Flows of water and nutrients to Lake Tarawera and connected lakes

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Abstract

Lake Tarawera is a large, deep lake located within the Taupō Volcanic zone, 12 km south-east of Rotorua. Seven smaller lakes within the “Greater Lake Tarawera catchment” (Lakes Ōkareka, Ōkaro, Ōkataina, Rerewhakaaitu, Rotokakahi, Rotomahana and Tikitapu) contribute flows to Lake Tarawera via groundwater and/or surface water. The quantity and quality of flows from these connected lakes is important in assessing hydrological inputs to Lake Tarawera.

Groundwater is recognised as a large component of the flow to Lake Tarawera, and previous investigations have been undertaken in the Greater Lake Tarawera catchment to assess groundwater resources and groundwater quality. Despite the extensive work of past researchers, there remain substantial uncertainties on the hydrology and chemistry of groundwater fluxes to Lake Tarawera.

This research aims to improve understanding of groundwater flows in the Greater Lake Tarawera catchment using a water balance approach and to assess and describe the fluxes of water and nutrient loads to Lake Tarawera and hydraulically connected lakes under different climate and land use scenarios. The stable isotopes of water, δ^2H and δ^{18}O, in groundwater and surface water have been used alongside water balances to supplement understanding of groundwater flow paths and hydraulic connections between lakes.

While previous research has focused on annual means to describe water fluxes and nutrient loads, with no expression of uncertainty, this research describes a range of annual water fluxes and nutrient loads. The ranges bracket the feasible possibilities of fluxes and loads, and account for interannual climatic variation, scientific uncertainties, and land use change, providing a means for policy makers to test outcomes of potential policy decisions.

Analysis of stable isotopes of water have been undertaken from groundwater collected from 11 locations and surface water from 26 locations. Isotopic analysis suggests that the location of lake-to-lake groundwater connections are not widespread and isolated to localised areas. Flow gains observed in the Tarawera River downstream of the Tarawera Falls are largely sourced from rainfall.

Annualised water balances and nutrient loads from 1972 to 2018 have been quantified for the Greater Tarawera Lakes and their catchments. The workflow has been automated using the R statistical computing language and a web-based tool that performs water balance calculations and nutrient load estimates has been developed using Shiny R technology. It is available for viewing at https://nickiwilson.shinyapps.io/TaraweraMsc/.

Evaporation can have a significant effect on the water fluxes and nutrient load to the lakes. This research considers land use, land cover, and soil water stress in the calculation of evaporation and provides the most accurate evaporation estimations in the Greater Lake Tarawera catchment to date. Groundwater contributes 62% of the inflows to Lake Tarawera, and 70% of this groundwater is estimated to have been recharged from outside of its local catchment. Approximately 20% of the current nutrient load to Lake Tarawera is received from the catchments of its connected upstream lakes. Management of nutrient loads to Lake Tarawera should consider flow and nutrient loading in upstream lake catchments, and opportunities for improvement include better land management practices and the reticulation of wastewater.

Acknowledgements

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Chapter 1

Introduction

1.1 Background

Lake water quality and biodiversity are affected as pressure from land use intensification, invasive species spread and global climate change increase in severity and scale (Hamilton et al., 2018). Specifically, freshwater quality in the region of Lake Tarawera is under pressure from agricultural surface run-off contributing nitrogen, phosphorus and sediments to lakes, streams, and groundwater; and urban development contributing pollution from septic tanks. Climate change also has the potential to impact flow regimes, groundwater levels and water temperatures.

Lake Tarawera is located in the North Island of New Zealand, and is highly valued by tangata whenua, residents, and visitors. A number of legislative documents, community processes and stakeholders support or require managing nutrient loads to Lake Tarawera to improve water quality (Bay of Plenty Regional Council, 2015, 2017; New Zealand Government, 2020; The Crown & The Rotorua Lakes Strategy Group, 2007). The Tarawera Lakes Restoration Plan (Bay of Plenty Regional Council, 2015) sets a target Trophic Level Index (TLI) of 2.6 for Lake Tarawera which is not currently met.

Seven smaller lakes within the “Greater Lake Tarawera catchment” (Lakes Ōkareka, Ōkaro, Ōkataina, Rerewhakaaitu, Rotokakahi, Rotomahana and Tikitapu) contribute flows to Lake Tarawera via groundwater and/or surface water. The quantity and quality of flows from these connected lakes is important in assessing hydrological inputs to Lake Tarawera. Groundwater flow to Lake Tarawera is estimated to account for at least 45% of total inflows to Lake Tarawera (White et al., 2016), with some estimations as high as 80% (Bay of Plenty Regional Council, 2015).

A number of investigations have been undertaken in the Greater Lake Tarawera catchment to assess groundwater resources and groundwater quality (Gillon et al., 2009; Lovett et al., 2012; Rose et al., 2012; Thorstad et al., 2011; Tschritter & White, 2014; White et al., 2016, 2020). Despite the extensive work of these past researchers, there remain substantial uncertainties on the hydrology and chemistry of groundwater fluxes to Lake Tarawera (Abell et al., 2020).

1.2 Aims and objectives

This research aims to develop an improved understanding of the role of groundwater flow in the Greater Lake Tarawera catchment and to assess how the fluxes of water and nutrients into Lake Tarawera and connected lakes differ under different climatic and land use scenarios using a water balance approach. These aims will be achieved by the following objectives:

1. Fill knowledge gaps on the conceptual understanding of groundwater flow through and out of the Greater Tarawera Lakes and catchments using water isotopes as environmental tracers.
2. Quantify annual water balances from 1972 to 2018 for the Greater Tarawera Lakes and their catchments.
3. Estimate annual lake nutrient loads from 1972 to 2018 for the Greater Tarawera Lakes.
4. Create best- and worst-case land use scenarios for nutrient loads to the Greater Tarawera Lakes.
5. Communicate the interannual variability and uncertainty in the water balances and nutrient loads of the Greater Tarawera Lakes using a bracketing approach to describe their range.

The bracketing approach of objective 5 provides a means for policy makers to test outcomes of potential policy decisions that account for variability in fluxes and loads. This will assist in the development of robust policy and allow more effective management of water quality.

1.3 Thesis outline

Chapter two: Study area

This chapter describes the study area, presenting a summary of available information including lake morphology, climate, land use, geology, soils, hydrology, and lake water quality.

Chapter three: Literature review

This chapter discusses lake water quality management based on New Zealand and global literature. It then describes and summarises relevant research that has been undertaken in the Greater Lake Tarawera catchment. Comparable research in the neighbouring catchment of Lake Rotorua is discussed in relation to assessing water and nutrient flows into lakes, and environmental limit setting. It describes the process of estimating lake water and nutrient budgets and the use of stable isotopes as environmental tracers.

Chapter four: Methods

This chapter describes the sampling and analysis of water for isotopes, and the methods and data used to calculate each component of the annual water balance and nutrient loads. It also describes the method used to assess interannual variability and uncertainty.

Chapter five: Water provenance

This chapter describes the results of the isotopic analysis of water collected from in and around the Greater Lake Tarawera catchment for the purpose of determining the provenance of the water. This information is used to understand groundwater flow in the study area and to supplement water balance assumptions.

Chapter six: Annualised water balances

This chapter presents and describes the annual water balance calculations for the Greater Tarawera Lakes and catchments with consideration of interannual variability and uncertainty.

Chapter seven: Annualised nutrient loads

This chapter presents the annual nutrient load estimates to the Greater Tarawera Lakes and describes the interannual variability and uncertainty of these estimates. It also presents the nutrient load estimates for best- and worst-case scenarios.

Chapter eight: Discussion

This chapter interprets and explains the results presented in the previous three chapters on water provenance, water balance and nutrient loads. It discusses the key findings and compares them to previous studies and other relevant literature.

Chapter nine: Conclusions

This chapter summaries the outcomes of this research and the implications and considerations for water quality management of Lake Tarawera. It also makes recommendations for further research.

Chapter 2

Study area

2.1 Location

The Greater Tarawera Lakes include eight lakes located in the North Island of New Zealand, approximately 12 km southeast of Rotorua, and include Lakes Ōkareka, Ōkaro, Ōkataina, Rerewhakaaitu, Rotokakahi, Rotomahana, Tarawera and Tikitapu (Figure 2.1). Lake areas and mean depths are shown in Table 2.1. Elevations within the study area range from 1,110 m at the summit of Mount Tarawera, to 300 m at the outlet of Lake Tarawera.

The catchment of Lake Tarawera includes the local catchments of all eight lakes (shown in Figure 2.1), which flow via groundwater and/or surface water towards Lake Tarawera, ultimately discharging from the local catchment of Lake Tarawera as groundwater and/or surface water. Some water from the Lake Rerewhakaaitu catchment discharges east to the Waikato via groundwater, and surface water via an engineered outlet to an upper tributary of the Mangaharakeke Stream when lake levels are high (White et al., 2016). The catchment of Lake Rotomahana includes the local catchments of Lakes Rerewhakaaitu, Rotomahana, and Ōkaro; and the catchment of Lake Rotokakahi includes the local catchments of Lakes Rotokakahi and Tikitapu. Catchments of Lakes Ōkareka, Ōkaro, Ōkataina, Rerewhakaaitu and Tikitapu include only their local catchments. Hydraulic connections between catchments are described in Section 2.5. Together, the local catchments of all eight lakes occupy an area of approximately 39,300 ha. Individual local catchment areas of the lakes are shown in Table 2.1. In this research, unless explicitly mentioned, the catchment of a lake refers to the total surface water catchment of the lake and includes its own local catchment as well as any other upstream lakes and their local catchments.

Figure 2.1 Location map showing the Greater Tarawera Lakes and climate stations Rotorua Aero Aws and VCS273368. Local catchment boundaries of the lakes are shown in red. The catchment of Lake Tarawera includes the local catchments of all lakes, the catchment of Lake Rotomahana includes the local catchments of Lakes Rerewhakaaitu, Rotamahana, and Ōkaro; the catchment of Lake Rotokakahi includes the local catchments of Lakes Rotokakahi and Tikitapu. Catchments of Lakes Ōkareka, Ōkaro, Ōkataina, Rerewhakaaitu and Tikitapu include only their local catchments.

Table 2.1 Lake morphology, local catchment areas, mean surface water quality measurements (from BOPRC data 2012 to 2017), and trophic level index (calculated using surface water measurements only). Total P = total phosphorus, total N = total nitrogen. Modified from McBride et al. (2020).

Lake	Area (km^2)	Mean depth (m)	Local surface water catchment (km^2)	Local groundwater catchment (km^2)	Total P (ppb)	Total N (ppb)	Trophic level index (TLI)
Ōkareka	3.34	19.0	19,780	12,490	8.54	190.98	3.14
Ōkaro	0.33	10.4	3,680	3,680	37.16	717.65	4.77
Ōkataina	10.73	46.5	62,920	70,920	6.04	87.79	2.54
Rerewhakaaitu	5.17	7.1	52,940	15,180	9.27	325.24	3.41
Rotokakahi	4.33	17.7	19,200	13,490	39.38	212.46	3.75
Rotomahana	9.02	53.1	83,700	101,630	23.09	185.66	3.63
Tarawera	41.15	55.3	145,260	159,290	8.90	93.99	2.71
Tikitapu	1.44	18.3	5,730	5,600	5.42	173.88	2.84

2.2 Climate

The nearest long-term climate station to the study area is Rotorua Aero AWS located approximately 10 km to the northeast of Lake Tarawera (Figure 2.1). From time to time, there have been other climate stations located within the study area, but their records have been short-term and sporadic. Virtual climate site 27368 (VCS27368), on the edge of Lake Tarawera (Figure 2.1), has been used for comparison with the long-term climate station[1]. Annual mean rainfall for Rotorua Aero AWS is 1353 mm and mean annual temperature is 12.7°C (over the period 1981 – 2010). Rainfall is predicted to be higher at VCS station 27368, with an annual mean of 2090 mm and higher monthly rainfall (Figure 2.2). Mean annual air temperature at VCS station 27368 is 12.6°C. Mean annual rainfall over the study area averaged 1400 mm y^{-1} and ranged from approximately 850 mm y^{-1} to 2400 mm y^{-1} (calculated from VCS data).

Figure 2.3 shows seasonal patterns in air temperature, evaporation, rainfall, solar radiation, and windspeed at VCS27368. Air temperature, evaporation, and solar radiation are at their lowest during the winter months of May to August, and their highest during the summer months of December to February. Rainfall is at its highest in the winter, during the months of June to August, and it lowest in the summer during the months January to March. Wind speeds peak in late spring and early summer (October to December) and are at their lowest during the autumn and winter (March to August).

[1] Details of the virtual climate data are presented in Tait et al. (2006)

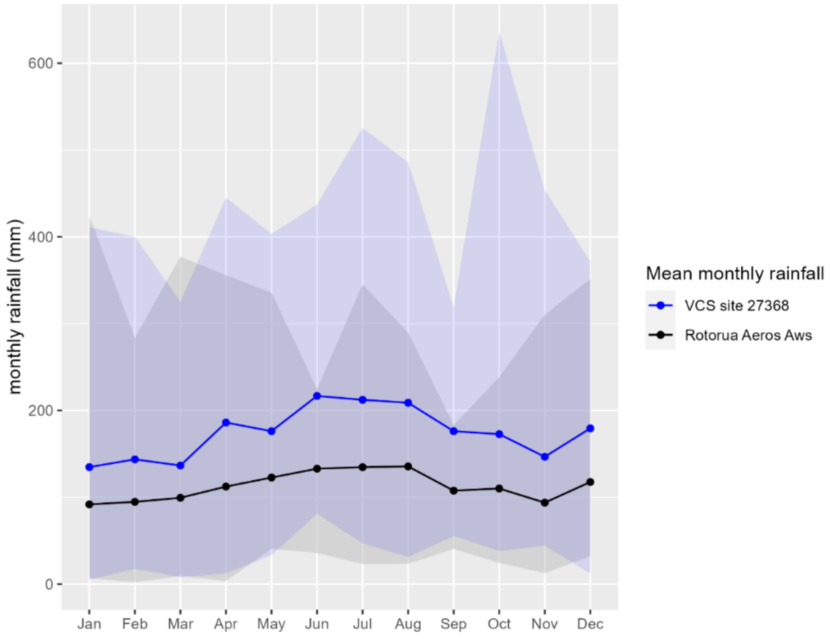

Figure 2.2 Thirty year (1981-2010) mean monthly rainfall at Rotorua Aero AWS climate station and virtual climate site (VCS) 27368 with minimum and maximum values shown by grey shading (Rotorua Aero AWS) and blue shading (VCS site 27368).

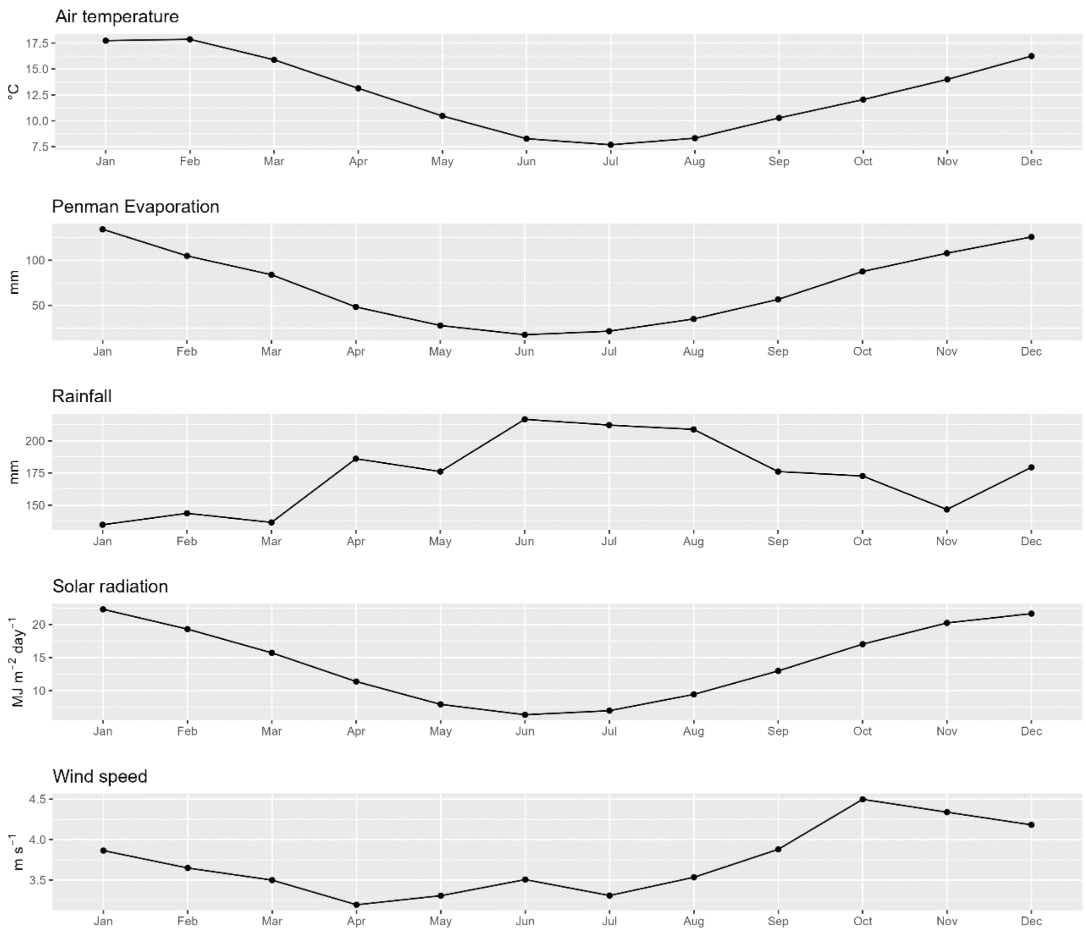

Figure 2.3 Thirty-year (1981-2010) mean monthly air temperature, penman evaporation, rainfall, solar radiation, and wind speed at VCS27368

2.3 Land use and cover

Land use in the study area is dominated by forest (native and exotic: 52%), agriculture (dairy, dairy support, dry stock, and lifestyle: 24%), and water (lakes and wetlands: 20%) (Table 2.2). Dairy and dairy support land uses are concentrated in the southern part of the study area, in the catchments of Lake Rerewhakaaitu and Lake Ōkaro. Dry stock is concentrated northwest of Lake Tarawera spanning the catchments of Lakes Ōkareka, Ōkaro, Rotokakahi and Tarawera (Figure 2.4 and Figure 2.5). Native forest dominates in the catchments of Lake Ōkataina and Lake Tikitapu, and is the largest land use in Lake Ōkareka, Rotomahana and Tarawera catchments. Exotic forest dominates in Lake Rotokakahi catchment.

Table 2.2 Breakdown of land uses in the Greater Lake Tarawera catchment

Land use	Area (ha)	%
Agriculture - dairy	4,073	10.4
Agriculture - dairy support	953	2.4
Agriculture - dry stock	3,720	9.5
Agriculture - lifestyle	562	1.4
Forest - exotic	5,395	13.7
Forest - native	15,159	38.6
Scrub/shrub	113	0.3
Unknown	1,126	2.9
Urban - infrastructure	438	1.1
Urban - parks	40	0.1
Water - lake or stream	7,617	19.4
Water - wetland	114	0.3
Total	39,310	100.0

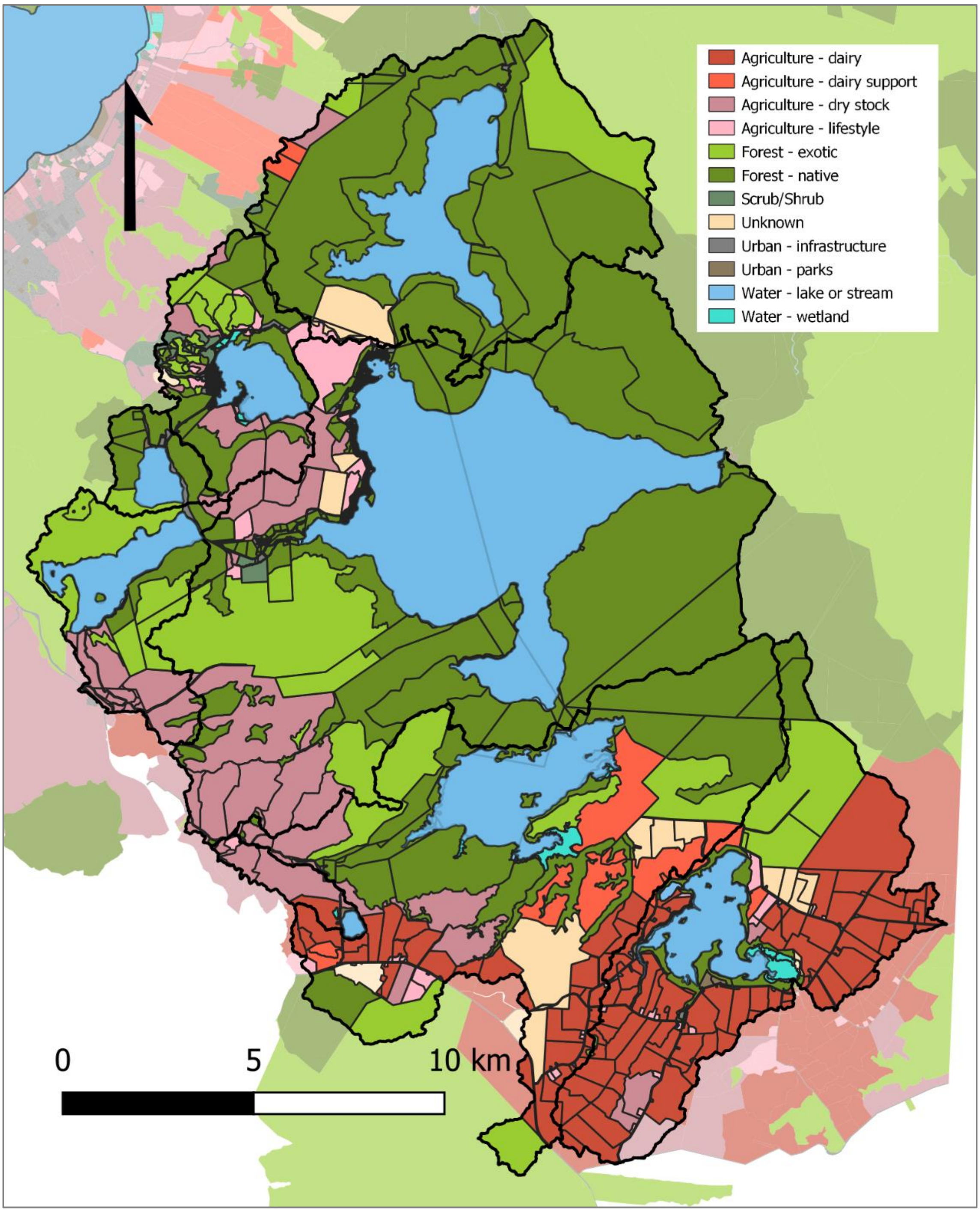

Figure 2.4 Land use of the study area (data: Bay of Plenty Regional Council, layer created based on 2016 land use). The Greater Tarawera Lake catchments are shown by the bold black outlines.

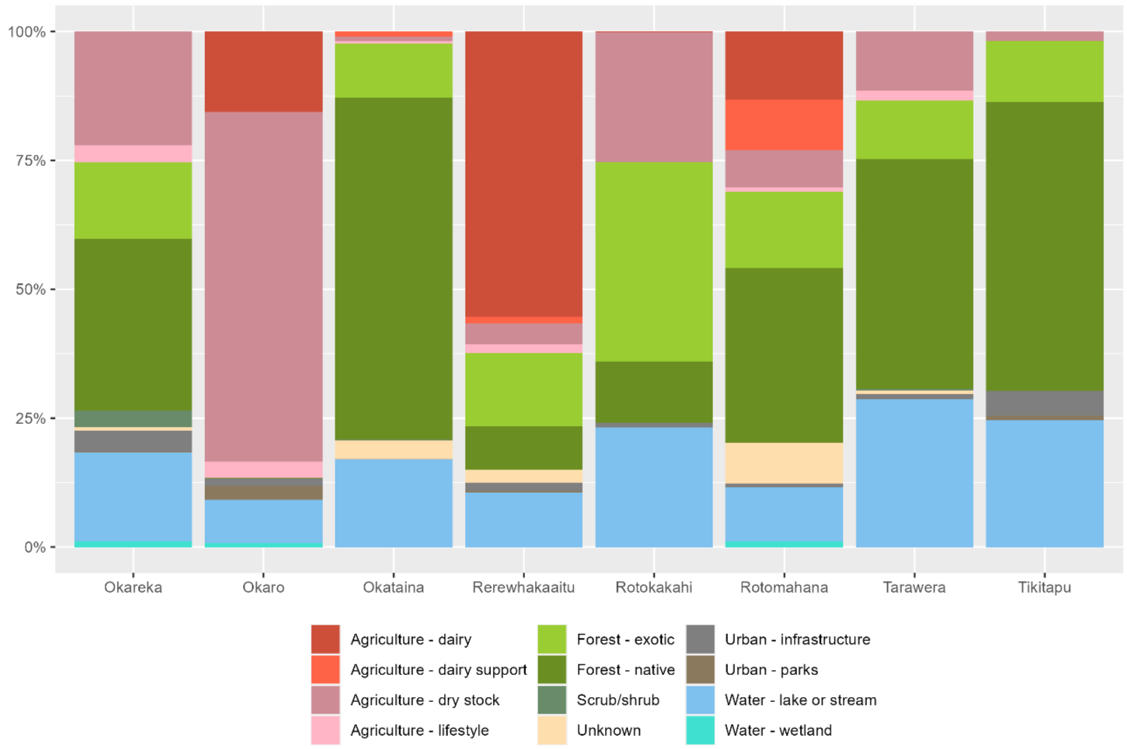

Figure 2.5 Proportion of land uses for each lakes local catchment (calculated from Bay of Plenty Regional Council data based on 2016 land use).

2.4 Geology and soils

The lakes and catchments of the Greater Tarawera Lakes complex are located within, partially within or on the edge of the Ōkataina Volcanic Centre (OVC). The OVC is the most recently active eruptive centre in the Taupō Volcanic Zone (TVZ), the most recent eruption being the 1886 Mount Tarawera Eruption (Nairn, 2002). Geology of the study area is mostly deposits of pyroclasitcs, rhyloites and ignimbrites (Figure 2.6). Groundwater flow within the rhyloites and ignimbrites of the study area is likely to be variable and fracture-dominated, with permeability depending on the size, amount and connectivity of fractures (Tschritter & White, 2014). Pyroclastics are relatively permeable but finer grained zones within them may inhibit groundwater flow (White et al., 2016). More detailed descriptions of the geological units within the study area can be found in Tschritter & White (2014).

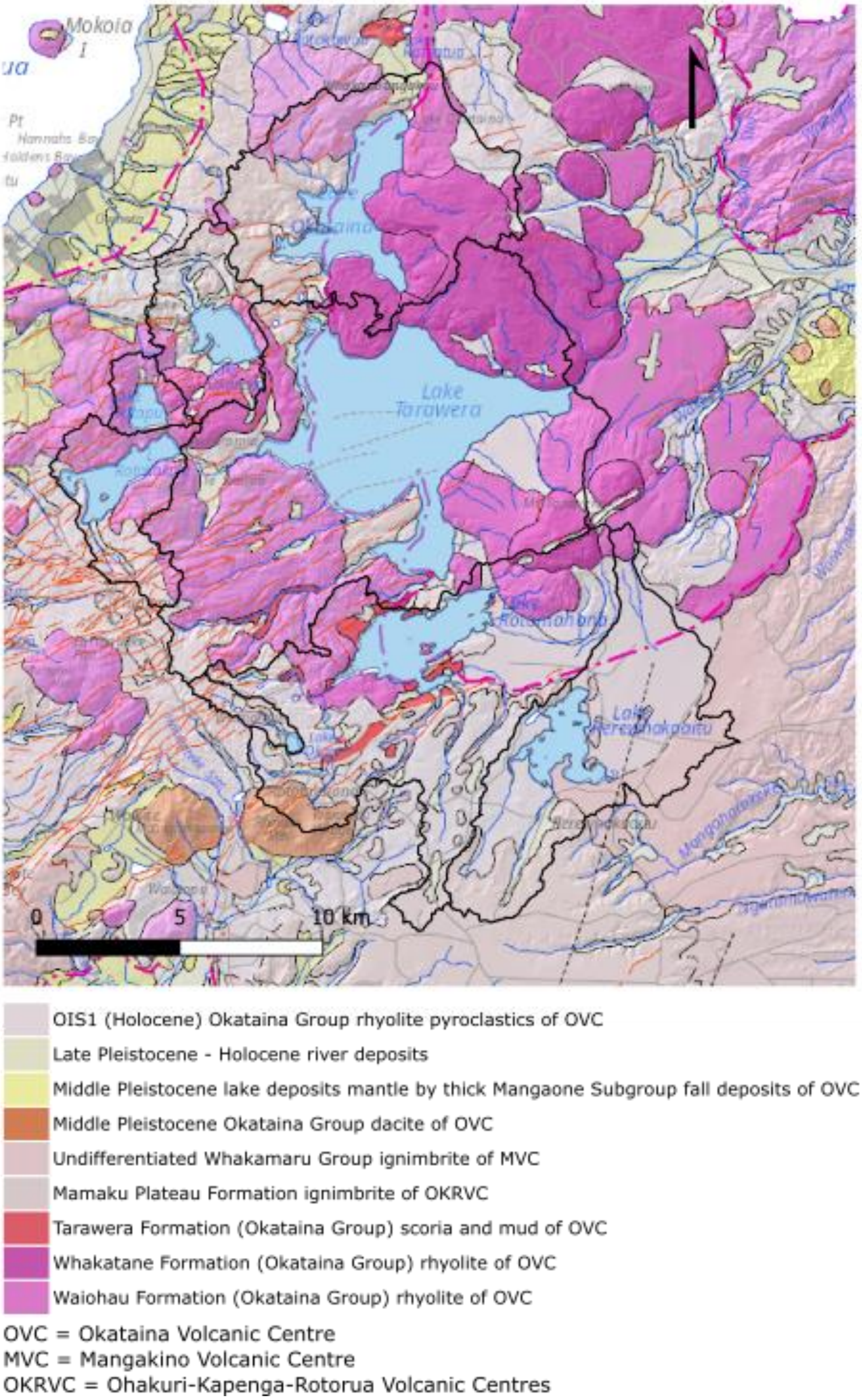

Figure 2.6 Geological map of the study area from QMAP (GNS Science, 2020). The Greater Tarawera Lake catchments are shown by the black outlines. Pink dashed lines indicate caldera boundaries, and orange lines indicate faults.

Soils of the study area are volcanic and are classified as pumice/recent and well drained (Figure 2.7). Across most of the study area soils are defined as loamy and deep, with areas of sandy, shallow soils to the east of Lakes Ōkataina, Rotomahana, and Rerewhakaaitu (Figure 2.7).

Profile (or total) available water (PAW) and profile readily available water (PRAW) indicate the amount of soil water available for plant growth (Webb & Wilson, 1995), and are expressed in units of millimetres of water in a defined depth of soil (NEMS, 2013b). PAW and PRAW have been used in this research for a soil water balance to calculate water stress (see Chapter 4). Using the classifications of Webb and Wilson (1995), PAW across the majority of the study area is high, and PRAW is moderate to moderately high (Figure 2.8).

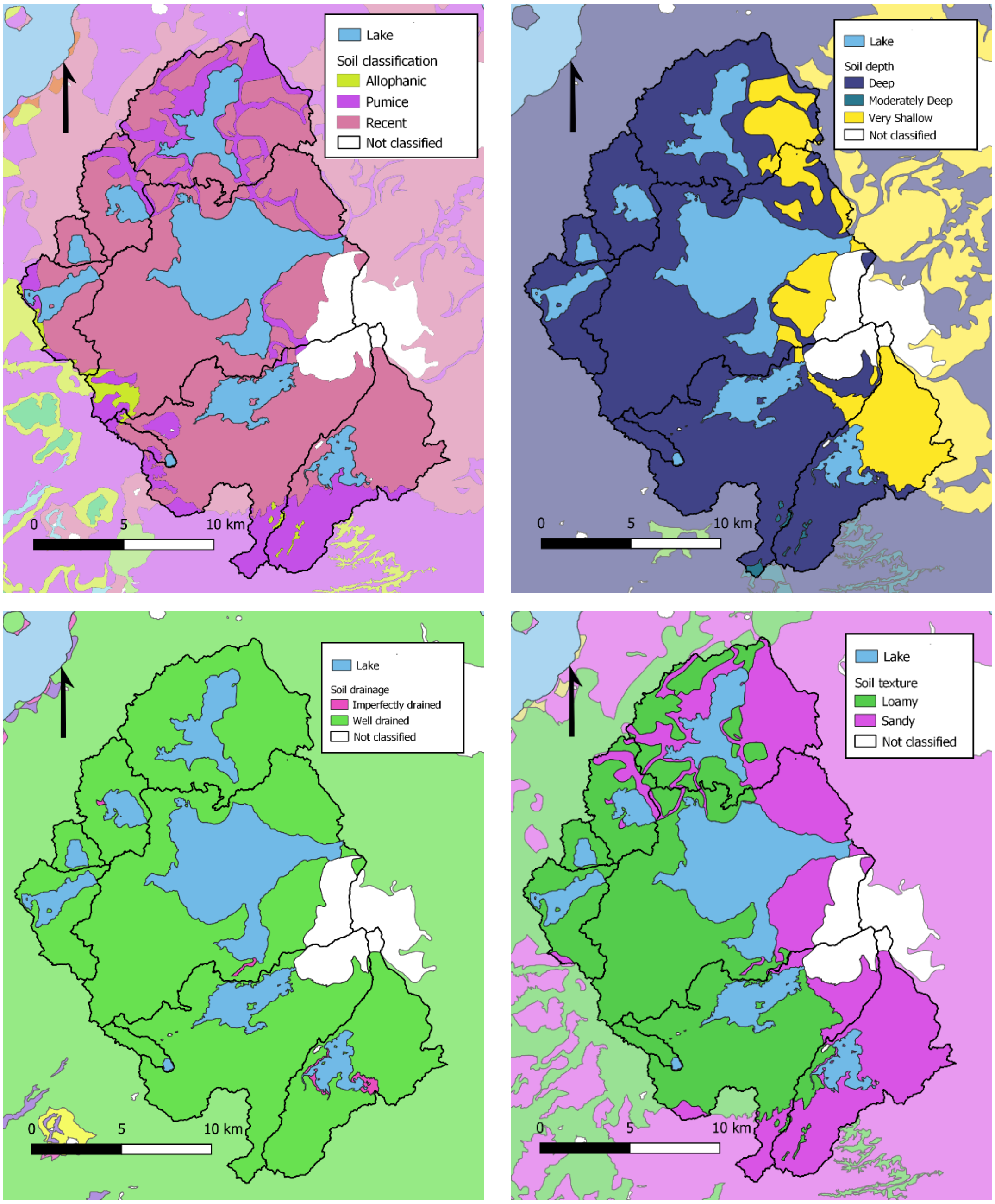

Figure 2.7 Soil classification, depth, drainage and texture of the study area from S-map (Landcare Research New Zealand Ltd, 2020b). Greater Tarawera Lake catchments are shown by the black outlines.

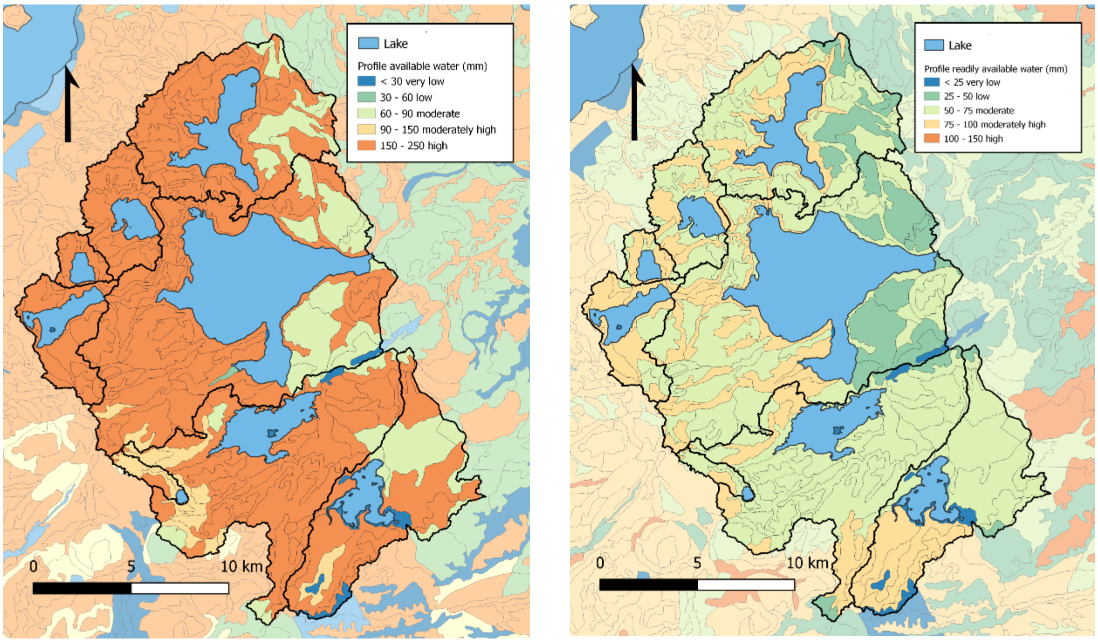

Figure 2.8 Profile available water and profile readily available water from the New Zealand Fundamental Soils Layer (Landcare Research New Zealand Ltd, 2000). The Greater Tarawera Lake catchments are shown by the black outlines. Classification system is from Webb and Wilson (1995). Values displayed are the PAW_MID and PRAW_MID values from this layer.

2.5 Hydrology

All eight lakes within the Greater Tarawera Lake catchments are hydraulically connected via groundwater and/or surface water and drain partly or wholly to the Tarawera River (White et al., 2016). Hydraulic connections between the lake catchments are summarised in Figure 2.9 and discussed in the flowing sections.

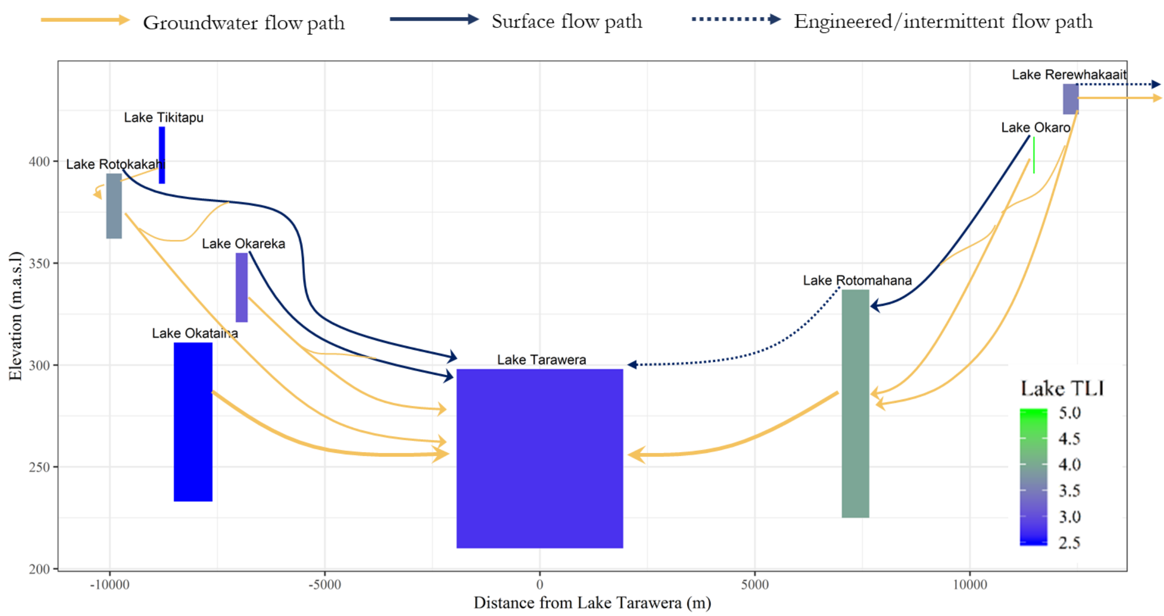

Figure 2.9 Cross section showing a conceptual model of the flow paths between the Greater Tarawera Lake catchments. The rectangles represent the lakes, their size and position relative to their depth, elevation, and location within the greater catchment. The colours represent the lakes' trophic level index (TLI). Image/design credit: Alastair MacCormick and Chris McBride.

2.5.1 Surface water

The characterisation of surface water flows out of and into lakes and catchments are described thoroughly in White et al. (2016) and summarised below and in Table 2.3. Locations of surface water features discussed in this research are shown on Figure 2.10.

Ōkareka

Lake Ōkareka has no permanent surface water inflows to the lake or its local catchment (White et al., 2016). Prior to 1960, there was no surface water outflow from Lake Ōkareka and it drained solely via groundwater towards Lake Tarawera, emerging at the Waitangi Springs (Wallace & Environment Bay of Plenty, 1999). Artificial drainage of the lake began in 1963 to control lake levels, initially by a pump scheme installed between Lake Ōkareka and the Waitangi Stream. In 1964 the pump scheme was replaced by a gravity pipeline (Wallace & Environment Bay of Plenty, 1999). Surface water outflows from Lake Ōkareka and its catchment average 164 l s^{-1} via the Waitangi Stream (White et al., 2016).

Table 2.3 Summary of annual mean surface water flows to and from lakes and local catchments. Values are from existing literature (McIntosh, 2012c; Noakes, 2016; Riley Consultants, 2003; White et al., 2016).

	Total surface water inflows (l s^{-1})		Total surface water outflows (l s^{-1})	
		Contributing streams/rivers		Outflowing streams/rivers
Lakes				
Lake Ōkareka	0	NA	164	Waitangi Stream
Lake Ōkaro	90	Two unnamed streams	30	Haumi Stream
Lake Ōkataina	0	Some negilible inflows	0	NA
Lake Rerewhakaaitu	55	Mangakino Stream and some ephermal tribs including Awaroa Stream	0	Negilible intermittent flows via upper tributary of Mangaharakeke Stream when lake levels are high
Lake Rotokakahi	150	Unnamed spring on lake edge	311	Te Wairoa Stream
Lake Rotomahana	326	Waimangu Stream, Te Kauae Stream, Putuonoa Stream and Rotomahana Stream	0	Negilible intermittent flows via Rotomahana siphon
Lake Tarawera	1750	Waitangi Stream, Te Wairoa Stream, Wairua Stream, Twin Creeks, and others	6738	Tarawera River
Lake Tikitapu	0	NA	0	NA
Local catchments				
Ōkareka local catchment	0	NA	164	Waitangi Stream
Ōkaro local catchment	0	NA	30	Haumi Stream
Ōkataina local catchment	0	NA	0	NA
Rerewhakaaitu local catchment	0	NA	0	NA
Rotokakahi local catchment	0	NA	311	Te Wairoa Stream
Rotomahana local catchment	30	Haumi Stream (and tributary of Waimangu Stream)	0	Negilible intermittent flows via Rotomahana siphon
Tarawera local catchment	475	Waitangi Stream and Te Wairoa Stream. Intermittent flows from Rotomahana siphon.	6738	Tarawera River
Tikitapu local catchment	0	NA	0	NA

Ōkaro

There are two unnamed streams that flow into Lake Ōkaro via a constructed wetland, inflows from these streams are estimated to be 90 l s^{-1} (White et al., 2016). There are no surface water inflows to the local catchment of Lake Ōkaro. Surface water outflows from Lake Ōkaro and its catchment are via the Haumi Stream which flows into the local catchment of Lake Rotomahana, subsequently merging with the Waimangu Stream before flowing into Lake Rotomahana. Outflows from the Haumi Stream average 30 l s^{-1} (White et al., 2016).

Ōkataina

There are no surface water inflows to the local catchment of Lake Ōkataina, and no major surface water inflows to the lake itself. Flow is usually present in stream beds on the western side of the lake, but these are considered negligible (White et al., 2016). There are no surface water outflows from Lake Ōkataina or catchment.

Rerewhakaaitu

There are no surface water inflows to the local catchment of Lake Rerewhakaaitu. Mangakino Stream is the only permanent inflow to the lake. Awaroa Stream and a number of other unnamed tributaries provide most of the inflows to the lake during flood flow events (McIntosh, 2012c). Total mean inflow to the lake from surface water has been estimated as 55 l s^{-1} (White et al., 2016). There are no permanent surface water outflows from Lake Rerewhakaaitu or its catchment. The only surface water outflow is an upper tributary of the Mangaharakeke Stream in the south east corner of the lake, which flows when lake levels are high (Reeves, Morgenstern, & Daughney, 2008). This tributary drains east, out of the Greater Lake Tarawera catchment.

Groundwater levels in the vicinity of Lake Rerewhakaaitu are generally below the level of the lake, classifying the lake as perched relative to the groundwater system (White et al., 2003, 2016).

Rotokakahi

There are no surface water inflows to the local catchment of Lake Rotokakahi. One small spring-fed surface water inflow to the lake is located near its southern shore (Noakes, 2016). Mean flow at the spring was recorded as 150 l s^{-1} during the period of January to July 2016 (Noakes, 2016). There is one surface water outflow from Lake Rotokakahi and its catchment, the Te Wairoa Stream, whose mean flow has been estimated as 311 l s^{-1} (White et al., 2016).

Rotomahana

The Haumi Stream flows into the local catchment of Lake Rotomahana, then joins the Waimangu Stream (located within the local catchment of Lake Rotomahana and draining the Waimangu Valley) before flowing into Lake Rotomahana. Other permanent streams drain into Lake Rotomahana along its southern shore including the Te Kauae Stream, Putuonoa Stream and Rotomahana Stream (White et al., 2016). Surface water inflows have been estimated as 30 l s^{-1} to the Rotomahana catchment and 326 l s^{-1} to Lake Rotomahana. (White et al., 2016). There are no permanent surface water outflows from Lake Rotomahana and its catchment. An overflow pipe (known as the Rotomahana siphon) was installed in 1972 to drain the lake towards Lake Tarawera when lake levels are high. The pipe invert is at 340.43 m (Riley Consultants, 2003). Levels in Lake Rotomahana rarely get greater than 340.3 m and flow through the siphon is rare.

Tarawera

The Te Wairoa Stream (draining Lake Rotokakahi) and the Waitangi Stream (draining Lake Ōkareka) are the only permanent surface water inflows to the local catchment of Lake Tarawera. Combined mean flow from these streams has been estimated to be 475 l s^{-1} (White et al., 2016). The local catchment also receives some rare flows from Lake Rotomahana, via the Rotomahana siphon when levels in Lake Rotomahana are high. In addition to inflows from Te Wairoa and Waitangi Streams (347 l s^{-1} and 164 l s^{-1} respectively), Lake Tarawera receives inflows from cold springs, hot springs and streams sourced within its local catchment including Twin Creeks (507 l s^{-1} combined), Wairua Stream (208 l s^{-1}), Rotomahana Waterfall (174 l s^{-1}) and numerous other flows. Total surface water inflows to Lake Tarawera are estimated as 1,750 l s^{-1} (White et al., 2016). Location of the inflows to Lake Tarawera are shown in Figure 2.10.

The Tarawera River is the only outflow from Lake Tarawera and its catchment, with an mean flow of 6,738 l s^{-1} (White et al., 2016). There is evidence from flow gauging (White & Cooper, 1991; White et al., 2016) that the Tarawera River gains a significant amount of flow downstream of Tarawera Falls (approximately 2 m^3 s^{-1}). White et al. (2016) assessed these gains to be too large to be derived solely from the topographic catchment between the outlet of Lake Tarawera and the Tarawera Falls, suggesting the majority of gains (approximately 1.5 m^3/sec) could represent groundwater outflow from Lake Tarawera and/or its catchment.

Tikitapu

There are no permanent surface water inflows or outflows from Lake Tikitapu or its local catchment (White et al., 2016).

Figure 2.10 Surface water features in and around the Greater Tarawera Lakes catchment. Local catchment boundaries are shown by red outlines.

2.5.2 Groundwater

With the exception of Lake Rerewhakaaitu, all lakes of the Greater Lake Tarawera catchment are hydraulically connected to the water table and groundwater from their catchments drains towards Lake Tarawera (White et al., 2016). Lake Rerewhakaaitu is perched[2] and is located on a groundwater divide, with groundwater flowing west on the

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[2] Groundwater levels in the vicinity of Lake Rerewhakaaitu are generally below the level of the lake, classifying the lake as perched relative to the groundwater system (White et al., 2003, 2016).

west side of the lake (towards Lake Rotomahana) and east on the east side of the lake (out of the Greater Lake Tarawera catchment) (White et al., 2003). Isotopic and water quality data suggest that only those aquifers to the west and north of Lake Rerewhakaaitu (those flowing towards Lake Rotomahana) have a lake water contribution (Reeves, Morgenstern, Daughney, et al., 2008).

Estimates of mean annual groundwater flows of the Greater Tarawera Lakes and/or their catchments have been undertaken by White et al. (2016) and White et al. (2020) and are summarised in Table 2.4. A groundwater flow model of the Greater Tarawera Lakes was developed by White et al. (2016). Findings of the flow model suggest that, except for Lake Rerewhakaaitu (which is perched), groundwater recharges the lakes of the Greater Lake Tarawera catchment. A piezometric map showing groundwater head (elevation) and flow directions developed from the flow model of White et al. (2016) is shown in Figure 2.11.

Local groundwater catchment boundaries of the Tarawera Lakes were delineated by White et al. (2020) and are shown in Figure 2.11 and Figure 2.12. Local groundwater catchment boundaries of the lakes in the Greater Lake Tarawera catchment do not always align with their local surface water catchments, and there are notable boundary and/or areal differences in all catchments except Tikitapu (Figure 2.12, Table 2.1). Rationale and explanation of these differences is given in White et al. (2020).

Table 2.4 Summary of annual mean groundwater flows to and from lakes and their local catchments. Values are from water balances undertaken in existing literature (White et al., 2016, 2020).

	Groundwater inflows (l/s)	Groundwater outflows (l/s)	Net groundwater flow (l/s)[1]
Lakes[2]			
Lake Ōkareka	-	-	70
Lake Ōkaro	-	-	-70
Lake Ōkataina	-	-	-400
Lake Rerewhakaaitu	-	-	-200
Lake Rotokakahi	-	-	190
Lake Rotomahana	-	-	-570
Lake Tarawera	-	-	3500
Lake Tikitapu	-	-	-400
Local catchments[3]			
Ōkareka local catchment	50	200	-150
Ōkaro local catchment	0	50	-50
Ōkataina local catchment	0	2600	-2600
Rerewhakaaitu local catchment	0	400	-400
Rotokakahi local catchment	50	80	-30
Rotomahana local catchment	50	2100	-2050
Tarawera local catchment	5000	3400	1600
Tikitapu local catchment	0	100	-100

[1] Negative values indicate net outflow, positive values indicate net inflow

[2] From water budget of White et al. (2016), Table 4.5

[3] From water budget of White et al. (2020), Table 3.4

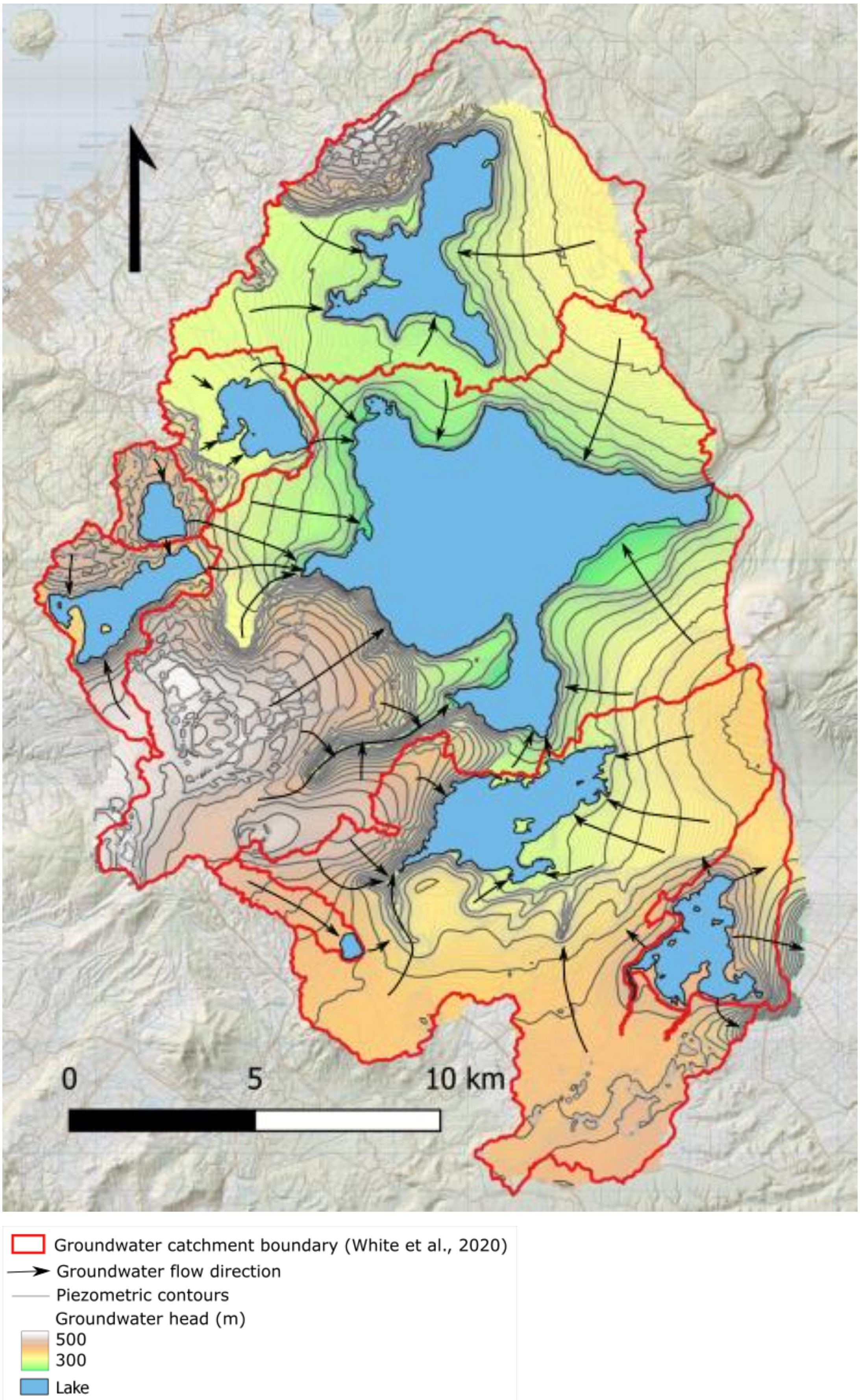

Figure 2.11 Piezometric map of the study area. The map shows the groundwater head (elevation) of the uppermost layer in the groundwater flow model developed by White et al. (2020). Flow directions are shown by arrows. Data source: GNS Science (White et al., 2016).

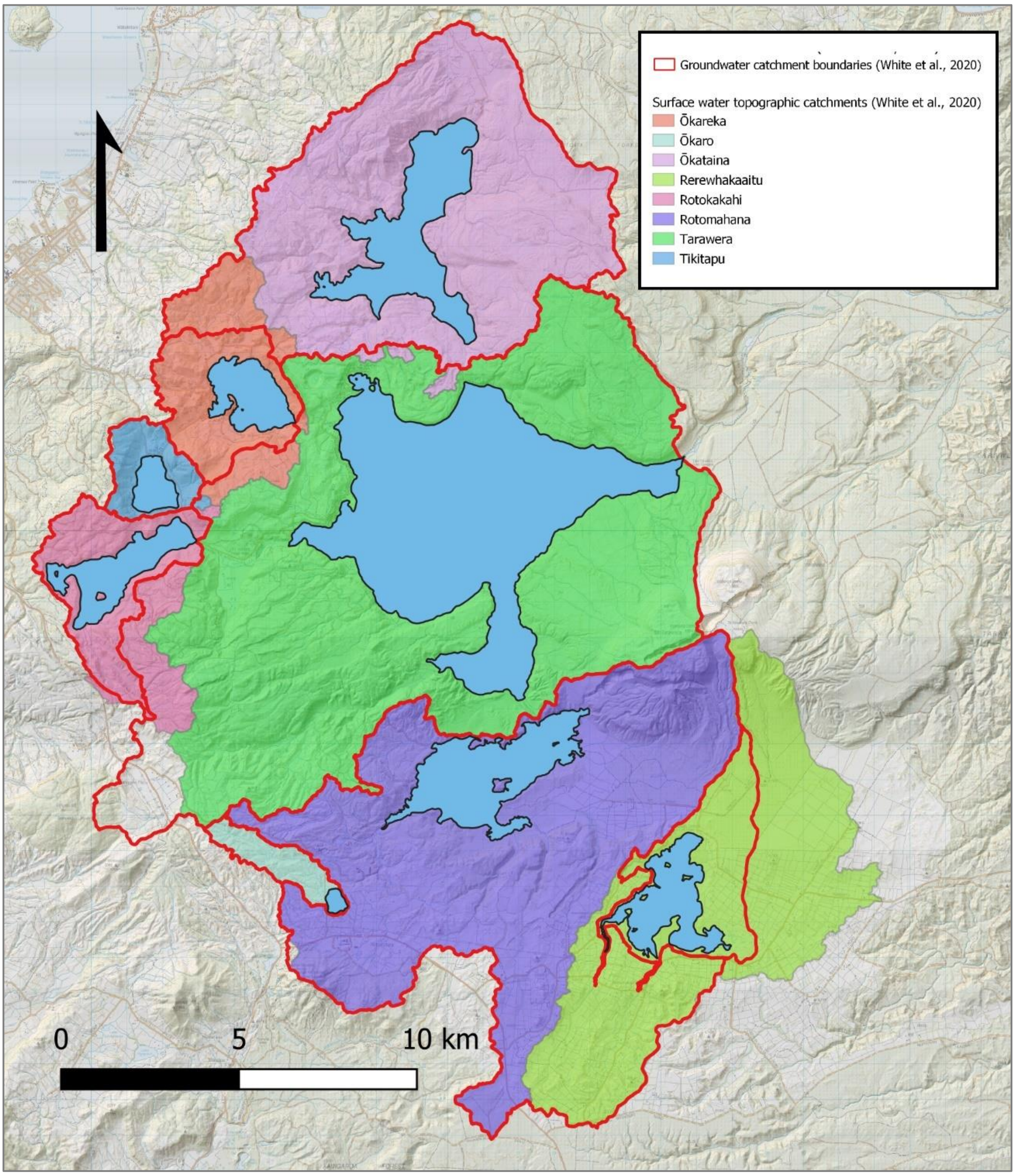

Figure 2.12 Map showing the differences between groundwater catchment boundaries (red outlines) and surface water catchments (coloured areas) as defined by White et al. (2020).

Tarawera

There are substantial uncertainties on the hydrology of groundwater fluxes to Lake Tarawera (Abell et al., 2020). Water balances of Lake Tarawera and/or its catchment have been undertaken by Hamilton et al. (2006), Gillon et al. (2009), White et al. (2016) and White et al. (2020), all of whom have concluded that groundwater is a dominant source of water entering and exiting Lake Tarawera. Hamilton et al. (2006) concluded that nearly 80% of water entering Lake Tarawera (not including rainfall) was from ungauged (predominantly groundwater) sources. Gillon et al. (2009) assessed groundwater outflow from the Lake Tarawera local catchment to be 0.918 m^3/s using Darcy's law. White et al. (2016) assessed a net gain of groundwater to Lake Tarawera of 3.54 m^3/s and a net gain of groundwater to the local catchment of Lake Tarawera of 1.87 m^3/s. After assessing groundwater catchment boundaries, White et al. (2020) calculated groundwater inflow to the Lake Tarawera local catchment to be 5.0 m^3/s, and outflow to be 3.4 m^3/s.

Other lakes and catchments

Water balances developed by White et al. (2016) suggest net gain of groundwater to Lake Rotokakahi (i.e. groundwater inflows are larger than groundwater outflows), and net loss of groundwater to Lakes Ōkataina, Rerewhakaaitu, and Rotomahana (i.e. groundwater outflows are larger than groundwater inflows) (Table 2.4). Small net flows (-100 to 100 $l\ s^{-1}$) in Lakes Ōkareka, Tikitapu, and Ōkaro are within the range of uncertainty and suggest the groundwater inflows and outflows to these lakes are approximately equal (White et al., 2016).

Net groundwater losses were calculated to the local catchments of Lakes Ōkareka, Ōkaro, Ōkataina, Rerewhakaaitu, Rotokakahi, Rotomahana, and Tikitapu (White et al., 2020). Significant net groundwater losses (> 1,000 $l\ s^{-1}$) where calculated for the local catchments of Ōkataina and Rotomahana (Table 2.4)

2.6 Lake water quality

Water quality of the Greater Tarawera Lakes has been assessed using the trophic level index (TLI)[3] and ranges from poor in eutrophic Lake Ōkaro (TLI = 4.77), to good in oligotrophic Lakes Ōkataina, Tarawera and Tikitapu (TLI's of 2.54, 2.71 and 2.84 respectively). Lake water quality is linked to land use and nutrient loads received from surface and groundwater flows within each catchment (McBride et al., 2020). Other sources of nutrients to the Greater Tarawera Lakes include atmospheric deposition to the water surface, nitrogen fixing shrubs (e.g. gorse and broom), geothermal inputs, wastewater, and hydrological connections from other lakes and catchments (McBride et al., 2020). A summary of the water quality of the Greater Tarawera lakes is shown in Table 2.1.

