DRP (orange) for the Ōhau Channel (Lake Rotorua Outflow). Composition is calculated from the average all load estimation methods.*

The impact of lake water on the Kaituna River

The Kaituna River flows northwards from the outflow of Lake Rotoiti to the Maketū coastline located approximately 45 km away. There has been concern over the contribution of degraded water from Lake Rotorua in elevating nutrient levels further down the catchment; therefore we have provided a brief analysis to examine the impact of lake water relative to other sources.

Figure 62 shows a comparison of nutrient concentration data between 2011 and 2016, across three sites: Ōhau Channel at SH 33, the outflow of Lake Rotorua; Kaituna at Rotoiti Outlet, the outflow of Lake Rotoiti; and Kaituna at Maungarangi Road, a routine monthly monitoring site located approximately 30 km downstream of the Kaituna at Rotoiti Outlet site. This timeframe was chosen to avoid complications that may affect lake outflow concentrations, such as: significant cyanobacteria blooms (2002-2006), the start of alum dosing schedules (2006 for the Utuhina, 2009 for the Puarenga), and installation of the Ōhau Channel wall (2008).

Results show that concentrations of all analytes are similar for the Ōhau Channel and Lake Rotoiti Outlet, which can be linked to the proximity of the monitoring sites and the effectiveness of the Ōhau Channel wall, in diverting the outflow from Lake Rotorua directly into the Kaituna River. Concentrations further downstream at the Kaituna at Maungarangi Road site are elevated above outflow sites for all years and all analytes except NH4-N. This pattern is particularly evident for inorganic nitrogen and phosphorus fractions (NNN and DRP) at the Maungarangi Road site, which make up approximately 60% and 50% of mean annual TN and TP concentrations, respectively. In comparison, NNN and DRP make up less than 25% of total nitrogen and phosphorus concentrations across most years at the two outflow sites (Figure 63). This implies that lake sourced nitrogen and phosphorus are predominantly exported in organic or particulate forms, which require mineralisation (organic fractions) or reduction (sediment bound fractions) to become bioavailable. Flow conditions within the Kaituna River are unlikely to provide conditions suitable for such processes to take place at a magnitude great enough to explain inorganic concentrations downstream, implying that elevated NNN and DRP concentrations must be sourced from elsewhere. Given the link between these nutrient fractions and intensive agricultural land uses, it is a reasonable assumption that nutrient losses from land use in the lower catchment are a major contributor.

NH4-N was the only analyte that had greater concentrations at lake outflow sites, than further down the catchment at Maungarangi Road. Previous results have shown that concentrations of NH4-N are abnormally high and increasing with time (especially since 2012) in the Waiohewa Catchment, while NH4-N concentrations from a number of other inflows had also increased over the most recent five year period. When this is combined with the release of NH4-N from lake sediments under anoxic conditions, it makes sense that Lake Rotorua and Rotoiti outflows are elevated above the lower catchment site at Maungarangi Road. Much of the exported NH4-N is likely to be oxidised to NNN within a short period of leaving the lake, as water travels over the Ōkere Falls. This process will contribute a small amount to Kaituna NNN concentrations, but the magnitude (NH4-N <0.02 mg/m3) is minimal compared to median concentrations observed at the lower catchment site (NNN = ~0.3 mg/m3).

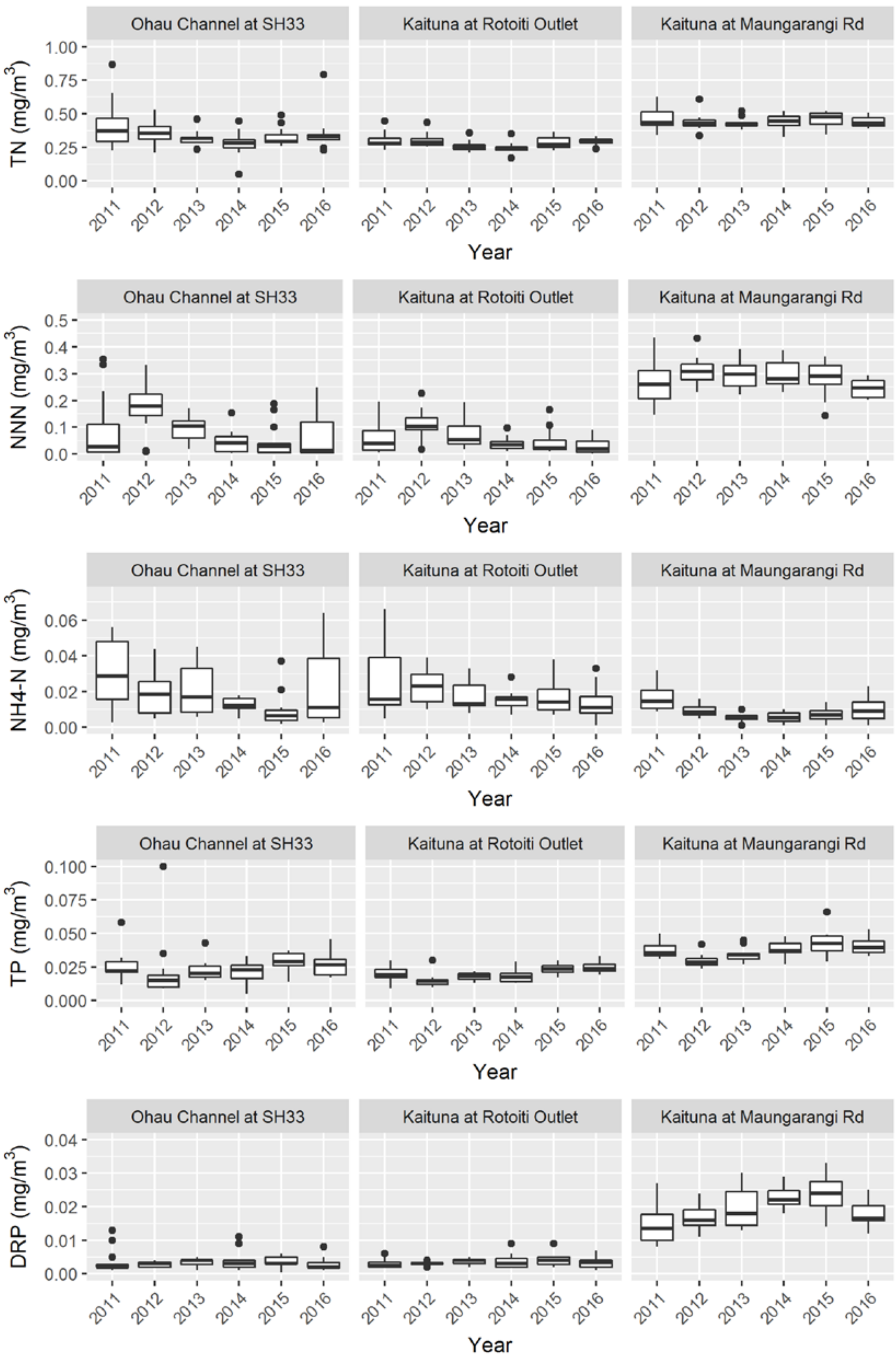


Figure 62 *Annualised boxplots for each nutrient constituent over the period of 2011-2016, for two lake outflow sites (Ōhau Channel at SH 33, Kaituna at Rotoiti Outlet) and one lower Kaituna Catchment site (Kaituna at Maungarangi Road).*

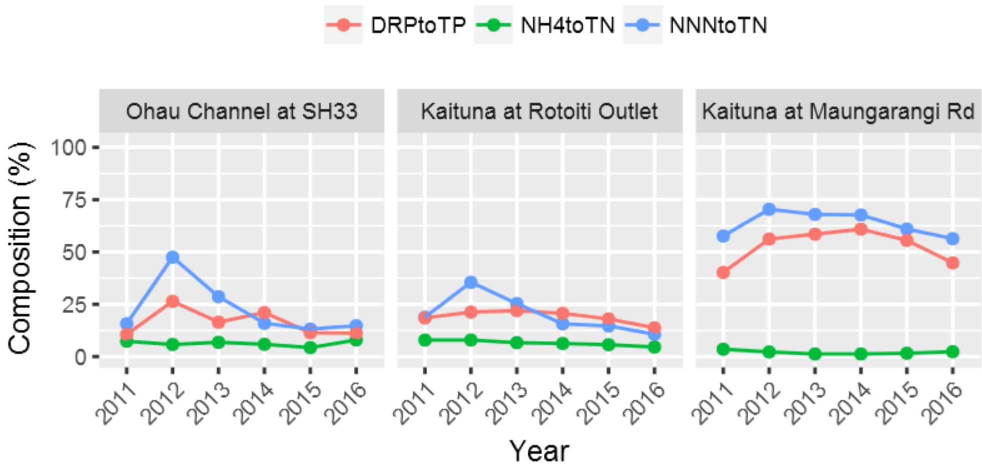


Figure 63 *The overall composition of TN that is attributed to NNN (blue) and NH4 (green), and TP attributed to DRP (orange) for three sites: Ōhau Channel at SH 33, Kaituna at Rotoiti Outlet, and Kaituna at Maungarangi Road. Composition is calculated from nutrient concentrations only (as opposed to load estimates).*

Relative load contribution

The relative contribution of each catchment to the overall load is shown in Figure 64. This figure is constructed using results from the LOADEST model for TN, NNN, TP, and DRP, as LOADEST estimates for these analytes were less influenced by extreme concentrations than numeric integration. However, the NH4-N comparison plot has been constructed using numeric integration due to the influence of geothermal inputs which result in flow independent concentrations.

The most obvious feature is the dominance of the NH4-N load coming from the Waiohewa Catchment, which in some years equates to over 75% of the total NH4-N load. This catchment has been recognised as a disproportionate contributor of NH4-N load since Fish (1969) first estimated the contribution to be in excess of 66% of the total ammonia load. The source of the high NH4-N has been traced back to the Tikitere geothermal area, where emerging groundwater is heated by steam containing high concentrations of NH3 , CO2, and H2S (Glover, 1974; cited in Williamson & Cooke, 1982). The combination of acid gases and oxidation of sulphide to sulphate result in acid ammonium sulphate drainage waters (Williamson & Cooke, 1982). A number of engineering solutions have been proposed, including a diversion pipeline directly into the outflow of Lake Rotorua (Williamson & Cooke, 1982). However, more recently the upscaling of a treatment system that will adsorb NH4-N from the upper Waiohewa Stream by passing it through a filter of locally sourced zeolite rock, is occurring. Construction for this project is due to commence in 2018 and should be completed in 2019.

The Puarenga Catchment is the next most dominant contributor of NH4-N load, while the contribution from all other catchments is relatively minor. The typical NH4-N signature for catchments that were able to be analysed using the EGRET package is one of a high flow source, suggesting diffuse agricultural losses. However the Puarenga and Utuhina catchments are also likely to be supplemented by contribution from urban areas (e.g. stormwater and/or wastewater treatment plant discharges).

The load contribution of TN and NNN are similar to each other, and dominated by the: Waitetī, Hamurana, Awahou, and Puarenga catchments. All of these catchments have a large portion of exotic pasture and significant groundwater contributions. Furthermore, the NNN to TN ratios for these sites are in excess of 80% for the Waitetī, Hamurana, and Awahou catchments, implying that NH4-N or organic N contribution is minimal. This shows that the main contributing catchments for TN load are driven by inorganic forms of nitrogen, predominantly NNN, although NH4-N plays a larger role for the Puarenga Catchment. The source of NNN could be via direct flushing of soil pore water following rain events, or via a more indirect route of enriched groundwater. Morgenstern et al. (2015) states that there is no further decrease in dissolved oxygen levels once groundwater has passed through the soil zone in the Lake Rotorua Catchment, hence there is an absence of bioavailable electron donors that could facilitate microbial denitrification. This means that any nitrate that leaches beyond the soil zone from agricultural land use can be expected to travel with groundwater to the lake. Furthermore, the lag time between land use intensification and effects on the surface water quality is likely to be several decades (Morgenstern et al., 2005), implying that current loads are at least partly caused by historical land use. This also means that for many catchments, the current expressed load is a mixture of enriched and pristine groundwater, which means that groundwater loads are expected to increase as pristine water works its way out of the system and is replaced by water enriched from historic agricultural intensification.

Our results show that TP load is dominated by the Hamurana Catchment, with around 25% contribution throughout the study period. DRP is also dominated by the Hamurana Catchment, with a slightly greater relative load contribution than TP. This result is consistent with previous studies that have found the Hamurana Catchment to be the major contributor of phosphorus to Lake Rotorua (e.g. Scholes, 2013). This is not due to excessive concentrations, as those in the Awahou and Waingaehe catchments are similar. However, neither the Awahou nor Waingaehe streams have the flow magnitude of the Hamurana Stream.

The source of TP in the Hamurana Stream is driven by DRP, which has been shown to increase relative to the mean groundwater residence time (Morgenstern et al., 2005). Given that the Hamurana has the second greatest mean residence time of all Lake Rotorua catchments (Morgenstern et al., 2015), it is understandable why DRP concentrations are elevated.

Other major phosphorus load contributors are the: Awahou, Utuhina, and Puarenga catchments, all of which have major groundwater sources, and in the case of the Utuhina and Puarenga, have been dosed with aluminium sulfate to bind reactive phosphorus fractions. Both of these catchments show a pattern of decreased DRP contribution to TP over time, which in the case of the Utuhina can be attributed to success of the alum dosing programme. For the Puarenga, the dosing site is downstream of the water quality monitoring site and shouldn’t affect the results, therefore, it can be concluded that particulate forms of phosphorus are becoming more prevalent in this catchment, possibly due to erosion events or increased overland flow.

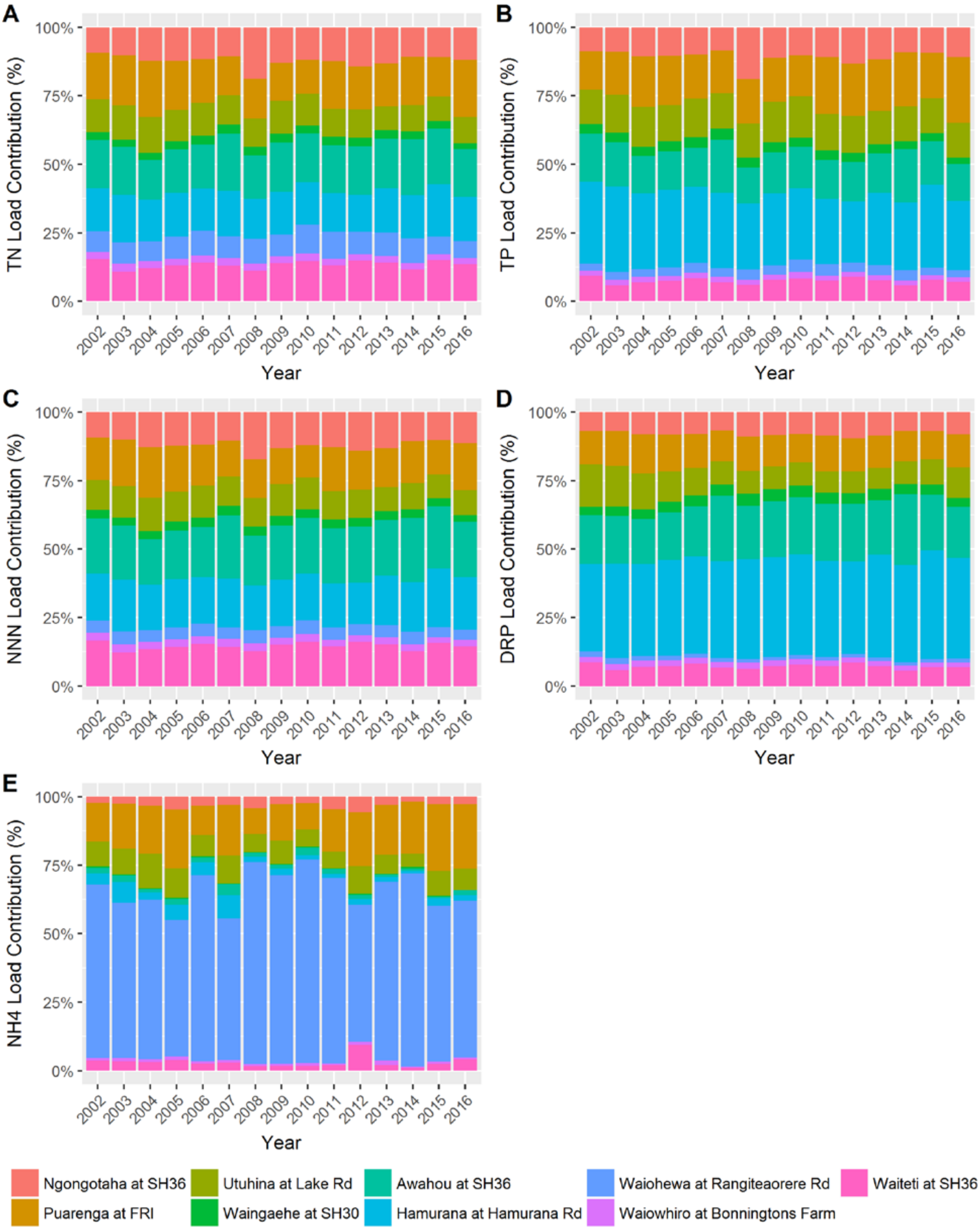


Figure 64 *Relative load contribution per analyte for each of the main Rotorua inflows. TN, NNN, TP, and DRP are calculated using the LOADEST model. NH4-N is calculated using Numeric Integration.*

