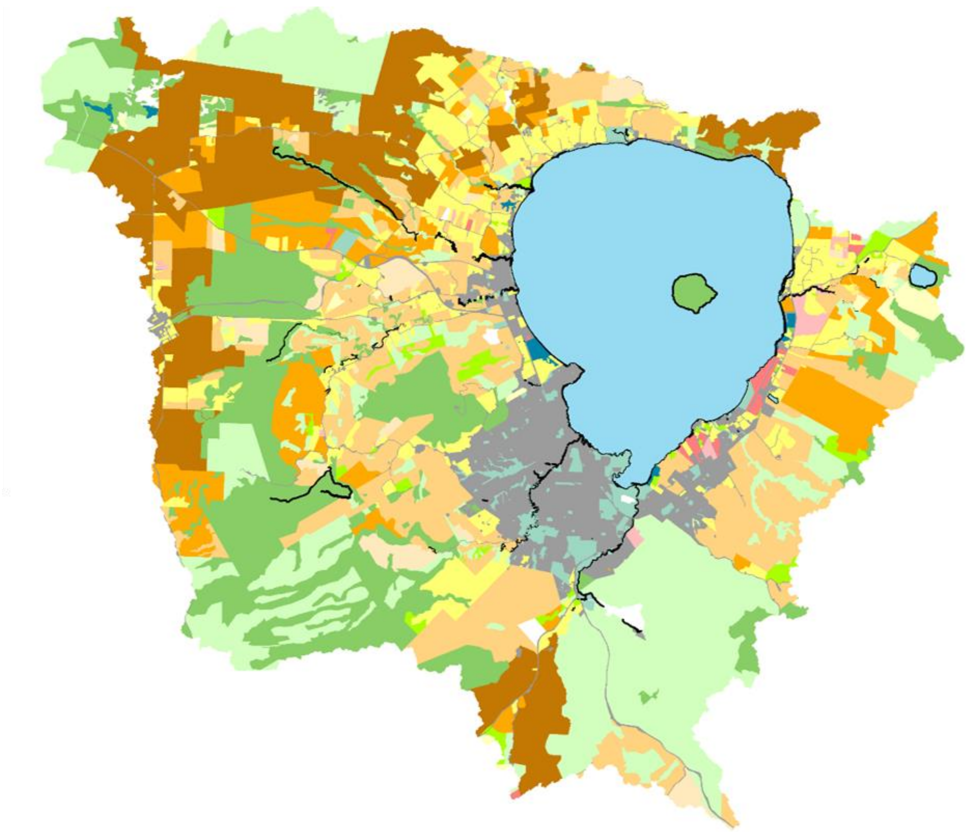
Long-term nutrient loads and water quality for Lake Rotorua: 1965 to 2017



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Prepared for Bay of Plenty Regional Council

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Availability

Data providers

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Cover image

Land use in the Lake Rotorua catchment (data: Bay of Plenty Regional Council).

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Executive Summary

Effective management of catchment nutrient loads is essential to protect water quality in lakes (Schindler 2006, Sondergaard et al. 2007). Lake Rotorua has a history of catchment urbanisation and pastoral development, which have been linked to water quality decline in the inflows and lake between the 1960s and 2000s (Hoare 1980, Rutherford et al. 1989, Rutherford et al. 2011, Hamilton et al. 2015). Increases in lake nutrient concentrations, reduced water clarity, and the occurrence of surface cyanobacteria ('blue-green algae') blooms have spurred decades of research into sustainable catchment nutrient loads to Lake Rotorua. The extent of data available for Lake Rotorua and its catchment is testament to the work of many dedicated researchers over more than half a century. This study seeks to collate these data and analyse them with a consistent method to construct estimates of long-term nutrient loading and lake water quality in Lake Rotorua from 1965 to 2017. These estimates can then be evaluated in the context of the previously established sustainable load estimates that were developed for restoring and maintaining Lake Rotorua water quality to meet community aspirations for this nationally significant waterbody.

A lake water balance was constructed, accounting for all sources and losses of water on a daily basis from July 1964 to June 2017. Daily stream nitrogen (N) and phosphorus (P) concentrations were estimated either by interpolating measurements or modelling discharge-concentration relationships during stormflows, using available data. Volume and nutrient concentration of additional inflow sources, including geothermal fluid, groundwater and atmospheric deposition, were estimated from monitoring data and literature review. Annual estimates of loading from various sources are presented in Figure A. This study provides estimates of only external (catchment) loading, acknowledging that internal nutrient recycling can greatly increase total loading to the lake water column on an annual basis and also reduce the rate that lake water quality improves following external load reductions (Rutherford et al. 1989, Burger et al. 2008).

Stream P concentrations were relatively stable between 1970 and 2010, however, total P load to the lake has varied considerably over time, reflecting fluctuations in particulate P loads and removal of direct inputs of treated wastewater to the lake in 1991. Groundwater-dominated inflows (Hamurana and Awahou) were the largest sources of dissolved P to the lake, and a substantial proportion of P loading is likely to be geologically-derived (Tempero et al. 2015). Total P concentrations have increased in several inflows since 2010. Total N load has increased substantially and steadily since the 1960s, principally due to increases in nitrate concentrations. Direct-discharge of wastewater (pre-1991) was a smaller component of total N load than for total P load, whereby treated wastewater accounted for as much as c. half of all total phosphorus load in the years leading to implementation of the land treatment system in 1991. The Total N load is currently well in excess of the target set for sustainability (435 t TN y^{-1}), the target also appears to be higher than observed N loading for the 1960s (as estimated here) which it was meant to represent.

Water quality data from 1967 to 2017 were collated from a variety of sources. Due to gaps and inconsistent sampling, an aggregation approach was adopted to reduce seasonal bias in annual mean values. Mid-lake water quality data collected from the late 1960s (early 1970s for nitrogen) until present, and annual estimated water quality and Trophic Level Index (Burns et al. 1999) are presented in Figures B and C. Presently, the Trophic Lake Index (TLI) target is being met and appears comparable to or better than that observed in the late 1960s, with the possible exception of the N component. High P concentrations in the 1980s to early 2000s appear to be pulse-like during warmer months, suggesting that particularly high internal loading associated with stratification occurred during that period. Since 2010, lake annual P concentrations are generally lower than any earlier observations.

Estimated catchment (external) loads do not indicate reductions over the past 10 years that could explain recent improvements in water quality. Therefore, lower lake phosphorus concentrations at present are most likely due to alum dosing of the Puarenga and Utuhina inflows, possibly coupled with partial exhaustion of historical (legacy) P from direct wastewater discharge stored in lake sediments since 1991. Substantial reductions in catchment loading, particularly for N, are required to meet the sustainable load targets, (Figure A) in order to reduce dependence on active in-lake and in-stream management strategies such as alum dosing that may carry greater ecological risk than management by sustainable land use practices alone.

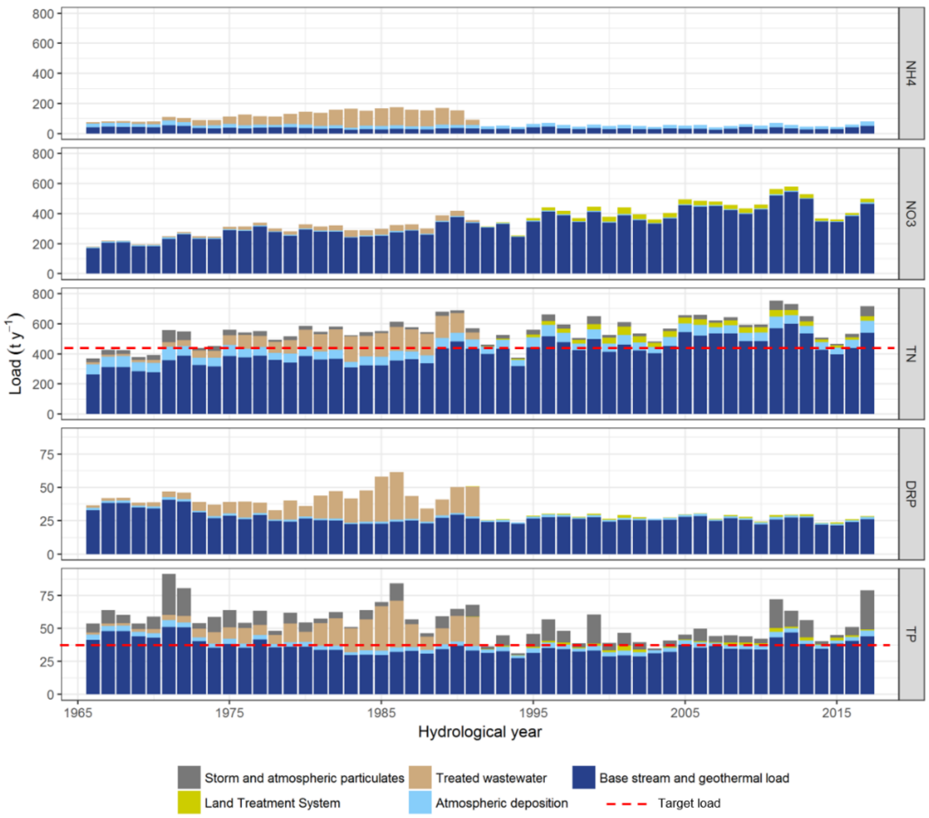

Figure A. Summary of nutrient loading to Lake Rotorua 1967 to 2017. Loads from stormflow and particulate deposition are shown in grey. Sustainable load targets (435 t TN y^{-1} & 37 t TP y^{-1}; Rutherford et al. 1989) are shown by the dashed red line.

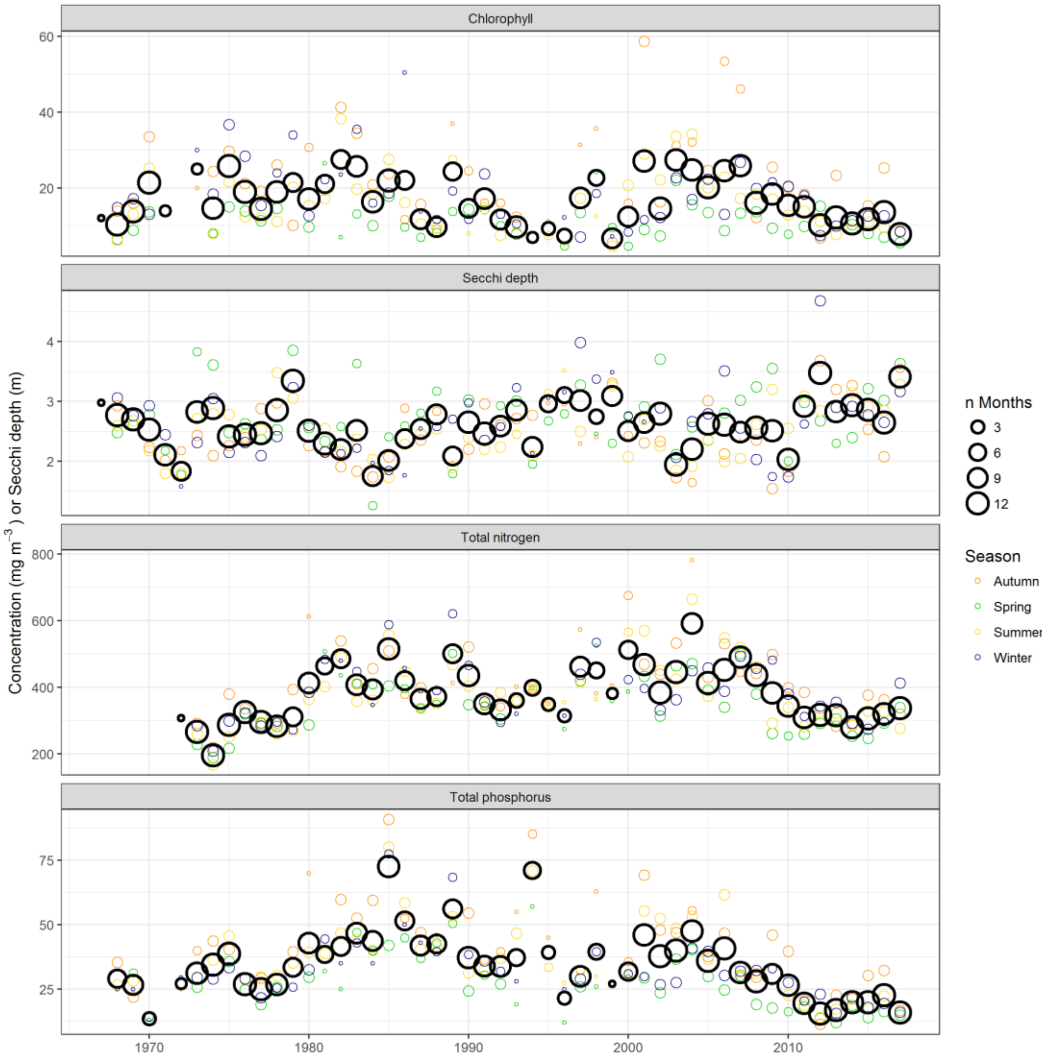

Figure B. Measurements of TLI variables at mid-lake sites in Lake Rotorua. Individual samples were aggregated, retaining only the median value for each month and variable. Monthly medians were then averaged seasonally, shown by the coloured circles. Black circles are the mean value of all available seasonal averages, and may differ slightly from values reported by BoPRC due to the 'average of seasonal averages' approach used here. The diameter of all circles is scaled by the number of monthly median measurements aggregated.

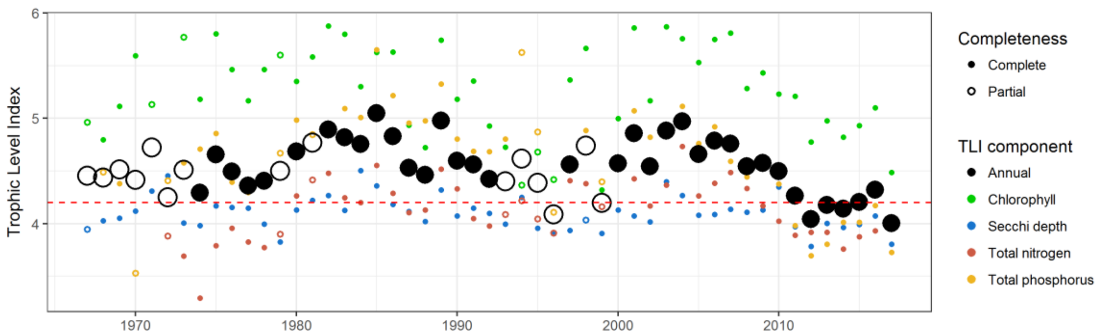

Figure C. Annual Trophic Level Index (TLI) at mid-lake sites by hydrological year (previous July to present June). Each coloured circle is the mean of seasonal means, with the TLI equation (Burns et al. 1999) applied. Large black circles are the annual TLI (average of four components). Solid circles denote years for which at least one measurement was available for all four seasons (solid black circles denote that all four component variables of the TLI were sampled each season). Open circles denote that measurements were missing for at least one season. The lake TLI target (4.2) is shown by the dashed red line. Values may differ from those routinely reported by BoPRC due to the aggregation method used here.

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Introduction

Effective management of catchment nutrient loads is essential in order to preserve lake water quality (Schindler 2006, Sondergaard et al. 2007). Lake Rotorua has a history of catchment urbanisation and pastoral development, processes which have been linked to water quality declines in the inflows and lake between the 1960s and 2000s (Hoare 1980, Rutherford et al. 1989, Rutherford et al. 2011, Hamilton et al. 2015). Increases in lake nutrient concentrations, reduced water clarity and the occurrence of surface cyanobacteria ('blue-green algae') blooms have spurred decades of research into achieving sustainable catchment nutrient loads. Consequently, Lake Rotorua is perhaps the most intensively studied lake catchment in New Zealand.

Objectives

This study collates data from all available sources in order to construct estimates of long-term nutrient loading and lake water quality of Lake Rotorua from 1965 to 2017. Specifically, we review and synthesise nutrient concentrations and loads associated with stream inflows and other water sources, along with lake nutrient concentrations and Trophic Level Index (TLI, Burns et al. 1999) to characterise in-lake water quality. This will provide a rationalised data-informed perspective to support policy review, including the application of predictive scenario modelling. These estimates can then be evaluated in the context of the previously established sustainable load estimates that were developed for restoring and maintaining Lake Rotorua water quality.

Brief history of the Lake Rotorua catchment

Lake Rotorua has a catchment of 538 km^2, with mixed land use spread among nine major sub-catchments drained by surface stream inflows to the lake, and substantial areas drained by smaller streams and groundwater. The Rotorua area was originally settled by Te Arawa in the 14th century, and was established as a town in the late 19th century (Matthews & Matthews 2007). Farming of the catchment also began in the late 19th century, when oats and maize were grown by Māori and Pakeha farmers, and by 1896 at least 25 farms were established in the Mamaku area. By the 1930s multiple herds were supplying the Ngongotaha dairy factory, and aerial topdressing began in 1950 (Matthews & Matthews 2007). The urban population of Rotorua grew steadily and the town was declared a city in 1962.

From the 1960s, nutrient loads to Lake Rotorua increased substantially, primarily due to the discharge of minimally treated municipal wastewater directly to the lake (Rutherford et al. 1989). In 1991, direct discharge to the lake ceased and treated wastewater was instead spray irrigated to the Whakarewarewa forest. However, due to land use intensification within the catchment, stream nitrogen loads – particularly as nitrate – have increased steadily in most stream inflows since the earliest measurements in the 1960s - 1970s (Hoare 1980, Rutherford 2003, Rutherford et al. 2011). The pumiceous (ignimbrite) soils of the Rotorua catchment are relatively free-draining, and nitrate is readily leached from the soil zone, particularly where livestock concentrate nitrogen in urine patches (Quinn et al. 2009). Much of the catchment hydrology is dominated by large, deep groundwater aquifers and many stream inflows to Rotorua are groundwater-fed. Morgenstern et al. (2015) analysed tritium concentrations to model mean water ages for the major stream inflows to Lake Rotorua, finding that mean residence time (MRT) of water in major sub-catchments ranged from 30 to 145 years under baseflow conditions. The net result of such groundwater 'lags' is that the effects of catchment land use intensification may not yet be fully realised in stream inflows (Rutherford et al. 2011, Morgenstern et al. 2015), i.e. observed stream nutrient concentrations may reflect land use from decades earlier. This temporal disconnect could prove a substantial barrier to effective catchment and lake management, as nutrient loads from aquifers have been expected to continue to increase long after land use mitigation actions have been implemented (Mueller et al. 2015).

Substantial effort has been undertaken to account for, and project, the effects of catchment land use and groundwater lags. The Rotorua Taupo Nitrogen Model (ROTAN), developed by NIWA (Rutherford et al. 2008, 2009 & 2011), is a catchment model accounting for the transport of nitrogen from land via surface flows and sub-surface aquifers to streams. In addition to meteorological forcing data, sub-catchment boundaries and hydrological connections, ROTAN requires input of spatially-resolved nitrogen loss estimates for different categories of land use within sub-catchments (Rutherford et al. 2009). These nutrient loss estimates are typically derived from the Overseer® model (Wheeler 2006). Overseer was originally developed as an on-farm decision support tool to help users develop nutrient budgets and manage fertiliser use (Wheeler et al. 2009); however, it has also found broad use among regional authorities tasked with managing land use impacts on water quality.

Modelling and managing the future water quality of any lake requires accurately quantifying the hydraulic and nutrient loading to the system over time. For Lake Rotorua, potential interactions between groundwater lags and processes of attenuation or retention mean that the relationship between predicted nutrient loss from the land and final 'load-to-lake' is highly complex. Furthermore, the large, old-age groundwater aquifers of the Rotorua catchment are unlikely to align well with surface sub-catchment boundaries (White 2005, Rutherford et al. 2011). Acquiring essential understanding of nutrient loading to Lake Rotorua requires a comprehensive dataset of measurements of inflow discharge and water chemistry. For Lake Rotorua there exist a number of previous studies of the lake and catchment that have generated a substantial dataset with which to make these estimates. The breadth of data available for Lake Rotorua and its catchment is testament to the work of many dedicated researchers over more than half a century – flow gauging commenced as early as the 1950s, and nutrient concentrations of major inflows have been measured intermittently from the 1960s to present.

Brief history of Lake Rotorua catchment research

Estimates of catchment loads to Rotorua have been made for a number of historical periods using a variety of methods, summarised in Table 1. Fish (1975) measured dissolved inorganic nutrients in major inflows to the lake over three years to estimate catchment nutrient loads from 1967 to 1969. This study measured only dissolved inorganic nutrients and did not sample the Waiowhiro or minor streams. Hoare (1980, 1987) undertook a comprehensive study of discharge and nutrient concentrations (dissolved and total forms) under baseflow and flood conditions in major and minor streams to estimate catchment nutrient loads to the lake for the period 1976–1979. In resulting nutrient budgets, particulate nutrients transported during flood flows were accounted as a separate category in the overall catchment budgets (Table 2). The budgets of Hoare (1980, 1987) accounted for dissolved inorganic nutrients deposited by rainfall (c. 30 t N y^{-1} and 1.2 t P y^{-1}), but not for dissolved organic nutrients or particulate (dry) deposition.

Rutherford et al. (1989) adapted the nutrient budgets of Hoare (1980, 1987) to estimate total nutrient budgets to the lake for four historical periods, as well as an estimate of sustainable nutrient loading to the lake (Table 3). These estimates were later revisited by Rutherford (2003), and Rutherford (2008) analysed stormflow loads to Lake Rotorua based on samples collected during floods in the mid-2000s.

Rutherford (2011) described nitrogen budgets for various periods, which were used as input to the ROTAN model and based on pastoral loss rates from Overseer®. Nutrient loads to Rotorua have also been estimated as part of configuring dynamic lake models for assessing the impacts of catchment and internal nutrient loading (Burger et al. 2008, Hamilton et al. 2012), climate change (Hamilton et al. 2012) and alum dosing (Hamilton et al. 2015). In Burger et al. (2008), both nitrogen and phosphorus loads were derived from linear interpolation of monthly instream measurements. Nitrogen load estimates presented in Hamilton et al. (2012, 2015) were taken from a ROTAN model output. Most recently, Dare et al. (2018) assessed trends in stream inflows to Lake Rotorua for the period 2002 – 2016. Various other studies have assessed nutrient loading by methods other than direct measurement, a number of which are referenced in the Rotorua Lakes bibliography (Miller 2003).

Table 1. Previous estimates of catchment total nutrient loads to Lake Rotorua. Internal loading has been excluded from total loads presented in the final two columns. Estimates of Fish (1975) are not shown because only dissolved nutrients were measured. Table shows whether each study accounted for atmospheric deposition (Yes (Y) or No (N))

Study	Source	Period	Atmospheric deposition (Y/N)	Geothermal (Y/N)	Wastewater nitrogen (t N y^{-1})	Wastewater phosphorus (t P y^{-1})	Total N load (t N y^{-1})	Total P load (t P y^{-1})
Estimated from Hoare 1987	Rutherford et al. (1989)	1965	Y	Streams only	70	5	475	39
Hoare (1987)	Rutherford et al. (1989)	1976-77	Y	Streams only	146	7.8	558	42
Estimated from Hoare 1987	Rutherford et al. (1989)	1981-82	Y	Streams only	149	20.6	554	55
Estimated from Hoare 1987	Rutherford et al. (1989)	1984-85	Y	Streams only	160	33.8	565	68
Burger et al. (2008)		2001-04	N	Y	ns	ns	502	33
BoPRC (2009)		2009	ns	ns	ns	ns	556	39
Rutherford (2003)		2002	Y	Y	32	1	692	35
Rutherford et al. (2011)		2000-10	N	Y	ns	ns	520-750*	ns
Hamilton et al. (2015)		2001-12	Y	Y	30	<2	661*	33
Abell et al. (2015)		2005-15	Y	Y	30	1.4	629	46

*Nitrogen load estimate from ROTAN for Rutherford et al. (2011) and Hamilton et al. (2015). ns = not specified.

Table 2. Phosphorus (left) and nitrogen (right) loads to Lake Rotorua for 1976 to 1977–Tables 1 and 2 in Hoare (1980).

Phosphorus and nitrogen loads in Lake Rotorua

TABLE 1 Phosphorus Inputs and Output of Lake Rotorua (tonnes)

	1976	1977
DRP* (major sites)	20.5	19.7
DRP (minor sites)	0.8	0.8
DRP (unmeasured flow)	3.4	3.3
DRP (rain)	1.2	1.0
DRP inputs from streams and rain	25.9	24.8
PP + DOP++ (base flow)	9.0	8.8
PP + DOP (floods)	10.0	10.0
Total PP + DOP from streams	19.0	18.8
Sewage (TP)**	7.5	8.0
Outflow (TP)	17.0	18.0

* Dissolved Reactive Phosphorus
++ Particulate phosphorus plus dissolved organic phosphorus
** Total phosphorus (persulphate digestion).

TABLE 2 Nitrogen Inputs and Output of Lake Rotorua (tonnes)

	1976	1977
TIN* (main streams)	295	276
TIN (minor streams)	11	11
TIN (unmeasured flow)	70	67
DON+	30	30
TIN (rain)	31	28
Dissolved N from streams and rain	437	412
PN** (base flow)	60	60
PN (floods)	50	50
Total PN from streams	110	110
Sewage (TN)++	68	64
Outflow (TN)	185	213

* Total inorganic nitrogen = ammonia plus nitrate nitrogen
\+ Dissolved organic nitrogen
** Particulate nitrogen
++ Total Kjeldahl nitrogen plus nitrate nitrogen

Table 3. Nutrient load estimates for four historical periods–Table 1 in Rutherford et al (1989). The nitrogen and phosphorus loads presented for period 3 (1976 – 1977) are average loads from Table 1 above, but do not include particulate nutrients from floods. Loads for the other periods, as well as the target loads, were calculated based on an estimated contribution to loading by septic tanks of 80 t N y^{-1} and 0 t P y^{-1}. The total nitrogen and phosphorus loads for each column are the sum of 'Stream (including septic tanks for nitrogen)', and 'treated sewage'. The 'Stream' categories also include dissolved inorganic nutrients from atmospheric deposition.

Factors (1)	1965 (2)	1976–77 (3)	1981–82 (4)	1984–85 (5)	Target (6)
Population	25,000	50,000	52,600	54,000	—
Phosphorus inputs (t/yr)					
Raw sewage	5	18	30	47	—
Treated sewage	5	7.8	20.6	33.8	3
Stream	34	34	34	34	34
Internal	0	0	20	35	0
Total	39	41.8	74.6	102.8	37
Nitrogen inputs (t/yr)					
Raw sewage	34	100	170	260	—
Treated sewage	20	72.5	134	150	30
Stream (including septic tanks)	455	485	420	415	405
Septic tanks	50	80	15	10	0
Internal	0	0	140	>260	0
Total	475	557.5	694	>825	435
Average lake water quality					
Total phosphorus (mg/m^3)	—	23.8	47.9	72.6	20
Total nitrogen (mg/m^3)	—	310	519	530	300
Chlorophyll (mg/m^3)	—	5.5	37.8	22.6	10
Chlorophyll a (peak; mg/m^3)	—	28	62	58	17–24
Secchi disc (m)	2.5–3	2.3	1.9	1.7	2.5–3
Oxygen depletion rate ($g/m^3/day$)	—	0.4	0.7	0.9	0.25

Note: Catchment area = 424 km^2; surface area = 81 km^2; mean depth = 10.7 m; volume = 0.865 km^3; outflow rate = 18.5 m^3/s; and residence time = 1.5 year.

Brief history of water quality monitoring of Lake Rotorua

The progression of early water quality sampling in Lake Rotorua is summarised in Rutherford (1984). Briefly, the Fisheries Research Laboratory, Ministry of Agriculture and Fisheries (MAF) conducted monitoring at intervals of between 1 week and 1 month at two fixed sites from March 1967 to September 1970, and at one site from April 1972 to July 1978. Methods, and some results were reported by Fish (1975). From October 1970 to May 1982 the Wildlife Service, Department of Internal Affairs (DIA), measured water temperature, dissolved oxygen, and Secchi disc depth at two sites at intervals of between 1 week and 1 month. Intensive surveys of the lake over shorter periods were made by Taupo Laboratory, Division of Marine & Freshwater Science, DSIR, (e.g., White et al. 1978).

From October 1978 the Bay of Plenty Catchment Commission (BOPCC) commenced regular monitoring, using similar sampling methods and determinants to MAF, but with laboratory analyses by the Water Quality Centre, Hamilton, and Ministry of Works and Development (MWD). In April 1980 sampling methods were changed to assess lake-wide means of chemical parameters, by taking depth-integrated samples at 10 sites, bulking, and analysing five replicates. Sampling intervals were changed to 2 months during winter and 1 month or 2 weeks in summer.

