Phosphorus and Nitrogen Budgets for Lake Horowhenua

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Executive Summary

Lake Horowhenua suffers from severe eutrophication, which is due to high nitrogen and phosphorus loads entering the lake from agriculture, horticulture, and urban development in the catchment. The Lake Horowhenua FMU Water Quality Interventions Programme aims to progress restoration efforts. This report calculates nitrogen and phosphorus budgets for the lake, as part of this lake restoration programme.

Horizons Regional Council has a comprehensive water quality monitoring programme for the Horowhenua catchment. Data collected on streams, groundwater and the lake water quality and hydrology were analysed to calculate the nutrient budgets.

Even though the lake receives very high nitrogen loads, nitrogen retention is also high. Thus, substantial in-lake processing of nitrogen by sedimentation/sequestration and denitrification occurs such that the nitrogen exported from the lake is approximately only one third of the sum of the nitrogen inputs to the lake. Two thirds of the total nitrogen input disappeared from the water column. The budget estimated that 56% of the catchment nitrogen load to the lake arrives in the form of groundwater; however, this component of the load is the most difficult to quantify accurately.

Phosphorus loads to the lake are much smaller than nitrogen loads and in 2020 the lake lost more phosphorus that it received from the catchment. The findings that the lake retains a large proportion of incoming nitrogen while exporting more phosphorus than the catchment delivers confirms the finding from nitrogen and phosphorus budgets previously calculated from data measured in 1988/89. It seems likely that the lake is still flushing historical excess phosphorus loads (e.g., from historical sewage inputs and superphosphate fertiliser use) accumulated over years and now incorporated into the lakebed. Mechanisms for the remobilisation and flushing of lakebed phosphorus likely include (1) the geochemical solubilisation of sediment-bound phosphorus under transient conditions of bottom water anoxia and high pH in the surface water, (2) the resuspension of lakebed sediment by wind-induced benthic shear stress, and (3) the "mining" of sediment phosphorus by the abundant macrophytes in the lake.

The similarities between the two budgets suggest that if land use has intensified in the past 33 years, mitigation actions in the catchment have succeeded in preventing major increase in measured nutrient losses from the catchment to the lake.

NIWA's CLUES catchment model estimated nitrogen loads from the catchment to be 8 to 34% greater than the nitrogen loads calculated in the budget, while CLUES estimated the catchment phosphorus load to be 25% less than that calculated in the budget.

An analysis of the seasonality of nutrient fluxes into and out of the lake showed that, in general, nutrient fluxes tended to be lowest in autumn and highest in spring and summer, although there were some exceptions to this tendency.

Several caveats regarding the nutrient budgets are discussed, including (1) errors associated with poor predictive power of the rating curves, (2) uncertainty around the nutrient loads from groundwater to the lake, (3) the lack of data for the Queen Street drain which may contribute substantial amounts of phosphorus to the lake during floods/rain events, and (4) the poorly understood effects of macrophytes on the nutrient budgets of the lake.

Work on the nutrient budgets could be extended by examining the contributions of macrophyte biomass and lakebed sediments to the stocks and flows of the nutrient budgets.

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1 BACKGROUND

Lake Horowhenua/Punahau is a shallow, polymictic lake that originally formed in a topographic depression amongst sand dunes along the Manawatu coast. The lake has a surface area of 2.9 km^2, a mean depth of 1.3 m and a maximum depth of approximately 1.8 m. It is located near the centre of a 62.5 km^2 catchment which has its headwaters to the east, in the Tararua hills and its outlet to the sea to the west, through the Hōkio Stream. Historically, the lake, its tributaries and the Hōkio Stream were important sites for the gathering of mahinga kai and freshwater species including crayfish/kōura, freshwater mussels/kākahi, galaxiids/kōkopu, kōaro and inanga, flounder/pātiki, and eels/tuna (Selby et al. 2010).

In 1953, sewage from the nearby, burgeoning town of Levin was diverted into the lake, starting a period of decline in the water quality of the lake and the Hōkio stream. Water quality deteriorated to the point that cyanobacterial blooms became common and aquatic macrophyte proliferation became problematic. In 1987, the sewage outfall was removed from the lake in favour of a land-based application, however occasional accidental spills of sewage into the lake continued to occur (Selby et al. 2010).

Water quality problems continue to plague the lake as do macrophyte proliferations. Since 2014, the lake's trophic level index (TLI) has exceeded 6, which is considered to reflect "very poor" water quality (i.e., the trophic state is supertrophic) (LAWA 2022). Sheep and beef farming, dairy farming, urban development, horticulture, and cropping all occur within the catchment and contribute to pollution entering the streams and lake. In addition to contemporary inflows of nutrients, there is likely to be a large legacy of historically high nutrients loads stored within the lakebed, which may contribute to internal nutrient loads to the water column and, thereby, to the continuing water quality problems that the lake has. The catchment activities will also be contributing nutrients to groundwater which can enter the lake through a gravel fan underlying the lake and surrounding soils.

The annual water residence time in the lake has been reported to average 47 days (down to <35 days in winter and up to > 95 days in summer) (Gibbs 2011). Thus, the lake is flushed with a combination of surface and groundwater almost eight times per year. The velocity of groundwater into the lake has been estimated to be 6.3 km y^{-1}, leading to the suggestion that the groundwater in the catchment can migrate to the lake within one year (Gibbs 2011). These hydrological characteristics indicate that the lake is rapidly replenished on average roughly every seven weeks with surface water and groundwater and with the contaminants that these waters bring with them to the lake.

Preliminary studies on the nitrogen and phosphorus concentrations in surface waters and groundwater in the Lake Horowhenua catchment indicate that these are generally on the high side (e.g., within the worst 25% of monitored river sites across New Zealand; Clark et al. 2015; LAWA 2022). Thus, together with high legacy nutrient concentrations within the lake sediments, the rapid replenishment of the lake with waters containing high nutrient concentrations represents a situation which is consistent with the algal blooms and poor water quality evident in the lake. Without the macrophyte beds present in the lake to compete with algae and to assimilate some nutrients into macrophyte and epiphytic biomass, the trophic state of the lake would likely be even worse than it currently is.

In lakes, phosphorus and nitrogen are the plant nutrients that usually stimulate algal blooms and aquatic plant growth (Schallenberg 2004), although the availability of micronutrients such as iron, boron, copper, manganese and others may also play a role in regulating algae and vascular plant productivity and biomass (Downs et al. 2008). Similarly, to stimulate the growth of terrestrial plants such as flowers, vegetables and trees, the most common forms of inorganic fertilisers used contain a mixture of nitrogen, phosphorus, and potassium, sometimes with added trace element micronutrients. In lakes, however, potassium seems not to play such an important role in regulating plant growth, perhaps because in terrestrial plants potassium plays an important role in regulating water use by the plants, thereby allowing plants to resist drought. So, in lake waters, the control of nitrogen and phosphorus availability, either directly or indirectly, is the most common way of managing algal and plant proliferations (Paerl et al. 2016; Verburg et al. 2018; Maberley et al. 2020), but trace element availability can also play a role at times (Downs et al. 2008).

Nitrogen and phosphorus can be found in different chemical forms in lake water (Fig. 1) and some of these forms are more easily assimilated than others. For example, algae and vascular plants can easily and rapidly assimilate nitrate and dissolved reactive phosphorus - forms more generally known as soluble inorganic nitrogen and dissolved reactive phosphorus (or phosphate).

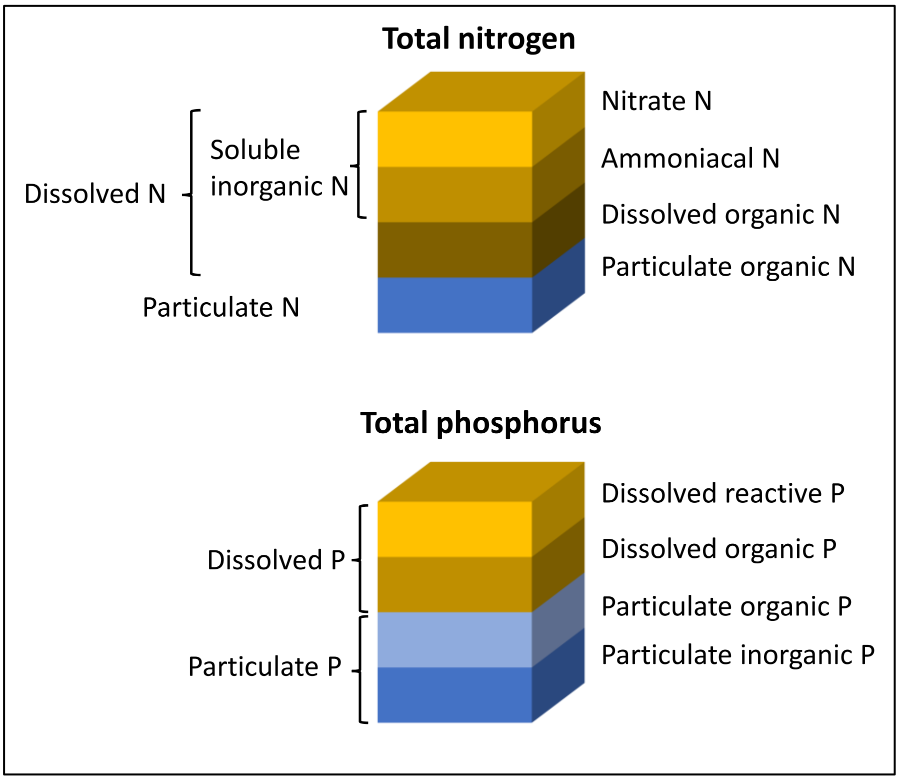

Figure 1. The common constituents of total nitrogen and total phosphorus in lake water. Relative proportions of the constituents can vary greatly.