Summary discussion

Nutrient concentrations and trends

Overview

Trends across all sites are summarised in Table 13 below. Of all analytes, NH4-N shows the greatest long term improvement, with 44.4% of sites showing improving trends over the 15 year study period. However, trend results over the two post-July 2009 datasets show NH4-N has deteriorated at more sites than it has improved, implying that a significant change may have occurred during this period. NNN, on the other hand, shows the opposite, where long term concentrations increased at 55.6% of sites, but more sites improved than deteriorated over the two most recent datasets (44.4% improving versus 11.1% deteriorating post July 2009; 22.2% improving versus 0.0% deteriorating between 2012 and 2016). More sites also expressed deteriorating trends for TN and DRP over the 15 year study period, than improving trends. This pattern was also found in the post-change dataset for DRP (0.0% improving versus 77.8% deteriorating), and over the last five years of the study for TN (22.2% improving versus 44.4% deteriorating) and DRP (0.0% improving versus 22.2% deteriorating). TP shows the greatest deterioration of all analytes, with 66.7% of sites deteriorating between 2002 and 2016. This pattern is primarily driven by changes occurring after July 2009 (88.9% of sites deteriorated), and in the last five years of the dataset (66.7% deterioration), as opposed to pre July 2008 (11.1% deterioration).

Table 13 A summary of significant trends found in the current study. Red cells represent increasing (deteriorating) trends, while green cells represent improving trends.

Analyte	2002-2016		2002-July 2008		July 2009-2016		2012-2016	
	↗	↘	↗	↘	↗	↘	↗	↘
TN	33.3%	11.1%	11.1%	22.2%	22.2%	22.2%	44.4%	22.2%
NNN	55.6%	11.1%	0.0%	22.2%	11.1%	44.4%	0.0%	22.2%
NH4-N	11.1%	44.4%	0.0%	22.2%	44.4%	0.0%	55.6%	0.0%
TP	66.7%	11.1%	11.1%	11.1%	88.9%	0.0%	66.7%	0.0%
DRP	33.3%	22.2%	0.0%	22.2%	77.8%	0.0%	22.2%	0.0%

Nitrogen

Trend analysis shows that adjusted TN concentrations increased between 2002 and 2017 at three sites: Awahou at SH 36, Hamurana at Hamurana Road, and Waitetī at SH 36. Significant increasing trends were also found for NNN at each of these sites, while load ratios show that the contribution of NNN to TN is close to 90%. This evidence demonstrates that increasing TN is driven predominantly by increasing NNN in these catchments. Rutherford et al. (2011) present land use maps for the Lake Rotorua Catchment, which illustrate the increasing prevalence of dairy in the Awahou and Waitetī catchments over time. This type of land use is renowned for high losses of inorganic nitrogen, therefore, it is understandable why concentrations of NNN have increased in the Waitetī and Awahou Streams over time. Dairy has also increased in the Hamurana Catchment over time although the spatial extent is less in comparison, predominantly due to the size of the catchment. Regardless, 60% of the catchment land use falls into the category of pasture and arable land, which implies that land use intensification for may also be a factor behind increasing NNN in this catchment.

While these trends were significant, it's worth noting that the maximum percentage increase for TN at these sites equated to only 1.0% per annum (Waitetī at SH 36), which is just the threshold that has been used in previous studies to determine trend 'meaningfulness' for environmental management purposes (e.g. Ballantine & Davies-Colley, 2010; Scarsbrook, 2006). This suggests that the magnitude of change is relatively low, and the 'meaningfulness' of such trends is up to the reader to decide.

One improving TN trend was identified across the entire 15 year dataset, located at the Puarenga at FRI water quality site. Similar to the Awahou, Hamurana, and Waitetī catchments, the high NNN to TN contribution (above 75%), shows that the declining TN trend is driven by reducing NNN concentrations. Much of the improvement in this catchment can be linked to the modification of the Puarenga Wastewater Treatment Plant's discharge regime that took place in 2002.

Deteriorating TN trends were identified at four sites, either between July 2009-2016 or in the last five years of the dataset; these were: Puarenga at FRI, Utuhina at Lake Road, Waiohwea at Rangiteaorere Road, and Waitetī at SH 36. Of these, the Utuhina and Waitetī sites revealed significant increasing trends for both of these datasets, with a greater magnitude of change for 2012-2016, implying that TN concentrations accelerated after 2012. Furthermore, none of the four sites express increasing NNN trends over the last five years of the dataset, yet all show deteriorating NH4-N, at rates above 7% per annum. This is discussed further below.

NH4-N makes up around 75% of TN in the Waiohewa Catchment, with the majority coming from geothermal sources (Williamson & Cooke, 1982). Therefore, it is logical to conclude that the increasing TN trend in this catchment is driven by fluctuation in geothermal loading. Plans to mitigate this source are in place, with a zeolite treatment system planned for construction by 2019. The Puarenga Stream has the next highest NH4-N to TN ratio, increasing from 6% in 2009 to 11% in 2016. NNN concentrations decreased in this stream over all datasets except the most recent five years; while, NH4-N concentrations were shown to have increased over the entire 15 year dataset, driven by predominantly by large increases post July 2009 (3.88% p.a.), and between 2012 and 2016 (13.36% p.a.). Given the overall contribution to TN, it seems likely that the exceptionally steep NH4-N trend for the last five years of the dataset has impacted the TN trend for this period. However, the source of this is debatable. Modelled flow-concentration evidence for the Puarenga Stream shows that elevated concentrations of NH4-N occur at elevated flows, which points to a rainfall-responsive pathway, rather than an unidentified point or geothermal source. This, however, leaves multiple possibilities, ranging from urban inputs in the lower catchment, to diffuse effluent sources in the upper catchment, highlighting the need for further investigation.

Patterns within the Utuhina and Waitetī catchments are less clear. NH4-N makes up around 6% of TN in the Utuhina Catchment, so it's possible that the increasing NH4-N trend has affected the TN trend. However, this value is less than 2% of TN in the Waitetī Catchment, making this outcome less likely. This suggests that although increasing NH4-N concentrations contribute to the increasing TN trend in these streams, it is unlikely to be the primary driver, and other N contributors (e.g. particulate organic nitrogen) must be present. NH4-N also increased in the Awahou Catchment between 2012 and 2016 (12.23% p.a.), although the contribution to TN at this site is less than 1%, so this result made no significant difference to the trajectory of TN concentrations.

Improving TN trends were identified at three sites in either the post-change or 2012-2016 dataset, these were: Awahou at SH 36, Hamuarana at Hamurana Road, and Waingaehe at SH 30. Reductions in the Awahou and Hamuarana catchments were closely linked with improving NNN trends, which shows that although TN and NNN has increased at these sites over the entire dataset, significant improvements have been made resulting in lower NNN concentrations, particularly after 2012. Given the long groundwater residence time, and the expected increase in NNN concentrations due to agricultural legacy (Morgenstern et al., 2005), this finding must be attributed to reduced contribution through direct pathways such as shallow aquifers, soil water flushing, or overland flow.

Phosphorus

Significant deteriorating trends for TP were found at six sites over the long term dataset, namely: Awahou at SH 36, Ngongotahā at SH 36, Puarenga at FRI, Utuhina at Lake Road, Waiohewa at Rangiteaorere Road, and Waitetī at SH 36. Of these, the Utuhina, Waiohewa, and Waitetī catchments all had rates of change greater than 1% per annum. When split into pre-change and post-change datasets, only one site was found to be deteriorating between 2002 and July 2008 (Puarenga at FRI), yet this number increased to eight sites between July 2009 and 2016, with Waingaehe at SH 30 being the only site not deteriorating over this period. Moreover, six sites were also found to be deteriorating in the last five years of the dataset.

The relationship between deteriorating TP trends and increasing DRP concentrations is obvious at some sites, but other sites show a more mixed signature where the dominance of DRP and particulate P has changed over time. The Awahou and Hamurana catchments are in the former group, where DRP composes more than 80% of TP, and TP trends roughly follow DRP trends for the same period. Both of these catchments also exhibit changes between the pre-change and post-change periods, where TP concentrations have increased at a greater rate than DRP in the post-change period, which suggests that the contribution of particulate phosphorus is increasing. However, the contribution of particulate P is comparatively minor (less than 20% of TP), suggesting that TP concentrations are still firmly controlled by DRP. The connection between DRP and TP in these catchments is most likely due to contribution from old groundwater, as detailed previous reports (Morgenstern et al., 2015 a, 2015 b, 2005), or through indirect losses from land use via groundwater pathways.

A number of other catchments show mixed phosphorus contribution patterns, where the DRP: TP ratio was high at the beginning of the dataset but reduced with time, causing TP and DRP trend directions to become more independent of each other. Sites that express this pattern include: Ngongotahā at SH 36, Puarenga at FRI, Waiohewa at Rangiteaorere Road, Waiowhiro at Bonningtons Farm, and Waitetī at SH 36. In contrast to the Awahou and Hamurana, recent increases in TP within these catchments are caused by elevated concentrations of non-reactive forms of phosphorus (i.e. particulate phosphorus). These forms may be supplied as overland flow pathways are activated, mobilising terrestrial stores of organic matter and effluent which can adsorb to sediment, as alluded to in Abell's (2013) study of the Puarenga and Ngongotahā Stream. Furthermore, extreme rainfall events can cause localised erosion and mobilise stores of phosphorus rich, volcanic soil. Such erosion events have been reported by members of the public, with evidence of slips and surface erosion in the upper Utuhina and Waitetī catchments, and river mouth delta formation caused by mobilised sediment lower down in the Utuhina and Waitetī Streams (P. Scholes, per comm). However, the rainfall section of this report showed that total annual rainfall, and the frequency of events greater than 30 mm or 50 mm, are broadly comparable between the pre and post-change periods. In addition, the period from 2013-2015 was drier than normal. Both of these findings conflict with the idea of an increasing supply of particulate P mobilised by either an increasing volume of rainfall per year, or an increasing frequency of high intensity rainfall events, suggesting that other factors must be contributing.

The exception to the two groups above is the Utuhina Stream, which has been subject to an alum dosing programme to reduce ambient DRP concentrations. Trend results show that DRP decreased significantly between 2002 and July 2009, but has since increased over the post-change dataset. As mentioned in the site discussion, this is likely to be the result of the changing objectives for the alum dosing programme, moving from an arbitrary experimental approach to more structured loading to manage a chlorophyll a levels in Lake Rotorua. TP concentrations remained constant during the pre-change dataset, but increased after July 2009, implying that, similar to other catchments, particulate phosphorus contribution is the major source driving increasing TP concentrations in recent years.

Impact of the lab methodology change

The change in lab methods used to analyse TN, TP, and DRP, resulted in lower TN and DRP, and greater TP concentrations after July 2009, relative to pre-July 2008 (Scholes & Hamill, 2016). These step changes were addressed by adjusting post-change data according to pre-established relationships defined in the methods section, and running long-term trend analysis on both adjusted and unadjusted datasets.

The fit of the adjusted data (refer to Appendix 3) was visually accurate for both TN and DRP, and acted to mitigate the significant step change. However, unadjusted TP did not shows the same step change, and adjustment seemed to exacerbate what already appeared to be a reasonable time series for each site. This may suggest that the TP relationship defined from pressure free lakes is less applicable to the river systems in this study.

When compared with unadjusted data, adjustment resulted in a change in trend direction on three occasions, and a shift from either direction to a neutral trend on 11 occasions. The greatest impacted analyte was DRP with eight overall changes, followed by TN and TP with three changes each (see Appendix 3 for a full table of changes). Bearing this in mind, caution should be applied when determining true environmental change for long-term TN, TP, or DRP, particularly at sites where the trend changed direction (i.e. increasing to decreasing or vice versa).

For the section above, it was assumed that adjusted data was more accurate than unadjusted data so discussion was based on the following analytes: TN (adjusted), NNN (unadusted), NH4-N (unadjusted), TP (adjusted), and DRP (adjusted). However, TP (adjusted) could arguably be replaced with TP (unadjusted) which would result in: deteriorating TP trends at Hamuarana at Hamurana Road, Waingaehe at SH 30, and Waiowhiro at Bonningtons Farm; and removal of the only improving TP trend, which was identified at Hamurana at Hamurana Road. This would change the first section of Table 13 into Table 14, and add further weight to the argument of increasing particulate phosphorus in the Lake Rotorua Catchment.

Table 14 Long-term trend summary based on unadjusted TP.

Analyte	2002-2016	
	⇗	⇘
TN	33.3%	11.1%
NNN	55.6%	11.1%
NH4-N	11.1%	44.4%
TP	100.0%	0%
DRP	33.3%	22.2%

The EGRET package

This is the first BOPRC report to use the EGRET package to try increase the amount of information that can be extracted from long term Council datasets. Overall, the method proved useful and alluded to flow-specific trends that otherwise would have been overlooked. It also provided information on whether nutrient concentration peaks were highest during high flows, typical of diffuse agricultural pollution, or low flows, consistent with groundwater or point source contribution. In addition, the contour plots allow the reader to determine the time of year when concentration peaks have been observed, and if this has changed throughout time.

One caveat with the WRTDS model is that it is suited to large hydrologically stable streams, that experience gradual changes over a long period (Hirsch & De Cicco, 2015). Many inflows around Lake Rotorua (e.g. the Puarenga, Utuhina, and Ngongotahā) are prone to short term flow increases which prevent the WRTDS model from operating to its full potential. In addition, alum dosing on the Utuhina Stream resulted in dramatic, short-term decreases in DRP, followed by a period of recovery. This rapid change resulted in modelled predictions of increasing TP concentrations at low flow, which is true for the ‘recovery’ period, but is unlikely to be the main source of TP, as additional results show that non-DRP forms of phosphorus (i.e. particulate phosphorus) have increased to well over 50% of the annual mean TP load. This is more indicative of a catchment derived diffuse source than a groundwater source. Another, albeit minor, problem with the EGRET package is that it is easy to manipulate the concentration scale to make relative differences seem more or less impressive. This may have been the case in the current study, where contour plots were optimised to display the relative trend at a site, and in future, it may be wiser to fix these scales across all sites.

Perhaps the most noteworthy problem has to do with the lack of targeted event flow sampling for each of the nine major inflows. As Abell (2013) showed in his work on the Puarenga and Ngongotahā catchments, significant loads can be delivered in a very short space of time, emphasising the importance of high flow events to the overall nutrient pool in Lake Rotorua. The lack of this type of information means that the load estimates presented in this study are undoubtedly less than the real loads from each of the sampled inflows. Empirical models, such as WRTDS, can only provide accurate interpolation for the parts of the hydrograph that have data, although they will still output estimates for data poor flow brackets. Therefore, to improve the quality of load estimates, regardless of the estimation method employed, it is recommended that high flow and event based sampling is added to the Council’s monitoring priorities.

Recommendations

Improvement of scientific data

1 Increase high flow sampling events to provide more robust load estimates and inform concentration-discharge analyses (such as WRTDS).