[3] TLI is a measure of water quality with values ranging from 0 to 9. The lower the TLI, the better the water quality. Categories of water quality based on the TLI are given by Land and Water Aotearoa (2020). More information on the TLI and how it is calculated can be found in Chapter 3

Lake Rotomahana, and to a lesser extent Tarawera, have naturally occurring nutrient loads due to geothermal inflows (McBride et al., 2020). Lake Ōkaro has been subject to intensive restoration efforts including aluminium dosing, modified zeolite dosing, wetland construction, riparian planting, farm planning, and farm nutrient management (Allan et al., 2020).

Chapter 3
Literature review

3.1 Lake water quality management

Eutrophication is the excessive accumulation of nutrients in a water body, commonly caused by inputs of phosphorus (P) and nitrogen (N) (Carpenter et al., 1998; Lee et al., 1978). The majority of freshwater lakes are phosphorus-limited (Lee et al., 1978; Lewandowski et al., 2015), meaning that algal growth is limited by the amount of phosphorus available in the lake. Most marine and some fresh-water lakes are nitrogen limited (Lee et al., 1978; Lewandowski et al., 2015). Agricultural and urban activities are major contributors of P and N to rivers and lakes (Carpenter et al., 1998). In New Zealand, N is added to the soil through biological N fixation and application of urea fertiliser (Parfitt et al., 2012), and P by the application of P fertilisers (Parfitt et al., 2008). Atmospheric deposition also contributes N to soils and waterbodies and additional P may be added through weathering of rocks (Parfitt et al., 2006, 2008).

Point source discharges of pollutants to water are relatively simple to measure and regulate, whereas non-point sources are difficult (Carpenter et al., 1998). Lake water quality management in New Zealand has historically focused on point source discharges and has been regulated by regional councils under the Resource Management Act (RMA) (1991). In contrast, little has been done until recently to manage non-point sources of pollution from land-use change or intensification (Hamilton & Dada, 2016). The National Policy Statement for Freshwater Management 2020[4] (NPS-FM) addresses the effects of land use on freshwater quality, requiring regional and local councils to set limits on water quality to improve degraded water bodies, and maintain or improve all other water bodies (New Zealand Government, 2020). The NPS-FM approaches water management from a catchment scale and recognises the interconnectedness of land and freshwater bodies, using freshwater management units (FMUs)[5] for management and accounting purposes.

[4] This replaced the 2014 NPS-FM (revised 2017)

[5] An FMU is defined by the NPS-FM as "all or any part of a water body or water bodies, and their related catchments, that a regional council determines under clause 3.8 is an appropriate unit for freshwater management and accounting purposes" (New Zealand Government, 2020, p. 6)

The NPS-FM sets out limits on chlorophyll-a, total nitrogen (TN), total phosphorus (TP), ammonia, *Escherichia coli*, and cyanobacteria (planktonic) for lakes, and requires that the concept of Te Mana o te Wai informs the governance of freshwater. Te Mana o te Wai refers to the vital importance of water and protects the health and well-being of water before enabling other water uses (Ministry for the Environment & Ministry for Primary Industries, 2020). It requires that authorities must involve tangata whenua, stakeholders, and communities in freshwater management and decisions.

Lake water quality in New Zealand is often reported by the Trophic Level Index (TLI), a measure of nutrient enrichment (Burns et al., 2000). TLI can be measured using either TN, TP, Chlorophyll a and Secchi data (TLI4), or without Secchi data (TLI3) (Verburg et al., 2010). The TLI of a lake gives an indication of lake water quality, allows for comparison between lakes (Land and Water Aotearoa, 2020), and has been adopted as a means of limit setting by some regional councils in New Zealand (Hamilton & Dada, 2016). The lower the TLI, the better quality the lake water (Table 3.1).

Table 3.1 Trophic Level Index (TLI) descriptions from Land and Water Aotearoa (2020). TLI is an indication of lake water quality which is measured using total nitrogen, total phosphorus, Chlorophyll a and/or Secchi data.

TLI score	Description
0 - 2	Microtrophic: The lake is very clean with very low levels of nutrients and algae. The lake can have snow or glacial sources.
> 2-3	Oligotrophic: The lake is clear and blue, with low levels of nutrients and algae
> 3-4	Mesotrophic: The lake has moderate levels of nutrients and algae.
> 4-5	Eutrophic: The lake is murky, with high amounts of nutrients and algae.
> 5	Supertrophic: The lake has very high amounts of phosphorus and nitrogen, and can be overly fertile and often associated with poor water clarity. Excessive algae growth can occur. Suitability for recreational purposes is often poor.

3.1.1 Water quality management of the Greater Tarawera Lakes

Numerous legislative documents, community groups and other stakeholders support or require managing nutrient loads to the Greater Tarawera Lakes to improve water quality. These include the NPS-FM, Rotorua Te Arawa Lakes Strategy Group[6] process (The Crown & The Rotorua Lakes Strategy Group, 2007) and strong local support from groups such as the Tarawera Ratepayers Association. TLI targets for the Greater Tarawera Lakes have been defined in the Bay of Plenty Regional Natural Resources Plan (Bay of Plenty

[6] A group of elected representatives from Bay of Plenty Regional Council, Te Arawa Lakes Trust and Rotorua Lakes Council, with support from the Ministry for the Environment

Regional Council, 2017) and recent TLI estimates are given in McBride et al. (2020) (Table 3.2). The Tarawera Lakes Restoration Plan (Bay of Plenty Regional Council, 2015) recognised the interconnectedness of lakes in the Greater Lake Tarawera catchment and required consideration and management of the nutrient loads in Lakes Ōkareka, Ōkaro, Ōkataina, Rerewhakaaitu, Rotokakahi, Rotomahana and Tikitapu when managing Lake Tarawera.

Table 3.2 Trophic Level Index (TLI) targets for the Greater Tarawera Lakes from the Bay of Plenty Council Regional Plan (2017) and current TLI measurements (McBride et al., 2020). Lower TLI values indicate better water quality.

	TLI target (BOPRC, 2017)	Current TLI (McBride et al., 2020)
Lake Ōkareka	3.0	3.14
Lake Ōkaro	5.0	4.77
Lake Ōkataina	2.6	2.54
Lake Rerewhakaaitu	3.6	3.41
Lake Rotokakahi	3.1	3.75
Lake Rotomahana	3.9	3.63
Lake Tarawera	2.6	2.71
Lake Tikitapu	2.7	2.84

3.2 Lake nutrient and catchment modelling

Computer modelling is a useful tool to assess and manage water resources (Singh & Woolhiser, 2002). Water management often requires the integration of catchment hydrological models with nutrient loss models, to link land use practices within the catchment to the quantity and/or quality of water in the receiving environment (Singh & Woolhiser, 2002). In New Zealand, various models have been used to predict nutrient loss and transport from pastoral land, and have been summarised by Cichota and Snow (2009). Singh and Woolhiser (2002) have summarised catchment models from an international perspective and Tuo et al. (2015) compared five commonly used catchment models used overseas.

Overseer® is the model most used to estimate nutrient losses from farmland in New Zealand (Science Advisory Panel, 2021) and has been used by BOPRC for this purpose in the Greater Tarawera Lakes Catchment (McBride et al., 2020). Overseer® was originally developed in the 1980's for farmers to estimate fertiliser requirement within a farm, and was not designed for its current use of estimating nutrient losses for scientists (Science Advisory Panel, 2021). Nonetheless, it has been adopted by some regional councils (including the BOPRC for Lake Rotorua and the Waikato Regional Council for Lake Taupō) for the regulation of diffuse (non-point source) discharges of nutrients to freshwater (Science Advisory Panel, 2021). Overseer® estimates long-term (30 year) average nutrient losses using long-term average climate data (rainfall, PET and temperature), soil data and user defined management, inputs (e.g. fertiliser) and production (Science Advisory Panel, 2021). Nutrient losses calculated by Overseer® are sensitive to rainfall, with higher rainfall resulting in higher nutrient losses. This is due to the increase in the absolute amount of drainage in a year and the number of months where drainage occurs (Overseer, 2012). Because of this rainfall-nutrient loss relationship, large fluctuations can exist in modelled nutrient discharges between years when calculated on an annual basis (Journeaux, 2014). These fluctuations are driven largely by rainfall, with soil type and management changes having little impact (Journeaux, 2014). There has been no testing of this rainfall-nutrient loss relationship in climates with high rainfall (> 1,600 mm y^{-1}) (Overseer, 2012).

Rutherford et al. (2019) undertook a review of available catchment models (SPARROW, CLUES, EnSus, AquiferSim and HBV-N models) to route Overseer® losses from individual land parcels to Lake Rotorua. After consideration of these models, the ROTAN (ROtorua and TAupō Nitrogen) model was adopted in the Rotorua Catchment to predict N loads to Lake Rotorua and inform policy (Rutherford et al., 2019; Rutherford, 2016). ROTAN was developed by NIWA, and is based on HBV-N, a conceptual rainfall-runoff model developed during the 1970s (Bergström & Lindström, 2015). ROTAN routed N losses from land to Lake Rotorua accounting for groundwater lags, land use intensification and attenuation (Rutherford et al., 2019). An early version of ROTAN used a daily time step and Overseer® v5.4.2 nutrient loss estimates (Rucinski et al., 2006; Rutherford et al., 2011). ROTAN was updated in 2019 to use an annual time step and Overseer® v6.2.0 estimates, predicting losses on average to be 88% higher than earlier versions of ROTAN (Rutherford et al., 2019).

3.3 Greater Tarawera Lakes – previous research

Numerous water flow and nutrient load studies have been undertaken on the lakes of the Greater Lake Tarawera catchment. Gillon et al. (2009) and White et al. (2016) have investigated flows to all eight lakes in the Greater Lake Tarawera catchment with the objective of modelling nutrient discharge to Lake Tarawera. McBride et al. (2020) estimated total nitrogen and phosphorus loads to all lakes in the Rotorua and Tarawera area using export coefficient modelling. GNS Science undertook a series of studies to investigate groundwater of the Greater Tarawera Lakes Catchment (Lovett et al., 2012; Rose et al., 2012; Thorstad et al., 2011; Tschritter & White, 2014; White et al., 2016, 2020). Arsenic concentrations in Lake Tarawera were investigated by Cochrane (2020) and results from groundwater sourced inflows to Lake Tarawera in the Wairua Arm confirmed a suspected hydrologic connection to Lake Rotomahana.

Lake water quality modelling has been undertaken on a number of Lakes in the Tarawera catchment including Ōkaro (Allan et al., 2020; Özkundakci et al., 2011), Rerewhakaaitu (Choi et al., 2019), Rotokakahi (Jones et al., 2014), Tarawera (Abell et al., 2020), and Tikitapu (McBride et al., 2016). All of these studies use the one-dimensional lake model DYRESM–CAEDYM, the most widely cited aquatic ecosystem model in the literature (Trolle et al., 2012). Various other studies and publications have reported lake water quality or undertaken nutrient budgets for lakes in the Greater Lake Tarawera catchment (Butterworth, 2012; Hamilton et al., 2006; McIntosh, 2012a, 2012b, 2012c; The Rotorua Lakes Protection and Restoration Action Programme, 2013; White & Cooper, 1991). Noakes (2016) used MODFLOW and ELCOM to model groundwater inflows into Lake Rotokakahi.

Water dating, geochemistry and isotope analysis have been used as a tool to understand groundwater movement and residence times in the Ōkareka (Morgenstern et al., 2005) and Rerewhakaaitu catchments (Reeves, Morgenstern, & Daughney, 2008; Reeves, Morgenstern, Daughney, et al., 2008). Studies in the Rerewhakaaitu catchment have shown that water from Lake Rerewhakaaitu is leaking to groundwater to the north and west of the lake, towards the Lake Rotomahana. Age dating using tritium, CFCs and SF_6, was undertaken on groundwater from 10 sites from permanent and temporary groundwater wells installed as part of the GNS Science Lake Tarawera Groundwater Investigations (Lovett et al., 2012; Rose et al., 2012; Thorstad et al., 2011). Groundwater age interpretations ranged from 4–256 years, with younger ages for shallower groundwater and older ages for deeper groundwater (Lovett et al., 2012; Rose et al., 2012; Thorstad et al., 2011).

White and Cooper (1991) noted that the flow gains in the Tarawera River from the outlet to below the falls (a gain of approximately 2 m^3/sec), were too large to be sourced from the topographic catchment between these two sites, suggesting the majority of those gains (approximately 1.5 m^3/sec) could represent groundwater outflow from Lake Tarawera and/or its catchment. This theory was also presented in later studies (White et al., 2016).

3.3.1 Gillon et al. (2009) investigation

The first detailed study on the surface and groundwater flows in and between the Greater Tarawera Lake catchments was undertaken by Gillon et al. (2009) who assessed current and future nitrogen loads to Lake Tarawera. Gillon et al. (2009) undertook a basic water balance for each of the Greater Tarawera Lake catchments in order to assess groundwater inflows and outflows to the Lake Tarawera local catchment. The results of the water balances, in conjunction with Darcy's law, were used to assess groundwater flows between the lakes of the Greater Lake Tarawera catchment under three different scenarios of flow:

- all groundwater flow is contained within the Greater Lake Tarawera catchment and discharges east through the Lake Tarawera local catchment; or
- groundwater flow may discharge to the north (towards lakes Rotorua and Rotoiti) and/or east through the Lake Tarawera local catchment; or
- groundwater flow may discharge to the north (towards lakes Rotorua and Rotoiti), south/west (towards Waikato) and/or east through the Lake Tarawera local catchment.

Each of the three scenarios were assessed and rainfall was varied by ±10%. Results suggested that different scenarios and varying rainfall result in large differences to the groundwater outflow from Lake Tarawera. The preferred scenario chosen by Gillon et al. (2009) was that in which groundwater flow discharged from the Greater Lake Tarawera catchment to the north (towards Rotorua and Rotoiti), south/west (towards Waikato) and east through the Lake Tarawera local catchment. This preferred scenario was then used to produce a more detailed water balance and groundwater flow model for the Lake Tarawera local catchment. Despite this, research following Gillon et al. (2009) adopted the conceptual understanding that all groundwater flow is contained within the

Greater Lake Tarawera catchment and discharges east through the Lake Tarawera local catchment (P. White, personal communication, January 15, 2021; White et al., 2016).

A conclusion of the water balance presented in the Gillon report that has been embraced in subsequent studies (Abell et al., 2020; White et al., 2016) was that groundwater outflow from Lake Tarawera was estimated to be 918 l/s (Table 10 of Gillon et al. (2009)).

3.3.2 GNS Science investigations

GNS Science undertook a series of investigations to assess groundwater resources in the Greater Lake Tarawera catchment, all of which have been summarised by Bruere and White (2016). The investigations were part of a three phase programme involving the drilling of bores and testing of groundwater (Lovett et al., 2012; Rose et al., 2012; Thorstad et al., 2011), the development of a geological model (Tschritter & White, 2014), and the development of a groundwater flow model to calculate nitrogen discharge to streams and lakes under different land use scenarios (White et al., 2016). Subsequent to the completion of this programme, additional work was undertaken to delineate surface water and groundwater catchment boundaries in the Greater Lake Tarawera catchment (White et al., 2020).

Nineteen wells were drilled at 10 locations during phase 1 of these investigations, with 12 of these wells installed as permanent monitoring wells[7]. Aquifer testing and groundwater sampling were undertaken on these wells to measure hydraulic conductivity, groundwater quality and groundwater age. Unexpected conditions were encountered at a well located at the Lake Tarawera outlet – water bearing materials were found at depths of 3 – 11 m below ground level (BGL) and 80 – 95 m BGL with dry conditions in between. Preferred tritium age ranges for this deep aquifer at the Tarawera Outlet ranged from 31 – 58 years (Thorstad et al., 2011). Thorstad et al. (2011) postulated that water may discharge from Lake Tarawera through this deep aquifer at the outlet to the Tarawera Falls. Chemical analysis of samples collected from shallow and deep groundwater at the Tarawera outlet indicated they were similar in origin with Lake Tarawera, and Lake Tarawera and/or the Tarawera River was identified as a possible water source (Thorstad et al., 2011).

[7] BOPRC began regular sampling of these wells in 2020

A three-dimensional geologic model was created of the Greater Lake Tarawera catchment and based on QMAP geological map units using a combination of GIS and EarthVision 8.1 modelling software (Tschritter & White, 2014). The geological model simplifies a complex, largely volcanic system and summarised its hydrogeological characteristics into a 16 layer model (Tschritter & White, 2014). The Rotorua QMAP geological map, published geological logs and cross sections, local scientific knowledge, and drillers logs were used inform the model (Tschritter & White, 2014).

White et al. (2016) synthesised information collected in the previous two phases of the GNS Science investigations to produce a groundwater flow model to calculate nitrogen discharge to Lake Tarawera. Steady state water balances were developed to provide the water flux for the groundwater flow model. To calculate the water balances, White et al. (2016) compiled a detailed description of surface water flows which was assembled from various sources. Mean annual rainfall values from Tait et al. (2006) and mean annual actual evapotranspiration (AET) values from Woods et al. (2006) were used in the water balance. AET values did not consider land use, land cover, soil type or groundwater recharge (Woods et al., 2006). Evaporation from lakes was assumed to be 41% of rainfall, groundwater flows were assessed as net values using water balances, and consumptive water use was assumed zero (White et al., 2016). White et al. (2016) assumed that with the exception of some groundwater flow from the Rerewhakaaitu catchment leaving the Greater Lake Tarawera catchment east towards the Rangitikei River catchment, all flows are contained within the catchment.

Following the water balance assessment described above, White et al. (2016) used the software GMS 10.0 to build a groundwater flow model of the Greater Tarawera Lakes catchment, and translated the 3-D geological model of Tschritter and White (2014) into a 3-D MODFLOW grid. Much of the outer perimeter of the model was assigned as a no-flow boundary (i.e., water could not flow across the boundary), with the exception of the Tarawera River and an area near Lake Rerewhakaaitu (based on the accepted conceptual understanding of the system). After calibration of the model, five land use scenarios were modelled using published nitrogen discharge estimates from different land uses – a forested scenario, low-intensity agriculture scenario, current scenario, foreseeable intensification, and a large-scale intensification. Groundwater flow maps were produced for the catchment and can be used to identify flow paths between lakes (Bruere & White, 2016). It is noted that the groundwater flow model of White et al. (2016) described above indicated that approximately 75% of the groundwater outflows from the Rerewhakaaitu catchment are lost eastwards towards the Rangitaiki River catchment (Table 4.7 of White et al. 2016).

Simulated groundwater levels and flow directions from the groundwater flow model of White et al. (2016) were used to inform the delineation of groundwater catchment boundaries in the Greater Tarawera Lakes complex (White et al., 2020). Surface water catchment boundaries were also estimated by White et al. (2020) by analysing existing boundaries, LIDAR data, and refining the interpretation of topographic features such as flat areas and gullies. Water balances were re-calculated using the updated catchment boundaries. The water balance calculated groundwater outflows from the Greater Lake Tarawera catchment to be 3.4 $m^3 s^{-1}$ flowing eastward from the Tarawera Catchment and Lake, and 0.4 $m^3 s^{-1}$ flowing eastward from the Rerewhakaaitu Catchment and Lake to the Rangitaiki River catchment (White et al., 2020).

3.4 Stable isotopes as environmental tracers

Stable isotopes of water, namely the ratios of hydrogen and oxygen ($^2H/^1H$ and $^{18}O/^{16}O$) can supplement traditional annual water balance studies that fail to consider geological and biological controls on the movement and distribution of water in time and space (McDonnell, 2017). They can be used to solve practical hydrological problems such as tracking water through the water cycle, determining the recharge source of groundwater, and groundwater contributions to/from lakes (Coplen et al., 1999; Elmarami et al., 2017; McDonnell, 2017; Phillips & Gregg, 2001; Zuber, 1983). For example, linear mixing models based on mass balance equations can be used to determine the proportional contributions of multiple water sources to a water mixture by using the isotopic signatures of each source (Phillips et al., 2005; Phillips & Gregg, 2001, 2003). Stewart et al. (2007) have demonstrated groundwater contributions to the Pukemanga Stream in New Zealand using stable isotopes of water. Morgenstern et al. (2015) used the isotopic and chemistry signature of groundwater to assess sources and dynamics of groundwater in the Rotorua catchment. Many other studies using water isotopes have shown mixtures of water sources in streams and groundwater (Eyberg, 2020; Jasechko et al., 2017; McDonnell, 2017).

Isotopic analysis of waters has revealed a "compartmentalisation" effect of water stored in catchments, that is, areas of a catchment will store water by different means (e.g., tightly bound soil moisture that does not move through the vadose zone during precipitation events vs mobile water which enters the groundwater system and forms streamflow), and for different periods of time resulting in a blend of water ages in discharge water (McDonnell, 2017; Renée Brooks et al., 2010). This blending is problematic for water management as it influences nitrogen cycling and involves complex processes in the water cycle, meaning historic contaminants may remain in the soil and nutrients flush through more quickly in younger water (McDonnell, 2017). Furthermore, multiple sources and different flow paths make mixed ages and sources possible in some complex catchments (Jasechko et al., 2017; Morgenstern et al., 2015).

3.4.1 Fundamentals of water isotopes

The isotopes of an element are atoms of that element that differ in mass due a difference in the number of neutrons. Isotopic fractionation is defined by Tiwari et al. (2015) as "the relative partitioning of the heavier and lighter isotopes between two coexisting phases in a natural system". The isotope ^{2}H is called deuterium and given the symbol D, the superscript indicates the number of protons plus neutrons in the isotope (in the case of deuterium this is one neutron and one proton) (Kendall & Doctor, 2003). Stable isotopes of hydrogen and oxygen in water can be fractionated by physical or chemical processes (Coplen et al., 1999). Evaporation is an example of a process that causes fractionation of water isotopes. In kinetic isotope reactions (i.e. evaporation) lighter isotopes (those with smaller numbers of protons and neutrons) are more reactive, thus are concentrated in reaction products, enriching the reactants with the heavier isotope (Coplen et al., 1999).

Stable isotope ratios are reported relative to a standard as δ (delta) in parts per thousand (‰). The isotopic composition of hydrogen and oxygen in precipitation is covariant, and the relationship between δ^{2}H and δ^{18}O of precipitation worldwide is called the global meteoric water line (GMWL) (Coplen et al., 1999). Local variations may exist to this relationship and will result in a local meteoric water line (LMWL), which has the same slope as the GMWL but sits either above or below it. Analysis and interpretation of isotope data is often done using a δ^{2}H / δ^{18}O plot with the GMWL as a reference (Coplen et al., 1999). Evaporation and geo-thermal exchange of oxygen with rocks can also cause water to deviate from the LMWL (Coplen et al., 1999; IAEA, 1981).

The isotopic composition of precipitation varies spatially due to altitude, latitude, the distance from the coast, the season, the amount of precipitation, and the temperature (Coplen et al., 1999). Baisden et al. (2016) produced mean annual precipitation δ^2H and δ^{18}O maps (isoscapes) for New Zealand, and daily and monthly precipitation isoscapes for the 2007-2009 period. The isotopic composition of shallow, rainfall recharged groundwater is often assumed to represent the isotopic composition of rainfall in a given locality (IAEA, 1981).

Due to evaporation resulting in the enrichment of heavier isotopic species (i.e. deuterium and ^{18}O), the majority of lakes are enriched in deuterium and ^{18}O compared to local meteoric water (Horton et al., 2016; Vystavna et al., 2021; Xiao et al., 2017). Deuterium and ^{18}O in lake waters are enriched along evaporation lines that divert from the meteoric water line, and geothermally influenced waters show a positive shift in ^{18}O (i.e. are displaced to the right of the LMWL or evaporation line) (IAEA, 1981). Isotopic data collected from the Greater Tarawera Lakes by the University of Waikato are shown in Figure 3.1. The position of lakes along the evaporation line indicates how much evaporation has occurred because fractionation of lake surface water by evaporation proceeds from an initial homogenous composition, or is presumed to (i.e. Tikitapu has been subject to the most evaporation and Ōkaro the least) (T. Baisden, personal communication, 2021). There is also some variability in the isotopic composition of each lake along the evaporation line, with samples from the epilimnion (upper layer) generally being the most evaporated (i.e., positioned higher on the evaporation line) (Figure 3.1). Seasonal thermo-stratification of lake waters occurs in most New Zealand lakes in warmer months, leading to the formation of a distinct epilimnion (upper layer) and preventing circulation (Hamilton et al., 2018). During the winter months mixing of lake water occurs. Thus, the isotopic composition of lake water from the epilimnion (when the lake is stratified) has been subject to more evaporation due to lack of mixing with bottom waters.

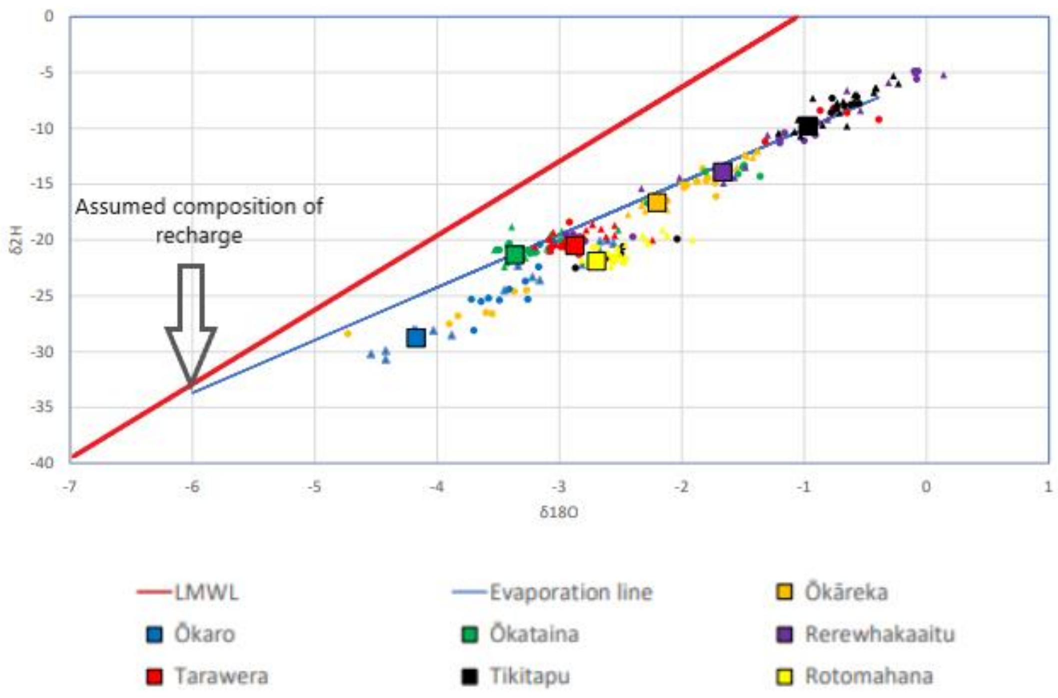

Figure 3.1 δ2H/δ18O ratios for Tarawera Lakes. Colours represent the lakes, small circles are samples from the hypolimnion (lower layer of water), triangles are samples from the epilimnion (upper layer of water), the larger squares represent the mean of the hypolimnion samples. LMWL is the local meteoric water line. (from University of Waikato, unpublished data).

3.5 Water balance

The water balance is a useful tool for guiding water policy and management (European Commission, 2015) and its accuracy is crucial to effective management of lakes (Rosenberry et al., 2015).

The water balance equation is a mathematical description of the hydrologic cycle operating within a given timeframe (Davie & Quinn, 2019). It incorporates the principle of conservation of mass and energy, defining the hydrological cycle as a closed system where no water is created or lost within it. It can be applied to an area (e.g. a lake or catchment) and solved for the purpose of providing a quantitative assessment of the movement of water through that unit (Robinson & Ward, 2017). In simple terms, the water balance equation takes the form (Healy et al., 2007):

$$\Delta S = Inflow - Outflow \quad (3\text{-}1)$$

Where ΔS is the change in storage over a defined period of time. Inflows, outflows and storage consist of a number of sub-components relevant to a particular area (Scanlon et al., 2002). With the Greater Tarawera Lake catchments in mind, the water balance equation can be defined as:

$$\Delta S = (P + Q_{sw,in} + Q_{gw,in}) - (Q_{sw.out} + Q_{gw.out} + E) \quad (3\text{-}2)$$

Where ΔS = change in storage in surface water reservoirs (e.g. lakes), the unsaturated zone and the saturated zone (includes consumptive water uses), P = precipitation (and may include irrigation), $Q_{sw.in}$ = surface water inflows, $Q_{gw.in}$ = groundwater inflows, $Q_{sw.out}$ = surface water outflows (includes runoff and baseflow from groundwater), $Q_{gw.out}$= groundwater outflow, and E = evaporation (includes evaporation from water (e.g. a lake surface) and land including transpiration from living vegetation, and evaporation of rainfall intercepted by plant canopies).

It is not likely that all components of the water balance equation will be relevant at any particular site, some will be negligible and can be ignored (Healy et al., 2007). Surface water inflows, surface water outflows, precipitation and evaporation are usually able to be measured or estimated satisfactorily, overland flow is often assumed negligible, but quantification of groundwater inputs and outputs are more difficult (Rosenberry et al., 2015). Components of the water balance equation and methods of estimating them are described in Sections 3.5.1 to 3.5.6.

3.5.1 Precipitation

Precipitation is usually the largest term in a water balance and values of precipitation over an area are often estimated from point data collected at nearby weather stations (Davie & Quinn, 2019). This interpolation should account for uneven spread of rain gauges, altitude, aspect, slope etc. (Davie & Quinn, 2019). The spatial distribution of rainfall across the Lake Rotorua sub-catchments was estimated by Rutherford et al. (2019) using reference rainfall stations (located within the Lake Rotorua study area) and by calculating a scaling factor for each sub-catchment using a contour map of 30-year average rainfall for the area. On a national scale, the National Institute of Water and Atmospheric Research (NIWA) have generated daily rainfall totals on a 5 km grid across New Zealand known as the Virtual Climate Station Network (VCS) (Tait & Turner, 2005). Rainfall data from the VCS have been used for many hydrological studies across New Zealand (Cichota et al., 2008).

3.5.2 Evaporation from land

Evaporation can be split between interception loss (wet leaf evaporation - where liquid water is converted to vapour and removed from an evaporating surface such as a leaf or the soil) and transpiration (dry leaf evaporation - vaporisation of liquid water contained in plant tissues and removed to the atmosphere) (Allen et al., 1998; Davie & Fahey, 2005). Evapotranspiration is a concatenation of the words evaporation and transpiration and is often used to refer to the sum of interception loss and transpiration. In this research the term evaporation will be used to refer to both interception loss and transpiration.

It is difficult to obtain direct and accurate estimates of all components of evaporation (European Commission, 2015), although the eddy covariance method can be used to do this (Foken et al., 2012). Potential evapotranspiration (PET) from the land can be calculated from meteorological data measured at weather stations using well known methods such as Penman (1963) and Priestly and Taylor (1972). Both of these methods assume the surface is covered with a short green crop and there is unlimited water supply (Srinivasan et al., 2016), NIWA's VCS data includes a daily interpolated PET surface by combining Penman and Priestly-Taylor methods and raised pan evaporation methods on a 5 km grid across New Zealand (Tait & Woods, 2007). PET provides an upper estimate for evaporation over land and is often greater than actual evapotranspiration (AET) (Srinivasan et al., 2016). The Food and Agriculture Organisation (FAO) of the United Nations has proposed a method (the FAO56 method) for calculating AET from various agricultural crops (Allen et al., 1998). Crop factors are used by the FAO56 method to adjust a reference crop evaporation to different land covers, and adjustments can be made for non-standard conditions such as water stressed crops. Other researchers (Lee et al., 2014) have used satellite-based estimates of PET. In the Rotorua catchment, Rutherford et al. (2019) estimated AET from land cover using the methods of Zhang et al. (2001) who developed a model to relate mean annual AET to rainfall, potential evapotranspiration and plant-available water capacity at a catchment scale.

Evaporation rates can differ with land use as it is affected by land cover and irrigation practices (Allen et al., 1998; Davie & Fahey, 2005). Tall vegetation (e.g. exotic or indigenous forest) has higher interception losses than pasture due to a larger leaf/needle area for rainfall to be intercepted on and greater turbulence above the canopy (Davie & Fahey, 2005). Therefore, evaporation rates from exotic or indigenous forest are higher than from pasture. Research in the Purukohukohu Experimental Basin, located in the Kaingaroa Forest, and neighbouring the Tarawera Lake catchments to the south and east has shown that afforestation of pasture reduced river flows (Dons, 1986). For neighbouring catchments which can be assumed to have the same precipitation and negligible groundwater losses, differences in water yield must be matched by differences in evapotranspiration (assuming $\Delta S = 0$ over a suitable period), thus the conclusion of Dons (1986), can be interpreted that evapotranspiration was higher in forested areas than pasture. Following this, further research showed pasture had the lowest evapotranspiration (i.e. highest yield), followed by native forest (1.6 times the flow from a pasture catchment), and pine forest (2.1 times the flow from a pasture catchment) (Dons, 1987). Thinning of pine forest reduced the evapotranspiration rates (i.e. increased the yield) (Whitehead & Kelliher, 1991), and harvesting reversed the trend with evapotranspiration from harvested pine catchments lower than from pasture for three years after harvest (Beets & Oliver, 2007). Beets and Oliver (2007) concluded that water yield averaged approximately 160–260 mm/year less from pine than pasture, and pine forest averaged around 100 mm/year less than from indigenous forest, their equivalent flow calculations to those of Dons (1987) being slightly less (1.2 and 1.5 times more flow than pasture for native and pine forest respectively) due to different hydrological assumptions.

In addition to the effect land use has on evapotranspiration, there are uncertainties surrounding plant physiological responses to increasing CO_2 concentrations (Frank et al., 2015) which result from climate change. Increasing CO_2 can change water use efficiency and therefore effect transpiration (Raczka et al., 2016, pp. 5188, equation 15).

3.5.3 Evaporation from a lake surface

Evaporation from lakes is difficult to measure (Lenters et al., 2011). It depends on relative humidity, water and air temperature, wind speed and air turbulence, and can be calculated using a thermal energy balance, mass-transfer methods or evaporation pan measurement (Spigel & Viner, 1992). Linacre (1977) proposed a simple formula to estimate lake evaporation from elevation, latitude and daily maximum and minimum temperatures. There are no published studies of evaporation from New Zealand lakes. Verburg (2021) has estimated annual lake evaporation from Lake Taupō to be 1167 mm y^{-1} using buoy data. Evaporation from a number of lakes in the Greater Lake Tarawera catchment have been calculated using the methods of the ELCOM (Estuary, Lake and Coastal Ocean Model) and DYRESM (DYnamic REServoir Simulation Model) (Hodges & Dallimore, 2011; Imerito, 2011). Evaporation from Lake Tarawera was estimated by White et al. (2016) to be 1.01 m^3 s^{-1} (756 mm y^{-1}) which was derived from 41% of rainfall falling on the lake. The rational of White et al. (2016) for using this percentage, was that this was the portion observed by Rutherford and Palliser (2014) from their evaporation calculations for Lake Rotorua (estimated to average 647 ± 98 mm y^{-1} using the methods of Jobson (1975) (as cited in Rutherford & Palliser, 2014)). Gillon (2009) estimated evaporation from Lake Tarawera to be 0.887 m^3 s^{-1} (680 mm y^{-1}) using meteorological data recorded at the Rotorua airport but do not specify the method used.

3.5.4 Surface water inflows and outflows

Surface water inflows and outflows are well studied and a number of methods have been developed to measure open channel flow (Winter, 1981) that are detailed in most hydrological text books (Davie & Quinn, 2019; Robinson & Ward, 2017; Waugh & Fenwick, 1979). The standardised methods for New Zealand are included in the National Environmental Monitoring Standard on open channel flow measurement (NEMS, 2013a). These can involve indirect measurements such as the conversion of measured water level (stage) to flow using a stage discharge relationship, or direct measurements such as gauging techniques (Waugh & Fenwick, 1979). Gauging techniques use the velocity-area method and involve the measurement of flow over the cross-sectional area of a stream. Weirs and flumes are commonly used, especially in experimental catchment studies e.g., the Puruki Experimental Catchment (Beets & Brownlie, 1987). Chemical tracers, ultrasonic and electromagnetic methods can also be used to measure stream discharge (Waugh & Fenwick, 1979).

3.5.5 Groundwater inflows and outflows

Groundwater is widespread and a significant component of the hydrological system of the Greater Tarawera Lakes (White et al., 2016). Natural sources of freshwater that become groundwater (i.e. recharge groundwater) include areal recharge from rainfall that percolates through the ground, and losses of water from streams, lakes and wetlands

(Alley et al., 1999). Groundwater travels along flow paths from recharge areas to discharge areas (e.g. a lake), the areal extent of which can vary and comprise of several groundwater flow systems at different scales (i.e., local, sub-regional and regional systems) which are in hydraulic connection with each other (Figure 3.2) (Alley et al., 1999).

Groundwater flow is very slow in comparison to stream flow and normally occurs as seepage through pore spaces (in unconsolidated rocks) or through fractures and solution openings (in consolidated rocks) (Alley et al., 1999). Groundwater flow in the rhyolites of the Greater Lake Tarawera catchment is likely to be fracture dominated with permeability variable and dependent on the size, amount and connectivity of fractures (Tschritter & White, 2014). Hydraulic conductivities estimated from aquifer tests in the Greater Lake Tarawera catchment are between 1 to 10 m day^{-1} in the carapace of a young rhyolite dome (Rose et al., 2012) and 200 to 3,100 m day^{-1} in a young pumiceous lava (Thorstad et al., 2011). These measured hydraulic conductivity values are in the upper range for fractured igneous rock and within the range of sand and gravel respectively (Freeze & Cherry, 1979, p. 29).

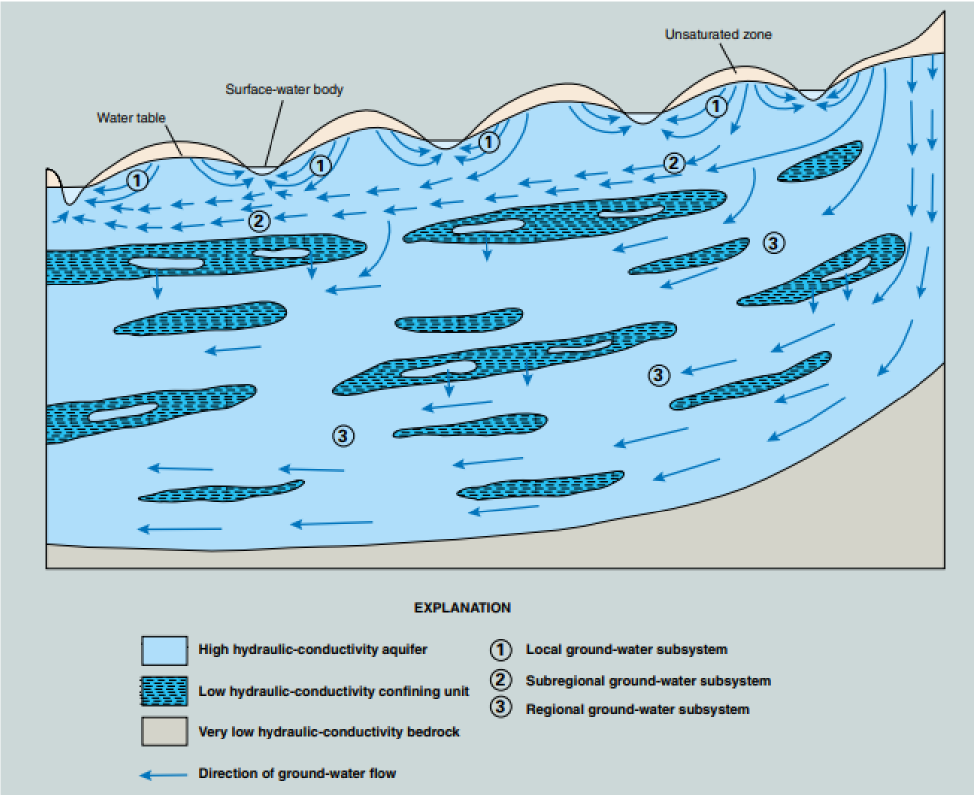

Figure 3.2 Conceptual illustration of a groundwater flow system that consists of local, subregional, and regional subsystems at different scales (Figure 6 from Alley et al., 1999, p. 9).

The most common way of estimating groundwater inflows and outflows in a water balance is the residual approach (Scanlon et al., 2002). In this approach, other components of the water balance are estimated or assumed negligible, and net groundwater flow is set to the residual. This yields only a net estimation of groundwater flow and results in all the uncertainties in other water balance components being included in the groundwater component. Direct measurements of groundwater recharge (i.e. infiltration) are not common but can be estimated using lysimeters (Healy et al., 2007).

Methods for assessing groundwater interaction with lakes are catchment-scale studies, lake-water balances, combined lake-water and chemical budgets, wells and flow net analysis, groundwater flow modelling, tracer studies, thermal methods, biological indicators and seepage meters (Rosenberry et al., 2015). In catchment-scale studies, a water balance residual approach is adopted whereby all rainfall to a lake's catchment is assumed to flow to the lake via surface water or groundwater (minus evaporation), and the groundwater outflow from the lake is assumed to be the residual of all other hydrological inputs and outputs (Rosenberry et al., 2015). Lake-water balances use a similar approach however, groundwater contributions to (G_i) and from (G_o) a lake are calculated as a net flow (Rosenberry et al., 2015). Combining lake-water and chemical balances for a lake enables the groundwater inflow and outflow components to a lake (G_i and G_o) to be calculated separately if conservative chemicals are used (i.e. those which are not altered by chemical reactions or biological processes as they travel through the catchment). A chemical budget for a lake works similar to a water balance – chemical masses are determined by multiplication of concentration by the volume of water (mass) of each of the water balance components (Rosenberry et al., 2015). Chloride and isotopes of oxygen and hydrogen are commonly used for such studies on lakes (Rosenberry et al., 2015). Flow net analysis is a field-based technique using measurements from wells to determine hydraulic gradients and hydraulic conductivities and by applying Darcy's law and assuming a cross sectional area of flow. The method is more suited to small areas as the density of a well network to determine groundwater flow at large scales would be cost prohibitive (Rosenberry et al., 2015). Groundwater flow models use computer software (e.g. MODFLOW) which solve the groundwater flow equation. Tracer studies involve the addition of a chemical to a stream/river/groundwater well/lake and subsequent monitoring of that chemical down-gradient to determine its flow path and velocity. Salt, fluorescent dye and lithium bromide are some tracers that have been used to determine the interaction of groundwater with lakes (Cole & Pace, 1998; Lee et al., 1980; Smart &

Smith, 1976). Thermal methods make use of the temperature differentials between groundwater and surface water to assess their interaction (Sebok et al., 2013). Biological indicators of lake water and groundwater interaction include the distributions and densities of specific plants and animals present in the lake (Frandsen et al., 2012; Meinzer, 1927; Sebestyen & Schneider, 2004). Seepage meters can provide a direct measurement of water flow across the lake bed, although only for a small area typically 0.25 m^2 (Rosenberry et al., 2015). This research uses a catchment-scale water balance approach (described above) to estimate groundwater inflows and outflows to each lake of the Greater Tarawera Lakes.

3.5.6 Storage changes

Water storage changes on the surface and subsurface can be estimated using repeated measurements over time (Healy et al., 2007). For example, the regular measurements of groundwater levels and lake levels can be used to assess volumetric storage changes. Typically surface storage of water is mainly in the form of snow[8], but precipitation falling directly onto surface water bodies (e.g. lakes) or intercepted by vegetation can also constitute surface storage (Healy et al., 2007). Except for glaciers and ice fields, surface storage of snow water is relatively short-lived. Sub-surface storage of water can include storage in the root zone, unsaturated zone and saturated zone. Sub-surface storage changes can be substantial in areas of groundwater extraction (e.g. for irrigation) and as a result of changes in climate (e.g. a drought) (Healy et al., 2007).

3.6 Nutrient processes and budgets of lakes

Nutrient budgets of lakes account for contributions of nutrients from a variety of sources and transport pathways. Transport pathways include overland flow, stream flow, groundwater flow and direct discharge (e.g. industrial discharges directly to the lake). Sources may include point source and non-point source inputs, in addition to direct inputs (e.g. atmospheric and geothermal). Export coefficient modelling is a recognised method for estimating nutrient loads to lakes, whereby the total nutrient load to a lake is calculated by multiplying nutrient loss rates from land uses (e.g. losses estimated by Overseer®) by the area of the lakes catchment in each land use, and applying an attenuation factor (McBride et al., 2020).

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[8] This doesn't apply to the Tarawera Lakes as snowfall is rare

Overseer® is the main software used to estimate on farm nutrient budgets in New Zealand despite recent reviews concluding its unreliability in predicting nutrient loss estimates (Science Advisory Panel, 2021). Overseer® outputs losses from the farm edge and root zone (the source) and does not consider attenuation (i.e. retention) from the farm source to the receiving environment. Processes such as sedimentation, plant uptake, and denitrification can remove nutrients prior to them entering a receiving environment and are commonly grouped together and adjusted for using a catchment attenuation factor to describe retention (Freeman et al., 2016). Catchment attenuation factors are typically in the order of 50%, (Freeman et al., 2016). Catchment attenuation factors also need to account for any lag times in the calculated loads reaching their receiving environment in addition to nutrient retention (Freeman et al., 2016).

In addition to retention of nutrients during their transport from a source to a receiving lake environment, further retention occurs within the receiving lake. Phosphorus retention usually occurs via sedimentation of particulate bound P and uptake of dissolved P by plants, whereas nitrogen retention occurs largely by de-nitrification, and to a lesser degree the incorporation in sedimenting organic matter (Søndergaard, 2007).

The relationship between land use and water quality was first characterised by Vollenweider (1976) who predicted annual mean lake TP concentrations using catchment phosphorus loads, mean depth and hydraulic retention times:

$$TP_{lake} = \frac{L}{z\,(\rho + \sigma)} \tag{3-3}$$

Where TP_{lake} = TP concentration in the lake (mg m^{-3}), L = areal TP loading rate (mg TP m^{-2} y^{-1}), z = mean lake depth (m), ρ = lake flushing rate (per year), σ = coefficient for TP loss from lake (per year, unitless). Sedimentation of P is generally the dominant in-lake process affecting the TP concentration of a lake (i.e. the σ value in equation 3-3), and P in lake sediments can be re-released if eutrophication leads to anoxic conditions (Brett & Benjamin, 2008). It follows from Vollenweider's model (equation 3-3), that lakes with large residence times have higher attenuation rates.

Techniques for assessing nutrient budgets of lakes in the Greater Lake Tarawera catchment have included nutrient export coefficient modelling (McBride et al., 2020; McIntosh, 2012a, 2012b, 2012c), lake modelling (Abell et al., 2020), groundwater modelling (Gillon et al., 2009; White et al., 2016), and a combination of nutrient export coefficient modelling and direct nutrient measurements from streams (Hamilton et al., 2006; White & Cooper, 1991).

Chapter 4
Methods

4.1 Water provenance

To determine provenance of groundwater and surface water in and around the Greater Lake Tarawera catchment, water samples were collected from 11 groundwater bores and five locations along the Tarawera River for isotopic analysis (Figure 4.1 and Table 4.1). Groundwater samples were collected to assess the source of groundwater recharge, and Tarawera River samples were collected to assess the proportional contributions of groundwater and lake water to flow in the Tarawera River. In addition to water samples collected as part of this research, data on the isotopic composition of 15 surface water inflows to Lake Tarawera, and 4 surface water inflows to Lake Rotorua held by the University of Waikato (UoW) was used in the interpretation of water provenance. Lake Tarawera inflows included three lake-sourced streams, Rotomahana Siphon, Te Wairoa Stream, and Waitangi Stream; and 12 spring-fed inflows, Hot Water Beach (HW1 and HW2), Island Waterfall, Middle flax A, Ramp 4 jetty spring, Rotomahana Spring, Rotomahana Waterfall, Spencer Road Ford Stream, Te Whekau Stream, Twin Creeks, Wairua Arm WA1, and Wairua Stream. Lake Rotorua inflows include Puarenga Stream, Utuhina Stream, Waingaehe Stream, and Waiohewa Stream. The location of inflows is shown on Figure 2.10.

Groundwater samples were obtained by BOPRC in conjunction with their regular monitoring programme and collected quarterly from August 2020 where possible[9]. Surface water samples were collected by the author. All samples were analysed for stable isotopes of water, hydrogen δ^2H-H_2O and oxygen δ^{18}O-H_2O at the UoW laboratory. The isotopic compositions of water samples were measured with a Los Gatos Research (LGR) TIWA laser spectrometer from 2 mL vials. The isotope ratios are reported in per mil (‰) relative to VSMOW-SLAP for two internal working standards (AURORA2: δ^2H = +1.63‰, δ^{18}O = -0.8‰ and ANT01: δ^2H = +1.63‰, δ^{18}O = -0.8‰) that have been previously calibrated using VSMOW2 (δ^{18}O = 0‰ and δ^2H = 0‰) and GRESP (δ^2H = -

[9] The well at the Tarawera outlet was damaged by an earthquake during the course of this research so only one sample was able to be obtained for analysis. BOPRC's sampling programme of the Tarawera catchment wells began in August 2020, and there were some delays to arrange access to some of the wells.

257.8‰, $\delta^{18}O$ = -33.39‰) international reference standards. Another laboratory standard, WAIKATO DISTILLED (δ^2H = -54.26‰, $\delta^{18}O$ = -9.15‰) was used as reference material for quality control. To minimise memory effects, isotopic values were determined by averaging isotopic values from the last four out of seven injections. A detailed description of the analysis technique is given by Wassenaar et al. (2008). The analytical uncertainty for results based on an IAEA Water Stable Isotope Intercomparison (Wassenaar et al., 2021) test was ~0.2‰, ~0.09‰ and ~0.76‰ for δ^2H, $\delta^{18}O$, and deuterium excess (d-excess), respectively.

Stable isotopes of water, δ^2H and $\delta^{18}O$ were used to determine the proportional contributions of lake water and rainwater in samples taken from the Tarawera River using a two end-member mixing model. The mixing model used is based on that described in Phillips et al. (2005), and uses two isotopic signatures (δ^2H and $\delta^{18}O$) to partition the contribution of two sources (*a* and *b*) to a mixture (*m*):

$$\begin{aligned} \delta^2 H_m &= f_a \delta^2 H_a + f_b \delta^2 H_b \\ \delta^{18} O_m &= f_a \delta^{18} O_a + f_b \delta^{18} O_b \\ 1 &= f_a + f_b \end{aligned} \tag{4-1}$$

Which can be simplified to:

$$\begin{aligned} \delta^2 H_m &= f_a \delta^2 H_a + (1 - f_a) \delta^2 H_b \\ \delta^{18} O_m &= f_a \delta^{18} O_a + (1 - f_a) \delta^{18} O_b \end{aligned} \tag{4-2}$$

Isotopic interpretation of the groundwaters was used to determine their recharge source using the methods and tools of Phillips and Greg (2003), which consider all feasible solutions to the linear mixing models and can account for multiple sources. The IsoSource tool was used to determine the bounds of the contribution of each source. The tool examines all possible combinations of each source contribution (0-100%) to the mixture. Combinations that sum to the observed mixture isotopic composition within a user defined small tolerance (±0.1% was used in this research) are considered feasible solutions. The IsoSource tool is available for download from the United States Environmental Protection Agency[10].

[10] https://www.epa.gov/eco-research/stable-isotope-mixing-models-estimating-source-proportions

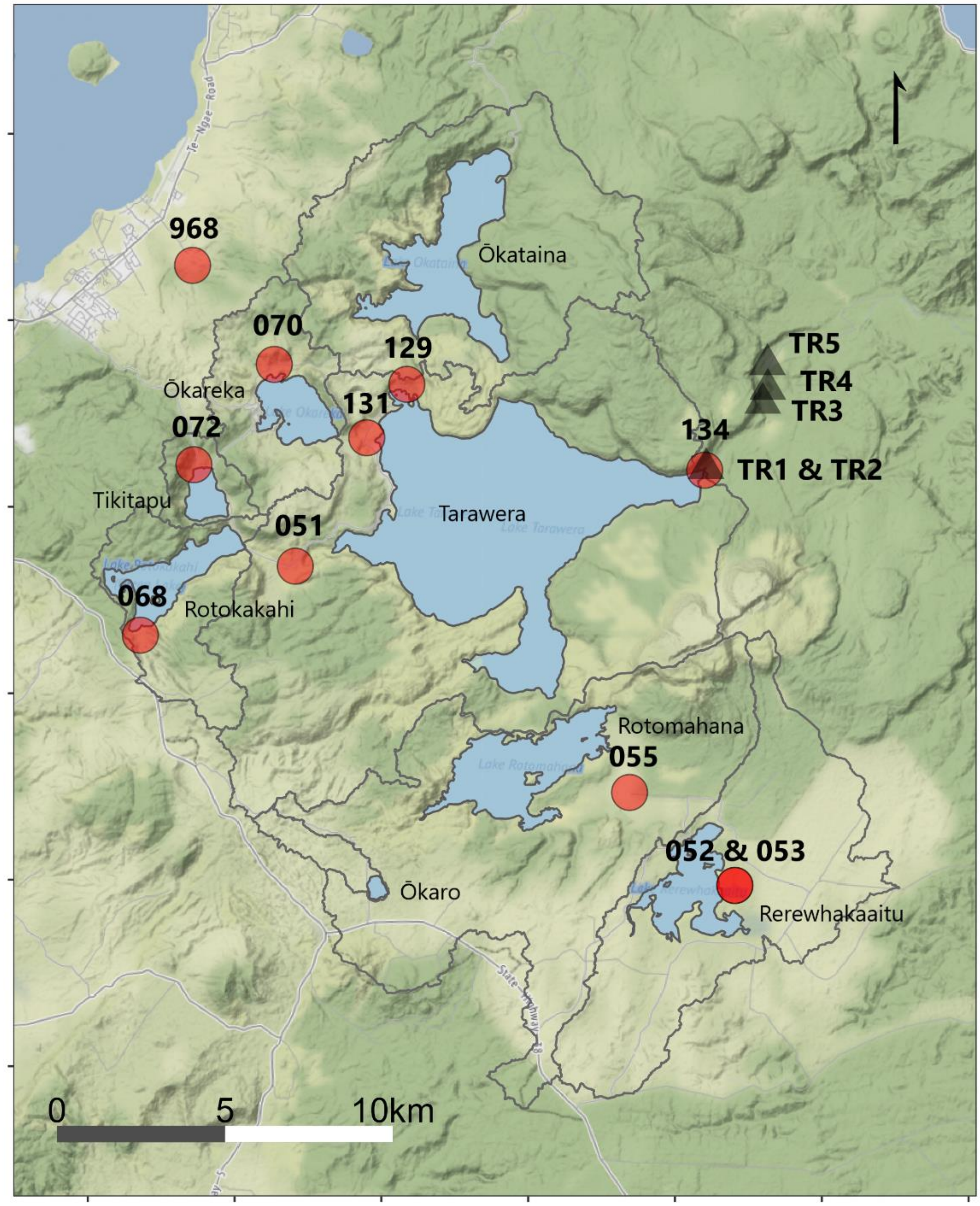


Figure 4.1 Location of water samples collected for isotopic analysis. Groundwater samples are shown by red dots, surface water samples collected from the Tarawera River are shown by black triangles. Local catchments of the lakes are given by grey outlines.

Table 4.1 Sampling sites/depths of water samples collected for isotope analysis

Site	Local catchment	Location	Type	Screen depth (m bgl)	Borehead elevation (m asl)	No. Samples collected
072	Lake Tikitapu	Tikitapu Reserve	Groundwater	37-40	429	4
051	Lake Tarawera	Buried Village	Groundwater	24-30	384	4
070	Lake Ōkareka	Millar Road	Groundwater	22 - 25	358	4
129	Lake Tarawera	Spencer Road - northern end	Groundwater	19-39	316	3
131	Lake Tarawera	Spencer Road - west of lake	Groundwater	40-60	321	4
068	Lake Rotokakahi	Highlands Loop Road	Groundwater	42 - 45	404	4
055	Lake Rotomahana	Ash Pit Road, western end	Groundwater	41 - 50	358	4
053	Lake Rerewhakaaitu	Ash Pit Road, east of Rerewhakaaitu	Groundwater	16 - 19	443	4
052	Lake Rerewhakaaitu	Ash Pit Road, east of Rerewhakaaitu	Groundwater	91 - 100	443	4
134	Lake Tarawera	Outlet camping ground	Groundwater	79-89	298	1
968	Lake Rotorua	Gee Road	Groundwater	unknown	332	3
TR1	Tarawera River	Tarawera River	Surface water	-	-	1
TR2	Tarawera River	Tarawera River	Surface water	-	-	1
TR3	Tarawera River	Tarawera River	Surface water	-	-	1
TR4	Tarawera River	Tarawera River	Surface water	-	-	1
TR5	Tarawera River	Tarawera River	Surface water	-	-	1

4.2 Water balance

Annual water balances and nutrient load estimates for the water years[11] 1972 to 2018 were calculated using various combinations of datasets and calculation methods. Calculations based on these combinations were automated using the R statistical computing language and uncertainties and variabilities are presented as range estimates with underlying distributions. A web-based tool [12] that performs water balance calculations and nutrient load estimates was developed using Shiny R technology.

4.2.1 Model setup

To calculate inflows and outflows for each catchment, a grid-based approach was used. A 500 m by 500 m grid was placed over the study area (Figure 4.2). The centroid of each of these grid cells was assigned an identification number (herein referred to as the grid_ID) and the co-ordinates were calculated. Variables for each grid_ID (e.g., annual rainfall, evaporation etc.) could then be spatially queried and summed over each catchment to

[11] The New Zealand water year runs from 1 July to 30 June
[12] The web tool is available for viewing at https://nickiwilson.shinyapps.io/TaraweraMsc/

calculate total values. It should be noted that this method results in areas of lakes and catchments slightly different to their actual areas (e.g., the actual area of Lake Ōkaro is 0.30 km^2, but because only one grid cell of the model represents the lake, the modelled lake area is 0.25 km^2). Different datasets and methods used for the calculations are described in the following sections.

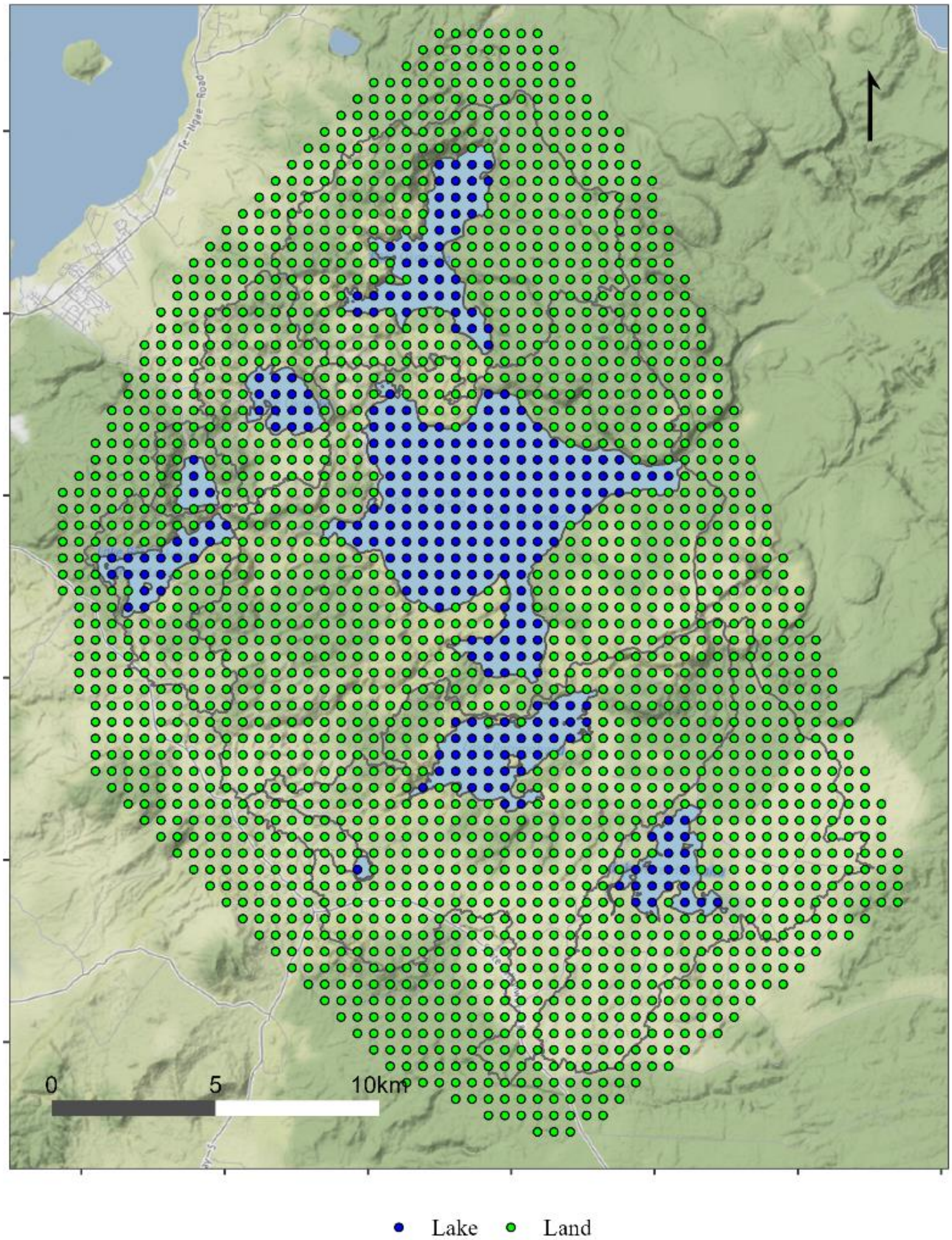


Figure 4.2 Centroid locations of the model grid used for the water balance and nutrient load calculations. The colours represent whether the grid cell was assigned to land or water (for the purpose of land use definition and evaporation calculations).