While the dissolved inorganic fractions are the most bioactive for plants and algae, in the long term, lakes are sinks for particulate materials and some particulate nutrients can be transformed into dissolved nutrients by chemical and biological transformations. For example, P bound to iron and aluminium minerals can be released under conditions of anoxia or high pH, respectively (Søndergaard et al. 2003; Hickey & Gibbs 2009) - conditions which occur in Lake Horowhenua (Gibbs 2011; Verburg et al. 2019). Furthermore, particulate organic P and N in living cells and in detritus can be mineralised by microbes and digested by aquatic consumer organisms, resulting in the transformation of some particle-bound nutrients into dissolved nutrients. Due to this biological mineralisation potential and to the geochemical adsorption/desorption potential of particulate nutrients, a proper accounting of nutrient inputs and outputs from lakes should focus on the total nutrients rather than on the most bioavailable forms (e.g., Vollenweider 1975; Verburg et al. 2018).

1.1 USE OF NUTRIENT BUDGETS IN LAKE MANAGEMENT AND RESTORATION

Efforts to restore lakes from a state of eutrophication can focus on reducing rates of nutrient input to the lake and/or on reducing the in-lake nutrient recycling rate. It is important to understand the relative importance of the external load, the internal load, and the nutrient loss/retention/sequestration rate with nutrient budgets being helpful in calculating these. Careful interpretation of the parameters of the nutrient budget can also provide insights into whether: (1) a lake is a net sink or source for nutrients, (2) phosphorus and nitrogen availability are balanced or unbalanced, (3) controlling one or both nutrients is necessary to reduce symptoms of eutrophication, and (4) how important the recycling of historical legacy loads might be. This information can help optimise restoration efforts for maximal cost-effectiveness. Typical nutrient budgets are simple mass-balance models, although, they usually ignore, or over-simplify, the complex nutrient dynamics and interactions that occur within lakes. With careful interpretation and acknowledgement of limitations, the long-standing interest in such models for lake management has been amply demonstrated (e.g., Vollenweider 1975, Brett & Benjamin 2008, Kelly et al. 2013; Verburg et al. 2018; Verburg & McBride 2022).

2 AIM AND SCOPE

Numerous management actions have already been undertaken by Manawatū – Whanganui Regional Council (Horizons) to attempt to remediate the eutrophication problem of Lake Horowhenua. In 2020, the Ministry for the Environment funded a four-year programme called Lake Horowhenua FMU Water Quality Interventions to progress restoration efforts. Part of this programme is focused on further developing a conceptual understanding of Lake Horowhenua and its catchment, specifically regarding contaminant flows. This will help inform future management and restoration actions as well as inform the implementation of the Essential Freshwater package of Central Government freshwater policy reforms (e.g., NPSFM 2020). A key component of this programme is the development of a contaminant accounting model (CAMS) for the catchment.

This report presents nitrogen and phosphorus budgets for Lake Horowhenua and inform the CAMS model which will be developed by the consultancy, Land Water People. The CAMS model will account for contaminant stocks and flows on an annual basis. Therefore, our nutrient budgets were also calculated on an annual basis to provide temporally relevant nutrient parameter estimates to the CAMS model. However, we also determined the seasonality of nutrient loads to, and export from, Lake Horowhenua.

3 DATA SOURCES

For reasons discussed in Section 1, the nutrient budgets focus on total nitrogen (TN) and total phosphorus (TP). The budget requires relatively complete calculations of nutrient inputs (loads), outputs (export) and the standing stock of nutrients in the lake. From this information, the net nutrient retention (nutrient losses from the water column) can be estimated.

To calculate the budgets, nutrient concentration, and hydrological discharge measurements from the main tributaries to the lake and from the Hōkio Stream are required to estimate nutrient fluxes such as loads to, and export from, the lake. In addition, nutrient standing stocks in the lake water are required, which are obtainable from lake monitoring data. All these data were provided by Horizons Regional Council.

Furthermore, estimates of groundwater and atmospheric nutrient loads to the lake are also required and these were obtained from Gibbs (2011) and Verburg et al. (2018), respectively. To validate the use of the groundwater loads in Gibbs (2011) in our budget, time series of groundwater nitrate and total dissolved phosphorus concentrations were provided by Horizons Regional Council.

4 METHODS

4.1 DATA COLLATION

4.1.1 Sites and datasets

Horizons Regional Council monitors water quality and flow at 9 lotic sites (Fig. 2), which include streams, drains and the outflow stream (the Hōkio at Lake Horowhenua site). The council also collects a composite sample pooled from three sites in Lake Horowhenua (Lake Horowhenua Composite). With the aim of constructing a nutrient budget using the maximum amount of data available, the time frames of the water quality and flow datasets were assessed to determine potential periods of overlap of the datasets (Table 1). Nutrient samples were from a dataset containing water quality information for monthly grab samples, while daily mean flow/discharges were calculated from high frequency flow meters at the sites, which measured flow/discharge at 15-minute intervals.

Figure 2. Locations of the lotic water quality and discharge sites monitored by Horizons Regional Council.

We compared the start and end dates of the time series for each site with the view to collating the most complete dataset available with contemporaneous nutrient and flow measurements for use in our nutrient budget calculations. No flow/discharge quality data were available for sites at Lake Horowhenua inflow at the culvert downstream of Queen Street, Lake Horowhenua inflow at Hōkio Sand Road, the Queen Street Drain at Lake Horowhenua, or Lake Horowhenua at Weir. Therefore, these sites were omitted from the nutrient budget calculations. The dataset collation and comparison exercise resulted in a selection of contemporaneous datasets for the sites, Arawhata Drain inflow at Hōkio Beach Road, Lake Horowhenua Inflow at Lindsay Road, Patiki Stream inflow at Kawiu Road, and Hōkio Stream outflow at Lake Horowhenua. The time period of contemporaneous nutrient and flow data from these sites was 12/12/2019 to 2/3/22, constituting a period of just under 27 months for nutrient budget calculations (Table 1).

Table 1. Time frames and sampling frequencies of Horizons Regional Council's water quality and stream discharge data.

Site	Parameter	Start	End	Data Frequency
Arawhata Drain at Hokio Beach Road	TN	26/07/2006	7/06/2022	Monthly
Arawhata Drain at Hokio Beach Road	TP	5/08/1998	7/06/2022	Monthly
Arawhata Drain at Hokio Beach Road	Flow	3/06/2017	16/03/2022	Daily
Hokio at Lake Horowhenua	TN	1/04/2008	7/06/2022	Monthly
Hokio at Lake Horowhenua	TP	8/04/1998	7/06/2022	Monthly
Hokio at Lake Horowhenua	Flow	2/05/2013	16/03/2022	Daily
L Horowhenua Inflow at culv d/s Queen St	TN	1/04/2008	14/02/2018	Monthly
L Horowhenua Inflow at culv d/s Queen St	TP	1/04/2008	14/02/2018	Monthly
L Horowhenua Inflow at culv d/s Queen St	Flow	N/A	N/A	N/A
L Horowhenua Inflow at Hokio Sand Rd	TN	27/11/2012	11/04/2018	Monthly
L Horowhenua Inflow at Hokio Sand Rd	TP	27/11/2012	11/04/2018	Monthly
L Horowhenua Inflow at Hokio Sand Rd	Flow	N/A	N/A	N/A
L Horowhenua Inflow at Lindsay Road	TN	1/04/2008	7/06/2022	Monthly
L Horowhenua Inflow at Lindsay Road	TP	1/04/2008	7/06/2022	Monthly
L Horowhenua Inflow at Lindsay Road	Flow	20/10/2019	16/03/2022	Daily
Lake Horowhenua Composite	TN	17/07/2013	20/04/2022	Monthly
Lake Horowhenua Composite	TP	17/07/2013	20/04/2022	Monthly
Lake Horowhenua Composite	Flow	N/A	N/A	N/A
Patiki Stream at Kawiu Road	TN	1/04/2008	7/06/2022	Monthly
Patiki Stream at Kawiu Road	TP	5/08/1998	7/06/2022	Monthly
Patiki Stream at Kawiu Road	Flow	13/11/2019	23/03/2022	Daily
Queen Street Drain at L Horowhenua	TN	1/04/2008	8/11/2017	Monthly
Queen Street Drain at L Horowhenua	TP	1/04/2008	8/11/2017	Monthly
Queen Street Drain at L Horowhenua	Flow	N/A	N/A	N/A
Lake Horowhenua at Weir	TN	N/A	N/A	N/A
Lake Horowhenua at Weir	TP	N/A	N/A	N/A
Lake Horowhenua at Weir	Flow	5/05/2017	22/03/2022	Daily

4.1.2 Groundwater nutrient loads to the lake

Gibbs (2011) showed that groundwater inputs were a substantial source of nutrients to the lake. Horizons Regional Council has a network of groundwater/bore water monitoring sites in the Lake Horowhenua catchment. However, it was beyond the scope of this study to develop a Lake Horowhenua groundwater nutrient input model from these data. Gibbs (2011) estimated groundwater nutrient inputs to the lake based on a groundwater dataset from the period July 1988 to January 1990. To assess whether the estimates from this study were likely to be relevant to this nutrient budget exercise, we sought to examine temporal trends in Horizons groundwater nutrient concentrations time series. Due to the likelihood of nitrogen attenuation in lowland peaty soils, we limited our investigation of groundwater nutrient trends to groundwater monitoring sites within approximately 1 km of the lake perimeter. We found one groundwater monitoring site (352099) that satisfied this distance criterion and which had a substantial nutrient data time series (Fig. 3).

The Gibbs (2011) groundwater nutrient load estimate used data collected in 1988/89. In order to assess whether data from 34 years ago could be reasonably applied to the current nutrient budget, we plotted the long-term trend in nitrate data from site 352099 to attempt to compare the nitrate concentrations from 1988/89 with recent nitrate concentration. If nutrient concentrations from in, or around, these time periods turned out to be similar, then we would feel confident in using the Gibbs (2011) estimates of groundwater nutrient inputs to the lake in our updated nutrient budget.