It is recommended that high flow event sampling is prioritised to provide a better understanding of the load asymmetry from each of inflows, and to decrease the uncertainty around load estimation. This would also enable tools such as the WRTDS model to be used more effectively as predictions at higher flow brackets would be more accurate. Capturing this information can be difficult if done manually, although automatic water samplers can be purchased for a reasonable cost (around $15 k) and triggered remotely.

2 Improve continuous flow measurements.

Our results revealed changes in the magnitude of corresponding flow values at certain sites for samples taken after 2010. It is not known if these reflect true hydrological changes in the catchment or if the sampling regime has become biased towards lower flows. A simple solution would be to employ surface water level loggers, and to gauge the site when samples are taken to create a 'temporary' continuous flow record. Continuous flow records for each of the inflows would also allow more robust load models and analytical techniques to be employed.

Additional investigations

3 Investigate the increasing trend of high-flow source of NH4-N the Puarenga Catchment.

The Puarenga Catchment had the second highest mean NH4-N concentrations of all main inflow sites, and a significant increasing trend, particularly over the short term dataset. Subsequently, the NH4-N load contribution from this stream has increased over the past three years. It is recommended that a catchment investigation is initiated to determine and minimise the source.

4 Identify hydrochemical signatures to clarify contaminant sources and pathways.

Finally, EGRET analysis alluded to emergence of different pathways over time. Based on current evidence, it is easy to state if elevated concentrations are likely to come from a diffuse catchment (i.e. high flow concentration peaks) or baseflow source. However, there is not enough information to determine the specific pathway (e.g. overland flow versus. flushed shallow aquifers), and hence apply appropriate mitigations. One method to address this may be to engage in work to identify discrete hydrochemical signatures that occur at different stages of the hydrograph (see Crespo et al., 2015). This could be traced back to a pathway, allowing for more effective land use management.

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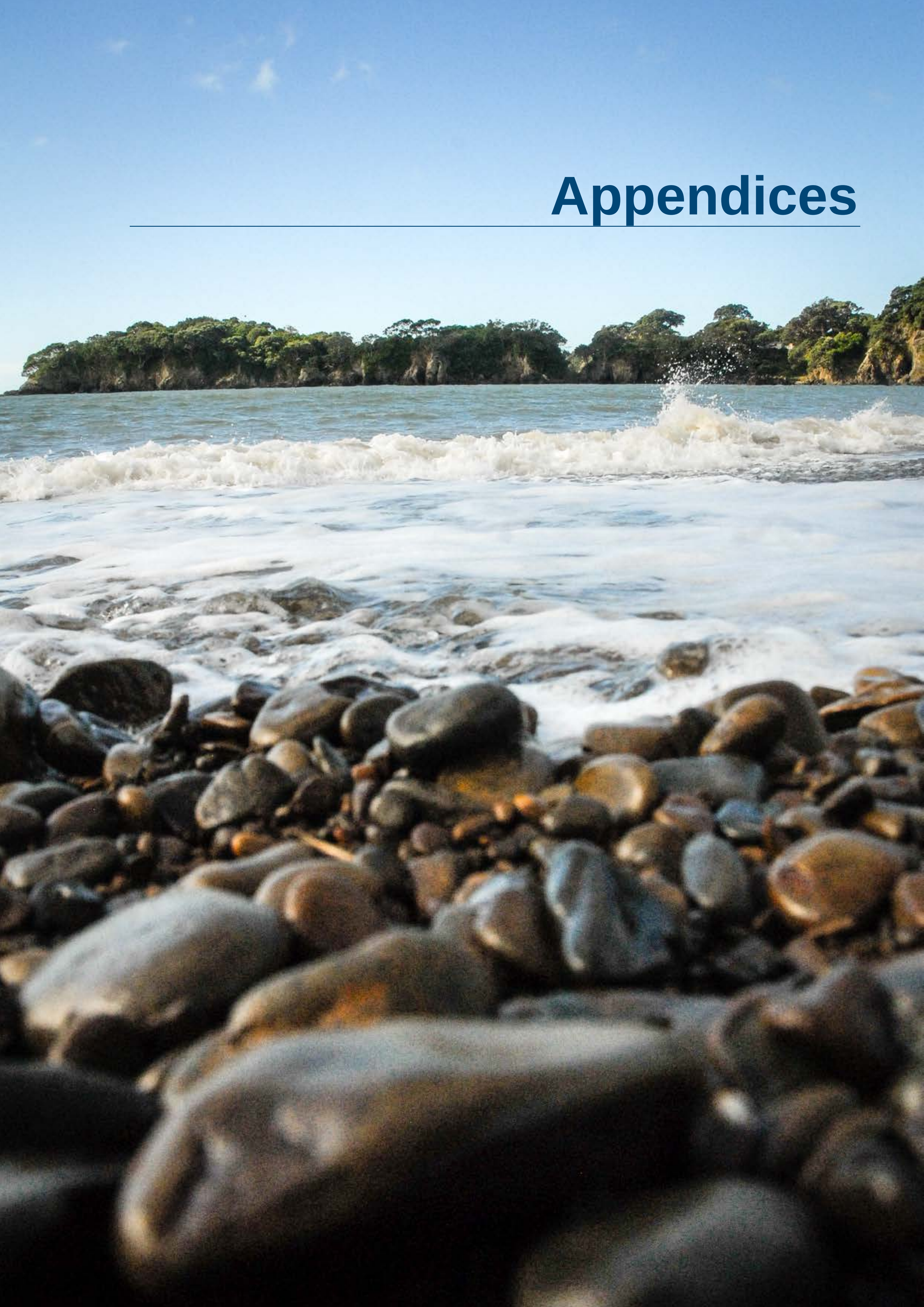
Appendices



Appendix 1:

Trend Analysis Tables

Appendix 1 - Table 1 *Time trends statistics for flow. Note that the table has been split into all data (All), pre lab method change (Pre Change), post lab method change (Post Change), and 2012 to the end of 2016 (2012-2016).*

Period	Site	n	Median	PAC	Z	Sen	Lower	Upper	p	Direction
All	Awahou at SH 36	155	1.63	0.48	2.88	0.00775	0.00340	0.01222	0.004	⬀
All	Hamurana at Hamurana Road	158	2.52	0.53	4.87	0.01348	0.00849	0.01825	0.000	⬀
All	Ngongotahā at SH 36	175	1.48	1.02	2.64	0.01506	0.00517	0.02449	0.008	⬀
All	Puarenga at FRI	175	1.72	0.37	1.37	0.00635	-0.00205	0.01444	0.172	□
All	Utuhina at Lake Road	166	1.58	-0.35	-1.07	-0.00555	-0.01464	0.00363	0.284	□
All	Waingaehe at SH 30	162	0.24	-0.34	-1.21	-0.00081	-0.00197	0.00025	0.228	□
All	Waiohewa at Rangiteaorere Road	150	0.33	-0.13	-0.42	-0.00043	-0.00283	0.00167	0.673	□
All	Waiowhiro at Bonningtons Farm	168	0.29	-0.86	-2.32	-0.00252	-0.00451	-0.00063	0.020	⬂
All	Waiteti at SH 36	161	1.11	0.19	0.55	0.00205	-0.00337	0.00754	0.584	□
Pre Change	Awahou at SH 36	65	1.60	0.92	1.51	0.01476	-0.00131	0.03152	0.132	□
Pre Change	Hamurana at Hamurana Road	62	2.49	-0.30	-0.69	-0.00748	-0.02353	0.00779	0.489	□
Pre Change	Ngongotahā at SH 36	76	1.36	1.70	1.42	0.02316	-0.00388	0.05300	0.155	□
Pre Change	Puarenga at FRI	75	1.67	-1.10	-0.85	-0.01841	-0.04914	0.01446	0.395	□
Pre Change	Utuhina at Lake Road	65	1.56	2.07	1.79	0.03227	0.00236	0.06405	0.073	□
Pre Change	Waingaehe at SH 30	61	0.24	3.21	3.19	0.00763	0.00408	0.01149	0.001	⬀

Pre Change	Waiohewa at Rangiteaorere Road	59	0.33	1.59	1.09	0.00523	-0.00236	0.01583	0.277	□
Pre Change	Waiowhiro at Bonningtons Farm	67	0.30	2.29	1.86	0.00692	0.00070	0.01316	0.063	□
Pre Change	Waiteti at SH 36	59	1.10	4.22	3.08	0.04646	0.02154	0.07490	0.002	⬀
Post Change	Awahou at SH 36	79	1.66	-0.98	-2.33	-0.01634	-0.03100	-0.00424	0.020	⬂
Post Change	Hamurana at Hamurana Road	85	2.57	0.97	2.95	0.02500	0.01078	0.03734	0.003	⬀
Post Change	Ngongotahā at SH 36	89	1.56	-3.78	-3.25	-0.05888	-0.08935	-0.03054	0.001	⬂
Post Change	Puarenga at FRI	89	1.74	-0.08	-0.16	-0.00135	-0.04985	0.03593	0.874	□
Post Change	Utuhina at Lake Road	90	1.66	-4.73	-4.44	-0.07842	-0.10370	-0.05298	0.000	⬂
Post Change	Waingaehe at SH 30	89	0.24	-4.03	-5.88	-0.00977	-0.01256	-0.00704	0.000	⬂
Post Change	Waiohewa at Rangiteaorere Road	80	0.34	-3.95	-3.61	-0.01337	-0.01984	-0.00628	0.000	⬂
Post Change	Waiowhiro at Bonningtons Farm	90	0.29	-3.94	-3.59	-0.01142	-0.01561	-0.00672	0.000	⬂
Post Change	Waiteti at SH 36	90	1.11	-2.09	-2.74	-0.02305	-0.04182	-0.00834	0.006	⬂
2012-2016	Awahou at SH 36	49	1.64	-3.38	-3.03	-0.05545	-0.08201	-0.02566	0.002	⬂
2012-2016	Hamurana at Hamurana Road	56	2.62	0.55	1.18	0.01452	-0.00468	0.04319	0.238	□
2012-2016	Ngongotahā at SH 36	60	1.48	-8.36	-3.42	-0.12390	-0.17752	-0.06814	0.001	⬂
2012-2016	Puarenga at FRI	60	1.73	-3.07	-1.77	-0.05313	-0.14309	-0.00129	0.077	□
2012-2016	Utuhina at Lake Road	60	1.45	-3.70	-1.75	-0.05370	-0.10546	-0.00201	0.079	□
2012-2016	Waingaehe at SH 30	59	0.24	-8.39	-8.19	-0.01981	-0.02272	-0.01716	0.000	⬂
2012-2016	Waiohewa at Rangiteaorere Road	50	0.32	-8.46	-2.88	-0.02683	-0.03912	-0.00442	0.004	⬂
2012-2016	Waiowhiro at Bonningtons Farm	60	0.27	-4.45	-2.46	-0.01215	-0.02048	-0.00342	0.014	⬂
2012-2016	Waiteti at SH 36	60	1.07	-5.28	-2.76	-0.05645	-0.09032	-0.02230	0.006	⬂

Appendix 1 - Table 2   *Time trends statistics for unadjusted values between 2002 and 2016.*

Site	Variable	n	Median	PAC	Z	Sen	Lower	Upper	P	Direction
Awahou at SH 36	TN	151	1.34	0.60	4.21	0.00806	0.00492	0.01103	0.000	⬀
Awahou at SH 36	NNN	151	1.30	1.06	6.89	0.01375	0.01081	0.01673	0.000	⬀
Awahou at SH 36	NH4	153	0.01	-4.76	-4.50	-0.00029	-0.00038	-0.00019	0.000	⬂
Awahou at SH 36	TP	154	0.07	2.03	7.37	0.00142	0.00111	0.00172	0.000	⬀
Awahou at SH 36	DRP	153	0.07	0.06	0.31	0.00004	-0.00016	0.00027	0.754	▫
Hamurana at Hamurana Road	TN	154	0.77	0.15	0.96	0.00117	-0.00058	0.00247	0.336	▫
Hamurana at Hamurana Road	NNN	154	0.73	0.58	4.02	0.00421	0.00260	0.00582	0.000	⬀
Hamurana at Hamurana Road	NH4	157	0.01	-3.60	-3.53	-0.00025	-0.00039	-0.00013	0.000	⬂
Hamurana at Hamurana Road	TP	158	0.09	1.12	5.71	0.00098	0.00071	0.00126	0.000	⬀
Hamurana at Hamurana Road	DRP	157	0.08	-0.49	-2.60	-0.00041	-0.00066	-0.00017	0.009	⬂
Ngongotaha at SH 36	TN	170	0.92	-0.76	-4.22	-0.00701	-0.00934	-0.00444	0.000	⬂
Ngongotaha at SH 36	NNN	168	0.82	0.21	1.74	0.00172	0.00005	0.00331	0.082	▫
Ngongotaha at SH 36	NH4	171	0.01	0.90	1.09	0.00013	-0.00007	0.00031	0.277	▫
Ngongotaha at SH 36	TP	173	0.05	2.19	6.02	0.00116	0.00086	0.00148	0.000	⬀
Ngongotaha at SH 36	DRP	168	0.03	-1.58	-3.69	-0.00047	-0.00067	-0.00027	0.000	⬂
Puarenga at FRI	TN	165	1.12	-2.40	-8.60	-0.02691	-0.03136	-0.02260	0.000	⬂
Puarenga at FRI	NNN	168	0.88	-1.97	-8.10	-0.01739	-0.02101	-0.01407	0.000	⬂
Puarenga at FRI	NH4	172	0.07	2.34	5.03	0.00161	0.00122	0.00217	0.000	⬀
Puarenga at FRI	TP	174	0.08	2.36	6.72	0.00181	0.00138	0.00227	0.000	⬀
Puarenga at FRI	DRP	171	0.04	-2.69	-5.60	-0.00110	-0.00133	-0.00078	0.000	⬂

Utuhina at Lake Road	TN	164	0.78	-1.13	-3.83	-0.00877	-0.01206	-0.00447	0.000	↘
Utuhina at Lake Road	NNN	164	0.65	-0.19	-0.91	-0.00126	-0.00365	0.00109	0.363	□
Utuhina at Lake Road	NH4	163	0.04	-0.05	-0.05	-0.00002	-0.00030	0.00037	0.961	□
Utuhina at Lake Road	TP	166	0.07	2.74	7.30	0.00183	0.00147	0.00218	0.000	↗
Utuhina at Lake Road	DRP	159	0.03	-4.58	-5.08	-0.00156	-0.00194	-0.00115	0.000	↘
Waingaehe at SH 30	TN	160	1.49	-0.14	-0.99	-0.00209	-0.00674	0.00196	0.321	□
Waingaehe at SH 30	NNN	160	1.43	0.37	2.40	0.00522	0.00170	0.00881	0.017	↗
Waingaehe at SH 30	NH4	160	0.01	-3.60	-3.05	-0.00025	-0.00039	-0.00012	0.002	↘
Waingaehe at SH 30	TP	161	0.12	1.39	5.60	0.00162	0.00118	0.00205	0.000	↗
Waingaehe at SH 30	DRP	160	0.10	-0.40	-2.52	-0.00039	-0.00073	-0.00017	0.012	↘
Waiohewa at Rangiteaorere Road	TN	152	2.68	0.18	0.40	0.00480	-0.01103	0.01824	0.687	□
Waiohewa at Rangiteaorere Road	NNN	151	1.33	-0.12	-0.35	-0.00162	-0.00953	0.00642	0.727	□
Waiohewa at Rangiteaorere Road	NH4	144	1.26	1.32	1.57	0.01689	-0.00060	0.03614	0.116	□
Waiohewa at Rangiteaorere Road	TP	152	0.07	3.14	5.90	0.00226	0.00170	0.00283	0.000	↗
Waiohewa at Rangiteaorere Road	DRP	143	0.02	-3.50	-4.09	-0.00077	-0.00104	-0.00049	0.000	↘
Waiowhiro at Bonningtons Farm	TN	164	1.00	-0.26	-1.61	-0.00262	-0.00575	0.00013	0.108	□
Waiowhiro at Bonningtons Farm	NNN	165	0.92	0.32	2.11	0.00297	0.00048	0.00535	0.035	↗
Waiowhiro at Bonningtons Farm	NH4	166	0.02	-0.40	-0.72	-0.00007	-0.00033	0.00018	0.473	□
Waiowhiro at Bonningtons Farm	TP	166	0.05	2.07	7.05	0.00104	0.00082	0.00130	0.000	↗
Waiowhiro at Bonningtons Farm	DRP	166	0.04	-2.15	-5.51	-0.00083	-0.00106	-0.00059	0.000	↘
Waiteti at SH 36	TN	159	1.46	0.74	5.22	0.01083	0.00728	0.01400	0.000	↗
Waiteti at SH 36	NNN	158	1.37	1.13	6.78	0.01544	0.01226	0.01858	0.000	↗