Rutherford (1984) reported that similar mid-lake sampling sites near the centre of the lake were used by MAF, DIA, and BOPCC and errors due to spatial differences should not be substantial. The Bay of Plenty Regional Council (then Environment Bay of Plenty) took over sampling of the lake in 1991, monitoring two central-lake sites (Sites 2 and 5) at multiple depths c. monthly until present, but with a break in sampling continuity over the mid- to late-1990s. Water quality findings are regularly reported by BoPRC in technical reports, and most recently, Stephens et al. (2018) assessed trends in in-lake water quality for the period 2001 – 2017.

Sustainable load targets

Sustainable nutrient load targets for Lake Rotorua of 435 t N y^{-1} and 37 t P y^{-1} were estimated in the 1980s, and have since been presented in numerous reports, Council policy, and been reconfirmed by Rotorua Lakes Water Quality Technical Advisory Group (TAG) statements. Clarity regarding where these estimates originated from and what they (or do not) encompass is thus important for any discussion of managing the lake, and modelling of future lake and catchment management scenarios.

The nutrient budgets of Hoare (1980, 1987) were used by Howard-Williams et al. (1986) and Rutherford et al. (1989) to propose sustainable catchment loads of 435 t N y^{-1} and 37 t P y^{-1}. Discussions of nutrient targets for Lake Rotorua at this time considered that particulate nutrients transported during floods should not be included in nutrient budgets or sustainable targets (due to rapid settling to the lake bottom and low bioavailability of these particles). Thus, the corresponding nutrient loads calculated by Hoare (i.e., excluding flood flow particulates) were 34 t P y^{-1} and 485 t N y^{-1}. These figures would have captured the contribution of any septic tank discharges upstream of measurement locations, and Hoare (1984) found that streams draining areas with septic tanks were enriched in nitrogen (but not phosphorus) relative to streams draining areas that lacked septic tanks but were otherwise similar. Rutherford et al. (1989) estimated the contribution of septic tank discharge in 1976-77 to be 80 t N y^{-1} (and 0 t P y^{-1} based on the findings of Hoare 1984). Subtracting this contribution from the budgets of Hoare (1987) gave estimated catchment loads without contribution from septic tanks of 34 t P y^{-1} and 405 t N y^{-1}. Loads from treated wastewater and internal nutrient recycling from lake sediments were then estimated for three additional time periods (1965, 1981-82 and 1984-85) to show total lake loading over time (Table 1 in Rutherford et al. 1989, reprinted as Table 3 in this report). Table 4 shows Table 1 from Rutherford (1989), reconfigured to show all components of the budgets and sustainable loads. In summary, the sustainable load targets include stream loads exclusive of particulate nutrients transported by floods, dissolved inorganic nutrients in rainfall, and allowances for additional treated wastewater loads of 30 t N y^{-1} and 3 t P y^{-1}.

Table 4. Rearrangement of Table 1 from Rutherford et al. (1989).

	1965	1976-77	1981-82	1984-85	Target
Phosphorus inputs (t P y^{-1})					
Streams (excluding septic tanks)	32.9	32.9	32.9	32.9	32.9
Rainfall	1.1	1.1	1.1	1.1	1.1
Septic tanks	0	0	0	0	0
(Sub-total) Catchment load	**34**	**34[a]**	**34**	**34**	**34**
Treated sewage	5	7.8	20.6	33.8	3
Internal load	0	0	20	35	0
(Total) External + internal load	**39**	**41.8**	**74.6**	**102.8**	**37**
Nitrogen inputs (t N y^{-1})					
Streams (excluding septic tanks)	375.5	375.5	375.5	375.5	375.5
Rainfall	29.5	29.5	29.5	29.5	29.5
Septic tanks	50	80	15	10	0
(Sub-total) Catchment load	**455**	**485[a]**	**420**	**415**	**405**
Treated sewage	20	72.5	134	150	30
Internal load	0	0	140	>260	0
(Total) External + internal load	**475**	**557.5**	**694**	**>825**	**435**

a) Measured by Hoare (1980), exclusive of particulate material delivered during stormflows.

Methods

Study site

Lake Rotorua is a relatively shallow (mean depth c. 10 m), polymictic lake, with an area of c. 80.6 km^2. Lake Rotorua's catchment is defined by the 'best estimate Lake Rotorua groundwater boundary' (Figure 1). This boundary is (mostly) based upon LiDAR data collected in 2006/2007 by Rotorua Lakes Council and, heading clockwise from roughly Kaharoa to Mamaku Township, it is coincident with the surface catchment boundary. However, the remaining area to the northwest on the Mamaku plateau is derived from topographic contours, water budgets and estimates of surface flow, and describes an additional area draining groundwater required to balance the water budgets in the Hamurana, Awahou and Waiteti streams (White et al. 2014). The total catchment area inclusive of this additional land is 538 km^2. This includes the lake and the 35.2 km^2 of land that is not within the surface topographic catchment.

The internal catchment boundaries represent surface sub-catchments based on 2006/2007 LiDAR data. The lake has nine major stream inflows which are monitored regularly by BoPRC for discharge and water chemistry (four are presently continuously gauged, in addition to the lake outflow). These nine inflows have individual mean annual discharges ranging from c. 0.3 to 2.6 $m^3 s^{-1}$. A substantial portion of the total catchment is not drained by any of these nine major streams (Figure 1). Multiple minor stream inflows each have estimated mean annual discharge of < 0.08 $m^3 s^{-1}$. Lake Rotokawau is included in the Rotorua catchment as it drains via a spring into the Waiohewa catchment, and subsequently Lake Rotorua (pers. comm., John McIntosh, 2009). The city of Rotorua lies entirely within the lake catchment and at present has c. 65,000 residents. Municipal wastewater is treated at the Rotorua Wastewater Treatment Plant and was previously pumped directly to the lake, but since 1991 has been discharged by spray-irrigation to the Whakarewarewa forest (Waipa/Puarenga sub-catchment). At present much of the catchment is pastoral, including substantial dairy and dairy support land. There are also large areas of forest, with native and exotic cover in roughly equal measure (Appendix figure 3a).

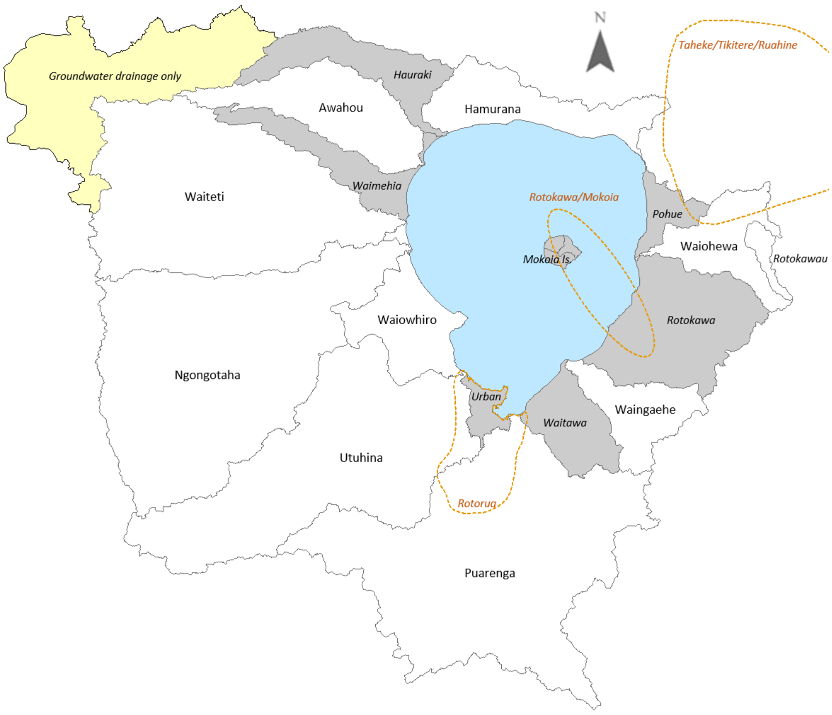

Figure 1. Map of the Lake Rotorua with surface sub- catchment boundaries. Major sub-catchments are shown in white, ungauged areas in grey, an area for which only groundwater drains to the lake in yellow (source: BoPRC), and geothermal fields are outlined in orange (source: LINZ).

Geothermal areas

Lake Rotorua is considered moderately geothermally influenced, with McColl (1975) observing lake water chloride concentrations of c. 25 mg Cl L^{-1}. The Rotorua catchment has three geothermal fields (Figure 1) with differing nitrogen concentrations. The Tikitere field discharges via the Waiohewa Stream inflow to the lake. Geothermal waters in this area are extremely high in ammonium, and recent monitoring suggests an estimated load of approximately 30 t N y^{-1} (pers. comm. P. Dine, in Rutherford et al. 2011), accounting for the majority of the nitrogen load in the stream. The Whakarewarewa (Rotorua) field has upflow regions in the Sulphur Bay and Polynesian Pools areas, Kuirau Park and Ohinemutu, Ngapuna may be a separate field with upflow near the mouth of the Puarenga Stream. Total nitrogen concentrations within the Whakarewarewa field are much lower, and the estimated load averages 0.32 t N y^{-1} (Ellis and Mahon 1977, White et al. 2004). Hoare (1985) estimated an ungauged discharge of geothermal fluid of approximately 0.6 m^3 s^{-1}.

Water quality

Lake Rotorua's water quality is classed as eutrophic, with average surface water concentrations of 321 mg TN m^{-3}, 20 mg TP m^{-3}, and 12.2 mg chl *a* m^{-3} for the period 2009 – 2014. Using these data, chl *a* violates the prescribed bottom line in the National Objectives Framework of the National Policy Statement for Freshwater Management (2014). The lake experienced severe blooms of the cyanobacteria *Dolichospermum* (formerly known as

Anabaena) sp. and *Microcystis* sp. in the early 2000s, but water quality has improved substantially over the past 10 years, coinciding with alum dosing of two major inflows, the Puarenga (commencing 2006) and Utuhina (commencing 2010) streams (Smith et al. 2016). The present TN:TP ratio of Lake Rotorua water is approximately 16:1 (by mass). This is comparatively high relative to other lakes in the region and likely due to the alum dosing which tends to preferentially suppresses phosphorus concentrations relative to nitrogen (Ozkundakci et al. 2014, Hamilton et al. 2015). Current dissolved and total nutrient concentrations suggest that lake phytoplankton may be predominantly P-limited; however, recent nutrient limitation assays conducted over several days have also observed primary N limitation and co-limitation in areas of the lake (e.g. Abell et al. 2015). A time sequence of nutrient limitation studies is provided by Smith et al. (2016), indicating predominantly N-limitation of phytoplankton in the 1970s but a greater frequency of co-limitation in the 2000s.

Study period

Model inputs, including daily inflow discharge and concentrations, meteorological data and lake water balance, were obtained or estimated for the period July 1964 to June 2017.

Meteorology

Rainfall, air temperature and relative humidity data were obtained from the National Climate Data Base (www.cliflo.co.nz ; 1964 to 2012) and the New Zealand MetService (2013 to 2017), for the Rotorua Airport climate stations (CLIFLO site ID 1768) located c. 50 m from the eastern shoreline of Lake Rotorua. Prior to 1966, Rotorua airport data were not available, therefore data from the nearest available site were used with linear regression of paired measurements during overlapping periods used to infill gaps with adjusted data from the substitute site. Data were standardised to daily average values, (daily total for rainfall).

Bathymetry

Bathymetric data were obtained from a multi-beam sonar survey (2006) by the Coastal Marine Group, University of Waikato, with data supplied by BoPRC.

Water balance

Daily water balance for Lake Rotorua was calculated as:

$$Outflow = \sum(inflows) + rainfall - E_L - \Delta S \quad (1a)$$

where:

E_L is evaporation in $m^3\ d^{-1}$

ΔS is change in storage in $m^3\ d^{-1}$

Evaporation was calculated following the DYRESM science manual (CWR 2012). Daily average Ohau Channel (outflow) discharge was calculated from sub-daily gauging taken by NIWA

(1989 to 2010) and BoPRC (2010 to 2017) at Mission Bay. Change in lake storage was calculated from daily water level data collected by BoPRC (Mission Bay) multiplied by the water level-dependent lake area derived from the hypsographic curve. For calculation of evaporation, airport air temperature for the entire period of 1954 – 2017 was adjusted using regression air temperature measurements from 2007 to 2012 against data from a high-frequency monitoring buoy at a mid-lake site.

Surface inflow discharge data for nine major stream inflows to the lake were collated from a range of datasets curated by BoPRC. Daily measurements of mean discharge were available for eight inflows, but for all inflows there were substantial periods with missing observations. Spot measurements of flow were available at all inflows for most years of the modelled period. To fill the gaps in the continuous flow records, a synthetic flow model was constructed for each major stream using symbolic regression (Eureqa®) or LOESS relationship (R statistics), optimised against available gauging/flow measurements and model coefficients were adjusted to minimise the error in total volume of water discharged over the continuously gauged period for each inflow. For each major inflow, a synthetic discharge time-series was made for the period 1 July 1964 to 30 June 2017, using continuous gauging data when available, and the synthetic flow model for non-observed periods. Hamurana Stream was not continuously gauged. This stream flows from a groundwater spring a short distance upstream of the lake and exhibits minimal ‘flashiness’, although total flow varies substantially over monthly to interannual timescales. Therefore, daily Hamurana flow was estimated by linear interpolation of c. monthly spot flow measurements, with some periods filled by a regression model, due to insufficient spot measurements.

Because gauging data are available for the Rotorua outflow, equation 1a was rearranged to calculate the residual (ungauged) inflow component of the water balance:

$$Ungauged = Outflow + E_L + \Delta S - \sum(major\ inflows) - Geo - rainfall \qquad (1b)$$

where:

Ungauged is the residual volume of water balance 1a

Geo is volume of geothermal water discharged to the lake, set as a constant volume of 0.5 $m^3\ s^{-1}$; a slightly conservative adoption of the 0.6 $m^3\ s^{-1}$ estimated by Hoare (1980).

Where the daily ungauged term was negative, this volume was transferred to the following day, with this process repeated for subsequent days until a positive daily volume occurred. Daily ungauged volume was then divided (somewhat arbitrarily) into components of ‘slow flow’ (groundwater, 30% of ungauged) and ‘quick flow’ (minor stream and overland flow, 70% of ungauged). Rolling averages of 15 days (slow flow) and two days (quick flow) were applied to these inflows.

Flow separation

Baseflow separation was performed for the flow time-series of each major inflow, following the method of Pettyjohn and Henning (1979), as in Rutherford (2008), i.e., baseflow was set as the minimum of the previous 10-days discharge. Flood flows were identified where discharge was greater than two-fold base flow for a given inflow and day.

Inflow nutrient concentrations

Nutrient concentrations were assigned to stream inflows based on measured data. Daily concentrations of dissolved inorganic nitrogen (NO_3-N and NH_4-N) and phosphorus (PO_4-P) were estimated by linear interpolation of monthly measurements collected by BoPRC. Samples collected during flows greater than 120% of baseflow were excluded from interpolation to reduce any bias introduced by inclusion of concentrations measured during transient events (e.g., dissolved reactive phosphate (PO_4-P) concentration may be temporarily depressed by adsorption to high particulate concentration during stormflows).

Inflow nutrient concentrations were not available for the beginning of the study period, however, McDowell (2013) estimated reference concentrations for streams of various New Zealand River Environment Classification (REC) classes, and Tempero et al. (2015) adapted these to account for geological evolution of dissolved phosphorus in old-age groundwater. These concentrations were adopted and assumed representative of local conditions in the year c. 1900. Concentrations as at July 1959 were then estimated by linear interpolation between 1900 and the first available nutrient measurements of Rotorua inflows (c. 1967).

Although Fish (1975) measured dissolved nutrients in eight major inflows from 1967 to 1969, raw data were unavailable and only mean concentrations (+/- standard deviation) were reported. These concentrations were adopted for dissolved nutrients of 1967 – 1969. Total nutrients were estimated by calculating the non-inorganic, (e.g., total nitrogen – dissolved inorganic) fraction for measurements 1975 – 1977, and adding these values to the measurements of the Fish (1975) study. For periods of more than one year with no samples available, concentrations were set as the average of the two years of adjacent data.

Baseflow concentrations of total nitrogen and total phosphorus were also estimated by linear interpolation. However, concentrations of particulate nitrogen and phosphorus have been shown to positively correlate with discharge for the Ngongotaha, Puarenga and Utuhina Streams (Hoare 1982; Rutherford 2008, Abell et al. 2013), and failure to account for this effect results in underestimation of long–term loads to the lake (Abell et al. 2015).

To investigate discharge-concentration relationships, log-log regression of nutrient concentrations on discharge was performed for (total nitrogen minus dissolved inorganic nitrogen) and (total phosphorus minus PO_4-P) all major inflows, using data for all available samples. A bias correction (as per Abell et al. 2013) was performed for these relationships.

Nutrient concentrations for the geothermal flow were estimated from measurements of geothermal springs in the Lake Rotorua catchment between 1992 and 1994 (eight springs with ~21 samples per stream). The volumetrically averaged value for each analyte from all springs was adopted as a constant concentration. The total discharge of all measured springs (~0.06 $m^3 s^{-1}$), was a small fraction of the total volume estimated by Hoare (1985) as 0.6 $m^3 s^{-1}$, and the representativeness of the measured springs for the total geothermal flow is unknown.

Nutrient concentrations for the slow-flow residual component of the water balance (broadly representative of groundwater discharge) were based on average values for the groundwater-dominated Hamurana and Awahou Streams. Concentrations for the quick-flow residual component were set as the average of the Utuhina, Ngongotaha, Waiowhiro, Waingaehe, and Waiteti Streams because total discharge in these streams comprises a relatively high proportion of quick-flow and they were assumed to be reasonably representative of most of the catchment (Waiohewa was excluded due to strong geothermal influence and Puarenga was not included due to the influence of the Land Treatment System).

Concentrations of nutrients in atmospheric deposition were taken from a recent literature review by Verburg et al. (2015) for available measurements from the North Island of New Zealand. Both wet (dissolved) and dry (particulate) nutrient deposition were accounted for using this method. Atmospheric deposited total nutrient concentrations were therefore higher than those used in previous Rotorua nutrient budgets, which typically only considered wet deposition. However, the values reported by Verburg gave similar dissolved inorganic nitrogen and PO_4-P yields for Lake Rotorua to those reported by Hoare (1980, 1987) which were widely adopted in literature, management and sustainable load targets.

Wastewater discharge concentrations pre-1991 were estimated by interpolation of data collected by Hoare (1987) and Rotorua District Council (RDC), and were set as constant concentrations for the early years when no data were available. Wastewater discharge volume was also interpolated from available measurements, but was estimated from records of Rotorua City's population for years where discharge data were unavailable, using the population-discharge relationship for years when data were available. From 1991 additional loads to Lake Rotorua from wastewater are captured by Puarenga Stream data, which are measured downstream of the confluence with Waipa Stream (which drains the LTS). Rotorua Lakes Council estimate total nutrient loads derived from the LTS based on regular monitoring of the Waipa Stream (a tributary to Puarenga Stream), but do not account separately for dissolved and particulate species. Therefore, an assumption was made that these loads would be 80% NO_3 (for total nitrogen from the Land Treatment Scheme) and 50% PO_4-P (for total phosphorus), because nitrogen is likely delivered predominantly by subsurface drainage, whereas phosphorus is more likely to be lost from land via erosion and overland flow (Me et al. 2018).

Lake water quality

Lake water quality datasets were obtained from various sources (see Introduction and Acknowledgements). Although temporal coverage was relatively good for most variables (Figure 18), sampling frequency was notably inconsistent when examined in detail. Although c. monthly data were available post-2002, sampling during earlier years was often less consistent. Further complicating matters was a switch from discrete-depth surface sampling to integrated tube sampling (usually 0 – 6 m depth) from 2002.

To minimise the effects of variable sampling frequency, we took a multi-step aggregation approach to estimate annual Trophic Level Index (TLI) values with a consistent as possible representation of intra-annual variation (i.e., this was to reduce bias in annual means due to seasonal variation when sampling was unevenly distributed throughout the hydrological year). Monthly median values were calculated for all mid-lake surface water samples for each month of all years from available data. Monthly medians were then used to calculate seasonal mean values, which in turn were used to calculate annual means. These annual means were then used to calculate the four component TLI values, the mean of which is the overall TLI.

The aggregation approach used here means that values may differ slightly from TLI values published elsewhere for recent years, however it should better enable comparison of recent TLI with estimated TLI from historical data (i.e., prior to the temporally consistent sampling from 2002 onward).

Results

Daily discharge and nutrient concentrations were collated and/or statistically modelled to resolve a complete water balance of Lake Rotorua, including the nine major inflows, atmospheric deposition, ungauged geothermal sources and residual (ungauged) catchment discharge. These data enabled estimation of annual nutrient loads for the entirety of the Lake Rotorua active monitoring and management period (approximately the mid-1960s to present). Loading estimates were derived using a range of sources and methods, the results of which are summarised below.

Meteorology

Daily meteorological inputs to the lake water balance are shown in Figure 2. Annual rainfall (Figure 3) recorded at Rotorua airport for hydrological years 1965 to 2017 varied substantially, ranging from less than 1000 mm to more than 2000 mm per year.

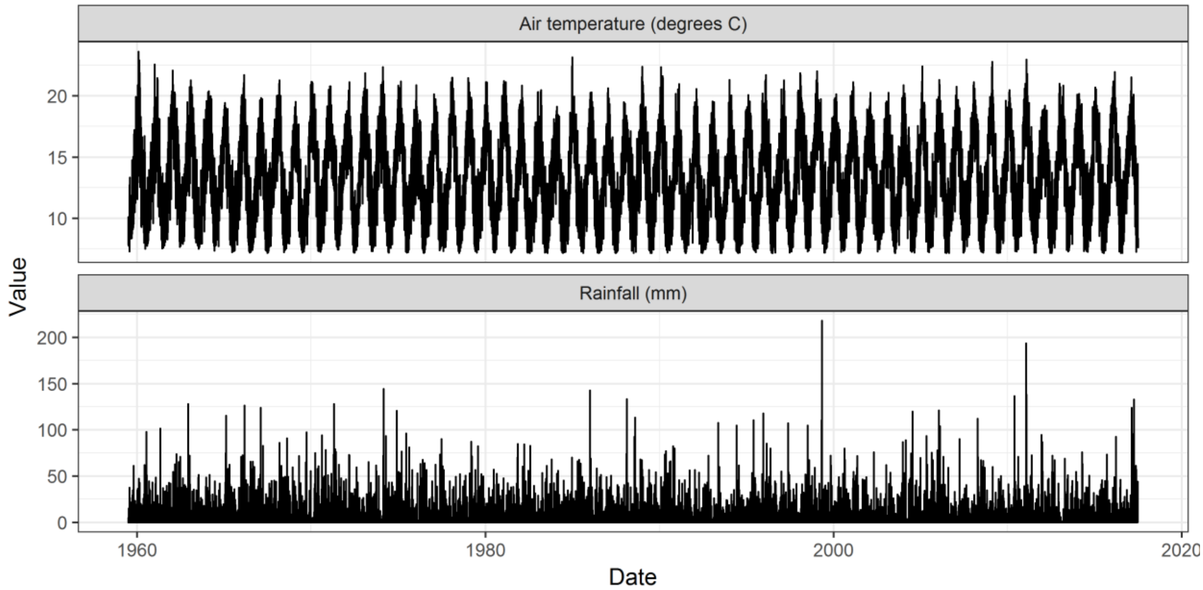

Figure 2. Summary of daily meteorological inputs to water balance and load calculations, 1964 to present.

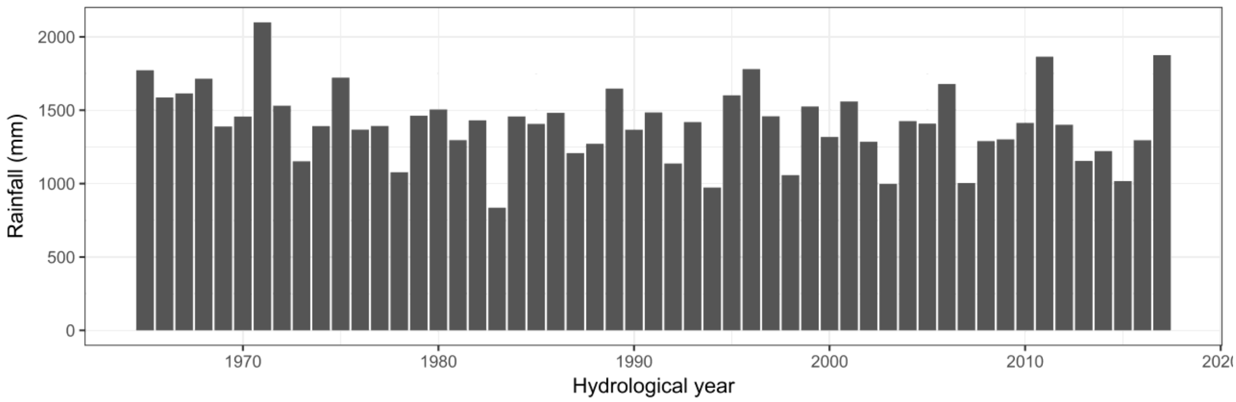

Figure 3. Summary of annual rainfall recorded at Rotorua airport (or adjusted data from Ngakuru prior to 1966), 1965 to present. For the model, airport rainfall was multiplied by a factor of 1.19 to account for spatial variation in rainfall across the lake surface (see Hoare 1980, Rutherford et al. 2011).

Stream discharge

Discharge was often strongly correlated among inflows (Figure 4). Modelled flows were derived from either LOESS relationship with the Utuhina discharge (where flow dynamics between streams were similar), or by symbolic regression using rainfall and soil moisture indices as predictive variables (generally, where stream discharge co-varied with average rainfall over time scales greater than one year, flow in the Utuhina was a poor predictor). For all stream flow models, coefficients were adjusted such that bias in total volume of water for modelled versus measured discharge was within ±0.5% across all periods with continuous gauging. Figures 5–7 summarise continuous flow gauging (blue lines), spot flow measurements (red dots) and modelled discharge (grey lines) for the nine major stream inflows to Lake Rotorua. Final daily time-series of discharge were compiled using continuous gauging data when available, and synthetic flow models for days where gauge data were unavailable.

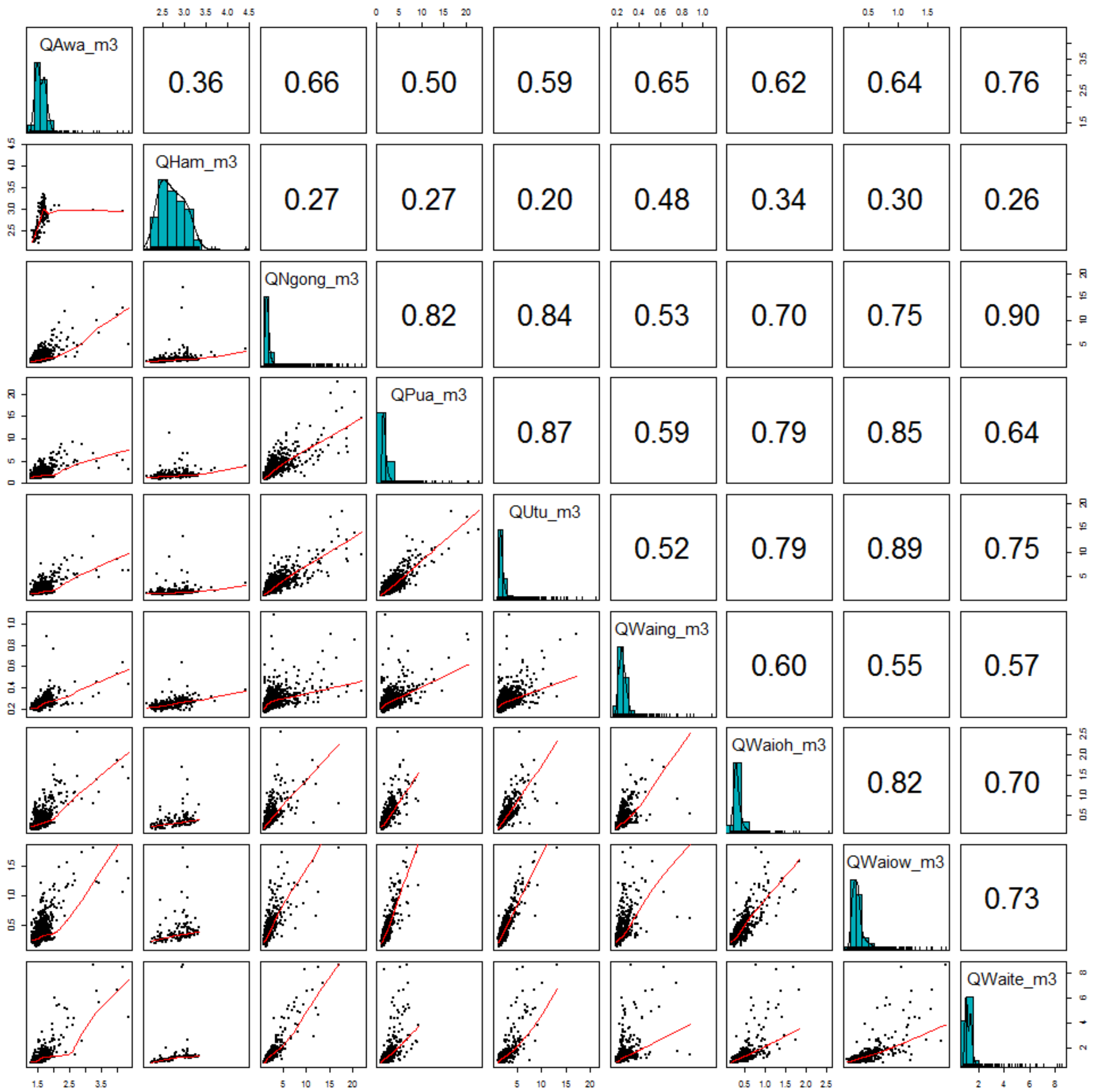

Figure 4. Matrix of discharge relationships between all possible pairs of major stream inflows to Lake Rotorua. Bivariate scatter plots of discharge (m^3 s^{-1}) with LOESS regression curves (red) are shown below the diagonal, histograms showing relative frequency of discharge are shown on the diagonal, and Pearson correlation for each inflow pair is shown above the diagonal.