4.2.2 Catchment boundaries

Three variations of local catchment boundaries have been used in the calculations of water balances and nutrient loads for the Greater Tarawera Lakes and their catchments:

1. Surface water local catchment boundaries determined by BOPRC using Light Detection and Ranging data (LIDAR);
2. Surface water local catchment boundaries as determined by White et al. (2020); and
3. Groundwater local catchment boundaries as determined by White et al. (2020).

Revisions of surface water local catchment boundaries and the definition of groundwater local catchment boundaries for the Greater Tarawera Lakes were undertaken by White et al. (2020) and represent the most up to date and (likely) accurate boundaries. The BOPRC LIDAR local catchment boundaries are the same boundaries that have been used by McBride et al. (2020) in the calculation of N and P catchment loads to the Rotorua Te Arawa Lakes. Although BOPRC LIDAR boundaries may not be the most up to date local catchment boundaries, they have been included in this study because they have been used in recent investigations and current policy (i.e., Bay of Plenty Regional Council, 2017; McBride et al., 2016). Local catchment boundaries are shown in Figure 4.3 and detailed in Table 4.2.

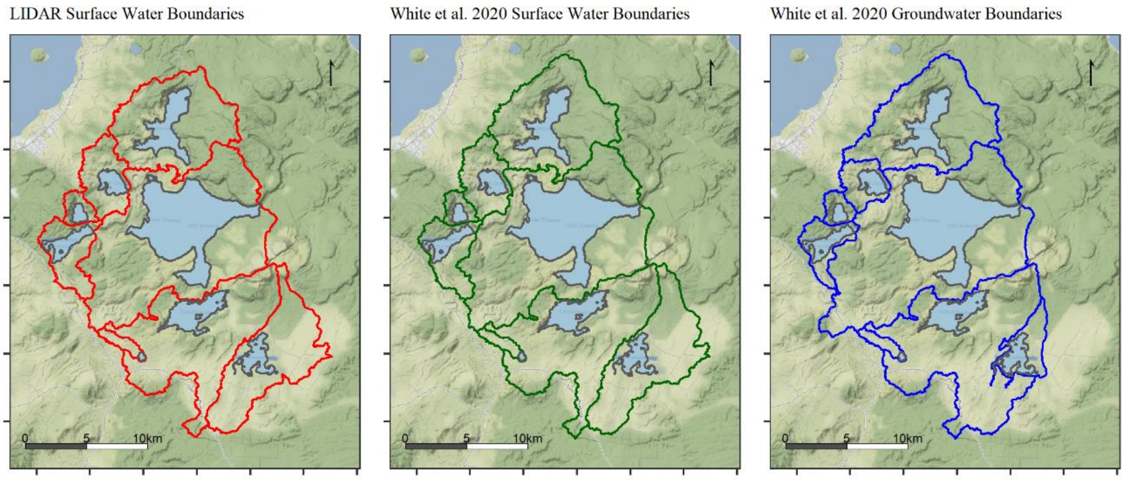


Figure 4.3 The three variations of Greater Tarawera Lakes local catchment boundaries used in water balance and nutrient load calculations.

Table 4.2 Areas for three variations of the Greater Tarawera Lakes local catchment boundaries used in water balance and nutrient load calculations. Areas are in km^2. Note with the exception of Lakes Rotokakahi, Rotomahana and Tarawera, each lakes local catchment is equivalent to its entire catchment.

Local catchment (unless specified)	Surface water (LIDAR)	Surface water (White et al., 2020)	Groundwater (White et al., 2020)
Ōkareka	19.78	19.96	12.49
Ōkaro	3.68	3.68	3.68
Ōkataina	62.92	66.90	70.92
Rerewhakaaitu	52.94	54.58	15.18
Rotokakahi	19.20	19.21	13.49
Rotokakahi (entire catchment)	164.46	164.10	172.78
Rotomahana	83.70	83.72	101.63
Rotomahana (entire catchment)	106.57	141.98	120.49
Tarawera	145.26	144.90	159.29
Tarawera (entire catchment)	393.21	398.64	382.28
Tikitapu	5.73	5.69	5.60
Total	393.21	398.64	382.28

4.2.3 Land use

Land use information is used in the calculations for evaporation from land (Section 4.2.6) and for the calculations of nutrient loads (Section 4.3). Spatial land use data were obtained from the New Zealand Land Cover Database (LCDB) version 5.0 (Landcare Research New Zealand Ltd, 2020a). The LCDB provides land cover information at five time steps: summer 1996/97, summer 2001/02, summer 2008/09, summer 2012/13 and summer 2018/19. Land cover classes for the LCDB were determined by Landcare Research using satellite imagery and have been refined over time with each release of the LCDB. The LCDB version 5 identifies 33 mainland land cover classes. For the purposes of calculating a water balance, these were simplified into four classes – pasture, native forest, exotic forest, and water. Harvested areas of forest were included in the pasture category for the calculation of the water balance as research has shown that water yield from these areas is more typical of pasture than forest (Whitehead & Kelliher, 1991). Land uses were assumed constant between time steps, and land uses for the period 1972-1996 were assumed the same as they were in 1996, a reasonable approximation given the majority of the farming development occurred in the 1960s (Bay of Plenty Regional Council, 2015). Details of the classification are included in Table A1 (Appendix A).

Land use data were downloaded from the LRIS portal under Creative Commons Attribution 4.0 International license then imported into R. The dataset was queried spatially and land use information extracted for each grid_ID. Simplification into four classes was automated, and data were manipulated into a dataframe containing annual land uses for each grid_ID.

4.2.4 Rainfall

There are no current long-term rainfall measurement sites located within the study area available on New Zealand's National Climate Database (NIWA, 2021b). The nearest long-term climate station is Rotorua Aero AWS located approximately 10 km to the northeast of Lake Tarawera (Figure 4.4). From time to time, there have been short term rainfall measurement sites in operation within the study area, with measurements usually ceasing by 2000 (Figure 4.4). BOPRC have two current rainfall measurement sites located in or close to the study area; Ōkaro and Rerewhakaaitu, with records starting in 2007 and 2019 respectively (Figure 4.4).

In absence of any long-term rainfall measurement sites in the study area, interpolated daily rainfall datasets (virtual climate data/stations (VCS)) have been obtained from New Zealand's National Institute of Water and Atmospheric Research (NIWA) (Figure 4.4).

Five variations of NIWA's VCS data have been used for calculations:

- VCS augmented rainfall data – 5 km and 500 m resolution
- VCS biased corrected data – 5 km resolution
- VCS operational data - – 5 km and 500 m resolution

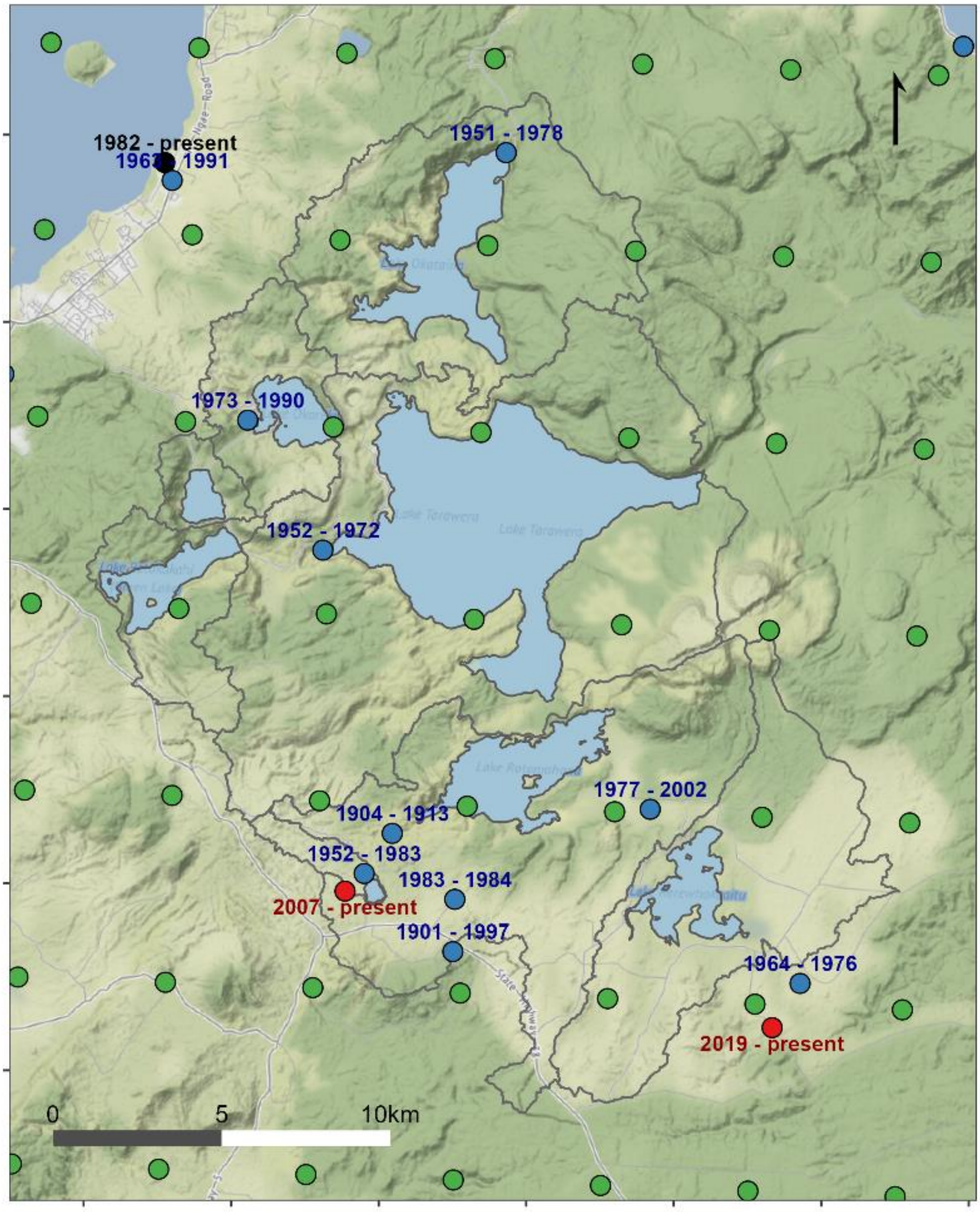


Figure 4.4 Location of Rotorua Aero AWS climate station, rainfall measurement sites recorded on New Zealand's National Climate Database (Cliflo), Bay of Plenty Regional Council (BOPRC) rainfall measurement sites, and virtual climate stations (VCS operational dataset 5km resolution) in and around the study area. The record length is shown for Rotorua Aero AWS, Cliflo, and BOPRC sites. VCS data is available from 1972. Local lake catchment boundaries are shown by the grey outline.

All datasets have been supplied by NIWA and were created as part of the Strategic Science Investment Fund Regional Hydrological modelling and New Zealand Water Model projects (NIWA, 2021a). Datasets were supplied as daily rainfall in NetCDF files and spanned the period 01/01/1972 to 01/07/2019. The three different rainfall datasets (augmented, biased corrected, and operational) were derived using the same methodology in their generation and differ only by the density of observations (C. Zammit, personal communication, May 3, 2021). The operational dataset (aka. NIWA's Virtual Climate Station Network) has roughly 500 rainfall measurement sites across New Zealand which are used to extrapolate rainfall data on a 5 km grid across the entire country. Locations of the operational virtual climate sites within the study area are shown on Figure 4.4. The biased corrected and augmented datasets include an additional 400 and 1,000 rainfall measurement sites respectively from regional council data (C. Zammit, personal communication, May 3, 2021). The bias corrected dataset is based on the operational dataset and has been bias-corrected according to the methods described in Tait et al. (2012) (C. Zammit, personal communication, May 3, 2021).

To calculate the rainfall in each catchment, the NetCDF file for each rainfall dataset was opened in R, data were read from the rain variable and stored in a 3-dimensional array (over space and time). The array was converted to a raster brick, and slices were taken from the raster brick containing each of the days within a water year. The daily values within each slice were summed to produce a raster representing the annual rainfall for that water year. This process was looped through for each water year from 1972 to 2018. Once annual rasters had been created for each water year, they were combined in a raster stack. The annual rainfall values from the raster stack were then extracted for each grid_ID and saved as dataframes in R.

4.2.5 Evaporation from the lake surface

Daily evaporation rates from each lake were calculated using the methodologies adopted in the models ELCOM (Estuary, Lake and Coastal Ocean Model) and DYRESM (DYnamic REServoir Simulation Model). ELCOM and DYRESEM are both hydrodynamic models for lakes and reservoirs developed by the Centre for Water Research, University of Western Australia (Hodges & Dallimore, 2011; Imerito, 2011). These methods were used to calculate lake evaporation from Lake Tarawera for a water balance by Abell et al. (2020). The underlying equations are based on Fischer et al. (1979) (citied in Hodges & Dallimore, 2011):

$$Q_{th} = min\left(0, \frac{0.622}{P} C_L \rho_a L_E U_a \left(e_a - e_s(T_{surf})\right) \Delta t\right) \quad (4\text{-}3)$$

Where Q_{th}= evaporative heat flux (i.e. evaporation) (l s^{-1}), P = atmospheric pressure (Pa), C_L = latent heat transfer coefficient for wind speed (0.0013, unitless), ρ_a = density of air (kg m^{-3}), L_E = latent heat of vaporisation of water (2,453,000 J kg^{-1}), U = measured wind speed (m s^{-1}), e_a = vapour pressure of the air (Pa), e_s = saturation vapour pressure of the air (Pa), T_{surf} = surface water temperature of the lake (°C), Δt = a given period of time. The selection of the minimum of zero and the computed part of the equation is set because the model does not consider condensation effects.

e_s was calculated by the Magus-Tetens formula as per Hodges and Dallimore (2011):

$$e_s(T_{surf}) = 100\ e^{\left[2.3026\left(\frac{7.5T_{surf}}{T_{surf}+237.3}\right)+0.758\right]} \tag{4-4}$$

The change in mass due to latent heat flux (i.e. the evaporation from the lake) was calculated as:

$$\Delta M^{th} = \frac{-Q_{th}A}{L_E} \tag{4-5}$$

Where ΔM^{th} = change in mass (kg), A = area of the lake (m^2).

Climate data from NIWA's operational VCS, and lake temperature profile data and lake level data (used to calculate lake area) provided by BOPRC were used in the calculations. Evaporation was calculated daily for each of the Greater Tarawera Lakes (using equations 4-3 to 4-5 above), and daily values were summed to calculate the annual evaporation over a given water year.

For each lake, daily meteorological data from the closest VCS site were used in the calculations (Table 4.3). On days that had no wind speed recorded in the VCS data, the average windspeed from all the data was used. Mean air temperature on a given day was assumed to be the mean of the maximum and minimum air temperatures.

Daily lake surface areas were calculated from daily lake level data using a hypsographic relationship for each lake[13]. The average lake level was used in the calculations on days where there was no level data available.

[13] Provided to the University of Waikato by BOPRC

Lake surface water temperatures were predicted on days they were missing using local polynomial regression fitting with smoothed air temperature as a numerical predictor. There was no lake temperature profile data available for Lake Rotokakahi, so the temperatures from Lake Tikitapu were used instead. This was considered a reasonable assumption given the proximity, similar size and similar elevation of the two lakes.

Table 4.3 Virtual Climate Station Network (VCS) sites used for lake evaporation calculations

Lake	VCSN site(s)
Ōkareka	27896
Ōkaro	31041
Ōkataina	31054
Rerewhakaaitu	28424
Rotokakahi	28942
Rotomahana	31053
Tarawera	27368 and 28957
Tikitapu	28404

4.2.6 Evaporation from land

Evaporation from the land surface (E) within the Greater Lake Tarawera catchments has been estimated using potential evapotranspiration (PET) data from the VCS with modifications made to adjust for soil water stress as described in the FAO56 guidelines (Allen et al., 1998). A correction has been applied to the annual evaporation from forested land uses based on the conclusions of Beets and Oliver (2007).

4.2.6.1 Calculation of evaporation for pasture

Two alternatives for land evaporation have been used for the calculations:

1. E assuming standard conditions (i.e. non-limiting soil moisture conditions)
2. E correcting for soil water stress

The FAO56 method uses a crop factor applied to reference crop E to estimate the actual E for a particular crop (under standard conditions):

$$E_C = K_C E_O \tag{4-6}$$

Where E_c = crop evaporation (mm day^{-1}), K_c = crop factor (dimensionless), and E_0 = reference crop evaporation (mm day^{-1}). The FAO56 method describes the reference crop as "a hypothetical grass reference crop with specific characteristics" [14] and details methods for calculating E_0 using the Penman-Monteith equation (Allen et al., 1998). New Zealand pasture commonly fits the description given in the FAO56 of a reference crop (Scotter & Heng, 2003). For the purposes of this study, daily potential evapotranspiration (PET) data were provided by NIWA from the VCS. PET values of the VSCN have been estimated by spatially interpolating records of PET from climate stations (primarily calculated using the original Penman formulas) (Burman and Pochop 1994, p. 81 as citied in Tait & Woods, 2007). Average annual E_0 calculated at the Rotorua airport using the FAO56 method by Scotter and Heng (2003) is 918 mm y^{-1}. In comparison, average annual Penman PET calculated by NIWA (and used for deriving the VCS) at the Rotorua Aero Aws site is 889 mm y^{-1}. Irrigation New Zealand (2015) recommend a default crop factor of 0.9 for pasture (based on the Tasman Regional Water Study, 2003), which if applied with equation 4-6 to the average annual E_0 value calculated by Scott and Heng (2003), results in an E_C of 826 mm y^{-1}. Based on the VCS PET value lying between the values of average annual E_0 and E_C presented above, it is assumed that the PET values of the VCS are an adequate representation for E_0. In this research, the crop factor (K_c) has been varied between 0.95 and 1.05 (Section 4.4) as this is roughly where the actual value may lie. Evaporation for pasture under standard conditions was calculated annually for each catchment using equation 4-6 and the assumptions described above.

Equation 4.6 can be adjusted for non-standard conditions brought about by differing management or environmental conditions (Allen et al., 1998). Of the conditions described in Allen et al. (1998), soil water stress is relevant in the Greater Tarawera Lakes catchments. A water stress coefficient, K_S can be applied to equation 4-6 to describe the effect of water stress on a crop:

$$E_{C\,adj} = K_S K_C E_O \tag{4-7}$$

[14] A "short green crop, completely shading the ground, of uniform height, and never short of water"

If a crop is under soil water stress, K_S < 1. When there is no soil water stress, K_S = 1. It should be noted that equation 4-7 gives a reasonable estimation of evaporation when evaporation from the soil is not a large component of E_c (Allen et al., 1998). Most soils in the Tarawera catchment are well drained and have good vegetation cover (thus evaporation from soil is not a large component of E), and equation 4-7 is appropriate in this area. K_S can be determined by:

$$K_S = \frac{TAW - D_r}{TAW - RAW} = \frac{TAW - D_r}{(1 - \rho)} \tag{4-8}$$

(if $D_r > RAW$, when $D_r < RAW$, then $K_S = 1$)

Where TAW = total available soil water in the root zone (mm), RAW = readily available soil water in the root zone (mm), D_r = daily root zone depletion (mm), ρ = the fractional value of TAW that can be extracted before moisture stress occurs (unitless). D_r is calculated by a daily water balance as per Pronger et al. (2016):

$$D_{r,i} = D_{r(i-1)} - P_i + E_{0,i} \tag{4-9}$$

$$0 \leq D_{r,i} \leq TAW$$

Where $D_{r,i}$ = root zone depletion at the end of day i (mm), $D_{r,i-1}$ = water content in the root zone at the end of the previous day (i-1) (mm), P_i = precipitation on day i (mm), $E_{0,i}$ = evaporation on day i (mm). To initiate the water balance at day zero, a period of heavy rain was chosen to begin, therefore it could be assumed that $D_{r,i-1} \approx 0$ (Allen et al., 1998). This coincided with the start of calendar year 1972 when approximately 80 mm of rainfall fell across the catchment over four days. D_r was set back to zero at the end of each water year to prevent any errors accumulating.

To calculate E for pasture under conditions of soil water stress, the methods and assumptions described above in equations 4-7 to 4-9 have been applied daily then averaged to provide annual values.

4.2.6.2 Calculation of evaporation for native and exotic forest

Beets and Oliver (2007) undertook studies on water yield and land use in the Purukohukohu Experimental Basin, located in the Kaingaroa Forest, and neighbouring the Tarawera Lake catchments to the south (see further discussion in Chapter 3). They concluded that annual water yields from pine forest and native forest were approximately

160-260 mm/year and 60-160 mm/year less respectively than from pasture (i.e., evaporation was between 60-260 mm/year higher in forest than in pasture).

There are no published crop factors for New Zealand forests, and the concept that evaporation is higher in forested areas than pasture is well established in the literature (Beets & Oliver, 2007; Davie & Fahey, 2005; Dons, 1986, 1987). This is largely due to interception loss, and in dry conditions transpiration from forest is likely higher than pasture due to deeper rooting systems if there is water available deep in the soil (Davie & Fahey, 2005). In addition, measured transpiration rates between pasture and pine forest are roughly similar when water supply is unlimited (Davie & Fahey, 2005). For these reasons, E in native and exotic forests was estimated by calculating E as though it were in pasture (as per the methods described above in Section 4.2.6.1), then adding an additional 60-160 mm/year or 160-260 mm/year (giving upper and lower estimates) for areas of native forest or exotic forest respectively based on the conclusions of Beets and Oliver (2007) described in the preceding paragraph.

PET data were provided by NIWA as daily values in a NetCDF file. Data were extracted from the NetCDF file and saved as annual values at each grid_ID as a dataframe (using the same methodology as for rainfall and described in Section 4.2.4). To save processing time, one set of daily K_S values were calculated for each of the eight lake catchments. Daily K_S values were calculated using the daily rainfall and PET data from a representative point in each catchment using the average of TAW and RAW values from within that catchment. TAW and RAW values were obtained from the Fundamental Soils Layer (Landcare Research New Zealand Ltd, 2020a) available on the Land Resource Information System (LRIS) Portal under the Landcare Data Use Licence. Daily K_S values were calculated (using equations 4-8 and 4-9), then were averaged over each water year. Annual K_S values were then applied to the annual PET dataset to obtain a PET_{adj} dataset. E_c and $E_{c\ adj}$ were calculated using the respective PET datasets and equations 4-6 and 4-7 respectively.

4.2.7 Drainage

Annual drainage has been calculated by subtracting annual land evaporation from the annual rainfall (from land only). Annual land evaporation is calculated considering daily water stress and daily soil moisture (Sections 4.2.6.1 and 4.2.6.2) thus accounts for the seasonality of drainage.

4.2.8 Surface water inflows and outflows

Stream gauging data and continuous flow records have been provided by BOPRC and obtained from the University of Waikato's sampling programmes where available. Daily flows from the Tarawera River at the outlet were downloaded from NIWA's Hydro Web Portal (site 15341) under the Creative Commons Attribution 4.0 International license. More inflow sites, typically with longer records and at higher frequencies were available for Lake Tarawera inflows and outflows than there were for other lakes in the Greater Tarawera Lakes complex.

For the inflows and outflows to and from Lake Tarawera, daily surface water flows from continuous flow recorders (where available) have been averaged to calculate average annual flows. This is the case for the Tarawera River and the Waitangi Stream (from 2017 onwards). For sites without automatic flow recorders, if there were enough gauging data available, and there was a correlation between the gauging measurements and the flow at the Tarawera River at the outlet, daily surface water flows were modelled using the same methods as Abell et al. (2020) (described below). If there were not enough gauging data available, or there was no correlation with the Tarawera River at the outlet, then a constant value (the mean of all gaugings) was applied for the flow into Lake Tarawera. The Rotomahana siphon[15] was modelled to flow only when the level in Lake Rotomahana was greater than 340.43 m (this is the invert level reported by Riley Consultants (2003)). Flow through the siphon was limited to 0.72 m^3 s^{-1} based information from BOPRC. For streams in other lake catchments, constant values were applied for inflows/outflows based on the water balances presented in Tables 4.5 and 4.6 of White et al. (2016). Details of the methods used to estimate inflows/outflows are included in Table A2 (Appendix A).

The code used to produce the time series of annual flow for inflows to Lake Tarawera by Abell et al. (2020) was provided by Chris McBride (University of Waikato). This code was re-run using the latest flow measurements and calculations extended back to 1972. Abell et al. (2020) assessed the relationship between Lake Tarawera tributary stream

[15] The Rotomahana Siphon is an engineered overflow from Lake Rotomahana to Lake Tarawera which flows only when levels in Lake Rotomahana are high

gaugings and their paired measurements from Tarawera River at the outlet. They determined six of these pairings to have positive correlations (shown by the red plots in Figure 4.5) and created a synthesised time series based on their correlations. A synthesised time series of flows was created for these six streams for water years 1972 to 2018 (Ramp 4 jetty stream, Te Wairoa Stream, Twin Creeks Main, Twin Creeks Smaller, Wairua Stream and Waitangi Stream) (Figure 4.6). For those inflows to Lake Tarawera without a synthesised discharge record, inflows were set to their average flows (excluding the Rotomahana Siphon as discussed above).

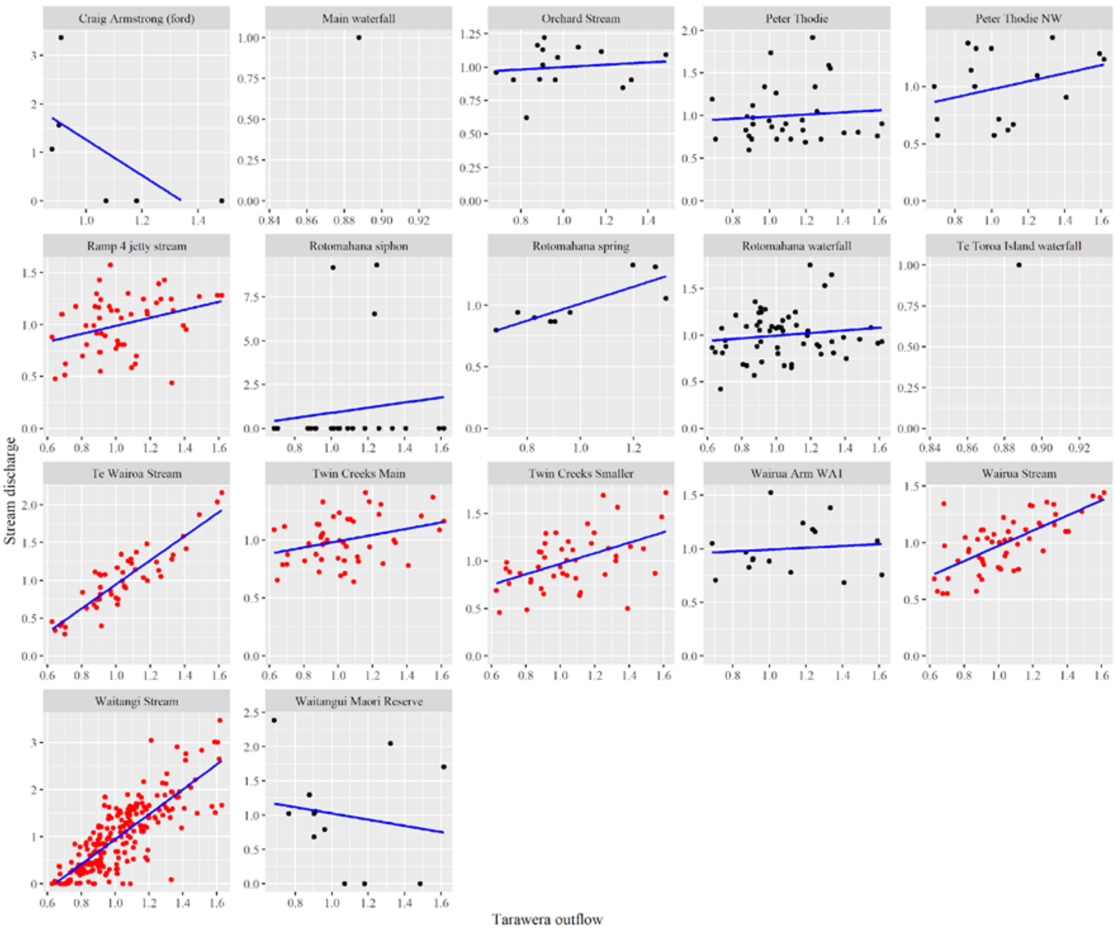


Figure 4.5 Relationships between Tarawera River outflow and significant tributary stream inflows to Lake Tarawera (updated from Abell at al. (2020) with latest flow data). Values are standardised by dividing measurements by the mean values for each stream (so axes are unitless). Red plots denote positive correlations.

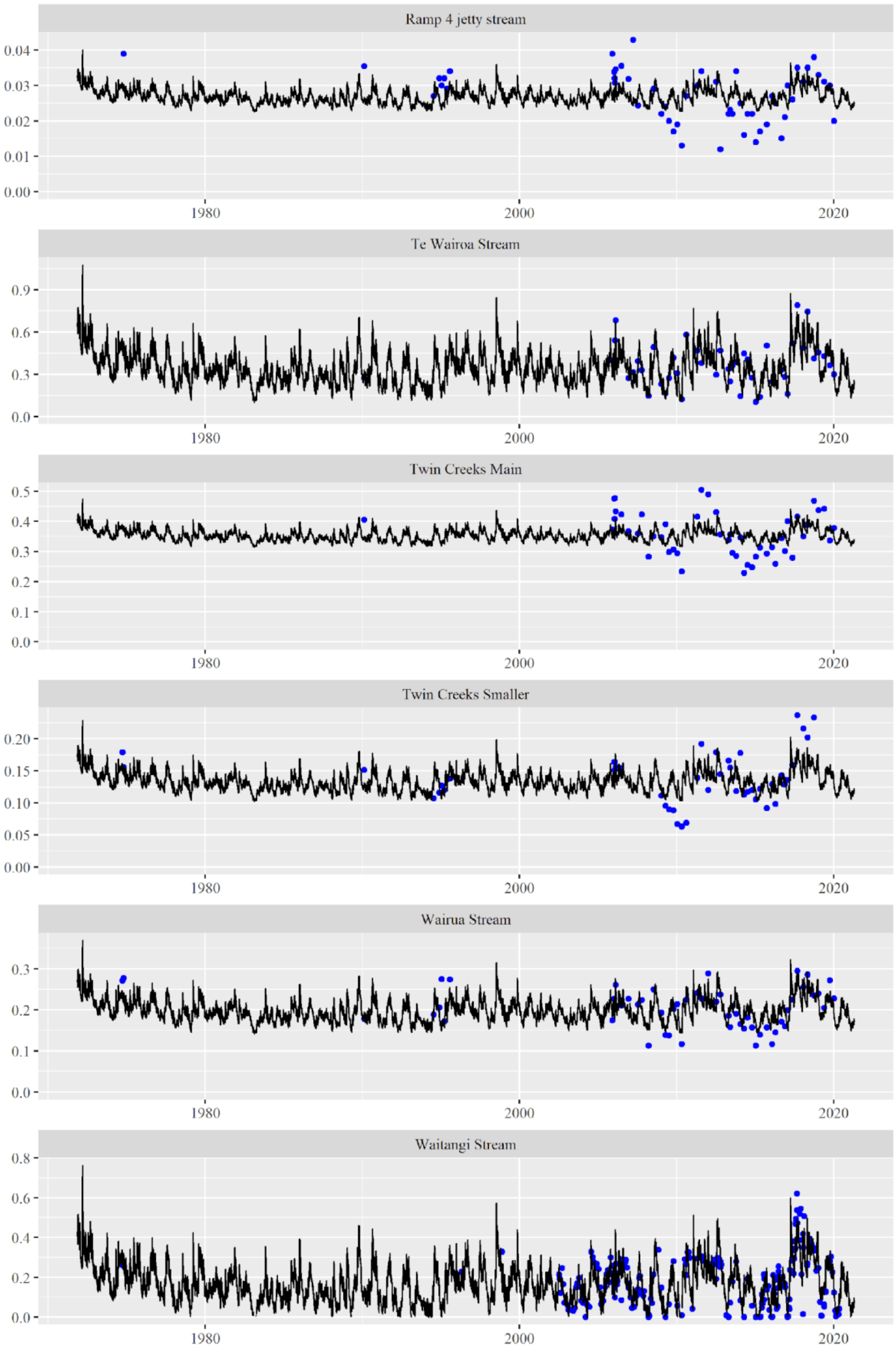


Figure 4.6 Comparison between synthesised time series of lake inflow discharge ($m^3\ s^{-1}$) (solid lines) and field measurements (circles). Updated and modified from Abell at al. (2020) with latest flow data.

4.2.9 Groundwater inflows and outflows

4.2.9.1 Catchment groundwater outflows

Groundwater outflows from the lake catchments were assumed to be the "residual" of the water balance (i.e., the amount of water required for water balance closure). There are no groundwater inflows to the lake catchments, however there will be some groundwater inflow to local lake catchments from any upstream local catchments (i.e., from the Lake Tikitapu local catchment into the Lake Rotomahana local catchment). It is beyond the scope of this research to estimate groundwater flows between local catchments.

4.2.9.2 Lake groundwater inflows and outflows

Groundwater inflows and outflows to and from the lakes themselves were estimated using a catchment-based water balance approach (described by Rosenberry et al. (2015)) using the groundwater catchment boundaries defined by White et al. (2020). The difference between annual rainfall and annual evaporation (when positive) within the groundwater catchment boundary (not including rainfall or evaporation from the lake surface itself for the lake in question), was assumed to flow to that lake via surface water and groundwater. Rainfall and evaporation from any upstream lakes within the lake's catchment were included in these calculations. This combined total surface/groundwater flow was calculated, and any surface water inflow to the lake was subtracted off the total. The result was assumed to represent the total groundwater inflow to the lake.

For lakes that include other lakes in their catchment (i.e., Rotokakahi, Rotomahana and Tarawera), a breakdown of groundwater inflow between that recharged within the lake's local catchment and that recharged outside of its local catchment was calculated. Groundwater flow to the lake from recharge within its local catchment was calculated using the same process described in the preceding paragraph. Groundwater inflow to the lake from recharge outside of its local catchment was calculated by subtracting the locally recharged groundwater inflow from the total groundwater inflow. These methods assume that all precipitation (minus evaporation) over a lake's catchment flows into that lake with none bypassing it via preferential flow paths.

If positive, the "residual" of the water balance (i.e., the amount of water required for water balance closure) was assumed to represent the groundwater outflow from the lake. In the case that the residual was negative, groundwater outflows were set to zero.

4.2.10 Storage changes

Annual storage changes in the lakes were calculated using the lake level/volume relationships presented in Ellery (2004). Records of lake levels were provided by BOPRC. Volume changes were calculated based on the difference from the previous record, then these were summed over each water year to obtain an annual volume change. Storage change for areas under land surfaces were assumed to be negligible.

4.2.11 Consumptive water uses

Consumptive water uses in the Greater Lake Tarawera catchment are negligible (White et al., 2016).

4.2.12 Water leaving Greater Tarawera Lake catchments

Based on the conceptual understanding of the Greater Tarawera Lake catchments (Section 2.5), all water is assumed to flow towards Lake Tarawera, except for some water leaving the Rerewhakaaitu Catchment to the southeast (Reeves, Morgenstern, Daughney, et al., 2008; Tschritter & White, 2014; White et al., 2003, 2016). Gillon et al. (2009) implied the possibility that some water from the Ōkataina, Ōkareka, and Tikitapu local catchments may flow towards Lakes Rotorua and Rotoiti, and although plausible, this is not the preferred hydrologic interpretation for these catchments (P. White, personal communication, January 15, 2021) and flow towards the Rotorua lakes is assumed to be zero for this work.

There are uncertainties surrounding how much water (as groundwater) flows from the Rerewhakaaitu catchment to the southeast (i.e. out of the Greater Lake Tarawera catchment towards the Waikato Region). Outflows from the zone balances of White et al. (2016, p. 63 Table 4.7) suggest this could be as high as 75% of the total outflow, and the work of Reeves et al. (2008) suggests the majority of groundwater outflow from the lake discharges west towards Lake Rotomahana. To capture the range of possibilities, the calculations undertaken by this research assumed that between 10% and 75% of the residual from the Rerewhakaaitu water balance (after accounting for inflows/outflows from rainfall, land evaporation, lake evaporation and surface water flows) exited the Greater Lake Tarawera catchment to the east via groundwater, with the reminder flowing west towards Lake Rotomahana (as groundwater).

4.3 Nutrient loads

Loads of N and P to each lake were estimated using two approaches:

1. Constant load (i.e. the nutrient concentrations reaching the lake will be diluted/increased with larger/smaller lake inflows)
2. Constant concentration (i.e. the load to the lake varies based on inflow volumes, thus the nutrient concentration reaching the lake is constant)

Nutrient yields by land use and catchment calculated by McBride et al. (2020) were used in the calculations. McBride et al. (2020) estimated N and P loads to each of the Tarawera Lakes using an export coefficient modelling approach. McBride (2020) used Overseer® modelling outputs of the BOPRC for agricultural land uses. Estimates from the literature (accounting for local differences) were used for other land uses. In this research, individual catchment loads (by land use, in kg ha^{-1} yr^{-1}) and attenuation rates calculated by McBride et al. (2020) were assumed to apply to each catchment. McBride et al. (2020) estimates a single attenuation factor for each lake in the Tarawera catchment relative to its local catchment area and based on the estimates of attenuation for Lake Rotorua using the ROTAN model (Rutherford, 2016). In the case that a catchment included an area that was not estimated by McBride et al. (2020) (i.e., some parts of the revised boundaries of White et al. (2020)), or there has been a land use change within a catchment, the value for catchment load, and the attenuation rate for that land use and catchment given in McBride et al. (2020) was adopted. Although this is an oversimplification (particularly for agricultural land uses where Overseer® modelling outputs would change depending on soil types, farming practices etc.), it is considered valid for the analysis of relative change in this research.

It is noted that despite a lack of confidence in predicted nutrient losses by Overseer®, its use is widespread by regional councils as a nutrient management tool in catchment-level modelling (Science Advisory Panel, 2021). Irrespective of the issues raised by the Science Advisory Panel (2021), there is currently lack of an alternative option, and the government has approved the continued use of Overseer® for the time being (Ministry for the Environment & Ministry for Primary Industries, 2021).

Land use areas within each catchment were calculated using land use information from the LCDB (details in Section 4.2.3). The yields and attenuation rates given in the nutrient balances for each individual catchment and land use (Appendix 1 of McBride et al. (2020)) were applied to these areas to obtain loads. The resulting loads were either kept constant (in the case of the constant load scenario) or varied based on rainfall or drainage (in the case of the constant concentration scenario). Studies into the pattern of nutrient discharge over time show drainage is the main driver of nutrient discharge (Journeaux, 2014), thus the constant concentration scenario using drainage to vary the load is likely more realistic. Results from the two sets of loads were reported as a distribution.

For the constant concentration scenario, loads were assumed to vary linearly with either rainfall or drainage (each was calculated separately to assess their affect). To achieve this, at each grid_ID the long-term average annual rainfall was calculated from the entire dataset (from 1972 to 2018). The proportional difference of each water year from the rainfall or drainage long-term average was obtained by dividing its value by the long-term average at that point. These proportional differences were averaged within each catchment to get a "rain factor" or "drainage factor" for each water year. The factors were then multiplied by the calculated (constant) nutrient load for each land use to obtain an estimate of the load for a constant concentration scenario in every water year. Loads from areas of water (lakes and wetlands), wastewater and geothermal sources were not adjusted for rainfall as these were assumed to remain constant.

In addition to the constant load and constant concentration scenarios, a special case was calculated for nitrogen loading whereby the nitrogen load was varied with rainfall only for agricultural land uses. This was based on the assumptions made in the Overseer® urine patch model and responsiveness of N leaching to increasing rainfall (Overseer, 2012). It was only applied to agricultural land uses because these are where urine patches occur; and N sourced from livestock urine contributes a large proportion of nitrogen leaching from farms (Foote et al., 2015).

4.3.1 Connected lakes

Lakes Tarawera, Rotomahana and Rotokakahi all receive groundwater and/or surface water flows from hydraulically up-gradient lakes (see Chapter 2). The nutrient loads to these receiving lakes from their connected lakes were calculated by McBride et al. (2020) by multiplying the outflows of the lakes (as calculated by Woods (2006)) by average surface water concentrations of TN and TP. The same method has been applied in this research. Assumed TN and TP concentrations from McBride et al. (2020) have been used directly with an option to apply a percentage increase or decrease to each lakes current concentration to represent improvement and/or degradation of water quality in the web tool developed.

4.3.2 Land use scenarios

To determine the outer boundaries of nutrient loads from improvements and/or degradation to the lakes via land use change, the nutrient calculations described above were run for two hypothetical end-member scenarios: a complete conversion to agriculture, and a complete conversion to native forest. Constant nutrient yields and attenuation values for the land use scenario were applied across the entire catchment complex. For the complete agricultural conversion this was the average of yields given by McBride et al. (2020) for all agricultural land uses within the Greater Tarawera Lakes complex (32.97 kg ha^{-1} yr^{-1} for N, and 2.93 kg ha^{-1} yr^{-1} for P). For the complete native forest conversion, the yield was the average of all native forest within the Greater Tarawera Lakes complex given in McBride et al. (2020) (3.70 kg ha^{-1} yr^{-1} for N, and 0.13 kg ha^{-1} yr^{-1} for P). Attenuation values were set at 0.4 as per McBride et al., (2020).

4.4 Interannual variability and uncertainty

4.4.1 Water balance

To assess the interannual variability and uncertainty in the water balance, the calculations were run with each possible combination of datasets/methods for the water years 1972-2018 (Table 4.4). End points of plausible ranges were chosen as options for the crop factor (K_c) of pasture, the annual yield differences between pasture and forested areas (see Section 4.2.6.2), and the proportion of groundwater exiting the Rerewhakaaitu lake and catchment to the east (and out of the Greater Lake Tarawera catchment). This produced 80 possible combinations of data/methods, run over 47 years, resulting in 3,760 annual water balances for each catchment and its lake. The final dataset was analysed as a distribution to assess interannual variability and uncertainty in water balance components.

Table 4.4 Alternatives used to assess water balance interannual variability and uncertainty

Water balance variable	Type	No. of alternatives		Description
Surface water catchment boundaries	Data	2	1.	LIDAR topographic SW catchments
			2.	White et al. (2020) SW topographic catchments
Groundwater catchment boundaries	Data	1	1.	White et al. (2020) GW catchments
Rainfall datasets	Data	5	1.	VCS augmented rainfall data - 5 km resolution
			2.	VCS augmented rainfall data - 500 m resolution
			3.	VCS biased corrected rainfall data - 5 km resolution
			4.	VCS operational rainfall data - 5 km resolution
			5.	VCS operational rainfall data - 500 m resolution
Evaporation from the lake surface	Method	1	1.	DYRESM method
Evaporation from land (method)	Method	1	1.	FAO56 method, adjusted for water stress
Evaporation from land (crop factor)	Data	2	1.	Crop factor 0.95
			2.	Crop factor 1.05
Evaporation from land (yield difference)	Data	2	1.	Annual yield difference from pasture: -160 mm/yr (pine) and -60 mm/yr (native forest)
			2.	Annual yield difference from pasture: -260 mm/yr (pine) and -160 mm/yr (native forest)
Storage changes	Method	1	1.	Storage changes in lake only (based on level data)
Surface water inflows/outflows	Data	1	1.	As estimated from from recorder and gauging data
Groundwater inflows/outflows	Method	1	1.	As estimated from residuals and assumptions
Water leaving Tarawera catchments complex	Method	2	1.	10% of the groundwater outflow from Rerewhakaaitu exits the complex
			2.	75% of the groundwater outflow from Rerewhakaaitu exits the complex
Water year	Data	47	1 - 47	Water years 1972 - 2018

4.4.2 Nutrient loads

To assess the interannual variability and uncertainty in the nutrient load estimations, the calculations were run with each possible combination of datasets/methods (Table 4.5). This produced 40 possible combinations for P loads, and 60 possible combinations for N loads. Loads from these combinations were then calculated for water years 1972 to 2018 (a total of 47 years), resulting in 1,880 and 2,820 annual nutrient load estimations for P and N respectively. The final datasets were analysed as distributions to assess interannual variability and uncertainty in the load estimates.

Table 4.5 Alternatives used to assess nutrient load interannual variability and uncertainty

Nutrient load estimate variable	Type	No. of alternatives		Description
Surface water catchment boundaries	Data	2	1.	LIDAR topographic SW catchments
			2.	White et al. (2020) SW topographic catchments
Rainfall datasets	Data	5	1.	VCS augmented rainfall data - 5 km resolution
			2.	VCS augmented rainfall data - 500 m resolution
			3.	VCS biased corrected rainfall data - 5 km resolution
			4.	VCS operational rainfall data - 5 km resolution
			5.	VCS operational rainfall data - 500 m resolution
Leaching method	Method	2	1.	Dependant on rainfall
			2.	Dependant on drainage
Calculation method	Method	2-3	1.	Constant load
			2.	Constant concentration
			3.	Constant concentration - agricultural land uses only (special case for N)
Water year	Data	47	1 - 47	Water years 1972 - 2018

Chapter 5
Water provenance

5.1 Introduction

This chapter describes the results of the isotopic analysis of water collected from groundwater and surface water in and around the Greater Lake Tarawera catchment. The purpose of isotopic analysis was to determine the provenance of the water in these locations and supplements water balance assumptions by considering the movement of water within and out of the Greater Lake Tarawera catchment.

5.2 Tarawera River

Water samples were collected from the Tarawera River on 2 February 2021. Sample TR1 was collected from the lake edge, TR2 from flowing river water at the outlet, TR3 from flowing river water immediately upstream of where the Tarawera River disappears underground (emerging later at the Tarawera Falls), TR4 from flowing river water 200 m downstream of the Tarawera Falls, and TR5 from flowing river water 1,100 m downstream of the falls (Figure 4.1, Table 4.1, and photographs in Appendix B). During sampling, numerous springs were observed on the riverbank of the Tarawera River immediately downstream of the falls (see photographs in Appendix B).

The flow in the Tarawera River at the outlet on the day of sampling was recorded at the NIWA monitoring site as 4.6 m^3s^{-1}, defined by NIWA as very low (in the lowest 10 percentile of discharge levels, <5.11 m^3s^{-1} for this site (NIWA, 2021c)). The hydrograph indicates that the river was in recession on the day of sampling (NIWA, 2021c). December 2020 and January 2021 were dry months, with below average rainfall (50-79% of the 1981-2010 normal), only 50.2 mm and 74.0 mm of precipitation were recorded in each month respectively (the 1981-2010 monthly normals for January and February are 91.8 mm and 94.7 mm respectively (NIWA, 2021b))[16]. The last rainfall event prior the collection of water samples from the Tarawera River was on 22 January 2021, when 1.2 mm of precipitation was recorded[16].

[16] Data from NIWA climate station 1770 Rotorua Aero Aws

Stable isotopes of water, δ^2H and $\delta^{18}O$ were used to determine the proportional contributions of lake water and rainwater in samples taken from the Tarawera River using a two end-member mixing model (described in Chapter 4). The isotopic composition of groundwater recharged from precipitation approximately matches the mean isotopic composition of precipitation over the recharge area and local shallow groundwater is often used to characterise the isotopic composition of precipitation in a given location (IAEA, 1981), a theory which has been applied globally (Jasechko et al., 2016). Seasonal variations in rainfall isotopic composition appear to be smoothed out in the groundwater signature (IAEA, 1981; Jasechko et al., 2017). For these reasons, two end-members were selected as possibilities to represent rainfall: the long-term Rotorua rainfall weighted average, and the isotopic signature of local groundwater[17]. The end-member chosen to represent lake water is the flow at the outlet of Lake Tarawera at the time of sampling (sample TR2) (Table 5.1). Proportional contributions estimated from δ^2H have been used because of greater precision of compared to $\delta^{18}O$, and because δ^2H end-members have greater spread due to underlying fractionation effects.

Table 5.1 End-members used for Tarawera River water composition estimates

End-member	Represents	δ^2H, in ‰	$\delta^{18}O$, in ‰
TR2 (outlet flow)	Lake water	-18.8	-2.59
Rotorua rainfall	Rainfall	-32.0	-5.60
Local groundwater	Rainfall	-36.7	-6.05

Calculated proportions of lake water present in the Tarawera River upstream and downstream of the Tarawera Falls are shown in Figure 5.1 and Table 5.2. An assumption is made that the water in the Tarawera River comprises a mixture of two water sources (i.e., end-members): local groundwater/rainfall and lake water (with the isotope ratio of lake water collected on the day of sampling), with no fractionation occurring enroute. All samples collected upstream of the Tarawera Falls (TR1, TR2, and TR3) indicate that water flowing the in Tarawera River is 100% lake water. Immediately downstream (200 m) from the Tarawera Falls, the percentage of lake water present in the river decreases to 85-89%. Further downstream (1,100 m from the falls), the percentage of lake water present in the river decreases further to 62-72% lake water. These results indicate that the

[17] the mean of samples collected from bore 129

significant flow gains observed in the Tarawera River downstream of the falls (approximately 2 m^3s^{-1}) (White & Cooper, 1991; White et al., 2016) are not sourced from Lake Tarawera itself, and are likely to be gains from rainfall recharged groundwater. Calculations indicate that these gains are too large to be sourced solely from groundwater originating from the catchments downstream of the Tarawera outlet (White & Cooper, 1991; White et al., 2016), therefore a portion are likely to be sourced from groundwater originating from the Greater Lake Tarawera catchment that has bypassed the lake.

Table 5.2 Tarawera River water composition estimates from isotope analysis of samples collected on 2 February 2021

Sampling location	Distance from lake	Distance from Tarawera Falls	Lake water	δ^2H, in ‰	δ^{18}O, in ‰
TR1 (lake water)	0 m	3,400 m upstream	100%	-18.7	-2.77
TR2 (outlet flow)	100 m	3,300 m upstream	100%	-18.8	-2.59
TR3	3,000 m	300 m upstream	100%	-18.6	-2.58
TR4	3,600 m	200 m downstream	85-89%	-20.8	-3.12
TR5	4,500 m	1,100 m downstream	62-72%	-23.7	-3.88

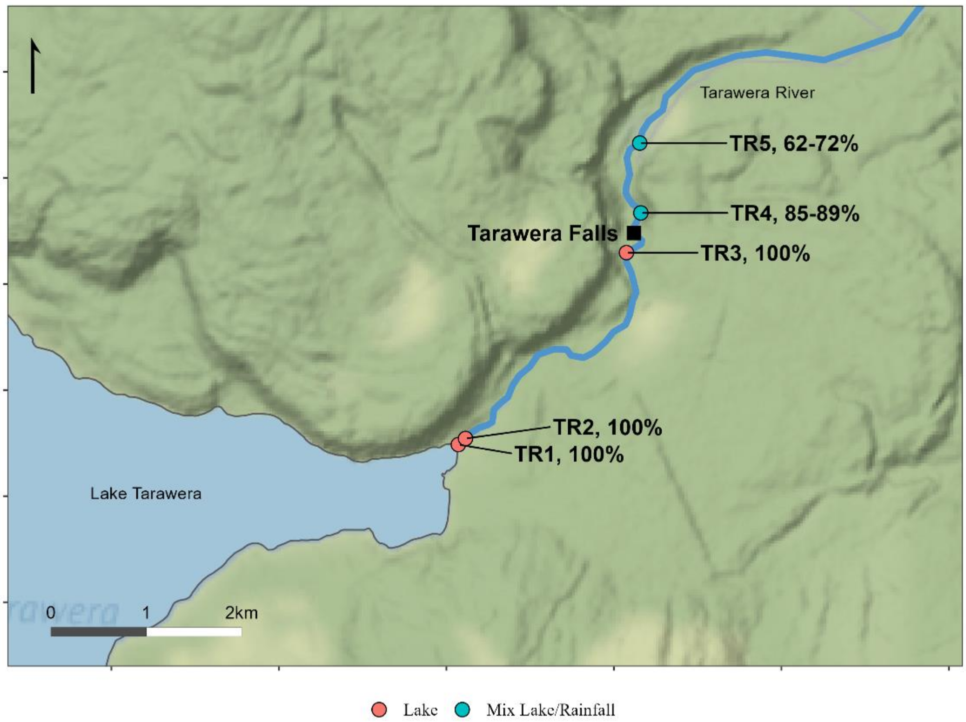


Figure 5.1 Map showing the location of water samples taken from Lake Tarawera (TR1) and the Tarawera River (samples TR2-TR4), and the location of the Tarawera Falls. Colours indicate the make-up of the water, and percentages indicate the percentage of lake water present in the sample as estimated by δ^2H values on 2 February 2021.

5.3 Groundwater provenance

Groundwater samples were collected by BOPRC from eleven groundwater bores in and around the Greater Tarawera Lakes catchment (Figure 4.1 and Table 4.1). Four sampling runs from theses bores were undertaken within a year in and around August 2020, November 2020, February 2021, and May 2021 (where possible) and sent to the University of Waikato for isotopic analysis.

The isotopic composition of the groundwater samples was compared to the isotopic compositions of Rotorua rainfall (mean), and lake water (mean hypolimnion values) for the lakes of the Greater Lake Tarawera catchment. Lake water samples have been collected and analysed for isotopes from various depths of the Tarawera Lakes by BOPRC and/or UoW technical and field staff since 2016. Monthly rainfall isotopic values from Rotorua for the period August 2007 to February 2010 were obtained from the CDRP (Cross Departmental Research Project) database (Keller et al., 2014) and have been collected by NIWA. End-members chosen for source analysis were the mean hypolimnion value for the nearest lake(s) (provided the screen depth was at or below the surface elevation of the lake), and the average of Rotorua rainfall. There is variation in the isotopic composition of Rotorua rainfall and lake waters (Figure 5.2). Rainfall variation is largely due to seasonality, and the isotopic signature for groundwater of meteoric origin is smoothed out by the transition of water through the unsaturated zone (IAEA, 1981), thus the mean rainfall value at Rotorua is appropriate to represent rainfall recharged groundwater. The most notable variations in the isotopic compositions of lakes are seasonal (IAEA, 1981), and the variation in the isotopic signature of lake water of the Tarawera Lakes is likely due to stratification and summer evaporation (T. Baisden, personal communication, 2021). It is considered that water infiltrating from the lake to groundwater would be best represented by well mixed waters (i.e., winter values and/or hypolimnion values), thus the mean hypolimnion value from each lake was selected to represent the lake source.

The methods and tools of Phillips et al. (2005), and Phillips and Greg (2003) were used to determine the recharge source of groundwaters (detailed in Chapters 3 and 4), with lake sources isolated down to individual lakes using the data held by UoW. Groundwater from four of the bores tested (031, 055, 072, and 134) indicated the recharge source to be a mixture of lake water and rainfall, and the remaining bores indicated a rainfall (or mostly rainfall) recharge source (Figures 5.3, 5.4, and Table 5.3).

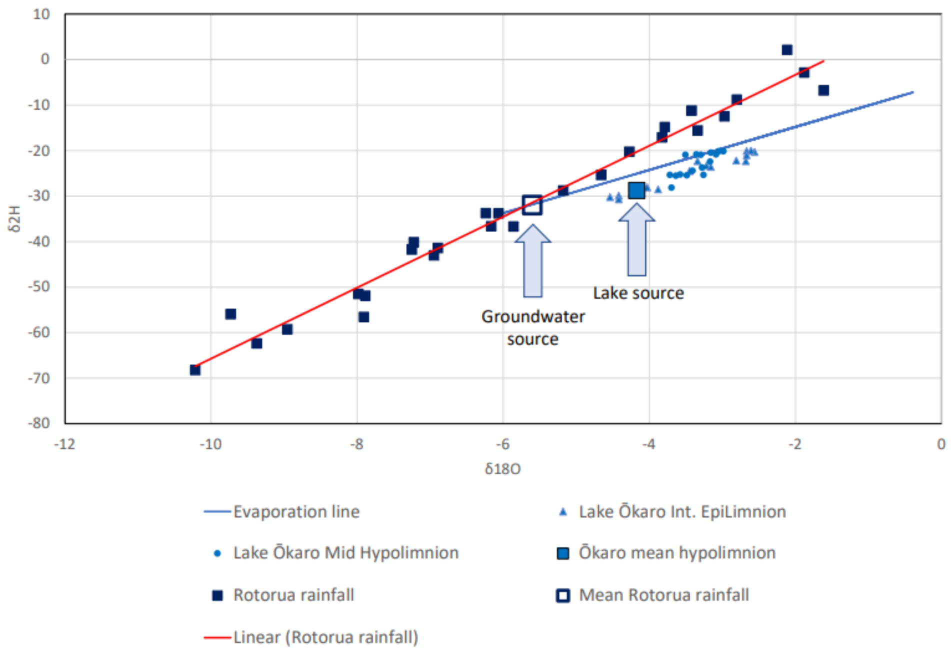


Figure 5.2 Isotopic variations in Rotorua rainfall and Lake Ōkaro water showing the sources (end-members) selected for isotopic analysis to represent groundwater and lake water. The groundwater source is the mean of rainfall from Rotorua, and the lake water source is the mean of the hypolimnion values for the lake. For clarity only Lake Ōkaro is shown, however a similar relationship exists for the other lakes in the Greater Lake Tarawera catchment.

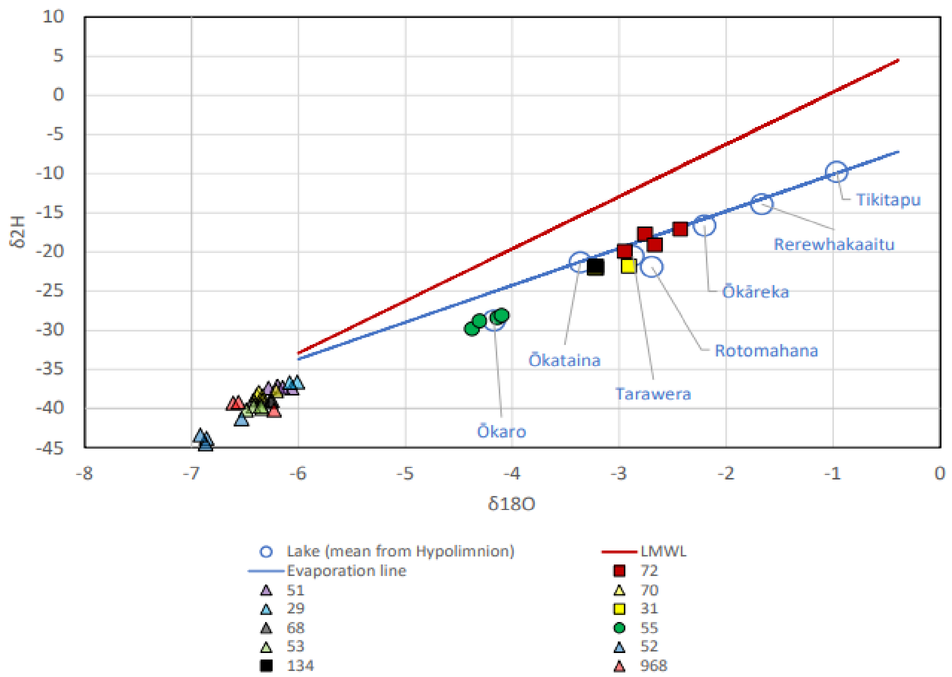


Figure 5.3 Isotopic composition of groundwater in and around the Greater Lake Tarawera catchment. The shapes indicate the isotopic interpretation; squares indicate water with some lake water source; triangles indicate a mostly rainfall source and circles some lake water and/or geothermal source. The mean hypolimnion value for lake waters is shown, and the local meteoric water line (LMWL) and evaporation line are shown for reference.