Waiteti at SH 36	NH4	159	0.02	-2.39	-2.55	-0.00038	-0.00057	-0.00013	0.011	⬂
Waiteti at SH 36	TP	160	0.05	2.84	7.53	0.00139	0.00112	0.00169	0.000	⬀
Waiteti at SH 36	DRP	159	0.03	-0.92	-2.44	-0.00032	-0.00052	-0.00011	0.015	⬂

Appendix 1 - Table 3 *Time trends statistics for adjusted TN, TP, and DRP values between 2002 and 2016.*

Site	Variable	n	Median	PAC	Z	Sen	Lower	Upper	P	Direction
Awahou at SH 36	TN	151	1.37	0.89	5.91	0.01225	0.00918	0.01536	0.000	↗
Awahou at SH 36	TP	154	0.07	0.42	2.00	0.00028	0.00005	0.00049	0.045	↗
Awahou at SH 36	DRP	153	0.07	1.00	5.63	0.00074	0.00054	0.00096	0.000	↗
Hamurana at Hamurana Road	TN	154	0.80	0.58	4.15	0.00470	0.00295	0.00644	0.000	↗
Hamurana at Hamurana Road	TP	158	0.08	-0.49	-2.48	-0.00039	-0.00064	-0.00013	0.013	↘
Hamurana at Hamurana Road	DRP	157	0.09	0.05	0.58	0.00005	-0.00016	0.00030	0.561	□
Ngongotaha at SH 36	TN	170	0.95	-0.27	-1.59	-0.00258	-0.00519	0.00024	0.112	□
Ngongotaha at SH 36	TP	173	0.05	0.73	2.12	0.00035	0.00008	0.00064	0.034	↗
Ngongotaha at SH 36	DRP	170	0.04	0.89	2.99	0.00033	0.00015	0.00052	0.003	↗
Puarenga at FRI	TN	165	1.15	-1.91	-7.27	-0.02188	-0.02686	-0.01808	0.000	↘
Puarenga at FRI	TP	174	0.07	0.73	2.09	0.00051	0.00012	0.00093	0.037	↗
Puarenga at FRI	DRP	172	0.05	-0.48	-1.64	-0.00022	-0.00045	0.00000	0.100	□
Utuhina at Lake Road	TN	164	0.80	-0.41	-1.72	-0.00326	-0.00724	-0.00013	0.085	□
Utuhina at Lake Road	TP	166	0.06	1.08	3.21	0.00066	0.00034	0.00096	0.001	↗
Utuhina at Lake Road	DRP	165	0.04	-1.74	-2.99	-0.00073	-0.00108	-0.00035	0.003	↘
Waingaehe at SH 30	TN	160	1.53	0.19	1.14	0.00294	-0.00143	0.00715	0.253	□
Waingaehe at SH 30	TP	161	0.11	-0.36	-1.63	-0.00039	-0.00085	0.00000	0.103	□
Waingaehe at SH 30	DRP	160	0.10	0.18	1.21	0.00019	-0.00009	0.00037	0.226	□
Waiohewa at Rangiteaorere Road	TN	152	2.72	0.32	0.70	0.00874	-0.00789	0.02210	0.482	□
Waiohewa at Rangiteaorere Road	TP	152	0.06	1.38	2.85	0.00089	0.00039	0.00144	0.004	↗

Waiohewa at Rangiteaorere Road	DRP	148	0.03	0.63	1.25	0.00019	-0.00005	0.00046	0.210	□
Waiowhiro at Bonningtons Farm	TN	164	1.02	0.17	1.09	0.00173	-0.00119	0.00429	0.277	□
Waiowhiro at Bonningtons Farm	TP	166	0.05	0.41	1.55	0.00019	-0.00002	0.00041	0.121	□
Waiowhiro at Bonningtons Farm	DRP	166	0.04	0.00	0.00	0.00000	-0.00018	0.00025	1.000	□
Waiteti at SH 36	TN	159	1.49	1.00	6.92	0.01491	0.01154	0.01803	0.000	⬀
Waiteti at SH 36	TP	160	0.05	1.02	3.21	0.00047	0.00023	0.00072	0.001	⬀
Waiteti at SH 36	DRP	160	0.04	1.18	4.48	0.00049	0.00032	0.00067	0.000	⬀

Appendix 1 - Table 4 Time trends statistics for unadjusted values prior to the lab method change (2002 to July 2008).

Site	Variable	n	Median	PAC	Z	Sen	Lower	Upper	P	Direction
Awahou at SH 36	TN	63	1.28	0.25	0.49	0.00323	-0.00876	0.01714	0.627	□
Awahou at SH 36	NNN	63	1.19	0.40	0.69	0.00480	-0.00609	0.01461	0.491	□
Awahou at SH 36	NH4	65	0.01	9.11	1.56	0.00064	-0.00004	0.00119	0.120	□
Awahou at SH 36	TP	65	0.07	-0.76	-1.89	-0.00051	-0.00101	-0.00007	0.059	□
Awahou at SH 36	DRP	65	0.07	-0.63	-1.06	-0.00045	-0.00118	0.00028	0.290	□
Hamurana at Hamurana Road	TN	58	0.76	0.04	0.08	0.00028	-0.00757	0.00884	0.936	□
Hamurana at Hamurana Road	NNN	58	0.70	-0.30	-0.63	-0.00207	-0.00770	0.00328	0.528	□
Hamurana at Hamurana Road	NH4	62	0.01	-1.61	-0.69	-0.00015	-0.00063	0.00038	0.488	□
Hamurana at Hamurana Road	TP	62	0.08	-1.47	-3.00	-0.00122	-0.00183	-0.00057	0.003	⇘
Hamurana at Hamurana Road	DRP	62	0.09	-1.86	-2.49	-0.00166	-0.00267	-0.00064	0.013	⇘
Ngongotaha at SH 36	TN	71	0.95	-0.86	-1.10	-0.00820	-0.01904	0.00337	0.270	□
Ngongotaha at SH 36	NNN	71	0.78	0.33	0.44	0.00254	-0.00509	0.00846	0.663	□
Ngongotaha at SH 36	NH4	74	0.01	-0.09	-0.02	-0.00001	-0.00054	0.00057	0.985	□
Ngongotaha at SH 36	TP	74	0.05	-0.08	-0.07	-0.00004	-0.00096	0.00088	0.944	□
Ngongotaha at SH 36	DRP	73	0.04	-1.79	-1.51	-0.00066	-0.00153	0.00006	0.130	□
Puarenga at FRI	TN	65	1.26	-2.82	-3.35	-0.03562	-0.04993	-0.02053	0.001	⇘
Puarenga at FRI	NNN	68	0.97	-2.41	-3.09	-0.02323	-0.03437	-0.01473	0.002	⇘
Puarenga at FRI	NH4	73	0.06	-1.28	-0.47	-0.00082	-0.00244	0.00105	0.637	□
Puarenga at FRI	TP	74	0.07	3.12	3.24	0.00215	0.00110	0.00332	0.001	⇗
Puarenga at FRI	DRP	73	0.05	-0.48	-0.47	-0.00024	-0.00123	0.00106	0.637	□

Utuhina at Lake Road	TN	64	0.83	-1.67	-1.67	-0.01396	-0.03038	-0.00041	0.096	□
Utuhina at Lake Road	NNN	64	0.66	-1.14	-1.17	-0.00755	-0.01537	0.00126	0.241	□
Utuhina at Lake Road	NH4	64	0.04	-6.60	-3.38	-0.00254	-0.00407	-0.00141	0.001	⬂
Utuhina at Lake Road	TP	65	0.06	0.50	0.62	0.00030	-0.00065	0.00134	0.537	□
Utuhina at Lake Road	DRP	65	0.05	-4.36	-3.54	-0.00226	-0.00376	-0.00120	0.000	⬂
Waingaehe at SH 30	TN	59	1.49	1.63	1.99	0.02426	0.00506	0.04670	0.047	⬀
Waingaehe at SH 30	NNN	59	1.37	0.91	1.24	0.01243	-0.00295	0.02441	0.214	□
Waingaehe at SH 30	NH4	60	0.01	-5.82	-1.46	-0.00052	-0.00117	0.00009	0.144	□
Waingaehe at SH 30	TP	61	0.11	1.05	1.85	0.00116	0.00011	0.00223	0.065	□
Waingaehe at SH 30	DRP	60	0.10	-0.11	-0.22	-0.00012	-0.00156	0.00111	0.823	□
Waiohewa at Rangiteaorere Road	TN	59	2.56	0.21	0.16	0.00528	-0.05936	0.06300	0.875	□
Waiohewa at Rangiteaorere Road	NNN	58	1.34	0.40	0.44	0.00532	-0.02385	0.03879	0.658	□
Waiohewa at Rangiteaorere Road	NH4	53	1.01	-7.71	-2.20	-0.07824	-0.14727	-0.02473	0.028	⬂
Waiohewa at Rangiteaorere Road	TP	59	0.06	2.63	1.36	0.00163	-0.00028	0.00380	0.174	□
Waiohewa at Rangiteaorere Road	DRP	57	0.03	-2.47	-1.04	-0.00074	-0.00188	0.00042	0.299	□
Waiowhiro at Bonningtons Farm	TN	65	1.01	-1.68	-2.17	-0.01693	-0.03210	-0.00364	0.030	⬂
Waiowhiro at Bonningtons Farm	NNN	65	0.89	-1.54	-2.29	-0.01368	-0.02519	-0.00399	0.022	⬂
Waiowhiro at Bonningtons Farm	NH4	67	0.02	-5.14	-1.22	-0.00092	-0.00203	0.00023	0.221	□
Waiowhiro at Bonningtons Farm	TP	66	0.05	0.97	0.78	0.00044	-0.00065	0.00099	0.436	□
Waiowhiro at Bonningtons Farm	DRP	67	0.04	-2.06	-1.46	-0.00092	-0.00197	0.00005	0.145	□
Waiteti at SH 36	TN	58	1.39	-0.97	-1.15	-0.01344	-0.03193	0.00521	0.249	□
Waiteti at SH 36	NNN	58	1.27	0.46	0.74	0.00585	-0.00657	0.01649	0.461	□

Waiteti at SH 36	NH4	59	0.02	-6.46	-1.83	-0.00123	-0.00243	-0.00015	0.067	□
Waiteti at SH 36	TP	59	0.05	1.67	1.35	0.00075	-0.00021	0.00161	0.178	□
Waiteti at SH 36	DRP	59	0.04	0.38	0.22	0.00016	-0.00076	0.00103	0.829	□

Appendix 1 - Table 5 *Time trends statistics for unadjusted values post the lab method change (July 2009 to end of 2016).*

Site	Variable	n	Median	PAC	Z	Sen	Lower	Upper	P	Direction
Awahou at SH 36	TN	78	1.38	0.28	1.03	0.00386	-0.00220	0.01001	0.304	▫
Awahou at SH 36	NNN	78	1.36	0.46	1.72	0.00622	0.00019	0.01232	0.086	▫
Awahou at SH 36	NH4	78	0.00	-3.81	-1.23	-0.00015	-0.00030	0.00004	0.220	▫
Awahou at SH 36	TP	78	0.08	3.36	5.24	0.00272	0.00202	0.00338	0.000	⬀
Awahou at SH 36	DRP	78	0.07	2.11	5.88	0.00144	0.00104	0.00181	0.000	⬀
Hamurana at Hamurana Road	TN	85	0.77	-0.12	-0.45	-0.00094	-0.00420	0.00257	0.652	▫
Hamurana at Hamurana Road	NNN	85	0.76	-0.55	-1.98	-0.00415	-0.00810	-0.00073	0.048	⬂
Hamurana at Hamurana Road	NH4	85	0.01	1.43	0.86	0.00009	0.00000	0.00025	0.391	▫
Hamurana at Hamurana Road	TP	85	0.09	2.13	4.34	0.00200	0.00130	0.00272	0.000	⬀
Hamurana at Hamurana Road	DRP	85	0.08	0.78	2.81	0.00063	0.00015	0.00099	0.005	⬀
Ngongotaha at SH 36	TN	89	0.90	-0.55	-1.98	-0.00498	-0.01240	-0.00080	0.048	⬂
Ngongotaha at SH 36	NNN	87	0.83	-0.65	-2.41	-0.00537	-0.01070	-0.00210	0.016	⬂
Ngongotaha at SH 36	NH4	88	0.02	1.94	1.44	0.00030	-0.00010	0.00073	0.149	▫
Ngongotaha at SH 36	TP	89	0.06	3.85	4.41	0.00219	0.00145	0.00295	0.000	⬀
Ngongotaha at SH 36	DRP	88	0.03	3.05	3.49	0.00082	0.00046	0.00122	0.000	⬀
Puarenga at FRI	TN	89	1.03	-1.12	-1.58	-0.01151	-0.02720	0.00032	0.113	▫
Puarenga at FRI	NNN	89	0.83	-2.48	-3.65	-0.02045	-0.02560	-0.01532	0.000	⬂
Puarenga at FRI	NH4	89	0.07	6.41	3.88	0.00474	0.00228	0.00713	0.000	⬀
Puarenga at FRI	TP	89	0.08	3.07	3.28	0.00252	0.00131	0.00383	0.001	⬀
Puarenga at FRI	DRP	89	0.03	3.56	4.99	0.00121	0.00086	0.00167	0.000	⬀

Utuhina at Lake Road	TN	90	0.74	0.98	1.99	0.00725	0.00089	0.01131	0.047	⬀
Utuhina at Lake Road	NNN	90	0.65	-0.05	-0.12	-0.00030	-0.00580	0.00691	0.907	□
Utuhina at Lake Road	NH4	89	0.04	4.84	3.17	0.00179	0.00102	0.00264	0.002	⬀
Utuhina at Lake Road	TP	90	0.07	3.60	4.26	0.00268	0.00173	0.00351	0.000	⬀
Utuhina at Lake Road	DRP	90	0.03	4.90	2.84	0.00142	0.00064	0.00213	0.005	⬀
Waingaehe at SH 30	TN	89	1.49	-0.71	-2.26	-0.01060	-0.01820	-0.00307	0.024	⬂
Waingaehe at SH 30	NNN	89	1.45	-0.88	-2.62	-0.01271	-0.02010	-0.00412	0.009	⬂
Waingaehe at SH 30	NH4	88	0.01	-2.83	-1.06	-0.00020	-0.00040	0.00010	0.291	□
Waingaehe at SH 30	TP	88	0.13	0.05	0.06	0.00007	-0.00110	0.00142	0.951	□
Waingaehe at SH 30	DRP	89	0.10	0.39	1.30	0.00037	-0.00010	0.00088	0.195	□
Waiohewa at Rangiteaorere Road	TN	80	2.71	1.25	1.17	0.03452	-0.01000	0.06867	0.240	□
Waiohewa at Rangiteaorere Road	NNN	80	1.35	-0.58	-0.57	-0.00782	-0.02900	0.01480	0.569	□
Waiohewa at Rangiteaorere Road	NH4	79	1.34	4.13	1.99	0.05674	0.01005	0.10472	0.047	⬀
Waiohewa at Rangiteaorere Road	TP	80	0.08	2.37	2.11	0.00194	0.00048	0.00332	0.034	⬀
Waiohewa at Rangiteaorere Road	DRP	80	0.02	7.04	4.41	0.00141	0.00091	0.00194	0.000	⬀
Waiowhiro at Bonningtons Farm	TN	89	0.98	-0.48	-1.39	-0.00472	-0.01030	0.00072	0.164	□
Waiowhiro at Bonningtons Farm	NNN	90	0.94	-0.24	-0.66	-0.00225	-0.00850	0.00284	0.512	□
Waiowhiro at Bonningtons Farm	NH4	89	0.02	-0.63	-0.16	-0.00012	-0.00070	0.00087	0.874	□
Waiowhiro at Bonningtons Farm	TP	89	0.06	2.09	2.79	0.00117	0.00052	0.00184	0.005	⬀
Waiowhiro at Bonningtons Farm	DRP	90	0.04	1.16	1.21	0.00042	-0.00010	0.00098	0.227	□
Waiteti at SH 36	TN	90	1.48	0.95	4.22	0.01410	0.00873	0.02012	0.000	⬀
Waiteti at SH 36	NNN	89	1.43	0.75	2.19	0.01079	0.00274	0.01798	0.029	⬀