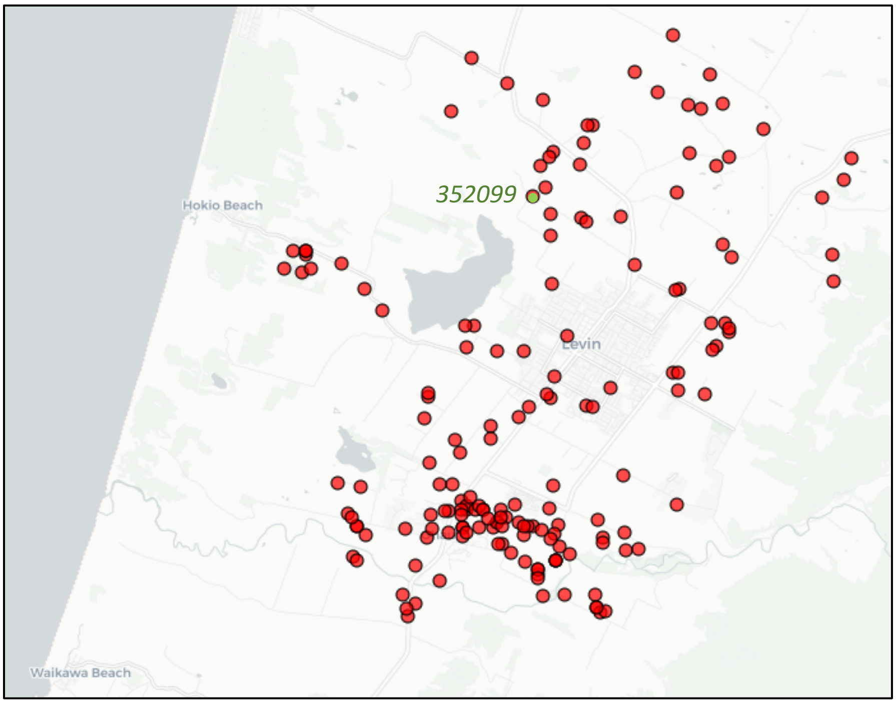

Figure 3. Horizons long-term ground water monitoring site within approximately 1 km of the lake perimeter. The site and site code are shown in green. Map provided by Horizons Regional Council.

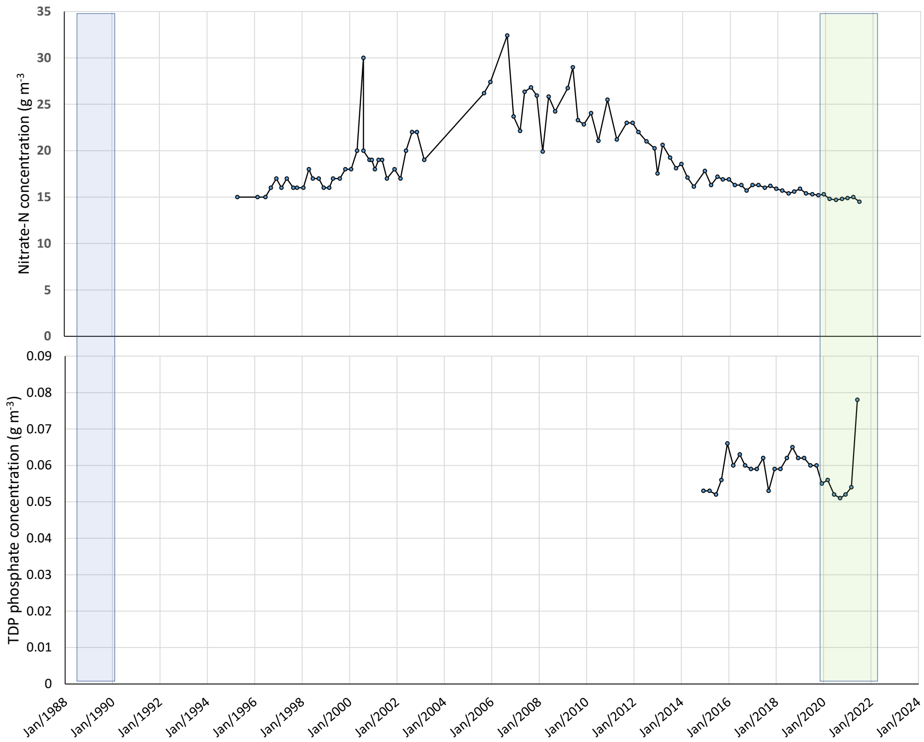

Figure 4. The time series of groundwater nitrate-N and phosphate concentrations at site 352099.0 from 1995 to 2022. The blue box is the period of groundwater nutrient load calculations of Gibbs (2011). The green box is the time frame of the current nutrient budget calculation.

The times series of nitrate-N concentrations in groundwater shows that between the years 2000 and 2017, a substantial pulse of nitrate moved through the aquifer at this site and that recent nitrate concentrations are similar to those from 1995. Therefore, based on this information, we decided that the Gibbs (2011) estimates of groundwater nutrient loads to Lake Horowhenua are likely to be a reasonable estimation of groundwater nitrogen loads to the lake. Unfortunately, the phosphorus time series wasn't long enough to allow us to validate the groundwater phosphorus load calculation of Gibbs (2011). However, based on the trend in nitrate, we elected to also use the groundwater phosphorus load estimate from Gibbs (2011). However, the most recent data point in the phosphorus time series in Figure 4 suggests that trends in groundwater nitrate may not reflect trends in groundwater phosphate concentrations.

Groundwater hydrological inputs to Lake Horowhenua have also been previously estimated. Gibbs (2011) estimated the annual mean groundwater input rate in the period from July 1988 to November 1989 to be 510 L s^{-1}, while Thomas & Garden (2021) estimated the figure to be 531 L s^{-1} for the period 2019 to 2021. These estimates are within ± 2% of each other. Furthermore, a steady state hydrological model using meteorological recharge from 1972 to 2021 produced a slightly higher estimate of groundwater discharge to the lake of 570 L s^{-1}. From these estimates, it seems that the groundwater discharge rates used by Gibbs (2011) for his estimates of groundwater nutrient loads are reasonable, lending further confidence regarding the use of the Gibbs (2011) groundwater nutrient load estimates in the current nutrient budgets.

4.2 NUTRIENT LOADS AND EXPORT RATES

We collated total nitrogen, total phosphorus, and flow/discharge data for each site. Nutrient data were from monthly grab samples, while flow data were daily mean flows. To assist with interpolating the gaps in the monthly nutrient data, we created rating curves (e.g., instantaneous nutrient concentration vs. daily mean flow/discharge) with the aim of interpolating daily nutrient concentrations for the lotic sites.

Although we chose to calculate nutrient budgets from a 27-month period of contemporaneous datasets, longer time series were available for most sites. With the aim of using as much data as possible to construct each rating curve, we plotted all the data available for each site, but coded the data for the period of nutrient budget calculation differently in the plots. This was done to assess whether there was any bias in the rating curves which plotted the full datasets vs the restricted datasets. In all cases, no bias was obvious and so we elected to use the full datasets for each site to construct the rating curves. This allowed for more robust statistical modelling of the relationships between nutrient concentration and flow/discharge.

When multiple entries existed in the datasets for one date, we averaged these. In some cases, there were gaps in the daily mean flow data, which we interpolated for the missing days using linear interpolation between the datapoints at each end of the gap. The number of days for which we had to interpolate flow is indicated in Table 2.

Table 2. Number and percentage of days for which flow data was linearly interpolated at four flow sites. The period was from 12 December 2019 to 2 March 2022.

Site	No. days interpolated	% Total days interpolated
Arawhata Drain at Hōkio Beach Road	42	5
Hōkio Stream at Lake Horowhenua (Outflow)	26	3
Lake Horowhenua Inflow at Lindsay Rd	303	37
Patiki Stream at Kawiu Road	105	13

4.2.1 Rating curves

We scrutinised the scatter plots of nutrient concentration vs flow to determine the most reasonable statistical models to fit to the data. In cases where relationships had low predictive power (i.e., $R^2 < 0.47$), the monthly nutrient data were interpolated to daily values using linear interpolation. Where the model fits were reasonable, we elected to use the rating curves to interpolate the daily nutrient concentrations, based on flow.

Predicted daily nutrient concentrations were then multiplied by the mean daily flow to derive a daily flux for each of the four lotic sites. Then daily fluxes were summed across the entire calendar years (2020 and 2021) and across the four seasons: summer (December to February), autumn (March to May), winter (June to August) and spring (September to November).

4.2.2 Atmospheric loads

Atmospheric loads of nitrogen and phosphorus have been estimated to be on average 6.37 kg N ha^{-1} yr^{-1} and 0.24 kg P ha^{-1} yr^{-1} (Verburg et al. 2018). These are estimates for the North Island and are for both dry and wet deposition, combined. Annual rainfall measurements for Levin for the years 2020 and 2021 were obtained from NIWA's climate data annual summaries (https://niwa.co.nz/climate/summaries/annual) and were used to estimate the annual amounts of precipitation falling directly on the lake. Rainfall for 2020 and 2021 was 1056 and 1270 mm yr^{-1}, respectively).

4.2.3 Other published estimates of nutrient loads to Lake Horowhenua

Other estimates of nutrient loads to, and export from, Lake Horowhenua were also collected. Gibbs (2011) provided nutrient load estimates based on measurements made during the period July 1988 to November 1989 and Verburg et al. (2019) included nutrient load estimates from NIWA's CLUES catchment model, specified for the Lake Horowhenua catchment.

4.3 Budgets

Nutrient budgets were constructed on annual basis from the nutrient load and export data together with the estimates of water column nutrient standing stocks in the lake:

$$\textit{Nutrient export} = \textit{Nutrient loads} - \textit{Nutrient retention} - \Delta\ \textit{Nutrient standing stock} \qquad (1)$$

Where Δ Nutrient standing stock is the change in the lake water column nutrient standing stock per unit time and where the other variables are also expressed as a mass per unit time (e.g., tonnes yr^{-1}).

In nutrient budgets, the term nutrient retention is calculated as a net loss or gain of nutrients as they pass through the lake. The term implicitly includes processes such as sedimentation, sequestration, internal loading, denitrification, and nitrogen fixation, where these processes contribute to in-lake nutrient processing. It doesn't distinguish between these potential processes and, therefore, provides estimates of net loss or gain. Nutrient retention was calculated by rearranging equation (1):

$$\textit{Nutrient retention} = \Delta\ \textit{Nutrient standing stock} + \textit{Nutrient loads} - \textit{Nutrient export} \qquad (2)$$

A dimensionless nutrient retention coefficient was also calculated, as per Vollenweider (1975):

$$\textit{Nutrient retention coefficient} = (1 - \textit{Nutrient export}/\textit{Nutrient loads}) \qquad (3)$$

Note that this equation used to estimate nutrient retention coefficient does not account for changes in lake water column nutrient standing stocks, over time.