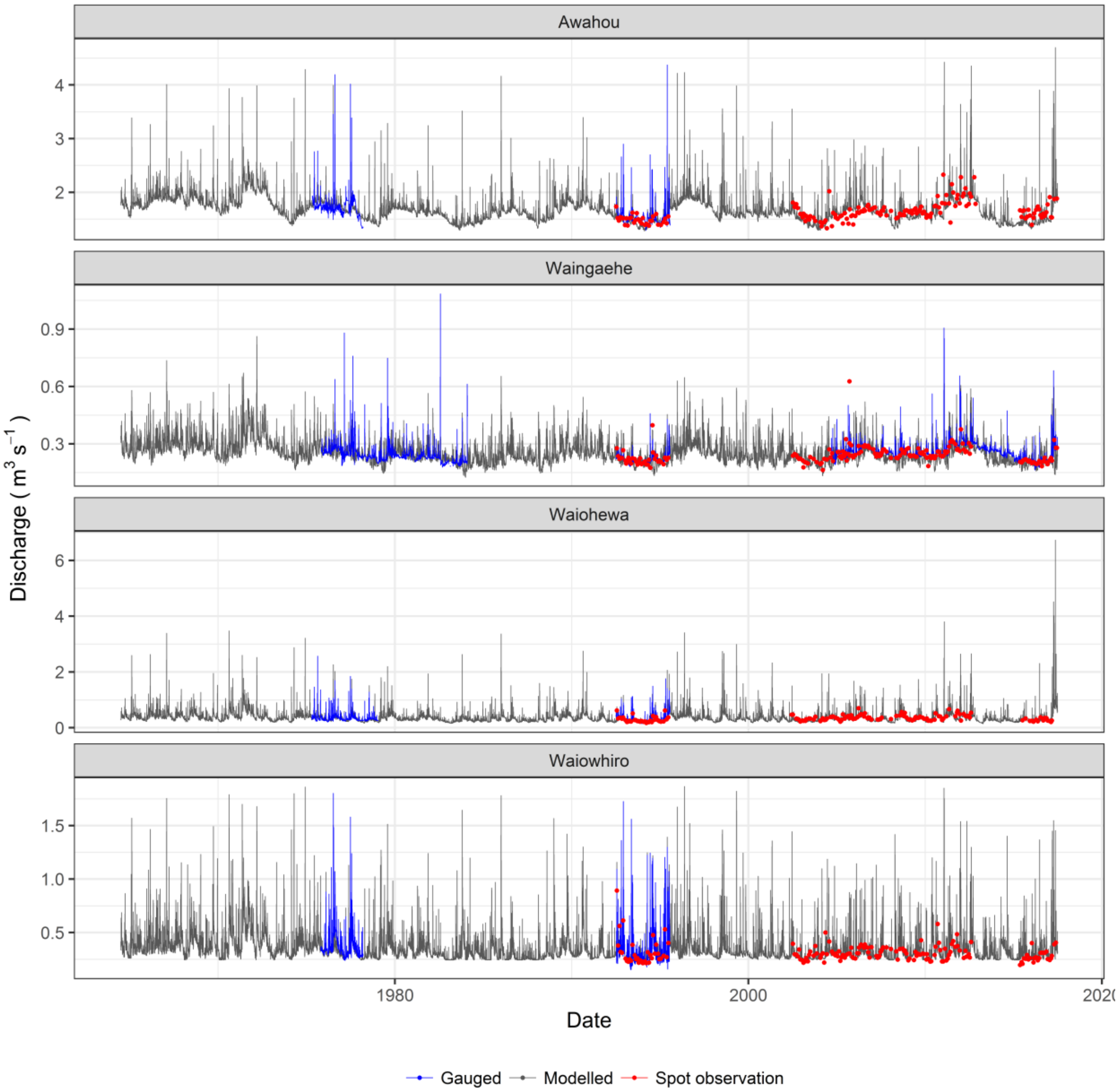

Figure 5. Simulated and measured discharge for four major inflows to Rotorua.

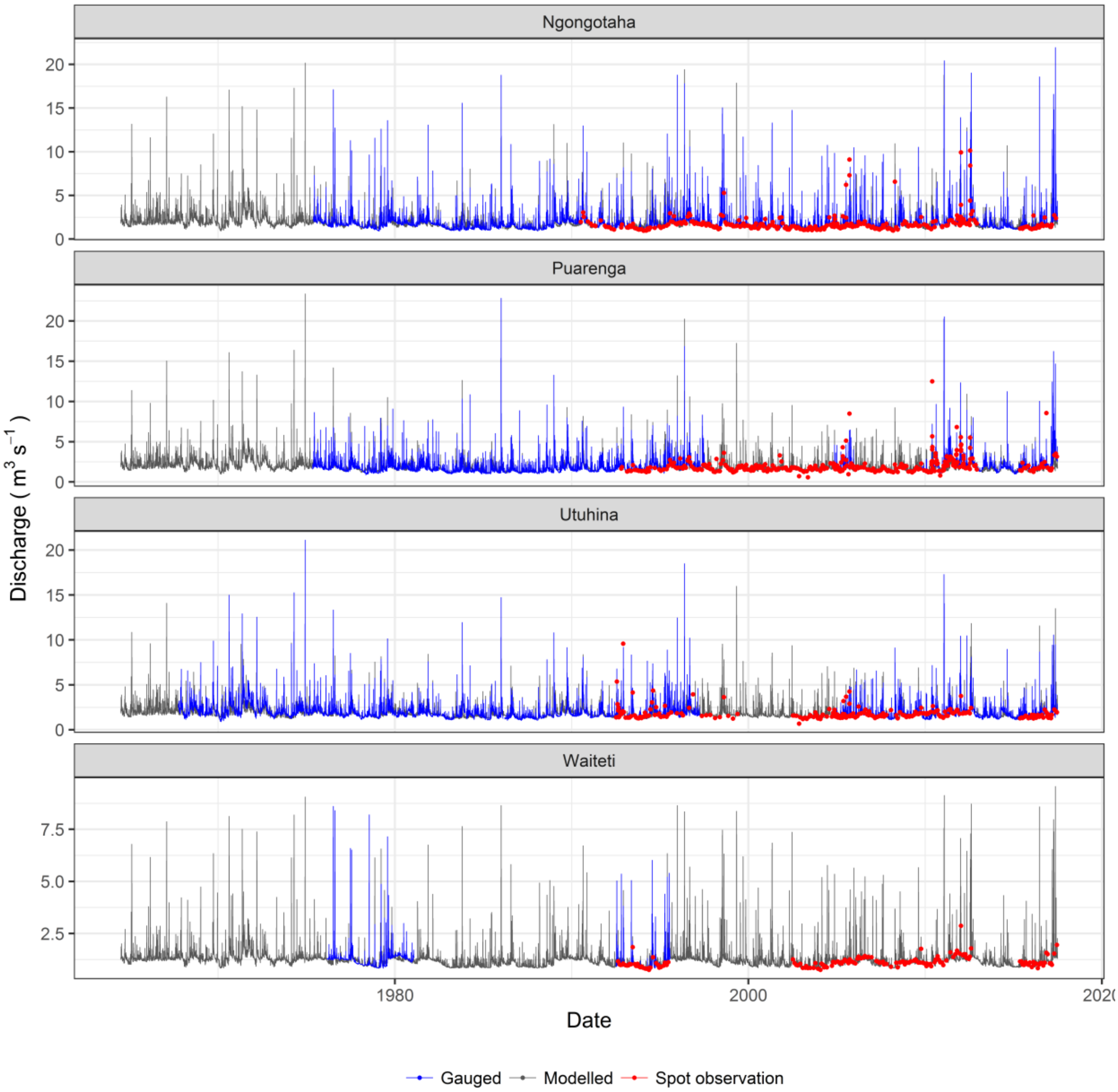

Figure 6. Simulated and measured discharge for four major inflows to Rotorua.

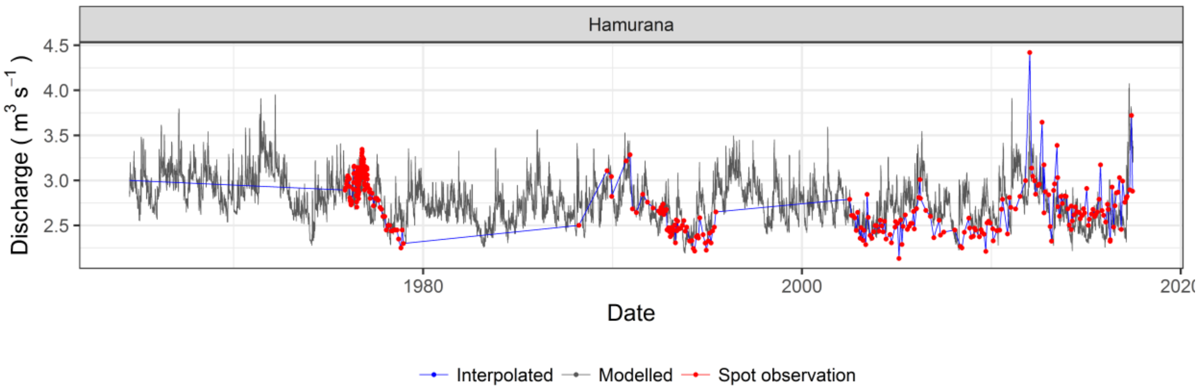

Figure 7. Simulated and measured discharge for the Hamurana Spring inflow to Rotorua.

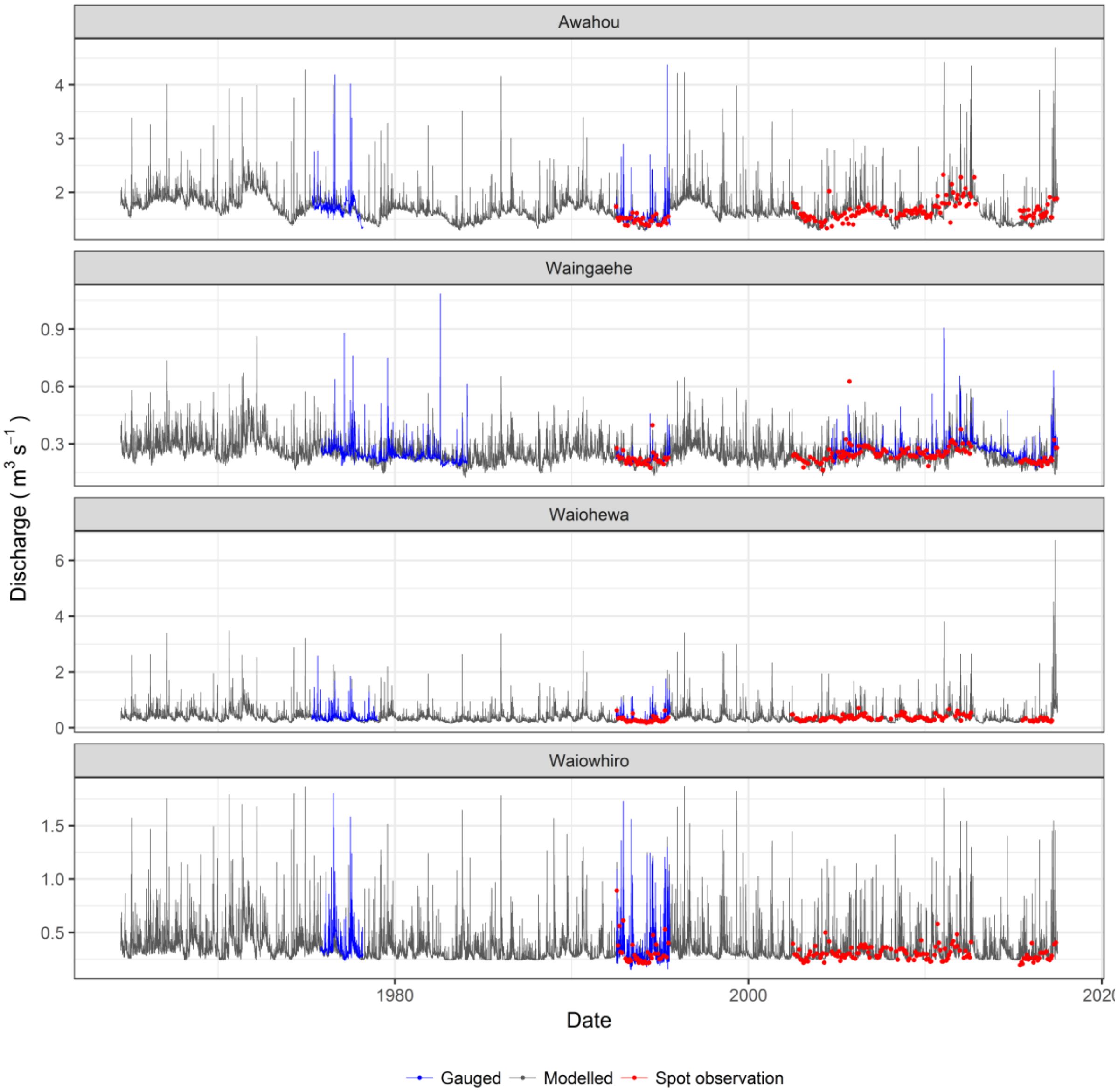

Figure 8. Simulated and measured discharge for four major stream inflows to Rotorua.

Water balance

A total catchment/lake water balance was resolved at a daily time-step for the period 1964 to 2017, and components of this water balance are summarised in Figure 8. The period 2005 to 2015 was characterised by a greater volume of (estimated) ungauged discharge. This could be due to a change in Ohau Channel gauging, inconsistencies between stream flow models and gauging, or a result of patterns of rainfall in these years that caused a high proportion of ungauged inflow such as overland runoff to the lake.

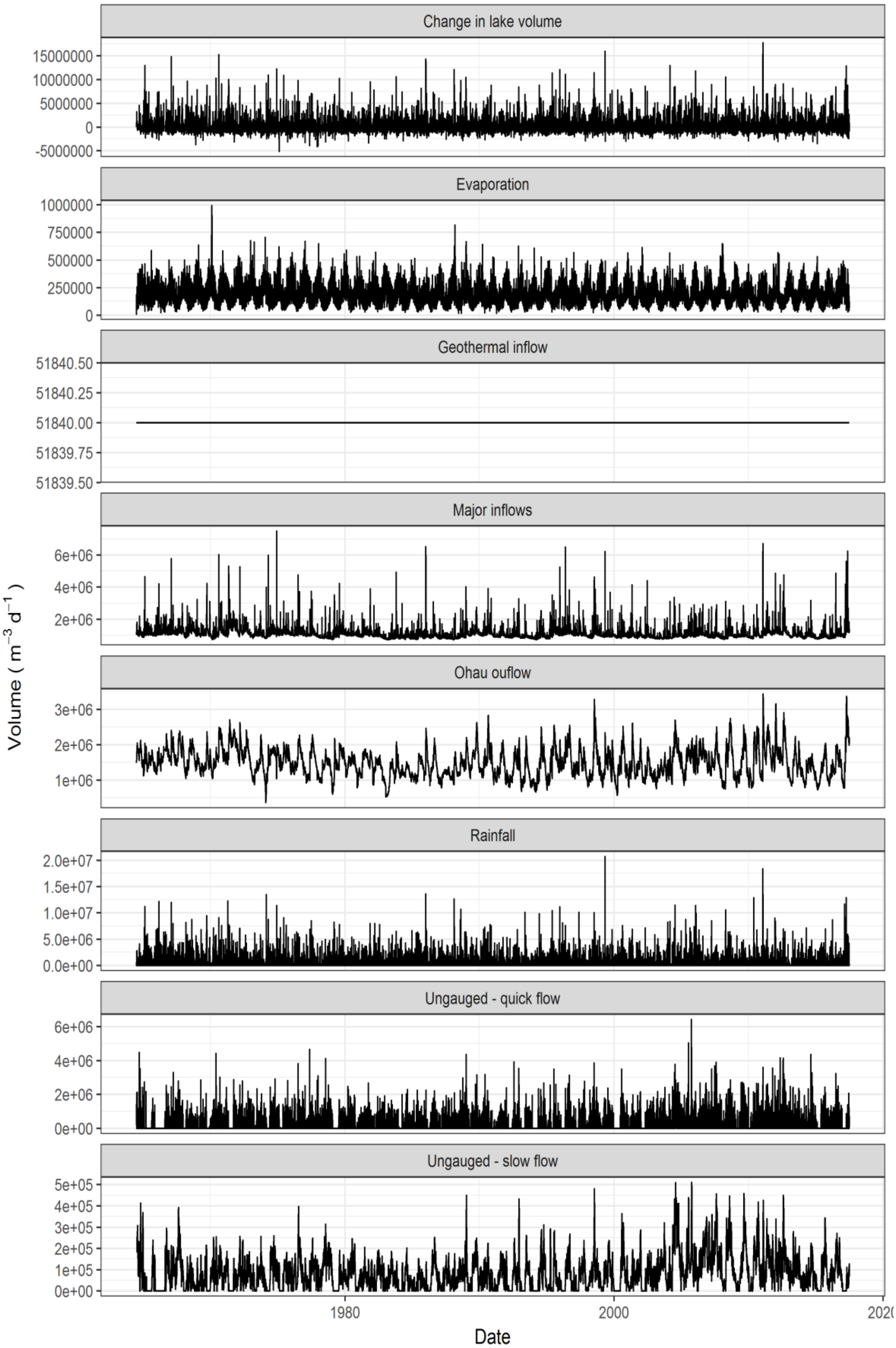

Figure 9. Summary of the water balance for load calculations for Lake Rotorua, 1964 to present.

Nutrient inputs

Table 5 presents estimated 'reference' concentrations of nitrogen and phosphorus in Lake Rotorua inflows. Reference concentrations are here assumed to be indicative of the pre-intensification period, ending c. 1900.

Table 5. Estimated reference concentrations (c. 1900) of nitrogen (N) and phosphorus (P) for major inflows to Lake Rotorua. Reference concentrations for nitrogen taken from McDowell (2013). Concentrations for phosphorus are from Tempero et al. (2015) and account for geologically derived phosphorus in old-age groundwater on a volumetrically-weighted basis.

	NH_4-N $g\ m^{-3}$	NO_3-N $g\ m^{-3}$	TN $g\ m^{-3}$	PO_4-P $g\ m^{-3}$	TP $g\ m^{-3}$
Awahou	0.001	0.016	0.027	0.053	0.059
Hamurana	0.001	0.013	0.030	0.073	0.081
Ngongotaha	0.001	0.016	0.027	0.020	0.027
Puarenga	0.002	0.102	0.107	0.031	0.042
Utuhina	0.001	0.016	0.027	0.034	0.041
Waingaehe	0.002	0.102	0.107	0.062	0.074
Waiohewa	0.002*	0.102*	0.107*	0.030	0.035
Waiowhiro	0.002	0.102	0.107	0.032	0.043
Waiteti	0.001	0.016	0.027	0.015	0.023

* assumed similar to Waiohewa, due to River Environment Classification category not being included in McDowell (2013), and is exclusive of geothermal load to Waiohewa Stream.

Table 6 summarises average stream dissolved inorganic nutrient concentrations reported by Fish (1975). Because source data (n ~ 60 sampling occasions 1967 – 1969) were unavailable, for the present study mean concentrations were adopted as static values for 1967 – 1969. Total nutrients were not measured by Fish (1975), hence, total nutrients for this period were estimated by summing the values from Table 6 to estimate total minus inorganic nutrients (e.g. TN – DIN) for the first two years of measurements of Hoare (1980, 1987). Concentrations at the beginning of the study period (01 July 1964) were then derived by linear interpolation between reference concentrations and the values measured and/or estimated for 1967.

Table 6. Average inflow concentrations for c. 60 measurements per stream from 1967 to 1969 (Fish 1975). Waiowhiro Stream and total nutrients were not measured.

	NH_4-N $g\ m^{-3}$	NO_3-N $g\ m^{-3}$	PO_4-P $g\ m^{-3}$
Awahou	0.010	0.640	0.066
Hamurana	0.001	0.310	0.081
Ngongotaha	0.020	0.300	0.035
Puarenga	0.100	0.090	0.090
Utuhina	0.050	0.410	0.071
Waingaehe	0.030	0.340	0.110
Waiohewa	1.500	0.650	0.059
Waiowhiro	-	-	-
Waiteti	0.020	0.490	0.040
Rainfall	0.300	0.060	0.019

Geothermal inputs

Monitoring of geothermal springs in the Rotorua catchment was undertaken by BoPRC in the early 1990s on approximately 20 occasions. Table 7 summarises these measurements, including the volumetrically weighted average values that were adopted for the entire geothermal component of the water balance in the present study (set to 0.5 $m^3 s^{-1}$ after Hoare 1985). This report presents this 0.5 $m^3 s^{-1}$ geothermal flow as the 'geothermal' component of the water balance, however, it should be noted that this is the ungauged geothermal load only, and that, for example, the gauged Waiohewa Stream includes substantial geothermal water and nutrients. Also notable are the high PO_4-P concentrations measured in most geothermal upwellings by BoPRC. Here it was assumed that these springs are indicative of the nutrient concentrations for the entire ungauged geothermal flow, however, this may not be the case.

Table 7. Average measured concentrations of geothermal springs in the Lake Rotorua catchment. Means for approximately 20 samples collected between 1992 and 1994. Averages are volumetrically-weighted.

	Discharge	PO_4-P	NH_4	NO_3	TKN	TP	TN
	$m^3 s^{-1}$	$g m^{-3}$	$g m^{-3}$	$g m^{-3}$	$g m^{-3}$	$g m^{-3}$	$g m^{-3}$
Black Stream	0.005	0.248	0.968	0.026	1.798	0.333	1.824
Ohinemutu Springs	0.010	0.075	0.258	0.013	0.462	0.096	0.475
Tunuhopu Springs	0.006	0.068	0.091	0.156	0.553	0.212	0.709
Sewer Stream	0.014	0.302	0.092	0.003	0.260	0.331	0.263
Pipe Stream	0.003	0.060	0.262	0.004	0.572	0.211	0.576
Polynesian Springs - South	0.001	0.244	0.355	0.003	0.522	0.398	0.525
Polynesian Springs - North	0.012	0.192	1.045	0.003	1.330	0.271	1.333
Springs Outlet	0.002	0.309	0.759	0.032	1.478	0.362	1.510
Total flow, mean concentration	*0.053*	*0.186*	*0.457*	*0.026*	*0.784*	*0.254*	*0.810*

Atmospheric deposition

Table 8 summarises previous and current estimates of atmospheric nutrient deposition rates to Lake Rotorua. Early estimates by Fish (1975) and Hoare (1987) included only dissolved inorganic nutrients. Recent estimates by Verburg et al. (2015) are somewhat lower for dissolved nutrients, although total deposition is greater because of the inclusion of dissolved organic nutrients and particulate deposition. Historically, values adopted for management of Lake Rotorua were typically based on the estimates of Hoare (1987) of c. 30 t N y^{-1} and 1 to 1.5 t P y^{-1}. Notably, if particulates are excluded (as they often are for informing the management of loads in stream inflows), then the recent estimates for total loading (including dissolved organic phosphorus and dissolved organic nitrogen) are similar to those of Hoare (1987; DIN and PO_4-P only). This is convenient as adopting the recent values of Verburg et al. (2015) does little to alter previously used estimates of atmospheric deposition.

Table 8. Summary of measurements of dissolved nutrient concentrations in rainfall (Fish 1975 and Hoare 1987), and areal loads taken from a literature review of North Island studies by Verburg et al. (2015). Note that early estimates did not account for dissolved organic species, nor dry (particulate) deposition. Values from Verburg et al. (2015) were converted into concentrations using mean Rotorua rainfall and were adopted for the present study. DIN = Dissolved Inorganic nitrogen (NO_3-N + NH_4-N), DON = Dissolved Organic Nitrogen, PN = Particulate Nitrogen, DOP = Dissolved Organic Phosphorus and PP = Particulate Phosphorus.

	Fish (1975)	Hoare (1987)		Verburg et al. (2015)	
	g m^{-3}	t y^{-1}	g m^{-3}	kg ha^{-1} y^{-1}	g m^{-3}
NO_3-N	0.06			0.72	0.05
NH_4-N	0.30			2.18	0.16
DIN	*0.360*	*29.5*	*0.264*	*2.40*	*0.18*
DON				2.10	0.15
PN				1.05	0.08
TN				***6.37***	***0.47***
PO_4-P	0.019	1.1	0.010	0.147	0.011
DOP				0.080	0.006
PP				0.110	0.008
TP				***0.340***	***0.025***

Inflow nutrient monitoring

Figure 9 summarises all nutrient measurements available from all sources (with sources represented by different colours) for Lake Rotorua's nine major inflows. Targeted stormflow monitoring studies of Abell et al. (2013) and NIWA (1990s and mid-2000s) are notable for the differences in concentration range compared with the c. monthly (generally baseflow) regular monitoring of BoPRC. Not accounting for additional nutrients (predominantly particulates) transported during high flows would result in underrepresentation of total 'load-to-lake'. Nevertheless, in the present study we have accounted for stormflow particulates separately, so that loads may be presented as both with (total load) and 'non-stormflow-particulate' (NSP) loads, to enable direct comparison with NSP loads that have been previously adopted for management targets for Lake Rotorua (e.g., Rutherford et al. 1989).

Dissolved nutrients

Figures 10 and 11 summarise measurements of nitrate and phosphorus (measured and estimated) for all water sources to Lake Rotorua. Daily concentrations were derived by linear interpolation of observations (blue dots). Those observations excluded from interpolation (i.e., taken at flows > 120 % of baseflow) are shown as red dots. Average PO_4-P concentrations for 1967 to 1969 reported by Fish (1975) are substantially higher than those reported for later periods (including by Hoare for samples taken less than a decade later). This could reflect fertiliser application methods at the time, or could be due to differences in sample collection and/or analytical methods. However, values reported for Waingaehe, Waiteti and Ngongotaha were only marginally elevated relative to later measurements from different laboratories, implying that a consistent (methodological) offset may be unlikely. Because source data are not available, the values reported by Fish, and presented here, should be treated with greater caution than later measurements.