Waiteti at SH 36	NH4	89	0.01	3.51	2.06	0.00049	0.00014	0.00086	0.039	⬀
Waiteti at SH 36	TP	89	0.06	3.64	4.19	0.00204	0.00129	0.00280	0.000	⬀
Waiteti at SH 36	DRP	90	0.03	2.72	4.73	0.00090	0.00059	0.00120	0.000	⬀

Appendix 1 - Table 6 *Time trends statistics for unadjusted values between 2012 and 2016.*

Site	Variable	n	Median	PAC	Z	Sen	Lower	Upper	P	Direction
Awahou at SH 36	TN	48	1.38	-0.82	-2.02	-0.01135	-0.02215	-0.00236	0.044	⇘
Awahou at SH 36	NNN	48	1.37	-1.01	-2.82	-0.01377	-0.02424	-0.00532	0.005	⇘
Awahou at SH 36	NH4	48	0.00	12.23	2.11	0.00037	0.00005	0.00070	0.035	⇗
Awahou at SH 36	TP	48	0.09	2.79	2.86	0.00241	0.00107	0.00365	0.004	⇗
Awahou at SH 36	DRP	48	0.07	2.24	3.64	0.00157	0.00080	0.00227	0.000	⇗
Hamurana at Hamurana Road	TN	56	0.78	-0.99	-3.23	-0.00771	-0.01223	-0.00413	0.001	⇘
Hamurana at Hamurana Road	NNN	56	0.76	-1.86	-4.01	-0.01414	-0.01831	-0.00931	0.000	⇘
Hamurana at Hamurana Road	NH4	56	0.01	4.25	1.53	0.00025	-0.00002	0.00054	0.127	□
Hamurana at Hamurana Road	TP	56	0.10	2.95	3.81	0.00289	0.00170	0.00382	0.000	⇗
Hamurana at Hamurana Road	DRP	56	0.08	0.62	1.22	0.00051	-0.00033	0.00109	0.221	□
Ngongotaha at SH 36	TN	60	0.88	0.41	0.68	0.00364	-0.00510	0.01342	0.495	□
Ngongotaha at SH 36	NNN	58	0.82	-0.34	-0.74	-0.00274	-0.01068	0.00393	0.461	□
Ngongotaha at SH 36	NH4	60	0.02	2.47	0.78	0.00037	-0.00040	0.00126	0.437	□
Ngongotaha at SH 36	TP	60	0.06	3.63	2.53	0.00220	0.00081	0.00373	0.011	⇗
Ngongotaha at SH 36	DRP	60	0.03	1.01	0.78	0.00029	-0.00041	0.00100	0.433	□
Puarenga at FRI	TN	60	0.98	3.61	3.89	0.03553	0.02796	0.04638	0.000	⇗
Puarenga at FRI	NNN	60	0.81	1.55	1.34	0.01252	-0.00514	0.02430	0.179	□
Puarenga at FRI	NH4	60	0.08	13.36	5.30	0.01069	0.00775	0.01330	0.000	⇗
Puarenga at FRI	TP	60	0.08	4.91	3.06	0.00415	0.00202	0.00663	0.002	⇗
Puarenga at FRI	DRP	60	0.04	1.37	1.48	0.00051	-0.00014	0.00109	0.138	□

Utuhina at Lake Road	TN	60	0.74	1.62	2.62	0.01190	0.00410	0.02396	0.009	↗
Utuhina at Lake Road	NNN	60	0.64	0.31	0.35	0.00198	-0.00512	0.01756	0.724	□
Utuhina at Lake Road	NH4	60	0.04	7.99	3.25	0.00308	0.00151	0.00456	0.001	↗
Utuhina at Lake Road	TP	60	0.08	4.41	3.58	0.00351	0.00193	0.00521	0.000	↗
Utuhina at Lake Road	DRP	60	0.03	-1.70	-0.78	-0.00054	-0.00162	0.00077	0.433	□
Waingaehe at SH 30	TN	59	1.45	-0.44	-1.08	-0.00644	-0.01790	0.00610	0.279	□
Waingaehe at SH 30	NNN	59	1.41	-0.06	-0.12	-0.00082	-0.01369	0.01147	0.906	□
Waingaehe at SH 30	NH4	58	0.01	0.60	0.16	0.00004	-0.00037	0.00030	0.872	□
Waingaehe at SH 30	TP	58	0.13	-0.09	-0.19	-0.00011	-0.00161	0.00129	0.851	□
Waingaehe at SH 30	DRP	59	0.10	0.30	0.41	0.00029	-0.00079	0.00147	0.685	□
Waiohewa at Rangiteaorere Road	TN	50	2.66	5.98	4.08	0.16518	0.10645	0.21088	0.000	↗
Waiohewa at Rangiteaorere Road	NNN	50	1.36	-0.58	-0.28	-0.00774	-0.04867	0.03691	0.776	□
Waiohewa at Rangiteaorere Road	NH4	50	1.26	11.98	3.20	0.16059	0.07674	0.25691	0.001	↗
Waiohewa at Rangiteaorere Road	TP	50	0.08	2.60	1.57	0.00221	-0.00005	0.00437	0.116	□
Waiohewa at Rangiteaorere Road	DRP	50	0.02	2.06	0.79	0.00045	-0.00043	0.00131	0.432	□
Waiowhiro at Bonningtons Farm	TN	59	0.97	-0.13	-0.20	-0.00129	-0.01186	0.00809	0.844	□
Waiowhiro at Bonningtons Farm	NNN	60	0.92	-0.41	-0.67	-0.00373	-0.01435	0.00404	0.503	□
Waiowhiro at Bonningtons Farm	NH4	59	0.02	3.24	1.08	0.00058	-0.00069	0.00201	0.279	□
Waiowhiro at Bonningtons Farm	TP	59	0.06	1.16	0.97	0.00066	-0.00056	0.00162	0.333	□
Waiowhiro at Bonningtons Farm	DRP	60	0.04	-1.68	-1.77	-0.00064	-0.00165	-0.00001	0.077	□
Waiteti at SH 36	TN	60	1.49	1.23	2.69	0.01826	0.00688	0.02962	0.007	↗
Waiteti at SH 36	NNN	59	1.45	0.22	0.33	0.00325	-0.01209	0.01682	0.744	□

Waiteti at SH 36	NH4	60	0.01	9.83	3.61	0.00138	0.00070	0.00222	0.000	⬀
Waiteti at SH 36	TP	59	0.06	3.66	2.54	0.00209	0.00087	0.00341	0.011	⬀
Waiteti at SH 36	DRP	60	0.03	2.35	2.01	0.00080	0.00017	0.00143	0.045	⬀

Appendix 2:

Land use Calculations

Appendix 2 - Table 1 2017 land use statistics for the Lake Rotorua Catchment.

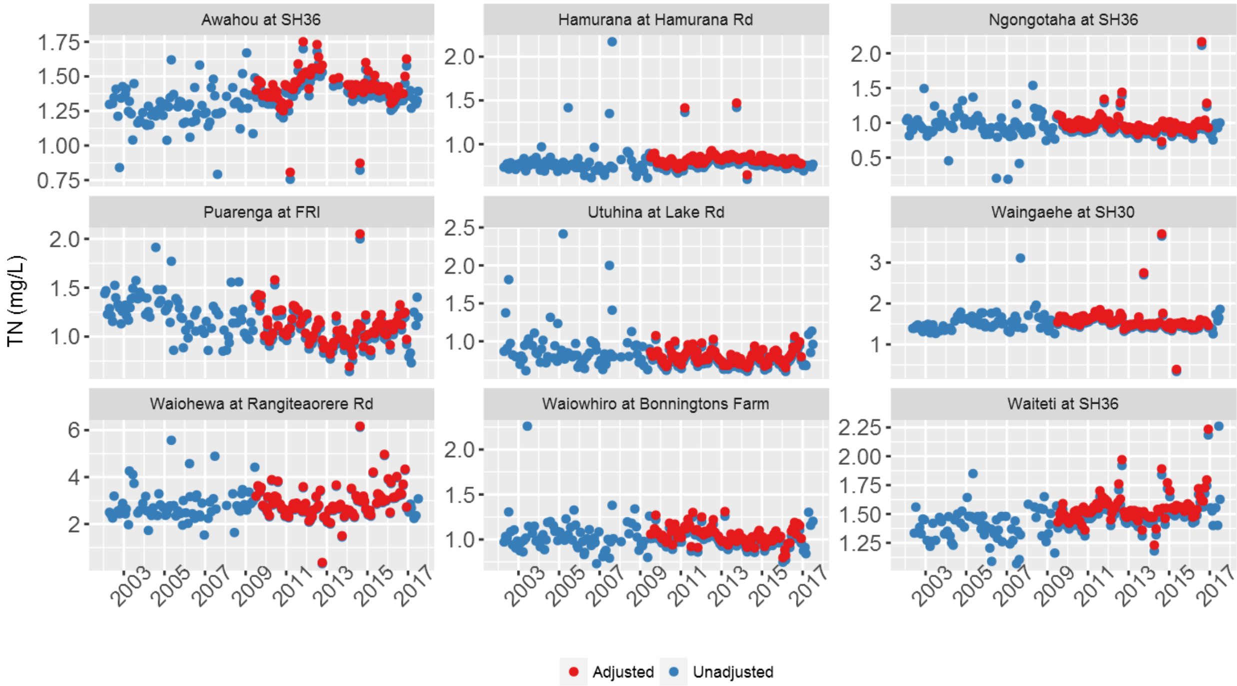
Catchment	Land Use Group	Area (ha)	Area (%)
Awahou	Exotic Forest	348.4	12.3
Awahou	Lifestyle/Mixed Land use	386.4	13.6
Awahou	Native Forest/Scrub	284.8	10.0
Awahou	Other	173.8	6.1
Awahou	Parks and Reserves	3.8	0.1
Awahou	Pasture/Arable	1598.8	56.3
Awahou	Urban/Road/Rail	45.7	1.6
Hamurana	Exotic Forest	71.3	4.7
Hamurana	Lifestyle/ Mixed Land use	285.3	18.7
Hamurana	Native Forest/Scrub	117.4	7.7
Hamurana	Other	15.1	1.0
Hamurana	Parks and Reserves	45.3	3.0
Hamurana	Pasture/Arable	909.8	59.8
Hamurana	Urban/Road/ Rail	78.0	5.1
Ngongotaha	Exotic Forest	1004.3	12.8
Ngongotaha	Horticulture	4.0	0.1
Ngongotaha	Lifestyle/ Mixed Land use	616.7	7.9
Ngongotaha	Native Forest/Scrub	2558.4	32.6
Ngongotaha	Other	17.0	0.2
Ngongotaha	Parks and Reserves	15.8	0.2
Ngongotaha	Pasture/Arable	3400.3	43.4
Ngongotaha	Urban/Road/Rail	224.2	2.9
Puarenga	Exotic Forest	4005.0	49.2
Puarenga	Horticulture	24.8	0.3
Puarenga	Lifestyle/ Mixed Land use	186.0	2.3
Puarenga	Native Forest/Scrub	834.4	10.3
Puarenga	Other	162.8	2.0
Puarenga	Parks and Reserves	196.4	2.4
Puarenga	Pasture/Arable	2255.4	27.7
Puarenga	Urban/Road/Rail	473.0	5.8
Utuhina	Exotic Forest	1074.0	18.0
Utuhina	Lifestyle/Mixed Land use	436.7	7.3
Utuhina	Native Forest/Scrub	1592.4	26.7
Utuhina	Other	8.6	0.1
Utuhina	Parks and Reserves	225.6	3.8

Utuhina	Pasture/Arable	1333.8	22.4
Utuhina	Urban/Road/Rail	1284.3	21.6
Waingaehe	Exotic Forest	299.5	28.3
Waingaehe	Lifestyle/Mixed Land use	22.2	2.1
Waingaehe	Native Forest/Scrub	51.0	4.8
Waingaehe	Other	0.1	0.0
Waingaehe	Parks and Reserves	8.3	0.8
Waingaehe	Pasture/Arable	623.3	58.8
Waingaehe	Urban/Road/Rail	55.6	5.2
Waiohewa	Exotic Forest	140.6	11.7
Waiohewa	Horticulture	22.8	1.9
Waiohewa	Lifestyle/Mixed Land use	228.5	19.0
Waiohewa	Native Forest/Scrub	220.8	18.4
Waiohewa	Other	197.5	16.5
Waiohewa	Parks and Reserves	0.2	0.0
Waiohewa	Pasture/Arable	363.0	30.3
Waiohewa	Urban/Road/Rail	26.4	2.2
Waiowhiro	Exotic Forest	62.9	4.3
Waiowhiro	Lifestyle/Mixed Land use	128.1	8.7
Waiowhiro	Native Forest/Scrub	300.3	20.3
Waiowhiro	Other	46.5	3.1
Waiowhiro	Parks and Reserves	49.7	3.4
Waiowhiro	Pasture/Arable	299.9	20.3
Waiowhiro	Urban/Road/Rail	592.2	40.0
Waiteti	Exotic Forest	328.1	4.6
Waiteti	Horticulture	9.2	0.1
Waiteti	Lifestyle/ Mixed Land use	468.4	6.6
Waiteti	Native Forest/Scrub	1652.1	23.4
Waiteti	Other	85.6	1.2
Waiteti	Parks and Reserves	46.1	0.7
Waiteti	Pasture/Arable	4236.6	60.0
Waiteti	Urban/Road/Rail	237.8	3.4

Appendix 3:

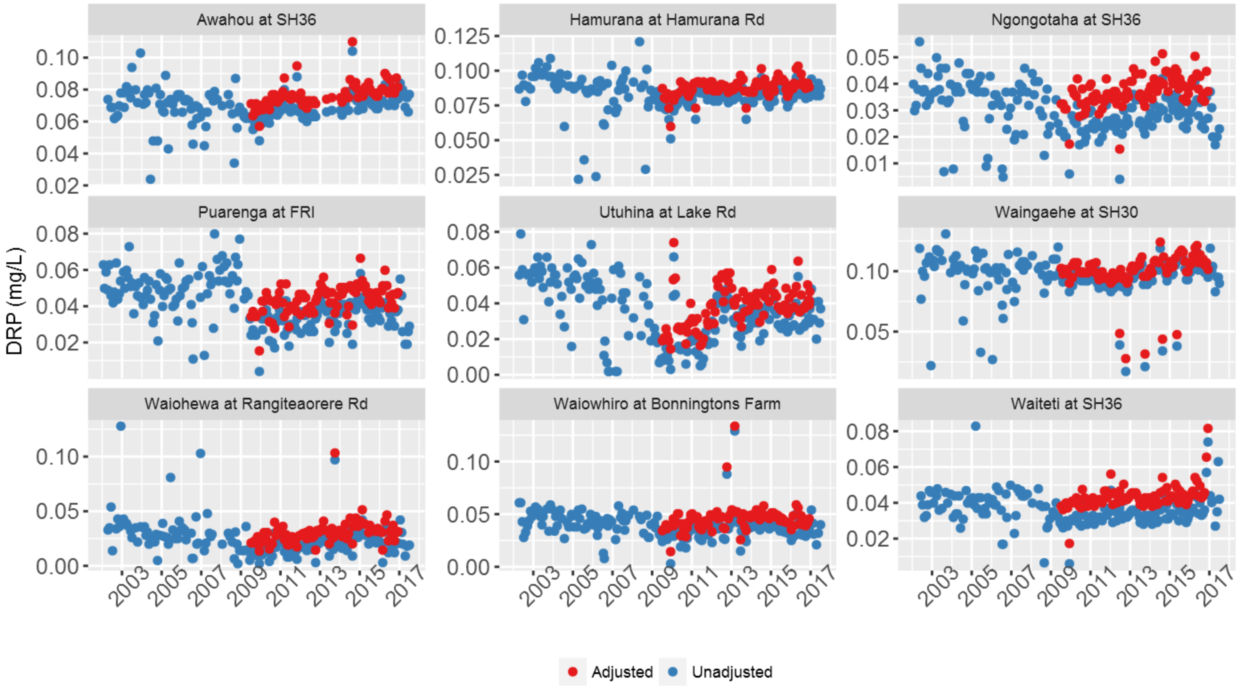
Lab Methodology Adjustment

TN



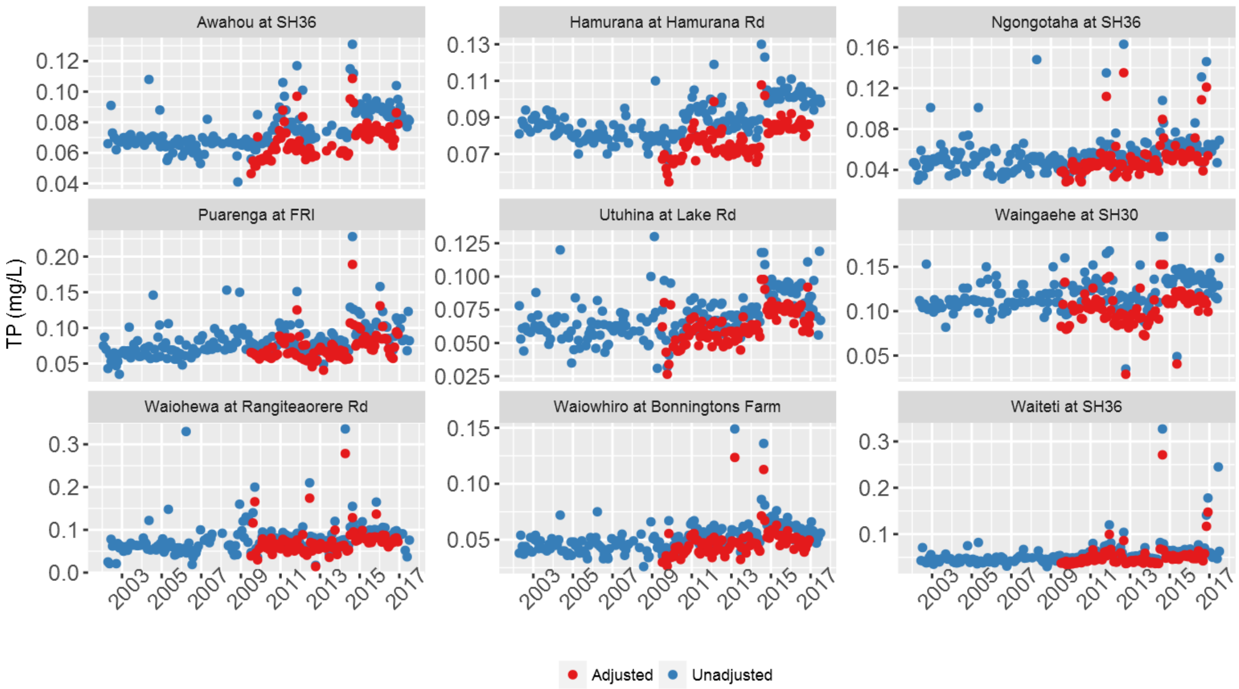
Appendix 3 - Figure 1 *Adjusted (red) versus unadjusted TN values for each main site. The adjustment equations are come from Scholes and Hamill (2016) and are detailed in the Methods Section.*

DRP



Appendix 3 - Figure 2 *Adjusted (red) versus unadjusted DRP values for each main site, using the equation defined in Appendix 3 – Figure 2.*

TP



Appendix 3 - Figure 3 *Adjusted (red) versus unadjusted TP values for each main site. The adjustment equations are come from Scholes and Hamill (2016) and are detailed in the methods section.*

Summary of Trend Changes

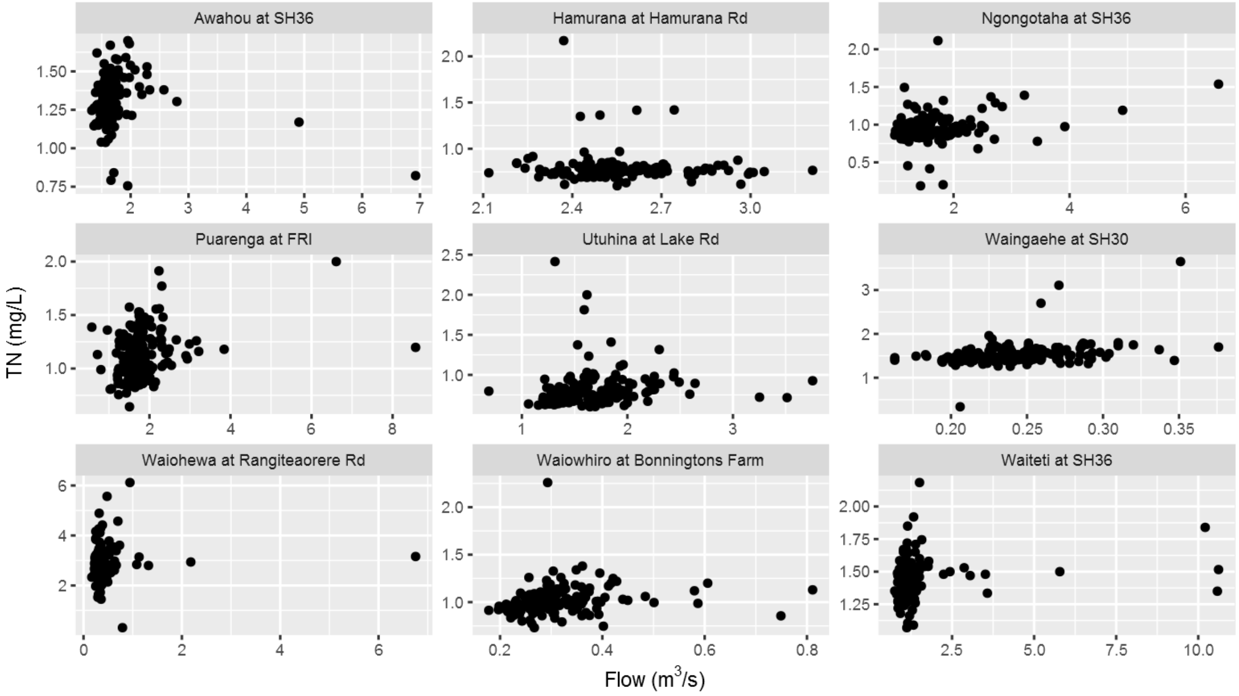
Appendix 3 - Table 1 *Summary of changes to identified trends caused by adjustment. The unadjusted column shows the trend that was identified using unadjusted data and the adjusted column shows the trend identified using adjusted data. Other columns detail the number of occurrences, and specific catchments, along with other metadata.*

Analyte	Unadjusted	Adjusted	Count	Comment	Change	Change Direction	Catchments
DRP	⬂	⬂	1	Trend became less negative	No	No	Utuhina
DRP	□	⬀	1		Yes	No	Awahou
DRP	⬂	□	5		Yes	No	Hamurana; Puarenga; Waingaehe; Waiohewa; Waiowhiro
DRP	⬂	⬀	2		Yes	Yes	Ngongotahā; Waitetī
TN	⬀	⬀	2	Trend became more positive	No	No	Awahou; Waitetī
TN	⬂	⬂	1	Trend became less negative	No	No	Puarenga
TN	□	□	3		No	No	Waingaehe; Waiohewa; Waiowhiro
TN	□	⬀	1		Yes	No	Hamurana
TN	⬂	□	2		Yes	No	Ngongotahā; Utuhina
TP	⬀	⬀	6	Trend became less positive	No	No	Awahou; Ngongotahā; Puarenga; Utuhina; Waiohewa; Waitetī
TP	⬀	□	2		Yes	No	Waingaehe; Waiowhiro
TP	⬀	⬂	1		Yes	Yes	Hamurana

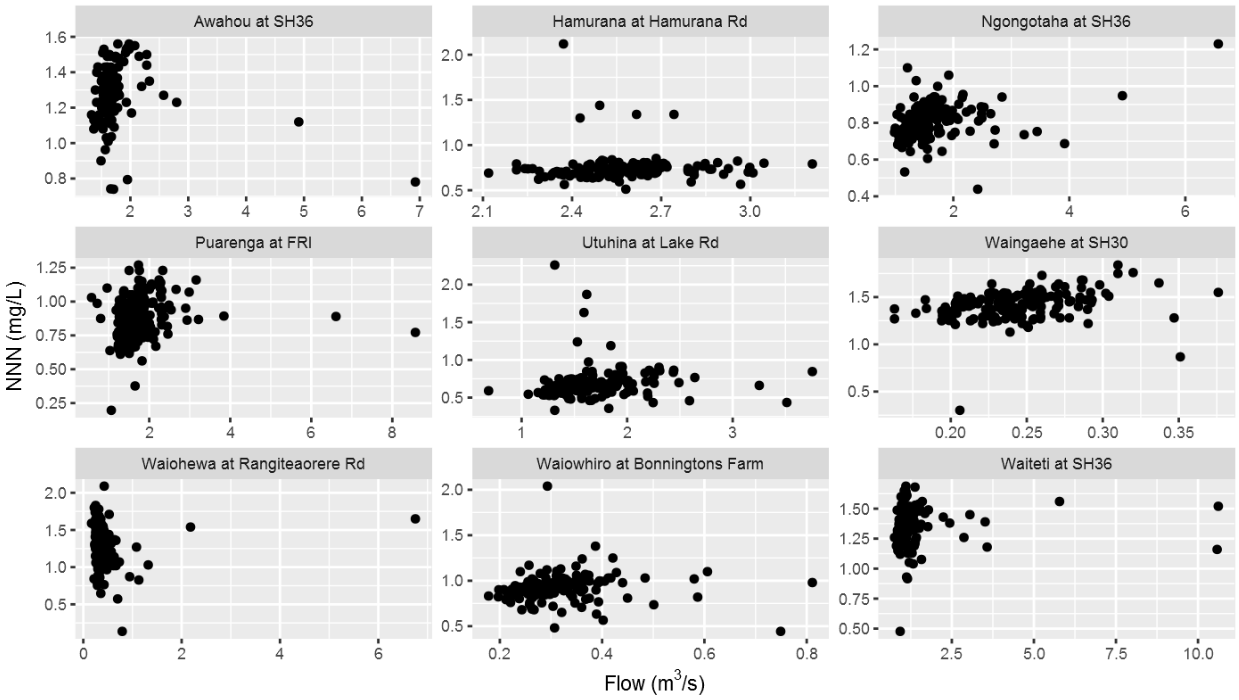
Appendix 4:

Flow Concentration Plots

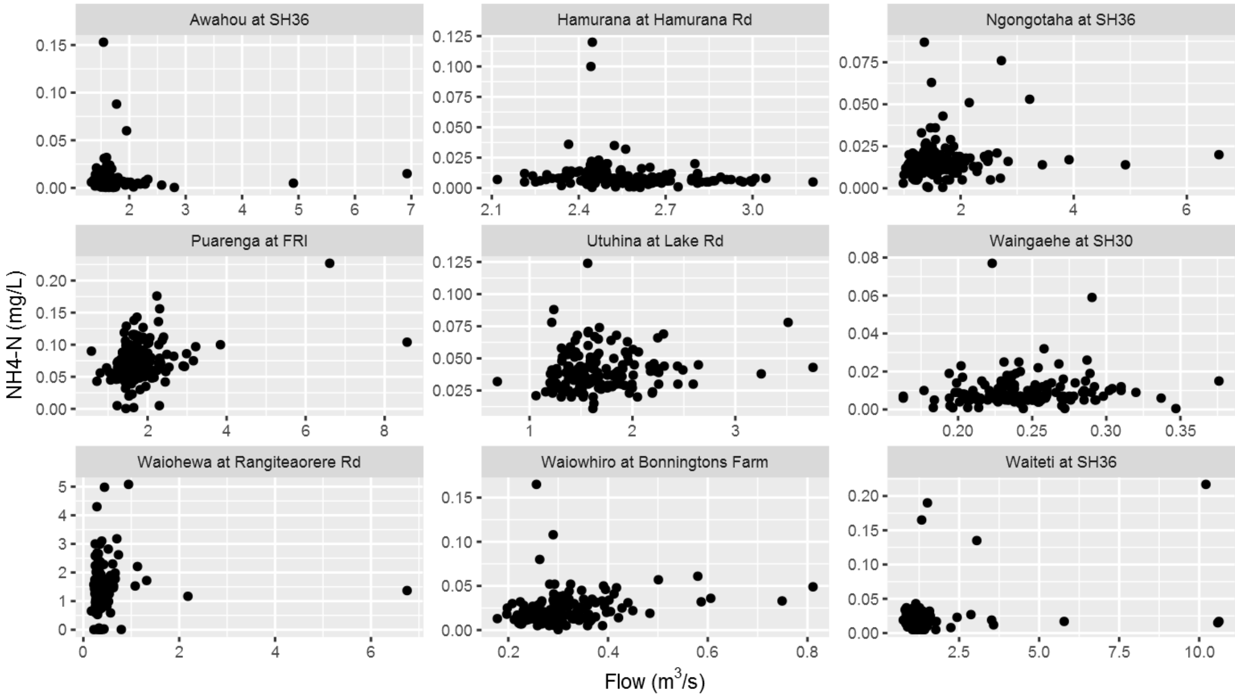
TN



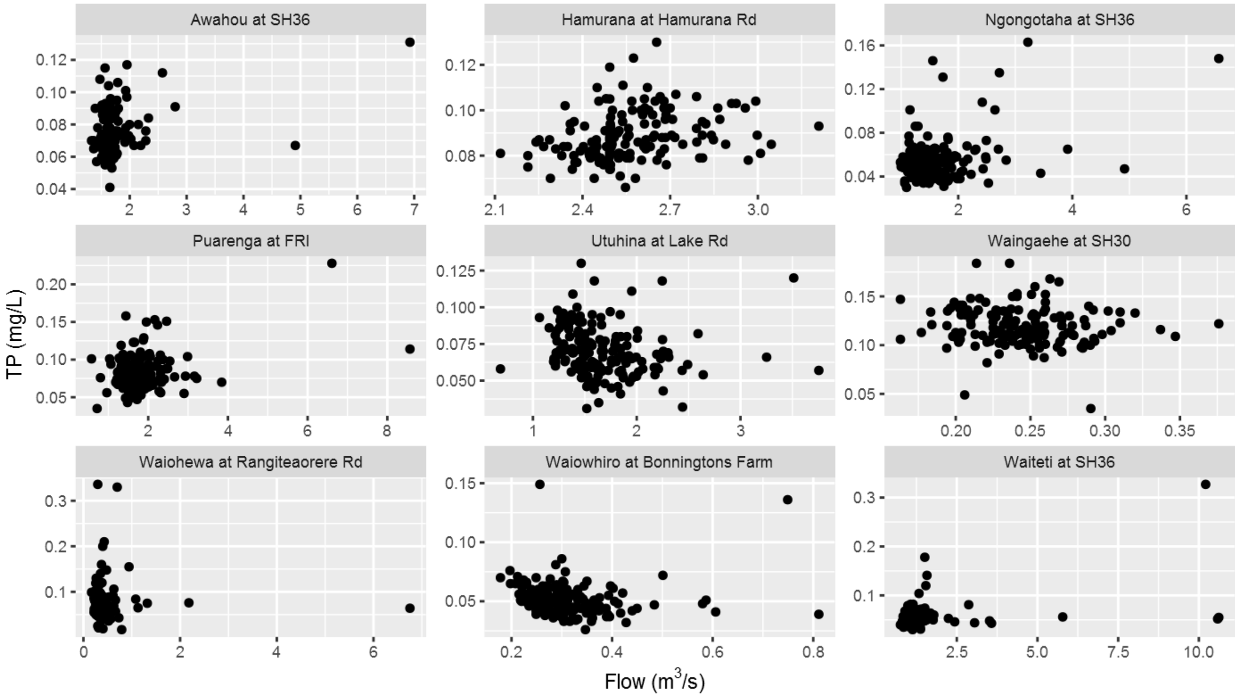
NNN



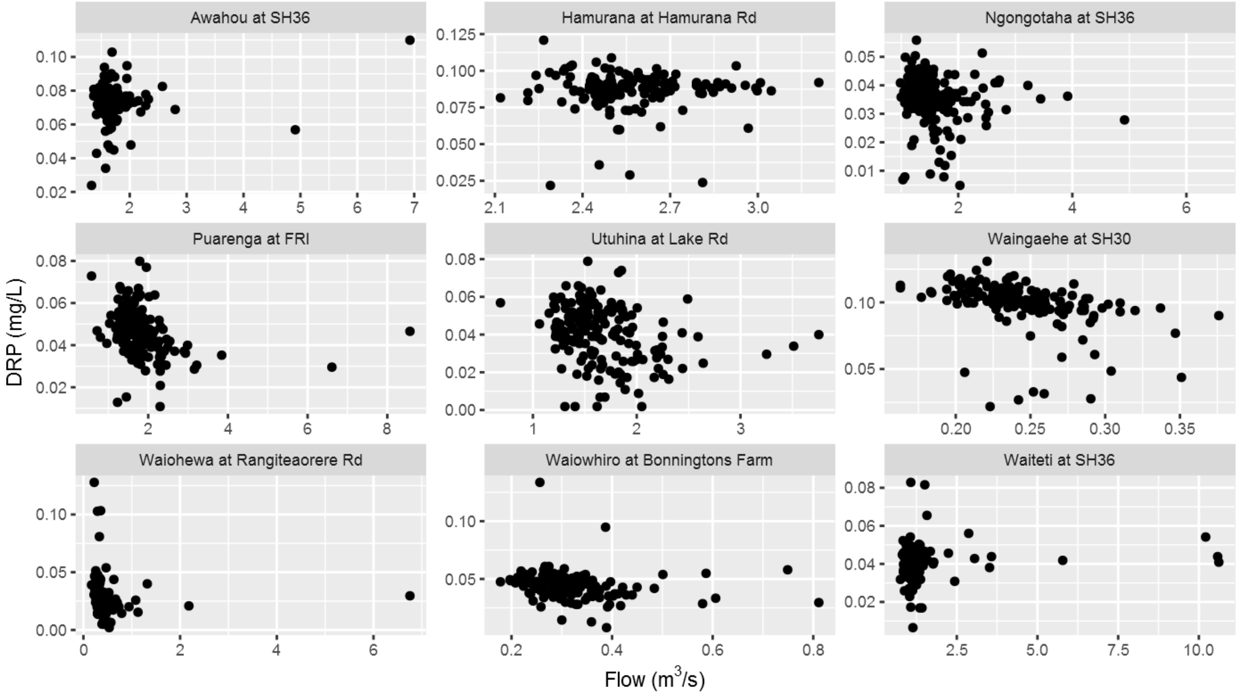
NH4


Awahou at SH36
Hamurana at Hamurana Rd
Ngongotaha at SH36
Puarenga at FRI
Utuhina at Lake Rd
Waingaehe at SH30
Waiohewa at Rangiteaorere Rd
Waiowhiro at Bonningtons Farm
Waiteti at SH36
NH4-N (mg/L)
Flow (m3/s)

TP


Awahou at SH36
Hamurana at Hamurana Rd
Ngongotaha at SH36
Puarenga at FRI
Utuhina at Lake Rd
Waingaehe at SH30
Waiohewa at Rangiteaorere Rd
Waiowhiro at Bonningtons Farm
Waiteti at SH36
TP (mg/L)
Flow (m3/s)

DRP

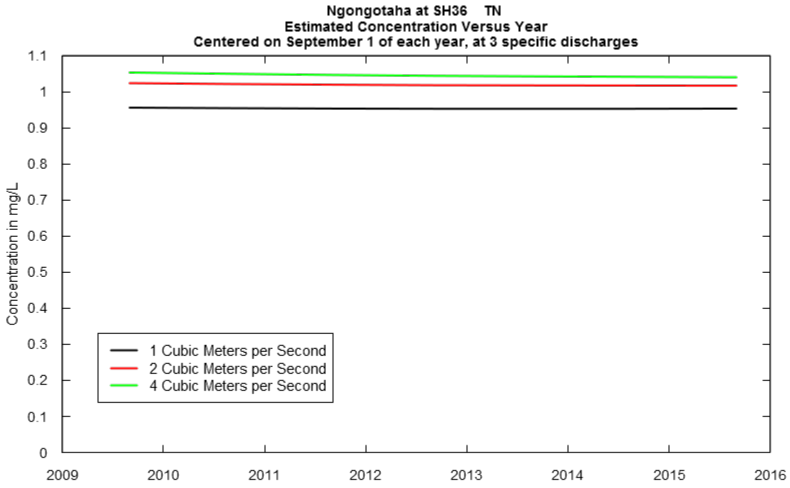

Awahou at SH36
Hamurana at Hamurana Rd
Ngongotaha at SH36
Puarenga at FRI
Utuhina at Lake Rd
Waingaehe at SH30
Waiohewa at Rangiteaorere Rd
Waiowhiro at Bonningtons Farm
Waiteti at SH36
DRP (mg/L)
Flow (m3/s)

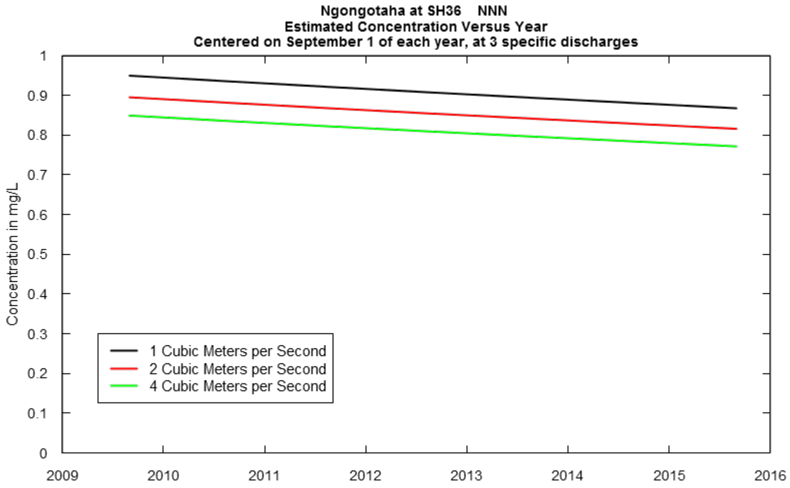
Appendix 5:

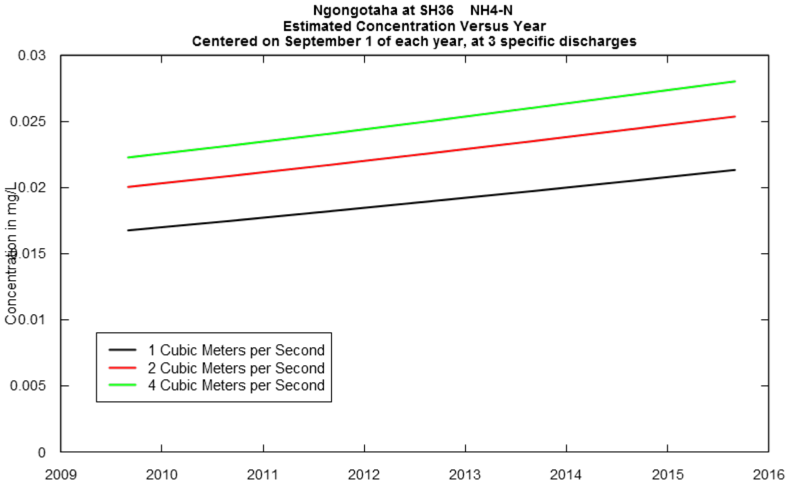
Additional EGRET Plots

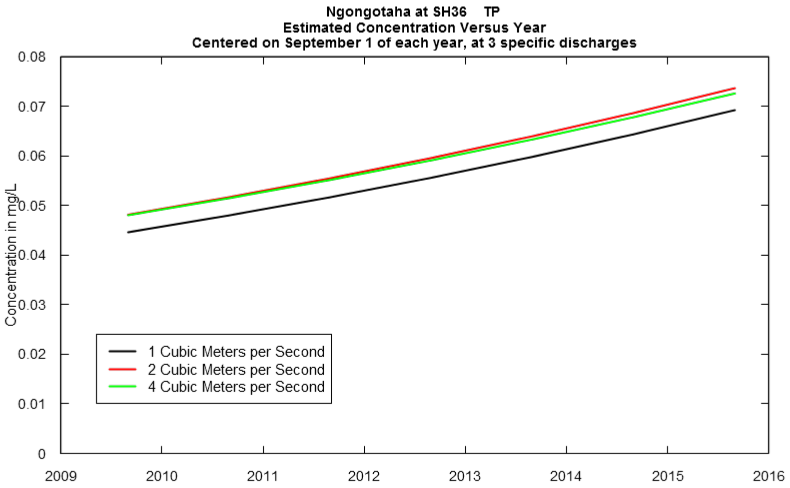
The following plots are produced by the EGRET package but were not selected for the main text. These show how the concentration of each analyte has changed over time, at three site-specific levels of flow (low, median, high). These plots are centred on the period of highest concentrations, which in most cases is 1 September each year.

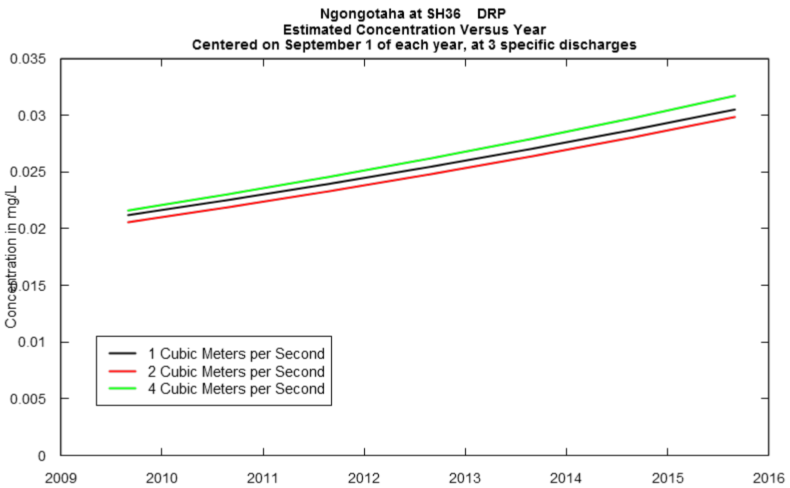
Ngongotaha at State Highway 36



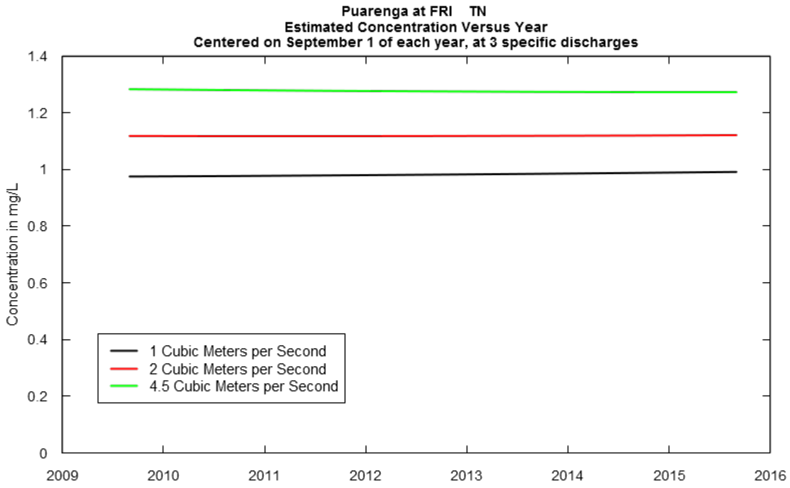


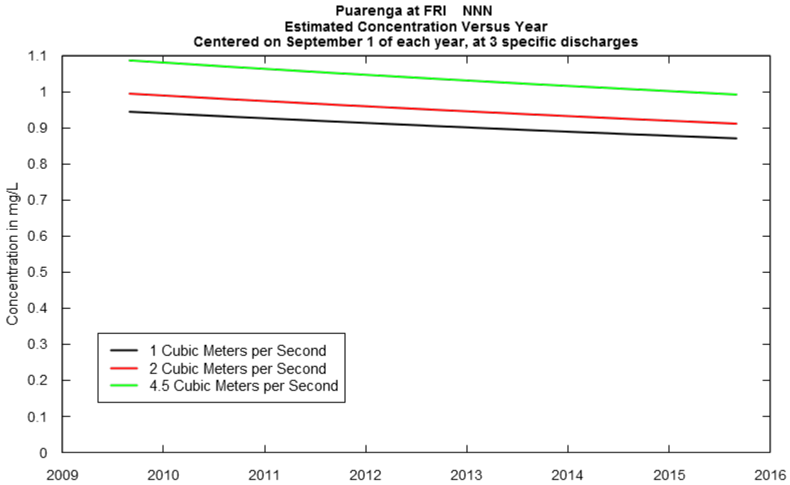

Ngongotaha at SH36 NH4-N
Estimated Concentration Versus Year
Centered on September 1 of each year, at 3 specific discharges
Concentration in mg/L
1 Cubic Meters per Second
2 Cubic Meters per Second
4 Cubic Meters per Second

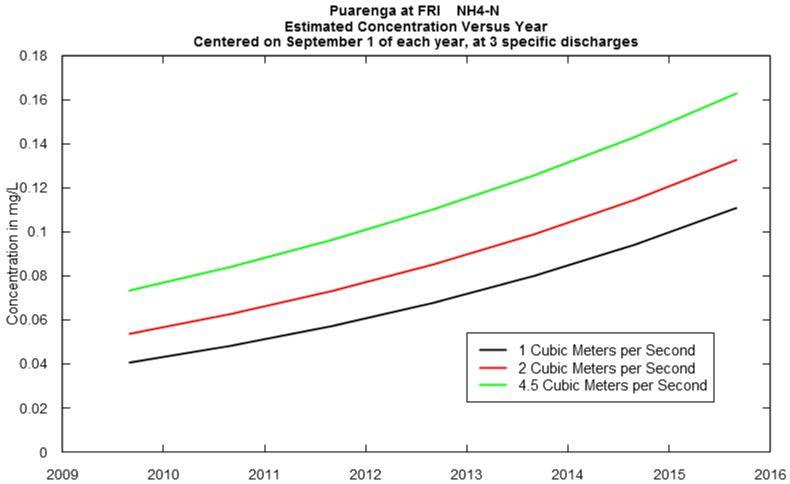

Ngongotaha at SH36 TP
Estimated Concentration Versus Year
Centered on September 1 of each year, at 3 specific discharges
Concentration in mg/L
1 Cubic Meters per Second
2 Cubic Meters per Second
4 Cubic Meters per Second

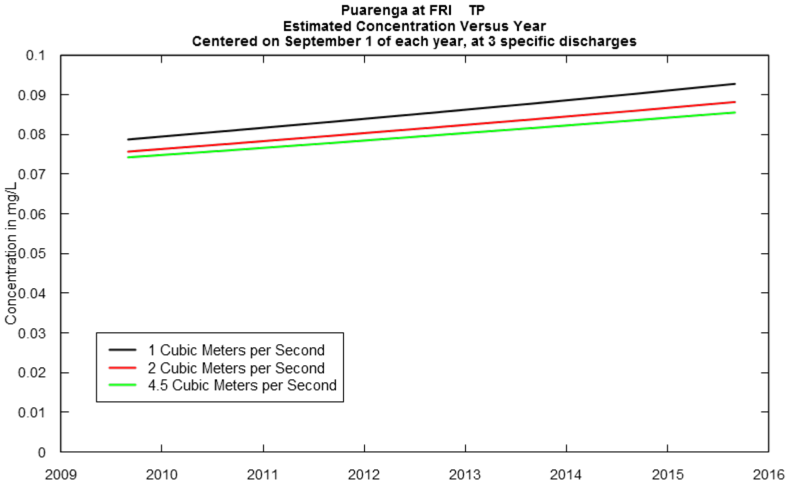

Ngongotaha at SH36 DRP
Estimated Concentration Versus Year
Centered on September 1 of each year, at 3 specific discharges
Concentration in mg/L
1 Cubic Meters per Second
2 Cubic Meters per Second
4 Cubic Meters per Second