5 Results

5.1 Summary statistics for the sites

The Arawhata Drain site showed the highest nutrient concentrations of all the sites (Fig. 5). One phosphorus sample in the Arawhata Drain was an extreme outlier. The sample was collected on March 17, 2021 and the Lake Horowhenua Composite collected on this date also showed extremely high total phosphorus concentrations (2.95 g P m^{-3}, along with an extremely high turbidity of 659 NTU). Neither the Patiki Stream nor the Lindsay Road sites showed unusually high measurements on that date. Given that extreme phosphorus outliers were observed both in the lake and at Arawhata Drain on the same date, together with equally extreme values of other water quality attributes at these sites on the day, we decided that the extreme measurements were probably not in error and may have reflected lake conditions during an extreme wind event, which apparently also affected the Arawhata Drain. Thus, we left these outliers in the datasets.

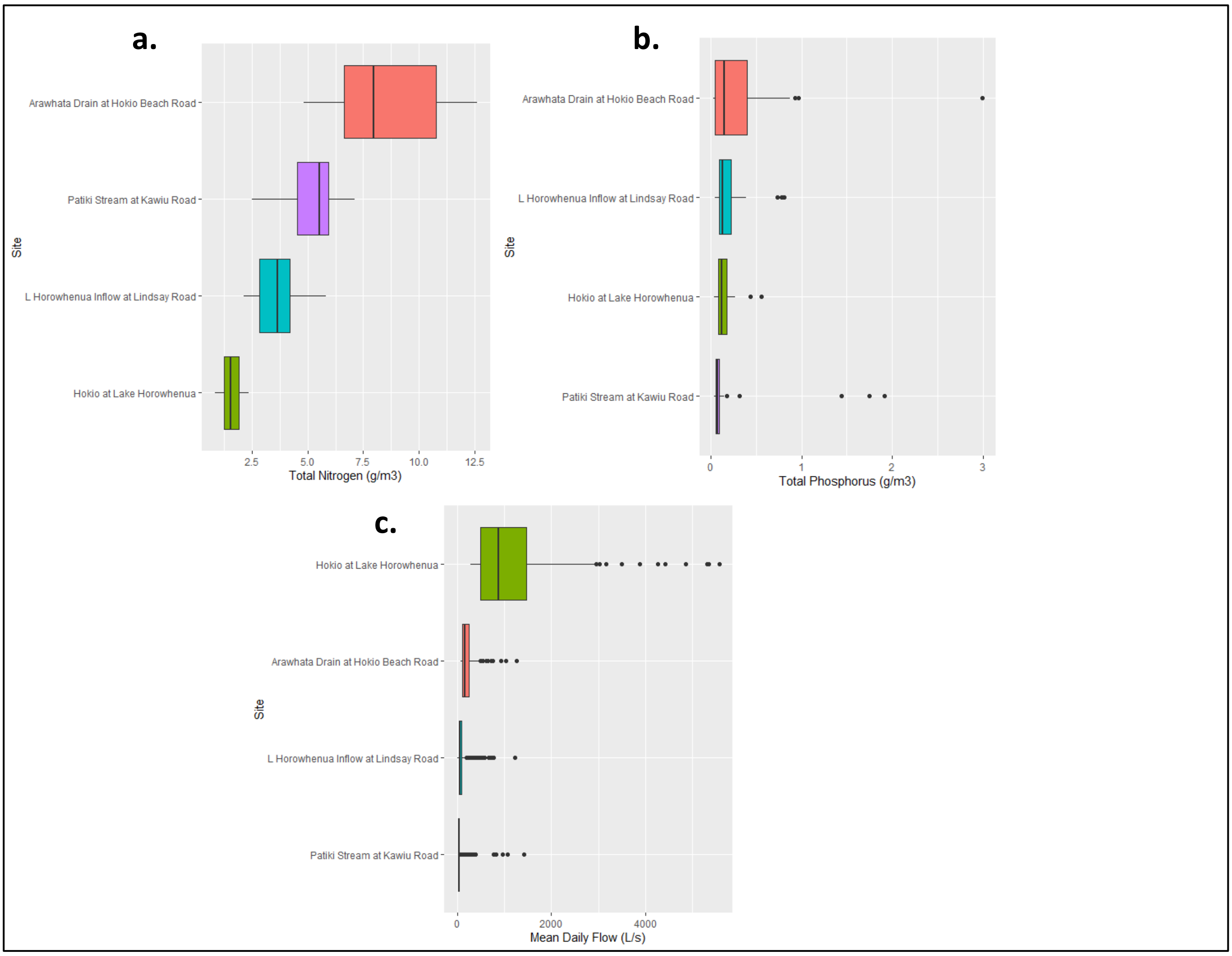

Figure 5. Summary statistics for total nitrogen, total phosphorus and mean daily flow discharge for the lotic sites. Statistics are shown for the full records and only for the period where the data at the sites overlap. The box plots show the medians, the interquartile range, the 95% confidence intervals and outliers.

5.2 Rating curve models

The relationships between nutrient concentrations and flow/discharge at the four sites are plotted in Appendix 1. The relationships were scrutinised and appropriate statistical models were fit to the data to allow interpolation of daily nutrient concentrations based on measured daily mean flow data at the four sites. Despite our best efforts to fit appropriate statistical models, three of the rating curves had very poor predictive power, as assessed by the R^2. Therefore, it was decided that total nitrogen at the Arawhata Drain and Hōkio outflow and total phosphorus at the Hōkio outflow would be interpolated to daily concentrations using linear interpolation from the nutrient grab sample data. The rest of the statistical models all had $R^2 \geq 0.47$ (Table 3) and were used to interpolate daily nutrient concentrations based on daily mean flows.

Table 3. Rating curve models. Plots of the data are presented in Appendix 1.

Site	Parameter	Model Type	Equation	R^2	P-value
Arawhata Drain inflow at Hōkio Beach Road	TN	Linear	TN = 8.56 + 0.0098 * (Flow)	0.16†	0.0073
Arawhata Drain inflow at Hōkio Beach Road	TP	Exponential	ln(TP) = -3.38 + 0.0042 * (Flow)	0.47	3.0 e^9
Hōkio at Lake Horowhenua outflow	TN	Linear	TN = 1.84 + 0.00018 * (Flow)	0.07†	0.0097
Hōkio at Lake Horowhenua outflow	TP	Inverse	TP = 0.096 + 82.44 * 1/(Flow)	0.17†	5.1 e^5
Lindsay Road inflow to Lake Horowhenua	TN	Logarithmic	TN = 0.917 + 0.574 * ln(Flow)	0.53	0.0006
Lindsay Road inflow to Lake Horowhenua	TP	Linear	TP = 0.088 + 0.0010 * (Flow)	0.82	7.9 e^8
Patiki Stream inflow at Kawiu Road	TN	Inverse	TN = 3.276 + 71.84 * 1/(Flow)	0.51	2.6 e^5
Patiki Stream inflow at Kawiu Road	TP	Linear	TP = -0.004 + 0.0018 * (Flow)	0.99	2.0 e^24

†Due to low predictive power, models were replaced by linear interpolation of the time series.

5.3 Nutrient loads to Lake Horowhenua

The largest calculated source of nitrogen to Lake Horowhenua was groundwater (56%; Fig. 6), a component of the nutrient budget that was estimated for a period from 1988 to 1989 by Gibbs (2011). Groundwater nitrate concentrations in the vicinity of Lake Horowhenua have declined in recent years from very high concentrations recorded during the period between 2002 and 2014, when concentrations of nitrate-N got as high as 30 mg m^{-3} (Figure 4). In recent years, the groundwater nitrate concentrations have declined to levels that were measured in the mid-1990s (around 15 mg m^{-3}).

The next largest source of nitrogen in our dataset was the Arawhata Drain (34%). The remaining 10% of the calculated annual nitrogen load came from a combination of the Lindsay Road inflow, Patiki Stream inflow and from atmospheric inputs.

The main sources of phosphorus to the lake were the Lindsay Road inflow (34%), the Arawhata Drain (28%) and Patiki Stream (24%; Fig. 6). Our estimate of groundwater input (from Gibbs, 2011) was only 10% of the total load, while atmospheric inputs (dry + wet deposition) contributed only 4% of the total phosphorus load.