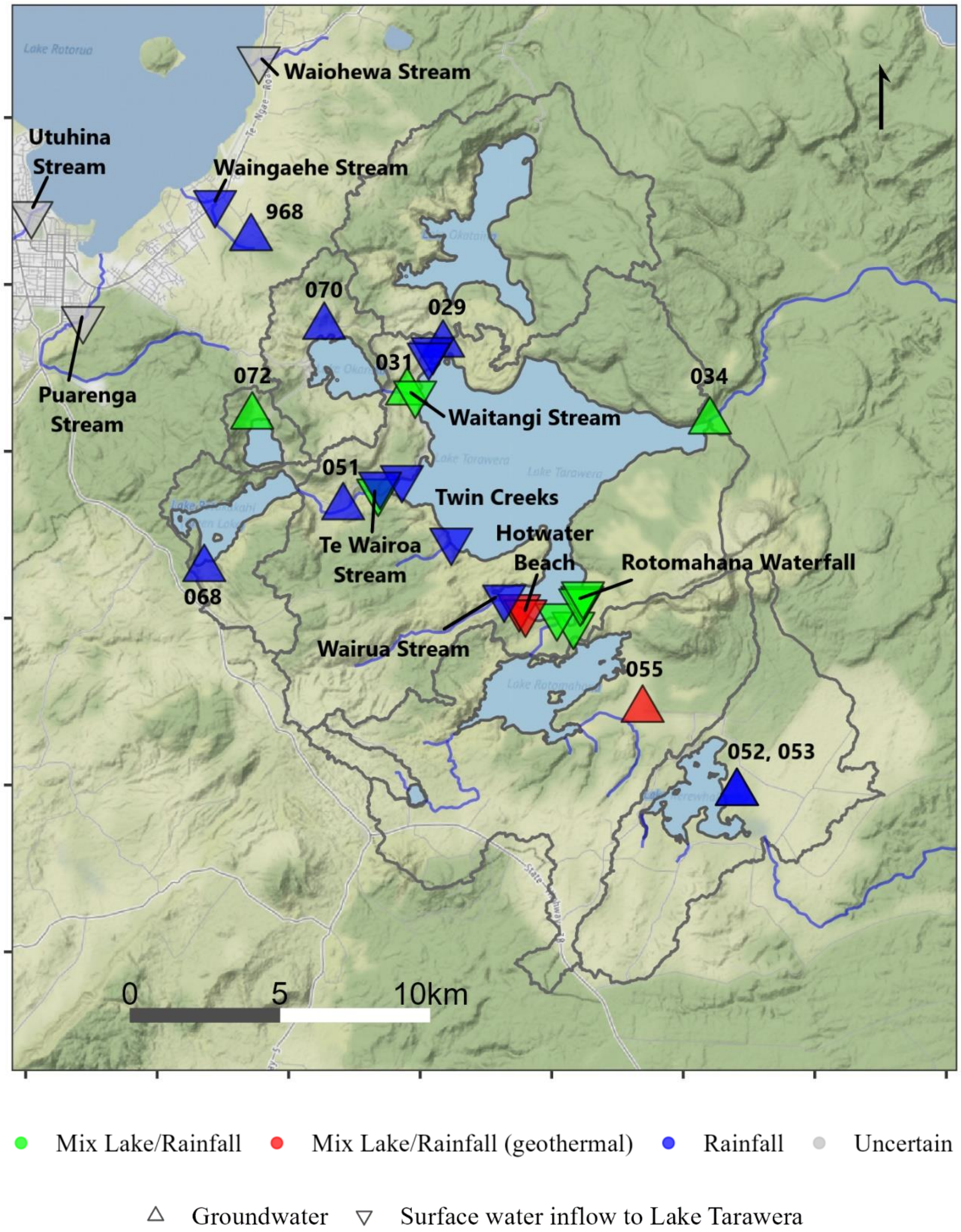


Figure 5.4 Isotopic interpretation of groundwater (upward triangles) and surface water inflows (downward triangles) to Lake Tarawera. Colours indicate the dominant source of the water as interpreted by isotope analysis. Bore numbers are shown for the groundwater locations.

Table 5.3 Isotopic interpretation of groundwater recharge sources isolated down to individual lakes. The proximity, mean base elevation and surface elevation of possible lake sources are shown. The screen elevation given is the middle of the bore screen. Only nearby lakes whose mean base elevation is above the nearby well screen are considered possible sources.

	Screen elevation (m asl)	Possible sources[1]	Proximity to nearest lake(s) source	Isotopic interpretation of water[2]	Average of $\delta^{18}O$, in ‰	Average of $\delta^{2}H$, in ‰
Bore 129	287	Rainfall, Lake Tarawera (242 m asl - 298 m asl), Lake Ōkataina (262 m asl - 309 m asl)	Lake Tarawera 200 m, Lake Ōkataina 1500 m	Rainfall (82-87%), Lake Tarawera (0-13%), Lake Ōkataina (0-18%)	−6.04	−36.7
Bore 131	271	Rainfall, Lake Tarawera (242 m asl - 298 m asl), Lake Ōkareka (334 m asl - 353 m asl)	Lake Tarawera 250 m, Lake Ōkareka 850 m	Rainfall (1-15%), Lake Tarawera (38-94%), Lake Ōkareka (0-47%)	−3.12	−22.0
Bore 134	214	Rainfall, Lake Tarawera (242 m asl - 298 m asl)	Lake Tarawera 10 m	Rainfall (5-11%), Lake Tarawera (89-95%)	−3.22	−21.8
Bore 051	357	Rainfall, Lake Tikitapu (399 m asl - 417 m asl), Lake Rotokakahi (377 m asl - 394 m asl)	Lake Tikitapu 2500 m, Lake Rotokakahi 1600 m	Rainfall (94-100%), Lake Tikitapu/Rotokakahi (0-6%)	−6.17	−37.3
Bore 052	348	Rainfall, Lake Rerewhakaaitu (428 m asl - 435 m asl)	Lake Rerewhakaaitu 500 m	Rainfall (100%)	−6.79	−43.2
Bore 053	426	Rainfall, Lake Rerewhakaaitu (428 m asl - 435 m asl)	Lake Rerewhakaaitu 500 m	Rainfall (100%)	−6.40	−39.9
Bore 055	313	Rainfall, Lake Rerewhakaaitu (428 m asl - 435 m asl), Lake Rotomahana (285 m asl - 338 m asl)	Lake Rerewhakaaitu 2100 m, Lake Rotomahana 1400 m	Rainfall (37-54%), Lake Rerewhakaaitu (0-37%), Lake Rotomahana (10-63%)	−4.23	−28.8
Bore 068	361	Rainfall, Lake Rotokakahi (377 m asl - 394 m asl)	Lake Rotokakahi 170 m	Rainfall (97-100%), Lake Tikitapu/Rotokakahi (0-3%)	−6.32	−39.0
Bore 070	334	Rainfall, Lake Ōkareka (334 m asl - 353 m asl)	Lake Ōkareka 350 m	Rainfall (92-95%), Lake Ōkareka (5-8%)	−6.33	−38.1
Bore 072	390	Rainfall, Lake Tikitapu (399 m asl - 417 m asl)	Lake Tikitapu 130 m	Rainfall (28-30%), Lake Tikitapu (70-72%)	−2.70	−18.4
Bore 068	332	Rainfall, Lake Ōkareka (334 m asl - 353 m asl), Lake Tikitapu (399 m asl - 417 m asl), Lake Ōkataina (262 m asl - 309 m asl)	Lake Ōkareka 4000 m, Lake Tikitapu 6000 m, Lake Ōkataina 5000 m	Rainfall (100%)	−6.47	−39.6

[1] Mean base elevation and surface elevation of lakes in brackets. Only nearby lakes whose depth range coincides with the well screen are considered possible sources.

[2] Using methods of Phillips et al. (2005), and Phillips and Greg (2003)

5.4 Inflows to Lake Tarawera

To inform the conceptual understanding of hydraulic connections between the lakes, the isotopic composition of surface water inflows to Lake Tarawera held by UoW were examined. Water samples from stream inflows to Lake Tarawera have been collected by UoW technical staff since 2018. Inflows were interpreted visually with the aid of a biplot. Quantitative mathematical analysis of Lake Tarawera inflows using the methods and tools of Phillips et al. (2005), and Phillips and Greg (2003) was outside of the scope of this investigation.

Several spring fed inflows in the south-eastern part of the Wairua Arm of Lake Tarawera indicate a Lake Rotomahana water source[18]. The only other inflows indicative of a lake water source are the Te Wairoa Stream and Waitangi Stream, both direct surface inflows from Lake Rotokakahi and Lake Ōkareka respectively (Figures 5.4 and 5.5).

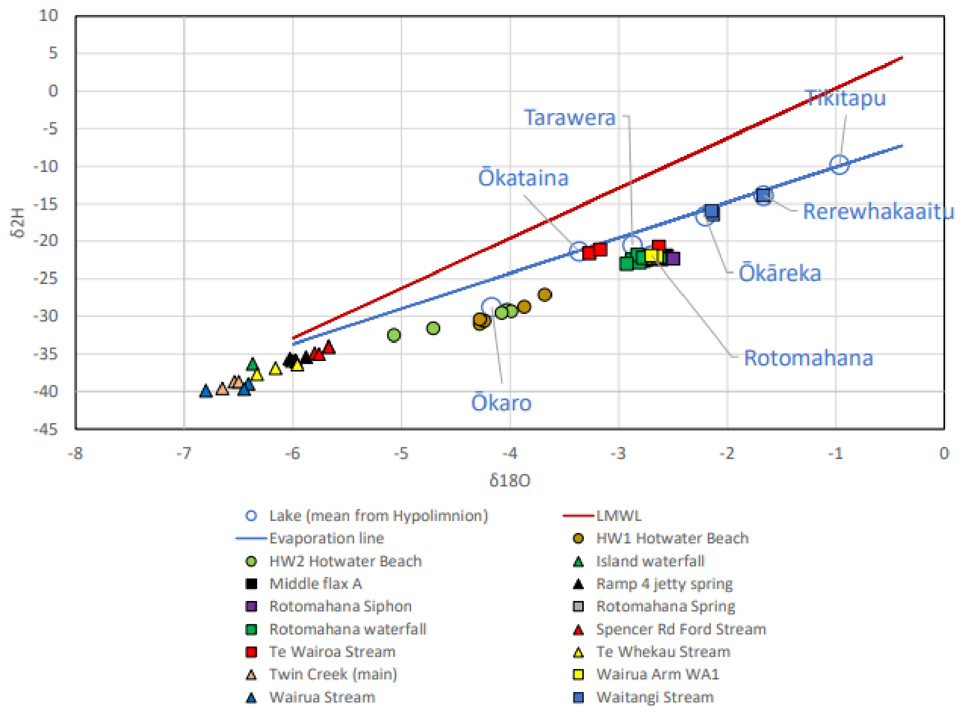


Figure 5.5 Isotopic composition of inflows to Lake Tarawera. The shapes indicate the isotopic interpretation; squares indicate water with some lake water source; triangles indicate a mostly rainfall source and circles some lake water and/or geothermal source. The mean hypolimnion value for lake waters is shown, and the local meteoric water line (LMWL) and evaporation line are shown for reference.

[18] Inflow sites Wairua Arm WA1, Rotomahana waterfall, Rotomahana spring, and Middleflax. The Rotomahana Siphon is also in this group but is a direct inflow from Lake Rotomahana.

5.5 Groundwater discharge towards Lake Rotorua

To assess the possibility of groundwater discharging from the Greater Lake Tarawera catchment towards the Rotorua Lakes, the isotopic composition of some surface water inflows to Lake Rotorua held by UoW were examined. Water samples from stream inflows to Lake Rotorua have been collected by UoW technical staff from 2018 - 2020. Inflows were interpreted visually with the aid of a biplot. Quantitative mathematical analysis of Lake Rotorua inflows using the methods and tools of Phillips et al. (2005), and Phillips and Greg (2003) was outside of the scope of this investigation.

Water in the Puarenga, Waiohewa, and Utuhina Streams indicate a departure from a rainfall source for some samples and the interpretation is uncertain (see Chapter 8). Water in the Waingaehe Stream indicates a rainfall source (Figures 5.4 and 5.6).

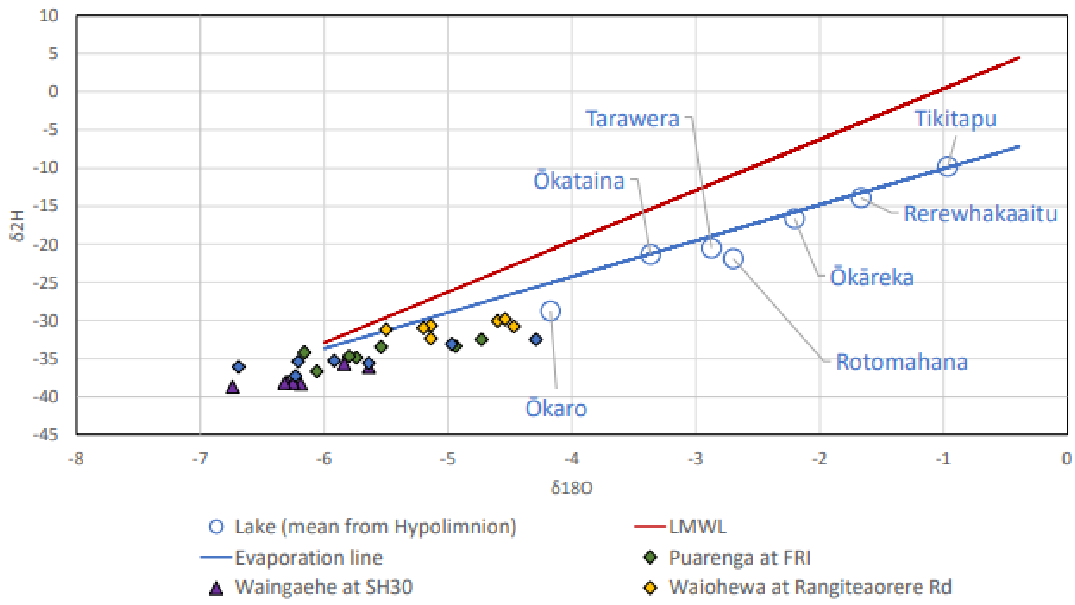


Figure 5.6 Isotopic composition of inflows to Lake Rotorua. The shapes indicate the isotopic interpretation; triangles indicate a mostly rainfall source and diamonds indicate uncertainty in the interpretation. The mean hypolimnion value for lake waters is shown, and the local meteoric water line (LMWL) and evaporation line are shown for reference.

Chapter 6

Annualised water balances of the Greater Tarawera Lakes and catchments

6.1 Introduction

This chapter presents the results of water balance calculations for the Greater Tarawera Lakes and their catchments. Data are generally presented in the units of cubic meters per second ($m^3 s^{-1}$) for all water balance components as these units capture the relative sizes of the flows and uncertainties between connected catchments. This differs from many water balance studies which use units of depth (e.g. mm y^{-1}). In addition to the results presented in this chapter, a web-based tool that performs water balance calculations and nutrient load estimates with user selected options was developed using Shiny R technology and is available at https://nickiwilson.shinyapps.io/TaraweraMsc/.

Overall numeric results and uncertainties presented use all possible datasets and methods for water balance components considered in this study (see Chapter 4). The goal of this approach is to communicate overall interannual variability and uncertainty as a probability distribution. In addition, to visualise interannual variations, a single set of calculations have been run using the datasets and methods that are considered to represent best estimates of the water balance (Table 6.1). The goal of these best-estimate calculations is to illustrate the variations that can exist year to year under a set of given assumptions. LIDAR surface water catchment boundaries have been used for best-estimate surface water catchment boundaries because they have been used in recent scientific investigations commissioned by BOPRC (e.g., Abell et al., 2020; McBride et al., 2020) and are currently used by BOPRC for planning and policy purposes. Where there is a range of possible values for a parameter (i.e., the crop factor, annual yield difference between pasture and exotic/native forest, and water leaving Tarawera catchments) the median was chosen to represent the best estimate.

Table 6.1 Best-estimate datasets and methods used to illustrate interannual variations of flows and nutrient loads

Component	Best estimate data/method
Surface water catchment boundaries	LIDAR topographic SW catchments
Groundwater catchment boundaries	White et al. (2020) GW catchments
Rainfall datasets	NIWA augmented rainfall data - 500 m resolution
Evaporation from the lake surface	DYRESM method
Evaporation from land (method)	FAO56 method, adjusted for water stress
Evaporation from land (crop factor)	Crop factor 1.00 for pasture
Evaporation from land (yield difference)	Annual yield difference from pasture: -210 mm/yr (pine) and -110 mm/yr (native forest)
Storage changes	Storage changes in lake only (based on level data)
Surface water inflows/outflows	As estimated from from recorder and gauging data
Groundwater inflows/outflows	As estimated from residuals and assumptions
Water leaving Tarawera catchments complex	50% of the groundwater outflow from Rerewhakaaitu exits the complex
Land use	Current and historical land uses from NZ LCDB
Leaching method	Dependant on drainage
Load calculation method	Constant concentration

6.2 Rainfall and drainage

The magnitude of flows calculated in the water balance are proportional to the magnitude of rainfall. Annual rainfall and drainage over the Greater Lake Tarawera catchment are shown in Figure 6.1 and Table C1 (Appendix C). Annual variations discussed in the following sections are described with reference to the long-term average rainfall or long-term average drainage for the study area (for the 47-year period from 1972-2018). Definitions of departures from the long-term average are defined as: well below average or very dry (< 50% of the long-term average), below average or dry (50-79% of the long-term average), average or near average (80-119% of the long-term average), above average or wet (120-149% of the long-term average), and well above average or very wet (> 149% of the long-term average).

Years with below average rainfall result in below average to well below average drainage, and vice versa with years with above average rainfall resulting in above average to well above average drainage (Figure 6.1). The variations in annual drainage are greater (16% to 191%) than the variations in annual rainfall (67% to 141%). The percentage of annual rainfall resulting in annual drainage (i.e., the amount of rainfall that doesn't evaporate assuming no surface runoff) varies from 11% to 63% with a mean of 46%.

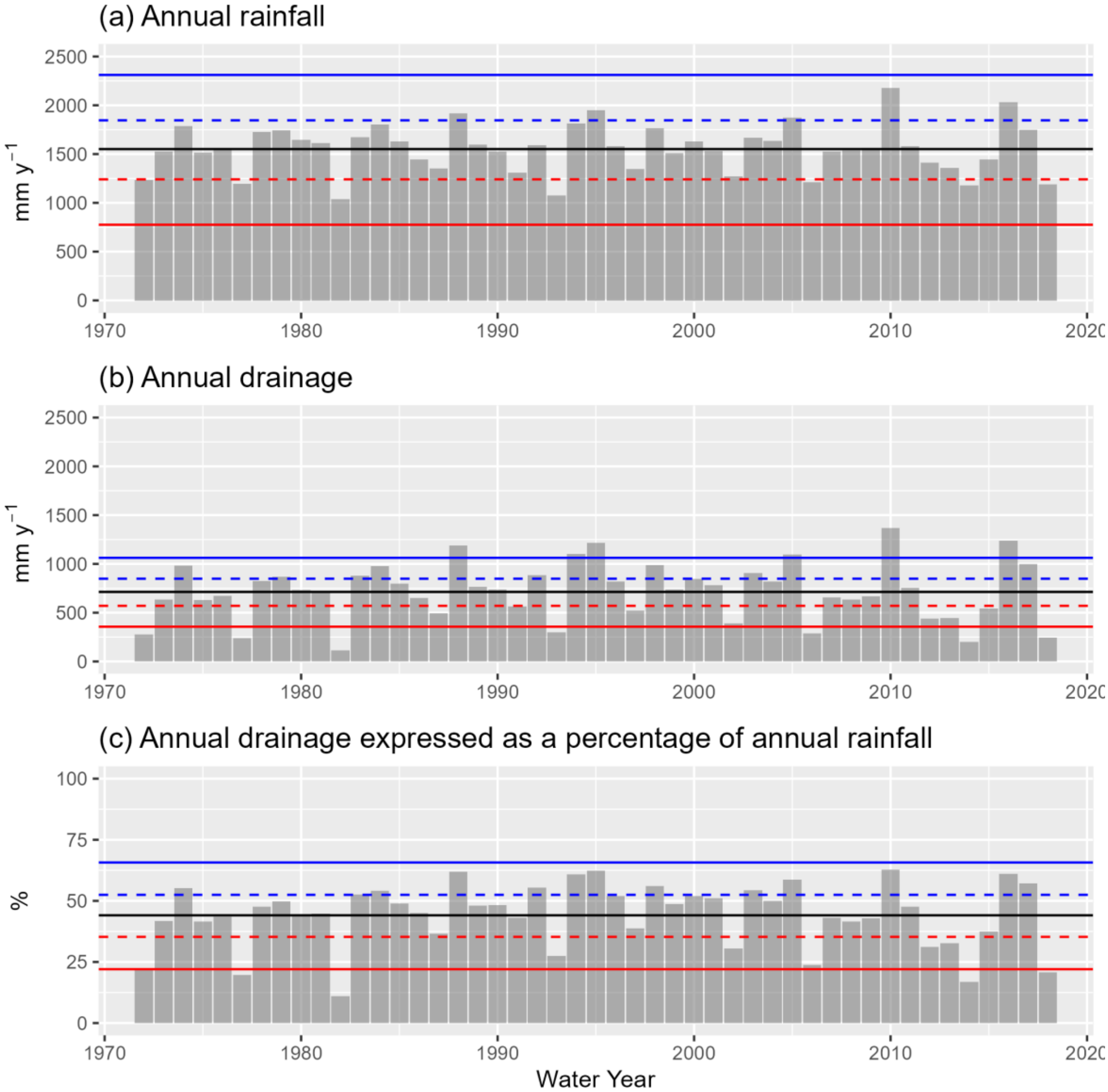


Figure 6.1 Annual totals of (a) rainfall, (b) drainage and (c) annual drainage expressed as a percentage of annual rainfall over the Greater Tarawera Lakes catchment. Black solid lines indicate the 1972 – 2018 long-term average. Solid blue lines indicate the well above average threshold (> 149% of long-term average), dashed blue indicate the above average threshold (> 119% of long-term average), dashed red indicate the below average threshold (< 80% of long-term average), and solid red indicate the well below average threshold (< 50% of long-term average). Annual drainage has been calculated by subtracting annual evaporation from annual rainfall (where evaporation has been calculated using the FAO56 methods of Allen et al. (1998) including a water stress correction.

The interannual variability and uncertainty of rainfall over the Greater Lake Tarawera catchment is shown in Figure 6.2 and all catchments are shown in Figure C1 (Appendix C). Three factors affect the rainfall estimated for a catchment: the surface water catchment boundary (of which there are two alternatives), the rainfall dataset used (five alternatives), and the water year (47 alternatives, 1972-2018). Thus there are 470 estimations of rainfall for a catchment (Figure 6.2(a)), and in any given water year there are 10 estimations of rainfall for the catchment (Figure 6.2(b), (c) and (d)). The VCS operational dataset predicts higher annual rainfall in any given year than the other datasets whose predictions are similar (Figure 6.2(b), (c) and (d)).

The interannual variability and uncertainty of rainfall to the Greater Lake Tarawera catchment is estimated with 95% confidence to be 12.78 – 26.92 $m^3 s^{-1}$ (mean of 19.48 $m^3 s^{-1}$ or 1563 mm y^{-1}) (Table 6.3).

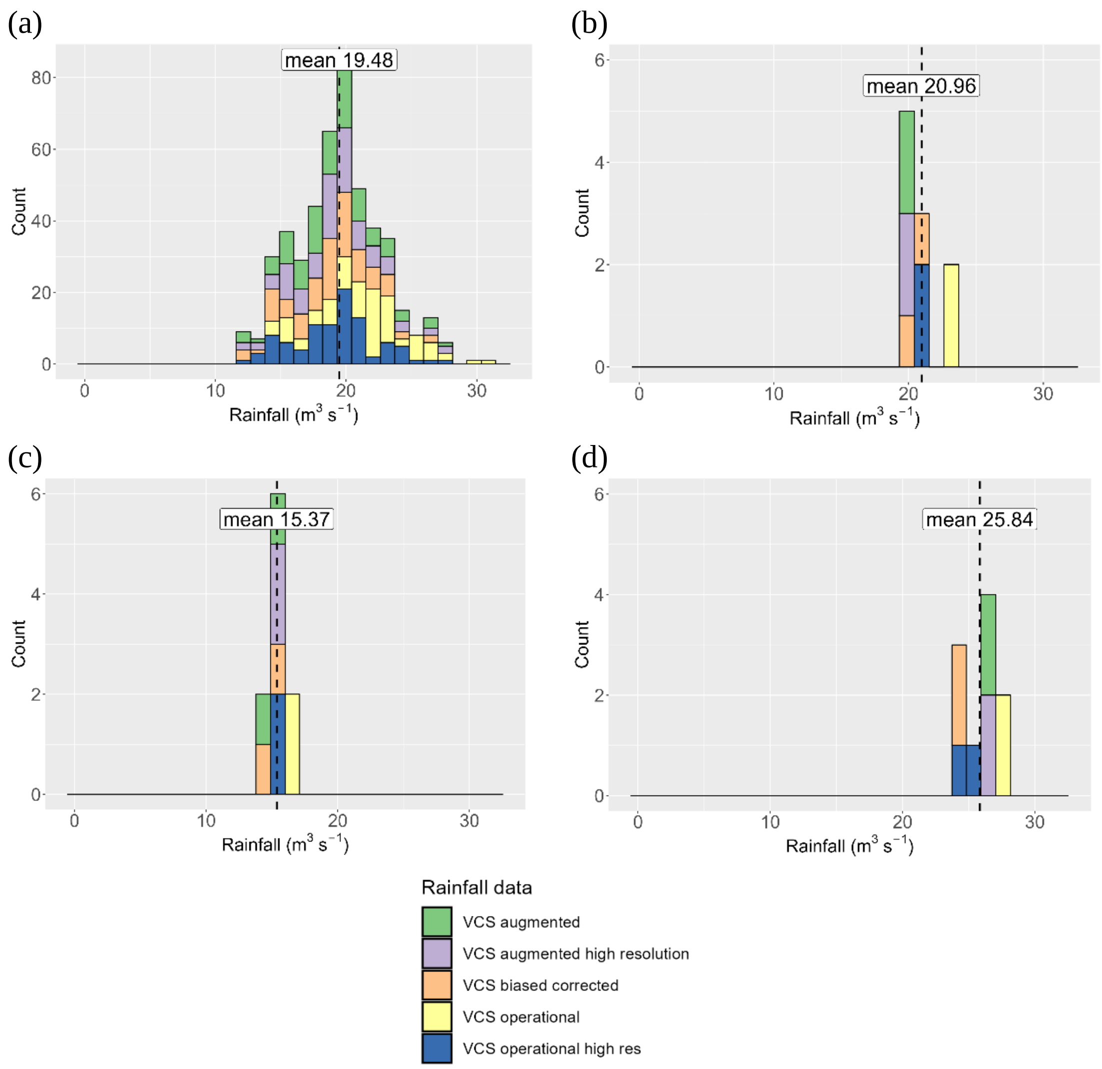


Figure 6.2 Annual rainfall for the Greater Lake Tarawera catchment showing (a) interannual variability and uncertainty for water years 1972-2018; (b) uncertainty for water year 2003, an average rainfall year; (c) uncertainty for water year 2006, a dry year; and (d) uncertainty for water year 2016, a wet year. Colour coding indicates the amount of the distribution made up from a particular rainfall dataset. Note the scale difference on the y-axis of plot (a).

6.3 Water balance annual averages

Annual averages of the water balance for each lake and its surface water catchment using the best estimate datasets and methods (Table 6.1) are shown in Figures 6.3 and 6.4, and Tables C2 and C3 (Appendix C). Results for the surface water catchments of a lake includes the lakes own local surface water catchment, and the lake and local surface water catchment of any upstream lakes (catchment definitions are described in Section 2.1).

Lakes

Inflows to lakes are dominated by groundwater for Lakes Ōkareka, Ōkataina, Rotomahana, Tarawera and Tikitapu (Figure 6.3(a) and Table C2 in Appendix C). Surface water inflows dominate for Lake Ōkaro. Rainfall contributes most of the inflow to Lake Rerewhakaaitu, followed by groundwater. Rainfall, surface water (via a groundwater fed spring) and groundwater contribute in relatively equal proportions to the inflows for Lake Rotokakahi. Lakes Rotokakahi, Rotomahana and Tarawera all have some contribution from groundwater recharged from outside of the lakes local catchment, comprising most groundwater flows to Lake Rotokakahi (average 82%) and Lake Tarawera (average 70%), and small amount to Lake Rotomahana (average 12%). Outflows are dominated by groundwater for Lakes Ōkaro Ōkataina, Rerewhakaaitu, Rotomahana and Tikitapu; and by surface water outflows for Lakes Ōkareka, Rotokakahi and Tarawera. Groundwater outflows can be zero in some years for Lakes Ōkareka, Rotokakahi and Tarawera.

The flows in and out of Lake Tarawera are significantly larger (average 10.8 $m^3 s^{-1}$) than the other lakes within the greater catchment (Figure 6.4(a) and Table C2 in Appendix C), with the next largest inflows/outflows being Lake Ōkataina (average 2.61 $m^3 s^{-1}$) and Lake Rotomahana (average 2.41 $m^3 s^{-1}$). Lake Ōkaro has the smallest inflows/outflows of the lakes in the greater catchment (average 0.10 $m^3 s^{-1}$).

Surface water catchments

Rainfall is the only source of inflow to the lake catchments (Figure 6.3(b) and Table C3 in Appendix C). Evaporation from land contributes a large part (averaging > 40%) of the outflows from all catchments, with groundwater outflows also contributing a large part (averaging > 40%) of the total outflows from the catchments with no surface water outflow (Ōkataina, Rerewhakaaitu, Rotomahana and Tikitapu), and a smaller part (averaging 10 – 30%) of the total outflows from the catchments with a surface water outlet (Ōkareka, Ōkaro, Rotokakahi and Tarawera).

The flows in and out of the Tarawera surface water catchment are significantly larger (average 19 m^3s^{-1}) than the other surface water catchments in the complex (Figure 6.4(b) and Table C3 in Appendix C), with the next largest inflows/outflows being the Rotomahana surface water catchment (average 5.8 m^3s^{-1}) and Ōkataina surface water catchment (average 3.6 m^3s^{-1}). Ōkaro surface water catchment has the smallest inflows/outflows of the surface water catchments (average 0.16 m^3s^{-1}).

(a)

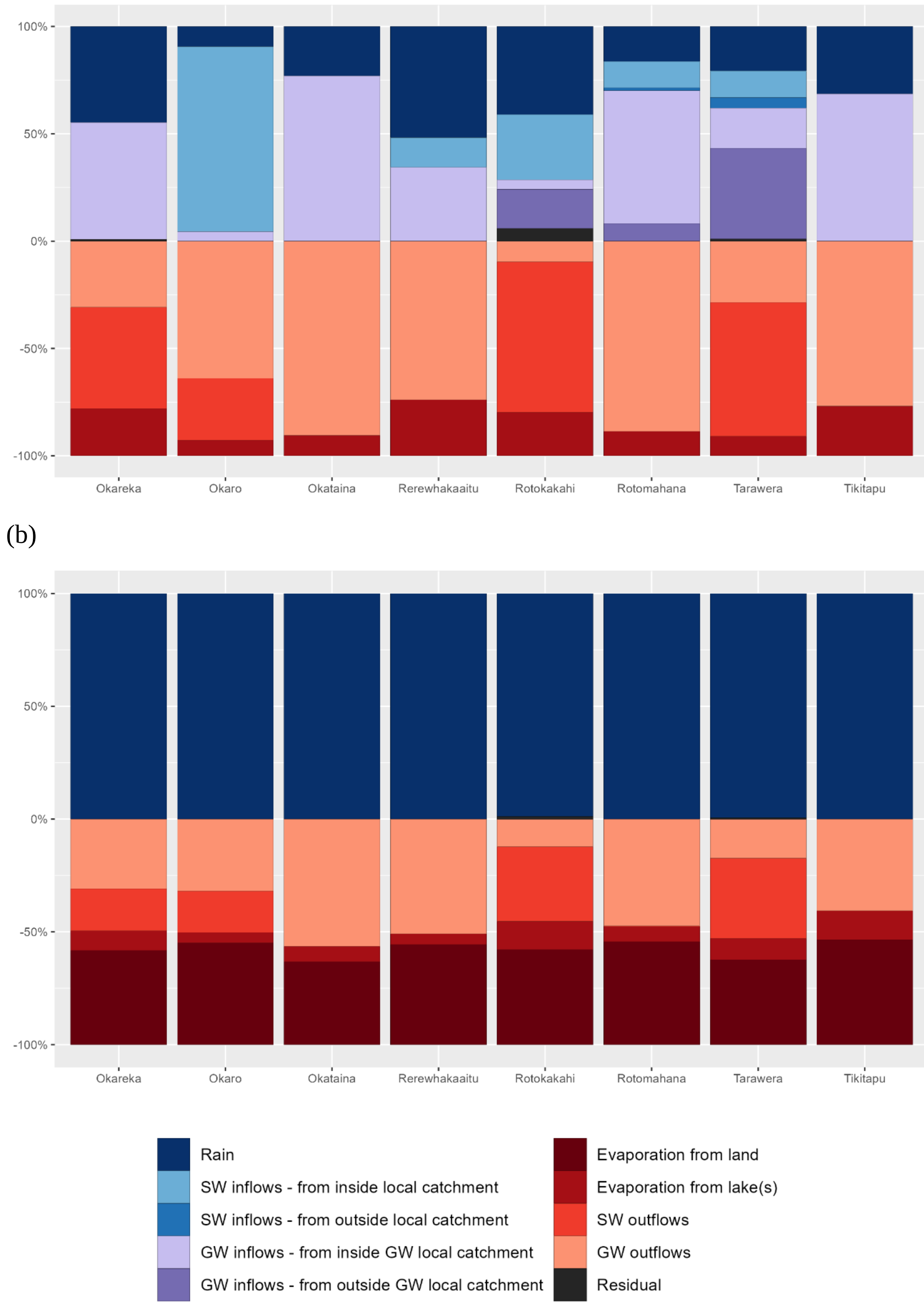
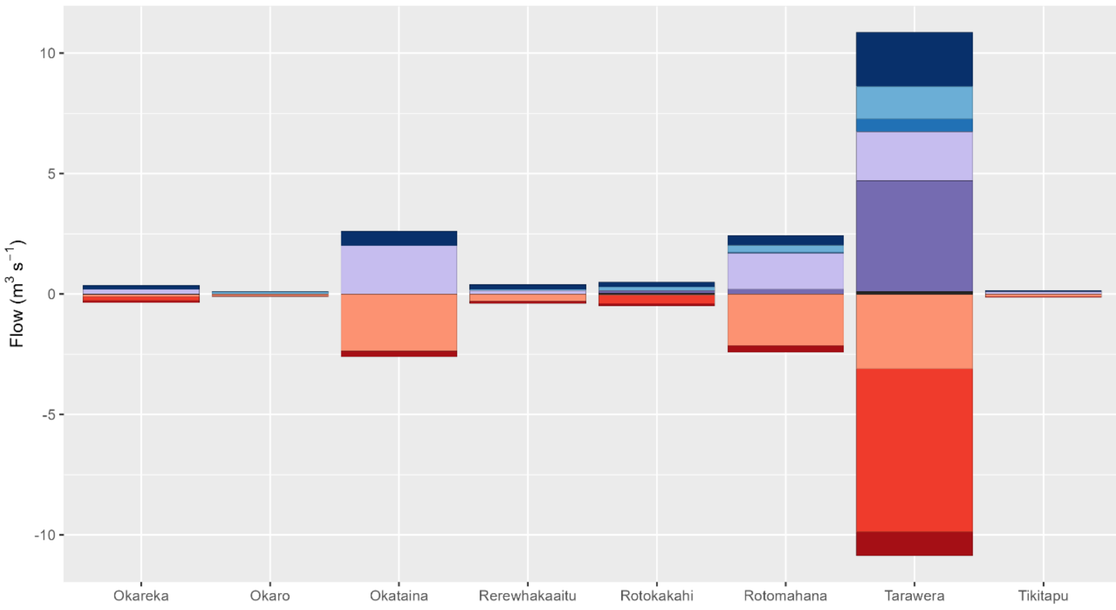


Figure 6.3 Percentage contributions of average annual flows to and from the (a) Greater Tarawera Lakes and (b) their catchments using best estimate datasets and methods calculated using a water balance method. Bars above and below zero indicate inflows and outflows respectively. SW is surface water, GW is groundwater, and the residual is the remaining inflow or outflow required to balance the water balance.

(a)



(b)

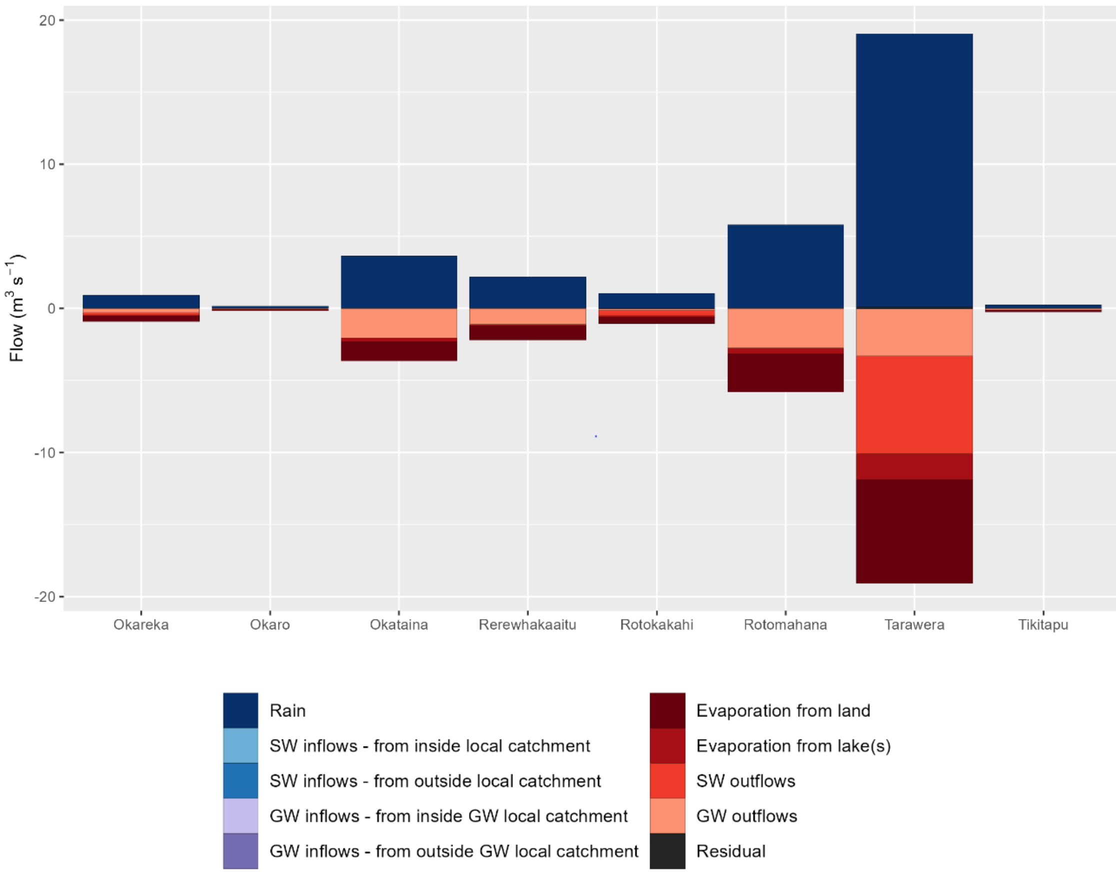


Figure 6.4 Magnitudes of average annual flows to and from the (a) Greater Tarawera Lakes and (b) their catchments using best estimate datasets and methods calculated using a water balance method. Bars above and below zero indicate inflows and outflows respectively. SW is surface water, GW is groundwater, and the residual is the remaining inflow or outflow required to balance the water balance. Note the difference in scale on the y axes.

6.4 Water balance interannual variations and uncertainty

Interannual variations of the water balance for each lake and its surface water catchment are illustrated in Figures 6.5 and 6.6, and Tables C2 and C3 (Appendix C) using the best estimate datasets and methods (Table 6.1). The results of the water balance calculation are given in Tables 6.2 and 6.3. Results account for both interannual variability and the uncertainties inherited from the datasets and methods used, using all realistic combinations of datasets and methods for water balance components considered by this study (Section 4.4). The purpose of this approach is to communicate overall uncertainty as a range of possible values. Results are presented as ranges (using the 95% confidence interval of the distribution) for each lake and its surface water catchment. Breakdowns of the probability distribution statistics for each lake and its surface water catchment are included in Appendix C. (Tables C4 to C19).

Interannual variations

Total inflows and outflows to the lakes and their catchments were at a minimum in years with below average rainfall and well below average drainage[19] (e.g., 1982, 1993 and 2006). Conversely, higher flow years were those with above average rainfall and well above average drainage (e.g., 2010 and 2016) (Figures 6.5 and 6.6). Relative contributions of each component of the water balance can vary year to year with groundwater comprising a larger percentage of the inflows and outflows for both lakes and catchments in wetter years.

Groundwater inflows to Lake Ōkaro and groundwater outflows from Lake Rotokakahi only occur in wetter years (Figure 6.5). In some dry years groundwater outflow from Lake Tarawera can be nil (approximately one in 10 years) (Figure 6.5).

The lack of variation seen in the total inflows and outflows to and from Lake Ōkaro (Figure 6.5) is due to constant values being assigned for surface water inflows and outflows in the absence of enough measurements to create a variable record. The use of these constant surface water inflows and outflows will have an influence on the groundwater inflows and outflows estimated.

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[19] As defined in Section 6.2

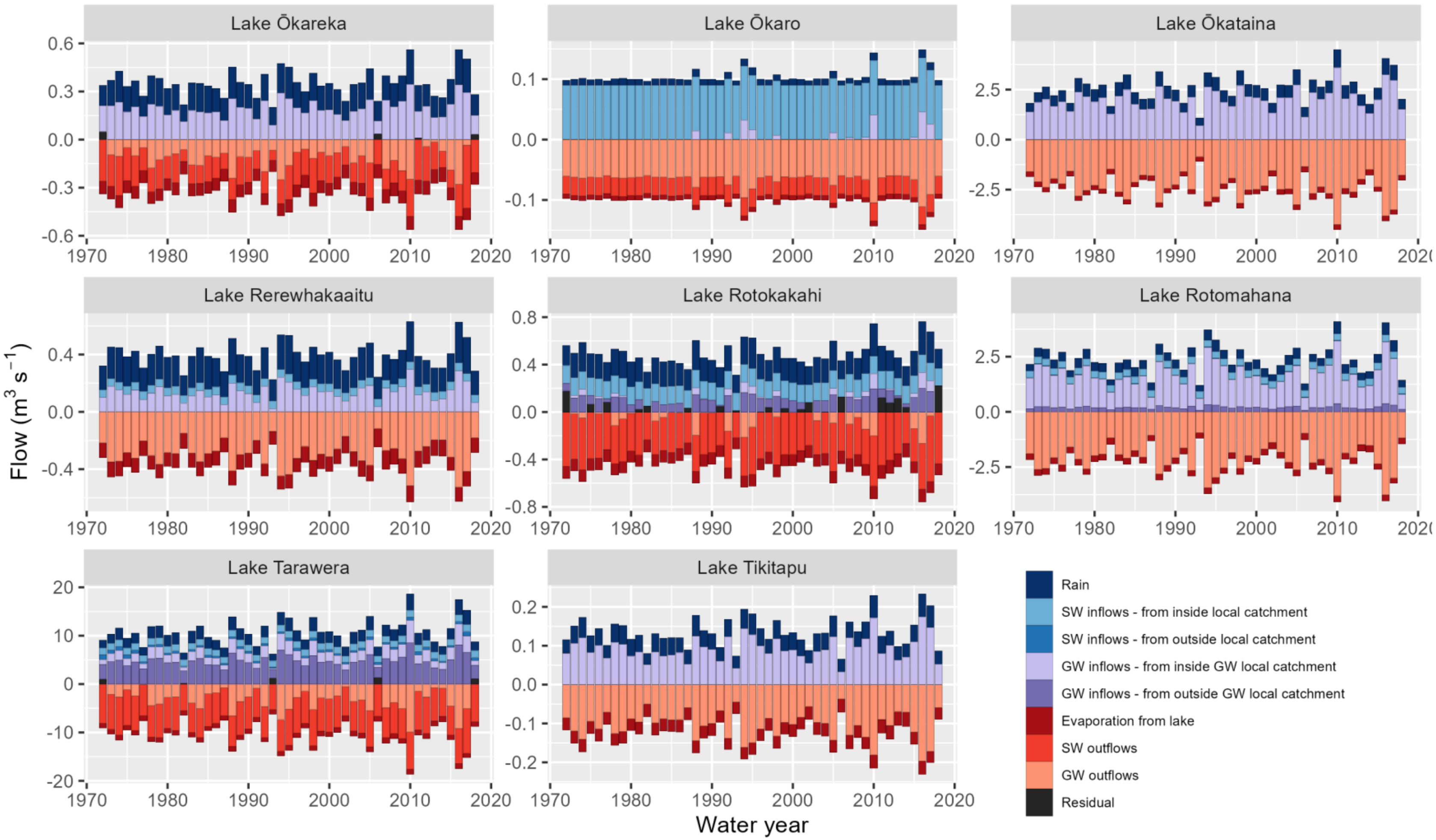


Figure 6.5 **Interannual water balances for Tarawera Lakes for water years 1972-2018 using best estimate datasets and methods calculated using a water balance method. Bars above and below zero indicate inflows and outflows respectively. SW is surface water, GW is groundwater, rain is rainfall directly onto the lake surface. The residual is the amount required to balance inflows and outflows for that water year. Note different y-axis scales.**

Table 6.2 Water balances of the Tarawera Lakes showing the mean and uncertainty range (in brackets) of the flow distributions. The 95% confidence interval of the flow distributions has been used to calculate the uncertainties and accounts for interannual variability.

	Lake Ōkareka	Lake Ōkaro	Lake Ōkataina	Lake Rerewhakaaitu	Lake Rotokakahi	Lake Rotomahana	Lake Tarawera	Lake Tikitapu
Inflows (m^3 s^{-1})								
Rainfall	0.163 (0.109 - 0.223)	0.010 (0.007 - 0.014)	0.609 (0.397 - 0.834)	0.213 (0.149 - 0.289)	0.208 (0.145 - 0.278)	0.405 (0.280 - 0.555)	2.264 (1.453 - 3.134)	0.044 (0.030 - 0.059)
SW in (total)	none	0.090 (0.090 - 0.090)	none	0.055 (0.055 - 0.055)	0.150 (0.150 - 0.150)	0.326 (0.326 - 0.326)	1.870 (1.582 - 2.391)	none
SW in (from inside local catchment) [1]	none	0.090 (0.090 - 0.090)	none	0.055 (0.055 - 0.055)	0.150 (0.150 - 0.150)	0.296 (0.296 - 0.296)	1.336 (1.274 - 1.398)	none
SW in (from outside local catchment) [1]	none	none	none	none	none	0.030 (0.030 - 0.030)	0.534 (0.308 - 0.948)	none
GW in (total)	0.202 (0.086 - 0.344)	0.008 (0.000 - 0.053)	1.887 (0.852 - 3.057)	0.152 (0.036 - 0.306)	0.129 (0.000 - 0.339)	1.903 (0.657 - 3.467)	6.770 (2.300 - 12.570)	0.100 (0.037 - 0.177)
GW in (from inside local catchment) [1]	0.202 (0.086 - 0.344)	0.008 (0.000 - 0.053)	1.887 (0.852 - 3.057)	0.152 (0.036 - 0.306)	0.030 (0.000 - 0.137)	1.661 (0.568 - 3.009)	2.029 (0.313 - 4.277)	0.100 (0.037 - 0.177)
GW in (from outside local catchment) [1]	none	none	none	none	0.099 (0.000 - 0.204)	0.241 (0.056 - 0.554)	4.741 (1.961 - 8.244)	none

[1] Breakdown of the total SW or GW inflow

[2] As (and included in) GW outflows

[3] Positive values represent inflows, negative values outflows

Table 6.2 (continued) Water balances of the Tarawera Lakes showing the mean and uncertainty range (in brackets) of the flow distributions. The 95% confidence interval of the flow distributions has been used to calculate the uncertainties and accounts for interannual variability.

	Lake Ōkareka	Lake Ōkaro	Lake Ōkataina	Lake Rerewhakaaitu	Lake Rotokakahi	Lake Rotomahana	Lake Tarawera	Lake Tikitapu
Outflows (m^3 s^{-1})								
Lake evaporation	0.078 (0.072 - 0.088)	0.008 (0.007 - 0.008)	0.249 (0.230 - 0.278)	0.104 (0.090 - 0.128)	0.100 (0.092 - 0.111)	0.276 (0.257 - 0.302)	0.989 (0.918 - 1.122)	0.032 (0.029 - 0.035)
SW out	0.168 (0.075 - 0.259)	0.030 (0.030 - 0.030)	none	none	0.345 (0.232 - 0.458)	none	6.775 (5.460 - 8.092)	none
GW out	0.123 (0.000 - 0.285)	0.071 (0.059 - 0.120)	2.249 (1.062 - 3.640)	0.317 (0.136 - 0.544)	0.068 (0.000 - 0.283)	2.358 (1.016 - 4.069)	3.275 (0.000 - 9.331)	0.112 (0.039 - 0.196)
Water out of GT catchments [2]	none	none	none	0.135 (0.015 - 0.373)	none	none	none	none
Totals (m^3 s^{-1})								
Inflow total	0.365 (0.202 - 0.567)	0.109 (0.097 - 0.158)	2.496 (1.315 - 3.881)	0.420 (0.243 - 0.647)	0.486 (0.295 - 0.773)	2.634 (1.288 - 4.354)	10.904 (5.511 - 17.646)	0.144 (0.069 - 0.237)
Outflow total	0.368 (0.216 - 0.567)	0.109 (0.097 - 0.158)	2.497 (1.316 - 3.881)	0.420 (0.243 - 0.647)	0.513 (0.336 - 0.763)	2.634 (1.289 - 4.353)	11.039 (6.462 - 17.645)	0.144 (0.071 - 0.229)
Other (m^3 s^{-1})								
Storage change [3]	0.000 (-0.000 - 0.000)	0.000 (-0.000 - 0.001)	-0.001 (-0.025 - 0.010)	0.000 (-0.000 - 0.000)	-0.000 (-0.006 - 0.005)	-0.000 (-0.001 - 0.001)	-0.000 (-0.001 - 0.000)	-0.000 (-0.004 - 0.003)
Residual [3]	0.003 (-0.000 - 0.052)	0.000 (-0.000 - 0.000)	0.000 (-0.000 - 0.000)	0.000 (-0.000 - 0.000)	0.027 (-0.000 - 0.195)	-0.000 (-0.000 - 0.000)	0.135 (-0.000 - 1.806)	0.000 (-0.000 - 0.000)

[1] Breakdown of the total SW or GW inflow

[2] As (and included in) GW outflows

[3] Positive values represent inflows, negative values outflows

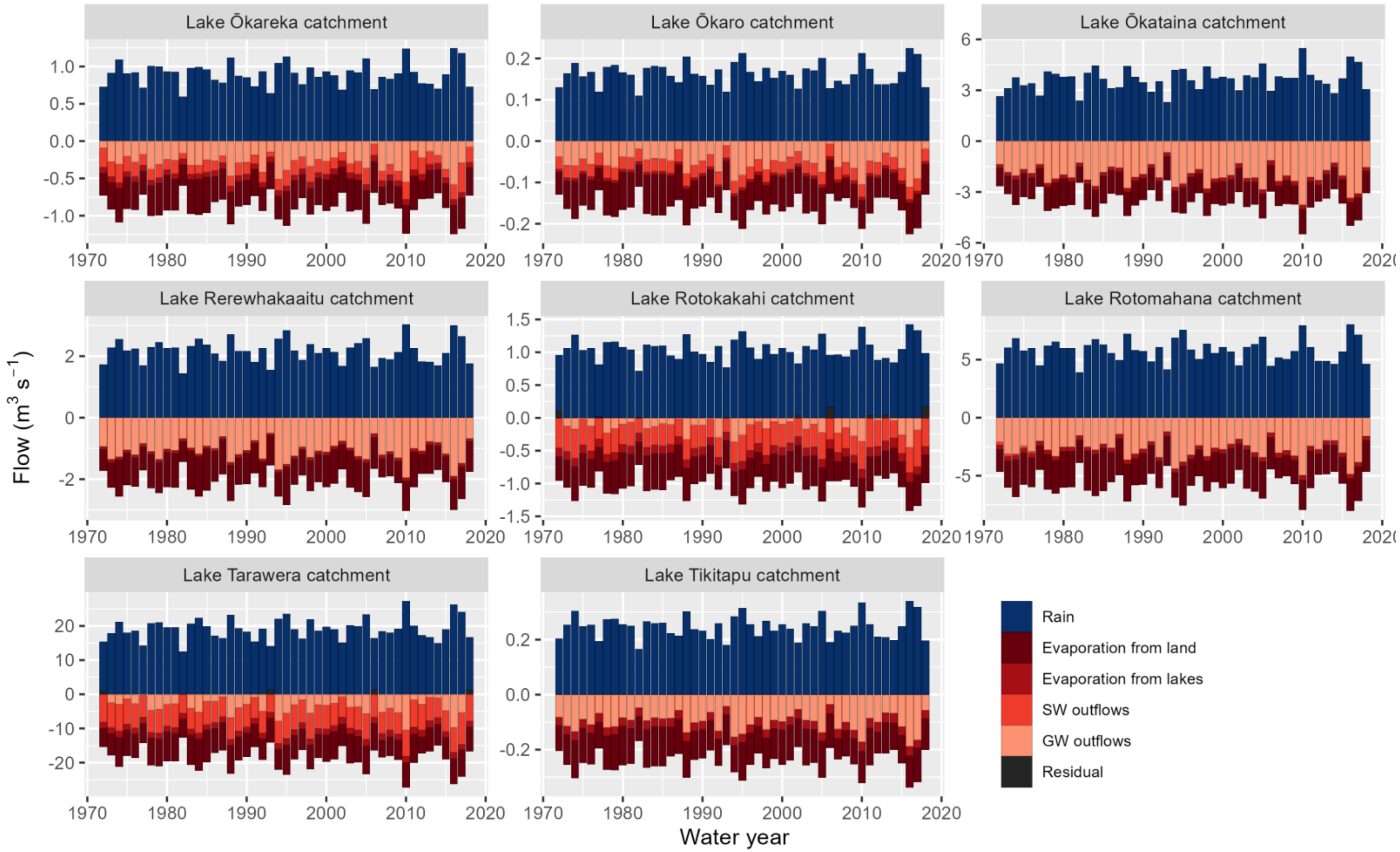


Figure 6.6 Interannual water balances for water years 1972-2018 for the catchments of the Tarawera Lakes using best estimate datasets and methods calculated using a water balance method. Bars above and below zero indicate inflows and outflows respectively. SW is surface water, GW is groundwater. The residual is the amount required to balance inflows and outflows for that water year. Note different y-axis scales.

Table 6.3 Water balances of the Tarawera Lake catchments showing the mean and uncertainty range (in brackets) of the flow distributions. The 95% confidence interval of the flow distributions has been used to calculate the uncertainties and accounts for interannual variability.

	Ōkareka catchment	Ōkaro catchment	Ōkataina catchment	Rerewhakaaitu catchment	Rotokakahi catchment	Rotomahana catchment	Tarawera catchment	Tikitapu catchment
Inflows ($m^3 s^{-1}$)								
Rainfall	0.921 (0.633 - 1.250)	0.170 (0.118 - 0.234)	3.765 (2.442 - 5.186)	2.291 (1.576 - 3.142)	1.061 (0.738 - 1.420)	6.065 (4.177 - 8.305)	19.478 (12.782 - 26.930)	0.253 (0.175 - 0.341)
Outflows ($m^3 s^{-1}$)								
Evaporation from land	0.378 (0.247 - 0.497)	0.073 (0.045 - 0.099)	1.396 (0.949 - 1.753)	0.980 (0.629 - 1.344)	0.440 (0.302 - 0.568)	2.664 (1.739 - 3.656)	7.253 (4.896 - 9.523)	0.115 (0.077 - 0.151)
Evaporation from lake(s)	0.078 (0.072 - 0.088)	0.008 (0.007 - 0.008)	0.249 (0.230 - 0.278)	0.104 (0.090 - 0.128)	0.131 (0.121 - 0.147)	0.387 (0.358 - 0.435)	1.802 (1.670 - 2.025)	0.032 (0.029 - 0.035)
SW out	0.168 (0.075 - 0.259)	0.030 (0.030 - 0.030)	none	none	0.345 (0.232 - 0.458)	0.021 (0.000 - 0.235)	6.775 (5.460 - 8.092)	none
GW out	0.297 (0.052 - 0.583)	0.059 (0.012 - 0.120)	2.122 (0.999 - 3.440)	1.208 (0.556 - 2.047)	0.157 (0.000 - 0.462)	2.992 (1.325 - 5.157)	3.753 (0.000 - 10.171)	0.107 (0.037 - 0.187)
Water out of GT catchments [1]	none	none	none	0.513 (0.064 - 1.392)	none	0.513 (0.064 - 1.392)	0.513 (0.064 - 1.392)	none
Totals ($m^3 s^{-1}$)								
Inflow total	0.921 (0.633 - 1.250)	0.170 (0.118 - 0.234)	3.765 (2.442 - 5.186)	2.291 (1.576 - 3.142)	1.061 (0.738 - 1.420)	6.065 (4.177 - 8.305)	19.478 (12.782 - 26.930)	0.253 (0.175 - 0.341)
Outflow total	0.921 (0.633 - 1.250)	0.170 (0.118 - 0.234)	3.766 (2.446 - 5.183)	2.291 (1.576 - 3.141)	1.073 (0.762 - 1.414)	6.065 (4.178 - 8.304)	19.583 (14.014 - 26.912)	0.253 (0.176 - 0.337)
Other ($m^3 s^{-1}$)								
Residual [2]	0.000 (-0.000 - 0.000)	-0.000 (-0.000 - 0.000)	0.000 (-0.000 - 0.000)	0.000 (-0.000 - 0.000)	0.012 (-0.000 - 0.159)	0.000 (-0.000 - 0.000)	0.104 (-0.000 - 1.469)	-0.000 (-0.000 - 0.000)
Storage change [2]	0.000 (-0.000 - 0.000)	0.000 (-0.000 - 0.001)	-0.001 (-0.025 - 0.010)	0.000 (-0.000 - 0.000)	-0.000 (-0.008 - 0.006)	-0.000 (-0.001 - 0.002)	-0.001 (-0.025 - 0.017)	-0.000 (-0.004 - 0.003)

[1] As (and included in) GW outflows

[2] Positive values represent inflows, negative values outflows

Storage changes predicted from lake levels are observed in all lakes but are most notable (>1% of total flow) in Lakes Ōkaro, Ōkataina, Rotokakahi and Tikitapu (Tables 6.2 and C2 (Appendix C)). Analysis indicates that positive storage changes (i.e., rising lake levels) generally occur in years when annual rainfall was greater than 1,600 mm (Figure 6.7).