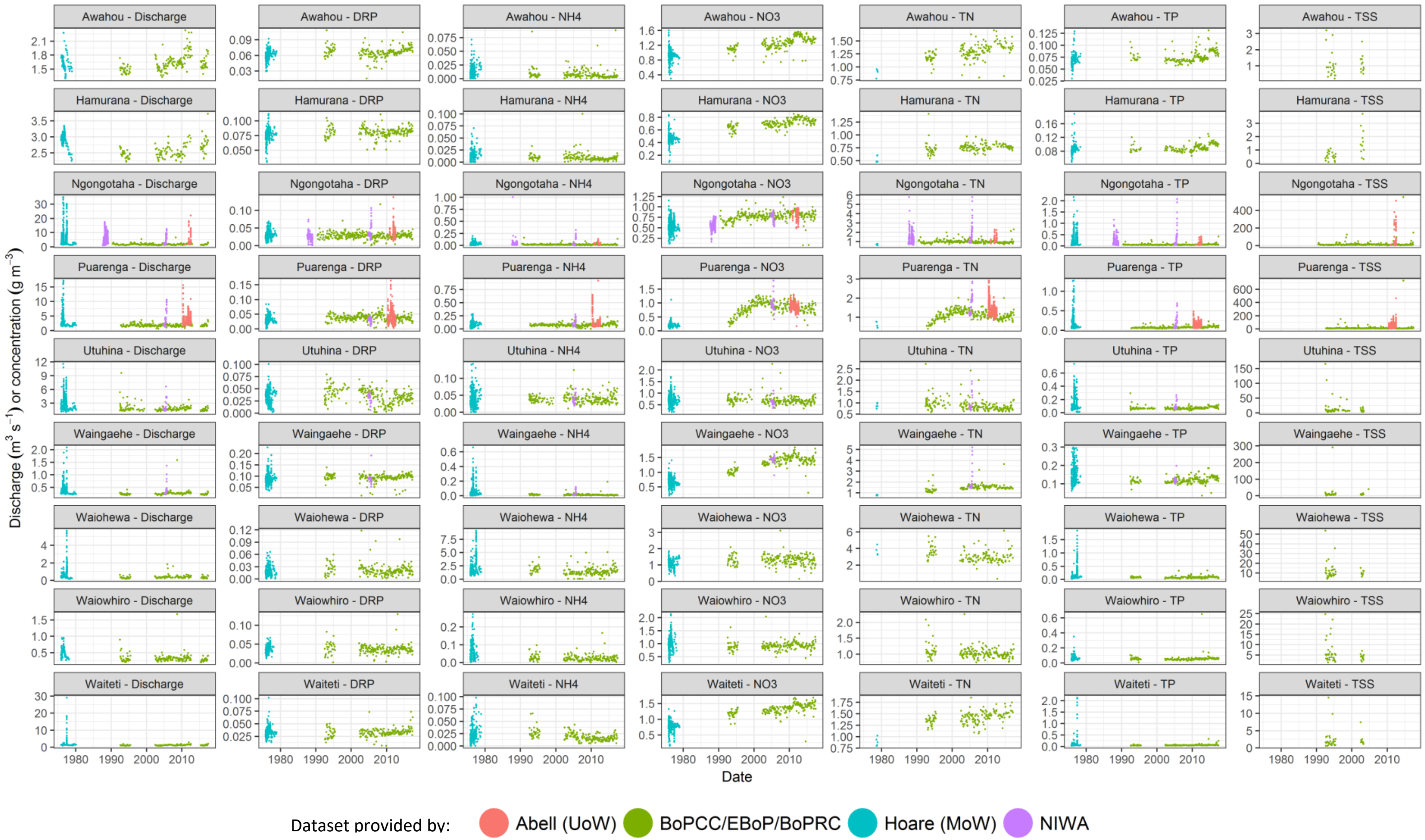

Figure 10. Summary of inflow measurements used to derive stream inflow loads to Lake Rotorua. The colour of each value represents the person or agency responsible for its collection and/or analysis. Plots show all samples prior to daily aggregation of values. The studies of Abell and Hoare show greater variability because they captured stormflows, whereas other datasets primarily captured baseflow conditions.

Following values reported by Fish (1975) for the late 1960s, PO_4-P concentrations in inflows to Lake Rotorua appear fairly stable. This would be consistent with a predominance of geologically-derived dissolved phosphorus. Measurements of PO_4-P (Figure 10, blue and red dots) in the Utuhina Stream reflect the effects of alum (the sampling point is downstream of the dosing site), whereas for the Puarenga Stream (monitored upstream of the dosing site), post-dosing concentrations of PO_4-P were estimated (grey line) after the method described in Hamilton et al. (2015). Thus, in Figure 10 the effects of alum dosing are visible in the estimated concentrations of PO_4-P in the Puarenga (post-2006) and Utuhina Streams (post-2010), where concentrations (grey line) are often substantially lower than earlier observations.

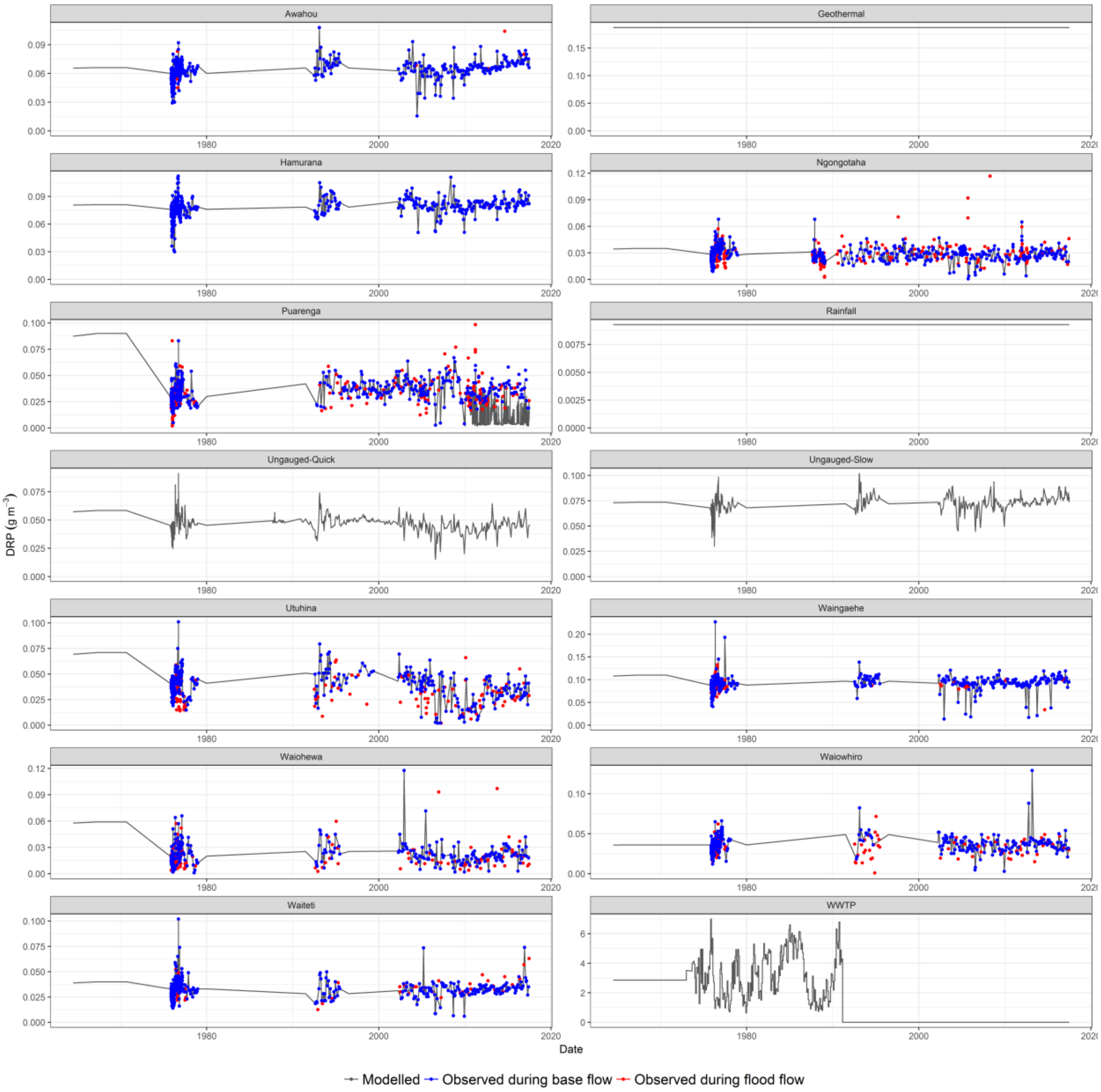

Figure 11. Summary of dissolved reactive phosphate (PO_4-P) measurements and interpolation used for generation of nutrient loads. Samples in red were collected outside of baseflow conditions and were excluded from interpolation. Relatively high values in the late 1960s represent the average values presented by Fish (1975). 'WWTP' (bottom right) is the wastewater treatment plant.

Figure 11 presents estimated nitrate concentrations over time. Increases in nitrogen concentration are notable in all stream inflows other than the Utuhina, Waiowhiro, and possibly Waiohewa. Generally, these increases are linear in character, although nitrate concentration increased steeply over a c. 10 year period in the Puarenga Stream following implementation of the LTS. This increase has been partly balanced by decreasing concentrations since approximately 2001. The early data of Hoare (1980, 1987) are notable for more variation in baseflow concentrations (for both DIN and PO_4-P) than later studies even at or near baseflow, the reasons for this are not known.

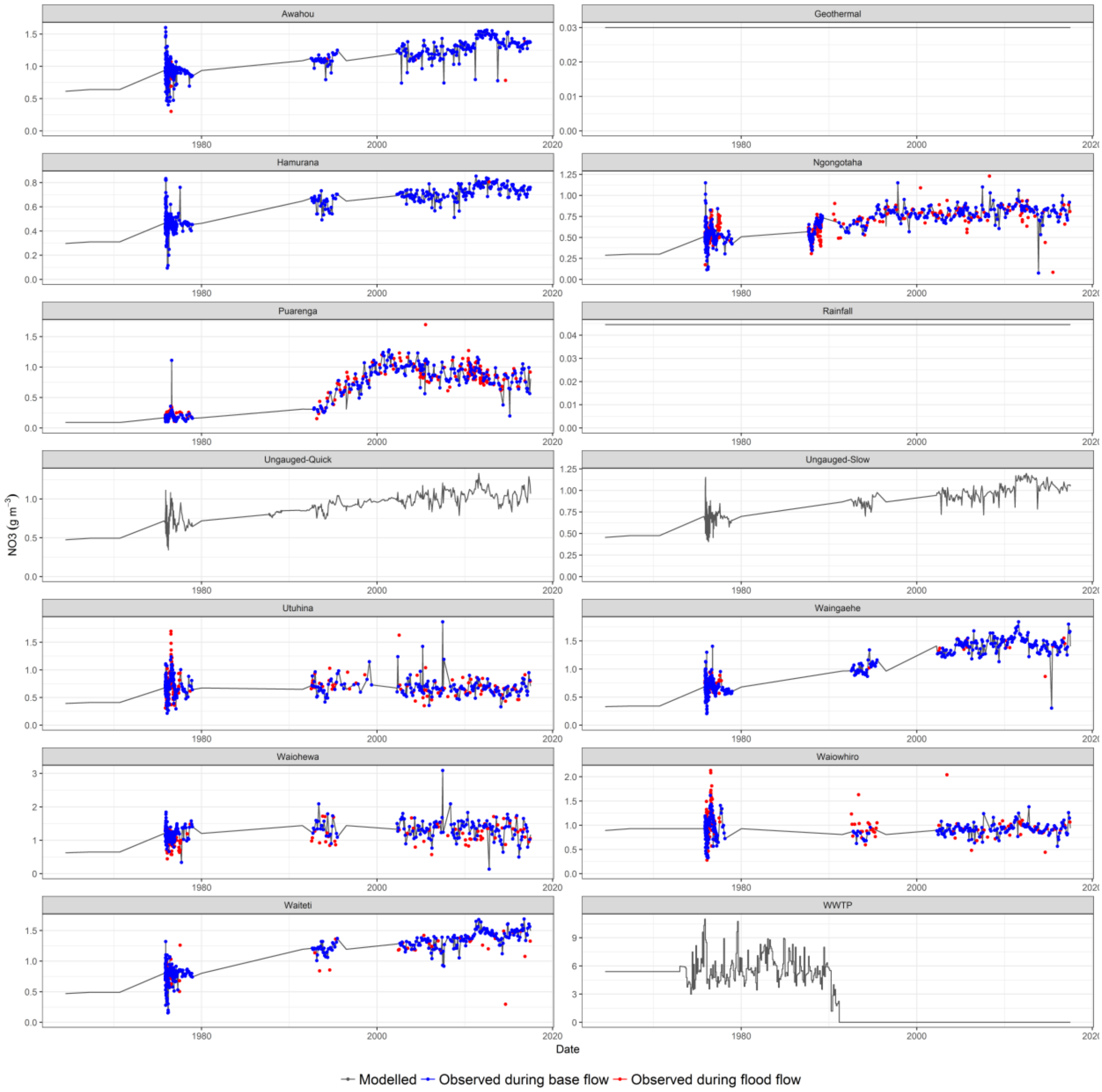

Figure 12. Summary of nitrate (mass as NO_3-N) measurements and interpolation used for generation of nutrient loads. Samples in red were collected outside of baseflow conditions and were excluded from interpolation. Values in the late 1960s represent the average values presented by Fish (1975). WWTP' (bottom right) is the wastewater treatment plant.

Total nutrients

Stormflow particulate nutrient concentrations showed strong positive relationships with discharge for multiple inflows. Figure 12 shows log-log linear relationships for nitrogen and phosphorus. Regressions were initially fitted separately for each decade to investigate whether there was evidence of a change of slope in the relationship, i.e., whether the change in slope was due to changes in land management. Although some evidence of change in slope was observed, there was uncertainty as to whether the observed differences reflected changes that had occurred or were statistical artefacts. The slopes of these relationships were sensitive to the concentrations measured during the largest events and the sampling effort and range of discharge conditions sampled varied among decades. Accordingly, a decision was made to pool data for individual streams across all time periods to maximise the sample size used to derive each relationship. Where discharge-concentration relationships were observed ($R^2 > 0.25$), the log-log relationship was applied to estimate concentration of particulate nutrients during flood flows.

Figures 13 and 14 show final estimated total nitrogen and phosphorus concentrations for all water sources to Lake Rotorua, representing a combination of changing baseflow concentrations over time, and static models of stormflow particulate discharge over the whole study period (as described above and shown in Figure 12). Sub-catchments where nitrogen has not increased substantially since the 1960s are notable for an overall lower proportion of agricultural land and/or an absence of dairy land (Appendix figure 3b). Baseflow total phosphorus concentrations generally changed little between 1975 and 2010, with relatively higher values reported by Fish (1975) for the late-1960s and some evidence of increases for multiple sub-catchments from 2010. The LTS does not appear to have substantially influenced baseflow total phosphorus concentrations in the Puarenga Stream, and effects on losses during stormflows are not discernible from available data. Stormflow concentrations measured by Hoare in the 1970s were generally higher than those measured from the 2000s, possibly reflecting broader changes in catchment land use or differences between the magnitudes of flow events sampled.

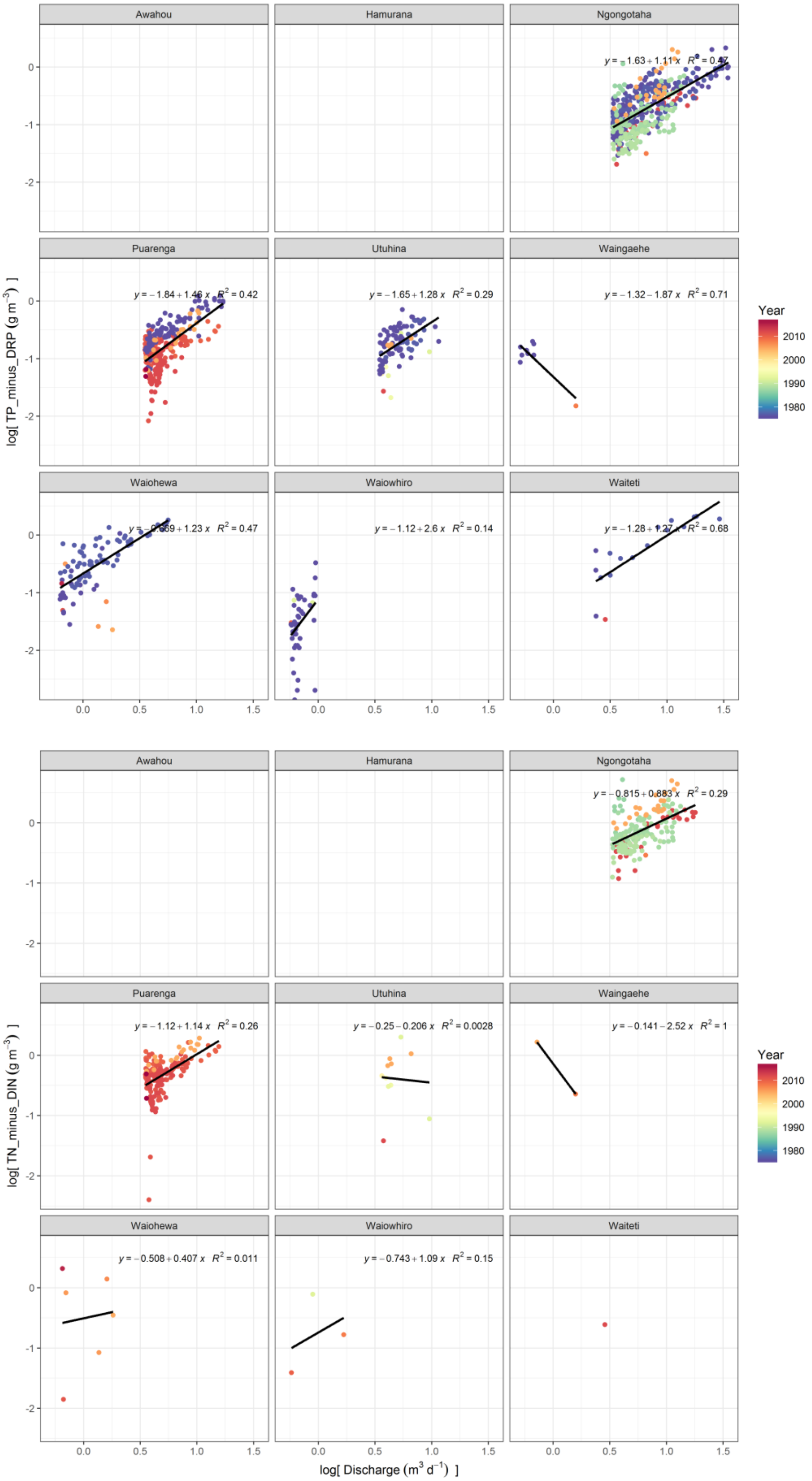

Figure 13. Total nutrients minus dissolved nutrients measured during flood flows in the nine major inflows to Lake Rotorua, 1975 to 2017. Sufficient flood flow measurements for estimation of discharge-concentration relationships were not available for all streams.

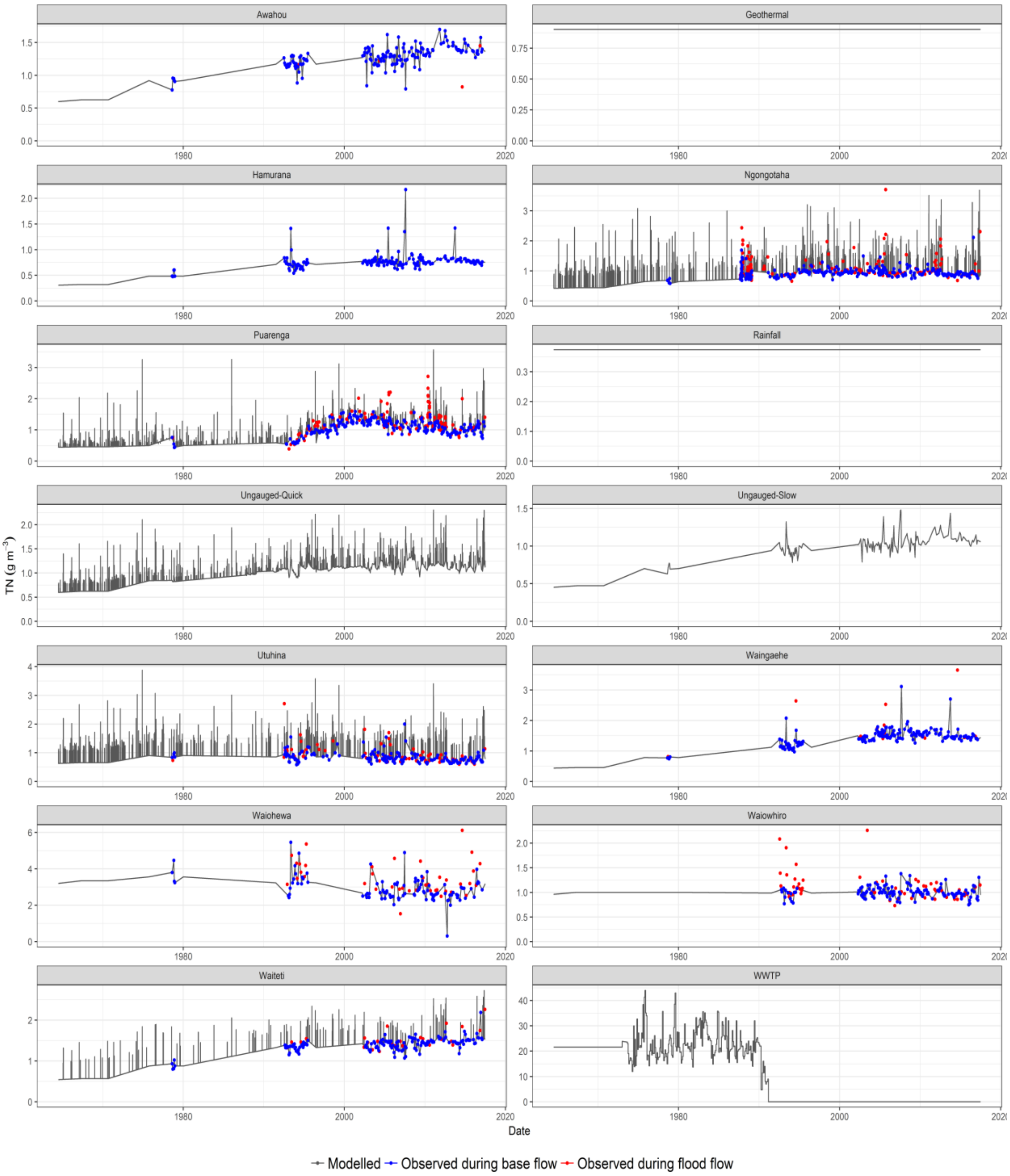

Figure 14. Summary of total nitrogen (TN) measurements and interpolation used for generation of nutrient loads, as well as results of storm flow concentration modelling. Samples in red were collected outside of baseflow conditions and were excluded from interpolation. Values in the late 1960s represent the average values presented by Fish (1975). WWTP' (bottom right) is the wastewater treatment plant.

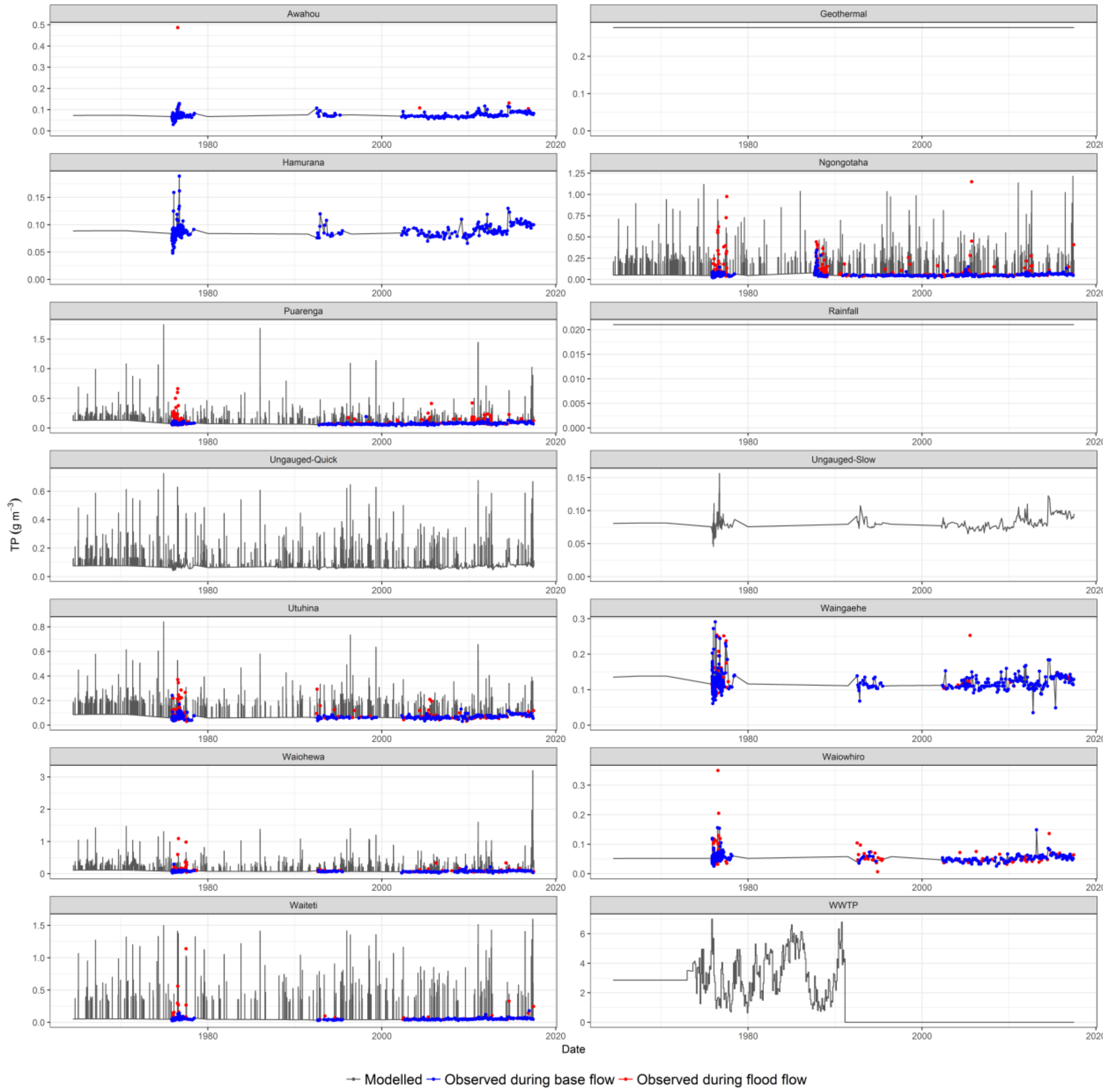

Figure 15. Summary of total phosphorus (TP) measurements and interpolation used for generation of nutrient loads, as well as results of storm flow concentration modelling. Samples in red were collected outside of baseflow conditions and were excluded from interpolation. Values in the late 1960s represent the average values presented by Fish (1975). WWTP' (bottom right) is the wastewater treatment plant.

Summary of loads

Total annual loads to Lake Rotorua were calculated for hydrological years from 1965 to 2017, and are presented in Figure 15 partitioned by water source. There were dramatic reductions in wastewater (and thus overall) nitrogen and phosphorus loads (brown and yellow bars) following the implementation of the Whakarewarewa LTS (yellow), demonstrating the efficacy of the LTS in reducing the impact of the resident population of Rotorua City on the lake.

Nitrate and total nitrogen loads have increased steadily and substantially since the 1960s, from as low as <400 t TN y^{-1} in 1965 to as high as >750 t TN y^{-1} in 2011. Dissolved and total phosphorus loads may have been reduced over recent decades relative to the period of direct wastewater discharge, however, recent increases in total phosphorus delivered by streams have somewhat reversed this reduction. It is notable that overall nitrogen and phosphorus load vary greatly with hydraulic loading, it should also be noted that the loads presented in Figure 15 are inclusive of stormflow particulates and are thus not directly comparable to management load targets.