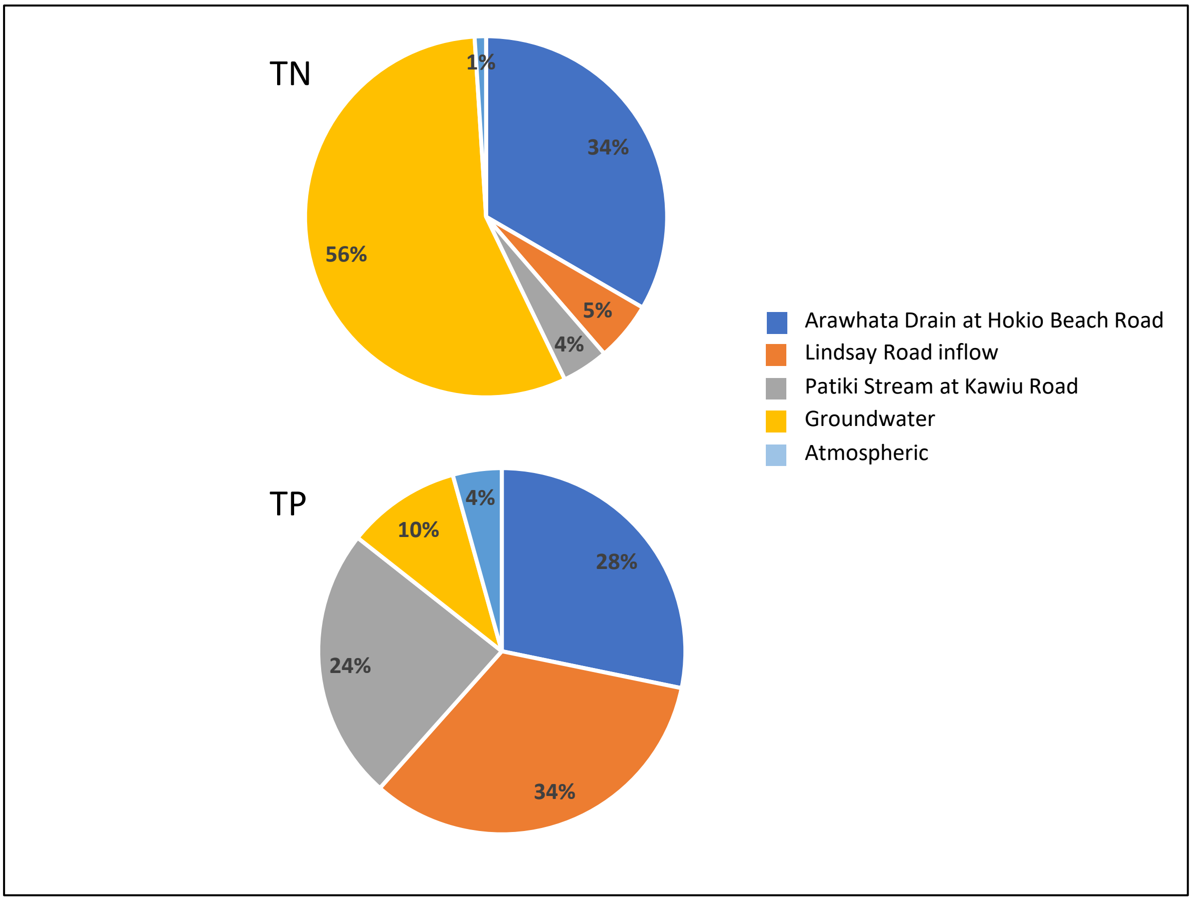

Figure 6. Distribution of total nitrogen (TN) and total phosphorus (TP) loads among different inflows to Lake Horowhenua.

5.4 BUDGETS

The water balance for Lake Horowhenua indicates that slightly more water was exported from the lake than could be accounted for by the measured and estimated inputs in the water balance (Table 4). Some of the minor inflows were not measured or accounted for. In addition, groundwater inflows were estimated from the measurements of Thomas & Garden (2021) and are subject to some uncertainty. For example, their measured groundwater inflow was 531 L s^{-1}, while their modelled inflow was 571 L s^{-1}. In Table 4, we used their measured groundwater inflow, which was similar to that measured by Gibbs (510 L s^{-1}; 2011). Using the total water inputs, outflows and the lake volume, the calculated mean annual theoretical water residence times for the lake varied between 38 and 49 days in the two years (slightly longer if using the inputs rather than the outflows for the calculation).

Two annual nutrient budgets for nitrogen and phosphorus (for 2020 and 2021) were calculated (Table 4).

The calculated total phosphorus load was more variable from year-to-year than the nitrogen load was. The annual loads of phosphorus were 2 to 3 × the average standing stock of phosphorus in the lake. Comparing the total phosphorus loads to the export from the lake via the outflow, a net loss of phosphorus from the lake via the outflow was calculated in both years. However, when factoring in the change in lake water column phosphorus standing stocks (storage), the lake showed a net discharge of phosphorus in 2020, but a net retention of phosphorus in 2021.

In contrast, nitrogen loads far exceeded nitrogen export in both years, indicating that 60 to 70% of the nitrogen entering the lake was lost from the water column either through denitrification or through biological uptake and sedimentation/sequestration. The nitrogen load to the lake was around 15 to 20 ×

the mean nitrogen standing stock in the lake for the annual period. If any nitrogen fixation occurred, the amount of nitrogen processing by the lake would simply increase by the amount of N-fixation that occurred. The nitrogen budget suggests that denitrification is a major nitrogen processing pathway in the lake.

Table 4. Nutrient budget for 2020 and 2021 for Lake Horowhenua. Values in italics are calculated from components of the budgets. See text for details.

Water Flows and Stocks	Component	Year1 2020 $10^6 m^3 yr^{-1}$	Year2 2021 $10^6 m^3 yr^{-1}$	Year1 2020 $10^6 m^3$	Year2 2021 $10^6 m^3$
Inputs	Arawhata	5.51	6.45		
	Lindsay	2.27	3.23		
	Patiki	1.49	1.65		
	Groundwater	16.7	16.7		
	Precipitation	3.07	3.68		
	Other inflows				
Total load		29.0	31.7		
Evapouration					
Outflow	Hokio	29.4	35.7		
Inflow deficit		0.4	4.0		
Lake volume				3.77	3.77
Total Phosphorus		**2020**	**2021**	**2020**	**2021**
Flows and stocks	**Component**	**$t\ yr^{-1}$**	**$t\ yr^{-1}$**	**t**	**t**
Inputs	Arawhata	0.525	1.94		
	Lindsay	0.626	1.2		
	Patiki	0.364	0.756		
	Groundwater	0.23	0.23		
	Dry and wet deposition	0.099	0.099		
	Other inflows				
Total load		***1.84***	***4.23***		
Outflow	Hokio	3.66	5.21		
Total load - Outflow		***-1.82***	***-0.98***		
Average lake storage				0.572	1.53
Storage	Change in lake storage	0.795	-0.733		
Retention		***-1.25***	***0.550***		
Total Nitrogen		**2020**	**2021**	**2020**	**2021**
Flows and Stocks	**Component**	**$t\ yr^{-1}$**	**$t\ yr^{-1}$**	**t**	**t**
Inputs	Arawhata	52.3	75.7		
	Lindsay	9.23	12.5		
	Patiki	7.17	7.66		
	Groundwater	101	101		
	Dry and wet deposition	1.85	1.85		
	Other inflows				
Total load		***172***	***199***		
Outflow	Hokio	48.3	65.7		
Total load - Outflow		***123***	***133***		
Average lake storage				9.52	12.7
Storage	Change in lake storage	3.36	5.75		
Retention		***133***	***146***		

5.5 SEASONAL LOADS AND EXPORT

We were unable to calculate seasonal nutrient budgets for the lake because we did not have confidence that we could partition the annual groundwater nutrient inputs provided by Gibbs (2011) into seasons. While Gibbs (2011) did show variation in groundwater nutrient loads throughout the year, during the two years that measurements were made and calculations were done, groundwater nutrient loads differed substantially during the periods from July to November (i.e., roughly a 5-fold difference between the years; Figure 7).

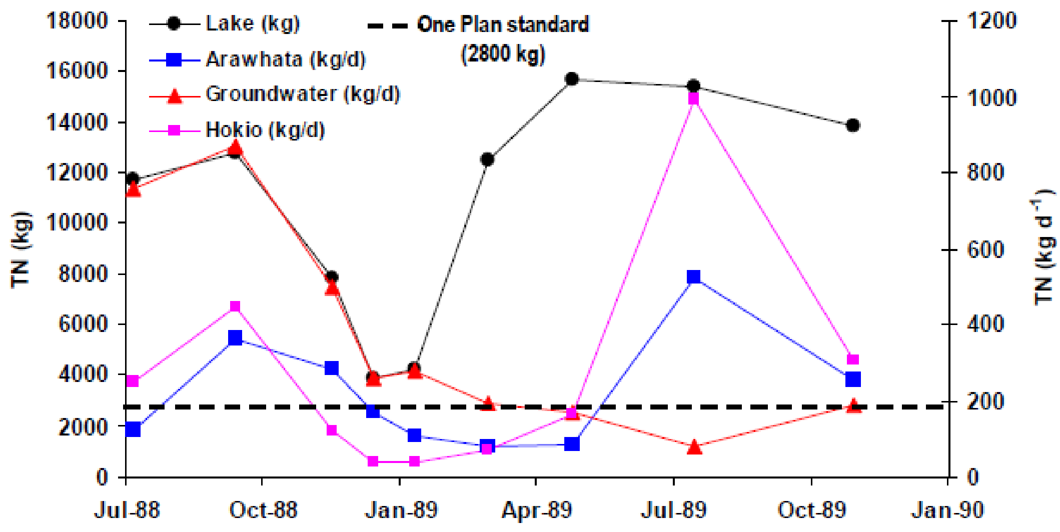

Figure 14. Mass (kg) of TN (left axis) in Lake Horowhenua water column compared with the flux (kg d^{-1}) into and out of the lake over the 1988/89 study period (right axis). The equivalent average TN mass in the lake for the One Plan standard(broken line) is 2800 kg (**Table 2-2**).

Figure 7. Groundwater nitrogen inputs to Lake Horowhenua (red line) over the period July 1988 to November 1989, as presented in Gibbs (2011).

Being unable to robustly partition the annual groundwater nutrient loads into seasonal loads, we did not pursue the calculation of seasonal nutrient budgets. However, we present seasonal variations in the measured inflows and the outflow of the lake in Figure 8. The data show that there is a general increase in groundwater nitrogen and phosphorus fluxes to, and from, the lake from autumn through to the next summer.