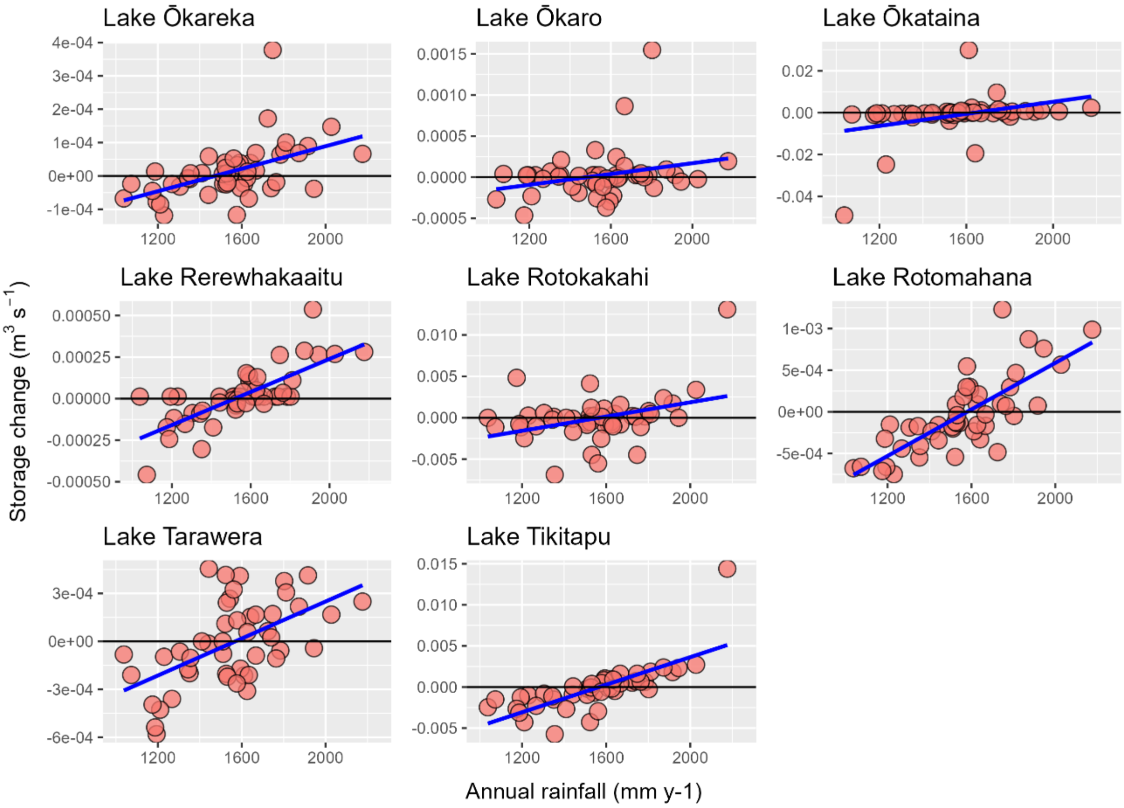
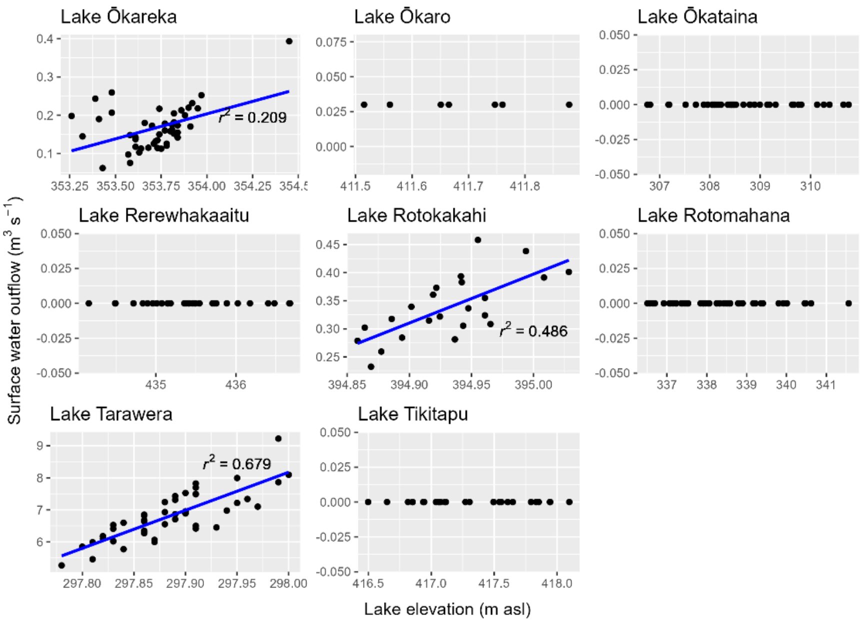


Figure 6.7 Relationship between annual rainfall and storage change in the Greater Tarawera Lakes. Black horizontal lines indicate zero storage change, points above the zero line indicate increasing lake levels (positive storage change), and points below the black line indicate declining lake levels (negative storage change). Blue lines show a linear trend line. Note the different scales on the y axes.

In some years (e.g., 1972, 2006, 2011, 2018), usually dry years with below average drainage, the estimated outflows from Lakes Ōkareka, Rotokakahi and Tarawera (and the catchments of Rotokakahi and Tarawera) exceed the estimated inflows, and there is a residual in the water balance suggesting groundwater outflows are zero (Figures 6.5 and 6.6). In case of Ōkareka and Tarawera, this residual usually follows a wet year, indicating water may be released from storage to sustain outflows in drier years. There is often a residual in the water balance of Lake Rotokakahi, occurring approximately half of the time, in both dry years and years with average rainfall. This residual could imply that local groundwater catchment boundary of Lake Rotokakahi and/or Lake Tikitapu is incorrect and may be larger than estimated by White et al. (2020) to sustain the estimated outflows (note that the local catchments of both Lake Tikitapu and Lake Rotokakahi are included in the water balance calculation for the (whole) catchment of Lake Rotokakahi).

Figure 6.8 shows the relationship between annual lake level and annual surface water and groundwater outflows estimated from the water balance calculations for the Tarawera Lakes. In those lakes with a surface water outlet (Ōkareka, Ōkaro, Rotokakahi, and Tarawera), there is an observable relationship between lake level and surface water outflow (Figure 6.8(a)), the exception being Lake Ōkaro whose surface water outflow was assigned as a constant value due to lack of data. No clear relationships between estimated groundwater outflows and lake level are observed in the results (Figure 6.8(b)).

(a)



(b)

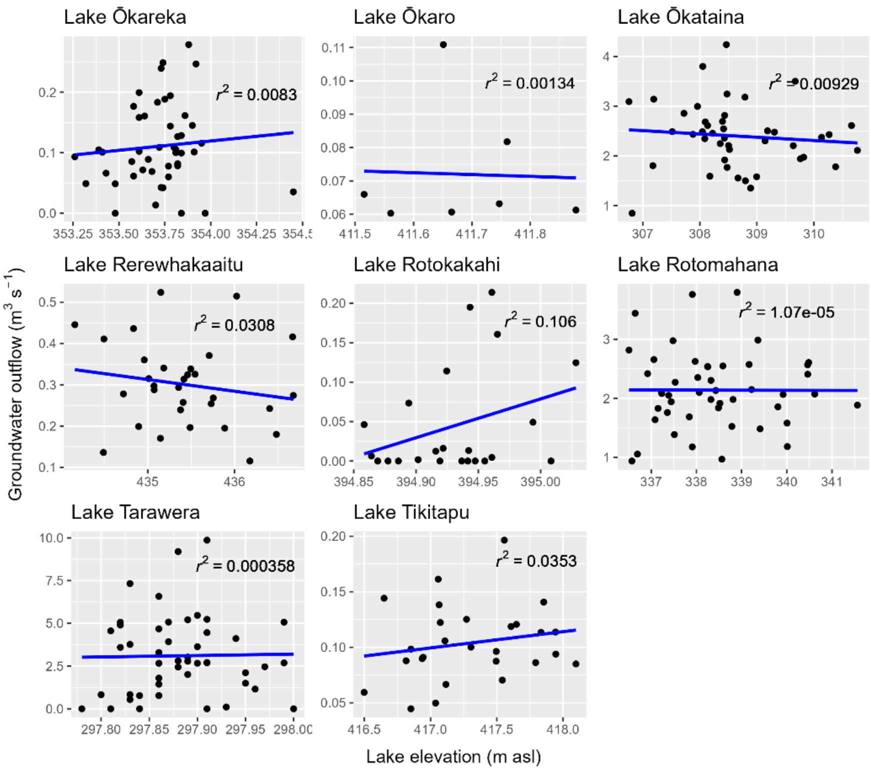


Figure 6.8 Relationship between estimated (a) annual surface water outflows and (b) annual groundwater outflows from lakes with annual lake elevations. Blue lines show a linear trend line. Annual lake elevations were only calculated in years in which there were at least 12 lake level measurements. The R squared value of a linear regression is shown on each graph where applicable

6.5 Surface water inflows and outflows

Single datasets were used to estimate the annualised flows for each inflow and outflow, with 47 water years used for the calculations (1972 to 2018). Uncertainty in streamflow estimation typically ranges from 3 – 17 % for median flows (Kiang et al., 2018), and this range likely to be a good indication of uncertainty in the mean annual surface water inflows to the lakes in a given year.

Inflows

Interannual variability of surface water inflows to Lake Tarawera are shown in Figure 6.9 and Table 6.2. Most surface water inflows to Lake Tarawera originate from inside its local catchment (6.9(b) and 6.9(c)). Flows originating from inside of the local catchment are largely sourced from groundwater fed springs and have less variability than those originating from outside of the local catchment which are sourced directly from upstream lakes. Variability in surface water inflows to the other lakes in the study area are shown in Figures C2, C3 and C4 (Appendix C).

The variability of annual surface water inflow to Lake Tarawera is estimated with 95% confidence to be 1.58 – 2.39 m^3 s^{-1} (mean of 1.87 m^3 s^{-1} or 1432 mm y^{-1}) (Table 6.2 and Figure 6.9).

Outflows

The variability of annual surface water outflows from Lake Tarawera and its catchment are shown in Figure 6.10, other lakes and catchments in the study area are shown in Figure C5 (Appendix C), Tables 6.2 and 6.3. The variability of annual surface water outflow from Lake Tarawera is estimated with 95% confidence to be 5.46 – 8.09 m^3 s^{-1} (mean of 6.78 m^3 s^{-1} or 5192 mm y^{-1}).

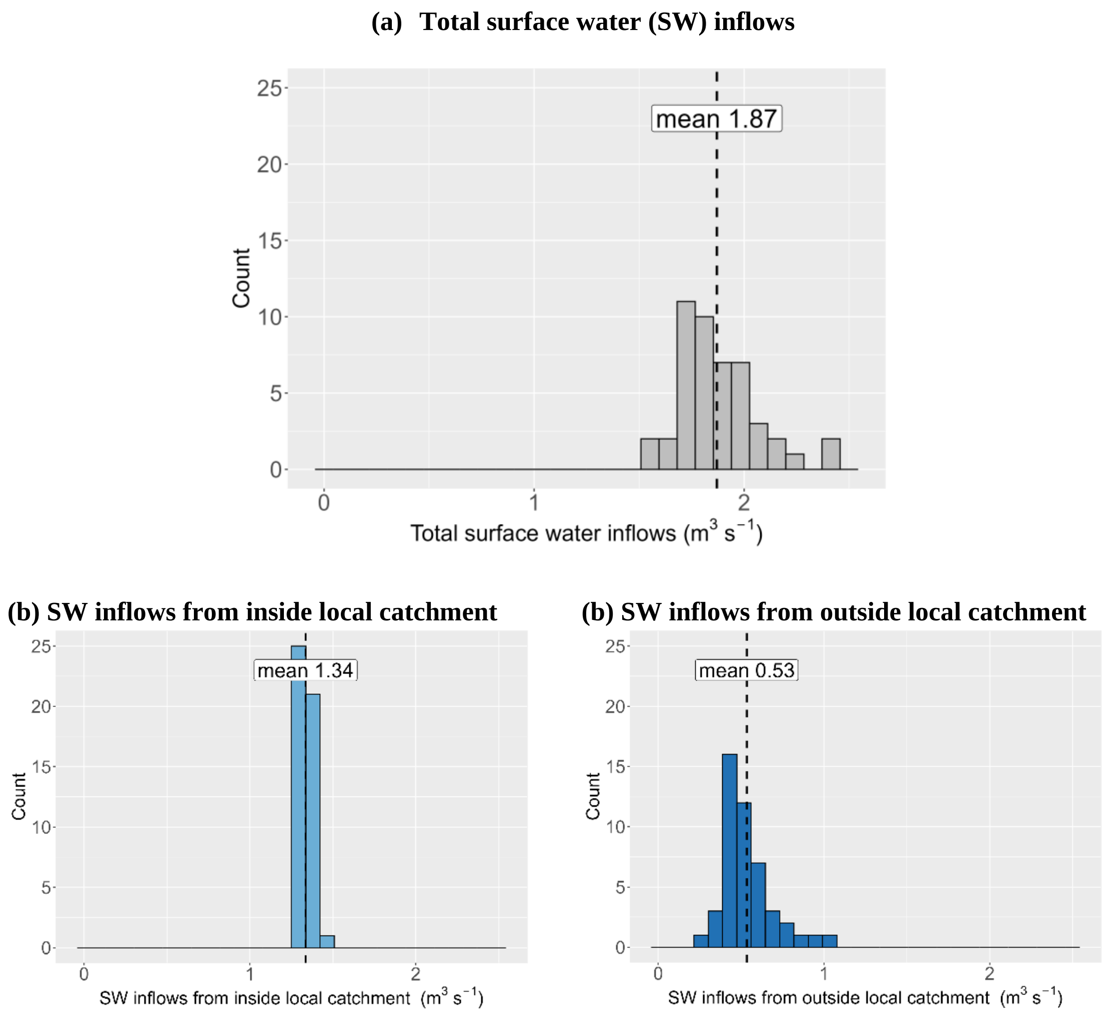


Figure 6.9 Interannual variability of surface water inflows to Lake Tarawera for water years 1972-2018 showing (a) total surface water inflows; (b) surface water inflows originating from inside of the Lake Tarawera local catchment; and (c) surface water inflows originating from outside of the Lake Tarawera local catchment. The dashed line indicates the mean of the distribution.

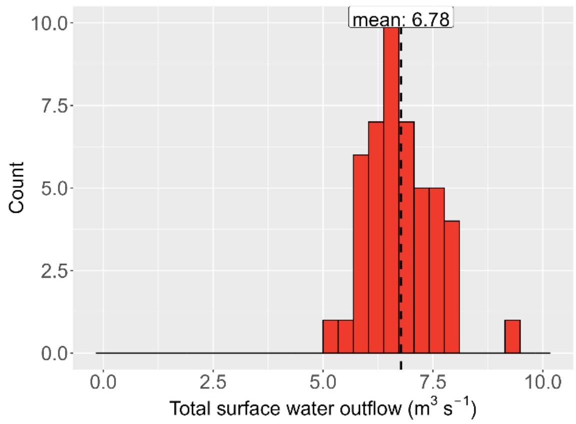


Figure 6.10 Interannual variability of surface water outflow for water years 1972-2018 from Lake Tarawera and its catchment (the Tarawera River at the outlet of Lake Tarawera). The dashed line indicates the mean of the entire distribution.

6.6 Groundwater inflows and outflows

Seven factors affect estimated groundwater inflows and outflows: the surface water catchment boundary (2 alternatives, applies only to the catchment water balance), the groundwater catchment boundary (1 option), the rainfall dataset (5 alternatives), the crop factor (2 alternatives), the forest evaporation correction factor (2 alternatives), the amount of groundwater leaving the Tarawera Lake catchments from the Rerewhakaaitu catchment (2 alternatives which apply only to the water balances for Rerewhakaaitu, Rotomahana and Tarawera), and the water year (47 alternatives). Thus, there are 1880 estimations of groundwater inflows and outflows to Lake Tarawera, and 3760 estimations of groundwater inflows and outflows to the catchment of Lake Tarawera.

Inflows

The interannual variability and uncertainty of groundwater inflows to Lake Tarawera are shown in Figures 6.11(a) and 6.12(a). Most groundwater inflows to Lake Tarawera originate from outside its local catchment (Figures 6.11(b) and 6.11(c)). Flows originating from inside of the local catchment have less variability than those originating from outside of the local catchment. Variability in groundwater inflows to the other lakes in the study area are shown in Figures C6, C7 and C8 (Appendix C).

The interannual variability and uncertainty of groundwater inflow to Lake Tarawera is estimated with 95% confidence to be 2.30 – 12.57 $m^3\ s^{-1}$ (mean of 6.77 $m^3\ s^{-1}$ or 5184 mm y^{-1}).

Outflows

The interannual variability and uncertainty of groundwater outflows from Lake Tarawera and its catchment are shown in Figures 6.13 and 6.14, other lakes and catchments in the study area are shown in Figures C9 and C10 (Appendix C). Groundwater outflows are estimated to be zero in some years for Lakes Ōkareka, Rotokakahi and Tarawera, and the catchments of Rotokakahi and Tarawera.

The interannual variability and uncertainty of groundwater outflow from Lake Tarawera is estimated with 95% confidence to be 0.00 – 9.33 $m^3\ s^{-1}$ (mean of 3.28 $m^3\ s^{-1}$ or 2511 mm y^{-1}) (Table 6.2), and from the catchment to be 0.00 – 10.17 $m^3\ s^{-1}$ (mean of 3.75 $m^3\ s^{-1}$ or 301 mm y^{-1}) (Table 6.3).

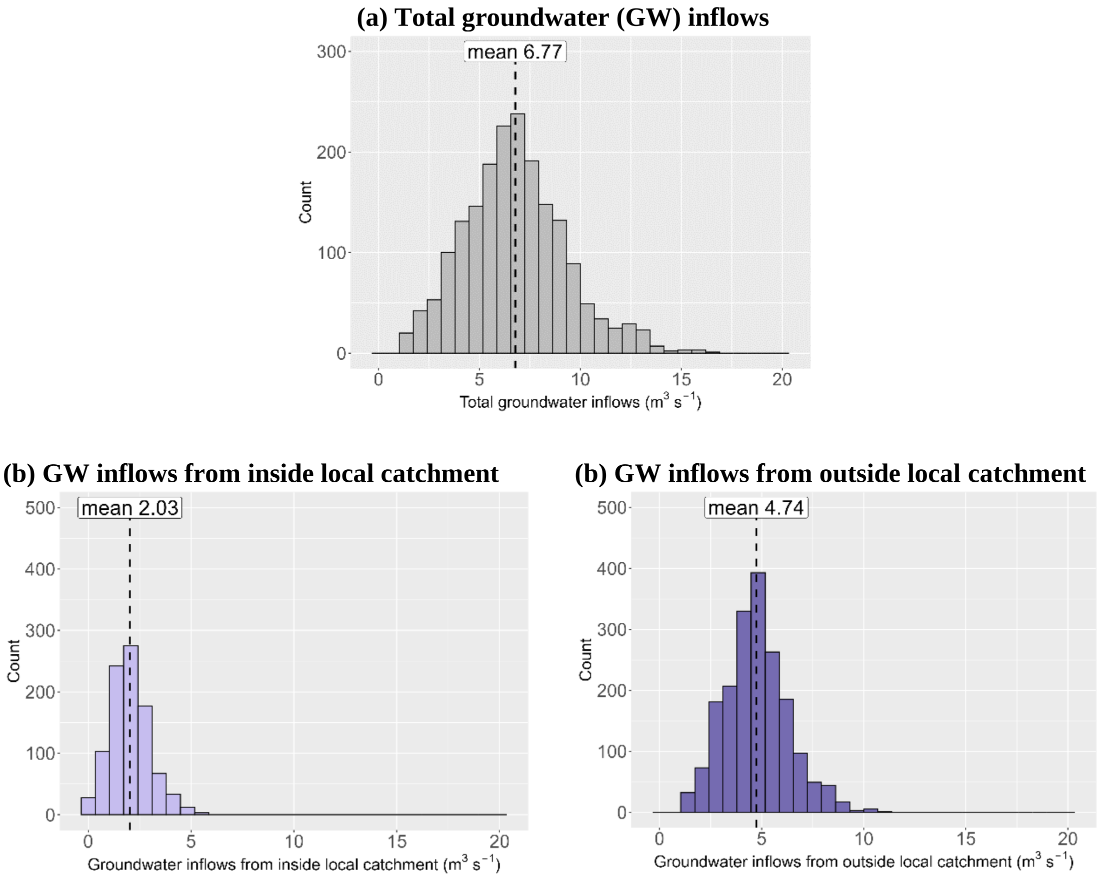


Figure 6.11 Interannual variability and uncertainty of groundwater inflows to Lake Tarawera for water years 1972-2018 showing (a) total groundwater inflows; (b) groundwater inflows originating from inside the Lake Tarawera local catchment; and (c) groundwater inflows originating from outside the Lake Tarawera local catchment. Note the scale difference on the y-axis of plot (a). The dashed line indicates the mean of the distribution.

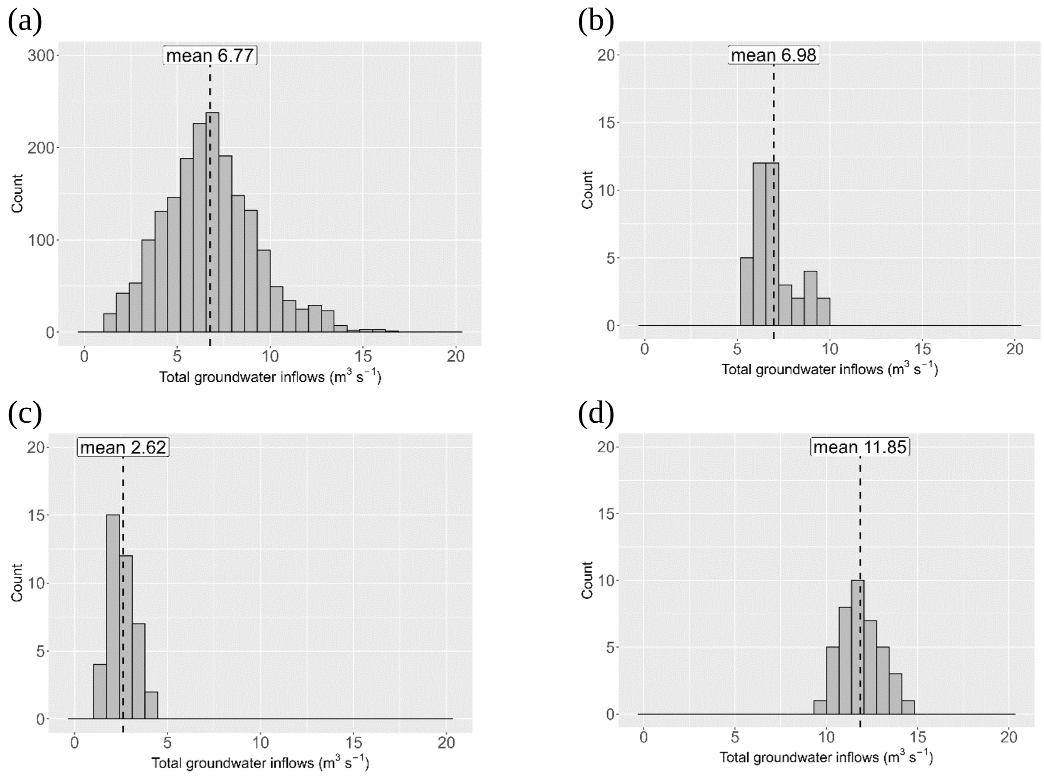


Figure 6.12 Groundwater inflow to Lake Tarawera showing (a) interannual variability and uncertainty for water years 1972-2018; (b) uncertainty for water year 2003, an average rainfall year; (c) uncertainty for water year 2006, a dry year; and (d) uncertainty for water year 2016, a wet year. Note the scale difference on the y-axis of plot (a). The dashed line indicates the mean of the distribution.

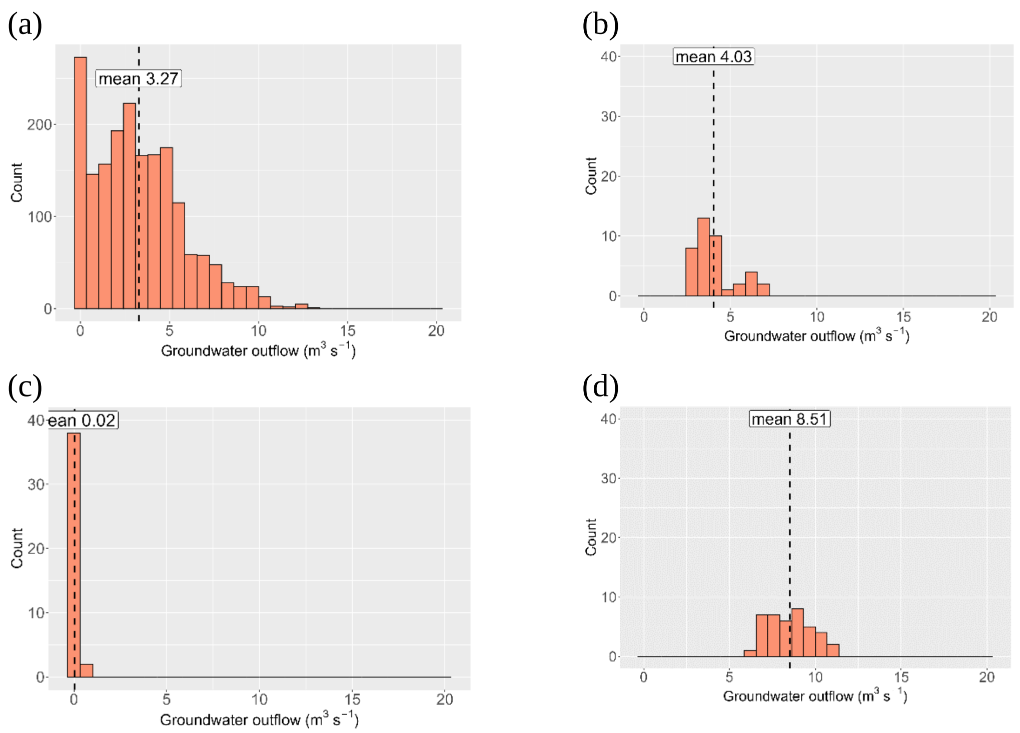


Figure 6.13 Groundwater outflow from Lake Tarawera showing (a) interannual variability and uncertainty for water years 1972-2018; (b) uncertainty for water year 2003, an average rainfall year; (c) uncertainty for water year 2006, a dry year; and (d) uncertainty for water year 2016, a wet year. Note the scale difference on the y-axis of plot. The dashed line indicates the mean of the distribution. (a).

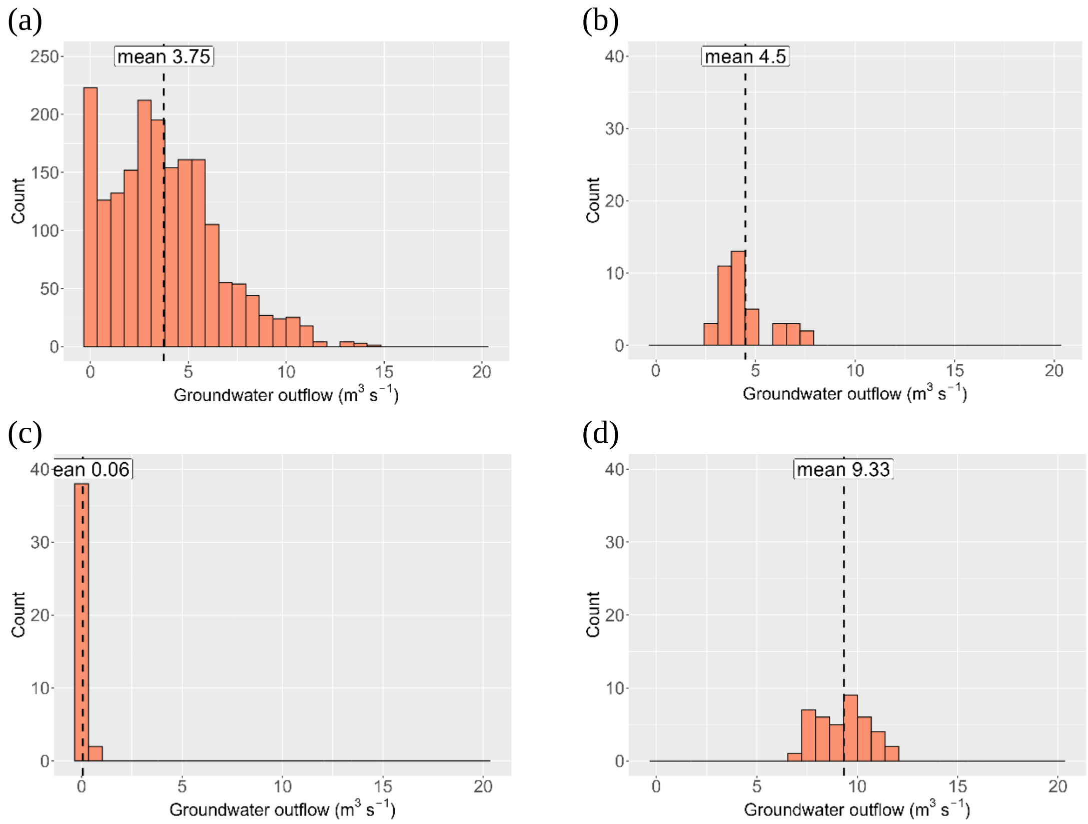


Figure 6.14 Groundwater outflow from the catchment of Lake Tarawera showing (a) interannual variability and uncertainty for water years 1972-2018; (b) uncertainty for water year 2003, an average rainfall year; (c) uncertainty for water year 2006, a dry year; and (d) uncertainty for water year 2016, a wet year. Note the scale difference on the y-axis of plot (a).

6.7 Evaporation from land

Six factors affect the estimated annual land evaporation: the surface water catchment boundary (2 alternatives, applies only to the catchment water balance), the rainfall dataset (5 alternatives), the crop factor (2 alternatives), the forest evaporation correction factor (2 alternatives), and the water year (47 alternatives). Thus, there are 1880 model estimates of annual land evaporation. The uncertainties and interannual variability of land evaporation over the Greater Lake Tarawera catchment are shown in Figure 6.15, the effect of adjusting for water stress is illustrated by the colour of the distribution (blue indicates the calculations have been performed adjusting for water stress, and red indicates no adjustment for water stress has been made). It should be noted that in the water balance and uncertainties presented in Sections 6.3 and 6.4 evaporation was adjusted for water stress; results for the no adjustment scenario are presented here solely for comparative purposes. Adjusting for water stress decreases the land evaporation estimation by an average of 2.06 $m^3\ y^{-1}$ (or 204 mm y^{-1}) over the Greater Lake Tarawera catchment (Figure 6.15(a)). Interannual variability and uncertainty in land evaporation from the other catchments in the study area are shown in Figure C11 (Appendix C).

The interannual variability and uncertainty of land evaporation from Greater Lake Tarawera catchment is estimated with 95% confidence to be 4.896 – 9.523 $m^3\ s^{-1}$ (mean of 7.253 $m^3\ s^{-1}$ or 582 mm y^{-1}) (Table 6.3).

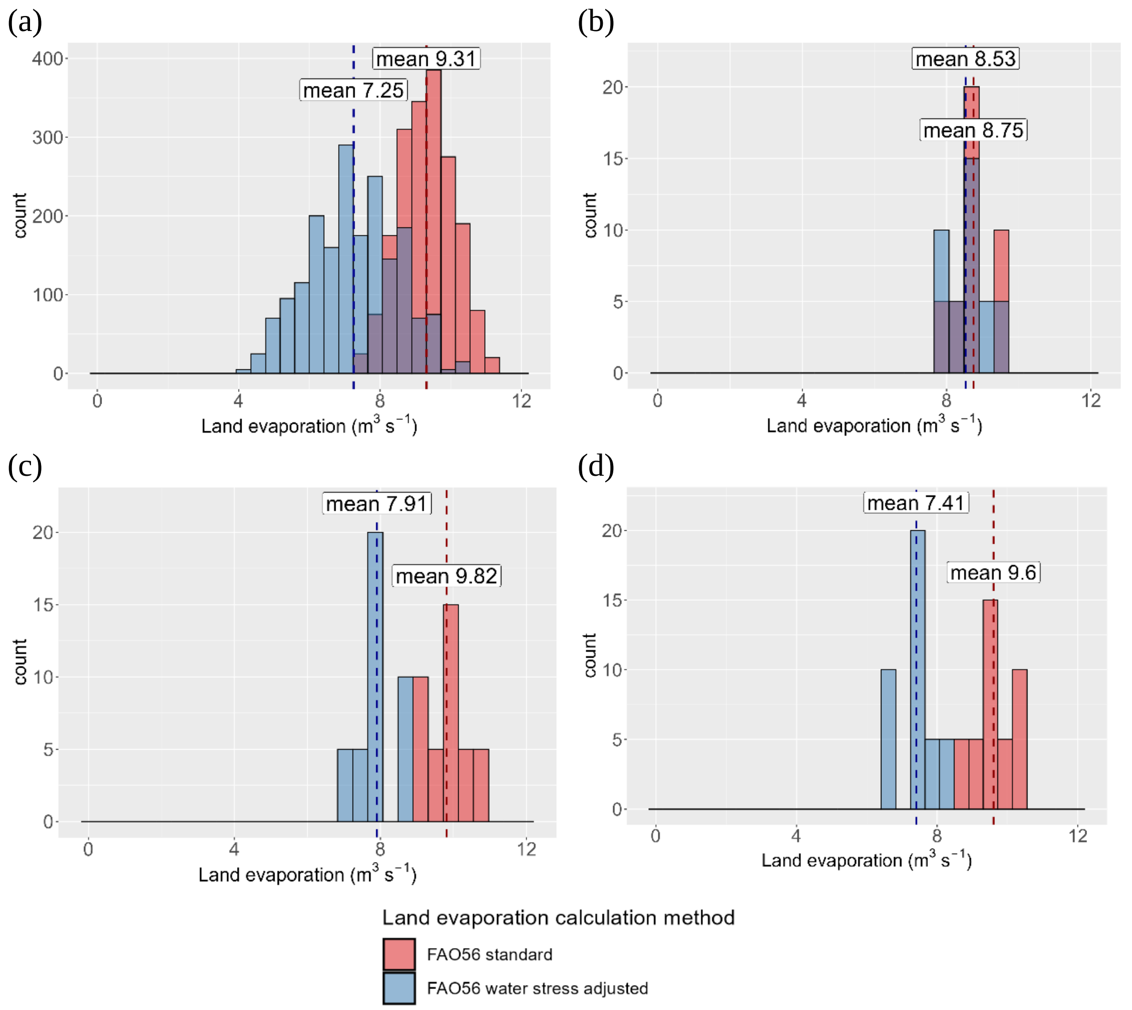


Figure 6.15 Land evaporation for the Greater Lake Tarawera catchment using two different calculation methods. Plots show (a) interannual variability and uncertainty for water years 1972-2018; (b) uncertainty for water year 2003, an average rainfall year; (c) uncertainty for water year 2006, a dry year; and (d) uncertainty for water year 2016, a wet year. Colours indicate the calculation method. Note the scale difference on the y-axis of plot (a).

6.8 Lake evaporation

Single meteorological datasets from the operational VCS were used to estimate the annualised lake evaporation, with 47 water years used for the calculations (1972 to 2018). The interannual variability of lake evaporation from Lake Tarawera over this period is shown in Figure 6.16. Interannual variability in lake evaporation from the other lakes in the study area are shown in Figure C12 (Appendix C). The interannual variability of lake evaporation from Lake Tarawera is estimated with 95% confidence to be 0.918 – 1.122 $m^3\ s^{-1}$ (mean of 0.989 $m^3\ s^{-1}$ or 757 mm y^{-1}) (Table 6.2).

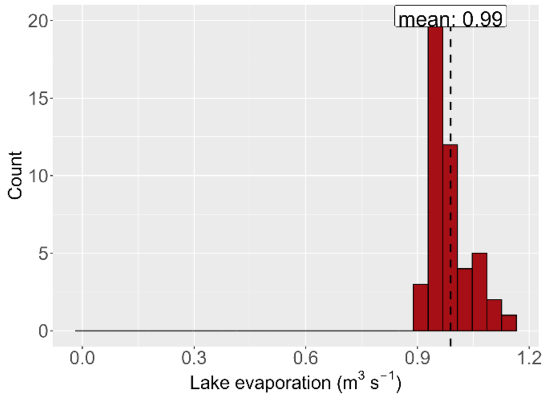


Figure 6.16 Interannual variation in lake evaporation from Lake Tarawera.

Chapter 7

Annualised nutrient loads to the Greater Tarawera lakes

7.1 Introduction

This chapter describes the modelled annual variations and uncertainties of nutrient loads to the Greater Tarawera lakes. Overall numeric results and uncertainties presented use all possible datasets and methods for nutrient load calculations considered in this study (Sections 4.3 and 4.4). The purpose of this approach is to communicate overall variability and uncertainty as ranges with an underlying probability distribution. In addition, to visualise annual temporal variations, a single set of calculations have been run using the datasets and methods that are considered to represent best estimates for the nutrient load calculation (Table 6.1). The purpose of these modelled best-estimate calculations is to illustrate the variations that can exist year to year under a set of given assumptions. Modelled nutrient loads are based on the current and historical land uses recorded in the LCDB (Section 4.2.3). The leaching method chosen for calculating the modelled best-estimate loads is based on drainage (rainfall minus evaporation), because drainage more accurately represents the amount of water moving through the soil and available for nutrient transport than rainfall alone. There are much greater variations in drainage than there are in rainfall for the study area (Section 6.2) which is reflected in the variation in nutrient loads calculated in the following sections. The load calculation method chosen for the modelled best-estimate loads uses a constant concentration of nutrients (in the drainage water), therefore the annual load received by the lake is variable dependant on the amount of drainage each year.

For comparison to modelled nutrient loads based on current land uses, two extreme scenarios have been modelled – a conversion of all land to native forest, and a conversion of all land to agriculture. This has been done to determine the best- and worst-case nutrient load scenarios, and to understand where the current land use sits on this spectrum. These scenarios are not intended to represent realistic land use change, but put outer limits on the range of possible loads.

7.2 Modelled annual averages

Modelled annual average nutrient loads to lakes from the current land use in their local catchments are shown in Figure 7.1, and Tables 7.1 and 7.2. Detailed breakdowns for each lakes are included in Appendix D (Tables D1 to D8).

The breakdown of nutrient loads to the Tarawera lakes is related to the proportion of land uses within the lakes local catchment, in addition to other nutrient sources such as geothermal, wastewater, and lake water quality, land uses and nutrient sources in any upstream lake local catchments (Figure 7.1). Lakes that have a greater proportion of agricultural land uses in their local catchment (e.g. Ōkaro), have relatively higher modelled nutrient loads relative to their size, than lakes with a greater proportion of forest in their local catchment (e.g. Ōkataina). Greater than 40% of modelled average annual TN load to the lakes is derived from agricultural land uses in Lakes Ōkareka, Ōkaro, Rerewhakaaitu, Rotokakahi, and Rotomahana; and greater than 40% of the modelled average annual TP load to Lakes Ōkareka, Ōkaro, Rotokakahi, and Rerewhakaaitu (Figure 7.1). A large amount (58%) of the TP load to Lake Rotomahana is from geothermal sources. There are loads received from groundwater and/or surface water connections from upstream lake catchments to Lakes Rotokakahi, Rotomahana and Tarawera, comprising 7%, 4%, and 22% of modelled average annual TN loads, and 3%,1%, and 23% of modelled average annual TP to the lakes respectively.

Atmospheric deposition of nutrient loads to the water surface of the lakes occurs from dissolved nutrients in rainfall (wet deposition) and from particulates (dry deposition) (McBride et al., 2020). Loads from atmospheric deposition have been applied to the Tarawera Lakes at a rate of 6.7 kg ha^{-1} $y-^{1}$ for TN and 0.34 kg ha^{-1} $y-^{1}$ for TP (Verburg (2015) as citied in McBride et al., 2020) and account for between 5.3% and 43% of modelled average annual TN loads (Lake Ōkaro and Lake Tikitapu respectively), and 1.5% and 41% of modelled average annual TP loads to the lakes. Unknown land uses have been assigned a nutrient yield similar to scrub/shrub as per McBride et al. (2020).

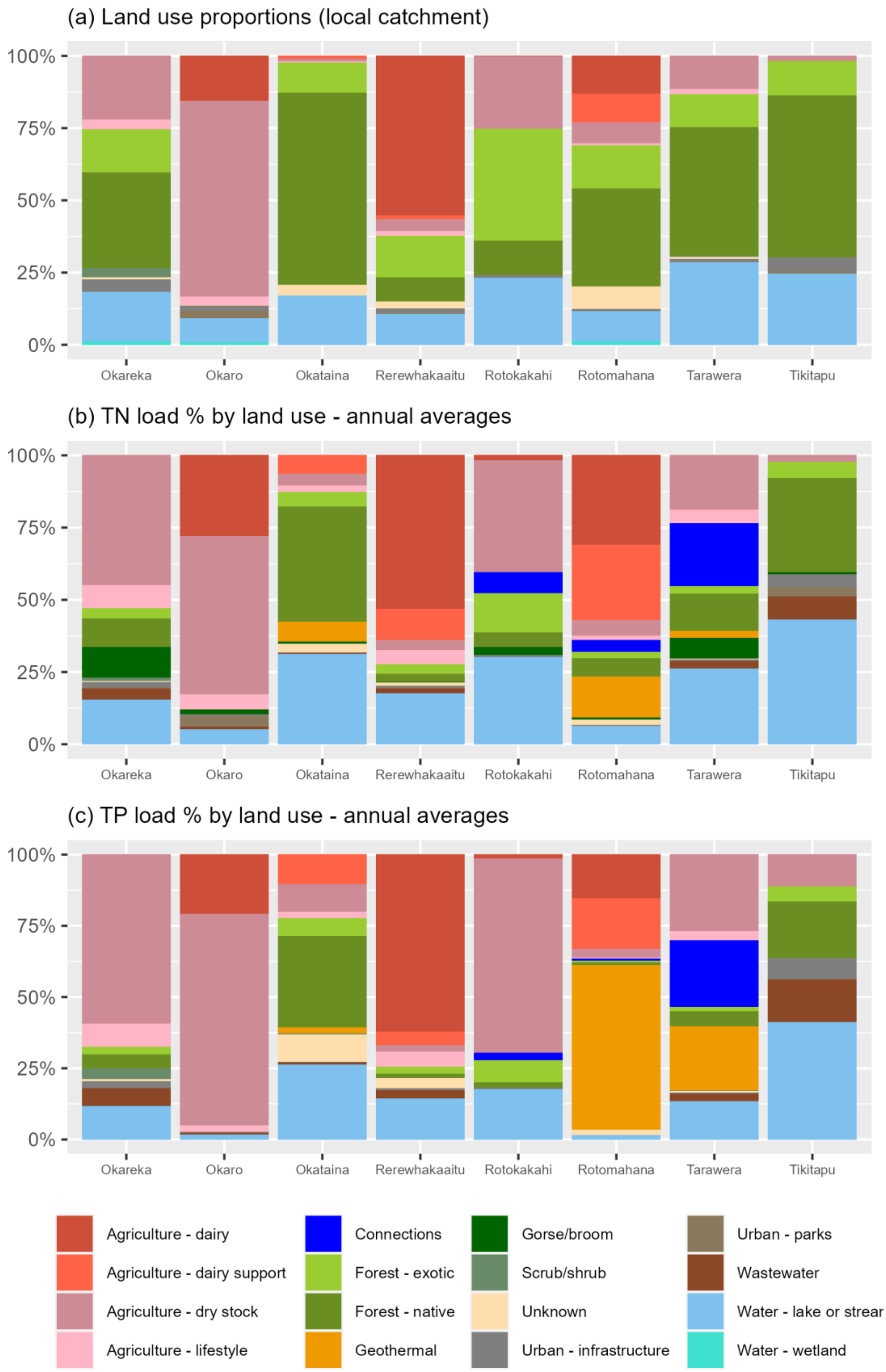


Figure 7.1 Percentage contributions of (a) current land use, (b) modelled average annual total nitrogen (TN) load, and (c) total phosphorus (TP) load to the Tarawera Lakes from the land uses in their local catchments. "Connections" are estimated loads received from upstream lake local catchment(s) via surface water and groundwater. Atmospheric deposition directly to the lakes and wetlands are represented by "water" in the key.

Table 7.1 Breakdown of modelled average annual total nitrogen load to the Tarawera lakes by land use/nutrient source. "Connections" are estimated loads received from upstream lake local catchments via surface water and groundwater. Atmospheric deposition directly to the lakes and wetlands are represented by "water".

	Average annual total nitrogen load to lake (t y^{-1})							
Land use/nutrient source	Ōkareka	Ōkaro	Ōkataina	Rerewhakaaitu	Rotokakahi	Rotomahana	Tarawera	Tikitapu
Agriculture - dairy	-	1.13	-	11.20	0.18	29.57	-	-
Agriculture - dairy support	-	-	1.46	2.30	-	24.80	-	-
Agriculture - dry stock	6.74	2.22	0.97	0.74	3.83	5.18	20.27	0.05
Agriculture - lifestyle	1.21	0.21	0.48	1.04	-	1.32	4.94	-
Connections	-	-	-	-	0.71	3.88	23.19	-
Forest - exotic	0.53	-	1.17	0.68	1.34	2.15	2.82	0.12
Forest - native	1.46	0.00	9.13	0.59	0.51	6.10	13.67	0.71
Geothermal	-	-	1.58	-	-	13.44	2.69	-
Gorse/broom	1.59	0.07	0.18	0.06	0.28	0.61	7.58	0.02
Scrub/shrub	0.19	-	0.02	-	-	-	0.12	-
Unknown	0.04	-	0.67	0.24	-	1.91	0.27	-
Urban - infrastructure	0.28	0.02	0.03	0.09	0.06	0.21	0.53	0.10
Urban - parks	0.04	0.15	-	0.08	-	0.01	0.03	0.07
Wastewater	0.61	0.04	0.11	0.37	-	0.07	2.84	0.17
Water - lake or stream	2.29	0.21	7.14	3.70	2.98	5.90	27.87	0.94
Water - wetland	0.00	−0.15	-	0.00	-	0.00	-	-
All sources	**14.98**	**3.90**	**22.94**	**21.09**	**9.89**	**95.16**	**106.82**	**2.19**

Table 7.2 Breakdown of modelled average annual total phosphorus load to the Tarawera lakes by land use/nutrient source. "Connections" are estimated loads received from upstream lake local catchments via surface water and groundwater. Atmospheric deposition directly to the lakes and wetlands are represented by "water".

	Average annual total phosphorus load to lake (t y^{-1})							
Land use/nutrient source	Ōkareka	Ōkaro	Ōkataina	Rerewhakaaitu	Rotokakahi	Rotomahana	Tarawera	Tikitapu
Agriculture - dairy	-	0.13	-	0.81	0.01	3.20	-	-
Agriculture - dairy support	-	-	0.15	0.06	-	3.65	-	-
Agriculture - dry stock	0.59	0.47	0.13	0.03	0.59	0.60	2.87	0.01
Agriculture - lifestyle	0.08	0.01	0.03	0.07	-	0.09	0.33	-
Connections	-	-	-	-	0.02	0.16	2.49	-
Forest - exotic	0.03	-	0.09	0.03	0.07	0.11	0.18	0.01
Forest - native	0.05	0.00	0.44	0.02	0.02	0.20	0.55	0.02
Geothermal	-	-	0.03	-	-	11.93	2.39	-
Gorse/broom	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Scrub/shrub	0.04	-	0.01	-	-	-	0.03	-
Unknown	0.01	-	0.13	0.05	-	0.38	0.05	-
Urban - infrastructure	0.02	0.00	0.00	0.01	0.01	0.02	0.05	0.01
Urban - parks	0.00	0.00	-	0.00	-	0.00	0.00	0.00
Wastewater	0.06	0.00	0.01	0.04	-	0.01	0.28	0.02
Water - lake or stream	0.12	0.01	0.36	0.19	0.15	0.30	1.41	0.05
Water - wetland	0.00	−0.04	-	0.00	-	0.00	-	-
All sources	**0.99**	**0.59**	**1.39**	**1.30**	**0.86**	**20.65**	**10.65**	**0.12**

7.3 Modelled annual variations

Annual variations of modelled total nitrogen and total phosphorus loads to Lake Tarawera using best-estimate datasets and methods (Table 6.1) are shown in Figure 7.2 and Table 7.3. The other lakes of the Tarawera catchment are included in Table 7.3 and shown in Appendix D (Figures D1-D16).

Estimated loads were at their minimum for all lakes in 2006 and their maximum in 2016 (Figure 7.2). Loads to Lake Tarawera have an interannual variability of between approximately 60% and 157% of the annual average (Table 7.3). Moving averages of loads have been included in the calculations because current council policy is based on three-year averages. Moving averages give smoother results, reducing the variability to between 83% and 130% for Lake Tarawera when considering the three-year moving average. Five-year and ten-year averages have been included for comparison to the three-year rolling average, and further reduce the variability to 87% - 113%, and 96% - 109% respectively.

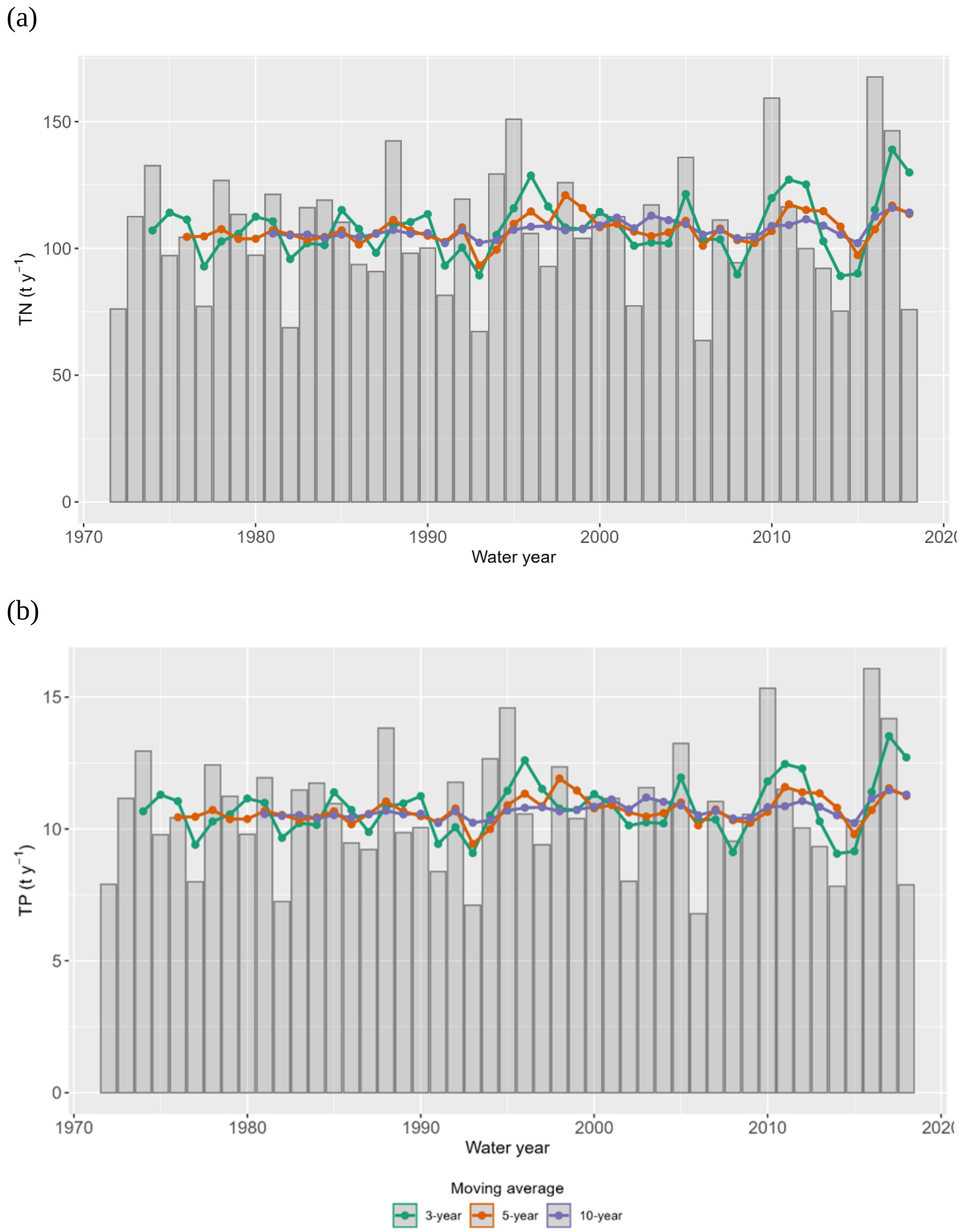


Figure 7.2 Modelled annual (a) total nitrogen (TN) loads, and (b) total phosphorus (TP) loads for Lake Tarawera from 1972 – 2018 using best estimate datasets and methods. Moving averages for 3-year, 5-year and 10-year loads are shown by lines. Note the scale difference on the y-axis.

Table 7.3 Modelled annual variations of total phosphorus (TP) and total nitrogen (TN) loads to the Tarawera Lakes with 3-year, 5-year and 10-year moving averages using best-estimate datasets and methods.

	TP range (t y^{-1})	TP range (%)	TN range (t y^{-1})	TN range (%)
Lake Ōkareka				
Annual	0.51 - 1.66	52% - 168%	7.87 - 24.99	53% - 167%
3-year average	0.79 - 1.34	80% - 136%	12.06 - 20.28	81% - 135%
5-year average	0.84 - 1.15	85% - 116%	12.75 - 17.31	85% - 116%
10-year avaerage	0.94 - 1.09	95% - 110%	14.20 - 16.49	95% - 110%
Mean	0.99		14.98	
Lake Ōkaro				
Annual	0.23 - 1.11	39% - 187%	1.66 - 7.05	43% - 181%
3-year average	0.44 - 0.87	74% - 147%	2.98 - 5.57	76% - 143%
5-year average	0.48 - 0.71	81% - 120%	3.20 - 4.64	82% - 119%
10-year avaerage	0.55 - 0.67	93% - 113%	3.65 - 4.38	94% - 112%
Mean	0.59		3.9	
Lake Ōkataina				
Annual	0.81 - 2.20	58% - 159%	14.64 - 34.63	64% - 151%
3-year average	1.15 - 1.82	83% - 131%	19.54 - 29.13	85% - 127%
5-year average	1.21 - 1.58	87% - 114%	20.34 - 25.67	89% - 112%
10-year avaerage	1.32 - 1.51	95% - 109%	22.03 - 24.71	96% - 108%
Mean	1.39		22.94	
Lake Rerewhakaaitu				
Annual	0.67 - 2.20	51% - 169%	11.07 - 35.18	53% - 167%
3-year average	1.04 - 1.78	80% - 137%	16.98 - 28.55	81% - 135%
5-year average	1.10 - 1.51	84% - 116%	17.94 - 24.37	85% - 116%
10-year avaerage	1.23 - 1.44	94% - 110%	19.99 - 23.22	95% - 110%
Mean	1.3		21.09	

Table 7.3 (continued) Modelled annual variations of total phosphorus and total nitrogen loads to the Tarawera Lakes with 3-year, 5-year and 10-year moving averages using best-estimate datasets and methods.

	TP range ($t\ y^{-1}$)	TP range (%)	TN range ($t\ y^{-1}$)	TN range (%)
Lake Rotokakahi				
Annual	0.44 - 1.45	51% - 168%	5.82 - 15.61	59% - 158%
3-year average	0.69 - 1.17	80% - 136%	8.22 - 12.92	83% - 131%
5-year average	0.73 - 1.00	85% - 116%	8.61 - 11.22	87% - 113%
10-year avaerage	0.82 - 0.95	95% - 110%	9.44 - 10.75	95% - 109%
Mean	0.86		9.89	
Lake Rotomahana				
Annual	15.70 - 27.62	76% - 134%	50.60 - 157.90	53% - 166%
3-year average	18.62 - 24.34	90% - 118%	76.88 - 128.36	81% - 135%
5-year average	19.10 - 22.28	92% - 108%	81.16 - 109.79	85% - 115%
10-year avaerage	20.11 - 21.70	97% - 105%	90.26 - 104.64	95% - 110%
Mean	20.65		95.16	
Lake Tarawera				
Annual	6.79 - 16.08	64% - 151%	63.63 - 167.63	60% - 157%
3-year average	9.06 - 13.52	85% - 127%	89.10 - 139.00	83% - 130%
5-year average	9.43 - 11.91	89% - 112%	93.25 - 121.00	87% - 113%
10-year avaerage	10.22 - 11.47	96% - 108%	102.08 - 116.01	96% - 109%
Mean	10.65		106.82	
Lake Tikitapu				
Annual	0.09 - 0.16	77% - 137%	1.56 - 3.08	71% - 140%
3-year average	0.10 - 0.14	86% - 120%	1.93 - 2.66	88% - 121%
5-year average	0.11 - 0.13	94% - 111%	2.00 - 2.40	91% - 109%
10-year avaerage	0.11 - 0.12	94% - 103%	2.12 - 2.33	97% - 106%
Mean	0.12		2.19	

7.4 Comparison of modelled loads to lake water quality data

Some temporal water quality data is available for the Tarawera Lakes from BOPRC monitoring (post 1985), the exception being Lake Rotokakahi which is a privately owned lake. BOPRC lake monitoring data is shown alongside modelled nutrient loads in Appendix D (Figures D1 – D16). In addition, the Tarawera River at the outflow from Lake Tarawera is monitored by NIWA as part of the National River Water Quality Network (Figure 7.3). Water quality data from the Tarawera River at the Lake Tarawera outflow monitored by NIWA is considered to better represent nutrient concentrations in Lake Tarawera due to problematic monitoring data of BOPRC (McBride & Baisden, 2019). There is no clear correlation between peaks in modelled nutrient loads and peaks in nutrient concentrations measured in the Tarawera Lakes or the outflow water from Lake Tarawera, however the full range of processes that lead to changes in lake nutrient concentrations (e.g., sedimentation and mixing) have not been explored in this research.

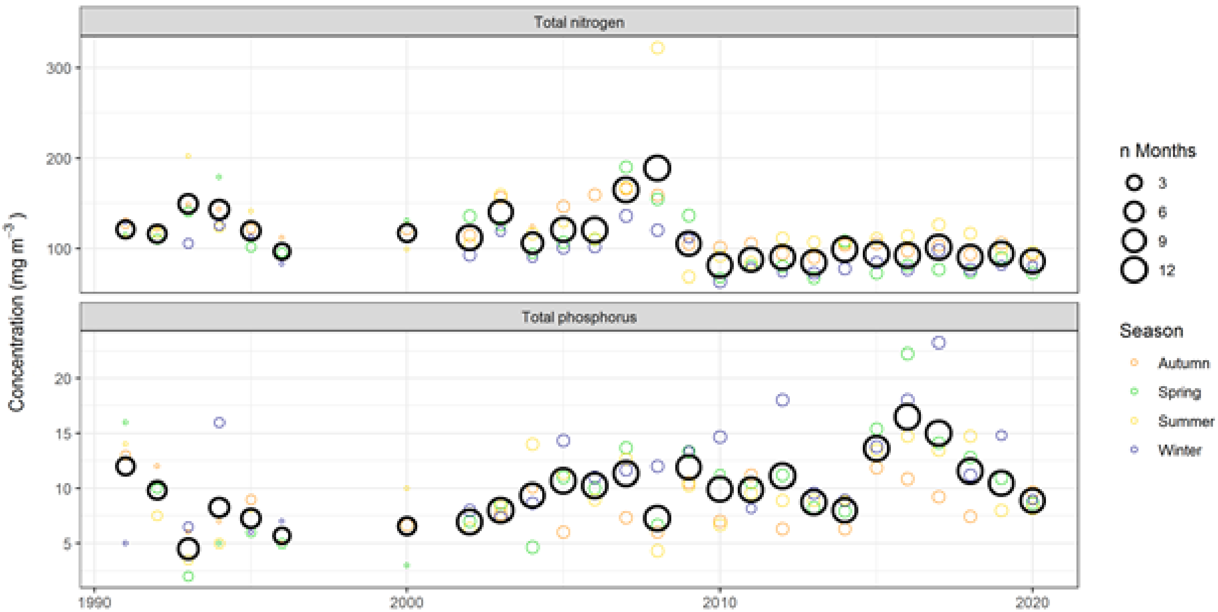


Figure 7.3 Lake Tarawera water quality data from 1991 to 2020. Total nitrogen and phosphorus concentrations were measured by NIWA at the lake outflow. Modified from Abell et al. (2020).

7.5 Uncertainty and land use scenario modelling

Uncertainty and scenario modelling results for nutrient loads to the Tarawera Lakes are shown in Table 7.4. Detailed modelling results and the modelling distributions for Lake

Tarawera are shown in Table 7.5 and in Figure 7.4, other lakes in the study area are included in Appendix D (Tables D9 - D16 and Figures D17 - D24).

Five factors affect the estimated nutrient load to a lake: the surface water catchment boundary (2 alternatives), the rainfall dataset (5 alternatives), the leaching method (2 alternatives), the load calculation method (3 options for TN and 2 options for TP), and the water year (47 alternatives). Thus, there are 2820 estimations of TN loads, and 1880 estimations of TP loads to the lakes.

Scenario modelling indicates that the mean annual nutrient load to Lake Tarawera could be as low as 79.70 t y^{-1} TN and 7.41 t y^{-1} TP in the best-case scenario, and as high as 262.17 t y^{-1} TN and 24.87 t y^{-1} TP in the worst-case scenario (Table 7.5).

The size of nutrient loads to the Tarawera Lakes depends on the size of the nutrient source (e.g., land use, stocking rate and fertiliser inputs) and the transport of the nutrients (e.g., soil type, amount of water drainage, and slope). This study presents uncertainties solely based on the transport of nutrients. The main factors affecting the nutrient loads are the leaching method (i.e., whether the load is calculated using solely rainfall, or rainfall minus evaporation (drainage)), and the load calculation method (i.e., whether a constant load of nutrients to the receiving environment is assumed, or a constant concentration of nutrients in the drainage water is assumed).

Histograms of the distribution of nitrogen loads to Lake Tarawera, showing the breakdown of the distribution made up from the leaching method and load calculation method are shown in Figure 7.5. A greater variation in the calculated loads is estimated when using a drainage-adjusted leaching method (red contributions to the histogram bars in Figure 7.5(a)) than what is calculated using a rainfall-adjusted leaching method (blue contributions to the histogram bars in Figure 7.5(a)), because the observed variations in drainage are greater than those in rainfall (Section 6.2). Unsurprisingly, using a constant load (to the receiving environment) for the load calculation method results in no variation in calculated loads (purple contributions to the histogram bars in Figure 7.5(b)). Using constant concentrations (in the drainage water) for load calculations increases the range of load estimates (yellow and green contributions to the histogram bars in Figure 7.5(b)). More variation in load estimates results when a constant concentration of loads is applied to all land uses (green contributions to the histogram bars in Figure 7.5(b)). rather than only agricultural land uses (yellow contributions to the histogram bars in Figure 7.5(b)).

Table 7.4 Nutrient loads to the Tarawera Lakes showing the mean and uncertainty range (in brackets) for the current land use, and the best- and worst-case scenarios. The 95% confidence interval of the flow distributions has been used to calculate the uncertainties and accounts for interannual variability.