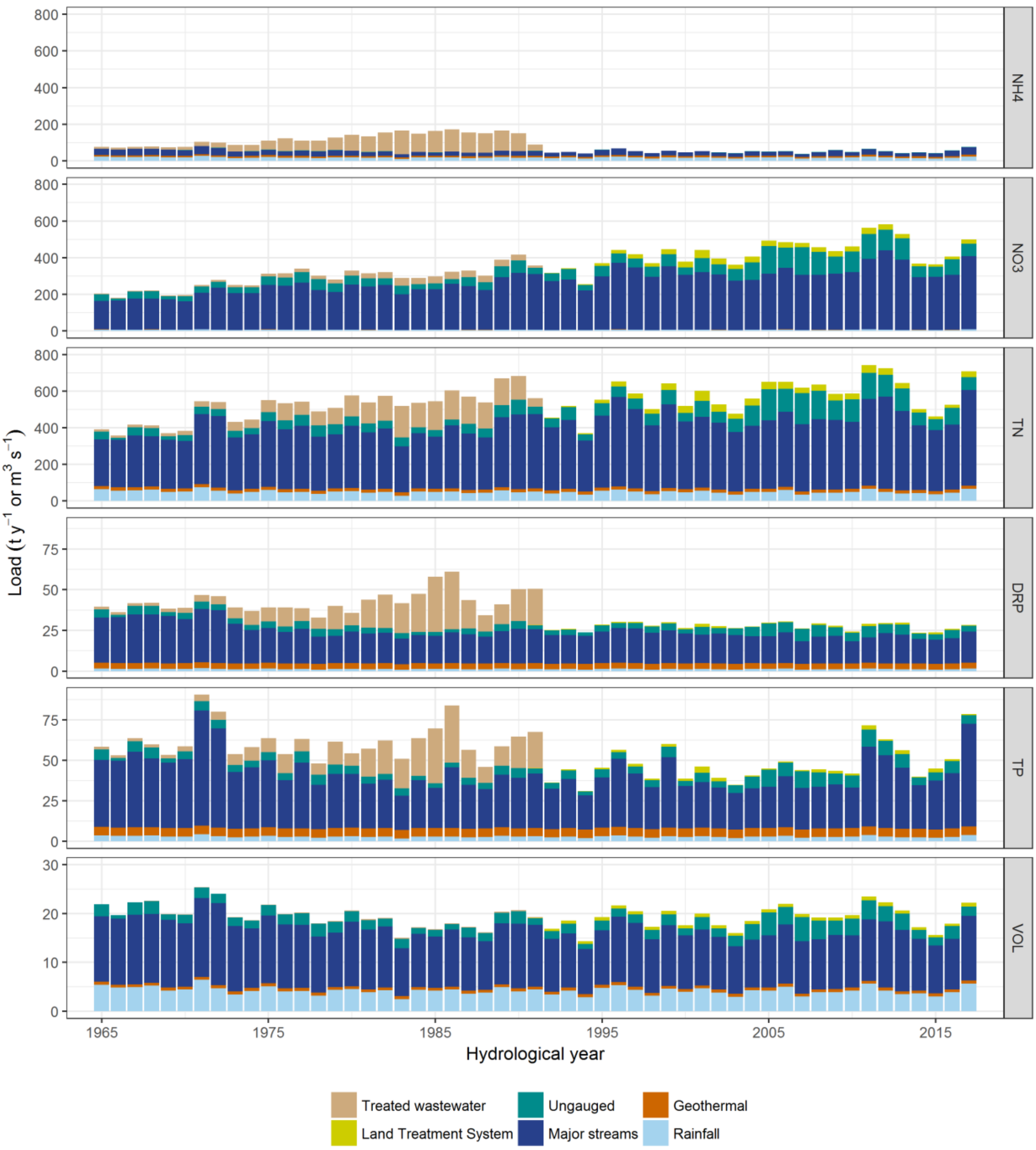

Figure 16. Summary of nutrient loading to Lake Rotorua 1959 to 2017(NH_4 = ammonium, NO_3 = nitrate, TN = total nitrogen, DRP = dissolved reactive phosphate, TP = total phosphorus and VOL = discharge). Loads are attributed to various sources. Loads include stormflow particulates and are thus not comparable to previous sustainable load targets. Nitrogen and phosphorus species are shown on common y-scales to aid comparison of dissolved inorganic and total nutrient loads.

Figure 16 displays the particulate nutrient component (in grey) delivered during stormflows as a separate component of total loading. Also provided are the 'sustainable load targets' for nitrogen and phosphorus (red dashed lines) which can be compared to total loads exclusive of stormflow particulates (i.e. each column exclusive of the upper, grey component).

Annual nitrogen loads estimated here were lower than the sustainable target during the 1960s, but have since steadily risen. Although near the target during the driest recent year (2015), annual total nitrogen loads have been as much as 300 t N y^{-1} above the target during recent wet years (e.g., 2011 – 2012). Annual phosphorus loads estimated here consistently met or bettered the target following the implementation of the LTS, however, they have recently substantially exceeded the target during medium to wet years. Notably, the phosphorus target was met consistently during years of substantial water quality problems and algal blooms at Lake Rotorua (late-1990s to late-2000s).

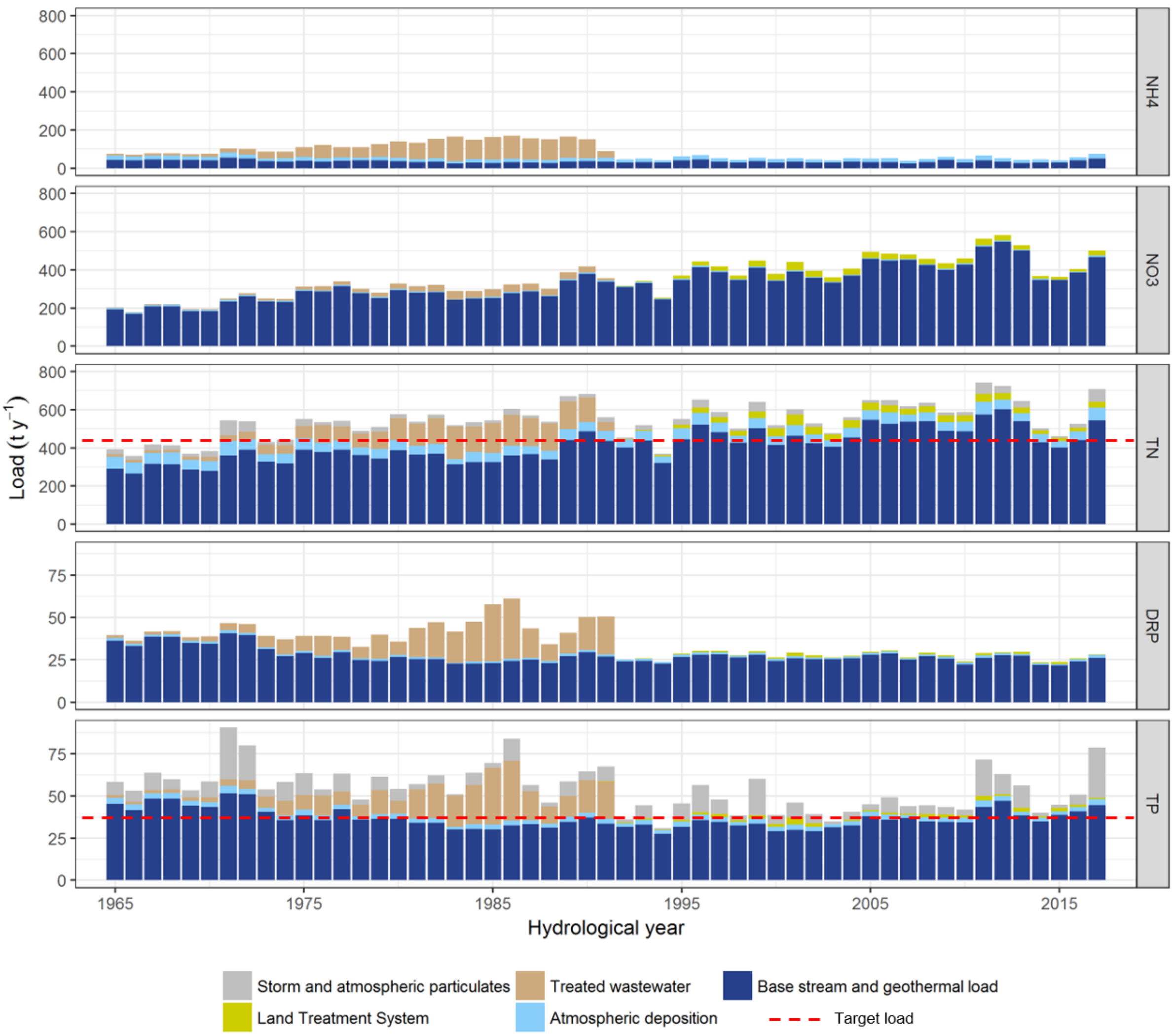

Figure 17. Summary of nutrient loading to Lake Rotorua 1965 to 2017 NH_4 = ammonium, NO_3 = nitrate, TN = total nitrogen, DRP = dissolved reactive phosphate, TP = total phosphorus). Loads from stormflow and particulate deposition are shown in grey. Loads from atmospheric deposition of dissolved nutrients are shown in light blue. Target loads are shown by the dashed red lines, and are exclusive of the stormflow particulates category (which are shown on the plots in grey).

Figure 17 shows the contribution of each sub-catchment (and additional sources of water) to annual average nutrient load for the years 2007 – 2017. Hamurana Spring contributes more than 20% of the dissolved phosphorus load to the lake, due to old groundwater sourced from high phosphate volcanic ignimbrite (Morgenstern et al. 2015). The Waiohewa Stream contributes more than 25% of ammonium, reflecting the influence of the Tikitere geothermal field. Six of the major inflows contribute much of the total nitrogen and phosphorus annual loads, with Waingaehe, Waiohewa and Waiowhiro making relatively minor contributions. The ungauged catchment contributes substantial loads of both nitrogen and phosphorus. Geothermal sources make a relatively minor contribution to the overall total nitrogen load, but are a more substantial component of the phosphorus load. Atmospheric deposition of nitrogen and phosphorus is similar in load to the larger major inflows, although the volume of water from rainfall is much larger.

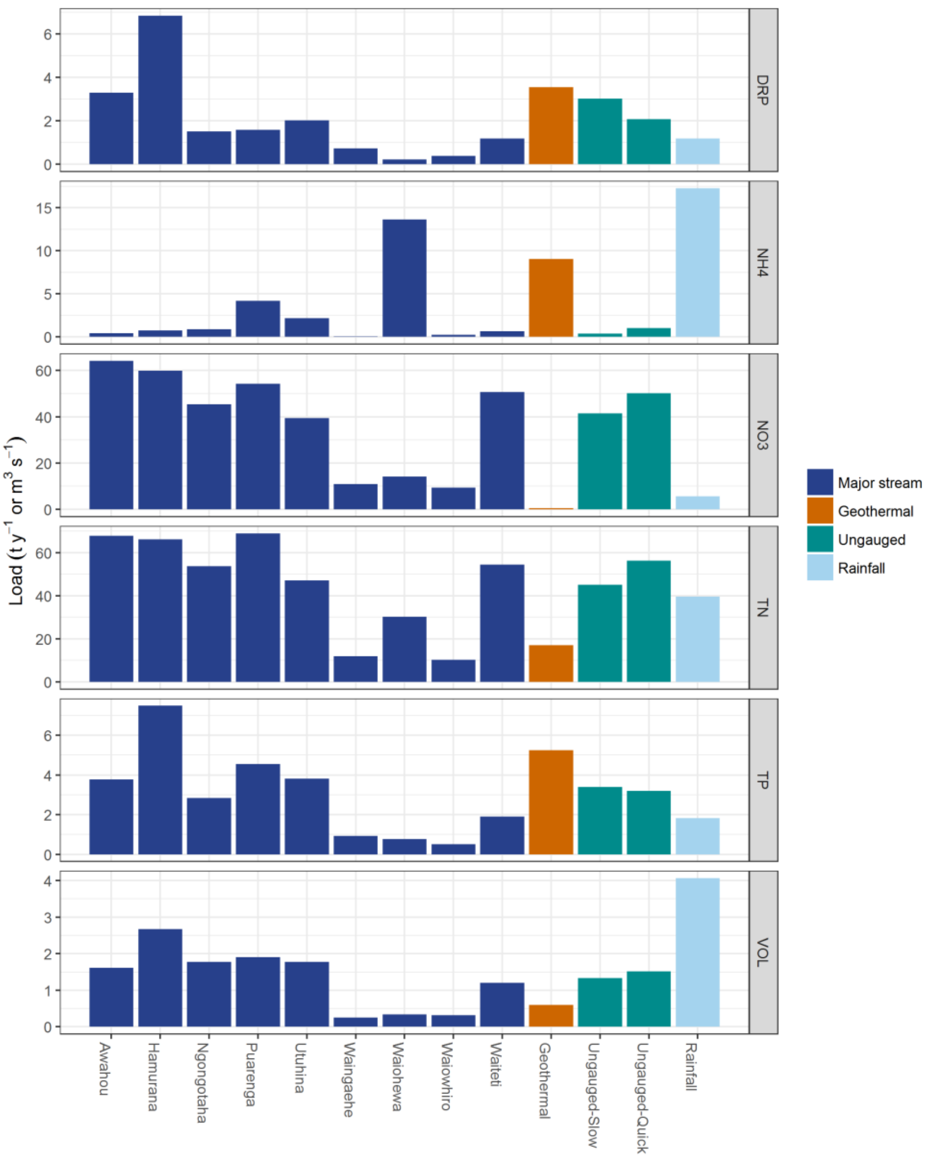

Figure 18. Summary of average nutrient loading from individual inflows to Lake Rotorua, for the period 2007 to 2017 (NH_4 = ammonium, $N0_3$ = nitrate, TN = total nitrogen, DRP = dissolved reactive phosphate, TP = total phosphorus and VOL = discharge). Values include flood-flow particulate nutrients.

The average concentration (volumetrically-weighted) of nitrate in major inflows to Lake Rotorua has nearly tripled between 1965 and 2017 (Figure 18). It is likely that phosphate concentrations would have remained relatively constant if not for (i) the high values reported by Fish (1975), (ii) slightly lower phosphate values from the mid-2000s, likely to the result of alum dosing of two major inflows, and (iii) elevated total phosphorus from 2010. Note that Figure 18 shows concentration trends in major streams only.

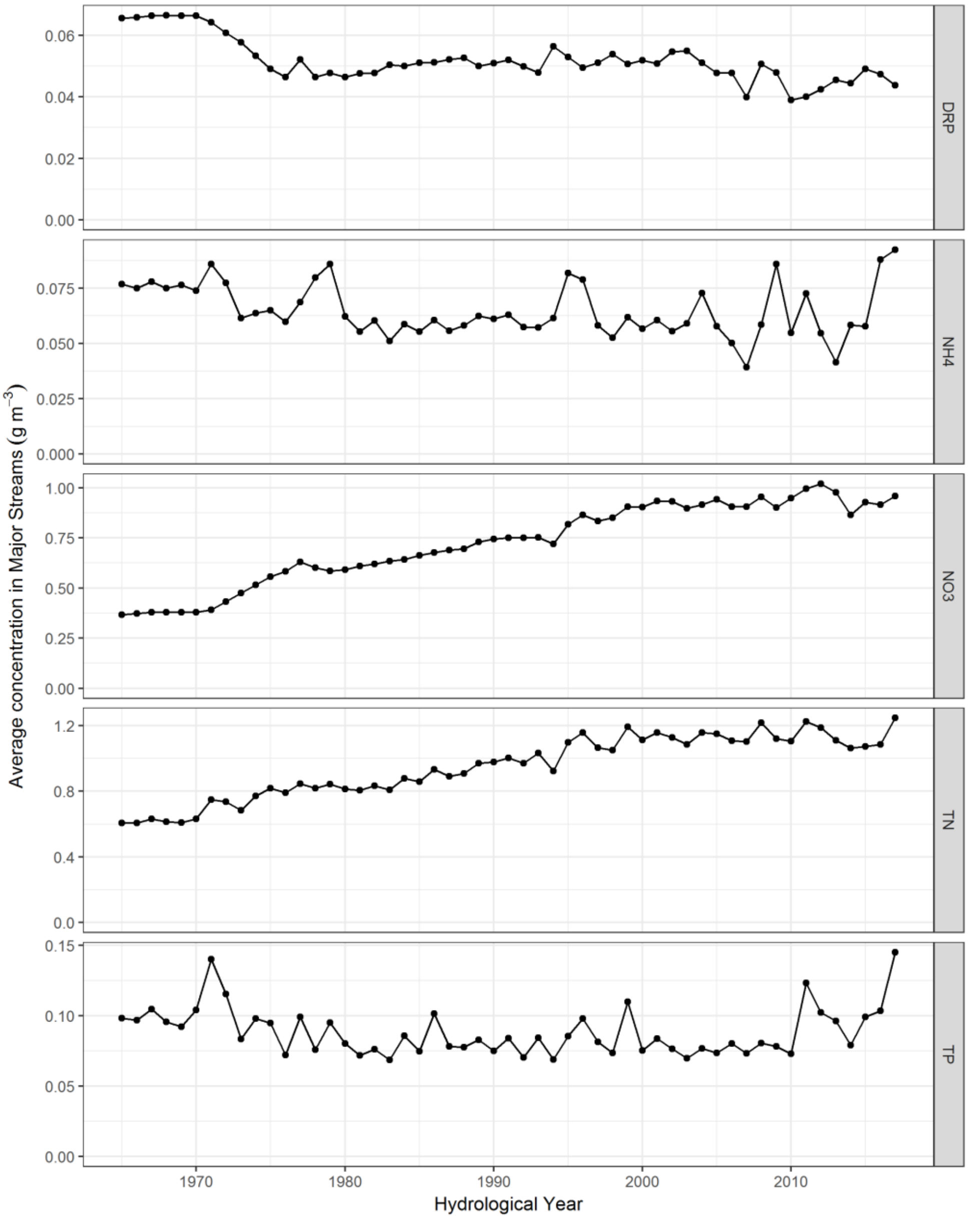

Figure 19. Volumetrically weighted average concentration of nutrients in nine major stream inflows to Lake Rotorua, 1965 to present (NH_4 = ammonium, $N0_3$ = nitrate, TN = total nitrogen, DRP = dissolved reactive phosphate, TP = total phosphorus and VOL = discharge). Values are presented for the hydrological year and are volumetrically-weighted. Total nutrients are *inclusive* of stormflow particulates.

Tables 9 and 10 summarise annual loads as 5-year averages from 1965, partitioned by nutrient species and by nutrient sources.

Table 9. Summary by decade of estimated average phosphorus loads from different sources to Lake Rotorua. 'NSP' load ('No Stormflow Particulates' load, in red) is load exclusive of stormflow particulate nutrients, and these are the loads that can be evaluated against sustainable load targets.

	Discharge			Phosphate-P				Total phosphorus					
	Atmospheric deposition	Treated wastewater	Total	Atmospheric deposition	Treated wastewater	Baseflow	Total load	Atmospheric deposition	Treated wastewater	Baseflow	Stormflow	NSP load	Total load
	$m^3\ s^{-1}$	$m^3\ s^{-1}$	$m^3\ s^{-1}$	$t\ y^{-1}$	$t\ y^{-1}$	$t\ y^{-1}$	$t\ y^{-1}$	$t\ y^{-1}$	$t\ y^{-1}$	$t\ y^{-1}$	$t\ y^{-1}$	$t\ y^{-1}$	$t\ y^{-1}$
1965 to 1970	4.9	0.0	21.3	1.4		36.3	39.6	3.3	1.9	45.7	6.9	50.8	57.7
1970 to 1975	4.6	0.1	21.4	1.4	5.5	34.6	41.5	3.1	5.5	44.5	15.2	53.1	68.3
1975 to 1980	4.2	0.1	19.7	1.2	9.9	26.8	37.9	2.8	9.9	37.7	7.7	50.4	58.1
1980 to 1985	3.9	0.2	18.2	1.1	17.4	24.6	43.2	2.6	17.4	33.0	4.6	53.1	57.7
1985 to 1990	4.2	0.2	17.7	1.2	21.7	24.6	47.5	2.8	21.7	32.3	6.1	56.8	63.0
1990 to 1995	3.8	0.4	18.0	1.1	8.5	25.5	35.1	2.5	8.7	32.6	5.0	43.8	48.8
1995 to 2000	4.5	0.7	19.8	1.3	0.7	27.4	29.4	3.0	1.3	33.6	11.7	37.9	49.7
2000 to 2005	3.9	0.6	17.9	1.2	0.9	25.3	27.4	2.6	1.7	30.4	5.1	34.8	39.9
2005 to 2010	4.0	0.7	20.2	1.2	0.6	26.9	28.7	2.7	1.2	36.0	5.4	39.9	45.3
2010 to 2015	4.2	0.7	20.6	1.2	0.8	25.1	27.2	2.8	1.6	39.7	10.4	44.1	54.5
2015 to 2020	4.2	0.6	18.6	1.2	0.7	24.0	26.0	2.8	1.4	41.4	12.5	45.6	58.1

Table 10. Summary by decade of estimated average hydraulic and nitrogen loads from different sources to Lake Rotorua. NSP ('No Stormflow Particulates') load (red) is load exclusive of stormflow particulate nutrients, and these are the loads that can be evaluated against sustainable load targets.

	Ammonium-N				Nitrate-N				Total nitrogen					
	Atmospheric deposition	Treated wastewater	Baseflow	Total load	Atmospheric deposition	Treated wastewater	Baseflow	Total load	Atmospheric deposition	Treated wastewater	Baseflow	Stormflow	NSP load	Total load
	$t\ y^{-1}$	$t\ y^{-1}$	$t\ y^{-1}$	$t\ y^{-1}$	$t\ y^{-1}$	$t\ y^{-1}$	$t\ y^{-1}$	$t\ y^{-1}$	$t\ y^{-1}$	$t\ y^{-1}$	$t\ y^{-1}$	$t\ y^{-1}$	$t\ y^{-1}$	$t\ y^{-1}$
1965 to 1970	20.9	10.6	43.4	75.0	6.9	3.5	192.7	203.2	58.1	14.1	294.2	23.5	366.4	389.9
1970 to 1975	19.7	27.7	43.3	90.7	6.5	9.2	228.8	244.6	54.7	37.0	335.0	42.0	426.6	468.6
1975 to 1980	17.8	59.2	38.8	115.8	5.9	19.7	284.3	309.9	49.4	78.9	372.7	24.0	501.0	525.0
1980 to 1985	16.6	100.6	31.5	148.7	5.5	33.5	269.8	308.8	46.0	134.1	352.1	16.5	532.1	548.6
1985 to 1990	17.8	113.0	30.5	161.4	5.9	37.7	284.6	328.1	49.4	150.7	366.0	19.0	566.2	585.2
1990 to 1995	16.2	26.4	32.3	75.0	5.4	11.4	320.6	337.4	45.1	38.5	416.6	16.9	500.1	517.0
1995 to 2000	19.0	0.0	37.1	56.1	6.3	21.3	382.0	409.6	52.6	26.6	475.3	32.0	554.5	586.5
2000 to 2005	16.8	0.0	31.6	48.4	5.5	32.3	358.6	396.4	46.5	40.3	433.2	17.0	520.1	537.0
2005 to 2010	17.0	0.0	32.5	49.5	5.6	28.1	436.5	470.2	47.3	35.1	527.4	17.8	609.8	627.6
2010 to 2015	18.0	0.0	33.0	51.0	6.0	25.6	469.0	500.6	50.0	32.0	526.3	31.7	608.3	640.0
2015 to 2020	17.8	0.0	40.1	57.9	5.9	17.2	399.4	422.4	49.4	21.5	462.1	31.6	533.0	564.7

Lake water quality

More than 14000 measurements of water quality were collated for mid-lake sites at Rotorua from all depths and for the variables shown in Figure 19, surface measurements are emphasised in blue, with mid- and deep-water measurements shown in grey. Chlorophyll values exhibited a sharp rise in the 2000s, when few measurements <10 mg m^{-3} were observed and values as high >70 mg m^{-3} were recorded (similar to those observed in 1980). For PO_4-P, an annual pattern with a strong peak in late summer is evident from the 1980s but is effectively absent by the late 2000s.

Total nitrogen and phosphorus follow a similar arc over the study period, with concentrations in recent years similar to those observed in the late 1960s and/or 1970s, and elevated values from the 1980s to 2000s. Total phosphorus since 2010 appears to be consistently lower than for any period on record. Observations of total nitrogen were not available before 1973 (1967 for total phosphorus), and concentrations of nitrogen and phosphorus in the early 1960s (upon which TLI targets are based) may have been lower than the earliest available observations.

Figure 20 presents seasonal (coloured circles) and annual (black circles) mean values for the four TLI component variables, with the diameter of each circle representing the number of monthly median values averaged. The most recent five years are characterised by consistently better water quality relative to earlier measurements, except for total nitrogen, which was marginally lower in the 1970s, and possibly lower again in the unmonitored 1960s than present concentrations. Annual TLI (Figure 21) has been at or below the target value for all but one of the past six years. For the earliest years when all seasons were sampled at least once for all four component variables (i.e., the first solid black circles on Figure 21, from 1974) the lake consistently exceeded the TLI target. An absence of total nitrogen measurements in the 1960s means that the TLI values reported here are likely higher than the actual TLI at that time, because Trophic Level nitrogen (TLn) values tend to be low compared to other trophic level indices in early data. Therefore, the TLI values reported here suggest that the assumed TLI of 4.2 for the 1960s (the decade used to set water quality targets) is likely to be reasonable.

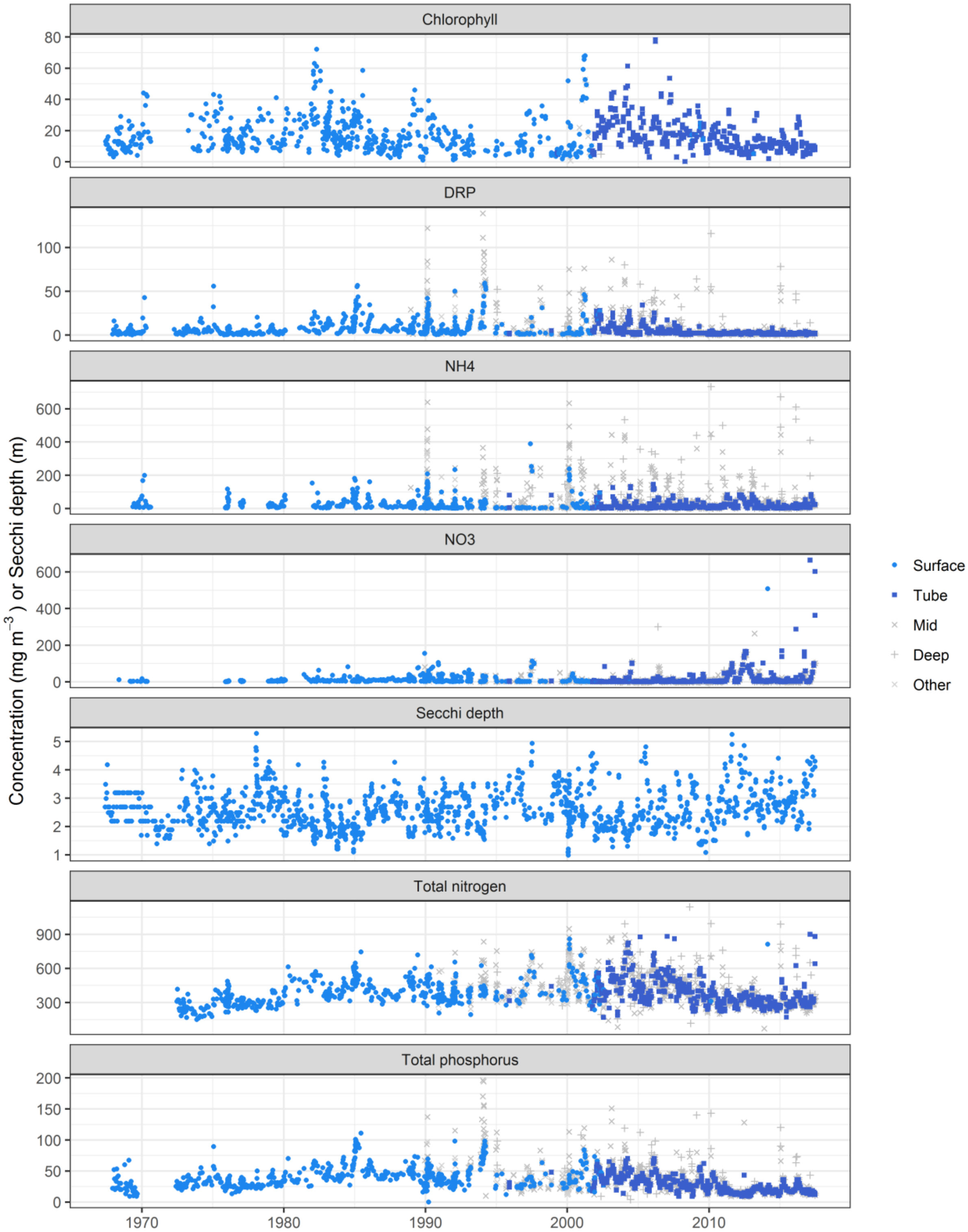

Figure 20. Summary of monthly median values for all mid-lake water quality data, 1967 to 2017 (NH_4 = ammonium, NO_3 = nitrate, DRP = dissolved reactive phosphate). Surface samples are emphasised in blue, and deep-water samples are in grey. Surface samples collected shallower than 1 m depth, 'Mid' samples from 10 to 19 m, and 'Deep' samples deeper than 19 m. 'Tube' samples were integrated across depth ranges of either 0 – 6 m or 0 – 10 m.