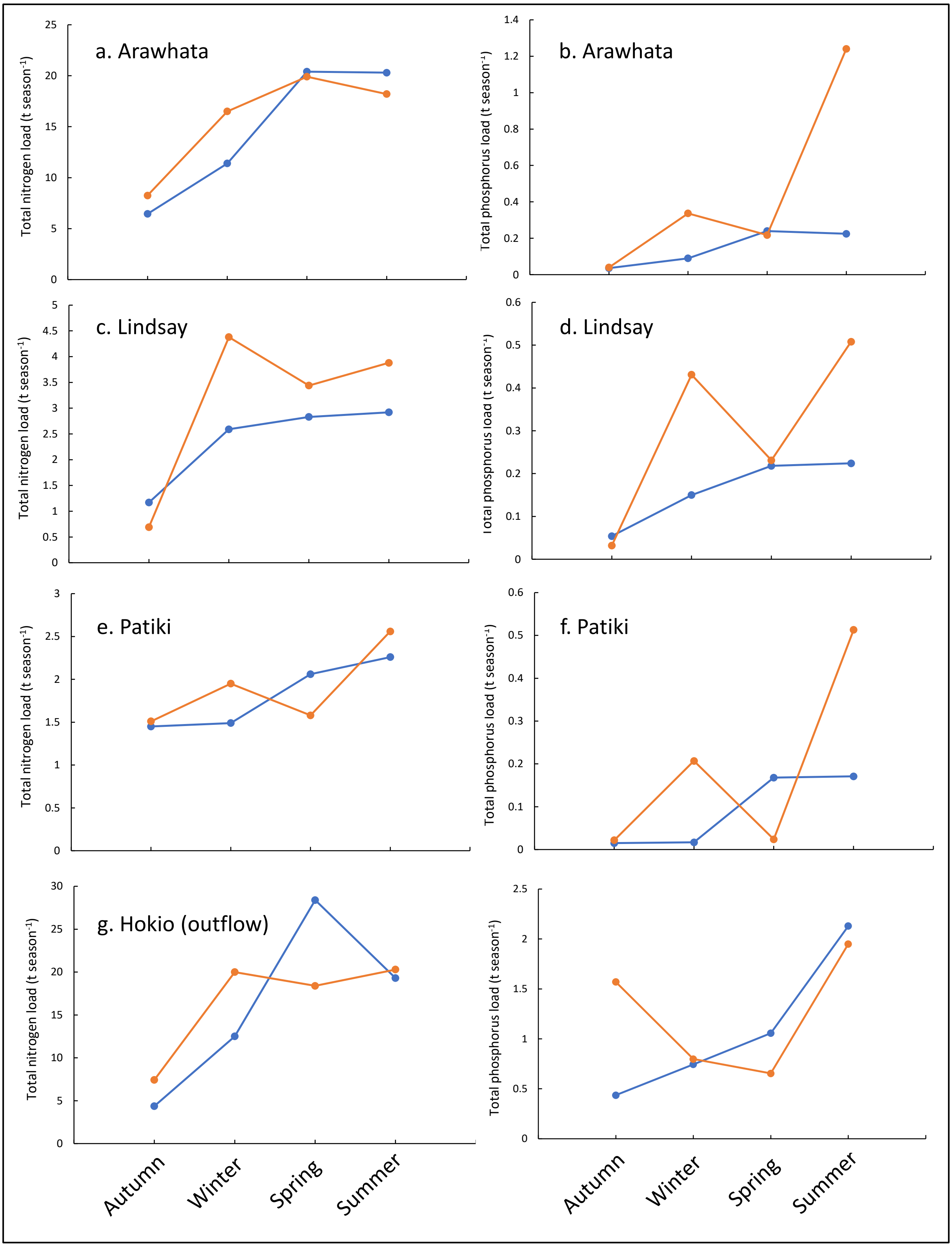

Figure 8. Seasonal variation in nutrient loads to (Arawhata, Lindsay, Patiki) and export from (Hōkio) Lake Horowhenua. The blue line is for the year March 2020 to February 2021 and the orange line represents the year March 2021 to February 2022. Autumn is March to May, winter is June to August, spring is September to November, and summer is December to February.

6 Discussion

6.1 Loads

Our calculations suggest that the current nutrient budgets of Lake Horowhenua are not much different to the budgets constructed by Gibbs (2011), using data from 1988/89 (Table 5). Given the importance of groundwater nutrient loads to the lake (especially in relation to the nitrogen load), it is perhaps not that surprising that the two budgets are similar because we used Gibbs' (2011) estimates for annual groundwater nutrient loads.

Table 5. Water balance and nutrient budgets for Lake Horowhenua from Gibbs (2011), assessed for a one-year period from June 1988 to June 1989.

Table 3-1. The estimated quantities of water and nutrients associated with a variety of sources and sinks over the period 29 June 1988 and 28 June 1989 (365 days) derived from a daily model output. (From Gibbs & White 1994).

Water ($\times 10^6$ m^3 y^{-1})	**Inputs**			**Outputs**	**Storage**
Rainfall (direct)	3.32				
Runoff (from Levin)	5.09				
Streams	8.57				
Groundwater	16.08			1.35	
Evaporation				2.34	
Hokio Stream (Outflow)				29.28	
Change in lake storage					0.09
Nutrients (t y^{-1})	**External inputs**	**Internal sources**	**Internal sinks**	**External outputs**	**Storage**
Phosphorus					
Rainfall (direct)	0.07				
Runoff (from Levin)	2.60				
Streams	0.27				
Groundwater	0.23				
Sediment release		5.77			
Sedimentation			4.39		
Hokio Stream (Outflow)				4.75	
Change in lake storage					-0.20
Nitrogen					
Rainfall (direct)	1.7				
Runoff (from Levin)	28.2				
Streams	71.6				
Groundwater	101.9				
Sediment release		30.0			
Sedimentation			39.7		
Denitrification			111.1		
Hokio Stream (Outflow)				77.2	
Change in lake storage					5.4

Nevertheless, the absolute fluxes of the streams + runoff, atmospheric loads and the outflow are quite similar in the two budgets. One difference is that Gibbs (2011) identified a specific load for "runoff (from Levin)", which represented the stormwater inflow from Levin via the Queen Street Drain, which Gibbs

(2011) reported to be the single largest phosphorus load to the lake. We were unable to include this drain in our nutrient budget because flow data from that site were not available. Therefore, it is possible that our nutrient budget missed a major source of phosphorus (and a substantial but relatively smaller source of nitrogen) to the lake. Only further investigations can confirm or deny that.

The loads we calculated can be compared with loads to the lake estimated by NIWA's CLUES catchment model. Verburg et al. (2019) reported CLUES total nitrogen and total phosphorus loads to the lake of 200 to 250 t N yr^{-1} and 3 t P yr^{-1}. Our average estimated loads of nitrogen and phosphorus were 186 and 4 t yr^{-1}, respectively. While the measured and modelled load estimates are roughly similar, CLUES appears to underestimate the phosphorus load by 25% and overestimate the nitrogen load by 8 to 34%.

6.2 NUTRIENT RETENTION

From the nutrient budget, the Vollenweider nitrogen and phosphorus retention coefficients can be calculated[1]. The phosphorus retention coefficients for 2020 and 2021 were -0.99 and -0.23, respectively, while the nitrogen retention coefficients for 2020 and 2021 were 0.72 and 0.67. These retention coefficients are similar to those calculated from the Gibbs (2011) nutrient budgets, which are -0.50 for phosphorus retention and 0.62 for nitrogen retention. Comparison of our nutrient retention coefficients with those calculated from Gibbs' (2011) nutrient budgets indicate that nutrient retention in the lake hasn't changed much since 1988/89.

Kelly et al. (2013) estimated phosphorus and nitrogen retention coefficients for 19 shallow South Island and Stewart Island lakes. The retention coefficients were based on CLUES-modelled nutrient loads. These authors found that five of the 19 lakes had negative phosphorus retention coefficients and ten of the 19 had negative nitrogen retention coefficients. Therefore, some of the shallow lakes that they studied did seem to export more phosphorus than they received from their catchments, as appears to have been the case in Lake Horowhenua since at least the late 1980s.

Lake Horowhenua is a net exporter of phosphorus either because a substantial source of phosphorus to the lake has been neglected in the modelling, or because the lake is not in equilibrium with the phosphorus loss rates in its catchment. In other words, there is a substantial legacy phosphorus load in the lakebed contributing to in lake phosphorus concentrations (Gibbs 2011; Verburg et al. 2019). We believe that both these explanations are plausible. More information is needed on both the groundwater phosphorus load to the lake and on the contribution of episodic inputs from the Queen Street drain to the lake phosphorus budget. In addition, there is a need for more information on how (1) transient bottom water anoxia, (2) episodic high water column pH, and (3) macrophyte "mining" of sediment phosphorus could elevate water column phosphorus concentrations and contribute to phosphorus export from the lake.

7 LIMITATIONS OF THE NUTRIENT BUDGETS

While undertaking the task of constructing a lake nutrient budget, it becomes clear that there are many sources of error that could affect the calculated outcome (Verburg et al. 2018). In addition, there are some caveats that should be considered when interpreting the nutrient budgets.

1. Perusal of the rating curve plots (Appendix 1) indicates that in some cases the modelled relationships between nutrient concentration and flow had low predictive power (Table 3). In addition to the "scatter" observed in many of the relationships, there was a paucity of nutrient

[1] Note that the usual formulation of the retention coefficient doesn't account for changes in water column standing stocks (see equation 3).

data measured at high flows in some of them. Due to such issues, substantial errors in calculating loads to, and export from, the lake can result.

2. It is very difficult to obtain robust, independent estimates of groundwater nutrient loads to a lake. Gibbs (2011) reported groundwater nutrient load estimates, using data from 1988/89. It would be useful to have more recent and more robust estimates of groundwater nutrient loads, especially since groundwater is such an important component of the nitrogen budget of Lake Horowhenua.
3. It is possible that we have neglected or underestimated substantial inputs to the lake. For example, the water balance indicates that the outflow was greater than the inflows in both years, suggesting that there was a missing source of input. In addition, Gibbs (2011), Clark et al. (2015) and Verburg et al. (2019) mentioned the importance the Queen Street drain had in supplying episodic inputs of phosphorus to Lake Horowhenua. We are missing this input in our nutrient budget due to the lack of flow data from that site.
4. Macrophyte cover and biomass is high in Lake Horowhenua and, therefore, macrophytes have the potential to affect the lake nutrient budgets (Gibbs 2011). Therefore, when interpreting aspects of the nutrient budget, such as nutrient retention or export, interannual variation in macrophyte biomass in the lake could substantially affect these calculations.

8 EXTRACTING FURTHER VALUE FROM THE NUTRIENT BUDGETS

The interpretive utility of the nutrient budgets presented here could be improved by examining two additional components of the lake nutrient budgets.

As mentioned above, macrophytes are an important component of the biomass in Lake Horowhenua. For example, Gibbs (2011) stated that the macrophyte biomass in the lake was substantial enough to take up all available nitrogen in the lake during the summer growing season. Macrophytes also have the potential to "mine" phosphorus from the lakebed, potentially recycling it into the water column as the macrophytes senesce and decompose. Given current knowledge of macrophyte biomass and distributions in the lake, it could be possible to add a macrophyte component to the lake nutrient budget, which would help interpret the nutrient budgets.