	Lake Ōkareka	Lake Ōkaro	Lake Ōkataina	Lake Rerewhakaaitu	Lake Rotokakahi	Lake Rotomahana	Lake Tarawera	Lake Tikitapu
Current land use (t y^{-1})								
Total nitrogen	15.151 (10.251 - 20.428)	3.912 (2.291 - 5.822)	23.440 (17.749 - 28.533)	21.181 (13.903 - 29.427)	9.904 (7.107 - 12.656)	95.487 (63.447 - 131.865)	106.893 (77.190 - 135.080)	2.192 (1.760 - 2.585)
Total phosphorus	1.002 (0.651 - 1.382)	0.595 (0.332 - 0.892)	1.416 (0.989 - 1.881)	1.308 (0.850 - 1.826)	0.863 (0.562 - 1.202)	20.682 (17.108 - 24.728)	10.653 (7.879 - 13.786)	0.117 (0.095 - 0.141)
Best-case scenario: native forest (t y^{-1})								
Total nitrogen	6.512 (5.058 - 7.865)	0.839 (0.539 - 1.099)	20.921 (16.178 - 25.182)	6.921 (5.774 - 7.978)	6.981 (5.369 - 8.379)	39.793 (31.584 - 46.983)	79.699 (61.027 - 97.448)	2.078 (1.692 - 2.429)
Total phosphorus	0.305 (0.251 - 0.366)	0.001 (0.000 - 0.013)	0.833 (0.649 - 1.031)	0.326 (0.283 - 0.374)	0.290 (0.231 - 0.357)	12.986 (12.668 - 13.345)	7.406 (6.001 - 8.996)	0.099 (0.085 - 0.116)
Worst-case scenario: agricultural (t y^{-1})								
Total nitrogen	35.132 (22.169 - 47.200)	6.729 (4.054 - 9.050)	116.550 (74.289 - 154.521)	29.508 (19.286 - 38.921)	32.988 (20.895 - 43.467)	170.248 (109.485 - 223.463)	262.165 (169.813 - 350.089)	9.655 (6.217 - 12.785)
Total phosphorus	3.044 (1.829 - 4.397)	0.564 (0.315 - 0.847)	9.984 (5.885 - 14.417)	2.487 (1.528 - 3.554)	2.779 (1.666 - 4.039)	25.469 (19.864 - 31.820)	24.866 (16.081 - 34.796)	0.825 (0.503 - 1.184)

Table 7.5 Detailed scenario and uncertainty model summary statistics for Lake Tarawera. Results for the current land use are highlighted by grey shading. The 95% confidence interval of the flow distributions has been used to calculate the uncertainties and accounts for interannual variability.

Lake Tarawera nutrient loads: land use scenarios

Summary statistics (t y^{-1})

	Nitrogen			Phosphorus		
	TN all native	TN current	TN all agriculture	TP all native	TP current	TP all agriculture
Mean	79.699	106.893	262.165	7.406	10.653	24.866
Median	79.649	106.822	262.077	7.397	10.646	24.837
95% CI lower limit	61.027	77.190	169.813	6.001	7.879	16.081
95% CI upper limit	97.448	135.080	350.089	8.996	13.786	34.796
Minimum	52.408	63.528	127.252	5.450	6.778	12.605
Maximum	117.953	167.632	451.476	10.138	16.077	42.022
Uncertainty and variability	(61.027 - 97.448)	(77.190 - 135.080)	(169.813 - 350.089)	(6.001 - 8.996)	(7.879 - 13.786)	(16.081 - 34.796)

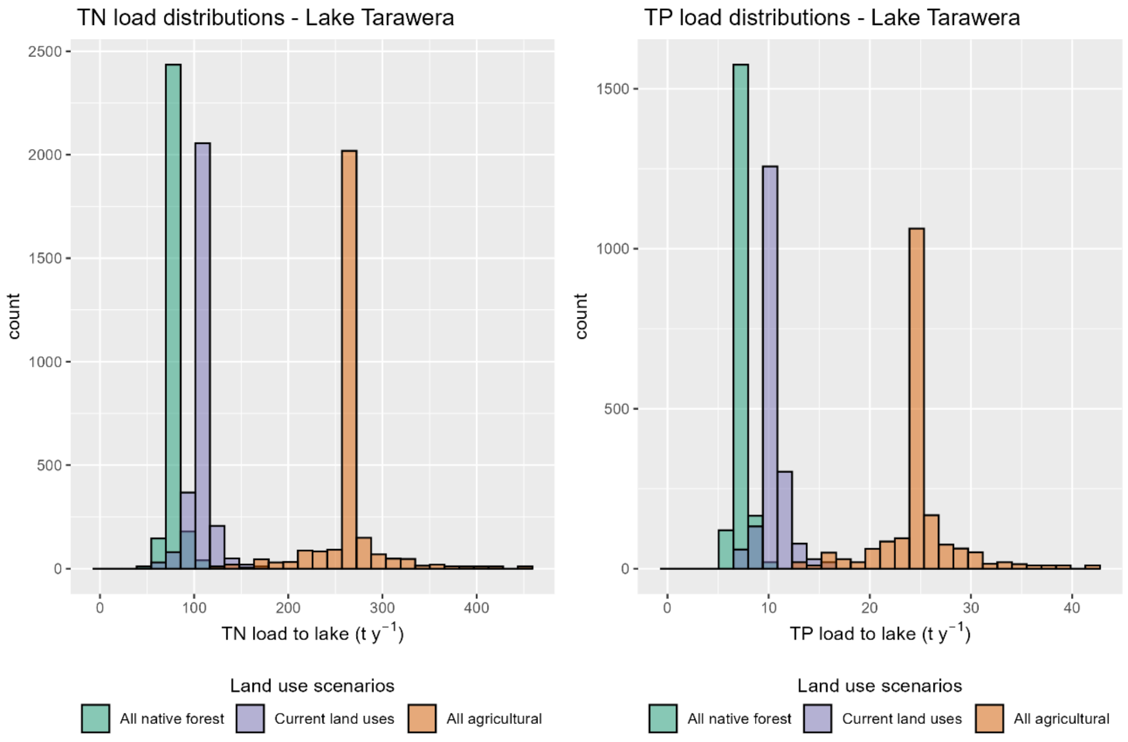


Figure 7.4 Lake Tarawera modelled total nitrogen (TN) and total phosphorus (TP) load distributions with uncertainty and interannual variability. Current land uses are shown by the blue distribution, and best-case scenario (native forest) is shown by the green distribution, and worst-case scenario (agricultural) is shown by the orange distribution.

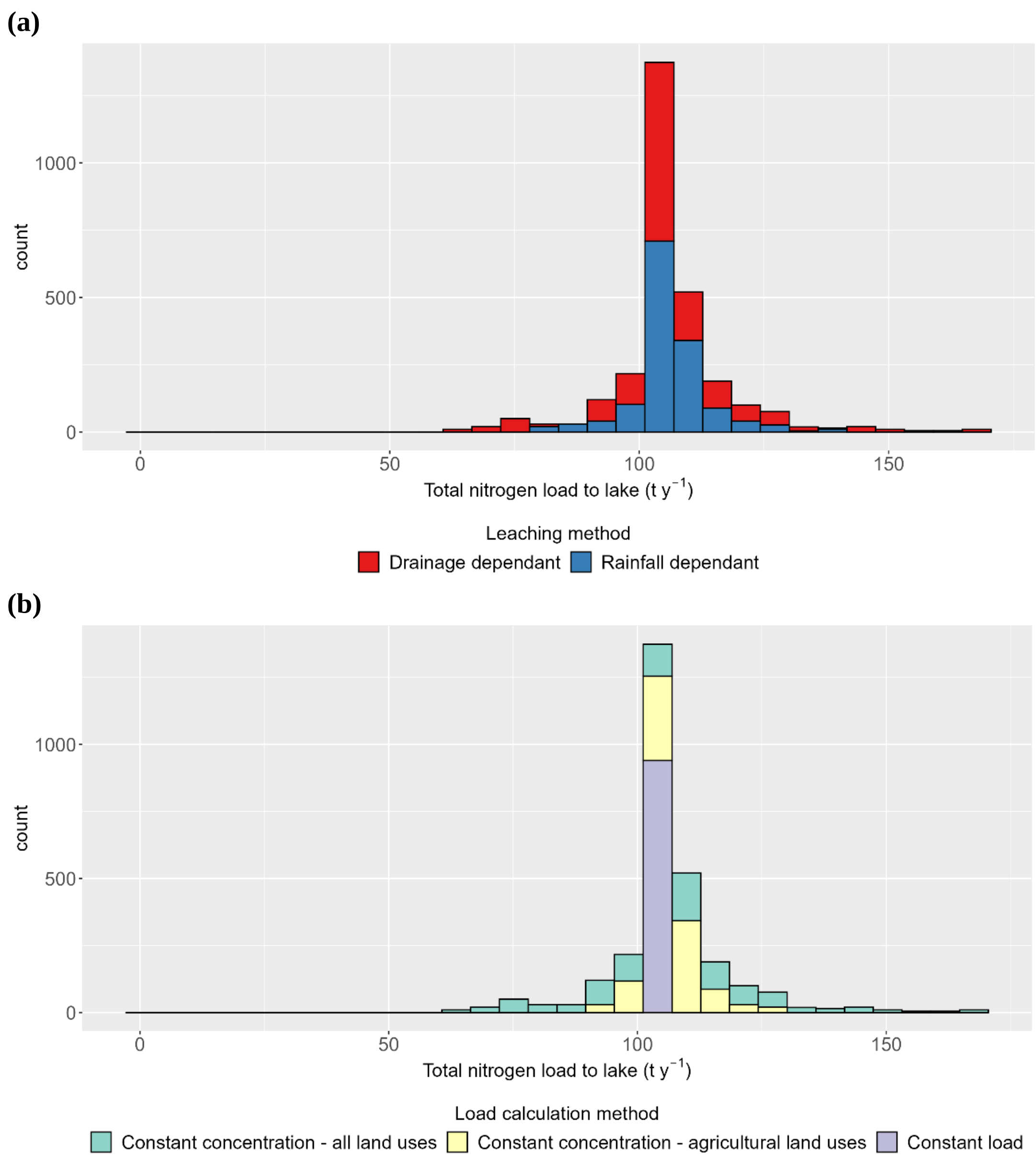


Figure 7.5 Modelled total nitrogen load distribution to Lake Tarawera from current land uses showing the contribution to the distribution by (a) leaching method, and (b) load calculation method. Both histograms represent the same distribution, the colours indicate the category of (a) leaching method, or (b) load calculation method that contributed to the total.

Chapter 8

Discussion

8.1 Introduction

The aim of this research is to improve the understanding of groundwater flow in the Greater Tarawera Lake catchments in order to assess the fluxes of water and nutrients into Lake Tarawera and connected lakes under different climatic and land use scenarios. This chapter synthesises information presented in previous chapters and discusses the key findings and implications of this research. It is structured following the presentation of results (Chapters 5 to 7) and addresses the objectives detailed in Chapter 1 to: (1) fill knowledge gaps on conceptual understanding of groundwater flow through and out of the Greater Tarawera Lakes catchment; (2) quantify annual water balances; (3) estimate annual lake nutrient loads; (4) estimate nutrient loads for a best- and worst-case land use scenarios; and (5) communicate uncertainties.

Uncertainty and interannual variability in the results of this research are presented as an annual mean with a range (5th percentile to 95th percentile). This approach differs from many water balance studies, which often use a single point estimate (e.g., the annual mean) to describe the results (e.g., White et al. 2016). The use of a single statistic can be misleading as it oversimplifies the results and does not communicate uncertainty and variability. It may also lead to misinterpretation, where unwarranted weight is put on a single value in decision making (van der Bles et al., 2019). Uncertainties and interannual variabilities in the results of this study are due to natural climatic variability (i.e., interannual rainfall differences), inadequacies of measurement (e.g., gauging errors), limited knowledge (e.g., lack of rainfall stations in study area, limited understanding of groundwater flow pathways and fluxes), and general assumptions made and applied over the entire study area (e.g., differences in evaporation from pasture and forest). The bracketing approach adopted to describe the results provides a tool for policy makers to test outcomes of potential policy options and will assist in the development of robust policy.

Flow and load estimates and their uncertainties in this study relate to historic and current climatic and land use conditions in the study area, and additional knowledge gained may revise these (e.g., more detailed rainfall records or land use information). Future water fluxes and nutrient loads will be affected by changes in land use, in addition to climatic changes resulting in changes to temperature, precipitation, and atmospheric CO_2 (and thus water use efficiency).

8.2 Water provenance (Objective 1)

8.2.1 Introduction

Isotopic data can help answer questions related to the movement and distribution of water throughout a catchment (McDonnell, 2017). This research has used isotopic data to supplement water balance calculations by considering the movement of water within and out of the Greater Lake Tarawera catchment. Lake water has a stable isotope composition significantly different from local rainfall (Horton et al., 2016; Vystavna et al., 2021; Xiao et al., 2017) therefore isotopic tracing can be a useful tool to determine flow pathways in the Greater Lake Tarawera catchment. The seasonality of isotopic variation in precipitation (Baisden et al., 2016; Jasechko et al., 2017), can be assumed to be smoothed out by the transition of water through the unsaturated zone (IAEA, 1981), as isotopic compositions of annual precipitation suggest (Jasechko et al., 2017). Thus, the isotopic signature of local groundwater (uninfluenced by lake recharge) is an appropriate proxy for local precipitation.

8.2.2 Tarawera River

Stable isotope analysis of surface water in the Tarawera River indicates that the significant flow gains observed in the Tarawera River downstream of the falls (approximately 2 m^3s^{-1}) are largely sourced from groundwater recharged by rainfall, and not lake water from Lake Tarawera moving underground via fractured rhyolite as postulated by previous research (White & Cooper, 1991; White et al., 2016). Upstream of the Tarawera Falls, the isotopic signature of water in the Tarawera River suggests it is sourced solely from Lake Tarawera, whereas downstream of the falls isotopic signatures suggest groundwater recharged from rainfall accounts for some of the flow gains observed in the Tarawera River, with the percentage of rainfall recharged groundwater increasing further downstream from the falls (at least 11% of water 200 m downstream of the falls and at least 28% 1,110 m downstream of the falls). It is likely that at least some of the flow gains observed in the Tarawera River downstream of the falls are from rainfall recharged groundwater originating from the Tarawera catchment that has bypassed the lake because calculations of White and Cooper (1991) and White et al. (2016) indicate the gains are too large to be sourced solely from groundwater originating from the catchments downstream of the Tarawera outlet.

Water samples used for isotopic analysis were collected in the summer after a long dry period when flow in the Tarawera River was very low (4.6 m^3s^{-1}), repeated water sampling and isotopic analysis undertaken during different flow regimes would be valuable to confirm these conclusions.

8.2.3 Groundwater flow paths

Isotopic analysis suggests that lake water contributions to the groundwater system of the Tarawera catchments is not widespread throughout the catchments.

Bores 968 and 070, and the Waingaehe Stream located between the Greater Tarawera lakes and Lake Rotorua show no evidence of lake water, suggesting there is no groundwater flow from the Tarawera Lakes towards Rotorua in these locations, supporting the conceptual model of this research and that of White et al. (2016, 2020). However, groundwater flow from the Tarawera catchments towards Lake Rotorua cannot be entirely ruled out as water in the Waiohewa and Puarenga Streams (flowing into Lake Rotorua and located between the Greater Lake Tarawera catchment and Lake Rotorua) have isotopic signatures suggestive of some influence from either evaporated water (i.e., lake water) and/or geothermal activity in some samples. These may represent seasonal variations in the source water of these streams. The Utuhina Stream (which would not be expected to have any lake water source) shows a similar pattern. It is beyond the scope of this research to further investigate geochemical and isotopic signatures in locations outside of the study area (with consideration of the need to evaluate intra-annual differences and potential risks of comparing data collected at different times and for different purposes) but is a recommendation of this research that the source water of these streams be investigated further (Section 9.4). Groundwater on the northern side of Lake Tikitapu (bore 072) shows some lake water source, however, it is located very close to the lake edge (130 m) and may just indicate local mixing.

Several inflows located in the Wairua Arm of Lake Tarawera indicate a Lake Rotomahana source (Rotomahana Waterfall, Rotomahana Spring, Wairua Arm WA1, Middleflax and

Rotomahana Siphon). Inflows at Hot Water Beach in the Wairua Arm of Lake Tarawera indicate a lake water source with some geothermal influence. This supports evidence from Cochrane (2020) where arsenic concentrations in Lake Tarawera inflows in the Wairua Arm (namely the Rotomahana Waterfall and Hot Water Beach) suggest a hydrologic connection to Lake Rotomahana. The inflow in the western-most part of the Wairua Arm (Wairua Stream), indicates a meteoric source and is likely fed from groundwater recharged from meteoric water falling on the land west of Lake Tarawera (as is also the case for Twin Creeks located in between the Wairua Arm and Kōtukutuku Bay).

Spring-fed inflows to Kōtukutuku Bay in Lake Tarawera (Ramp 4 Jetty spring and Island waterfall) and groundwater between Lakes Rotokakahi and Tarawera (bore 051) suggest a meteoric source and support the conclusions of the water balance of this study that groundwater outflows from Lake Rotokakahi are minor and negligible in some years (Sections 6.4, 6.6, and 8.3.5). The only lake water-sourced inflow in this area is from the Te Wairoa Stream (draining Lake Rotokakahi) which, as expected, shows a clear lake water isotopic signature.

Groundwater between Lakes Ōkareka and Tarawera (bore 131) indicate a lake water source and suggests groundwater outflow from Lake Ōkareka contributes to Lake Tarawera in addition to the direct surface water connection via the Waitangi Stream. This seems logical given that prior to construction of an engineered outflow from Lake Ōkareka in 1960, the lake drained via groundwater resurfacing in the Waitangi Spring (Wallace & Environment Bay of Plenty, 1999). Water from the Waitangi Stream shows a clear lake water isotopic signature as expected.

There is no evidence of lake water discharging from Lake Ōkataina and emerging in the spring-fed inflows or groundwater (bore 129) in the north-western part of Lake Tarawera. It is possible that groundwater discharge from Lake Ōkataina to Lake Tarawera is occurring further east from where testing was undertaken through the isthmus between Ōtangimoana Bay and Lake Tarawera.

There is evidence of lake water in the groundwater between Lakes Rerewhakaaitu and Rotomahana (bore 055), supporting evidence of previous studies using water dating, geochemistry and isotopes that water from Lake Rerewhakaaitu is leaking to groundwater to the north and west of the lake, towards the Lake Rotomahana (Reeves, Morgenstern,

& Daughney, 2008; Reeves, Morgenstern, Daughney, et al., 2008). Groundwater from bore 055 also shows a geothermal influence, perhaps indicating some connection to Lake Rotomahana and/or geothermal activity in the subsurface. There is no evidence of lake water from Rerewhakaaitu recharging the groundwater to the east of the lake (bores 052 and 053).

The deep well at the outlet of Lake Tarawera (bore 134) displays an isotopic signature like that of Lake Tarawera, indicating that some water from the lake is leaking to deep groundwater. Thorstad et al., (2011) arrived at the same conclusion using water chemistry data from this bore.

This study has looked solely the isotopic evidence of groundwater connections between lakes. Other geochemical evidence may provide further insights including interpretation of major ions and statistical clustering. Analysis of major ion data could be used and has proved beneficial in determining recharge areas and hydraulic connection of springs in the Rotorua catchment (Morgenstern et al., 2015) and hierarchical cluster analysis has been used in New Zealand to evaluate trends in groundwater quality and assess the representativeness of monitoring networks (Daughney et al., 2012; Daughney & Reeves, 2006). These types of methodologies have been integrated into recent classification of landscape attributes (physiographic classification and process attribute mapping (PoAM)) to account for much of the variability in water quality in New Zealand (Rissmann et al., 2021, 2019), but PoAM has not yet considered lake water sources.

8.3 Water balances (Objectives 2 and 5)

This research has provided insights into the variation and contribution of each water balance component to the total flow into and out of the Tarawera Lakes. Annual water balances have been quantified from 1972-2018 and used to describe interannual variability and uncertainty. Results show that flow to and from each lake varies year to year, and with the selection of calculation methods, datasets and parameters used. Key findings are summarised in the Sections 8.3.1 to 8.3.8.

8.3.1 Rainfall

Water balance calculations indicate that rainfall is the biggest driver of water fluxes in the Greater Lake Tarawera catchment. Rainfall is the largest component of the water balance on a catchment scale and is the primary driver of the amount of groundwater inflow estimated to the lakes. There are no long-term rainfall measurement sites located within the study area, but rainfall modelled by VCS data indicate that annual rainfall over the Greater Tarawera Lake catchments varies between 67% and 141% of the mean annual rainfall (1,551 mm/y) (1972-2018).

Mean rainfall estimates from the water balances of this study are lower than those estimated by White et al. (2016) who used a national rainfall dataset for the period 1960 – 2001 (Tait et al., 2006; Woods et al., 2006) (Table 8.1 and Figure 8.1). The rainfall dataset used by White et al. (2016), was a precursor to the VCS operational dataset used in this research, which also predicted higher rainfall than the other four rainfall datasets considered by this research (Section 6.2). Three of the rainfall datasets used in this research (VCS bias corrected, VCS augmented low resolution, and VCS augmented high resolution), include additional rainfall measurement sites from regional council data (Section 4.2.4) and are likely to include some sites within the study area, but confirmation of this was outside the scope of this research.

Table 8.1 Comparison of rainfall estimates to each lake within the Greater Tarawera Lakes catchment from the water balance model of this research and the water balance of White et al. (2016).

Mean rainfall to lake surface				
	This study[1]		White et al. (2016)[2]	
	$m^3\ s^{-1}$	$mm\ y^{-1}$	$m^3\ s^{-1}$	$mm\ y^{-1}$
Lake Ōkareka	0.163	1469	0.168	1544
Lake Ōkaro	0.010	1262	0.014	1465
Lake Ōkataina	0.609	1829	0.677	1994
Lake Rerewhakaaitu	0.213	1280	0.232	1432
Lake Rotokakahi	0.208	1381	0.208	1533
Lake Rotomahana	0.405	1345	0.409	1451
Lake Tarawera	2.264	1742	2.458	1882
Lake Tikitapu	0.044	1388	0.068	1478

[1] Conversion to mm y^{-1} has been undertaken using the lake area of the water balance model (i.e., the number of grid cells assigned to the lake) because this was the area used to estimate rainfall units of $m^3\ s^{-1}$ in this study (see Section 4.2.1)

[2] Conversion to mm y^{-1} has been undertaken using the actual lake area

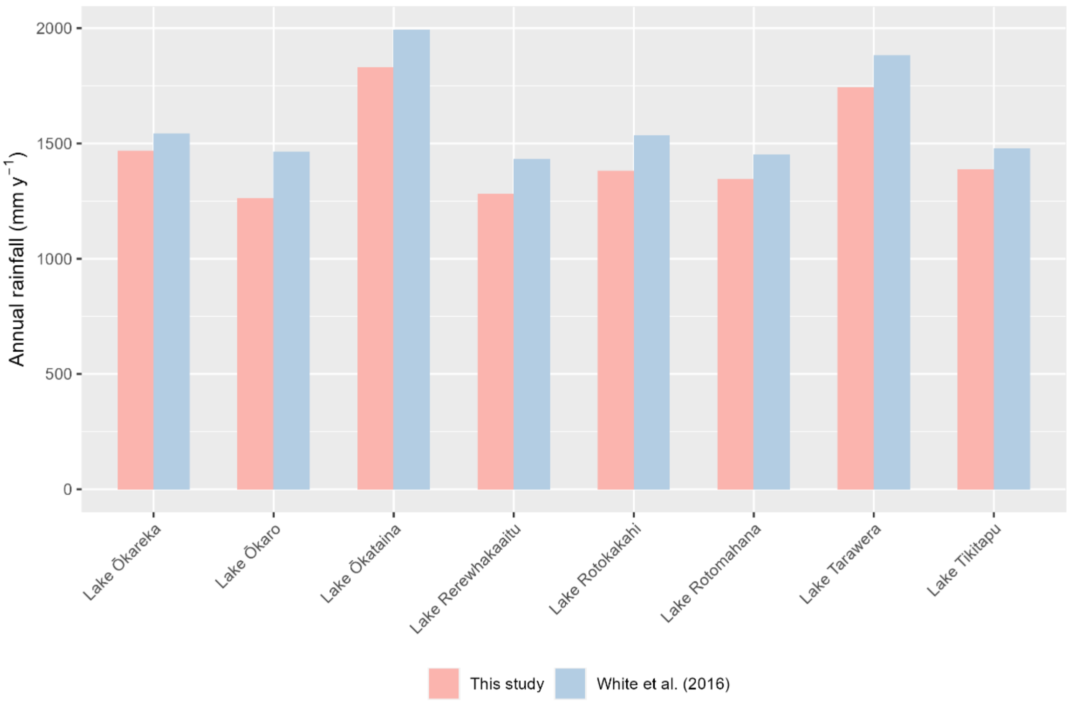


Figure 8.1 Comparison of rainfall estimates to each lake within the Greater Tarawera Lakes catchment from the water balance model of this research and the water balance of White et al. (2016).

8.3.2 Drainage

Annual drainage varied between 16% to 191% of the mean annual drainage over the Greater Lake Tarawera catchment (713 mm y^{-1}). Between 11% and 63% (mean 46%) of annual rainfall has been estimated to result in drainage across the study area. These estimates are slightly lower than predicted by lysimeter studies in the Rotorua area, where a mean of 51% of annual rainfall resulted in drainage (Freeman, 2010); and higher than water balance studies on the Canterbury Plains where between 20-40% of rainfall is predicted to contribute to drainage under non-irrigated conditions (Scott, 2004, p. 18). Davies (2005) suggested that drainage under forestry in the Lake Taupō Catchment could be approximated by 30% of annual rainfall. Sparling et al. (2016) calculated drainage to be 43% of annual rainfall in the year 2012 at a pasture site near Matamata, New Zealand (a year with annual rainfall close to the 30-year average). It is expected that estimates from the Greater Tarawera Lakes catchment will be higher than those on the Canterbury Plains which are subject to relatively low rainfall, and high median annual days of soil moisture deficit (Macara, 2016). In contrast, the Rotorua, Taupō and Matamata areas have relatively high rainfall and low median annual days of soil moisture deficit (Chappell, 2013, 2021). Drainage estimates from the Greater Tarawera Lakes catchment are likely to be closer to those measured in Rotorua, Matamata and Taupō than the Canterbury Plains because of similarities in climate, soil and land use.

8.3.3 Land evaporation

Mean annual land evaporation estimates from this research are in the range of 572 – 687 mm y^{-1}, generally lower than those from previous water balance studies of the Greater Tarawera Lakes catchment of White et al. (2016) (Table 8.2 and Figure 8.2), whose estimates indicate a larger range (530 – 1175 mm y^{-1}) than those of this study. Estimates from this research are considered more accurate as they consider land use, land cover, and soil water stress, whereas estimates of White et al. (2016) used a national scale map of average annual penman potential evapotranspiration (presented in Woods et al., 2006) for the period 1972-2003, using only meteorological data and without consideration land use, land cover, and soil water stress.

Evaporation rates from forest are higher than those from pasture (Beets & Oliver, 2007; Davie & Fahey, 2006; Dons, 1986), an effect illustrated in an area adjacent the study area by Dons (1986), who showed that afforestation downstream of Lake Tarawera reduced flow in the Tarawera River. This study not only calculates land evaporation by land use (i.e., pasture or forest), but also considers land cover in evaporation calculations (i.e., mature pine forest or harvested pine forest) to account for reduced evaporation from thinning and harvesting of pine forest (Beets & Oliver, 2007; Whitehead & Kelliher, 1991).

In addition to land use, soil water stress has been considered in the evaporation calculations of this study by calculating a daily soil moisture balance with consideration of soil water availability, and applying a water stress coefficient to evaporation calculations (as per the methods of Allen et al., 1998; Pronger et al., 2016). Applying these calculations daily and summing to obtain annual values for the water balances, accounts for the seasonality of plant transpiration due to water stress, and the drainage pulses moving through the soil profile (resulting in groundwater recharge and nutrient transport). Results of this study show that adjusting for soil water stress decreases estimated land evaporation over the Greater Lake Tarawera catchment by an average of 204 mm y^{-1} (Section 6.7).

The magnitude of differences in evaporation between the estimates of this study and that of White et al. (2016), has implications for the estimation of groundwater fluxes to and from the lakes as both studies use some form of a residual method to estimate these (i.e., estimated groundwater fluxes are based on a water balance closure assumption). There are also implications for estimated nutrient loads to lakes because drainage (which is related to evaporation) is driving force in the transport of nutrients (Overseer, 2012).

Table 8.2 Comparison of land evaporation estimates from the water balance model of this research and the water balance of White et al. (2016).

	Mean land evaporation			
	This study[1]		White et al. (2016)[2,3]	
	$m^3\ s^{-1}$	$mm\ y^{-1}$	$m^3\ s^{-1}$	$mm\ y^{-1}$
Lake Ōkareka catchment	0.378	589	0.417	805
Lake Ōkaro catchment	0.073	576	0.090	840
Lake Ōkataina catchment	1.396	688	1.264	764
Lake Rerewhakaaitu catchment	0.980	589	0.805	531
Lake Rotokakahi catchment[4]	0.440	572	0.556	1176
Lake Rotomahana catchment[4]	2.664	596	1.876	791
Lake Tarawera catchment[4]	7.253	579	2.618	793
Lake Tikitapu catchment	0.115	631	0.118	870

[1] Conversion to mm y^{-1} has been undertaken using the catchment area of the water balance model (i.e., the number of grid cells assigned to land in each catchment)

[2] Conversion to mm y^{-1} has been undertaken using the actual land area in the local catchment

[3] Land evaporation has not been separated from total catchment evaporation by White et al. (2016). These values were obtained by subtracting lake evaporation (evaporation from Table 4.5 of White et al. (2016)), from catchment evaporation (AET from Table 4.6 of White et al. (2016))

[4] The evaporation units of $m^3\ s^{-1}$ for Lake Rotokakahi, Rotomahana and Tarawera catchments are not directly comparable as White et al. (2016) estimates are from the local catchment only. Evaporation units of mm y^{-1} only should be compared for these catchments

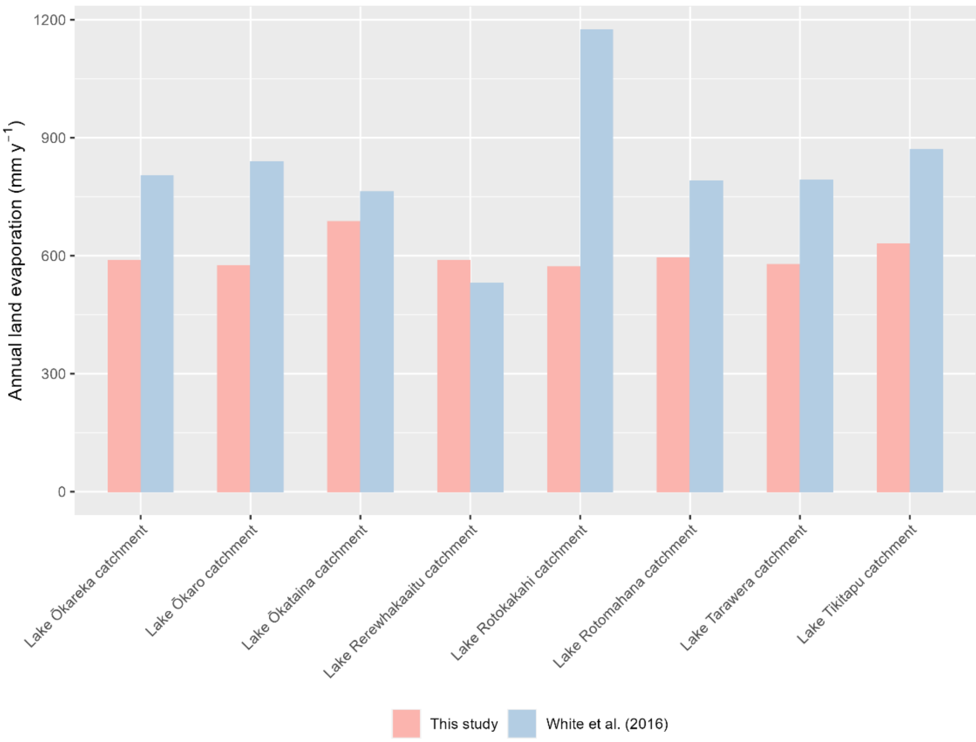


Figure 8.2 Comparison of land evaporation estimates from the water balance model of this research and the water balance of White et al. (2016).

8.3.4 Lake evaporation

Estimates of lake evaporation from this research use meteorological data from the virtual climate site closest to each lake, and are considered more accurate than those of previous researchers who applied data from the Rotorua Aero (airport) AWS to all lakes of the Greater Lake Tarawera catchment (Gillon et al., 2009), or used an assumed percentage (41%) of annual rainfall (White et al., 2016). Estimates of lake evaporation from this research are higher than those estimated by Gillon et al. (2009), by between 68 mm y^{-1} and 324 mm y^{-1} (Table 8.3 and Figure 8.3). White et al. (2016)'s method of estimating lake evaporation as a percentage of rainfall does not follow hydrological logic as rainfall on a lake is not a driver of evaporation (Verburg, 2021). Estimates of lake evaporation from this research are generally higher than those estimated by White et al. (2016). As is the case with land evaporation, the magnitude of differences in lake evaporation between the estimates of this study and that of White et al. (2016), have implications for the estimation of groundwater fluxes to and from the lakes.

Annual evaporation rates estimated for the Tarawera Lakes are similar to those reported in both deep and shallow lakes in the temperate northern parts of North America (Lake Ontario, 86 m deep, 730 mm y^{-1}; Hungry Horse Reservoir, 149 m deep, 505 mm y^{-1}; Dauphin Lake, 5m deep, 690 mm y^{-1}; and Pretty Lake, 7.8m deep, 800 mm y^{-1}) (Andersen & Jobson, 1982). There are no published studies of lake evaporation in New Zealand, however annual evaporation rates for Lake Taupō (100 m deep) have been estimated using land based meteorological data at roughly 950 mm y^{-1} (Scotter & Kelliher, 2004), and recent evaporation estimates from Lake Taupō using buoy data were estimated to be 1167 mm y^{-1} and equivalent to 16% of the annual average outflow from the lake (Verburg, 2021). Lake evaporation estimates from buoy data are considered more reliable as they consider conditions on the lake (e.g., air temperature, water temperature, wind speed, relative humidity) which can be very different from conditions on the land (Verburg, 2021). Although located at a similar elevation to the Tarawera Lakes, evaporation estimates from Lake Taupō may differ from those of the Tarawera lakes due to its larger size (616 km^2 compared to Lake Tarawera at 41 km^2) and greater depth (mean depth 110m), which will affect driver variables such as wind speed, air temperature and relative humidity.

Table 8.3 Comparison of lake evaporation estimates from the water balance model of this research and the water balances of White et al. (2016) and Gillon et al. (2009).

	Mean evaporation from lake surface					
	This study		White et al. (2016)		Gillon et al. (2009)	
	$m^3 s^{-1}$	mm y^{-1} [1]	$m^3 s^{-1}$	mm y^{-1} [1]	$m^3 s^{-1}$	mm y^{-1} [1]
Lake Ōkareka	0.078	717	0.069	634	0.059	542
Lake Ōkaro	0.008	837	0.006	628	0.006	628
Lake Ōkataina	0.249	733	0.278	819	0.214	630
Lake Rerewhakaaitu	0.104	642	0.095	586	0.093	574
Lake Rotokakahi	0.100	737	0.085	626	0.056	413
Lake Rotomahana	0.276	979	0.168	596	0.213	756
Lake Tarawera	0.989	757	1.008	772	0.887	679
Lake Tikitapu	0.032	695	0.028	608	0.024	521

[1] Conversion to mm y^{-1} has been undertaken using the actual lake area because this was used in the calculations of lake evaporation for all studies

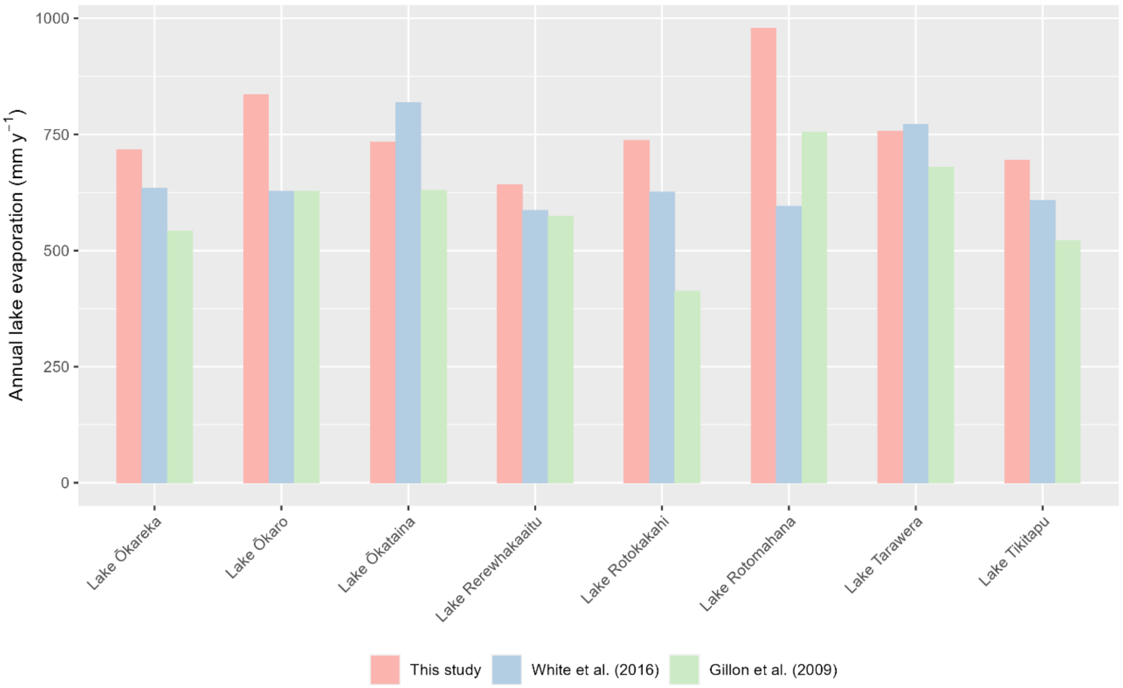


Figure 8.3 Comparison of lake evaporation estimates from the water balance model of this research and the water balances of White et al. (2016) and Gillon et al. (2009).

8.3.5 Groundwater flow

This study demonstrates that groundwater is a significant contributor to the water balances of the Greater Tarawera Lakes (Table 8.4). Groundwater contributes most (>50%) of the inflow to Lakes Ōkareka, Ōkataina, Rotomahana, Tarawera and Tikitapu; and most of the outflow leaving Lakes Ōkaro, Ōkataina, Rerewhakaaitu, Rotomahana and Tikitapu. In dry years, groundwater inflow to Lakes Ōkaro and Ōkareka, and groundwater outflow from Lakes Ōkareka, Rotokakahi and Tarawera may be negligible. However, estimations for Lake Ōkaro are less certain due to the use of constant surface water inflows and outflow to the lake which have an influence on the estimated groundwater flows.

Most of the groundwater flowing into Lake Tarawera (mean of 70% of total groundwater inflow) is predicted to come from groundwater recharged outside of its local catchment (i.e., the catchments of the seven other upstream lakes). Lakes Rotokakahi and Rotomahana also have groundwater contributions from groundwater recharged outside of their local catchments (mean 76% and 13% of total groundwater inflow respectively).

Lake levels do not show any obvious correlation to estimated groundwater flow (Figure 6.8). This may indicate that groundwater is bypassing the lakes and/or that groundwater flows in and out of the lakes are so responsive that they don’t affect lake levels. It may also be a scale effect and a correlation may be observed at a daily or monthly scale.

Table 8.4 Contributions of groundwater inflows and outflows to total inflows and outflows to lakes from this study

Contributions of groundwater flows to total flow to and from lakes						
	Area (km^2)		Inflow		Outflow	
	Lake	Groundwater catchment	Mean	Range	Mean	Range
Lake Ōkareka	3.34	12.49	54%	40-62%	29%	0-53%
Lake Ōkaro	0.33	3.68	3%	0-31%	64%	61-74%
Lake Ōkataina	10.73	70.92	77%	65-80%	90%	78-94%
Lake Rerewhakaaitu	5.17	15.18	33%	10-47%	72%	47-84%
Lake Rotokakahi	4.33	13.49	21%	0-44%	8%	0-35%
Lake Rotomahana	9.02	101.63	68%	49-79%	88%	76-93%
Lake Tarawera	41.15	159.29	60%	40-71%	25%	0-53%
Lake Tikitapu	1.44	5.60	67%	50-75%	75%	52-85%

Groundwater inflows and outflows to lakes and their catchments presented in this research are based on flow pathways and assumptions of the conceptual model described in Section 2.5. Evidence from isotopic analysis of groundwater generally supports these assumptions (Section 8.2.3). It is possible that the groundwater flow paths are different to those assumed by this research or that they vary under different flow regimes, nonetheless the water balance model here represents a realistic and useful description of groundwater flow based on existing knowledge. Gillon et al. (2009) considered different conceptual scenarios of groundwater flow out of the Greater Lake Tarawera catchment, including groundwater flow directions north-west towards the Rotorua Lakes, which cannot be ruled out and warrants further investigation (Section 8.2.3). The conceptual scenario of this research follows that of more recent studies (Abell et al., 2020; White et al., 2016, 2020), that all flow from the Greater Lake Tarawera catchment is towards Lake Tarawera and discharges east, via groundwater and surface water, with a small portion discharging east as groundwater from Lake Rerewhakaaitu. It is beyond the scope of this study to explore different conceptual scenarios. The possibility of flow discharging elsewhere (i.e., west towards the Rotorua Lakes) would have implications on the water balances presented in this study and could be investigated using water level information and isotopic analysis from a greater density of groundwater bores (see Section 9.4).

Comparison of predicted groundwater flows to and from the lakes by this study with those estimated by previous water balance studies (White et al., 2016) and CLUES (Catchment Land use and Environmental Sustainability) simulations (McBride et al., 2020) are shown in Table 8.5, and Figures 8.4 and 8.5. CLUES is a budget-based model with its spatial structure based on New Zealand River Environments Classification (REC) (Elliott et al., 2016). Groundwater inflow to lakes is not estimated by CLUES due to its structure (lake outlets are identified as river reaches), and the groundwater flow estimates to the lakes of White et al. (2016) are only reported as net flows.

There is reasonable agreement between the net groundwater flows of the Greater Tarawera Lakes of this research and White et al. (2016), with differences most notable in the net estimates to Lake Tikitapu and Lake Rotokakahi (Table 8.5). Despite the evaporation estimation methods of White et al. (2016) lacking accuracy (see Sections 8.3.3 and 8.3.4), thus having potential implications on the groundwater flux estimates; the net effect of overestimation of land evaporation and under estimation of lake evaporation by White et al. (2016) (compared to this study) appear to mitigate this, if only by chance. Outflows from CLUES simulations are also in reasonable agreement for most lakes, with differences most notable for Lakes Ōkareka, Rotokakahi and Tarawera. CLUES groundwater outflow estimates fall within the range of the water balance outflow estimates (Lake Ōkareka) or within the 95% confidence interval of the range of estimates (Lakes Rotokakahi and Tarawera) (Tables C4, C8, and C10, Appendix C). The use of higher resolution annual data (rather than mean annual averages), and consideration of land use, land cover and soil moisture in the water balance calculations are likely to explain the differences in these estimates.

Table 8.5 Comparison of predicted groundwater flows to and from the Greater Tarawera Lakes

	Mean groundwater flows to/from lakes				
	Inflow	Outflow		Net flow[1]	
	This study (m^3 s^{-1})	This study (m^3 s^{-1})	CLUES estimates (m^3 s^{-1})[2]	This study (m^3 s^{-1})	White et al. (2016) (m^3 s^{-1})
Lake Ōkareka	0.202	0.123	0.366	0.079	0.065
Lake Ōkaro	0.008	0.071	0.080	-0.063	-0.068
Lake Ōkataina	1.887	2.249	2.330	-0.362	-0.399
Lake Rerewhakaaitu	0.152	0.317	0.320	-0.165	-0.192
Lake Rotokakahi	0.129	0.068	0.189	0.061	0.188
Lake Rotomahana	1.903	2.358	2.120	-0.455	-0.567
Lake Tarawera	6.770	3.275	2.162	3.495	3.538
Lake Tikitapu	0.100	0.112	0.130	-0.012	-0.400

[1] A positive value for net flow indicates that the lake gains flow from groundwater

[2] Calculated by substracting mean annual surface water outflow from lake outflow (includes surface water and groundwater flows) predicted by CLUES estimates presented in McBride et al. (2020)

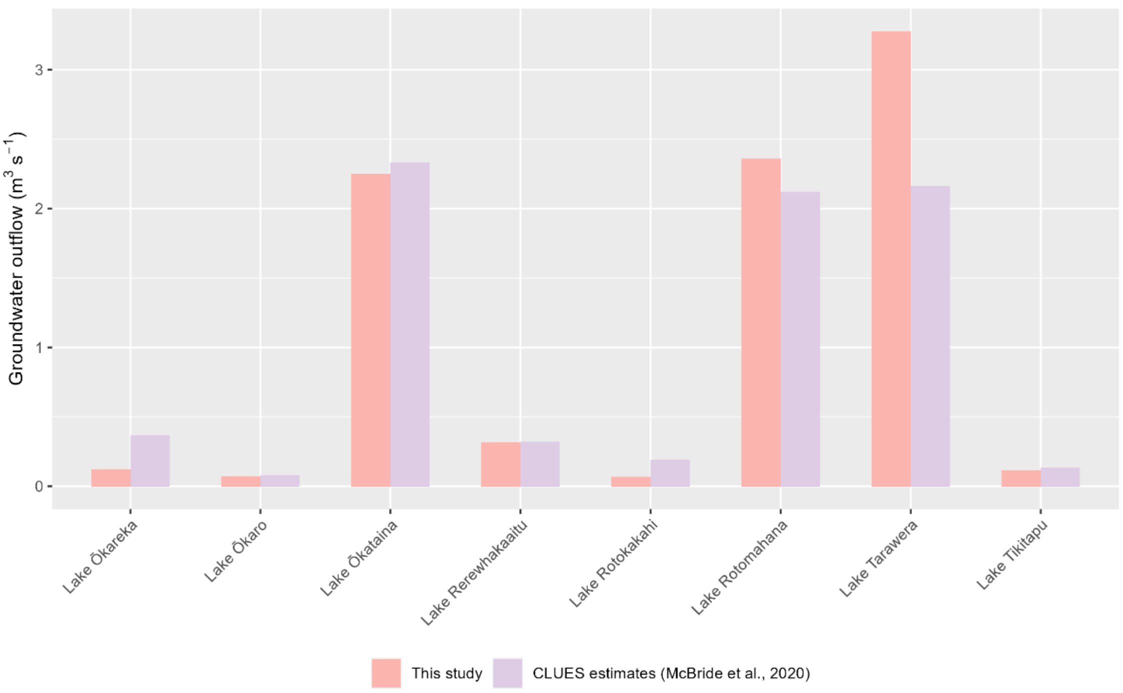


Figure 8.4 Comparison of predicted groundwater outflows from the Greater Tarawera Lakes from the water balance model of this research and CLUES estimates from McBride et al. (2020).

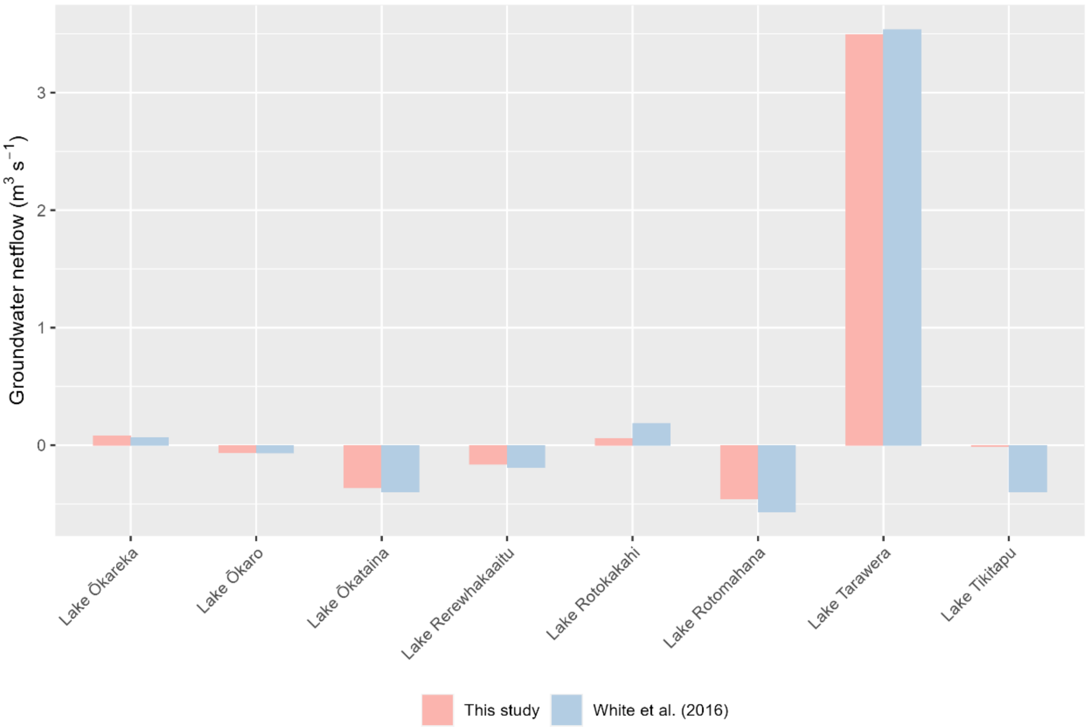


Figure 8.5 Comparison of predicted net groundwater flows to and from the Greater Tarawera Lakes from the water balance model of this research and the water balance of White et al. (2016)

Rosenberry et al. (2015) report globally large differences in groundwater flow to and from 110 lakes with groundwater contributions to the total inflows and outflows ranging from 0% to 94%, and 0% to 91% respectively. Results from this research show similarly large ranges of groundwater contributions to the total inflows and outflow (Table 8.4). Mean percentage contributions of groundwater to total lake inflow vary between 3% and 77% (Lakes Ōkaro and Ōkataina respectively), and outflow between 8% and 90% (Lakes Rotokakahi and Ōkataina respectively). The Tarawera lakes are all located in a similar climate and geological setting, and it is considered that the large range is likely reflective of the presence or absence of surface water inflows and/or outflows from the lake, a factor not considered in the Rosenberry et al. (2015) synthesis study.

Exchange between groundwater and lake water is often concentrated near the shoreline (Rosenberry et al., 2015), a phenomenon confirmed by Rosenberry et al. (2015) who observed that the percentage of the groundwater component to lake inflows decreased as lake area increased in lakes over 1 km^2. There was no similar percentage-versus-lake area relationship evident for groundwater inflows to the Tarawera Lakes (Table 8.4). The percentage of groundwater inflows to the total inflow of the Tarawera Lakes is likely related to other lake characteristics such as whether or not the lake has any surface water inflows, and whether it is perched above the local groundwater table (i.e. Lake Rerewhakaaitu). Rosenberry et al. (2015) observed no groundwater outflow percentage-versus-lake area relationship to total outflows, nor was there one evident in the Tarawera Lakes, however lakes with no permanent surface water outflow (Ōkataina, Rotomahana and Tikitapu) had higher percentages of groundwater outflows (Table 8.4).

In calculating the groundwater inflows to lakes, all the drainage estimated within the groundwater catchment of a lake is assumed to flow into the lake. This may not be the case as some groundwater flow may bypass the lake by travelling underneath or around it via preferential flow paths and/or drain deeper joining sub-regional and regional flow systems. Thus estimates of groundwater flow to and from the lakes presented in this study are an upper estimate.

Comparison of catchment groundwater flows between this research and the estimates of White et al. (2020) is not relevant as White et al. (2020) considers the "lake and catchment" to be what this research refers to as the "local catchment". Thus, there are groundwater inflows reported for some "lakes and catchments" by White et al. (2020) which come from upstream "lakes and catchments".

8.3.6 Surface water flows

This study draws largely on the collation of surface water flow data presented in White et al. (2016) to inform surface water flows to and from the Tarawera Lakes, with the inclusion of additional flow records and information available since the publication of White et al. (2016) (see Sections 2.5.1 and 4.2.8). Comparison of flow data used in this research with those of White et al. (2016) is shown in Table 8.6.

There are likely to be small ungauged surface water inflows into Lake Ōkataina and other lakes which are not accounted for in the surface water inflow data. These will be accounted for in the groundwater inflows of the water balance.

Table 8.6 Comparison of estimated mean surface water flows to and from the Greater Tarawera Lakes showing those flows which used a constant record for this research.

	Mean surface water flows to/from lakes			
	Inflow		Outflow	
	This study ($m^3 s^{-1}$)	White et al. (2016) ($m^3 s^{-1}$)	This study ($m^3 s^{-1}$)	White et al. (2016) ($m^3 s^{-1}$)
Lake Ōkareka	-	-	0.168	0.164
Lake Ōkaro	0.090	0.090	0.030	0.030
Lake Ōkataina	-	-	-	-
Lake Rerewhakaaitu	0.055	0.055	-	-
Lake Rotokakahi	0.150	-	0.345	0.311
Lake Rotomahana	0.326	0.326	-	-
Lake Tarawera	1.870	1.750	6.775	6.738
Lake Tikitapu	-	-	-	-

8.3.7 Storage changes

Storage changes in lakes account for a small part of the water balance (mean < 1% of the total flow) and are relatively larger in Lakes Tikitapu and Ōkataina which have no surface water inflows or outflows. Positive storage changes (i.e., increasing lake levels) tend to occur in years when rainfall is greater than 1,600 mm y^{-1}.

8.3.8 Water balance closure

The water balances of Lakes Ōkareka, Rotokakahi and Tarawera do not have closure in some dry years with well below long-term average drainage (e.g., 1972, 1993, 2006 and 2018). The lack of closure in all cases indicates that additional water must be entering the system to sustain surface water outflows. Lack of closure is more frequent and relatively larger in Lake Rotokakahi (occurring in approximately 40% of years, averaging 5% of the total outflow) [20] than for Lakes Ōkareka and Tarawera (occurring in approximately 10% of years, and averaging 1% of the total outflow)[20].

Kampf et al. (2020) advocates for an open water balance (i.e., closure is not an assumption used to estimate unknown fluxes) in which the residuals left over after known water fluxes

[20] Calculated from means and ranges in Table 6.2

are considered are used to gain insights about unknown water balance components such as deep groundwater recharge or storage changes. Safeeq et al. (2021) showed that the long-term water balance can be closed within 10% of precipitation in river basins but up to 25% in small headwater catchments. Lack of closure of the lake water balances for Lakes Ōkareka, Rotokakahi and Tarawera is 2%, 13% and 6% of precipitation respectively[21]. The less frequent and relatively smaller residuals in the flows of Lakes Ōkareka and Tarawera are likely explained by propagated uncertainties inherent in the water balance (Kampf et al., 2020; Safeeq et al., 2021), water released from storage and /or deep groundwater upwelling. The relatively larger lack of closure in the water balance of Lake Rotokakahi gives some indication of an unknown component of the water balance. This is unlikely to be deep groundwater upwelling as the catchment is located at a high elevation (Kampf et al., 2020), and is more likely to represent water released from storage from the catchment of the lake (only storage changes in the lake itself were accounted for in the water balance), or that the catchment of Lake Rotokakahi is larger than is currently understood. It is possible that the catchment may extend further west, with additional groundwater flow routed towards the lake along fault lines trending northeast (shown in Figure 2.6, Chapter 2).

8.4 Nutrient loads (Objectives 3, 4 and 5)

8.4.1 Loads under current land use and climatic conditions

This research describes the variation of annual nutrient loads to the Tarawera lakes, expanding on single point estimates made in previous research based on annual averages (e.g. McBride et al., 2020; White et al., 2016). Water balances developed in this research have been quantified and used concurrently with current nutrient budgets (from McBride et al., 2020) to estimate interannual nutrient loads and their associated uncertainties for the Greater Tarawera Lakes from 1972-2018.

Nutrient load estimates from diffuse land uses presented in this research are based on Overseer® estimates calculated by BOPRC and presented in McBride et al. (2020). It is acknowledged that a recent review (Science Advisory Panel, 2021) described a lack of confidence in nutrient losses predicted by Overseer® in its current form. However, due to the widespread use of Overseer® by regional councils as a nutrient management tool

[21] Calculated from means and ranges in Table 6.2

in catchment-level modelling, and lack of any other suitable options, the government has approved the continued use of Overseer® until improvements are made which address issues raised by the review, or there is an alternative approach available for managing diffuse nutrient loss (Ministry for the Environment & Ministry for Primary Industries, 2021). With the exception of atmospheric contributions, nutrient loads from diffuse sources (e.g., agricultural land uses) are assumed to vary with drainage and rainfall, an effect inherent in Overseer® (Journeaux, 2014; Overseer, 2012), and observed in other catchment models (e.g., Aguilera et al., 2012). Nutrient loads from point sources (e.g., wastewater discharges and geothermal sources) are assumed constant and not to vary with rainfall because of their proximity to the lake shore effectively acting as direct discharges.

By analysing the effect that different methodologies have on the estimates of water flows and nutrient loads, this research highlights the importance of considering drainage and seasonality when estimating interannual nutrient loads rather than annual rainfall alone. Climatic seasonality affects the annual evaporation and drainage in a catchment (McMillan, 2012; Potter et al., 2005; Srinivasan et al., 2016). Previous research in New Zealand concluded that nutrient output from farms are largely driven by annual rainfall (Journeaux, 2014; Overseer, 2012), and the methods of Overseer consider soil type and rainfall seasonality in the estimation of the mean annual absolute load (Overseer, 2012). The seasonality of drainage will also affect the timing and transport of nutrient loads to their receiving environment. To mitigate seasonal transport effects (i.e., drainage pulses typically occurring in the winter), this study estimates annual drainage (rainfall minus evaporation) by calculating drainage at a daily timestep, with consideration of soil moisture deficits, and summing daily values to obtain annual values. This is considered to more accurately reflect the water available for nutrient transport than annual rainfall alone, and results in a greater variation of interannual nutrient load. The value of daily or monthly timesteps to better reflect seasonality is well understood (Kelly et al., 2000; Srikanthan & McMahon, 2001; White et al., 1997). However, in the absence of data or time available to calculate daily drainage, the results of this research indicate that adjustments to nutrient loads based on rainfall alone can approximate their annual variation in a fairly simple way.

Results show that annual nutrient loads to each lake can vary significantly interannually (between approximately 40% to 190% of the mean). Nutrient loads are coupled to lake inflows, so in dry years estimated nutrient loads are smaller and the apportionment of the total nutrient load to point sources was greater. In wet years nutrient loads are bigger, and the apportionment of the total nutrient load to point sources was smaller. Moving averages of the annual nutrient load give a better indication of the overall trend compared to the annual loads (Journeaux, 2014). Although the approach advocated by Journeaux (2014) was to use a five year moving average, it is recommended to use a three-year moving average to assess nutrient loads in the Greater Tarawera Lakes because this will align with current policy, which measures outcomes using three-year moving averages (i.e. Bay of Plenty Regional Council, 2017).

The interannual load variation of TN and TP (calculated as the maximum load divided by the minimum load) for the Tarawera lakes range from 1.8 – 4.8, similar to interannual load variations of TN and TP calculated for temperate climates in the UK and USA, which suggest maximum interannual variability of 10.9, but are often in the order of 1.6 – 5.5 (McKee et al., 2000). In contrast, interannual variability of TN and TP assessed in sub-tropical Australian catchments is larger, with reported values up to 33 (Eyre & Pont, 2003; McKee et al., 2000). Similarities in interannual load variation with other temperate climates give confidence that the modelled interannual load variations for the Greater Tarawera Lakes estimated by this research are likely to be a reasonable approximation of the actual variation.

Evidence is inconclusive that peaks in estimated nutrient loads translate to peaks in measured lake nutrient concentrations for the lakes, most likely because other factors affecting nutrient concentrations have not been considered by the research. These include fixation of atmospheric nitrogen, microbial denitrification, anaerobic ammonium oxidation, and processes relating to the sedimentation (temporarily or permanently) of nutrients in their particulate bound form or in organic matter (Søndergaard, 2007; Verburg et al., 2018).