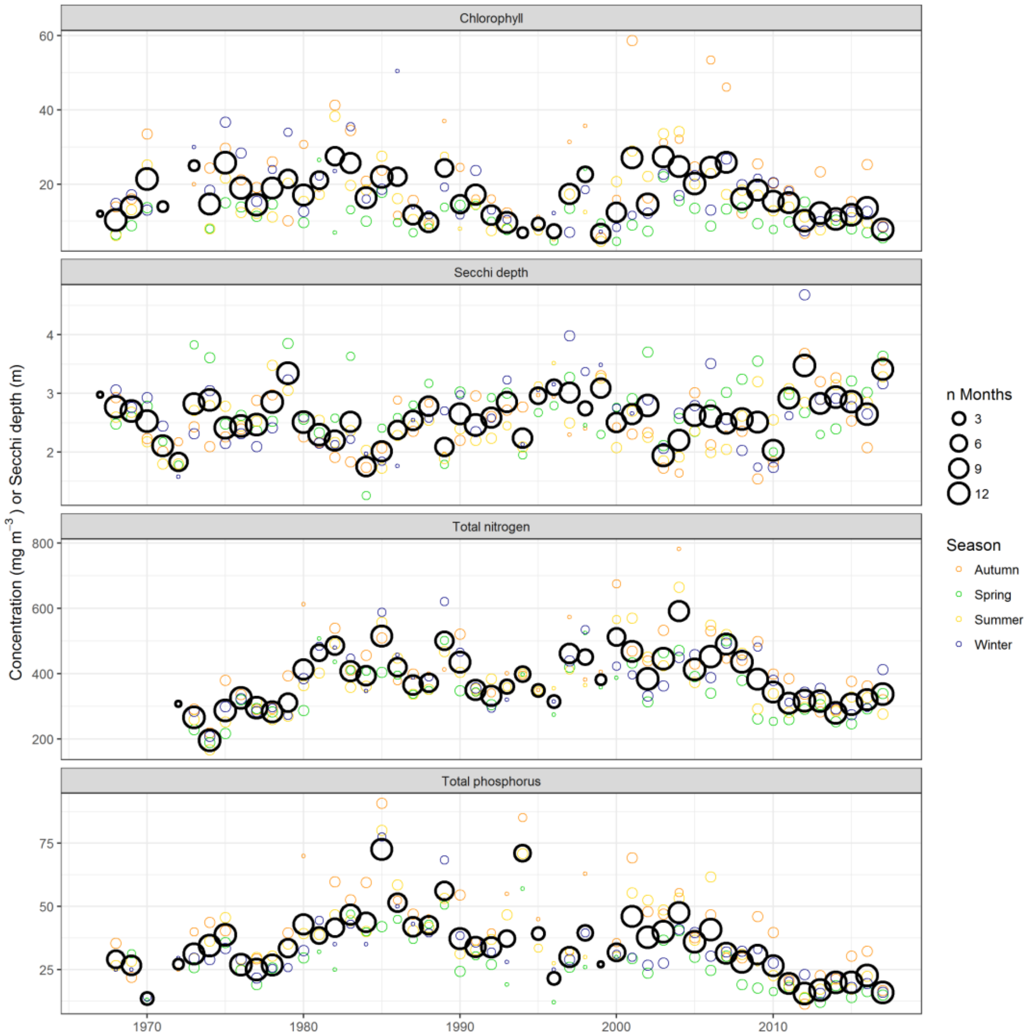

Figure 21. Measurements of Trophic Level Index variables at mid-lake sites in Lake Rotorua. Individual samples were aggregated, retaining only the median value for each month and variable. Monthly medians were then averaged seasonally, shown by the coloured circles. Black circles are the mean value of all available seasonal averages, and may differ slightly from values reported by Bay of Plenty Regional Council due to the 'average of seasonal averages' approach used here. The diameter of all circles is scaled by the number of monthly median measurements aggregated.

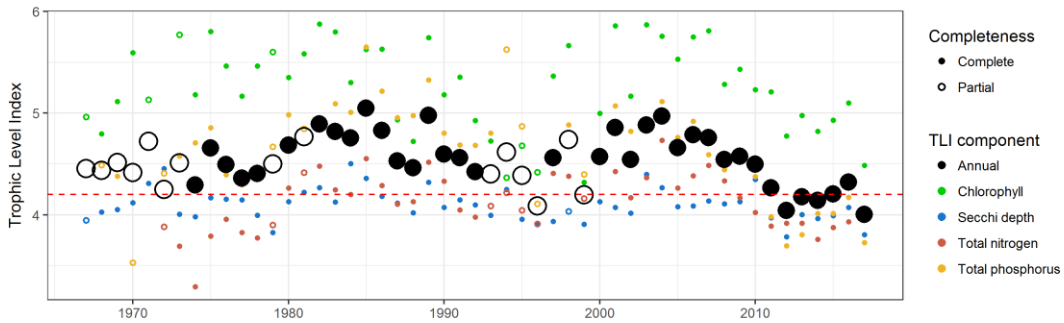

Figure 22. Long-term Trophic Level Index (TLI) at mid-lake sites by hydrological year (previous July to present June). Each coloured circle is the mean of seasonal means, with the Trophic Level Index equation (Burns et al. 1999) applied, and where solid dots denote years for which at least one measurement was available for all four seasons. Large black circles are the annual Trophic Level Index (average of four components), where solid dots denote 'complete' years; where all four seasons were sampled for all four component variables of the TLI. The lake TLI target is shown by the dashed red line. Values may differ from those routinely reported by Bay of Plenty Regional Council due to the seasonal aggregation method used here.

Review and synthesis

This study has collated and analysed catchment and lake water quality data to describe long-term changes in catchment loading and water quality of Lake Rotorua from 1965 to 2017. The impact of direct discharge of Rotorua wastewater to the lake on total nutrient loading, and in-lake water quality is evident from the available data. Consequently, the implementation of the Whakarewarewa Land Treatment System (LTS) in 1991 made a large impact on loading and likely saved the lake from substantial further degradation. In contrast, there has been a steady and substantial rise in nitrogen loading , primarily as nitrate, from other catchment sources over the entire study period, and total nitrogen loads are now similar to or greater than during the later years of direct wastewater discharge to the lake (i.e., immediately prior to 1991). Nitrogen loads are once again well in excess of the designated sustainable target, which itself appears to be greater than nitrogen loading for the 1960s as estimated here. Dissolved nitrogen loads estimated for 2005 to 2017 are approximately double the estimated loads for the late 1960s.

Excluding direct inputs of wastewater, phosphorus loads have been relatively stable since the 1970s, other than a slight increase in total phosphorus over recent years. Phosphate (PO_4-P) loads are largely unchanged meaning the observed increase in total phosphorus primarily reflects increased particulate and/or organic phosphorus. High 1960s phosphorus loads reported here are taken from average values reported by Fish (1975), and could reflect fertiliser application practices, inconsistencies in laboratory practice, and/or uncertainty due to a paucity of continuous gauging during this time. Groundwater-dominated inflows (Hamurana and Awahou) are the largest sources of dissolved phosphate to the lake, and thus a substantial component of phosphorus loading is geologically-derived (see Tempero et al. 2015). Current total phosphorus loads are comparable with loads in the 1960s, prior to wastewater diversion.

Where adequate data were available, all nutrient species showed some evidence of discharge-concentration relationships where adequate data were available. Phosphate (PO_4-P) and nitrate generally decreased with discharge, whereas ammonium and particulates generally increased. This may be due to dilution of nitrate during initial flood pulses, flushing of ammonium from shallow groundwater into streams during storms, or adsorption of PO_4-P and/or ammonium to abundant particulates during flood flows (Abell et al. 2013, 2015). Hysteresis effects further complicate these relationships. No attempt was made to adjust dissolved nutrients for flow-discharge relationships but this simplification is expected to have relatively minor effects on calculations of dissolved inorganic nitrogen and phosphorus loads at annual timescales. This is because the differing responses of nitrate and ammonium described above moderate fluctuations in dissolved inorganic nitrogen to some extent. Generally, fluctuations in dissolved nutrients during storm flows are smaller than those of particulate nutrients, and differences between ascending and descending limbs of the hydrograph for dissolved nutrients further complicate derivation of a single conceptual pattern (Abell et al. 2013).

Total nitrogen or phosphorus minus dissolved inorganic nitrogen or phosphorus were strongly related to discharge during flood flows. There was some evidence for temporal changes in discharge-flow relationships of particulate nutrients over long (~decadal) timescales (see Appendix 2), however, more detailed investigation is required to confirm this. Modelled storm flow particulates make up a relatively small proportion of the overall load and are likely less bioavailable than other components of the load (Hoare 1987, Rutherford 2008, Abell et al. 2013). Therefore, the logic of excluding these from management targets likely holds. However, more recent work (e.g., Abell et al. 2013) has emphasised the potential bioavailability of flood flow particulates, and a greater understanding of these dynamics would be valuable for informing management practices in the catchment, for example, by flood detainment bunds (see Peryer-Fursdon et al. 2015).

Atmospheric deposition rates reported by Verburg (2015) indicate that atmospheric loading of total nitrogen and phosphorus may be greater than previously considered, because early studies accounted for only dissolved inorganic species. Targeted work at Rotorua could help resolve this disparity. Geothermal load (additional to that captured by Waiohewa Stream monitoring) may be a substantial source of nitrogen and phosphorus loading. However, the geothermal loads estimated here depend largely on the Hoare (1985) discharge estimate of 0.6 m^3 s^{-1} and an assumed representativeness of hot spring sampling by BoPRC in the early 1990s, therefore there is a comparatively high level of uncertainty. The ungauged catchment is a substantial component of overall load, although nutrient loading varies greatly among years and decades. The uncertainty is associated with some the sensitivity of estimated ungauged volume to the accuracy of modelled and/or measured discharge in the major inflows and outflow.

The present study quantifies only external (catchment) loading, and not internal recycling, which may dramatically alter total loading to the system over time (Rutherford et al. 1989). Internal loading has been found to be a substantial and variable source of nutrients to Rotorua, probably greater than the external catchment load for some periods (Rutherford et al. 1989, Burger et al. 2008), and improved estimation of internal loading over recent years is the focus of ongoing lake modelling studies. Results from this study signal the importance of internal loading as it is notable that estimates of external nitrogen and phosphorus loads during the 2000s (Figure 17) were not unusually high, despite particularly poor lake water quality during this period (Figure 21; discussed further below). Changes in internal loading will follow from changes to external loading (Nurnberg 1989), and may be directly and/or indirectly modified by geoengineering approaches such as sediment capping or alum dosing (Hamilton et al. 2015).

Using the TLI and its associated components, present water quality appears comparable to or better than observed in the late 1960s, with the possible exception of nitrogen. Annual mean phosphorus concentrations are presently lower than for any earlier observation period (Figure 21). Relatively higher water column phosphorus concentrations in the 1980s – 90s appear to have been driven by pulses during warmer months, suggesting internal loading during temperature stratification. Because catchment phosphorus loads estimated here have not reduced since 1991, the relatively low water column phosphorus of recent years is likely a result of alum dosing of inflows and its residual in-lake effects, and/or partial exhaustion of recycling of the historical high P load from direct wastewater discharge (Hamilton et al. 2015). Monthly measurements post-2010 show pulses of dissolved inorganic nitrogen in surface waters of a magnitude previously infrequently observed (Figure 19), and may be indicative of periods of phosphorus-limitation of phytoplankton leading to excess, unused dissolved inorganic nitrogen.

Conclusions

Water quality post-2010 generally meets the TLI target on average, although exceedances have occurred in certain years. Rotorua is polymictic and eutrophic, and therefore subject to internal loading, it is likely more sensitive to the influences of annual (or long-term) climate variability than deeper, less productive lakes. Estimated catchment (external) loads do not reveal reductions over the past 10 years that would explain recent improvements in water quality. This suggests that active management (i.e., alum dosing) may be responsible for present water quality (mostly) meeting the TLI target. Partial exhaustion of the legacy of wastewater loads (~reduction of internal loading) may also contribute, however, it is difficult to separate this effect from any reduction in organic matter deposition over recent years due to water quality improvement (see estimates of HVOD reported in Scholes and Hamill 2015).

Substantial reductions in catchment nitrogen loading are required to meet the sustainable load targets, and moderate reductions are required for phosphorus (Figure 15). On the balance of evidence presented here, an average catchment target load of 435 t N y^{-1} appears somewhat higher than estimated loading for the 1960s (the period to which water quality targets were set). The present analysis suggests that meeting or exceeding catchment nutrient load targets will be vital to maintaining water quality at or near TLI targets in the long-term in order to reduce the need for ongoing active management and/or geoengineering approaches such as inflow alum dosing.

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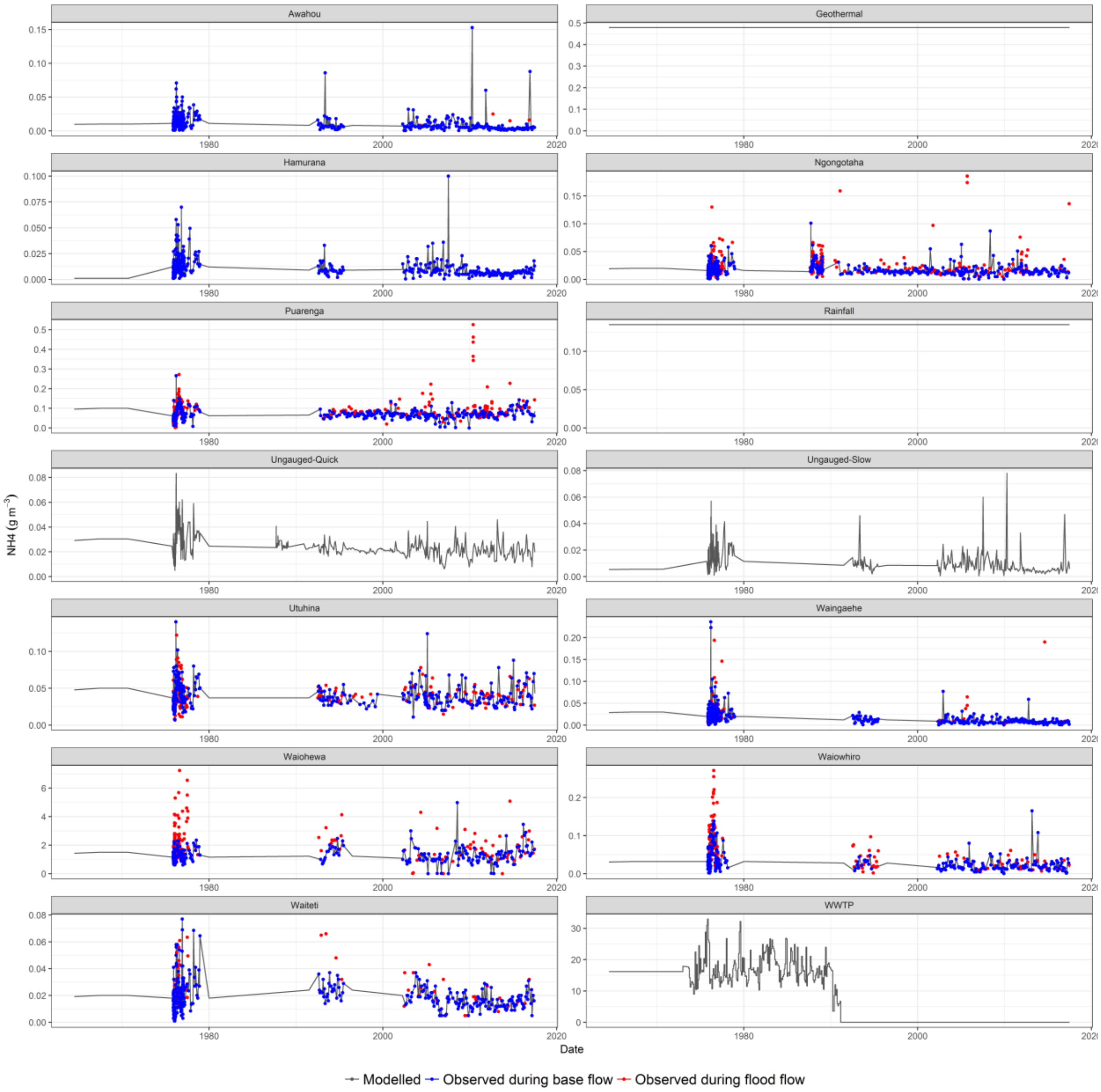
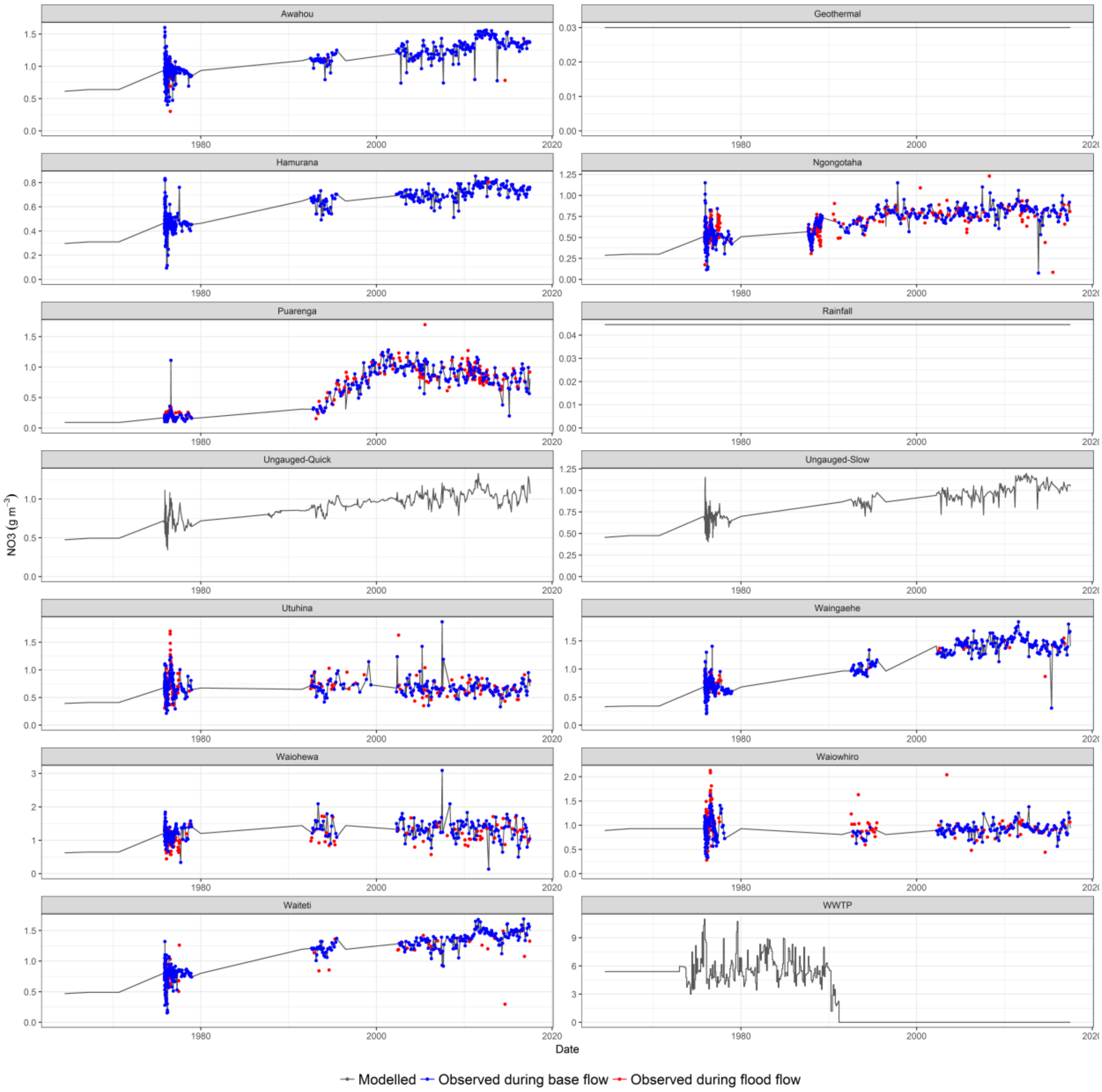
Appendices

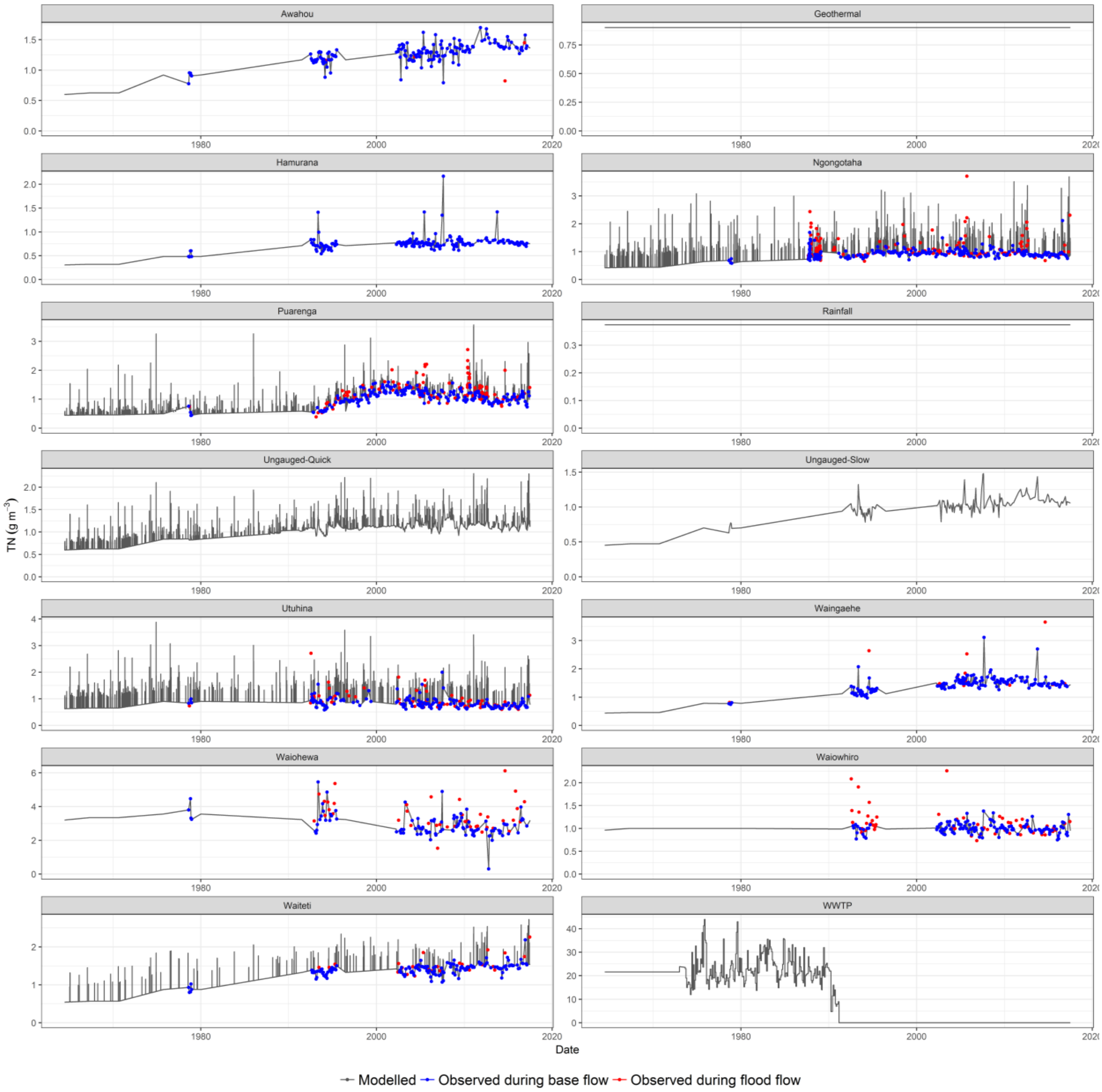
Appendix 1 – Nutrient concentrations over time in inflows to Lake Rotorua



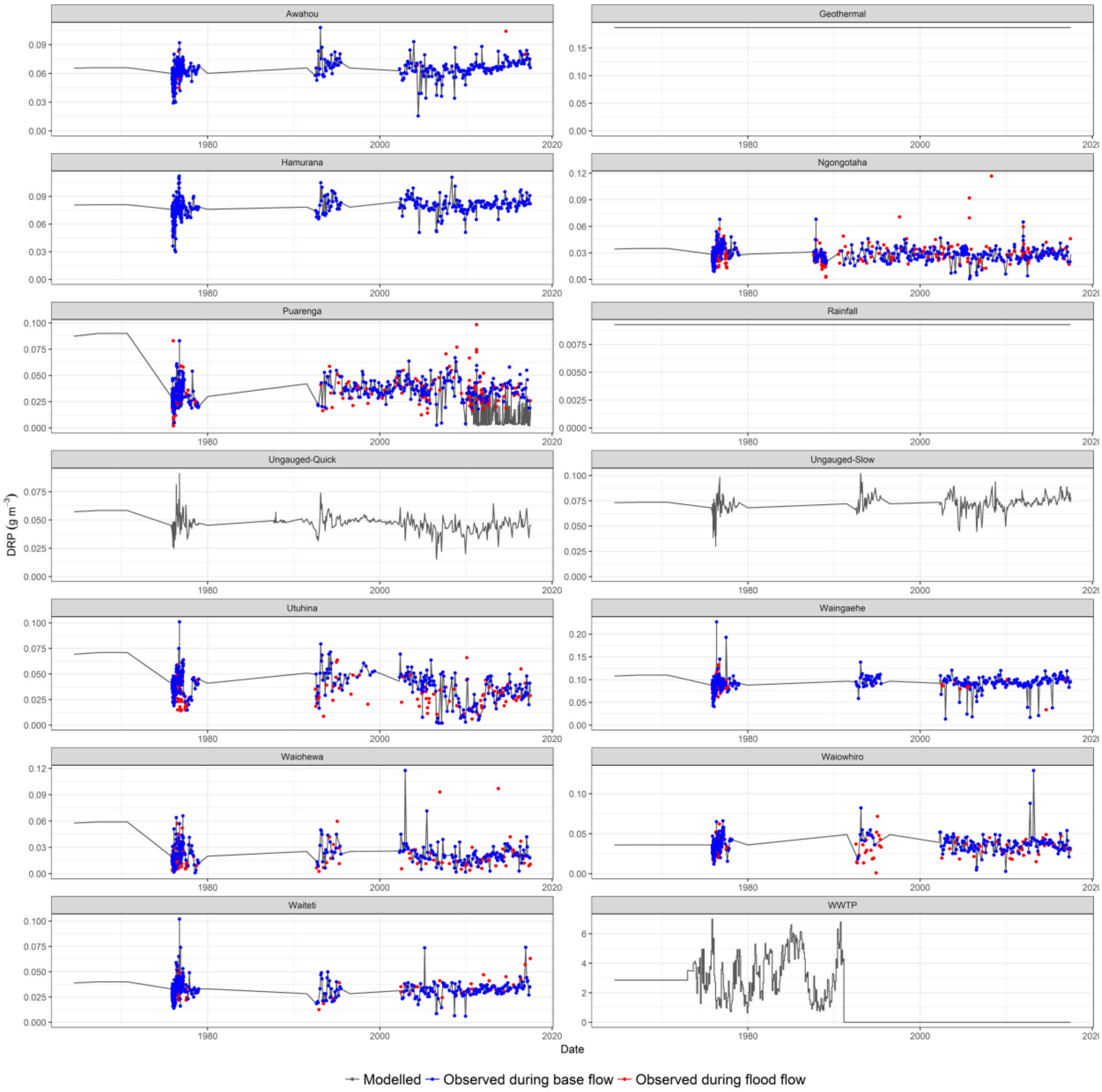
Appendix figure 1a. Summary of ammonium (mass as NH_4-N) measurements and interpolation used for generation of nutrient loads, as well as results of storm flow concentration modelling. Samples in red were collected outside of baseflow conditions and were excluded from interpolation. Values in the late 1960s represent the average values presented by Fish (1975).