Furthermore, quite a bit of work has been done on nutrient standing stocks in the lakebed (Verburg et al. 2019) and on the potential for nutrient exchange across the sediment-water interface (Gibbs 2011). Using this information, it may be possible to: (1) directly estimate phosphorus and nitrogen sequestration in the lakebed, thereby directly quantifying a component of lake nutrient retention, and (2) estimate a sediment-water nutrient exchange flux, which would further help quantify the importance of internal phosphorus loading in the lake (Gibbs 2011).

9 ACKNOWLEDGEMENTS

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11 APPENDIX 1: SUPPORTING INFORMATION

Table A1. Total nitrogen (TN), total phosphorus (TP) and flow discharge summary statistics for the monitored sites.

Total nitrogen summary statistics 12/12/2019 to 2/3/2022	**median**	**min**	**max**	**sd**
Site	**$g\ m^{-3}$**	**$g\ m^{-3}$**	**$g\ m^{-3}$**	**$g\ m^{-3}$**
Arawhata Drain at Hokio Beach Road	7.96	4.81	12.60	2.29
L Horowhenua Inflow at Lindsay Road	3.63	2.12	5.84	0.90
Patiki Stream at Kawiu Road	5.51	2.50	7.10	1.33
Hokio at Lake Horowhenua (outflow)	1.54	0.84	2.37	0.47
Total phosphorus summary statistics 12/12/2019 to 2/3/2022	**median**	**min**	**max**	**sd**
Site	**$g\ m^{-3}$**	**$g\ m^{-3}$**	**$g\ m^{-3}$**	**$g\ m^{-3}$**
Arawhata Drain at Hokio Beach Road	0.15	0.03	2.99	0.45
L Horowhenua Inflow at Lindsay Road	0.13	0.05	0.81	0.20
Patiki Stream at Kawiu Road	0.07	0.03	1.91	0.49
Hokio at Lake Horowhenua (outflow)	0.12	0.04	0.55	0.11
Mean daily flow summary statistics 12/12/2019 to 2/3/2022	**median**	**min**	**max**	**sd**
Site	**$L\ s^{-1}$**	**$L\ s^{-1}$**	**$L\ s^{-1}$**	**$L\ s^{-1}$**
Arawhata Drain at Hokio Beach Road	166.00	68.00	1258.00	113.15
L Horowhenua Inflow at Lindsay Road	54.00	4.00	1233.00	119.32
Patiki Stream at Kawiu Road	35.00	18.00	1420.00	90.54
Hokio at Lake Horowhenua (outflow)	869.50	291.00	5567.00	713.59

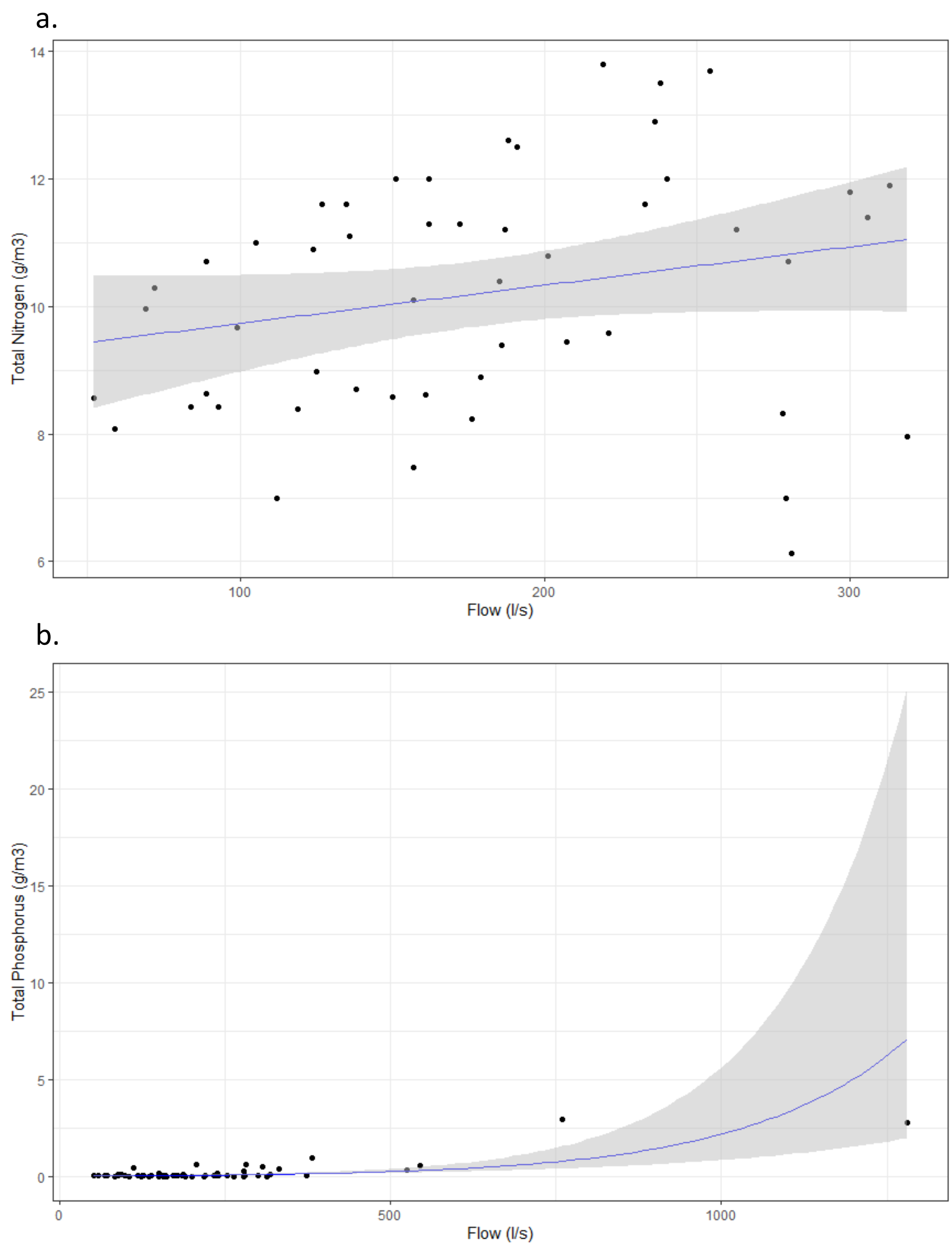
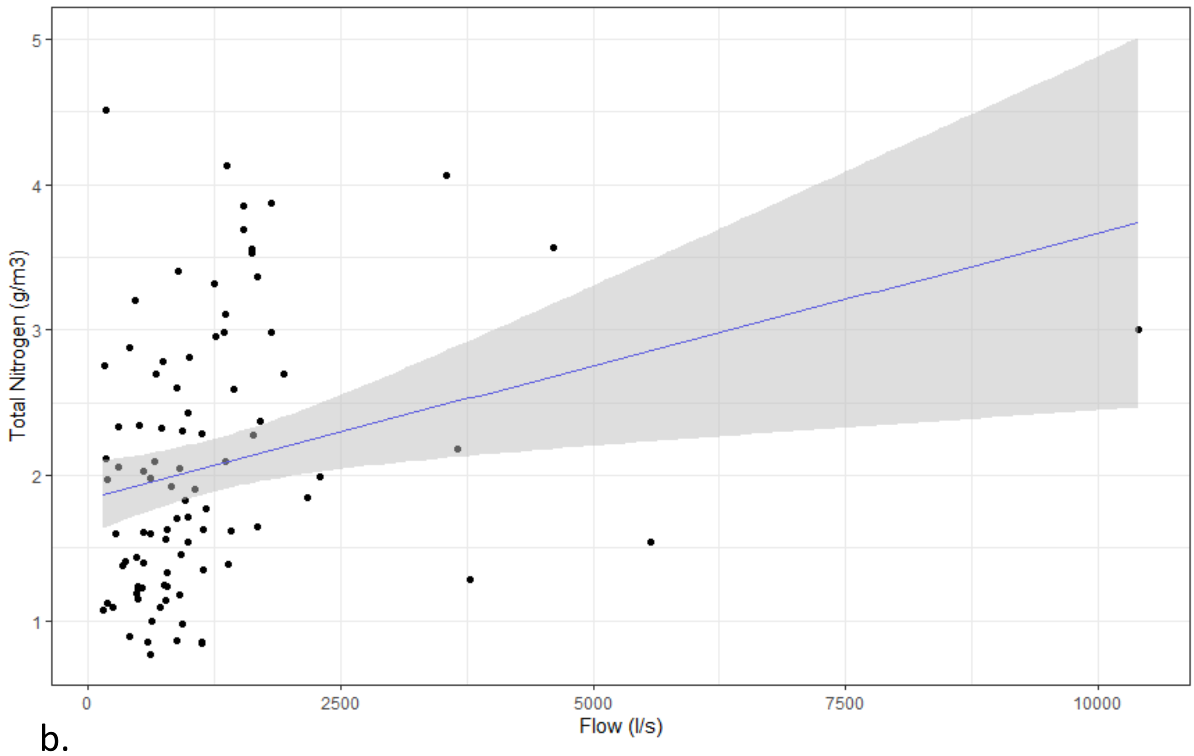


Figure A1. Rating curves for the Arawhata Drain inflow. Equations and statistics are shown in Table 3. The model in a. was rejected due to low predictive power.

a.



b.