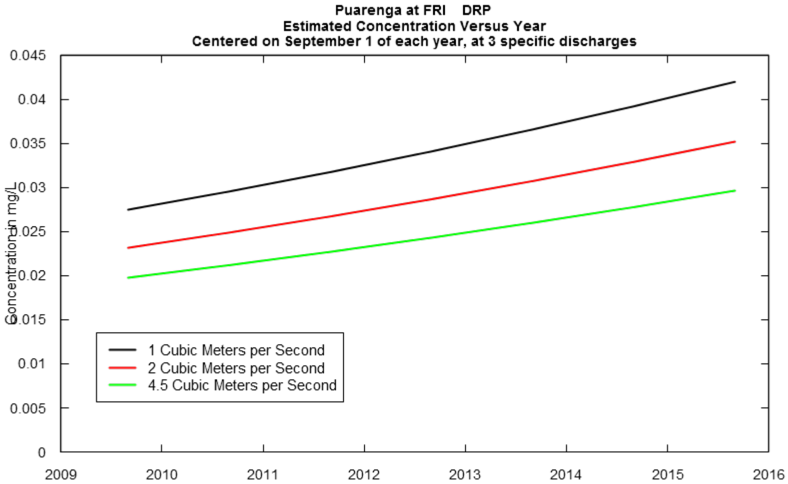
Puarenga at FRI



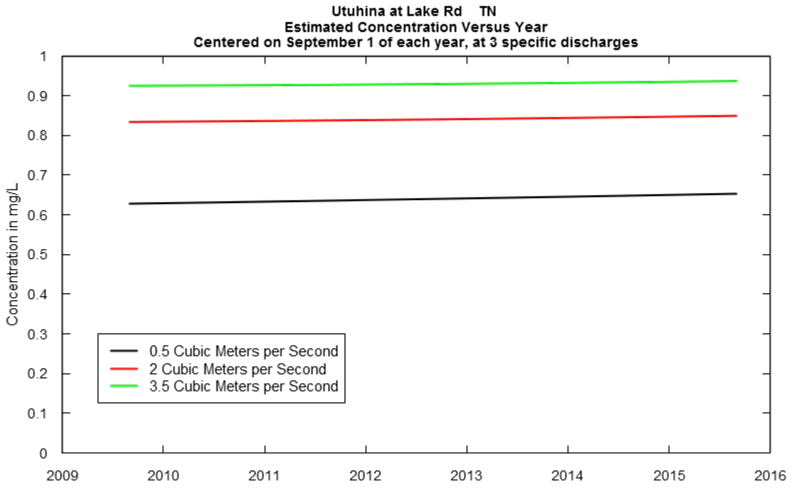


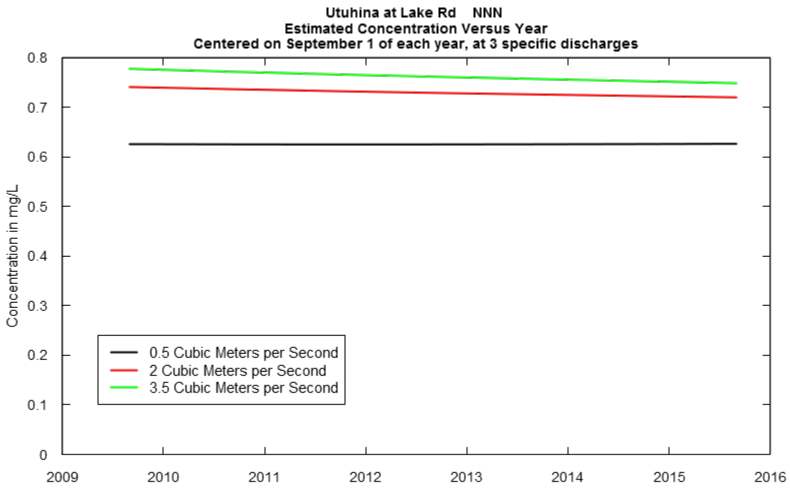


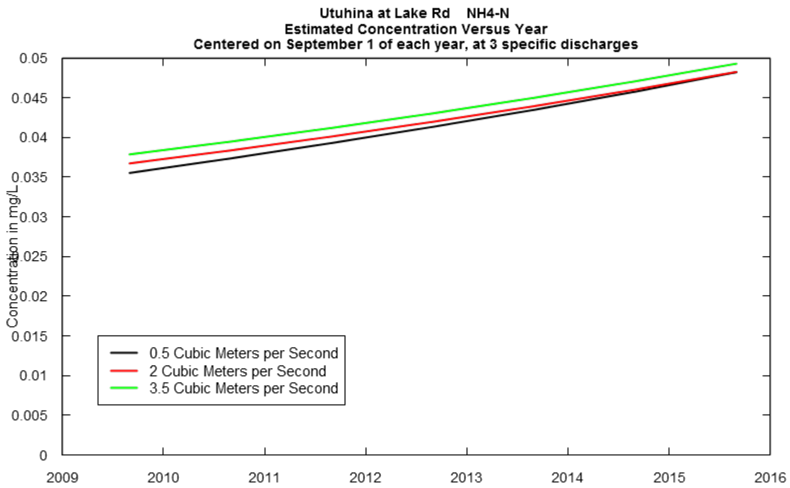

Puarenga at FRI TP
Estimated Concentration Versus Year
Centered on September 1 of each year, at 3 specific discharges
Concentration in mg/L
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
2009
2010
2011
2012
2013
2014
2015
2016
1 Cubic Meters per Second
2 Cubic Meters per Second
4.5 Cubic Meters per Second

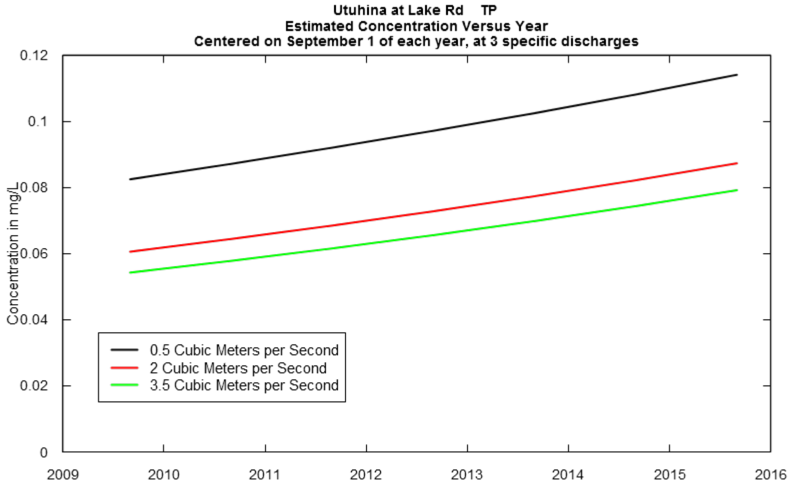

Puarenga at FRI DRP
Estimated Concentration Versus Year
Centered on September 1 of each year, at 3 specific discharges
Concentration in mg/L
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
2009
2010
2011
2012
2013
2014
2015
2016
1 Cubic Meters per Second
2 Cubic Meters per Second
4.5 Cubic Meters per Second

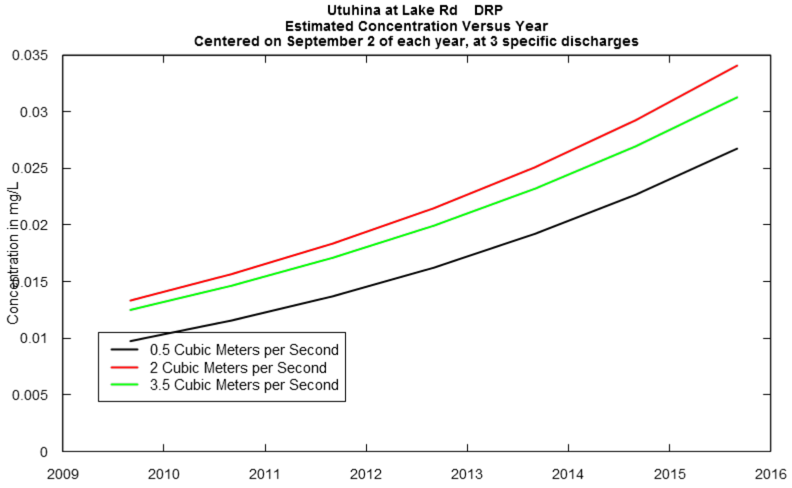
Utuhina at Lake Road



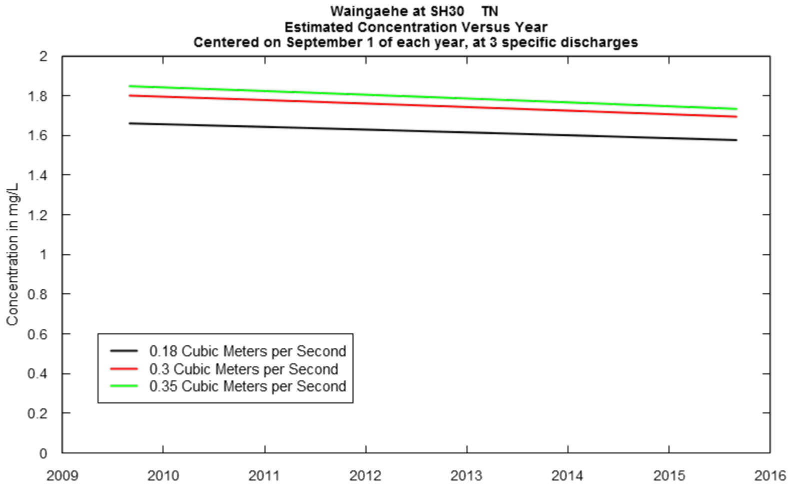


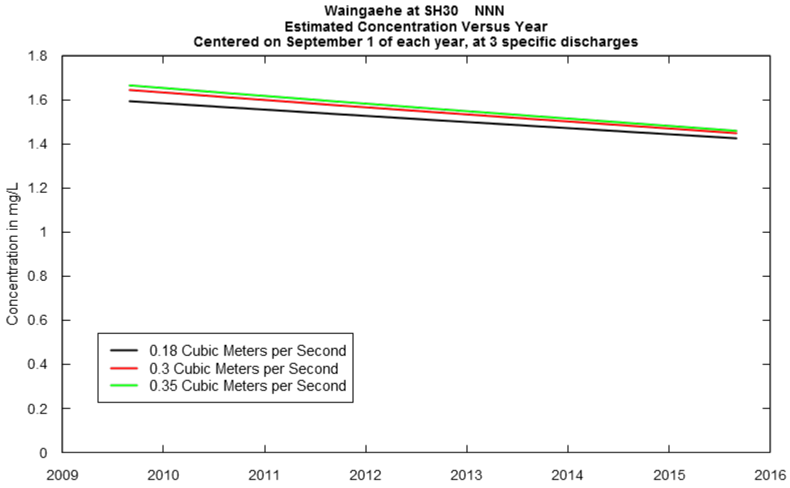


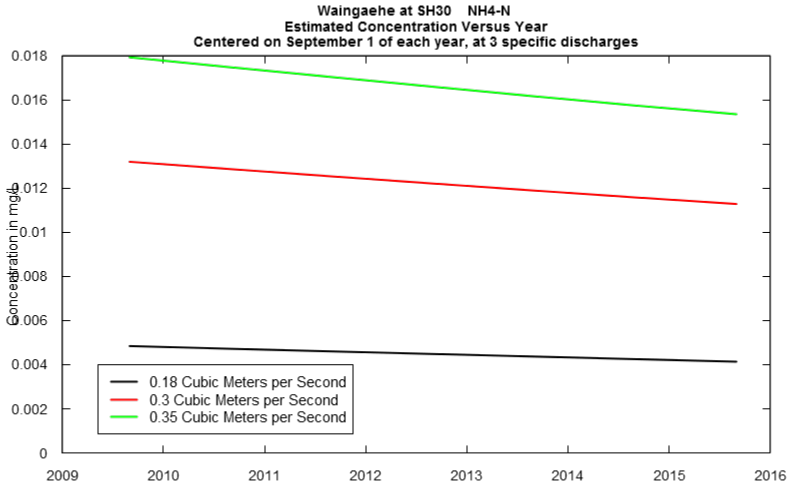

Utuhina at Lake Rd TP
Estimated Concentration Versus Year
Centered on September 1 of each year, at 3 specific discharges
Concentration in mg/L
0.12
0.1
0.08
0.06
0.04
0.02
0
2009
2010
2011
2012
2013
2014
2015
2016
0.5 Cubic Meters per Second
2 Cubic Meters per Second
3.5 Cubic Meters per Second

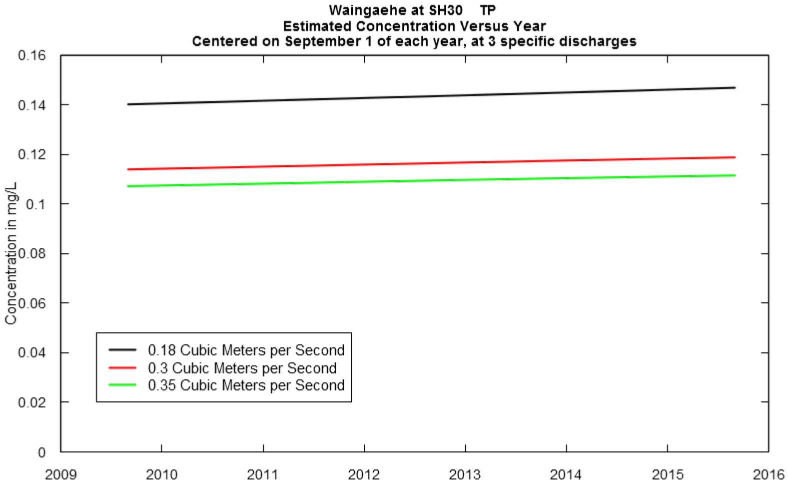

Utuhina at Lake Rd DRP
Estimated Concentration Versus Year
Centered on September 2 of each year, at 3 specific discharges
Concentration in mg/L
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
2009
2010
2011
2012
2013
2014
2015
2016
0.5 Cubic Meters per Second
2 Cubic Meters per Second
3.5 Cubic Meters per Second

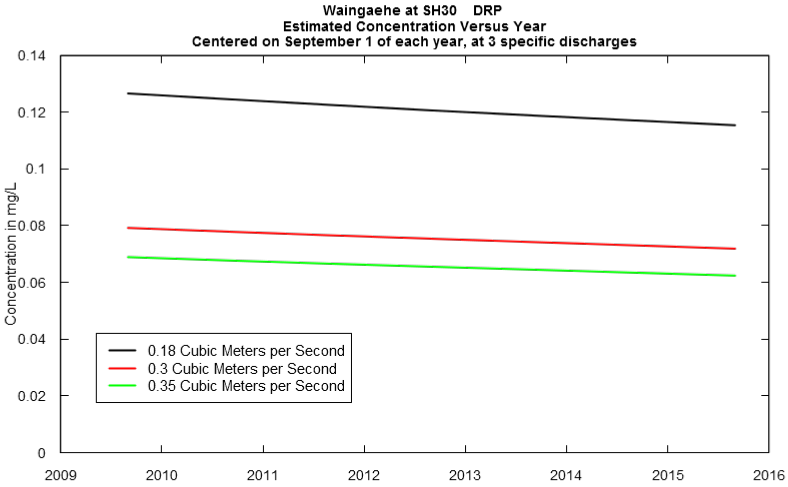
Waingaehe at State Highway 30








Waingaehe at SH30 TP
Estimated Concentration Versus Year
Centered on September 1 of each year, at 3 specific discharges
Concentration in mg/L
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
2009
2010
2011
2012
2013
2014
2015
2016
0.18 Cubic Meters per Second
0.3 Cubic Meters per Second
0.35 Cubic Meters per Second


Waingaehe at SH30 DRP
Estimated Concentration Versus Year
Centered on September 1 of each year, at 3 specific discharges
Concentration in mg/L
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
2009
2010
2011
2012
2013
2014
2015
2016
0.18 Cubic Meters per Second
0.3 Cubic Meters per Second
0.35 Cubic Meters per Second