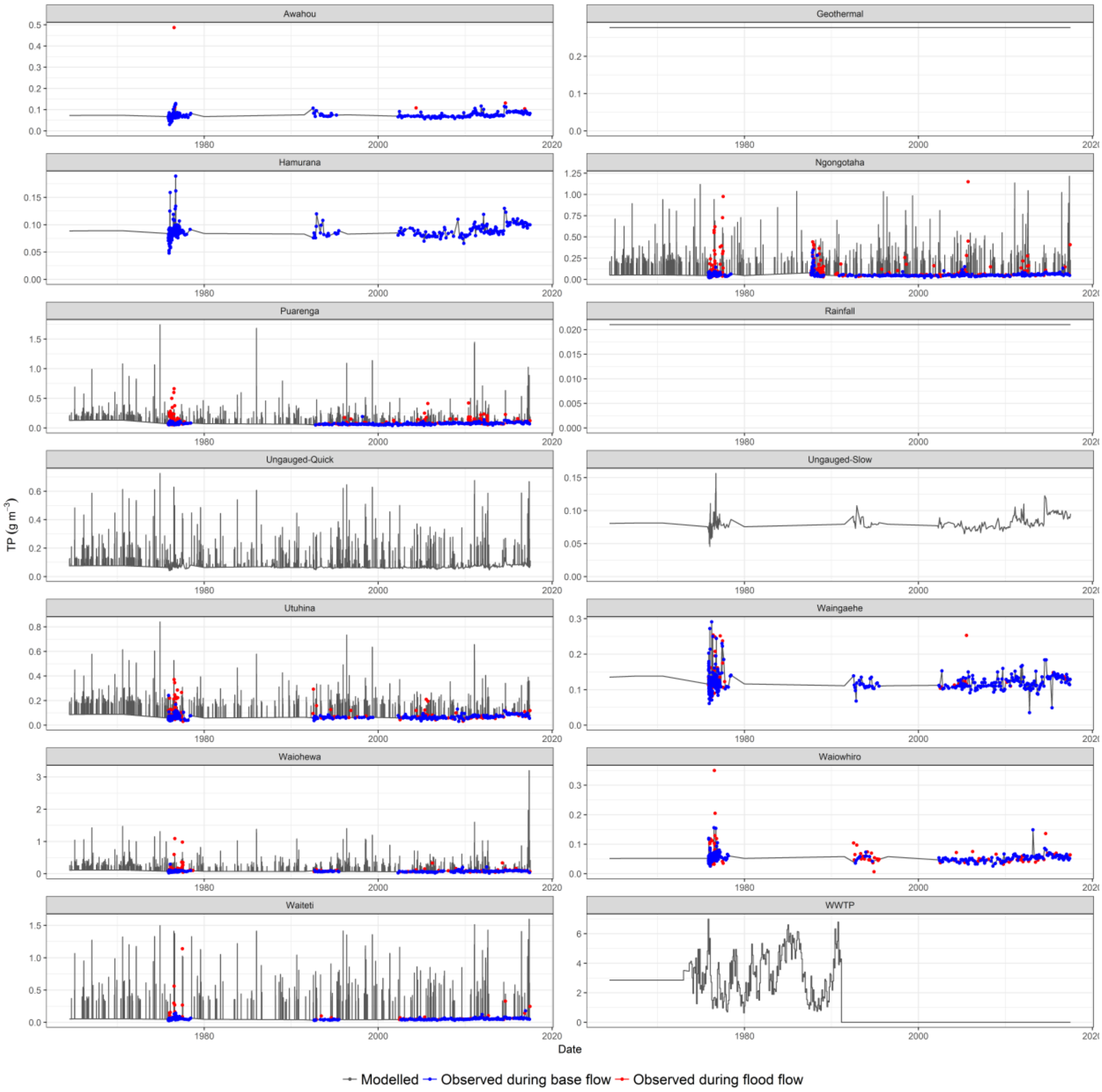
Appendix figure 1b. Summary of nitrate (mass as NO_3-N) measurements and interpolation used for generation of nutrient loads, as well as results of storm flow concentration modelling. Samples in red were collected outside of baseflow conditions and were excluded from interpolation. Values in the late 1960s represent the average values presented by Fish (1975).



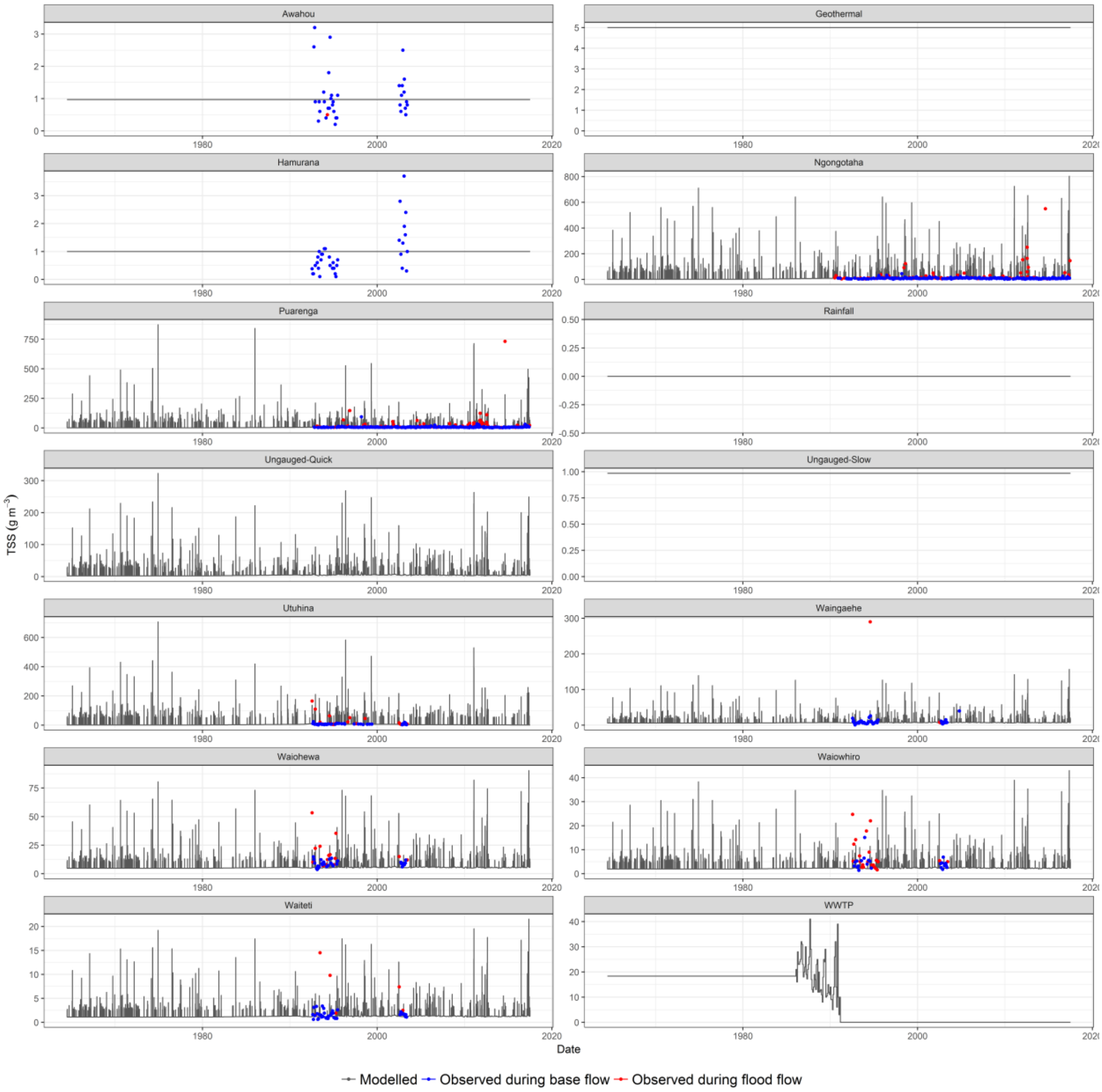
Appendix figure 1c. Summary of total nitrogen (TN) measurements and interpolation used for generation of nutrient loads, as well as results of storm flow concentration modelling. Samples in red were collected outside of baseflow conditions and were excluded from interpolation. Values in the late 1960s represent the average values presented by Fish (1975).



Appendix figure 1d. Summary of dissolved reactive phosphorus (DRP, mass as PO_4-P) measurements and interpolation used for generation of nutrient loads, as well as results of storm flow concentration modelling. Samples in red were collected outside of baseflow conditions and were excluded from interpolation. Values in the late 1960s represent the average values presented by Fish (1975).

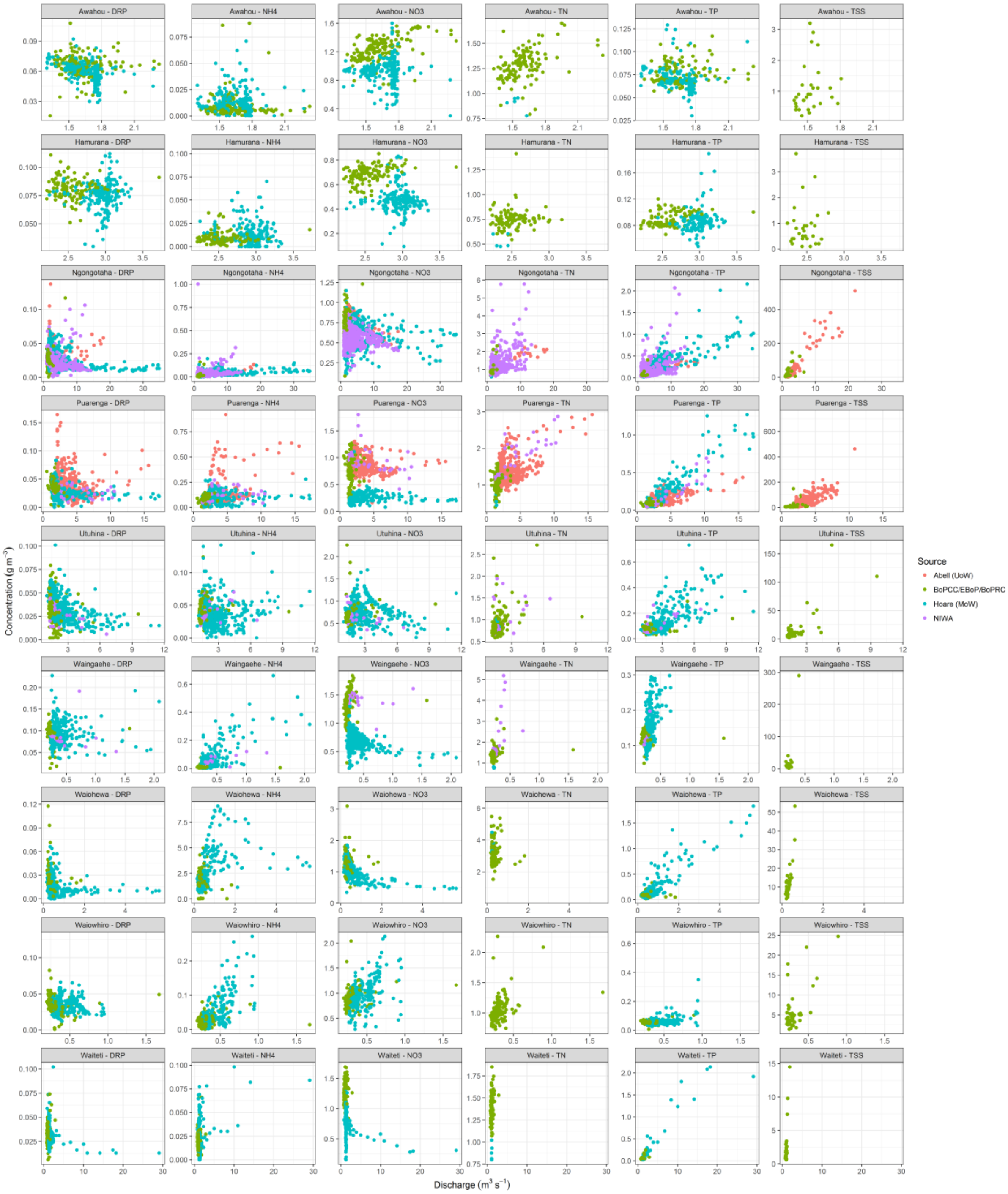


Appendix figure 1e. Summary of total phosphorus (TP) measurements and interpolation used for generation of nutrient loads, as well as results of storm flow concentration modelling. Samples in red were collected outside of baseflow conditions and were excluded from interpolation. Values in the late 1960s represent the average values presented by Fish (1975).

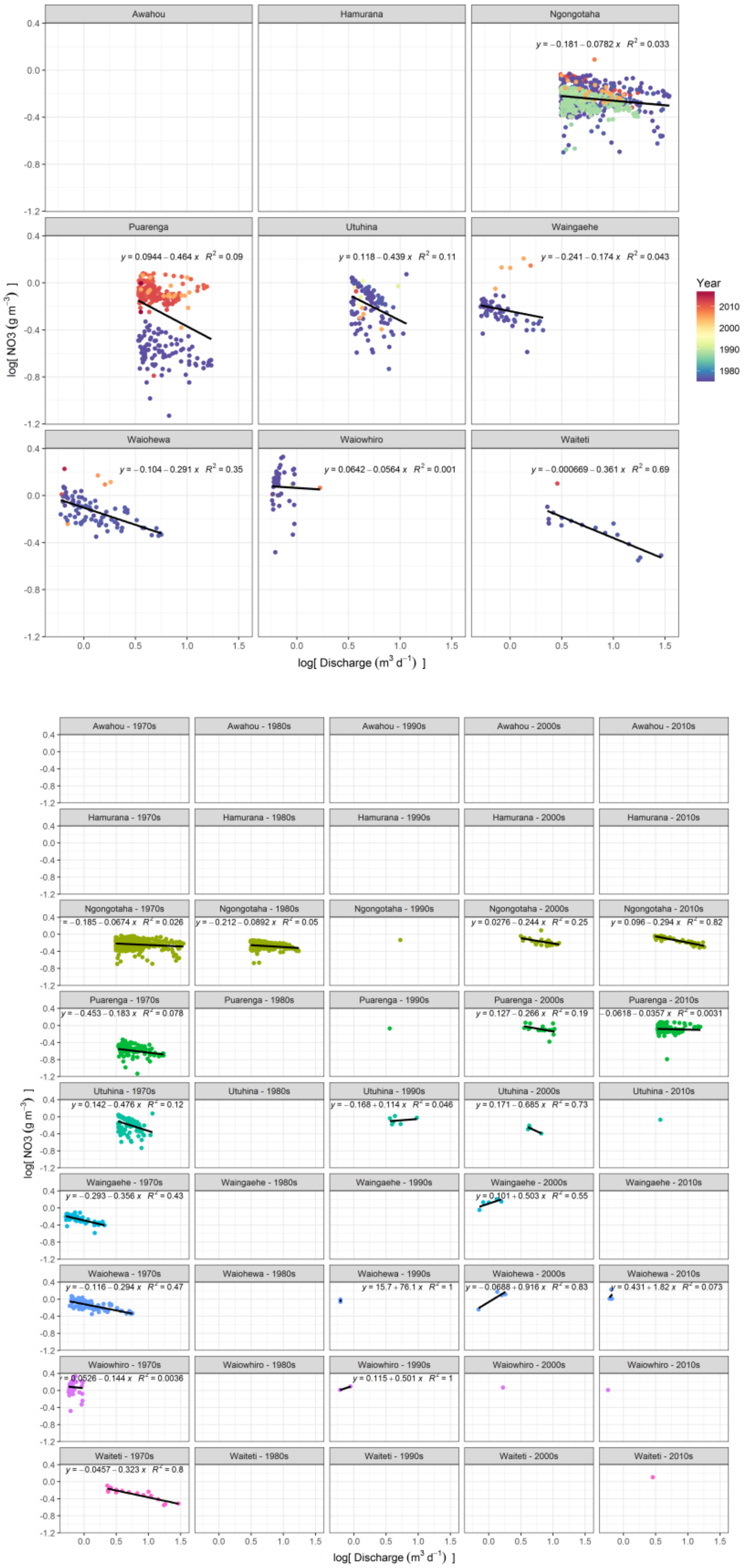


Appendix figure 1f. Summary of total suspended sediment (TSS) measurements and interpolation used for generation of nutrient loads, as well as results of storm flow concentration modelling. Samples in red were collected outside of baseflow conditions and were excluded from interpolation. Values in the late 1960s represent the average values presented by Fish (1975).

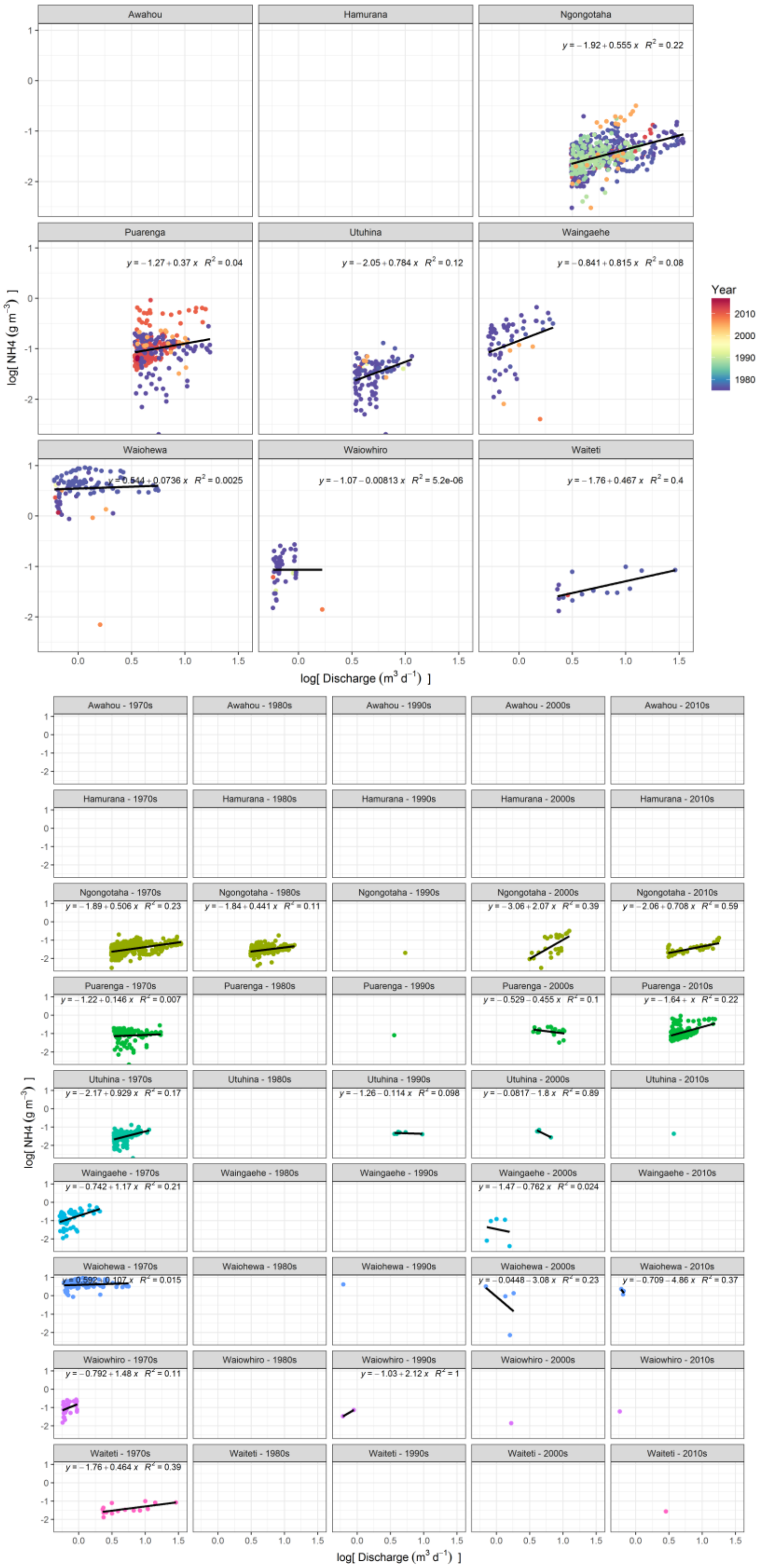
Appendix 2 – Discharge-concentration relationships in major inflows to Lake Rotorua



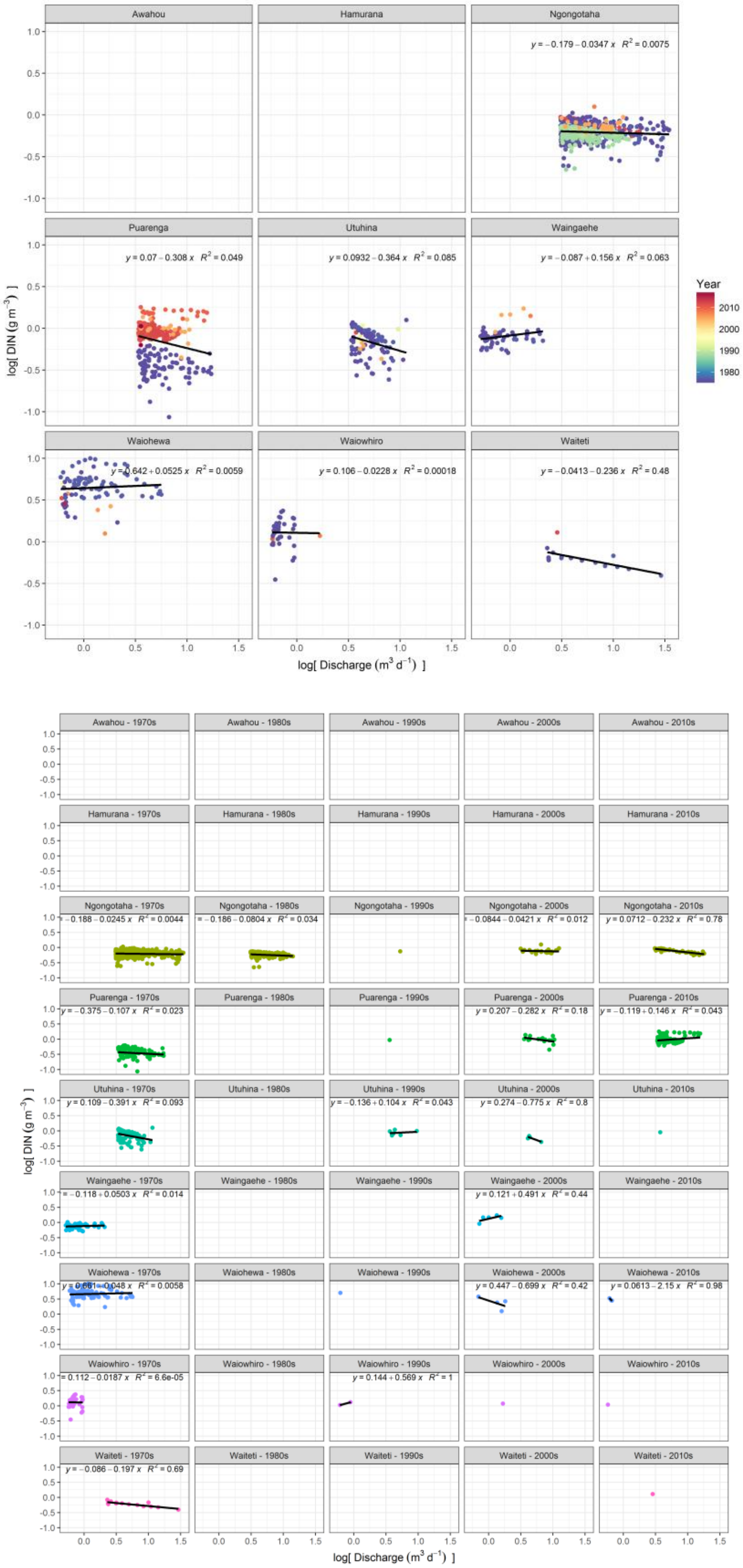
Appendix figure 2a. Summary of all nutrient and sediment measurements against discharge for each major inflow to Lake Rotorua. Colour of the dots represents the data source. Dissolved nutrients are reported as mass (i.e., NO_3-N, NH_4-N, PO_4-P).



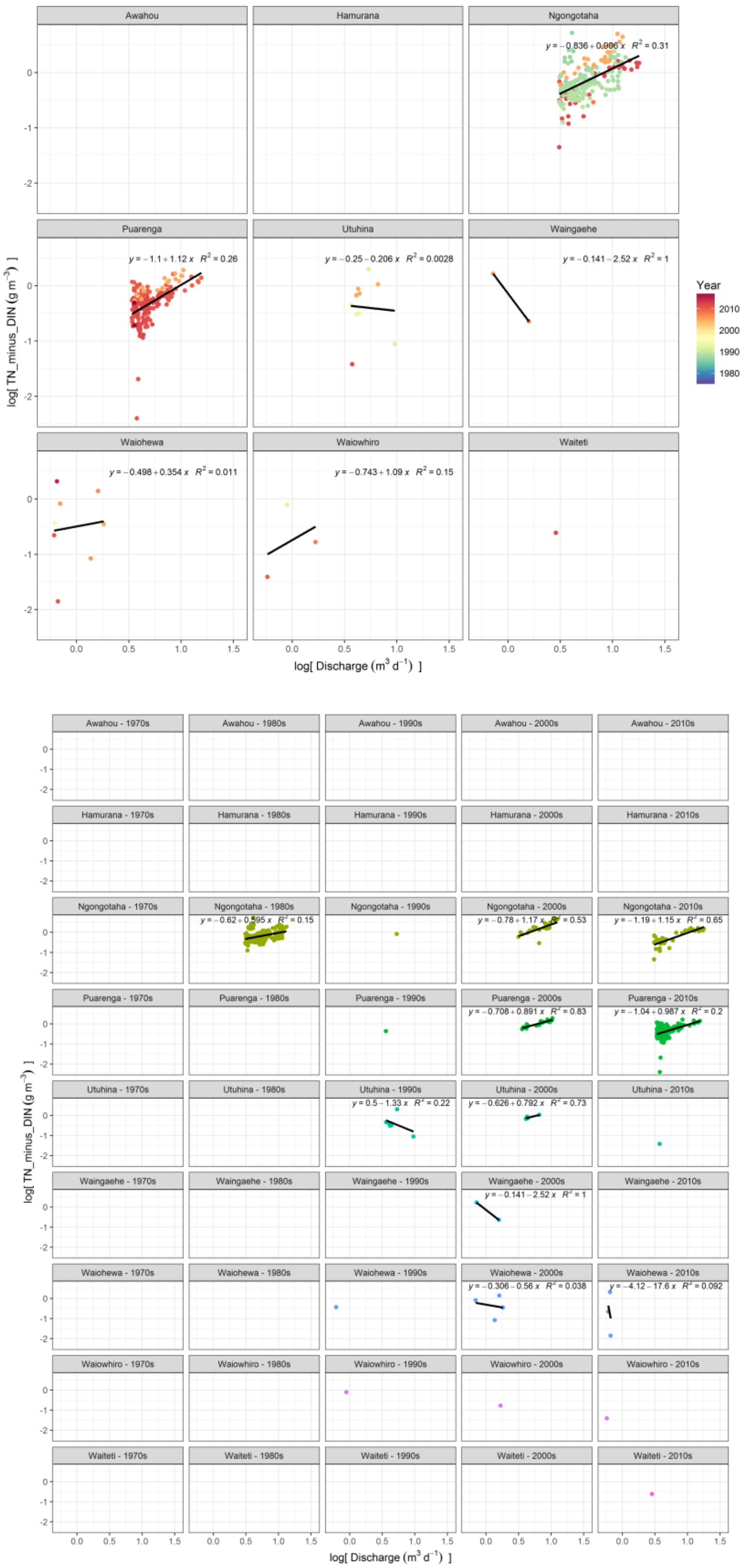
Appendix figure 2b. Relationships between nitrate concentration (mass as NO_3-N) and discharge for all available samples (top, coloured by year of sample collection) and on a decade by decade basis (bottom).