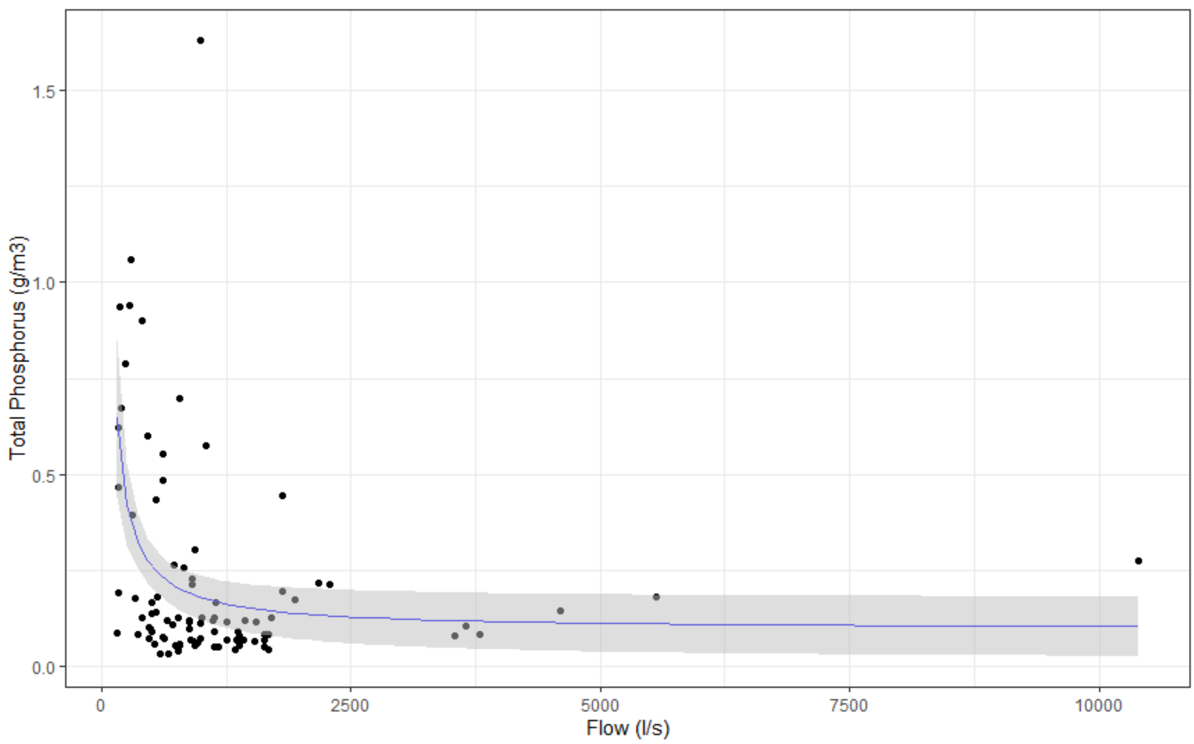


Figure A2. Rating curves for the Hokio Stream outflow. Equations and statistics are shown in Table 3. The models in a. and b. were rejected due to low predictive power.

a.

b.

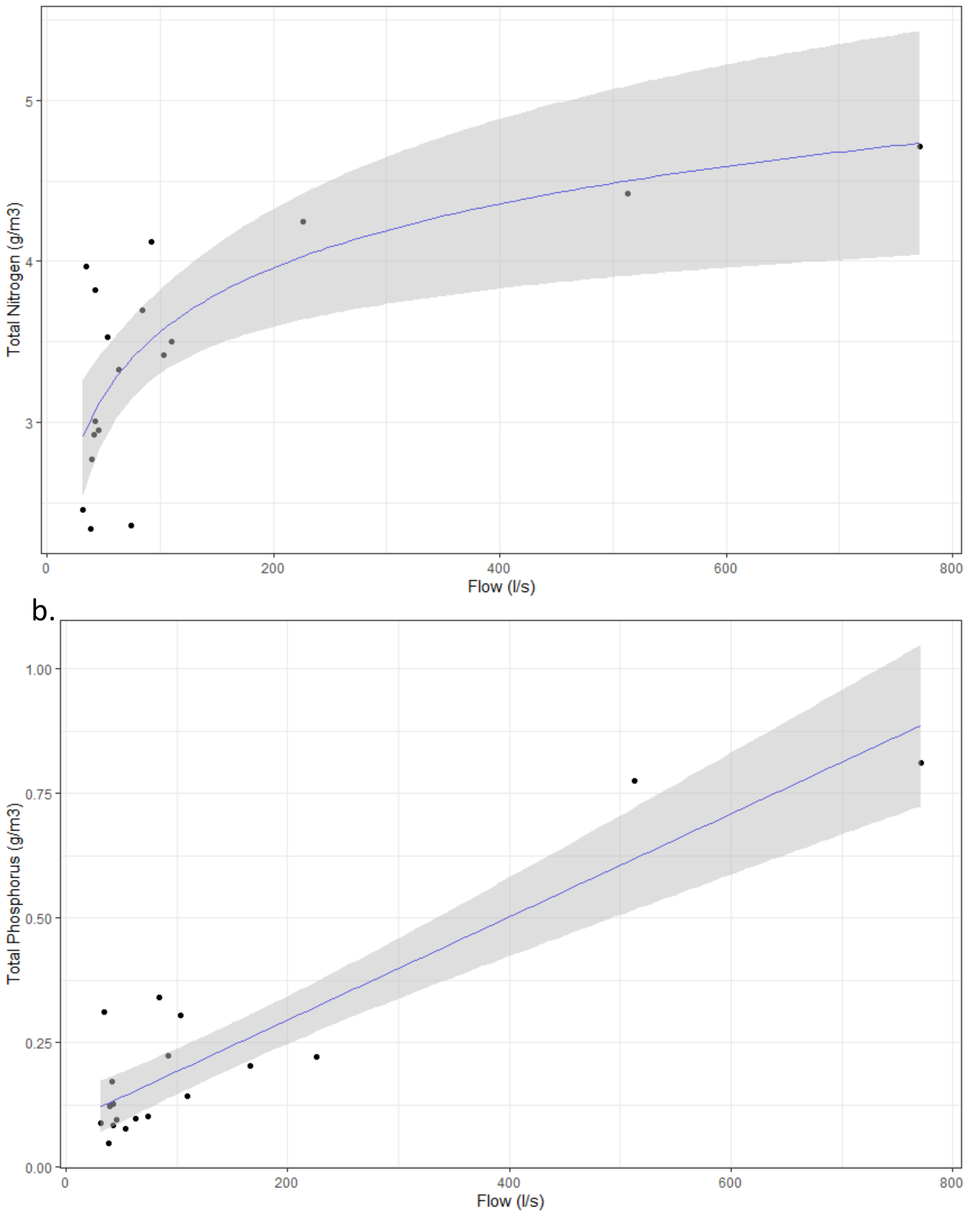


Figure A3. Rating curves for the Lindsay Road inflow. Note: one outlier for TN (5.84 g/m3) on 6/12/21 was removed. Equations and statistics are shown in Table 3.

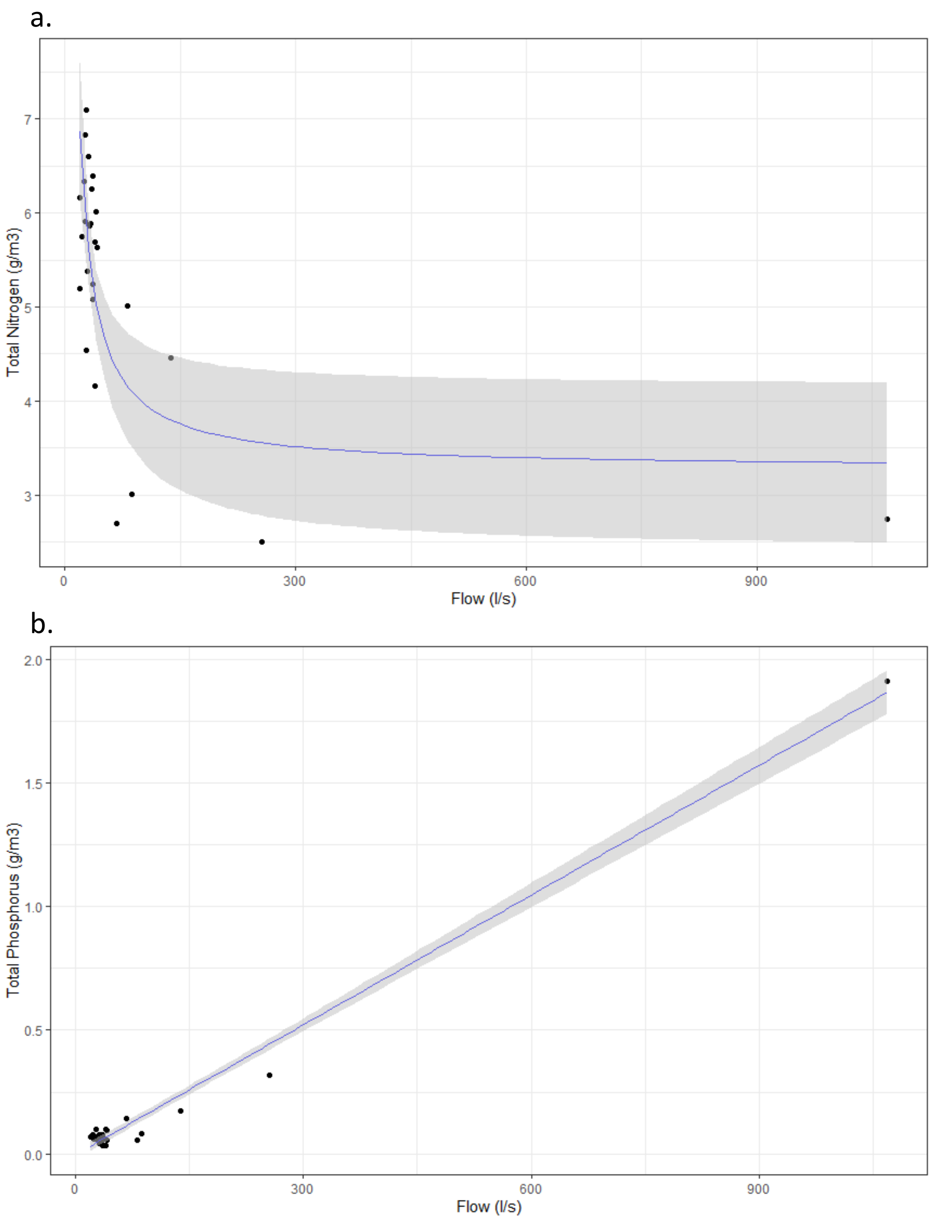


Figure A4. Rating curves for the Patiki Stream inflow. Equations and statistics are shown in Table 3.

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