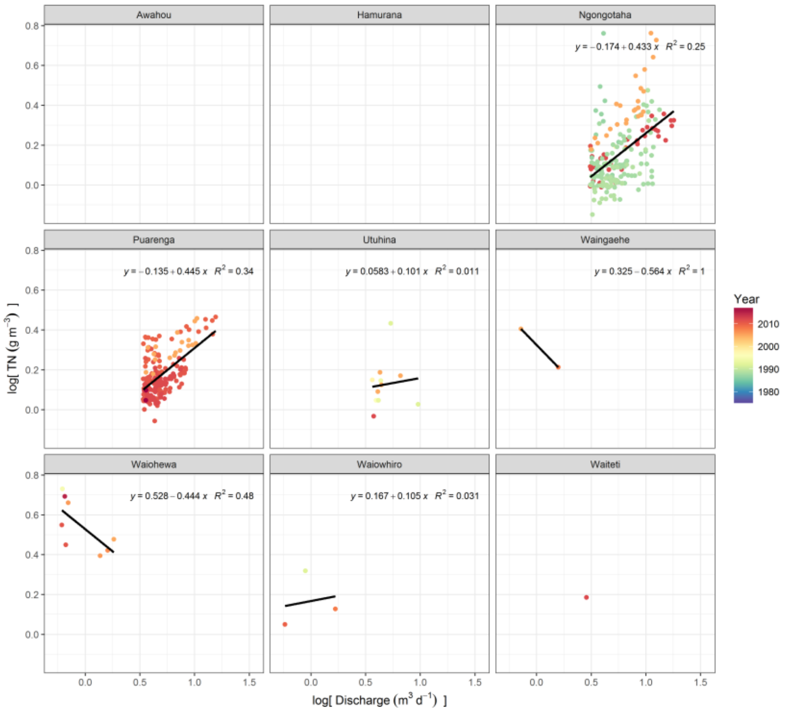
Appendix figure 2c. Relationships between ammonium concentration (mass as NH_4-N) and discharge for all available samples (top, coloured by year of sample collection) and on a decade by decade basis (bottom).

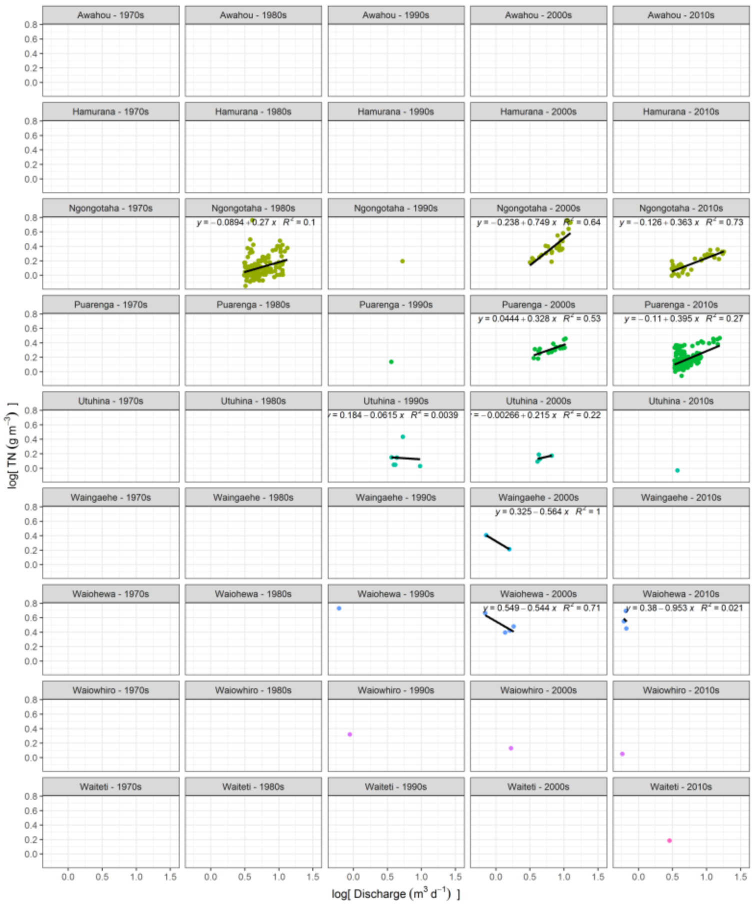


Appendix figure 2d. Relationships between dissolved inorganic nitrogen (DIN) concentration and discharge for all available samples (top, coloured by year of sample collection) and on a decade by decade basis (bottom).

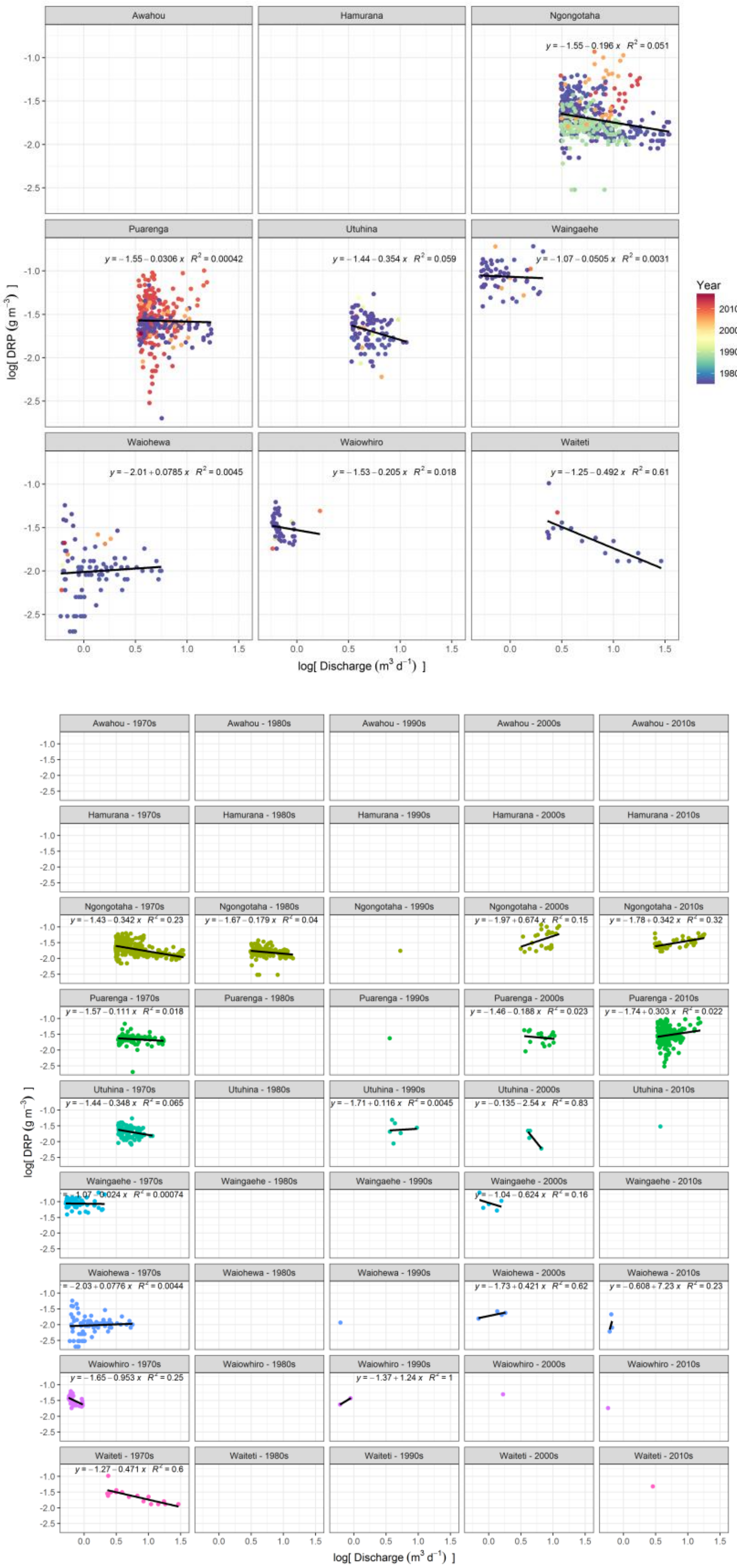


Appendix figure 2e. Relationships between total (TN) minus dissolved nitrogen concentration (DIN) (i.e., particulate and dissolved organic N) and discharge for all available samples (top, coloured by year of sample collection) and on a decade by decade basis (bottom).

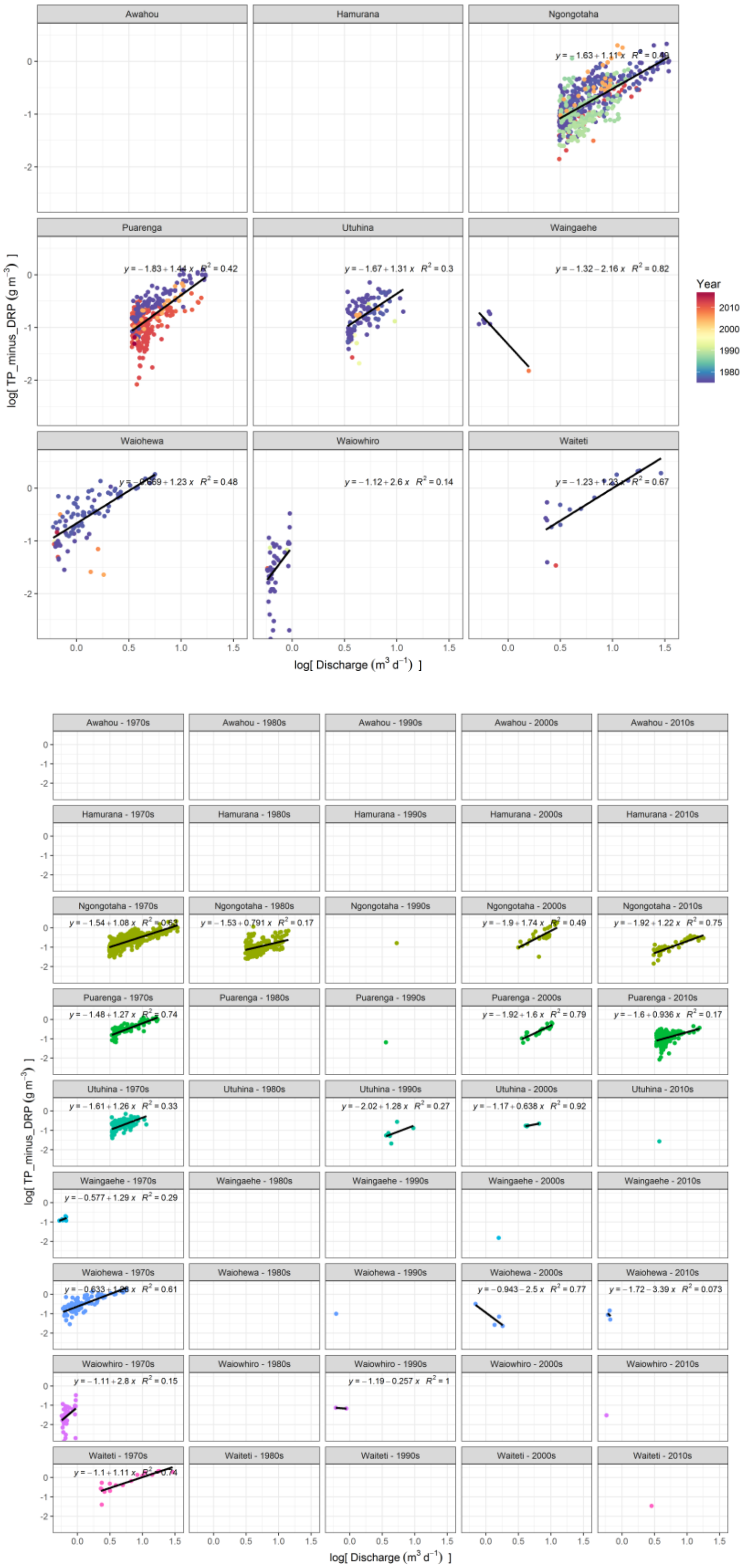




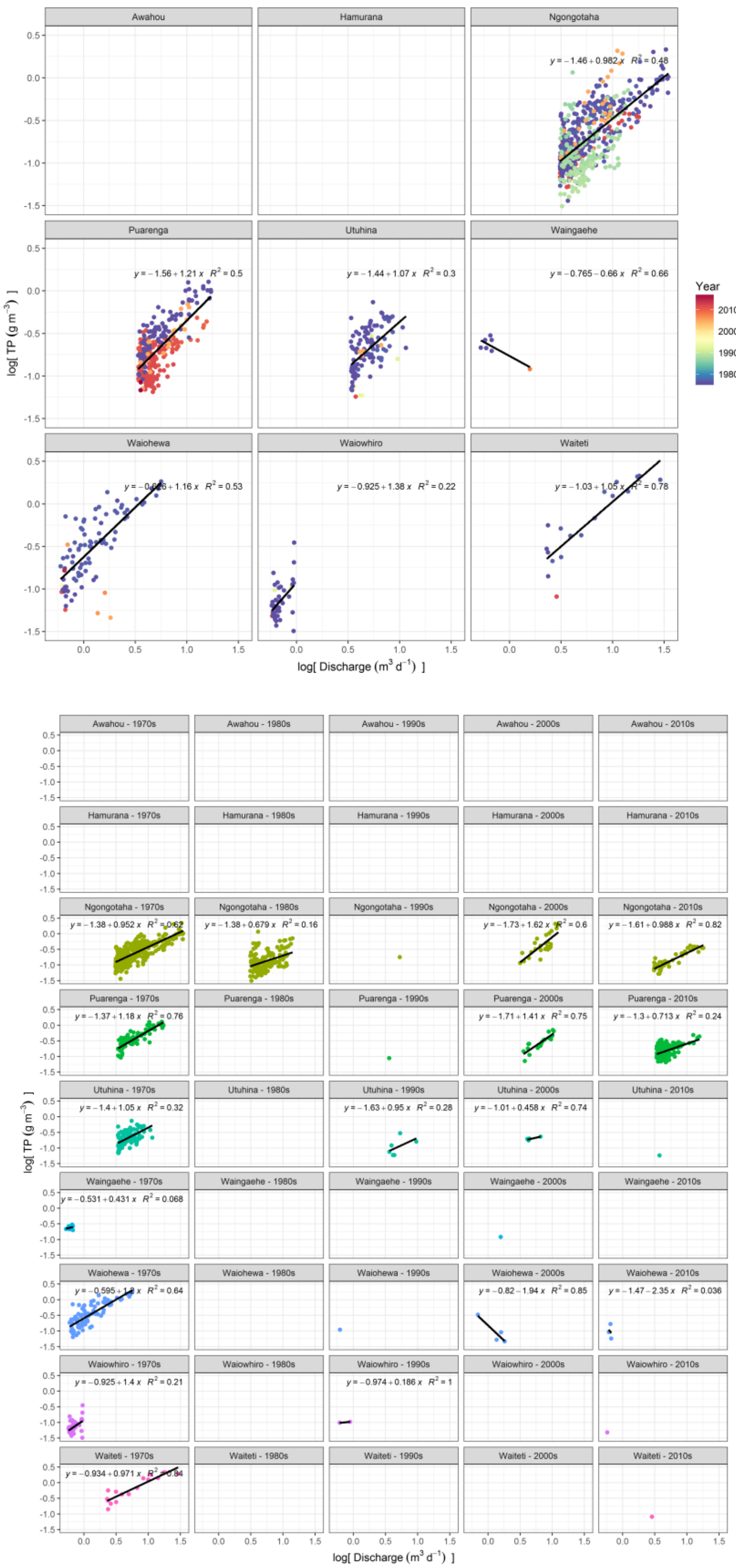
Appendix figure 2f. Relationships between total nitrogen (TN) concentration and discharge for all available samples (top, coloured by year of sample collection) and on a decade by decade basis (bottom).



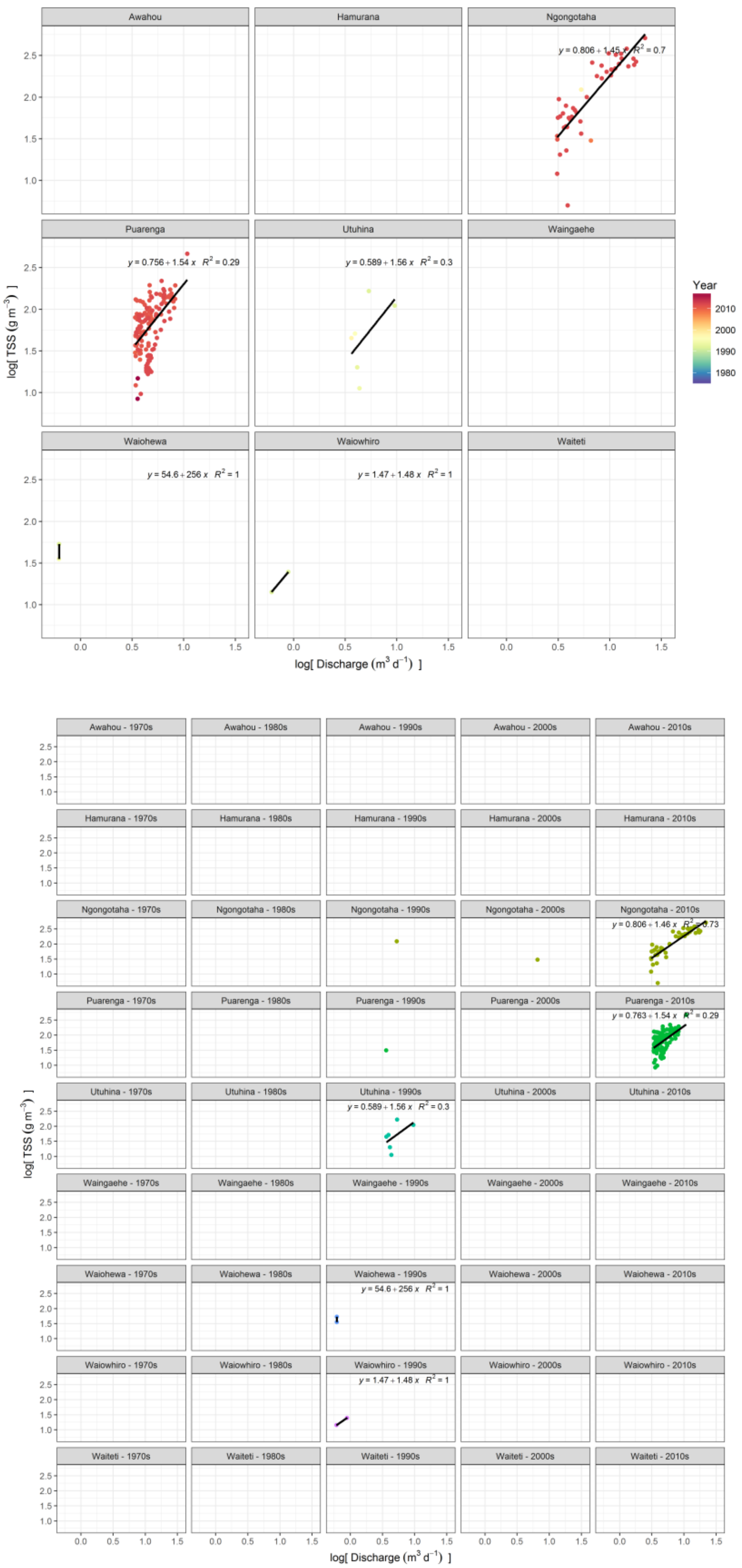
Appendix figure 2g. Relationships between dissolved reactive phosphorus (DRP) concentration (mass as PO_4-P) and discharge for all available samples (top, coloured by year of sample collection) and on a decade by decade basis (bottom).



Appendix figure 2h. Relationships between total (TP) minus dissolved phosphorus concentration (DRP) (i.e., particulate and dissolved organic P) and discharge for all available samples (top, coloured by year of sample collection) and on a decade by decade basis (bottom).

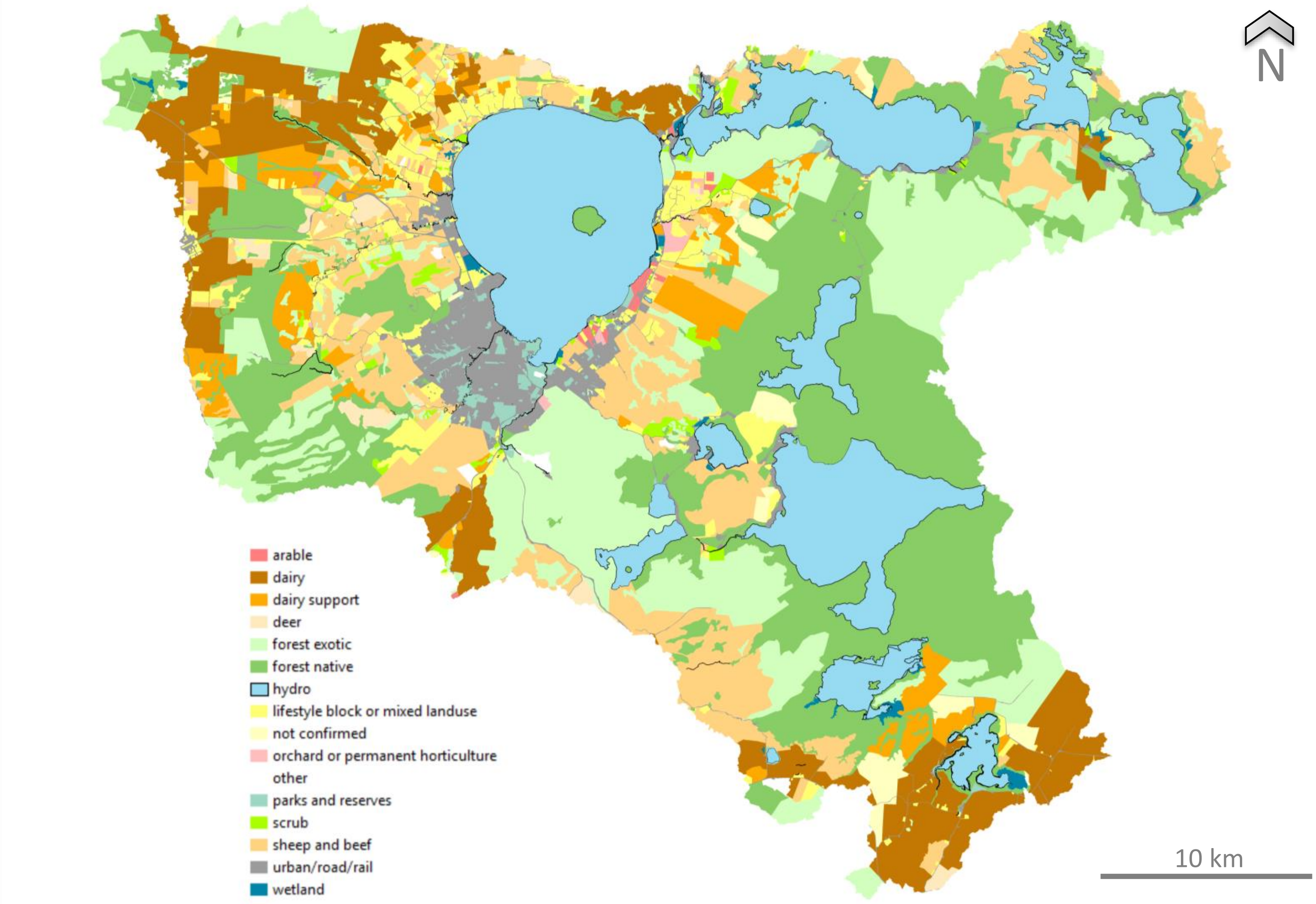


Appendix figure 2i. Relationships between total phosphorus (TP) and discharge for all available samples (top, coloured by year of sample collection) and on a decade by decade basis (bottom).

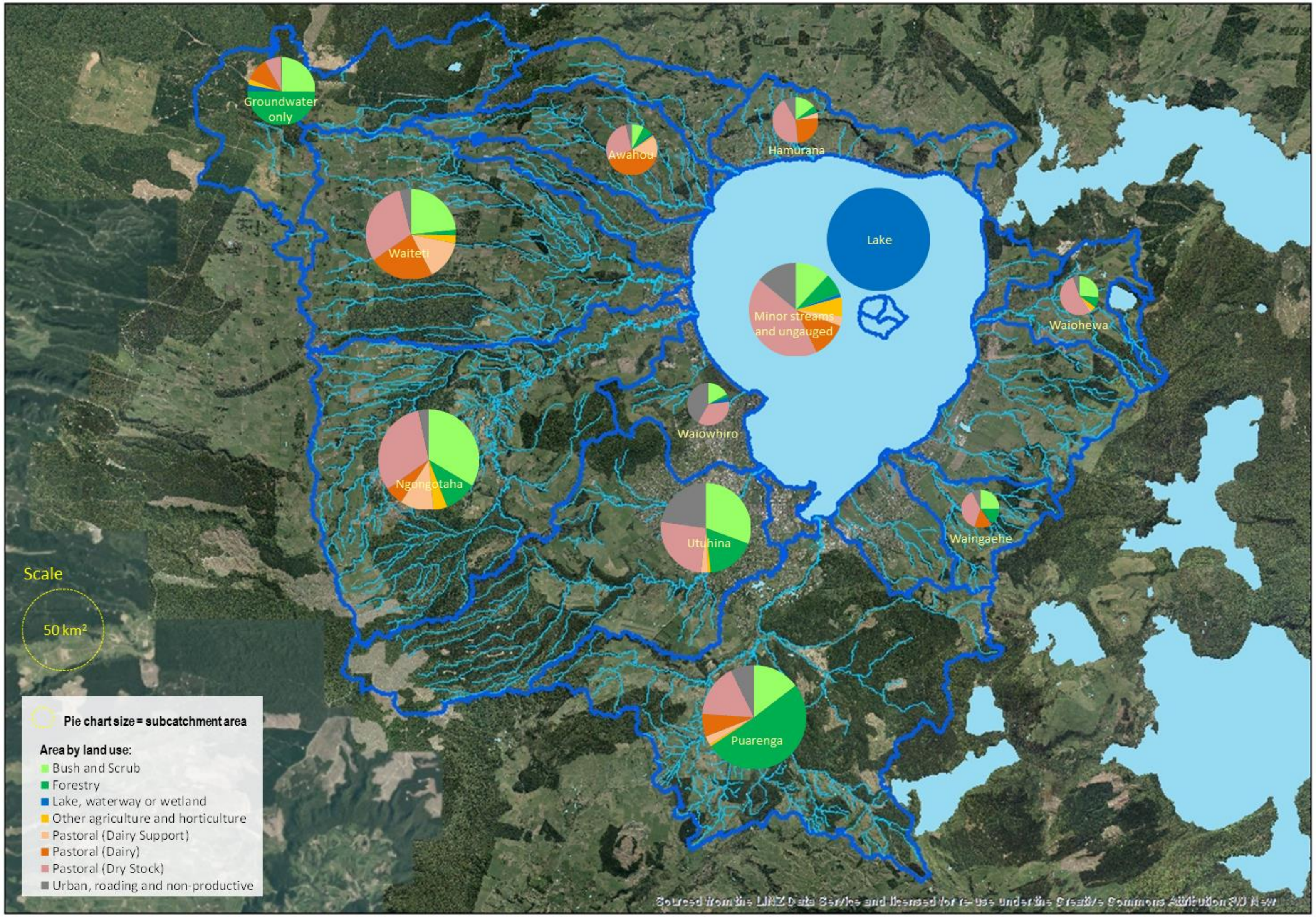


Appendix figure 2j. Relationships between total suspended sediment (TSS) and discharge for all available samples (top, coloured by year of sample collection) and on a decade by decade basis (bottom).

Appendix 3 – Land use Lake Rotorua and the Te Arawa Lakes



Appendix figure 3a. Land use in the Rotorua Te Arawa Lakes region (data: BoPRC 2017).



Appendix figure 3b. Land use in the Lake Rotorua catchment and its sub-catchments (Data: BoPRC, figure adapted from Tempero et al 2015).

Appendix Table 3a. Land use in the Lake Rotorua catchment and its sub-catchments (Data: BoPRC). Land use for the 'groundwater only' areas (see Appendix figure 3b) is not shown.

Land use area (ha)	**Awahou**	**Hamurana**	**Minor & ungauged**	**Ngongotaha**	**Puarenga**	**Utuhina**	**Waingaehe**	**Waiohewa**	**Waiowhiro**	**Waiteti**	**Total**
Bush/scrub	152	236	794	2593	1201	1870	16	308	236	1445	**8850**
Forestry	127	72	517	815	4201	1073	340	102	32	115	**7395**
Lake/waterway/wetland	17	2	79	0	0	0	10	0	44	5	**158**
Pastoral (Dairy Support)	271	65	215	831	222	152	0	21	0	868	**2646**
Pastoral (Dairy)	766	398	819	458	579	0	162	0	0	1433	**4614**
Other ag/horticulture	19	1	457	349	58	66	6	47	0	186	**1190**
Pastoral (dry stock)	533	698	2942	2436	1363	1553	490	633	479	1895	**13021**
Urban/roading/other	69	133	970	211	607	1390	81	59	570	241	**4330**
Total	**1955**	**1604**	**6794**	**7694**	**8230**	**6104**	**1106**	**1169**	**1361**	**6188**	**42204**