Nutrients loads derived from land closer to streams or the lake edge are more likely to result in transport via overland flow, surface water flow or groundwater flow directly to the lake rather than bypassing the lake via sub-regional or regional groundwater flow systems and discharging to a downstream lake or discharging outside of the Greater Lake Tarawera catchment. It follows that land use practices closer to a lake will have the most immediate effect on the nutrient load received by the lake (Creed & Band, 1998; Hunsaker & Levine, 1995; Soranno et al., 2015). There is also less chance of nutrient retention (i.e., attenuation) along shorter flow paths from land closer to streams and lakes. This is reflected in the attenuation factors applied by McBride et al. (2020), and adopted in this research. McBride et al. (2020) estimated a single attenuation factor for each lake in the Tarawera catchment relative to its local catchment area and based on estimates of attenuation for Lake Rotorua using the ROTAN model (Rutherford, 2016). In reality, attenuation is likely to vary throughout a catchment and will be influenced by elevation, soil, geology, slope, riparian planting, wetlands, and any attenuation in the vadose zone (Burbery, 2018; McBride et al., 2020). Elliot et al. (2005) estimated attenuation rates of nitrogen lost at a national scale in New Zealand to be 0.55. Other researchers have estimated nitrogen attenuation rates in the order of 0.29 – 0.75 in parts of the Waikato and Manawatu (Alexander et al., 2002; Clothier et al., 2007; Elwan et al., 2005). Until recently, research in New Zealand has assumed that all nitrogen entering an aquifer from the vadose zone will remain in the aquifer until discharging at a surface water body, but recent research has shown that natural attenuation of nitrogen in groundwater can occur under certain conditions (Burbery, 2018; Burbery et al., 2013; Waikato Regional Council, 2007).

The load received by Lakes Rotokakahi, Rotomahana and Tarawera from connected lakes was estimated by McBride et al. (2020), based on the current nutrient concentration within the upstream lake(s) and that lake's outflow volume (as modelled using CLUES). This outflow volume for connected lake(s) accounts for outflows via both surface water and groundwater, and it is assumed that all water from the upstream lake's local catchment flows into the upstream lake prior to discharging directly into (via surface water) or re-surfacing (via groundwater) in the downstream lake. It is implicit that some of the nutrient load to the upstream lake will be attenuated by in-lake processes during its residence time in the upstream lake, thus reducing the nutrient load to the downstream lake. If any of the nutrient load to the upstream lake bypasses the upstream lake, flowing directly into the downstream lake via groundwater, the opportunity for nutrient retention in the upstream lake is lost. Some attenuation may occur along alternative groundwater flow paths that bypass the upstream lake, and that may compensate for this lost opportunity of in-lake nutrient retention, but the magnitude of nutrient attenuation in New Zealand groundwater is an area so far addressed by only a few scientific studies (Burbery, 2018).

Climate change predictions for the Bay of Plenty indicate a decrease in spring precipitation by the end of the current century, and more frequent and intense drought periods (Ministry for the Environment, 2018). These factors will result, on average, in less drainage, and thus decreased nutrient loads. Drought may also result in substantial changes in sub-surface water storage (Healy et al., 2007). Predictions are also for more extreme rainfalls, which are likely to result in fewer events delivering a greater proportion of the total nutrient load. However, there are uncertainties surrounding plant physiological responses to increasing CO_2 concentrations (Frank et al., 2015) which result from climate change. Increasing CO_2 can change water use efficiency and therefore affect transpiration (Raczka et al., 2016). Estimation of interannual nutrient loads under alternative climate scenarios are outside the scope of this research.

8.4.2 Land use contributions to total nutrient load

This research gives an indication, based on averages of current land use practices in each catchment, of which areas are best targeted for adjustments or limitations to land use and/or land use practices to make improvements to lake water quality. Nutrient loads from diffuse agricultural sources contribute the overwhelming majority of nutrient load to the lakes within highly developed local catchments (e.g., >90% of the total load to Lake Ōkaro, and > 70% of the total load to Lake Rerewhakaaitu). Lakes with less developed local catchments (e.g., Ōkataina and Tikitapu) receive most of their nutrient load from atmospheric deposition (26-43%) and native forest (19-40%). Nutrient leaching from diffuse agricultural land uses can be improved by better on-farm management of land, plants and animals (Foundation for Arable Research et al., 2015). The Bay of Plenty Natural Resources Regional Plan (Bay of Plenty Regional Council, 2017) acknowledges that many resource users and land owners have adopted good management practices, but indicates there may be room for improvement by some. It is beyond the scope of this research to assess current land use practices within the catchment.

Nutrient loading from wastewater systems contributes between 0.1% (Lake Rotomahana) to 15% (Lake Tikitapu) to the total nutrient load of lakes in the Great Tarawera Catchment. The exception being Lake Rotokakahi for which there are no wastewater systems contributing to the lake (although the lake will receive some indirectly via its connection with Lake Tikitapu catchment). Loads from wastewater were estimated in this research to contribute approximately 2.7% of the TN and TP loads to Lake Tarawera, similar to the 3-5% estimate of Dada et al. (2016). Although minor compared to other sources of nutrients, improvements to wastewater systems (e.g., reticulation), could contribute to the improvement of lake water quality as load to the lake from other some other sources (e.g., geothermal) is more difficult to manage (Dada et al., 2016). Furthermore, as most septic tanks are located on properties close to lake shores (where most urban development is situated), lag times in nutrients reaching the lakes are shorter and opportunities for attenuation along flow pathways are minimal.

Natural geothermal processes contribute a sizeable proportion of the phosphorus load (and to a lesser extent the nitrogen load) to Lake Rotomahana (McBride et al., 2020) (14% of TN and 58% of TP as indicated by this research). Lakes Tarawera and Ōkataina also have some nutrient loads attributed to natural geothermal processes (3% and 7% of TN and 22% and 2% of TP respectively).

Water quality of connected lake catchments plays a significant role in the water quality in Lake Tarawera (approximately 20% of the total nutrient load under current land uses), and a smaller role in the catchments of lakes Rotokakahi (< 8% of the total nutrient load) and Rotomahana (< 5% of the total nutrient load). No other lakes receive nutrient loads from connected lakes.

8.4.3 Land use scenarios (Objective 3)

Two hypothetical land-use scenarios have been modelled and assessed to describe best- and worst-case nutrient loading to the lakes. Land use scenarios modelled for this purpose included a complete native forest conversion, and a complete agricultural conversion. Agricultural conversion leads to higher nutrient loads, which will result in poorer water quality due to nutrient enrichment and eutrophication (Abell et al., 2010, 2019; Hamilton & Dada, 2016; Howard-Williams et al., 2011).

Estimates of nitrogen loading to Lake Tarawera under different land use scenarios between this research and that of White et al. (2016) are in approximate agreement after consideration of the differences and limitations of their different estimation methods (Table 8.7). The estimates of White et al. (2016) do not include atmospheric deposition to the lake surface, which is approximately 28 t y^{-1} (Verburg (2015) as citied in McBride et al., 2020), nor do they include attenuation (which this research has). Therefore, with the addition of atmospheric deposition, the estimates of White et al. (2016) are likely to be over-estimates. The forested scenario of White et al. (2016) is a mixture of exotic and native forest, which would be expected to predict lower nitrogen loading than this study, as total nitrogen yields are estimated to be lower for exotic forest (3.0 kg ha^{-1} y^{-1}) than native forest (3.7 kg ha^{-1} y^{-1}) (estimates of McBride et al., 2020). The large-scale intensification scenario of White et al. (2016) includes agricultural intensification only of land already used for agriculture, thus would predict much lower loads to the lake than this research, which assesses a complete agricultural conversion of all land. A more realistic scenario of agricultural intensification would be useful and could be run using this model if requested by the community or council, although consideration should be made of rules limiting land use changes for the purpose of capping nitrogen and reducing phosphorus to the lake set out in the Tarawera Lakes Restoration Plan (Bay of Plenty Regional Council, 2015).

Table 8.7 Comparison of total nitrogen load estimates to Lake Tarawera between this research and the flow model of White at al. (2016). Note that that estimates of White et al. (2016) do not include atmospheric deposition to the lake surface which is estimated to be approximately 28 t y^{-1}. (Verburg (2015) as citied in McBride et al., 2020)

White et al. (2016) scenario[1]	White et al. (2016) steady state nitrogen loading to Lake Tarawera (t y^{-1}) (from Table 4.9, p 67)	White et al. (2016) estimate including atmospheric deposition of 28 t y^{-1}	Comparable scenario from this research[2]	Estimated range (5th percentile to 95th percentile) and mean (in brackets) nitrogen load to Lake Tarawera (t y^{-1}) from this research
Forested (scenario 1)[3]	80	108	All native forest	61 - 97 (80)
Current land use (scenario 3)	140	168	Current land use	77 - 135 (107)
Large scale intensification (sceanrio 5)[4]	240	268	All Agricultural[5]	170 - 350 (262)

[1] No attenutation considered

[2] Attenutation considered

[3] Includes native and exotic forest

[4] Intensification of existing agricultual land uses only

[5] Intensification of all land

Chapter 9
Conclusion

This research has improved the understanding of groundwater flow within and out of the Greater Lake Tarawera catchment. It has quantified the fluxes of water and nutrients to the lakes of the Greater Lake Tarawera catchment with associated interannual variability and uncertainty. Best- and worst-case scenarios of nutrient load to the lakes have also been described. The ranges presented constrain water fluxes and nutrient loads within feasible limits and can inform robust management and policy of water resources.

This chapter concludes the research by summarising the overall findings. It is structured following the presentation and discussion of results, and each section discusses the significance of the findings and their limitations. Finally, it makes recommendations for further research.

9.1 Water provenance

Geochemical evidence suggests that the location of lake-to-lake groundwater connections between the lakes of the Greater Lake Tarawera catchment are not widespread and likely to be isolated to localised areas. A summary of lake-to-lake groundwater connections based on the conclusions of this research is shown in Table 9.1. Groundwater flow out of the Greater Lake Tarawera catchment towards Lake Rotorua cannot be ruled out, although is not likely to comprise large part of the total groundwater outflow.

Flow gains observed in the Tarawera River downstream of the Tarawera Falls are sourced from rainfall-recharged groundwater, challenging postulations of previous research that these gains were sourced from Lake Tarawera water. Some of these flow gains are sourced from groundwater recharged in the Greater Lake Tarawera catchment that has bypassed the lake. Geochemical evidence and water balance calculations indicate Lake Tarawera is discharging some water to groundwater, however this does not comprise a large proportion of the total outflow of the lake.

Conclusions drawn from isotopic analysis in this research are based on information gathered from several locations and may not represent conditions at a wider scale, particularly where there are either fractures or impermeable layers present in the subsurface.

Table 9.1 Summary of lake-to-lake groundwater connections assessed using water balances and geochemical evidence

		Groundwater receiving lake							
		Ōkareka	Ōkaro	Ōkataina	Rerewhakaaitu	Rotokakahi	Rotomahana	Tarawera	Tikitapu
Groundwater exporting lake	Ōkareka		-	Possible	-	-	-	Occuring	-
	Ōkaro	-		-	-	-	Likely	Possible	-
	Ōkataina	-	-		-	-	-	Likely	-
	Rerewhakaaitu	-	-	-		-	Occuring	Possible	-
	Rotokakahi	Unlikely	-	-	-		-	Not occuring	-
	Rotomahana	-	-	-	-	-		Occuring	-
	Tarawera	-	-	-	-	-	-		-
	Tikitapu	Possible	-	Unlikely	-	Likely	-	Possible	

Dark shading indicates confirmed connections

Light shading or no shading indicates unconfirmed connections

9.2 Water balance

Annual water balances have been quantified for Lakes Ōkareka, Ōkaro, Ōkataina, Rerewhakaaitu, Rotokakahi, Rotomahana, Tarawera and Tikitapu for the water years 1972 – 2018. This research differs from and contributes to existing research by describing the interannual variability and uncertainty in the water balance along with the mean, where existing research has solely described mean annual values. In addition to the description of the water balance, this research has also developed an interactive web tool to explore the water balance and the affect different datasets and calculation methods have on the results. This tool is the first of its kind for the Greater Lake Tarawera catchment and can be a useful educational tool for the public, scientists, and decision makers. The tool is available at https://nickiwilson.shinyapps.io/TaraweraMsc/.

This research confirms the conclusions of previous research that groundwater plays a significant role in the flow of water and transport of nutrients to and from the lakes of the Greater Lake Tarawera catchment. The magnitude and variability of groundwater inflows and outflows to and from the lakes is primarily driven by rainfall. Groundwater inflows to Lake Tarawera typically account for 62% of the total inflows to the lake, approximately 70% of which have been recharged from outside of the local catchment of Lake Tarawera. Groundwater outflows from Lake Tarawera and Lake Ōkareka may be negligible in dry years, and water is likely to be released from storage to sustain surface water flows in the Tarawera River and Waitangi Stream during dry periods.

Evaporation has the potential to have a considerable influence on the water balance and its variability. This study is the first water balance undertaken on the lakes of the Greater Lake Tarawera catchment that accounts for seasonality, land use, land cover, and water stress in the calculation of annual land evaporation, thus evaporation estimates presented are considered more accurate than those of previous research. Although overall evaporation estimates are similar to those of previous studies, the relative contribution of evaporation from the land or lake differs which has implications for the estimation of groundwater fluxes to and from the lakes and estimated nutrient loads to the lakes. Accounting for seasonal water stress in land evaporation estimates has been shown to decrease land evaporation by an average of 204 mm y^{-1}.

Frequent lack of closure in the water balance for Lake Rotokakahi may indicate there are groundwater inflows sourced from outside of the currently understood catchment. It is likely that additional groundwater flow may be sourced from the west and routed towards the lake along fault lines trending northeast from the Waikato region.

Lake levels do not show a strong correlation to estimated groundwater outflow from lakes at an annual scale, and generally rise in years when annual rainfall is greater than 1,600 mm.

9.3 Nutrient loads

Nutrient loads to the Greater Tarawera Lakes can vary significantly from year to year and are dependent on climate and land use. This study describes the variation in nutrient loads that can arise from these dependencies, in contrast to previous research which has only described average annual loads. This has implications for the assessment of lake water quality and the factors effecting it. It is considered that three-year rolling averages of nutrient loads are most useful to describe trends and align with current council policy.

For Lake Tarawera three-year rolling averages of nutrient loads have been estimated to be 89 – 139 t y^{-1} for total nitrogen, and 9 – 14 t y^{-1} for total phosphorus for the period 1972 to 2018. Nutrient loads are higher in wet years as they are coupled to lake inflows.

Analysis identifies improvements to the water quality in Lake Tarawera may be achieved by improvements to land use management practices and wastewater systems in the Greater Lake Tarawera catchment. Best- and worst-case scenario modelling is useful to bracket the affect of possible improvement or deterioration on nutrient loads, although more realistic scenarios will be valuable to inform policy.

9.4 Further research recommendations

Insights from this research have highlighted some knowledge gaps leading to the following recommendations for future research:

Improved understanding on the affect that land use change or improved management practices will have on nutrient loads to the lakes could be gained by modelling detailed and realistic land use scenarios. The relative changes in flows and nutrient loads under different land use scenarios may assist policy decisions. Calculations and workflows undertaken by this research have been scripted in R programming language. Some minor code modifications would allow nutrient loads for different land use scenarios to be estimated with relative ease. Similarly, calculations could be re-run using different options for datasets or methods to investigate their effects on the results and add further credibility to the uncertainty ranges described. For example, all rainfall datasets used in this research are variations of the NIWA VCS data, a different method for estimating rainfall could be added to the options and the scripts re-run (e.g. using a reference rainfall station and scaling factors similar to how Rutherford et al., 2019 did in the Rotorua catchment).

Several lake-to-lake groundwater connections have not been confirmed and require further investigation. These include the hypothesised connection between Lake Ōkataina and Lake Tarawera, which may be confirmed by the installation of a well on the isthmus between Ōtangimoana Bay and Lake Tarawera where the connection is most likely to be. The connection between Lake Ōkaro and Lake Rotomahana could be investigated by collecting additional data on the surface water flows in and out of Lake Ōkaro to obtain a more accurate water balance, and by the installation one or more wells located between the lakes to detect geochemical signatures. The connection between Lake Tikitapu and Lakes Rotokakahi, Ōkareka and Tarawera, would be best confirmed by the installation and testing of wells between the lakes.

The deep well at the outlet of Lake Tarawera was damaged by an earthquake during this research allowing only one groundwater sample to be collected and analysed from it. This sample indicated that the groundwater in this location comprised of 94% lake water. Once repaired, it is recommended that further groundwater samples are collected and analysed for isotopes to confirm this result.

Detailed studies could be undertaken in selected areas of the lakes to quantify the interactions between groundwater and lake water. It is recommended that any investigations target a range of areas groundwater flow velocities as identified by the groundwater flow model of White et al. (2016). The installation of several piezometers and subsequent flow net analysis could quantify fluxes along given specific shoreline segments, however the detail and accuracy would be proportional to the densities of the well networks (Rosenberry & Hayashi, 2013, as citied in Rosenberry et al., 2015). Seepage meters and tracer studies could also be used to undertake surveys of groundwater interaction with the lake bed as was undertaken in Lake Taupō by Gibs et al. (2005), although their use is limited to shallower water.

Further isotopic testing and analysis of groundwater and surface water from a greater density of locations could offer an improved understanding of groundwater recharge sources and flow paths within and out of the Greater Lake Tarawera catchment. Notably, stream inflows to Lake Rotorua (Waiohewa, Puarenga, and Waingaehe Streams) require further investigation to determine if there is evidence of groundwater discharging from the Greater Lake Tarawera catchment towards Lake Rotorua. In addition to isotopic analysis, other geochemical analyses could be undertaken to gain further understanding of groundwater flow paths within and out of the Greater Lake Tarawera catchment. These could include analysis and interpretation of major ion data by graphical (e.g., a piper plot) or statistical means (e.g., hierarchical cluster analysis) to determine water types. These types of methodologies have been integrated into recent physiographic classification and process attribute mapping (PoAM) recently undertaken in New Zealand (Rissmann et al., 2021, 2019), which could benefit from using water isotopes and other tracers to delineate land use, lake, and geothermal sources in its approaches to classify and apportion contaminant sources.

Collection of samples from the Tarawera River during a variety of different flow regimes is recommended to confirm the conclusion that flow gains in the river downstream of the falls are sourced from groundwater recharged by rainfall (and not lake water). Concurrent flow gauging at sampling locations would assist in confirming these conclusions and quantifying water fluxes.

Evaporation estimates from the lakes in the Greater Lake Tarawera catchment could be refined using meteorological data from buoys. Evaporation from the lakes has been calculated in this study using lake water temperatures and land-based meteorological data. Meteorological conditions on the lake may be different to those on the land, and data from buoys would provide a more accurate estimation of evaporation.

The relationship of lake level to the estimated groundwater outflow from lakes predicted from this study could be investigated in more detail. This could involve comparing datasets using a monthly or daily time step. Alternatively, estimation of net groundwater flow to/from the lakes could also be derived by using the changes in lake level as a proxy for net groundwater flow after accounting for evaporation and any surface water inflows and outflows (including runoff or assuming runoff is zero).

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Appendices

Appendix A: Methods

Table A1 Simplification of Land Cover Database (LCDB) classes for evaporation calculations

LCDB class code	LCDB class name	Simplification
0	Not land	Water
1	Built-up Area (settlement)	Pasture
2	Urban Parkland/Open Space	Pasture
5	Transport Infrastructure	Pasture
6	Surface Mine or Dump	Pasture
10	Sand or Gravel	Pasture
12	Landslide	Pasture
14	Permanent Snow and Ice	Pasture
15	Alpine Grass/Herbfield	Pasture
16	Gravel or Rock	Pasture
20	Lake or Pond	Water
21	River	Water
22	Estuarine Open Water	Water
30	Short-rotation Cropland	Pasture
33	Orchard, Vineyard or Other Perennial Crop	Pasture
33	Orchards, Vineyards or Other Perennial Crops	Pasture
40	High Producing Exotic Grassland	Pasture
41	Low Producing Grassland	Pasture
43	Tall Tussock Grassland	Pasture
44	Depleted Grassland	Pasture
45	Herbaceous Freshwater Vegetation	Forest - native
46	Herbaceous Saline Vegetation	Pasture
47	Flaxland	Pasture
50	Fernland	Forest - native
51	Gorse and/or Broom	Pasture
52	Manuka and/or Kanuka	Forest - native
54	Broadleaved Indigenous Hardwoods	Forest - native
55	Sub Alpine Shrubland	Pasture
56	Mixed Exotic Shrubland	Forest - native
58	Matagouri or Grey Scrub	Forest - native
64	Forest - Harvested	Pasture
68	Deciduous Hardwoods	Forest - native
69	Indigenous Forest	Forest - native
70	Mangrove	Water
71	Exotic Forest	Forest - pine
80	Peat Shrubland (Chatham Is)	Pasture
81	Dune Shrubland (Chatham Is)	Pasture

Table A2 Methods of estimating annual flows of surface water features

Surface water body	Lake flows out of	Lake flows into	Sub-catchment flows out of	Sub-catchment flows into	Estimation method
Waitangi Stream	Ōkareka	Tarawera	Ōkareka	Tarawera	Annual averages from continuous flow recorder data (from 2017). Pre 2017 synthesised time series created from correlation with gaugings and their paired mesurements from the Tarawera River at outlet
Haumi Stream	Ōkaro	Rotomahana	Ōkaro	Rotomahana	Constant value (mean of all gaugings)
Two unnamed streams flowing into Lake Ōkaro	NA	Ōkaro	NA	NA	Constant value (mean of all gaugings)
Mangakino Stream, Awaroa Stream and ephermal triburaries	NA	Rerewhakaaitu	NA	NA	Constant value (mean of all gaugings)
Upper tributaries of Mangaharakeke Stream	Rerewhakaaitu	NA	Rerewhakaaitu	Out of Tarawera catchments	Considered negilible
Unnamed spring flowing into Rotokakahi	NA	Rotokakahi	NA	NA	Constant value (mean of all gaugings)
Waimangu Stream, Te Kauae Stream, Putuonoa Stream and Rotomahana Stream	NA	Rotomahana	NA	NA	Constant value (mean of all gaugings)
Rotomahana Siphon	Rotomahana	Tarawera	Rotomahana	Tarawera	Modelled to flow when levels in Lake Rotomahana are greater than 340.43 m asl, and limited to 0.72 m3 s-1
Te Wairoa Stream	Rotokakahi	Tarawera	Rotokakahi	Tarawera	Synthesised time series created from correlation with gaugings and their paired mesurements from the Tarawera River at outlet
Wairua Stream	NA	Tarawera	NA	NA	Synthesised time series created from correlation with gaugings and their paired mesurements from the Tarawera River at outlet
Twin creeks	NA	Tarawera	NA	NA	Synthesised time series created from correlation with gaugings and their paired mesurements from the Tarawera River at outlet
Ramp 4 jetty stream	NA	Tarawera	NA	NA	Synthesised time series created from correlation with gaugings and their paired mesurements from the Tarawera River at outlet
Other minor inflows to Lake Tarawera	NA	Tarawera	NA	NA	Constant value (mean of all gaugings where available)
Tarawera River	NA	NA	Tarawera	NA	Annual averages from continuous flow reocrder data

Appendix B: Water provenance

Photograph B1 Sampling location of TR1 on the lake edge, approximately 3,400 m upstream of the Tarawera Falls

Photograph B2 Sampling location of TR2 downstream of the footbridge, and approximately 3,300 m upstream of the Tarawera Falls

Photograph B3 Sampling location of TR3 immediately upstream of where the Tarawera River disappears underground, and approximately 300 m upstream of the Tarawera Falls

Photograph B4 The Tarawera River disappearing underground

Photograph B5 The Tarawera Falls showing the Tarawera River re-emerging from the cliff face

Photograph B6 Sampling location of TR4 approximately 200m downstream of the Tarawera Falls

Photograph B7 Springs emerging from the riverbank downstream of the Tarawera Falls

Photograph B8 Sampling location of TR5, 1,000 m downstream from the Tarawera Falls

Water isotope analysis results

Sample name	Alternative name	Date collected	NZTME	NZTMN	dD	d18O	Type
Bore 1000129 at Spencer Rd	FK779059	24/02/2021 10:25	1897760	5770596	-36.6	-6.01	Groundwater
Bore 1000129 at Spencer Rd	FK779059	26/05/2021 0:00	1897760	5770596	-36.7	-6.08	Groundwater
Bore 1000129 at Spencer Rd*	FK779059	18/11/2020 10:20	1897760	5770596	-21.7	-3.28	Groundwater
Bore 1000131 at Spencer Rd	FJ656900	10/08/2020 14:45	1896564	5769004	-22.1	-3.22	Groundwater
Bore 1000131 at Spencer Rd	FJ656900	24/02/2021 12:35	1896564	5769004	-21.8	-2.91	Groundwater
Bore 1000131 at Spencer Rd	FJ656900	26/05/2021 0:00	1896564	5769004	-22	-3.23	Groundwater
Bore 1000131 at Spencer Rd*	FJ656900	18/11/2020 9:25	1896564	5769004	-36.5	-6.06	Groundwater
Bore 1000134 at Tarawera Outlet	GJ663803	7/10/2020 13:50	1906635	5768037	-21.8	-3.22	Groundwater
Bore 1001051 at Tarawera Rd	FJ443517	10/08/2020 13:10	1894435	5765178	-37.1	-6.2	Groundwater
Bore 1001051 at Tarawera Rd	FJ443517	19/11/2020 8:15	1894435	5765178	-37.4	-6.28	Groundwater
Bore 1001051 at Tarawera Rd	FJ443517	25/02/2021 10:35	1894435	5765178	-37.4	-6.06	Groundwater
Bore 1001051 at Tarawera Rd	FJ443517	26/05/2021 0:00	1894435	5765178	-37.3	-6.15	Groundwater
Bore 1001052 at Ash Pit Rd	GI753566_52	26/08/2020 13:17	1907536	5755666	-41.3	-6.53	Groundwater
Bore 1001052 at Ash Pit Rd	GI753566_52	3/11/2020 12:20	1907536	5755666	-43.8	-6.86	Groundwater
Bore 1001052 at Ash Pit Rd	GI753566_52	26/01/2021 13:00	1907536	5755666	-44.5	-6.87	Groundwater
Bore 1001052 at Ash Pit Rd	GI753566_52	20/05/2021 0:00	1907536	5755666	-43.4	-6.92	Groundwater
Bore 1001053 at Ash Pit Rd	GI753566_53	26/08/2020 13:35	1907532	5755666	-40	-6.34	Groundwater
Bore 1001053 at Ash Pit Rd	GI753566_53	3/11/2020 11:23	1907532	5755666	-39.7	-6.42	Groundwater
Bore 1001053 at Ash Pit Rd	GI753566_53	26/01/2021 13:22	1907532	5755666	-39.7	-6.35	Groundwater
Bore 1001053 at Ash Pit Rd	GI753566_53	20/05/2021 0:00	1907532	5755666	-40.2	-6.49	Groundwater
Bore 1001055 at Ash Pit Rd	GI439843	26/08/2020 11:31	1904397	5758437	-29.8	-4.38	Groundwater
Bore 1001055 at Ash Pit Rd	GI439843	3/11/2020 13:35	1904397	5758437	-28.8	-4.31	Groundwater
Bore 1001055 at Ash Pit Rd	GI439843	26/01/2021 11:00	1904397	5758437	-28.4	-4.14	Groundwater
Bore 1001055 at Ash Pit Rd	GI439843	20/05/2021 0:00	1904397	5758437	-28.1	-4.1	Groundwater
Bore 1001068 at Highlands Loop Rd	EJ981312	7/09/2020 13:02	1889816	5763122	-39	-6.25	Groundwater
Bore 1001068 at Highlands Loop Rd	EJ981312	30/11/2020 13:56	1889816	5763122	-38.9	-6.42	Groundwater
Bore 1001068 at Highlands Loop Rd	EJ981312	3/03/2021 12:22	1889816	5763122	-39.1	-6.26	Groundwater
Bore 1001068 at Highlands Loop Rd	EJ981312	31/05/2021 0:00	1889816	5763122	-38.9	-6.34	Groundwater
Bore 1001070 at Millar Rd	FK380119	10/08/2020 10:45	1893807	5771190	-38.3	-6.39	Groundwater
Bore 1001070 at Millar Rd	FK380119	19/11/2020 9:05	1893807	5771190	-37.7	-6.21	Groundwater
Bore 1001070 at Millar Rd	FK380119	24/02/2021 14:50	1893807	5771190	-37.9	-6.37	Groundwater
Bore 1001070 at Millar Rd	FK380119	26/05/2021 0:00	1893807	5771190	-38.4	-6.34	Groundwater
Bore 1001072 at Tikitapu Reserve	FJ141820	10/08/2020 9:30	1891413	5768201	-19.9	-2.95	Groundwater
Bore 1001072 at Tikitapu Reserve	FJ141820	19/11/2020 10:00	1891413	5768201	-17.7	-2.76	Groundwater
Bore 1001072 at Tikitapu Reserve	FJ141820	24/02/2021 13:45	1891413	5768201	-19.1	-2.67	Groundwater
Bore 1001072 at Tikitapu Reserve	FJ141820	26/05/2021 0:00	1891413	5768201	-17.1	-2.43	Groundwater
Bore 10968 at Gee Rd	FK137414	17/11/2020 8:15	1891373	5774141	-39.3	-6.61	Groundwater
Bore 10968 at Gee Rd	FK137414	10/02/2021 9:25	1891373	5774141	-40.2	-6.23	Groundwater
Bore 10968 at Gee Rd	FK137414	3/05/2021 0:00	1891373	5774141	-39.2	-6.56	Groundwater
HW1 Hotwater Beach	HW1		1900290	5761848	-28.7	-3.87	Inflow to Lake Tarawera
HW1 Hotwater Beach	HW1		1900290	5761848	-27.1	-3.68	Inflow to Lake Tarawera

Water isotope analysis results

Sample name	Alternative name	Date collected	NZTME	NZTMN	dD	d18O	Type
HW1 Hotwater Beach	HW1 Hotwater Beach		1900290	5761848	-31	-4.28	Inflow to Lake Tarawera
HW1 Hotwater Beach	HW1 Hotwater Beach 01_06_19		1900290	5761848	-30.6	-4.24	Inflow to Lake Tarawera
HW1 Hotwater Beach	HW1 Hotwater Beach 05_10_19		1900290	5761848	-30.4	-4.28	Inflow to Lake Tarawera
HW2 Hotwater Beach	Hotwater beach proper		1900500	5761672	-29.1	-4.03	Inflow to Lake Tarawera
HW2 Hotwater Beach	Hotwater beach proper 05_10_19		1900500	5761672	-29.3	-3.99	Inflow to Lake Tarawera
HW2 Hotwater Beach	HW2		1900500	5761672	-32.5	-5.07	Inflow to Lake Tarawera
HW2 Hotwater Beach	HW2		1900500	5761672	-31.6	-4.71	Inflow to Lake Tarawera
HW2 Hotwater Beach	HW2(Hotwater Beach Proper 01_06_19		1900500	5761672	-29.5	-4.08	Inflow to Lake Tarawera
Island waterfall	039 Island waterfall		1896393	5766149	-36.3	-6.37	Inflow to Lake Tarawera
Island waterfall	039 Island waterfall 05_10_19		1896393	5766149	-35.8	-5.98	Inflow to Lake Tarawera
Island waterfall	39 Island waterfall 01_06_19		1896393	5766149	-35.9	-6.01	Inflow to Lake Tarawera
Middle flax A	Middle Flax A		1902097	5761264	-22.4	-2.79	Inflow to Lake Tarawera
Middle flax A	middle flax A		1902097	5761264	-22.4	-2.61	Inflow to Lake Tarawera
Middle flax A	Middle Flax A		1902097	5761264	-21.9	-2.56	Inflow to Lake Tarawera
Middle flax A	middle flax A 01_06_19		1902097	5761264	-22.6	-2.82	Inflow to Lake Tarawera
Middle flax A	middle flax A 05_10_19		1902097	5761264	-22.6	-2.77	Inflow to Lake Tarawera
Middle flax A	MiddleFlaxAISOOH152130819		1902097	5761264	-22.3	-2.76	Inflow to Lake Tarawera
Middle flax A	MiddleFlaxAISOOH152300419		1902097	5761264	-22.1	-2.69	Inflow to Lake Tarawera
Ramp 4 jetty spring	Ramp 4 Jetty 01_06_19		1895666	5765931	-35.6	-6.03	Inflow to Lake Tarawera
Ramp 4 jetty spring	Ramp 4 Jetty Stream		1895666	5765931	-36	-5.97	Inflow to Lake Tarawera
Ramp 4 jetty spring	Ramp 4 Jetty Stream 05_10_19		1895666	5765931	-34	-5.67	Inflow to Lake Tarawera
Ramp 4 jetty spring?	02 Orchard		1895666	5765931	-35.4	-5.88	Inflow to Lake Tarawera
Rotomahana Siphon	RMH1ISOOH26300419		1901547	5761544	-22.3	-2.5	Inflow to Lake Tarawera
Rotomahana Siphon	RMHS		1901547	5761544	-22	-2.75	Inflow to Lake Tarawera
Rotomahana Siphon	RMHSISOOH176130819		1901547	5761544	-22.1	-2.63	Inflow to Lake Tarawera
Rotomahana Spring	015377 Rotomahana Spring		1902394	5762118	-22.4	-2.74	Inflow to Lake Tarawera
Rotomahana Spring	015377 Rotomahana Spring 05_10_19		1902394	5762118	-22.4	-2.74	Inflow to Lake Tarawera
Rotomahana Spring	Rotomahana spring 01_06_19		1902394	5762118	-22.2	-2.69	Inflow to Lake Tarawera
Rotomahana waterfall	034 Rotomahana waterfall		1902325	5762041	-22.4	-2.88	Inflow to Lake Tarawera
Rotomahana waterfall	034 Rotomahana waterfall 05_10_19		1902325	5762041	-22.8	-2.81	Inflow to Lake Tarawera
Rotomahana waterfall	RMHW		1902325	5762041	-21.8	-2.83	Inflow to Lake Tarawera
Rotomahana waterfall	RMHW		1902325	5762041	-22.2	-2.78	Inflow to Lake Tarawera
Rotomahana waterfall	RMHWISOOH35130819		1902325	5762041	-22.1	-2.62	Inflow to Lake Tarawera
Rotomahana waterfall	Rotomahana waterfall 01_06_19		1902325	5762041	-23	-2.93	Inflow to Lake Tarawera
Spencer Rd Ford Stream	06 Craig Armstrong(ford) 01_06_19		1897416	5770409	-34.9	-5.8	Inflow to Lake Tarawera
Spencer Rd Ford Stream	06 Craig Armstrongs		1897416	5770409	-35	-5.76	Inflow to Lake Tarawera
Spencer Rd Ford Stream	06 Craig Armstrongs 05_10_19		1897416	5770409	-34.1	-5.67	Inflow to Lake Tarawera
Te Wairoa Stream	01 Te Wairoa		1895602	5765696	-20.7	-2.63	Inflow to Lake Tarawera
Te Wairoa Stream	01 Te Wairoa 05_10_19		1895602	5765696	-21.6	-3.27	Inflow to Lake Tarawera
Te Wairoa Stream	01 Te Wairoa Stream 01_06_19		1895602	5765696	-21.1	-3.17	Inflow to Lake Tarawera
Te Whekau Stream	040 Peter Thodie		1897285	5770229	-37.7	-6.33	Inflow to Lake Tarawera

Water isotope analysis results

Sample name	Alternative name	Date collected	NZTME	NZTMN	dD	d18O	Type
Te Whekau Stream	040 Peter Thodie 01_06_19		1897285	5770229	-36.4	-5.96	Inflow to Lake Tarawera
Te Whekau Stream	040 Peter Thodie 05_10_19		1897285	5770229	-36.9	-6.16	Inflow to Lake Tarawera
Twin Creek (main)	029 Main Twin Creek		1898032	5764062	-39.6	-6.65	Inflow to Lake Tarawera
Twin Creek (main)	029 Main Twin Creek 01_06_19		1898032	5764062	-38.7	-6.54	Inflow to Lake Tarawera
Twin Creek (main)	029 Main Twin Creek 05_10_19		1898032	5764062	-38.7	-6.5	Inflow to Lake Tarawera
Wairua Arm WA1	WA 01_06_19		1902413	5762275	-22.2	-2.68	Inflow to Lake Tarawera
Wairua Arm WA1	wairua arm WA 1		1902413	5762275	-22	-2.65	Inflow to Lake Tarawera
Wairua Arm WA1	wairua arm WA 1 05_10_19		1902413	5762275	-21.9	-2.7	Inflow to Lake Tarawera
Wairua Stream	026 Wairua		1899795	5762167	-39.9	-6.8	Inflow to Lake Tarawera
Wairua Stream	026 Wairua 05_10_19		1899795	5762167	-39	-6.41	Inflow to Lake Tarawera
Wairua Stream	wairua stream 01_06_19		1899795	5762167	-39.7	-6.45	Inflow to Lake Tarawera
Waitangi Stream	04 Waitangi Stm 01_06_19		1896832	5768960	-16.4	-2.13	Inflow to Lake Tarawera
Waitangi Stream	04 Waitangi Stream		1896832	5768960	-13.9	-1.67	Inflow to Lake Tarawera
Waitangi Stream	04 Waitangi Stream 05_10_19		1896832	5768960	-15.9	-2.15	Inflow to Lake Tarawera
CDPR_20/2007/Aug/30493					-36.66	-5.86	Rotorua rainfall
CDPR_20/2007/Dec/30493					-28.7663	-5.18118	Rotorua rainfall
CDPR_20/2007/Nov/30493					-2.86481	-1.88	Rotorua rainfall
CDPR_20/2007/Oct/30493					-14.82	-3.79	Rotorua rainfall
CDPR_20/2007/Sept/30493					-25.35	-4.66	Rotorua rainfall
CDPR_20/2008/April/30493					-41.3956	-6.89678	Rotorua rainfall
CDPR_20/2008/Aug/30493					-41.731	-7.25358	Rotorua rainfall
CDPR_20/2008/Dec/30493					-36.6207	-6.16655	Rotorua rainfall
CDPR_20/2008/June/30493					-51.4555	-7.98592	Rotorua rainfall
CDPR_20/2008/Mar/30493					-56.5523	-7.90948	Rotorua rainfall
CDPR_20/2008/May/30493					-55.9154	-9.73151	Rotorua rainfall
CDPR_20/2008/Nov/30493					-11.1893	-3.42177	Rotorua rainfall
CDPR_20/2008/Oct/30493					-33.7962	-6.06414	Rotorua rainfall
CDPR_20/2008/Sept/30493					-40.1032	-7.22402	Rotorua rainfall
CDPR_20/2009/April/30493					-17.0894	-3.82776	Rotorua rainfall
CDPR_20/2009/Aug/30493					-62.3614	-9.37495	Rotorua rainfall
CDPR_20/2009/Dec/30493					-8.79195	-2.80394	Rotorua rainfall
CDPR_20/2009/Feb/30493					-59.2565	-8.95756	Rotorua rainfall
CDPR_20/2009/Jan/30493					-6.80456	-1.61368	Rotorua rainfall
CDPR_20/2009/June/30493					-68.2134	-10.2177	Rotorua rainfall
CDPR_20/2009/Mar/30493					-12.4787	-2.97199	Rotorua rainfall
CDPR_20/2009/May/30493					-51.8697	-7.88865	Rotorua rainfall
CDPR_20/2009/Nov/30493					-15.5458	-3.33903	Rotorua rainfall
CDPR_20/2009/Oct/30493					-33.7365	-6.23921	Rotorua rainfall
CDPR_20/2009/Sept/30493					-20.2477	-4.27252	Rotorua rainfall
CDPR_20/2010/Feb/30493					2.139388	-2.11377	Rotorua rainfall
CDPR_20/2010/Jan/30493					-43.0193	-6.95106	Rotorua rainfall

Water isotope analysis results

Sample name	Alternative name	Date collected	NZTME	NZTMN	dD	d18O	Type
TR1 (lake water)		2/02/2021	1906605	5768026	-18.7	-2.77	Tarawera River
TR2 (outlet flow)		2/02/2021	1906681	5768090	-18.8	-2.59	Tarawera River
TR3		2/02/2021	1908366	5770037	-18.6	-2.58	Tarawera River
TR4		2/02/2021	1908517	5770453	-20.8	-3.12	Tarawera River
TR5		2/02/2021	1908505	5771185	-23.7	-3.88	Tarawera River
Puarenga at FRI	Stream	19/06/2018	1885887	5771442	-32.5	-4.73	Inflow to Lake Rotorua
Puarenga at FRI	Stream	15/08/2018	1885887	5771442	-36.7	-6.06	Inflow to Lake Rotorua
Puarenga at FRI	Stream	4/09/2018	1885887	5771442	-33.4	-4.94	Inflow to Lake Rotorua
Puarenga at FRI**	Stream	14/11/2018	1885887	5771442	-16.5	-1.84	Inflow to Lake Rotorua
Puarenga at FRI	Stream	11/05/2019	1885887	5771442	-34.9	-5.74	Inflow to Lake Rotorua
Puarenga at FRI	Stream	6/12/2019	1885887	5771442	-33.5	-5.54	Inflow to Lake Rotorua
Puarenga at FRI	Stream	15/01/2020	1885887	5771442	-34.2	-6.16	Inflow to Lake Rotorua
Puarenga at FRI	Stream	25/02/2020	1885887	5771442	-34.7	-5.8	Inflow to Lake Rotorua
Waingaehe at SH30	Stream	19/06/2018	1890187	5775300	-36.1	-5.64	Inflow to Lake Rotorua
Waingaehe at SH30	Stream	15/08/2018	1890187	5775300	-38.3	-6.19	Inflow to Lake Rotorua
Waingaehe at SH30	Stream	4/09/2018	1890187	5775300	-35.7	-5.84	Inflow to Lake Rotorua
Waingaehe at SH30**	Stream	14/11/2018	1890187	5775300	-32.8	-5.22	Inflow to Lake Rotorua
Waingaehe at SH30	Stream	11/05/2019	1890187	5775300	-38.1	-6.3	Inflow to Lake Rotorua
Waingaehe at SH30	Stream	6/12/2019	1890187	5775300	-38.2	-6.25	Inflow to Lake Rotorua
Waingaehe at SH30	Stream	15/01/2020	1890187	5775300	-38.7	-6.74	Inflow to Lake Rotorua
Waingaehe at SH30	Stream	25/02/2020	1890187	5775300	-38.2	-6.32	Inflow to Lake Rotorua
Waiohewa at Rangiteaorere Rd	Stream	19/06/2018	1892078	5779651	-30.1	-4.6	Inflow to Lake Rotorua
Waiohewa at Rangiteaorere Rd	Stream	15/08/2018	1892078	5779651	-32.4	-5.14	Inflow to Lake Rotorua
Waiohewa at Rangiteaorere Rd	Stream	4/09/2018	1892078	5779651	-29.8	-4.54	Inflow to Lake Rotorua
Waiohewa at Rangiteaorere Rd**	Stream	14/11/2018	1892078	5779651	-32.7	-4.94	Inflow to Lake Rotorua
Waiohewa at Rangiteaorere Rd	Stream	11/05/2019	1892078	5779651	-30.7	-5.14	Inflow to Lake Rotorua
Waiohewa at Rangiteaorere Rd	Stream	6/12/2019	1892078	5779651	-31	-5.2	Inflow to Lake Rotorua
Waiohewa at Rangiteaorere Rd	Stream	15/01/2020	1892078	5779651	-31.2	-5.5	Inflow to Lake Rotorua
Waiohewa at Rangiteaorere Rd	Stream	25/02/2020	1892078	5779651	-30.8	-4.47	Inflow to Lake Rotorua
Utuhina at Lake Rd	Stream	19/06/2018	1884266	5774803	-33.1	-4.97	Inflow to Lake Rotorua
Utuhina at Lake Rd	Stream	15/08/2018	1884266	5774803	-37.3	-6.23	Inflow to Lake Rotorua
Utuhina at Lake Rd	Stream	4/09/2018	1884266	5774803	-32.5	-4.29	Inflow to Lake Rotorua
Utuhina at Lake Rd**	Stream	14/11/2018	1884266	5774803	-36.2	-6.13	Inflow to Lake Rotorua
Utuhina at Lake Rd	Stream	11/05/2019	1884266	5774803	-35.3	-5.92	Inflow to Lake Rotorua
Utuhina at Lake Rd	Stream	6/12/2019	1884266	5774803	-35.4	-6.21	Inflow to Lake Rotorua
Utuhina at Lake Rd	Stream	15/01/2020	1884266	5774803	-36.1	-6.69	Inflow to Lake Rotorua
Utuhina at Lake Rd	Stream	25/02/2020	1884266	5774803	-35.6	-5.64	Inflow to Lake Rotorua

* Spencer Road groundwater samples from 18/11/2020 may have been mixed up so are excluded from analysis

** Samples from the November 2018 Rotorua inflows are anamolous and have been excluded from the analysis

Bore 129 – IsoSource Output

Date:	9/11/2021	Time:	3:42:01 pm
Title:	Bore 129		
Increment:	1%		
Tolerance:	0.5		
Isotopes:	O	H	
Mixtures:	-6.05	-36.7	
Sources:			
Rainfall (bore 968)		-6.47	-39.57
Lake Tarawera		-2.87	-20.5
Lake Okataina		-3.37	-21.3
	***************		***************

FEASIBLE OUTPUT:

Rainfall (bore 968)	Lake Tarawera	Lake Okataina
0.82	0	0.18
0.82	0.01	0.17
0.82	0.02	0.16
0.82	0.03	0.15
0.82	0.04	0.14
0.82	0.05	0.13
0.82	0.06	0.12
0.82	0.07	0.11
0.82	0.08	0.1
0.82	0.09	0.09
0.82	0.1	0.08
0.83	0	0.17
0.83	0.01	0.16
0.83	0.02	0.15
0.83	0.03	0.14
0.83	0.04	0.13
0.83	0.05	0.12
0.83	0.06	0.11
0.83	0.07	0.1
0.83	0.08	0.09
0.83	0.09	0.08
0.83	0.1	0.07
0.83	0.11	0.06
0.83	0.12	0.05
0.83	0.13	0.04
0.83	0.14	0.03
0.83	0.15	0.02
0.83	0.16	0.01
0.83	0.17	0
0.84	0	0.16
0.84	0.01	0.15
0.84	0.02	0.14
0.84	0.03	0.13
0.84	0.04	0.12
0.84	0.05	0.11
0.84	0.06	0.1
0.84	0.07	0.09
0.84	0.08	0.08
0.84	0.09	0.07
0.84	0.1	0.06
0.84	0.11	0.05
0.84	0.12	0.04
0.84	0.13	0.03
0.84	0.14	0.02
0.84	0.15	0.01
0.84	0.16	0
0.85	0	0.15
0.85	0.01	0.14
0.85	0.02	0.13
0.85	0.03	0.12
0.85	0.04	0.11
0.85	0.05	0.1
0.85	0.06	0.09
0.85	0.07	0.08
0.85	0.08	0.07
0.85	0.09	0.06
0.85	0.1	0.05
0.85	0.11	0.04
0.85	0.12	0.03
0.85	0.13	0.02
0.85	0.14	0.01
0.85	0.15	0
0.86	0	0.14
0.86	0.01	0.13
0.86	0.02	0.12
0.86	0.03	0.11
0.86	0.04	0.1
0.86	0.05	0.09
0.86	0.06	0.08
0.86	0.07	0.07
0.86	0.08	0.06
0.86	0.09	0.05
0.86	0.1	0.04
0.86	0.11	0.03
0.86	0.12	0.02
0.86	0.13	0.01
0.86	0.14	0
0.87	0	0.13
0.87	0.01	0.12
0.87	0.02	0.11
0.87	0.03	0.1
0.87	0.04	0.09
0.87	0.05	0.08
0.87	0.06	0.07
0.87	0.07	0.06
0.87	0.08	0.05
0.87	0.09	0.04
0.87	0.1	0.03
0.87	0.11	0.02
0.87	0.12	0.01
0.87	0.13	0

Bore 151 – IsoSource Output

Date: 9/11/2021 Time: 3:52:47 pm
Title: Bore 051
Increment: 1%
Tolerance: 0.5
Isotopes: O H
Mixtures: -6.17 -37.3
Sources:
Rainfall (bore 968) -6.47 -39.57
Lake Tikitapu -2.87 -20.5
Local rainfall (bore 029) -6.05 -36.7
*************** ***************

FEASIBLE OUTPUT:

Rainfall (bore 968)	Lake Tikitapu	Local rainfall (bore 029)
0.04	0	0.96
0.05	0	0.95
0.06	0	0.94
0.07	0	0.93
0.08	0	0.92
0.09	0	0.91
0.1	0	0.9
0.1	0.01	0.89
0.11	0	0.89
0.11	0.01	0.88
0.12	0	0.88
0.12	0.01	0.87
0.13	0	0.87
0.13	0.01	0.86
0.14	0	0.86
0.14	0.01	0.85
0.15	0	0.85
0.15	0.01	0.84
0.15	0.02	0.83
0.16	0	0.84
0.16	0.01	0.83
0.16	0.02	0.82
0.17	0	0.83
0.17	0.01	0.82
0.17	0.02	0.81
0.18	0	0.82
0.18	0.01	0.81
0.18	0.02	0.8
0.19	0	0.81
0.19	0.01	0.8
0.19	0.02	0.79
0.2	0	0.8
0.2	0.01	0.79
0.2	0.02	0.78
0.21	0	0.79
0.21	0.01	0.78
0.21	0.02	0.77
0.21	0.03	0.76
0.22	0	0.78
0.22	0.01	0.77
0.22	0.02	0.76
0.22	0.03	0.75
0.23	0	0.77
0.23	0.01	0.76
0.23	0.02	0.75
0.23	0.03	0.74
0.24	0	0.76
0.24	0.01	0.75
0.24	0.02	0.74
0.24	0.03	0.73
0.25	0	0.75
0.25	0.01	0.74
0.25	0.02	0.73
0.25	0.03	0.72
0.26	0	0.74
0.26	0.01	0.73
0.26	0.02	0.72
0.26	0.03	0.71
0.27	0	0.73
0.27	0.01	0.72
0.27	0.02	0.71
0.27	0.03	0.7
0.27	0.04	0.69
0.28	0	0.72
0.28	0.01	0.71
0.28	0.02	0.7
0.28	0.03	0.69
0.28	0.04	0.68
0.29	0	0.71
0.29	0.01	0.7
0.29	0.02	0.69
0.29	0.03	0.68
0.29	0.04	0.67
0.3	0	0.7
0.3	0.01	0.69
0.3	0.02	0.68
0.3	0.03	0.67
0.3	0.04	0.66
0.31	0	0.69
0.31	0.01	0.68
0.31	0.02	0.67
0.31	0.03	0.66
0.31	0.04	0.65
0.32	0	0.68
0.32	0.01	0.67
0.32	0.02	0.66
0.32	0.03	0.65
0.32	0.04	0.64
0.32	0.05	0.63
0.33	0	0.67
0.33	0.01	0.66
0.33	0.02	0.65
0.33	0.03	0.64
0.33	0.04	0.63
0.33	0.05	0.62
0.34	0	0.66
0.34	0.01	0.65
0.34	0.02	0.64
0.34	0.03	0.63
0.34	0.04	0.62
0.34	0.05	0.61
0.35	0	0.65
0.35	0.01	0.64
0.35	0.02	0.63
0.35	0.03	0.62
0.35	0.04	0.61
0.35	0.05	0.6
0.36	0	0.64
0.36	0.01	0.63
0.36	0.02	0.62
0.36	0.03	0.61
0.36	0.04	0.6
0.36	0.05	0.59
0.37	0	0.63
0.37	0.01	0.62
0.37	0.02	0.61
0.37	0.03	0.6
0.37	0.04	0.59
0.37	0.05	0.58
0.38	0	0.62
0.38	0.01	0.61
0.38	0.02	0.6
0.38	0.03	0.59
0.38	0.04	0.58
0.38	0.05	0.57
0.38	0.06	0.56
0.39	0.01	0.6
0.39	0.02	0.59
0.39	0.03	0.58
0.39	0.04	0.57
0.39	0.05	0.56
0.39	0.06	0.55
0.4	0.01	0.59
0.4	0.02	0.58
0.4	0.03	0.57
0.4	0.04	0.56
0.4	0.05	0.55
0.4	0.06	0.54
0.41	0.01	0.58
0.41	0.02	0.57
0.41	0.03	0.56
0.41	0.04	0.55
0.41	0.05	0.54
0.41	0.06	0.53
0.42	0.01	0.57
0.42	0.02	0.56
0.42	0.03	0.55
0.42	0.04	0.54
0.42	0.05	0.53
0.42	0.06	0.52
0.43	0.01	0.56
0.43	0.02	0.55
0.43	0.03	0.54
0.43	0.04	0.53
0.43	0.05	0.52
0.43	0.06	0.51
0.43	0.07	0.5
0.44	0.02	0.54
0.44	0.03	0.53
0.44	0.04	0.52
0.44	0.05	0.51
0.44	0.06	0.5
0.44	0.07	0.49
0.45	0.02	0.53
0.45	0.03	0.52
0.45	0.04	0.51
0.45	0.05	0.5
0.45	0.06	0.49
0.45	0.07	0.48
0.46	0.02	0.52
0.46	0.03	0.51
0.46	0.04	0.5
0.46	0.05	0.49
0.46	0.06	0.48
0.46	0.07	0.47
0.47	0.02	0.51
0.47	0.03	0.5
0.47	0.04	0.49
0.47	0.05	0.48
0.47	0.06	0.47
0.47	0.07	0.46
0.48	0.02	0.5
0.48	0.03	0.49
0.48	0.04	0.48
0.48	0.05	0.47

Bore 052 – IsoSource Output

Date: 9/11/2021 Time: 3:54:41 pm
Title: Bore 052
Increment: 1%
Tolerance: 0.5
Isotopes: O H
Mixtures: -6.8 -43.3
Sources:
Rainfall (bore 968) -6.47 -39.57
Lake Rerewhakaaitu -1.67 -13.9
Local rainfall (bore 029) -6.05 -36.7
*************** ***************

FEASIBLE OUTPUT:

Rainfall (bore 968)	Lake Rerewhakaaitu	Local rainfall (bore 029)

Bore 053 – IsoSource Output

Date:	9/11/2021	Time:	3:58:33 pm
Title:	Bore 053		
Increment:	1%		
Tolerance:	0.5		
Isotopes:	O	H	
Mixtures:	-6.4	-39.9	
Sources:			
Rainfall (bore 968)		-6.47	-39.57
Lake Rerewhakaaitu		-1.67	-13.9
Local rainfall (bore 029)		-6.05	-36.7
	***************		***************

FEASIBLE OUTPUT:

Rainfall (bore 968)	Lake Rerewhakaaitu	Local rainfall (bore 029)
---------------	---------------	---------------
0.95	0	0.05
0.96	0	0.04
0.97	0	0.03
0.98	0	0.02
0.99	0	0.01
1	0	0

Bore 055 – IsoSource Output

Date:	9/11/2021	Time:	4:00:10 pm
Title:	Bore 055		
Increment:	1%		
Tolerance:	0.5		
Isotopes:	O	H	
Mixtures:	-4.23	-28.8	
Sources:			
Rainfall (bore 968)		-6.47	-39.57
Lake Rerewhakaaitu		-1.67	-13.9
Lake Rotomahana		-2.70	-21.9
	***************		***************

FEASIBLE OUTPUT:

Rainfall (bore 968)	Lake Rerewhakaaitu	Lake Rotomahana
---------------	---------------	---------------
0.37	0	0.63
0.37	0.01	0.62
0.38	0	0.62
0.38	0.01	0.61
0.38	0.02	0.6
0.38	0.03	0.59
0.39	0	0.61
0.39	0.01	0.6
0.39	0.02	0.59
0.39	0.03	0.58
0.39	0.04	0.57
0.39	0.05	0.56
0.39	0.06	0.55
0.4	0	0.6
0.4	0.01	0.59
0.4	0.02	0.58
0.4	0.03	0.57
0.4	0.04	0.56
0.4	0.05	0.55
0.4	0.06	0.54
0.4	0.07	0.53
0.4	0.08	0.52
0.41	0	0.59
0.41	0.01	0.58
0.41	0.02	0.57
0.41	0.03	0.56
0.41	0.04	0.55
0.41	0.05	0.54
0.41	0.06	0.53
0.41	0.07	0.52
0.41	0.08	0.51
0.41	0.09	0.5
0.41	0.1	0.49
0.42	0.01	0.57
0.42	0.02	0.56
0.42	0.03	0.55
0.42	0.04	0.54
0.42	0.05	0.53
0.42	0.06	0.52
0.42	0.07	0.51
0.42	0.08	0.5
0.42	0.09	0.49
0.42	0.1	0.48
0.42	0.11	0.47
0.42	0.12	0.46
0.43	0.03	0.54
0.43	0.04	0.53
0.43	0.05	0.52
0.43	0.06	0.51
0.43	0.07	0.5
0.43	0.08	0.49
0.43	0.09	0.48
0.43	0.1	0.47
0.43	0.11	0.46
0.43	0.12	0.45
0.43	0.13	0.44
0.43	0.14	0.43
0.44	0.05	0.51
0.44	0.06	0.5
0.44	0.07	0.49
0.44	0.08	0.48
0.44	0.09	0.47
0.44	0.1	0.46
0.44	0.11	0.45
0.44	0.12	0.44
0.44	0.13	0.43
0.44	0.14	0.42
0.44	0.15	0.41
0.44	0.16	0.4
0.44	0.17	0.39
0.45	0.07	0.48
0.45	0.08	0.47
0.45	0.09	0.46
0.45	0.1	0.45
0.45	0.11	0.44
0.45	0.12	0.43
0.45	0.13	0.42
0.45	0.14	0.41
0.45	0.15	0.4
0.45	0.16	0.39
0.45	0.17	0.38
0.45	0.18	0.37
0.45	0.19	0.36
0.46	0.1	0.44
0.46	0.11	0.43
0.46	0.12	0.42
0.46	0.13	0.41
0.46	0.14	0.4
0.46	0.15	0.39
0.46	0.16	0.38
0.46	0.17	0.37
0.46	0.18	0.36
0.46	0.19	0.35
0.46	0.2	0.34
0.46	0.21	0.33
0.47	0.12	0.41
0.47	0.13	0.4
0.47	0.14	0.39
0.47	0.15	0.38
0.47	0.16	0.37
0.47	0.17	0.36
0.47	0.18	0.35
0.47	0.19	0.34
0.47	0.2	0.33
0.47	0.21	0.32
0.47	0.22	0.31
0.47	0.23	0.3
0.48	0.14	0.38
0.48	0.15	0.37
0.48	0.16	0.36
0.48	0.17	0.35
0.48	0.18	0.34
0.48	0.19	0.33
0.48	0.2	0.32
0.48	0.21	0.31
0.48	0.22	0.3
0.48	0.23	0.29
0.48	0.24	0.28
0.48	0.25	0.27
0.48	0.26	0.26
0.49	0.16	0.35
0.49	0.17	0.34
0.49	0.18	0.33
0.49	0.19	0.32
0.49	0.2	0.31
0.49	0.21	0.3
0.49	0.22	0.29
0.49	0.23	0.28
0.49	0.24	0.27
0.49	0.25	0.26
0.49	0.26	0.25
0.49	0.27	0.24
0.49	0.28	0.23
0.5	0.18	0.32
0.5	0.19	0.31
0.5	0.2	0.3
0.5	0.21	0.29
0.5	0.22	0.28
0.5	0.23	0.27
0.5	0.24	0.26
0.5	0.25	0.25
0.5	0.26	0.24
0.5	0.27	0.23
0.5	0.28	0.22
0.5	0.29	0.21
0.5	0.3	0.2
0.51	0.21	0.28
0.51	0.22	0.27
0.51	0.23	0.26
0.51	0.24	0.25
0.51	0.25	0.24
0.51	0.26	0.23
0.51	0.27	0.22
0.51	0.28	0.21
0.51	0.29	0.2
0.51	0.3	0.19
0.51	0.31	0.18
0.51	0.32	0.17
0.52	0.23	0.25
0.52	0.24	0.24
0.52	0.25	0.23
0.52	0.26	0.22
0.52	0.27	0.21
0.52	0.28	0.2
0.52	0.29	0.19
0.52	0.3	0.18
0.52	0.31	0.17
0.52	0.32	0.16
0.52	0.33	0.15
0.52	0.34	0.14
0.53	0.25	0.22
0.53	0.26	0.21
0.53	0.27	0.2
0.53	0.28	0.19
0.53	0.29	0.18
0.53	0.3	0.17
0.53	0.31	0.16
0.53	0.32	0.15
0.53	0.33	0.14
0.53	0.34	0.13
0.53	0.35	0.12
0.53	0.36	0.11
0.53	0.37	0.1
0.54	0.27	0.19
0.54	0.28	0.18

Bore 056 – IsoSource Output

Date: 9/11/2021 Time: 8:58:54 pm
Title: Bore 056
Increment: 1%
Tolerance: 0.5
Isotopes: O H
Mixtures: -4.23 -28.8
Sources:
Rainfall (bore 968) -6.47 -39.57
Lake Rerewhakaaitu -1.67 -13.9
Lake Okaro -4.17 -28.8
*************** ***************
FEASIBLE OUTPUT:

Rainfall (bore 968)	Lake Rerewhakaaitu	Lake Okaro
0	0	1
0	0.01	0.99
0	0.02	0.98
0	0.03	0.97
0.01	0	0.99
0.01	0.01	0.98
0.01	0.02	0.97
0.01	0.03	0.96
0.01	0.04	0.95
0.02	0	0.98
0.02	0.01	0.97
0.02	0.02	0.96
0.02	0.03	0.95
0.02	0.04	0.94
0.03	0	0.97
0.03	0.01	0.96
0.03	0.02	0.95
0.03	0.03	0.94
0.03	0.04	0.93
0.03	0.05	0.92
0.04	0	0.96
0.04	0.01	0.95
0.04	0.02	0.94
0.04	0.03	0.93
0.04	0.04	0.92
0.04	0.05	0.91
0.04	0.06	0.9
0.05	0.01	0.94
0.05	0.02	0.93
0.05	0.03	0.92
0.05	0.04	0.91
0.05	0.05	0.9
0.05	0.06	0.89
0.06	0.01	0.93
0.06	0.02	0.92
0.06	0.03	0.91
0.06	0.04	0.9
0.06	0.05	0.89
0.06	0.06	0.88
0.06	0.07	0.87
0.07	0.02	0.91
0.07	0.03	0.9
0.07	0.04	0.89
0.07	0.05	0.88
0.07	0.06	0.87
0.07	0.07	0.86
0.07	0.08	0.85
0.08	0.03	0.89
0.08	0.04	0.88
0.08	0.05	0.87
0.08	0.06	0.86
0.08	0.07	0.85
0.08	0.08	0.84
0.08	0.09	0.83
0.09	0.04	0.87
0.09	0.05	0.86
0.09	0.06	0.85
0.09	0.07	0.84
0.09	0.08	0.83
0.09	0.09	0.82
0.1	0.04	0.86
0.1	0.05	0.85
0.1	0.06	0.84
0.1	0.07	0.83
0.1	0.08	0.82
0.1	0.09	0.81
0.1	0.1	0.8
0.11	0.05	0.84
0.11	0.06	0.83
0.11	0.07	0.82
0.11	0.08	0.81
0.11	0.09	0.8
0.11	0.1	0.79
0.11	0.11	0.78
0.12	0.06	0.82
0.12	0.07	0.81
0.12	0.08	0.8
0.12	0.09	0.79
0.12	0.1	0.78
0.12	0.11	0.77
0.12	0.12	0.76
0.13	0.07	0.8
0.13	0.08	0.79
0.13	0.09	0.78
0.13	0.1	0.77
0.13	0.11	0.76
0.13	0.12	0.75
0.14	0.07	0.79
0.14	0.08	0.78
0.14	0.09	0.77
0.14	0.1	0.76
0.14	0.11	0.75
0.14	0.12	0.74
0.14	0.13	0.73
0.15	0.08	0.77
0.15	0.09	0.76
0.15	0.1	0.75
0.15	0.11	0.74
0.15	0.12	0.73
0.15	0.13	0.72
0.15	0.14	0.71
0.16	0.09	0.75
0.16	0.1	0.74
0.16	0.11	0.73
0.16	0.12	0.72
0.16	0.13	0.71
0.16	0.14	0.7
0.17	0.09	0.74
0.17	0.1	0.73
0.17	0.11	0.72
0.17	0.12	0.71
0.17	0.13	0.7
0.17	0.14	0.69
0.17	0.15	0.68
0.18	0.1	0.72
0.18	0.11	0.71
0.18	0.12	0.7
0.18	0.13	0.69
0.18	0.14	0.68
0.18	0.15	0.67
0.18	0.16	0.66
0.19	0.11	0.7
0.19	0.12	0.69
0.19	0.13	0.68
0.19	0.14	0.67
0.19	0.15	0.66
0.19	0.16	0.65
0.19	0.17	0.64
0.2	0.12	0.68
0.2	0.13	0.67
0.2	0.14	0.66
0.2	0.15	0.65
0.2	0.16	0.64
0.2	0.17	0.63
0.21	0.12	0.67
0.21	0.13	0.66
0.21	0.14	0.65
0.21	0.15	0.64
0.21	0.16	0.63
0.21	0.17	0.62
0.21	0.18	0.61
0.22	0.13	0.65
0.22	0.14	0.64
0.22	0.15	0.63
0.22	0.16	0.62
0.22	0.17	0.61
0.22	0.18	0.6
0.22	0.19	0.59
0.23	0.14	0.63
0.23	0.15	0.62
0.23	0.16	0.61
0.23	0.17	0.6
0.23	0.18	0.59
0.23	0.19	0.58
0.24	0.14	0.62
0.24	0.15	0.61
0.24	0.16	0.6
0.24	0.17	0.59
0.24	0.18	0.58
0.24	0.19	0.57
0.24	0.2	0.56
0.25	0.15	0.6
0.25	0.16	0.59
0.25	0.17	0.58
0.25	0.18	0.57
0.25	0.19	0.56
0.25	0.2	0.55
0.25	0.21	0.54
0.26	0.16	0.58
0.26	0.17	0.57
0.26	0.18	0.56
0.26	0.19	0.55
0.26	0.2	0.54
0.26	0.21	0.53
0.26	0.22	0.52
0.27	0.17	0.56
0.27	0.18	0.55
0.27	0.19	0.54
0.27	0.2	0.53
0.27	0.21	0.52
0.27	0.22	0.51
0.28	0.17	0.55
0.28	0.18	0.54
0.28	0.19	0.53
0.28	0.2	0.52

Bore 068 – IsoSource Output

Date:	9/11/2021	Time:	9:01:44 pm	
Title:	Bore 068			
Increment:	1%			
Tolerance:	0.5			
Isotopes:	O	H		
Mixtures:	-6.32	-39		
Sources:				
Rainfall (bore 968)		-6.47	-39.57	
Lake Tikitapu		-0.97	-9.8	
Local groundwater (bore 072)			-2.70	-18.5
	***************		***************	

FEASIBLE OUTPUT:

Rainfall (bore 968)	Lake Tikitapu	Local groundwater (bore 072)
---------------	---------------	---------------
0.95	0	0.05
0.96	0	0.04
0.96	0.01	0.03
0.96	0.02	0.02
0.97	0	0.03
0.97	0.01	0.02
0.97	0.02	0.01
0.97	0.03	0
0.98	0	0.02
0.98	0.01	0.01
0.98	0.02	0
0.99	0	0.01
0.99	0.01	0

Bore 070 – IsoSource Output

Date:	9/11/2021	Time:	9:04:46 pm
Title:	Bore 070		
Increment:	1%		
Tolerance:	0.5		
Isotopes:	O	H	
Mixtures:	-6.33	-38.1	
Sources:			
Rainfall (bore 968)		-6.47	-39.57
Lake Okareka		-2.20	-16.6
Lake Okareka		-2.20	-16.6
	***************		***************

FEASIBLE OUTPUT:

Rainfall (bore 968)	Lake Okareka	Lake Okareka
---------------	---------------	---------------
0.92	0	0.08
0.92	0.01	0.07
0.92	0.02	0.06
0.92	0.03	0.05
0.92	0.04	0.04
0.92	0.05	0.03
0.92	0.06	0.02
0.92	0.07	0.01
0.92	0.08	0
0.93	0	0.07
0.93	0.01	0.06
0.93	0.02	0.05
0.93	0.03	0.04
0.93	0.04	0.03
0.93	0.05	0.02
0.93	0.06	0.01
0.93	0.07	0
0.94	0	0.06
0.94	0.01	0.05
0.94	0.02	0.04
0.94	0.03	0.03
0.94	0.04	0.02
0.94	0.05	0.01
0.94	0.06	0
0.95	0	0.05
0.95	0.01	0.04
0.95	0.02	0.03
0.95	0.03	0.02
0.95	0.04	0.01
0.95	0.05	0

Bore 072 – IsoSource Output

Date: 9/11/2021 Time: 9:03:31 pm
Title: Bore 072
Increment: 1%
Tolerance: 0.5
Isotopes: O H
Mixtures: -2.7 -18.5
Sources:
Rainfall (bore 968) -6.47 -39.57
Lake Tikitapu -0.97 -9.8
Lake Tikitapu -0.97 -9.8
*************** ***************

FEASIBLE OUTPUT:

Rainfall (bore 968)	Lake Tikitapu	Lake Tikitapu
0.28	0	0.72
0.28	0.01	0.71
0.28	0.02	0.7
0.28	0.03	0.69
0.28	0.04	0.68
0.28	0.05	0.67
0.28	0.06	0.66
0.28	0.07	0.65
0.28	0.08	0.64
0.28	0.09	0.63
0.28	0.1	0.62
0.28	0.11	0.61
0.28	0.12	0.6
0.28	0.13	0.59
0.28	0.14	0.58
0.28	0.15	0.57
0.28	0.16	0.56
0.28	0.17	0.55
0.28	0.18	0.54
0.28	0.19	0.53
0.28	0.2	0.52
0.28	0.21	0.51
0.28	0.22	0.5
0.28	0.23	0.49
0.28	0.24	0.48
0.28	0.25	0.47
0.28	0.26	0.46
0.28	0.27	0.45
0.28	0.28	0.44
0.28	0.29	0.43
0.28	0.3	0.42
0.28	0.31	0.41
0.28	0.32	0.4
0.28	0.33	0.39
0.28	0.34	0.38
0.28	0.35	0.37
0.28	0.36	0.36
0.28	0.37	0.35
0.28	0.38	0.34
0.28	0.39	0.33
0.28	0.4	0.32
0.28	0.41	0.31
0.28	0.42	0.3
0.28	0.43	0.29
0.28	0.44	0.28
0.28	0.45	0.27
0.28	0.46	0.26
0.28	0.47	0.25
0.28	0.48	0.24
0.28	0.49	0.23
0.28	0.5	0.22
0.28	0.51	0.21
0.28	0.52	0.2
0.28	0.53	0.19
0.28	0.54	0.18
0.28	0.55	0.17
0.28	0.56	0.16
0.28	0.57	0.15
0.28	0.58	0.14
0.28	0.59	0.13
0.28	0.6	0.12
0.28	0.61	0.11
0.28	0.62	0.1
0.28	0.63	0.09
0.28	0.64	0.08
0.28	0.65	0.07
0.28	0.66	0.06
0.28	0.67	0.05
0.28	0.68	0.04
0.28	0.69	0.03
0.28	0.7	0.02
0.28	0.71	0.01
0.28	0.72	0
0.29	0	0.71
0.29	0.01	0.7
0.29	0.02	0.69
0.29	0.03	0.68
0.29	0.04	0.67
0.29	0.05	0.66
0.29	0.06	0.65
0.29	0.07	0.64
0.29	0.08	0.63
0.29	0.09	0.62
0.29	0.1	0.61
0.29	0.11	0.6
0.29	0.12	0.59
0.29	0.13	0.58
0.29	0.14	0.57
0.29	0.15	0.56
0.29	0.16	0.55
0.29	0.17	0.54
0.29	0.18	0.53
0.29	0.19	0.52
0.29	0.2	0.51
0.29	0.21	0.5
0.29	0.22	0.49
0.29	0.23	0.48
0.29	0.24	0.47
0.29	0.25	0.46
0.29	0.26	0.45
0.29	0.27	0.44
0.29	0.28	0.43
0.29	0.29	0.42
0.29	0.3	0.41
0.29	0.31	0.4
0.29	0.32	0.39
0.29	0.33	0.38
0.29	0.34	0.37
0.29	0.35	0.36
0.29	0.36	0.35
0.29	0.37	0.34
0.29	0.38	0.33
0.29	0.39	0.32
0.29	0.4	0.31
0.29	0.41	0.3
0.29	0.42	0.29
0.29	0.43	0.28
0.29	0.44	0.27
0.29	0.45	0.26
0.29	0.46	0.25
0.29	0.47	0.24
0.29	0.48	0.23
0.29	0.49	0.22
0.29	0.5	0.21
0.29	0.51	0.2
0.29	0.52	0.19
0.29	0.53	0.18
0.29	0.54	0.17
0.29	0.55	0.16
0.29	0.56	0.15
0.29	0.57	0.14
0.29	0.58	0.13
0.29	0.59	0.12
0.29	0.6	0.11
0.29	0.61	0.1
0.29	0.62	0.09
0.29	0.63	0.08
0.29	0.64	0.07
0.29	0.65	0.06
0.29	0.66	0.05
0.29	0.67	0.04
0.29	0.68	0.03
0.29	0.69	0.02
0.29	0.7	0.01
0.29	0.71	0
0.3	0	0.7
0.3	0.01	0.69
0.3	0.02	0.68
0.3	0.03	0.67
0.3	0.04	0.66
0.3	0.05	0.65
0.3	0.06	0.64
0.3	0.07	0.63
0.3	0.08	0.62
0.3	0.09	0.61
0.3	0.1	0.6
0.3	0.11	0.59
0.3	0.12	0.58
0.3	0.13	0.57
0.3	0.14	0.56
0.3	0.15	0.55
0.3	0.16	0.54
0.3	0.17	0.53
0.3	0.18	0.52
0.3	0.19	0.51
0.3	0.2	0.5
0.3	0.21	0.49
0.3	0.22	0.48
0.3	0.23	0.47
0.3	0.24	0.46
0.3	0.25	0.45
0.3	0.26	0.44
0.3	0.27	0.43
0.3	0.28	0.42
0.3	0.29	0.41
0.3	0.3	0.4
0.3	0.31	0.39
0.3	0.32	0.38
0.3	0.33	0.37
0.3	0.34	0.36
0.3	0.35	0.35
0.3	0.36	0.34
0.3	0.37	0.33
0.3	0.38	0.32
0.3	0.39	0.31

Bore 131 – IsoSource Output

Date:	9/11/2021	Time:	3:44:59 pm
Title:	Bore 131		
Increment:	1%		
Tolerance:	0.5		
Isotopes:	O	H	
Mixtures:	-3.12	-22	
Sources:			
Rainfall (bore 968)	-6.47	-39.57	
Lake Tarawera	-2.87	-20.5	
Lake Okareka	-2.20	-16.6	

***************   ***************

FEASIBLE OUTPUT:

Rainfall (bore 968)	Lake Tarawera	Lake Okareka
0.06	0.91	0.03
0.06	0.92	0.02
0.06	0.93	0.01
0.06	0.94	0
0.07	0.85	0.08
0.07	0.86	0.07
0.07	0.87	0.06
0.07	0.88	0.05
0.07	0.89	0.04
0.07	0.9	0.03
0.07	0.91	0.02
0.07	0.92	0.01
0.07	0.93	0
0.08	0.79	0.13
0.08	0.8	0.12
0.08	0.81	0.11
0.08	0.82	0.1
0.08	0.83	0.09
0.08	0.84	0.08
0.08	0.85	0.07
0.08	0.86	0.06
0.08	0.87	0.05
0.08	0.88	0.04
0.08	0.89	0.03
0.08	0.9	0.02
0.08	0.91	0.01
0.08	0.92	0
0.09	0.73	0.18
0.09	0.74	0.17
0.09	0.75	0.16
0.09	0.76	0.15
0.09	0.77	0.14
0.09	0.78	0.13
0.09	0.79	0.12
0.09	0.8	0.11
0.09	0.81	0.1
0.09	0.82	0.09
0.09	0.83	0.08
0.09	0.84	0.07
0.09	0.85	0.06
0.09	0.86	0.05
0.09	0.87	0.04
0.09	0.88	0.03
0.09	0.89	0.02
0.09	0.9	0.01
0.09	0.91	0
0.1	0.67	0.23
0.1	0.68	0.22
0.1	0.69	0.21
0.1	0.7	0.2
0.1	0.71	0.19
0.1	0.72	0.18
0.1	0.73	0.17
0.1	0.74	0.16
0.1	0.75	0.15
0.1	0.76	0.14
0.1	0.77	0.13
0.1	0.78	0.12
0.1	0.79	0.11
0.1	0.8	0.1
0.1	0.81	0.09
0.1	0.82	0.08
0.1	0.83	0.07
0.1	0.84	0.06
0.1	0.85	0.05
0.1	0.86	0.04
0.1	0.87	0.03
0.1	0.88	0.02
0.1	0.89	0.01
0.1	0.9	0
0.11	0.61	0.28
0.11	0.62	0.27
0.11	0.63	0.26
0.11	0.64	0.25
0.11	0.65	0.24
0.11	0.66	0.23
0.11	0.67	0.22
0.11	0.68	0.21
0.11	0.69	0.2
0.11	0.7	0.19
0.11	0.71	0.18
0.11	0.72	0.17
0.11	0.73	0.16
0.11	0.74	0.15
0.11	0.75	0.14
0.11	0.76	0.13
0.11	0.77	0.12
0.11	0.78	0.11
0.11	0.79	0.1
0.11	0.8	0.09
0.11	0.81	0.08
0.11	0.82	0.07
0.11	0.83	0.06
0.11	0.84	0.05
0.11	0.85	0.04
0.11	0.86	0.03
0.12	0.55	0.33
0.12	0.56	0.32
0.12	0.57	0.31
0.12	0.58	0.3
0.12	0.59	0.29
0.12	0.6	0.28
0.12	0.61	0.27
0.12	0.62	0.26
0.12	0.63	0.25
0.12	0.64	0.24
0.12	0.65	0.23
0.12	0.66	0.22
0.12	0.67	0.21
0.12	0.68	0.2
0.12	0.69	0.19
0.12	0.7	0.18
0.12	0.71	0.17
0.12	0.72	0.16
0.12	0.73	0.15
0.12	0.74	0.14
0.12	0.75	0.13
0.12	0.76	0.12
0.12	0.77	0.11
0.12	0.78	0.1
0.12	0.79	0.09
0.12	0.8	0.08
0.13	0.5	0.37
0.13	0.51	0.36
0.13	0.52	0.35
0.13	0.53	0.34
0.13	0.54	0.33
0.13	0.55	0.32
0.13	0.56	0.31
0.13	0.57	0.3
0.13	0.58	0.29
0.13	0.59	0.28
0.13	0.6	0.27
0.13	0.61	0.26
0.13	0.62	0.25
0.13	0.63	0.24
0.13	0.64	0.23
0.13	0.65	0.22
0.13	0.66	0.21
0.13	0.67	0.2
0.13	0.68	0.19
0.13	0.69	0.18
0.13	0.7	0.17
0.13	0.71	0.16
0.13	0.72	0.15
0.13	0.73	0.14
0.13	0.74	0.13
0.14	0.44	0.42
0.14	0.45	0.41
0.14	0.46	0.4
0.14	0.47	0.39
0.14	0.48	0.38
0.14	0.49	0.37
0.14	0.5	0.36
0.14	0.51	0.35
0.14	0.52	0.34
0.14	0.53	0.33
0.14	0.54	0.32
0.14	0.55	0.31
0.14	0.56	0.3
0.14	0.57	0.29
0.14	0.58	0.28
0.14	0.59	0.27
0.14	0.6	0.26
0.14	0.61	0.25
0.14	0.62	0.24
0.14	0.63	0.23
0.14	0.64	0.22
0.14	0.65	0.21
0.14	0.66	0.2
0.14	0.67	0.19
0.14	0.68	0.18
0.15	0.38	0.47
0.15	0.39	0.46
0.15	0.4	0.45
0.15	0.41	0.44
0.15	0.42	0.43
0.15	0.43	0.42
0.15	0.44	0.41
0.15	0.45	0.4
0.15	0.46	0.39
0.15	0.47	0.38
0.15	0.48	0.37
0.15	0.49	0.36
0.15	0.5	0.35

Bore 134 – IsoSource Output

Date:	9/11/2021	Time:	3:50:34 pm
Title:	Bore 134		
Increment:	1%		
Tolerance:	0.5		
Isotopes:	O	H	
Mixtures:	-3.22	-21.8	
Sources:			
Rainfall (bore 968)		-6.47	-39.57
Lake Tarawera		-2.87	-20.5
Local rainfall (bore 029)		-6.05	-36.7
	***************		***************

FEASIBLE OUTPUT:

Rainfall (bore 968)	Lake Tarawera	Local rainfall (bore 029)
0	0.89	0.11
0	0.9	0.1
0	0.91	0.09
0	0.92	0.08
0	0.93	0.07
0	0.94	0.06
0	0.95	0.05
0.01	0.9	0.09
0.01	0.91	0.08
0.01	0.92	0.07
0.01	0.93	0.06
0.01	0.94	0.05
0.01	0.95	0.04
0.02	0.9	0.08
0.02	0.91	0.07
0.02	0.92	0.06
0.02	0.93	0.05
0.02	0.94	0.04
0.02	0.95	0.03
0.03	0.9	0.07
0.03	0.91	0.06
0.03	0.92	0.05
0.03	0.93	0.04
0.03	0.94	0.03
0.03	0.95	0.02
0.04	0.9	0.06
0.04	0.91	0.05
0.04	0.92	0.04
0.04	0.93	0.03
0.04	0.94	0.02
0.04	0.95	0.01
0.05	0.9	0.05
0.05	0.91	0.04
0.05	0.92	0.03
0.05	0.93	0.02
0.05	0.94	0.01
0.05	0.95	0
0.06	0.9	0.04
0.06	0.91	0.03
0.06	0.92	0.02
0.06	0.93	0.01
0.06	0.94	0
0.07	0.91	0.02
0.07	0.92	0.01
0.07	0.93	0
0.08	0.91	0.01
0.08	0.92	0
0.09	0.91	0

Appendix C: Annualised water balances

Table C1 Rainfall and drainage summaries over the Greater Lake Tarawera catchment between 1972 – 2018. Drainage has been calculated by subtracting annual evaporation from annual rainfall (where evaporation has been calculated using the FAO56 methods of Allen et al. (1998) including a water stress correction).

Water year	Rainfall (mm)	Rainfall summary†	Drainage (mm)	Drainage summary†	% of rainfall draining
1972	1,230	Below average	276	Well below average	22
1973	1,522	Average	633	Average	42
1974	1,784	Average	981	Above average	55
1975	1,511	Average	628	Average	42
1976	1,543	Average	671	Average	43
1977	1,194	Below average	234	Well below average	20
1978	1,724	Average	821	Average	48
1979	1,740	Average	865	Above average	50
1980	1,641	Average	731	Average	45
1981	1,611	Average	721	Average	45
1982	1,037	Below average	113	Well below average	11
1983	1,667	Average	877	Above average	53
1984	1,803	Average	972	Above average	54
1985	1,626	Average	794	Average	49
1986	1,441	Average	648	Average	45
1987	1,352	Average	493	Below average	36
1988	1,916	Above average	1,184	Well above average	62
1989	1,594	Average	763	Average	48
1990	1,526	Average	735	Average	48
1991	1,305	Average	562	Below average	43
1992	1,591	Average	881	Above average	55
1993	1,073	Below average	293	Well below average	27
1994	1,812	Average	1,101	Well above average	61
1995	1,945	Above average	1,210	Well above average	62
1996	1,579	Average	817	Average	52
1997	1,344	Average	519	Below average	39
1998	1,764	Average	988	Above average	56
1999	1,509	Average	733	Average	49
2000	1,627	Average	843	Average	52
2001	1,529	Average	781	Average	51
2002	1,267	Average	385	Below average	30
2003	1,667	Average	903	Above average	54
2004	1,634	Average	814	Average	50
2005	1,873	Above average	1,095	Well above average	58
2006	1,211	Below average	287	Well below average	24
2007	1,524	Average	654	Average	43
2008	1,532	Average	634	Average	41
2009	1,562	Average	666	Average	43
2010	2,176	Above average	1,365	Well above average	63
2011	1,577	Average	750	Average	48
2012	1,410	Average	438	Below average	31
2013	1,356	Average	442	Below average	33
2014	1,175	Below average	198	Well below average	17
2015	1,443	Average	538	Below average	37
2016	2,027	Above average	1,237	Well above average	61
2017	1,748	Average	996	Above average	57
2018	1,187	Below average	244	Well below average	21

† Ranges are defined as: well below average <50% of the long-term average, below average 50-79% of the long-term average, average 80-119% of the long-term average, above average 120-149% of the long-term average, well above average >149% of the long-term average

Table C2 Annual flow means and ranges (in brackets) from 1972-2018 for Tarawera Lakes using best estimate datasets and methods.

	Ōkareka	Ōkaro	Ōkataina	Rerewhakaaitu	Rotokakahi	Rotomahana	Tarawera	Tikitapu
Inflows ($m^3 s^{-1}$ and % of total inflow)								
Rainfall	0.16 (0.1-0.22)	0.01 (0.01-0.01)	0.6 (0.37-0.91)	0.21 (0.14-0.28)	0.2 (0.14-0.28)	0.39 (0.26-0.55)	2.26 (1.43-3.38)	0.04 (0.03-0.06)
	46% (38-60%)	9% (7-11%)	23% (20-35%)	53% (44-66%)	45% (36-54%)	17% (12-26%)	21% (18-29%)	33% (25-50%)
SW in total	0 (0-0)	0.09 (0.09-0.09)	0 (0-0)	0.06 (0.06-0.06)	0.15 (0.15-0.15)	0.33 (0.33-0.33)	1.87 (1.54-2.4)	0 (0-0)
	0% (0-0%)	87% (60-93%)	0% (0-0%)	15% (9-24%)	34% (20-52%)	15% (8-27%)	18% (11-31%)	0% (0-0%)
SW in (from inside sub-catchment)[1]	0 (0-0)	0.09 (0.09-0.09)	0 (0-0)	0.06 (0.06-0.06)	0.15 (0.15-0.15)	0.3 (0.3-0.3)	1.34 (1.27-1.45)	0 (0-0)
	0% (0-0%)	87% (60-93%)	0% (0-0%)	15% (9-24%)	34% (20-52%)	13% (7-25%)	13% (7-26%)	0% (0-0%)
SW in (from outside sub-catchment)[1]	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.03 (0.03-0.03)	0.53 (0.28-0.99)	0 (0-0)
	0% (0-0%)	0% (0-0%)	0% (0-0%)	0% (0-0%)	0% (0-0%)	1% (1-3%)	5% (3-12%)	0% (0-0%)
GW in total	0.19 (0.08-0.34)	0 (0-0.05)	2.01 (0.7-3.59)	0.14 (0.02-0.29)	0.11 (0-0.33)	1.69 (0.59-3.21)	6.63 (1.98-13.18)	0.09 (0.03-0.17)
	54% (40-62%)	3% (0-31%)	77% (65-80%)	33% (10-47%)	21% (0-44%)	68% (49-79%)	60% (40-71%)	67% (50-75%)
GW in (from inside sub-catchment)[1]	0.19 (0.08-0.34)	0 (0-0.05)	2.01 (0.7-3.59)	0.14 (0.02-0.29)	0.02 (0-0.13)	1.5 (0.51-2.85)	2.03 (0.18-4.69)	0.09 (0.03-0.17)
	54% (40-62%)	3% (0-31%)	77% (65-80%)	33% (10-47%)	4% (0-18%)	60% (41-70%)	18% (4-25%)	67% (50-75%)
GW in (from outside sub-catchment)[1]	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.09 (0-0.2)	0.2 (0.06-0.37)	4.6 (1.79-8.49)	0 (0-0)
	0% (0-0%)	0% (0-0%)	0% (0-0%)	0% (0-0%)	18% (0-26%)	8% (5-9%)	42% (33-47%)	0% (0-0%)
Outflows ($m^3 s^{-1}$ and % of total outflow)								
Lake Evaporation	0.08 (0.07-0.09)	0.01 (0.01-0.01)	0.25 (0.23-0.29)	0.1 (0.09-0.13)	0.1 (0.09-0.12)	0.28 (0.25-0.31)	0.99 (0.92-1.15)	0.03 (0.03-0.04)
	23% (14-37%)	7% (5-9%)	10% (6-22%)	28% (16-53%)	21% (14-31%)	12% (7-24%)	10% (6-16%)	25% (15-48%)
SW out	0.17 (0.06-0.39)	0.03 (0.03-0.03)	0 (0-0)	0 (0-0)	0.35 (0.22-0.56)	0 (0-0)	6.78 (5.27-9.22)	0 (0-0)
	48% (30-78%)	29% (20-31%)	0% (0-0%)	0% (0-0%)	71% (51-82%)	0% (0-0%)	65% (41-89%)	0% (0-0%)
GW out	0.11 (0-0.28)	0.07 (0.06-0.11)	2.36 (0.85-4.24)	0.29 (0.12-0.52)	0.05 (0-0.26)	2.14 (0.94-3.79)	3.1 (0-9.86)	0.1 (0.04-0.2)
	29% (0-53%)	64% (61-74%)	90% (78-94%)	72% (47-84%)	8% (0-35%)	88% (76-93%)	25% (0-53%)	75% (52-85%)
Water out of GT catchments[2]	0 (0-0)	0 (0-0)	0 (0-0)	0.15 (0.06-0.26)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)
	0% (0-0%)	0% (0-0%)	0% (0-0%)	36% (24-42%)	0% (0-0%)	0% (0-0%)	0% (0-0%)	0% (0-0%)
Totals ($m^3 s^{-1}$)								
Inflow total	0.35 (0.2-0.56)	0.1 (0.1-0.15)	2.61 (1.08-4.5)	0.4 (0.23-0.63)	0.46 (0.29-0.76)	2.41 (1.2-4.08)	10.76 (4.95-18.6)	0.14 (0.07-0.23)
Outflow total	0.35 (0.2-0.56)	0.1 (0.1-0.15)	2.61 (1.08-4.5)	0.4 (0.23-0.63)	0.49 (0.31-0.76)	2.41 (1.2-4.08)	10.87 (6.21-18.6)	0.14 (0.07-0.23)
Other ($m^3 s^{-1}$ and % of total inflow and/or outflow)								
Storage change[3]	0 (0-0)	0 (0-0)	0 (-0.05-0.03)	0 (0-0)	0 (-0.01-0.01)	0 (0-0)	0 (0-0)	0 (-0.01-0.01)
	0% (0-0%)	0% (0-2%)	0% (0-3%)	0% (0-0%)	0% (0-2%)	0% (0-0%)	0% (0-0%)	1% (0-6%)
Residual[3]	0 (0-0.05)	0 (0-0)	0 (0-0)	0 (0-0)	0.03 (0-0.22)	0 (0-0)	0.11 (0-1.34)	0 (0-0)
	1% (0-18%)	0% (0-0%)	0% (0-0%)	0% (0-0%)	8% (0-71%)	0% (0-0%)	2% (0-26%)	0% (0-0%)

[1] Breakdown of the total SW or GW inflow

[2] As (and included in) GW outflows

[3] Positive values represent inflows, negative values outflows

Table C3 Annual flow means and ranges (in brackets) from 1972-2018 for surface water catchments of the Tarawera Lakes using best estimate datasets and methods.

	Ōkareka	Ōkaro	Ōkataina	Rerewhakaaiti	Rotokakahi	Rotomahana	Tarawera	Tikitapu
Inflows ($m^3\ s^{-1}$ and % of total inflow)								
Rainfall	0.9 (0.6-1.25)	0.16 (0.11-0.22)	3.64 (2.28-5.48)	2.17 (1.44-3.02)	1.03 (0.7-1.42)	5.8 (3.87-8.01)	18.96 (12.46-27.2)	0.25 (0.17-0.34)
	100% (100-100%)	100% (100-100%)	100% (100-100%)	100% (100-100%)	100% (100-100%)	100% (100-100%)	100% (100-100%)	100% (100-100%)
SW in	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)
	0% (0-0%)	0% (0-0%)	0% (0-0%)	0% (0-0%)	0% (0-0%)	0% (0-0%)	0% (0-0%)	0% (0-0%)
GW in	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)
	0% (0-0%)	0% (0-0%)	0% (0-0%)	0% (0-0%)	0% (0-0%)	0% (0-0%)	0% (0-0%)	0% (0-0%)
Outflows ($m^3\ s^{-1}$ and % of total outflow)								
Land evaporation	0.38 (0.24-0.48)	0.07 (0.04-0.1)	1.34 (0.91-1.61)	0.96 (0.61-1.35)	0.44 (0.29-0.55)	2.65 (1.71-3.67)	7.19 (4.85-9.39)	0.11 (0.08-0.14)
	42% (28-60%)	46% (30-65%)	38% (27-61%)	45% (30-62%)	43% (30-56%)	46% (31-64%)	38% (26-50%)	47% (33-65%)
Lake evaporation	0.08 (0.07-0.09)	0.01 (0.01-0.01)	0.25 (0.23-0.29)	0.1 (0.09-0.13)	0.13 (0.12-0.15)	0.39 (0.35-0.45)	1.8 (1.66-2.09)	0.03 (0.03-0.04)
	9% (6-13%)	5% (3-7%)	7% (5-10%)	5% (3-8%)	13% (9-19%)	7% (5-10%)	10% (7-15%)	13% (9-20%)
SW out	0.17 (0.06-0.39)	0.03 (0.03-0.03)	0 (0-0)	0 (0-0)	0.35 (0.22-0.56)	0.02 (0-0.28)	6.78 (5.27-9.22)	0 (0-0)
	19% (10-36%)	19% (13-27%)	0% (0-0%)	0% (0-0%)	33% (24-48%)	0% (0-6%)	36% (27-53%)	0% (0-0%)
GW out	0.28 (0.04-0.58)	0.05 (0.01-0.11)	2.05 (0.65-3.75)	1.1 (0.49-1.95)	0.13 (0-0.45)	2.74 (1.19-4.96)	3.3 (0-10.42)	0.1 (0.03-0.19)
	30% (5-49%)	31% (5-50%)	55% (29-69%)	50% (31-66%)	11% (0-32%)	47% (29-64%)	16% (0-38%)	40% (18-56%)
Water out of GT catchments[1]	0 (0-0)	0 (0-0)	0 (0-0)	0.55 (0.25-0.98)	0 (0-0)	0.55 (0.25-0.98)	0.55 (0.25-0.98)	0 (0-0)
	0% (0-0%)	0% (0-0%)	0% (0-0%)	25% (16-33%)	0% (0-0%)	9% (6-12%)	3% (2-4%)	0% (0-0%)
Totals ($m^3\ s^{-1}$)								
Inflow total	0.9 (0.6-1.25)	0.16 (0.11-0.22)	3.64 (2.28-5.48)	2.17 (1.44-3.02)	1.03 (0.7-1.42)	5.8 (3.87-8.01)	18.96 (12.46-27.2)	0.25 (0.17-0.34)
Outflow total	0.9 (0.6-1.25)	0.16 (0.11-0.22)	3.64 (2.28-5.48)	2.17 (1.44-3.02)	1.04 (0.71-1.41)	5.8 (3.87-8)	19.06 (12.55-27.18)	0.25 (0.17-0.34)
Other ($m^3\ s^{-1}$ and % of total inflow and/or outflow)								
Storage change[2]	0 (0-0)	0 (0-0)	0 (-0.05-0.03)	0 (0-0)	0 (-0.01-0.03)	0 (0-0)	0 (-0.05-0.03)	0 (-0.01-0.01)
	0% (0-0%)	0% (0-1%)	0% (0-2%)	0% (0-0%)	0% (0-2%)	0% (0-0%)	0% (0-0%)	1% (0-4%)
Residual[2]	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0.01 (0-0.17)	0 (0-0)	0.1 (0-1.35)	0 (0-0)
	0% (0-0%)	0% (0-0%)	0% (0-0%)	0% (0-0%)	1% (0-20%)	0% (0-0%)	1% (0-10%)	0% (0-0%)

[1] As (and included in) GW outflows

[2] Positive values represent inflows, negative values outflows

Table C4

Lake Ōkareka water balance: summary statistics sample size: 3760							
	Mean	Median	95% CI lower limit	95% CI upper limit	Minimum	Maximum	Uncertainty and variability
Inflows ($m^3 s^{-1}$)							
Rainfall	0.16	0.16	0.11	0.22	0.10	0.25	± 54%
SW in (total)	-	-	-	-	-	-	-
SW in (from inside sub-catchment)[1]	-	-	-	-	-	-	-
SW in (from outside sub-catchment)[1]	-	-	-	-	-	-	-
GW in (total)	0.20	0.20	0.086	0.34	0.049	0.44	± 120%
GW in (from inside sub-catchment)[1]	0.20	0.20	0.086	0.34	0.049	0.44	± 120%
GW in (from outside sub-catchment)[1]	-	-	-	-	-	-	-
Outflows ($m^3 s^{-1}$)							
Lake evaporation	0.078	0.077	0.072	0.088	0.070	0.088	± 13%
SW out	0.17	0.16	0.075	0.26	0.062	0.39	± 130%
GW out	0.12	0.11	0.0	0.28	0.0	0.37	± 200%
Water out of GT catchments[2]	-	-	-	-	-	-	-
Totals ($m^3 s^{-1}$)							
Inflow total	0.36	0.36	0.20	0.57	0.16	0.69	± 88%
Outflow total	0.37	0.36	0.22	0.57	0.16	0.69	± 87%
Other ($m^3 s^{-1}$)							
Storage change[3]	1.3e-05	5.4e-06	-0.00012	0.00017	-0.00012	0.00038	± 2700%
Residual[3]	0.0034	6.5e-19	-1.4e-17	0.052	-2.3e-17	0.098	± 2800%

[1] Breakdown of the total SW or GW inflow

[2] As (and included in) GW outflows

[3] Positive values represent inflows, negative values outflows (except for standard deviation and IQR statistics which are always positive)

Table C5

Lake Ōkaro water balance: summary statistics sample size: 3760							
	Mean	Median	95% CI lower limit	95% CI upper limit	Minimum	Maximum	Uncertainty and variability
Inflows (m^3 s^{-1})							
Rainfall	0.010	0.010	0.0072	0.014	0.0066	0.017	± 61%
SW in (total)	0.090	0.090	0.090	0.090	0.090	0.090	± 0%
SW in (from inside sub-catchment)[1]	0.090	0.090	0.090	0.090	0.090	0.090	± 0%
SW in (from outside sub-catchment)[1]	-	-	-	-	-	-	-
GW in (total)	0.0083	0.0	0.0	0.053	0.0	0.097	± 1100%
GW in (from inside sub-catchment)[1]	0.0083	0.0	0.0	0.053	0.0	0.097	± 1100%
GW in (from outside sub-catchment)[1]	-	-	-	-	-	-	-
Outflows (m^3 s^{-1})							
Lake evaporation	0.0076	0.0075	0.0069	0.0085	0.0067	0.0086	± 14%
SW out	0.030	0.030	0.030	0.030	0.030	0.030	± 0%
GW out	0.071	0.063	0.059	0.12	0.059	0.17	± 130%
Water out of GT catchments[2]	-	-	-	-	-	-	-
Totals (m^3 s^{-1})							
Inflow total	0.11	0.10	0.097	0.16	0.097	0.20	± 87%
Outflow total	0.11	0.10	0.097	0.16	0.097	0.20	± 87%
Other (m^3 s^{-1})							
Storage change[3]	2.3e-05	1.6e-05	-0.00037	0.00086	-0.00047	0.0015	± 6800%
Residual[3]	9.4e-21	6.8e-21	-6.5e-18	6.7e-18	-6.9e-18	1.3e-17	± 140000%

[1] Breakdown of the total SW or GW inflow

[2] As (and included in) GW outflows

[3] Positive values represent inflows, negative values outflows (except for standard deviation and IQR statistics which are always positive)

Table C6

Lake Ōkataina water balance: summary statistics sample size: 3760							
	Mean	Median	95% CI lower limit	95% CI upper limit	Minimum	Maximum	Uncertainty and variability
Inflows (m^3 s^{-1})							
Rainfall	0.61	0.62	0.40	0.83	0.37	0.93	± 53%
SW in (total)	-	-	-	-	-	-	-
SW in (from inside sub-catchment)[1]	-	-	-	-	-	-	-
SW in (from outside sub-catchment)[1]	-	-	-	-	-	-	-
GW in (total)	2	2	0.89	3.1	0.38	3.8	± 95%
GW in (from inside sub-catchment)[1]	2	2	0.89	3.1	0.38	3.8	± 95%
GW in (from outside sub-catchment)[1]	-	-	-	-	-	-	-
Outflows (m^3 s^{-1})							
Lake evaporation	0.25	0.25	0.23	0.28	0.23	0.29	± 18%
SW out	-	-	-	-	-	-	-
GW out	2.3	2.3	1.1	3.7	0.51	4.5	± 93%
Water out of GT catchments[2]	-	-	-	-	-	-	-
Totals (m^3 s^{-1})							
Inflow total	2.6	2.6	1.4	3.9	0.74	4.7	± 85%
Outflow total	2.6	2.6	1.4	3.9	0.75	4.7	± 84%
Other (m^3 s^{-1})							
Storage change[3]	-0.0013	-0.00019	-0.025	0.0096	-0.049	0.030	± -3800%
Residual[3]	4.1e-18	9.4e-18	-2.2e-16	2.1e-16	-2.6e-16	4.0e-16	± 9800%

[1] Breakdown of the total SW or GW inflow

[2] As (and included in) GW outflows

[3] Positive values represent inflows, negative values outflows (except for standard deviation and IQR statistics which are always positive)

Table C7

Lake Rerewhakaaitu water balance: summary statistics sample size: 3760							
	Mean	Median	95% CI lower limit	95% CI upper limit	Minimum	Maximum	Uncertainty and variability
Inflows (m^3 s^{-1})							
Rainfall	0.21	0.21	0.15	0.29	0.14	0.35	± 63%
SW in (total)	0.055	0.055	0.055	0.055	0.055	0.055	± 0%
SW in (from inside sub-catchment)[1]	0.055	0.055	0.055	0.055	0.055	0.055	± 0%
SW in (from outside sub-catchment)[1]	-	-	-	-	-	-	-
GW in (total)	0.15	0.15	0.036	0.31	0.0043	0.45	± 200%
GW in (from inside sub-catchment)[1]	0.15	0.15	0.036	0.31	0.0043	0.45	± 200%
GW in (from outside sub-catchment)[1]	-	-	-	-	-	-	-
Outflows (m^3 s^{-1})							
Lake evaporation	0.10	0.10	0.090	0.13	0.088	0.13	± 27%
SW out	-	-	-	-	-	-	-
GW out	0.32	0.31	0.14	0.54	0.096	0.74	± 130%
Water out of GT catchments[2]	0.13	0.073	0.015	0.37	0.0096	0.56	± 310%
Totals (m^3 s^{-1})							
Inflow total	0.42	0.41	0.24	0.65	0.21	0.85	± 100%
Outflow total	0.42	0.41	0.24	0.65	0.21	0.85	± 100%
Other (m^3 s^{-1})							
Storage change[3]	1.6e-05	1.2e-05	-0.00030	0.00029	-0.00046	0.00054	± 3300%
Residual[3]	1.5e-18	-2.7e-20	-2.7e-17	2.6e-17	-5.0e-17	4.6e-17	± 3400%

[1] Breakdown of the total SW or GW inflow

[2] As (and included in) GW outflows

[3] Positive values represent inflows, negative values outflows (except for standard deviation and IQR statistics which are always positive)

Table C8

Lake Rotokakahi water balance: summary statistics

sample size: 3760

	Mean	Median	95% CI lower limit	95% CI upper limit	Minimum	Maximum	Uncertainty and variability
Inflows (m^3 s^{-1})							
Rainfall	0.21	0.21	0.14	0.28	0.13	0.32	± 52%
SW in (total)	0.15	0.15	0.15	0.15	0.15	0.15	± 0%
SW in (from inside sub-catchment)[1]	0.15	0.15	0.15	0.15	0.15	0.15	± 0%
SW in (from outside sub-catchment)[1]	-	-	-	-	-	-	-
GW in (total)	0.13	0.12	0.0	0.34	0.0	0.49	± 280%
GW in (from inside sub-catchment)[1]	0.030	0.0089	0.0	0.14	0.0	0.22	± 650%
GW in (from outside sub-catchment)[1]	0.099	0.11	0.0	0.20	0.0	0.26	± 170%
Outflows (m^3 s^{-1})							
Lake evaporation	0.100	0.099	0.092	0.11	0.091	0.12	± 16%
SW out	0.35	0.34	0.23	0.46	0.22	0.56	± 61%
GW out	0.068	0.027	0.0	0.28	0.0	0.42	± 510%
Water out of GT catchments[2]	-	-	-	-	-	-	-
Totals (m^3 s^{-1})							
Inflow total	0.49	0.47	0.29	0.77	0.28	0.95	± 96%
Outflow total	0.51	0.50	0.34	0.76	0.31	0.94	± 83%
Other (m^3 s^{-1})							
Storage change[3]	-6.5e-05	0.0	-0.0055	0.0048	-0.0069	0.013	± -20000%
Residual[3]	0.027	8.6e-18	-1.0e-17	0.20	-2.3e-17	0.23	± 750%

[1] Breakdown of the total SW or GW inflow

[2] As (and included in) GW outflows

[3] Positive values represent inflows, negative values outflows (except for standard deviation and IQR statistics which are always positive)

Table C9

Lake Rotomahana water balance: summary statistics sample size: 3760							
	Mean	Median	95% CI lower limit	95% CI upper limit	Minimum	Maximum	Uncertainty and variability
Inflows (m^3 s^{-1})							
Rainfall	0.41	0.40	0.28	0.56	0.26	0.65	± 60%
SW in (total)	0.33	0.33	0.33	0.33	0.33	0.33	± 0%
SW in (from inside sub-catchment)[1]	0.30	0.30	0.30	0.30	0.30	0.30	± 0%
SW in (from outside sub-catchment)[1]	0.030	0.030	0.030	0.030	0.030	0.030	± 0%
GW in (total)	1.9	1.8	0.65	3.5	0.40	5.0	± 160%
GW in (from inside sub-catchment)[1]	1.7	1.6	0.55	3	0.36	4.2	± 150%
GW in (from outside sub-catchment)[1]	0.24	0.20	0.056	0.55	0.026	0.83	± 250%
Outflows (m^3 s^{-1})							
Lake evaporation	0.28	0.27	0.26	0.30	0.25	0.31	± 13%
SW out	-	-	-	-	-	-	-
GW out	2.3	2.3	1.0	4.1	0.75	5.7	± 140%
Water out of GT catchments[2]	-	-	-	-	-	-	-
Totals (m^3 s^{-1})							
Inflow total	2.6	2.6	1.3	4.3	1.0	6	± 130%
Outflow total	2.6	2.6	1.3	4.3	1.0	6	± 130%
Other (m^3 s^{-1})							
Storage change[3]	-3.9e-05	-0.00013	-0.00071	0.00099	-0.00075	0.0012	± -3300%
Residual[3]	-1.0e-17	-1.7e-17	-2.2e-16	2.0e-16	-4.1e-16	4.3e-16	± -4400%

[1] Breakdown of the total SW or GW inflow

[2] As (and included in) GW outflows

[3] Positive values represent inflows, negative values outflows (except for standard deviation and IQR statistics which are always positive)

Table C10

Lake Tarawera water balance: summary statistics sample size: 3760							
	Mean	Median	95% CI lower limit	95% CI upper limit	Minimum	Maximum	Uncertainty and variability
Inflows (m^3 s^{-1})							
Rainfall	2.3	2.3	1.5	3.1	1.4	3.5	± 54%
SW in (total)	1.9	1.8	1.6	2.4	1.5	2.4	± 28%
SW in (from inside sub-catchment)[1]	1.3	1.3	1.3	1.4	1.3	1.5	± 9%
SW in (from outside sub-catchment)[1]	0.53	0.50	0.31	0.95	0.28	0.99	± 86%
GW in (total)	6.9	6.8	2.5	13	1.1	17	± 140%
GW in (from inside sub-catchment)[1]	2.1	2.1	0.42	4.4	0.0	5.7	± 170%
GW in (from outside sub-catchment)[1]	4.8	4.7	2	8.3	1.1	11	± 130%
Outflows (m^3 s^{-1})							
Lake evaporation	0.99	0.97	0.92	1.1	0.92	1.1	± 16%
SW out	6.8	6.7	5.5	8.1	5.3	9.2	± 36%
GW out	3.4	3.1	0.0	9.5	0.0	13	± 290%
Water out of GT catchments[2]	-	-	-	-	-	-	-
Totals (m^3 s^{-1})							
Inflow total	11	11	5.7	18	4.1	22	± 100%
Outflow total	11	11	6.5	18	6.2	22	± 98%
Other (m^3 s^{-1})							
Storage change[3]	-1.0e-05	-4.3e-05	-0.00054	0.00042	-0.00058	0.00045	± -5500%
Residual[3]	0.12	2.4e-17	-4.3e-16	1.6	-8.6e-16	3.4	± 2700%

[1] Breakdown of the total SW or GW inflow

[2] As (and included in) GW outflows

[3] Positive values represent inflows, negative values outflows (except for standard deviation and IQR statistics which are always positive)

Table C11

Lake Tikitapu water balance: summary statistics sample size: 3760							
	Mean	Median	95% CI lower limit	95% CI upper limit	Minimum	Maximum	Uncertainty and variability
Inflows ($m^3 s^{-1}$)							
Rainfall	0.044	0.044	0.030	0.059	0.028	0.067	± 53%
SW in (total)	-	-	-	-	-	-	-
SW in (from inside sub-catchment)[1]	-	-	-	-	-	-	-
SW in (from outside sub-catchment)[1]	-	-	-	-	-	-	-
GW in (total)	0.100	0.098	0.037	0.18	0.011	0.23	± 130%
GW in (from inside sub-catchment)[1]	0.100	0.098	0.037	0.18	0.011	0.23	± 130%
GW in (from outside sub-catchment)[1]	-	-	-	-	-	-	-
Outflows ($m^3 s^{-1}$)							
Lake evaporation	0.032	0.031	0.029	0.035	0.029	0.037	± 16%
SW out	-	-	-	-	-	-	-
GW out	0.11	0.11	0.039	0.20	0.013	0.25	± 120%
Water out of GT catchments[2]	-	-	-	-	-	-	-
Totals ($m^3 s^{-1}$)							
Inflow total	0.14	0.14	0.069	0.24	0.042	0.30	± 110%
Outflow total	0.14	0.14	0.071	0.23	0.047	0.28	± 97%
Other ($m^3 s^{-1}$)							
Storage change[3]	-0.00013	-0.00019	-0.0043	0.0027	-0.0057	0.014	± -11000%
Residual[3]	4.8e-19	6.5e-19	-1.2e-17	1.3e-17	-1.3e-17	1.4e-17	± 2800%

[1] Breakdown of the total SW or GW inflow

[2] As (and included in) GW outflows

[3] Positive values represent inflows, negative values outflows (except for standard deviation and IQR statistics which are always positive)

Table C12

Ōkareka catchment water balance: summary statistics sample size: 3760							
	Mean	Median	95% CI lower limit	95% CI upper limit	Minimum	Maximum	Uncertainty and variability
Inflows (m^3 s^{-1})							
Rainfall	0.92	0.93	0.63	1.3	0.58	1.4	± 54%
SW in	-	-	-	-	-	-	-
GW in	-	-	-	-	-	-	-
Outflows (m^3 s^{-1})							
Evaporation from land	0.38	0.38	0.25	0.50	0.21	0.52	± 43%
Evaporation from lake(s)	0.078	0.077	0.072	0.088	0.070	0.088	± 13%
SW out	0.17	0.16	0.075	0.26	0.062	0.39	± 130%
GW out	0.30	0.29	0.052	0.58	0.0	0.76	± 150%
Water out of GT catchments[1]	-	-	-	-	-	-	-
Totals (m^3 s^{-1})							
Inflow total	0.92	0.93	0.63	1.3	0.58	1.4	± 54%
Outflow total	0.92	0.93	0.63	1.3	0.58	1.4	± 54%
Other (m^3 s^{-1})							
Residual[2]	5.5e-05	4.6e-19	-2.6e-17	3.5e-17	-5.5e-17	0.031	± 57000%
Storage change[2]	1.3e-05	5.4e-06	-0.00012	0.00017	-0.00012	0.00038	± 2700%

[1] As (and included in) GW outflows

[2] Positive values represent inflows, negative values outflows

Table C13

Ōkaro catchment water balance: summary statistics

sample size: 3760

	Mean	Median	95% CI lower limit	95% CI upper limit	Minimum	Maximum	Uncertainty and variability
Inflows (m^3 s^{-1})							
Rainfall	0.17	0.17	0.12	0.23	0.11	0.27	± 58%
SW in	-	-	-	-	-	-	-
GW in	-	-	-	-	-	-	-
Outflows (m^3 s^{-1})							
Evaporation from land	0.073	0.073	0.045	0.099	0.041	0.10	± 44%
Evaporation from lake(s)	0.0076	0.0075	0.0069	0.0085	0.0067	0.0086	± 14%
SW out	0.030	0.030	0.030	0.030	0.030	0.030	± 0%
GW out	0.059	0.056	0.012	0.12	0.0023	0.17	± 180%
Water out of GT catchments[1]	-	-	-	-	-	-	-
Totals (m^3 s^{-1})							
Inflow total	0.17	0.17	0.12	0.23	0.11	0.27	± 58%
Outflow total	0.17	0.17	0.12	0.23	0.11	0.27	± 58%
Other (m^3 s^{-1})							
Residual[2]	-3.5e-19	6.8e-21	-6.6e-18	5.8e-18	-1.1e-17	1.3e-17	± -3700%
Storage change[2]	2.3e-05	1.6e-05	-0.00037	0.00086	-0.00047	0.0015	± 6800%

[1] As (and included in) GW outflows

[2] Positive values represent inflows, negative values outflows

Table C14

Ōkataina catchment water balance: summary statistics sample size: 3760							
	Mean	Median	95% CI lower limit	95% CI upper limit	Minimum	Maximum	Uncertainty and variability
Inflows (m^3 s^{-1})							
Rainfall	3.8	3.8	2.4	5.2	2.2	5.9	± 57%
SW in	-	-	-	-	-	-	-
GW in	-	-	-	-	-	-	-
Outflows (m^3 s^{-1})							
Evaporation from land	1.4	1.4	0.95	1.8	0.80	1.9	± 43%
Evaporation from lake(s)	0.25	0.25	0.23	0.28	0.23	0.29	± 18%
SW out	-	-	-	-	-	-	-
GW out	2.1	2.1	1.0	3.4	0.46	4.2	± 98%
Water out of GT catchments[1]	-	-	-	-	-	-	-
Totals (m^3 s^{-1})							
Inflow total	3.8	3.8	2.4	5.2	2.2	5.9	± 57%
Outflow total	3.8	3.8	2.4	5.2	2.2	5.9	± 57%
Other (m^3 s^{-1})							
Residual[2]	9.9e-18	3.0e-17	-1.9e-16	2.0e-16	-2.0e-16	4.0e-16	± 4000%
Storage change[2]	-0.0013	-0.00019	-0.025	0.0096	-0.049	0.030	± -3800%

[1] As (and included in) GW outflows

[2] Positive values represent inflows, negative values outflows

Table C15

Rerewhakaaitu catchment water balance: summary statistics sample size: 3760							
	Mean	Median	95% CI lower limit	95% CI upper limit	Minimum	Maximum	Uncertainty and variability
Inflows (m^3 s^{-1})							
Rainfall	2.3	2.3	1.6	3.1	1.4	3.8	± 67%
SW in	-	-	-	-	-	-	-
GW in	-	-	-	-	-	-	-
Outflows (m^3 s^{-1})							
Evaporation from land	0.98	0.99	0.63	1.3	0.56	1.5	± 51%
Evaporation from lake(s)	0.10	0.10	0.090	0.13	0.088	0.13	± 27%
SW out	-	-	-	-	-	-	-
GW out	1.2	1.2	0.56	2.0	0.43	2.8	± 130%
Water out of GT catchments[1]	0.51	0.30	0.064	1.4	0.043	2.1	± 310%
Totals (m^3 s^{-1})							
Inflow total	2.3	2.3	1.6	3.1	1.4	3.8	± 67%
Outflow total	2.3	2.3	1.6	3.1	1.4	3.8	± 67%
Other (m^3 s^{-1})							
Residual[2]	1.2e-18	-7.6e-18	-1.0e-16	1.1e-16	-1.8e-16	2.2e-16	± 18000%
Storage change[2]	1.6e-05	1.2e-05	-0.00030	0.00029	-0.00046	0.00054	± 3300%

[1] As (and included in) GW outflows

[2] Positive values represent inflows, negative values outflows

Table C16

Rotokakahi catchment water balance: summary statistics sample size: 3760							
	Mean	Median	95% CI lower limit	95% CI upper limit	Minimum	Maximum	Uncertainty and variability
Inflows (m^3 s^{-1})							
Rainfall	1.1	1.1	0.74	1.4	0.68	1.6	± 53%
SW in	-	-	-	-	-	-	-
GW in	-	-	-	-	-	-	-
Outflows (m^3 s^{-1})							
Evaporation from land	0.44	0.44	0.30	0.57	0.26	0.60	± 41%
Evaporation from lake(s)	0.13	0.13	0.12	0.15	0.12	0.15	± 16%
SW out	0.35	0.34	0.23	0.46	0.22	0.56	± 61%
GW out	0.16	0.13	0.0	0.46	0.0	0.63	± 300%
Water out of GT catchments[1]	-	-	-	-	-	-	-
Totals (m^3 s^{-1})							
Inflow total	1.1	1.1	0.74	1.4	0.68	1.6	± 53%
Outflow total	1.1	1.1	0.76	1.4	0.68	1.6	± 48%
Other (m^3 s^{-1})							
Residual[2]	0.012	8.7e-19	-2.0e-17	0.16	-4.7e-17	0.25	± 2000%
Storage change[2]	-0.00019	-0.00045	-0.0085	0.0061	-0.013	0.027	± -14000%

[1] As (and included in) GW outflows

[2] Positive values represent inflows, negative values outflows

Table C17

Rotomahana catchment water balance: summary statistics

sample size: 3760

	Mean	Median	95% CI lower limit	95% CI upper limit	Minimum	Maximum	Uncertainty and variability
Inflows (m^3 s^{-1})							
Rainfall	6.1	6.0	4.2	8.3	3.9	9.9	± 63%
SW in	-	-	-	-	-	-	-
GW in	-	-	-	-	-	-	-
Outflows (m^3 s^{-1})							
Evaporation from land	2.7	2.6	1.7	3.7	1.5	4	± 49%
Evaporation from lake(s)	0.39	0.38	0.36	0.44	0.35	0.45	± 16%
SW out	0.021	0.0	0.0	0.23	0.0	0.28	± 1200%
GW out	3	2.9	1.3	5.2	0.99	7.0	± 140%
Water out of GT catchments[1]	0.51	0.30	0.064	1.4	0.043	2.1	± 310%
Totals (m^3 s^{-1})							
Inflow total	6.1	6.0	4.2	8.3	3.9	9.9	± 63%
Outflow total	6.1	6.0	4.2	8.3	3.9	9.9	± 63%
Other (m^3 s^{-1})							
Residual[2]	4.6e-18	1.7e-17	-3.5e-16	2.2e-16	-4.2e-16	4.2e-16	± 9200%
Storage change[2]	-3.4e-07	-0.00010	-0.0011	0.0015	-0.0013	0.0015	± -460000%

[1] As (and included in) GW outflows

[2] Positive values represent inflows, negative values outflows

Table C18

Tarawera catchment water balance: summary statistics sample size: 3760							
	Mean	Median	95% CI lower limit	95% CI upper limit	Minimum	Maximum	Uncertainty and variability
Inflows (m^3 s^{-1})							
Rainfall	19	19	13	27	12	31	± 57%
SW in	-	-	-	-	-	-	-
GW in	-	-	-	-	-	-	-
Outflows (m^3 s^{-1})							
Evaporation from land	7.3	7.2	4.9	9.5	4.3	10	± 42%
Evaporation from lake(s)	1.8	1.8	1.7	2.0	1.7	2.1	± 16%
SW out	6.8	6.7	5.5	8.1	5.3	9.2	± 36%
GW out	3.8	3.5	0.0	10	0.0	14	± 280%
Water out of GT catchments[1]	0.51	0.30	0.064	1.4	0.043	2.1	± 310%
Totals (m^3 s^{-1})							
Inflow total	19	19	13	27	12	31	± 57%
Outflow total	20	19	14	27	12	31	± 56%
Other (m^3 s^{-1})							
Residual[2]	0.10	-1.3e-18	-4.3e-16	1.5	-5.8e-16	3.2	± 3000%
Storage change[2]	-0.0013	-0.00064	-0.025	0.017	-0.050	0.029	± -3700%

[1] As (and included in) GW outflows

[2] Positive values represent inflows, negative values outflows

Table C19

Tikitapu catchment water balance: summary statistics sample size: 3760							
	Mean	Median	95% CI lower limit	95% CI upper limit	Minimum	Maximum	Uncertainty and variability
Inflows (m^3 s^{-1})							
Rainfall	0.25	0.25	0.17	0.34	0.16	0.39	± 53%
SW in	-	-	-	-	-	-	-
GW in	-	-	-	-	-	-	-
Outflows (m^3 s^{-1})							
Evaporation from land	0.11	0.11	0.077	0.15	0.066	0.16	± 42%
Evaporation from lake(s)	0.032	0.031	0.029	0.035	0.029	0.037	± 16%
SW out	-	-	-	-	-	-	-
GW out	0.11	0.10	0.037	0.19	0.012	0.24	± 120%
Water out of GT catchments[1]	-	-	-	-	-	-	-
Totals (m^3 s^{-1})							
Inflow total	0.25	0.25	0.17	0.34	0.16	0.39	± 53%
Outflow total	0.25	0.25	0.18	0.34	0.16	0.37	± 47%
Other (m^3 s^{-1})							
Residual[2]	-2.7e-19	-2.2e-19	-1.1e-17	1.3e-17	-1.3e-17	1.4e-17	± -5200%
Storage change[2]	-0.00013	-0.00019	-0.0043	0.0027	-0.0057	0.014	± -11000%

[1] As (and included in) GW outflows

[2] Positive values represent inflows, negative values outflows

Figure C1

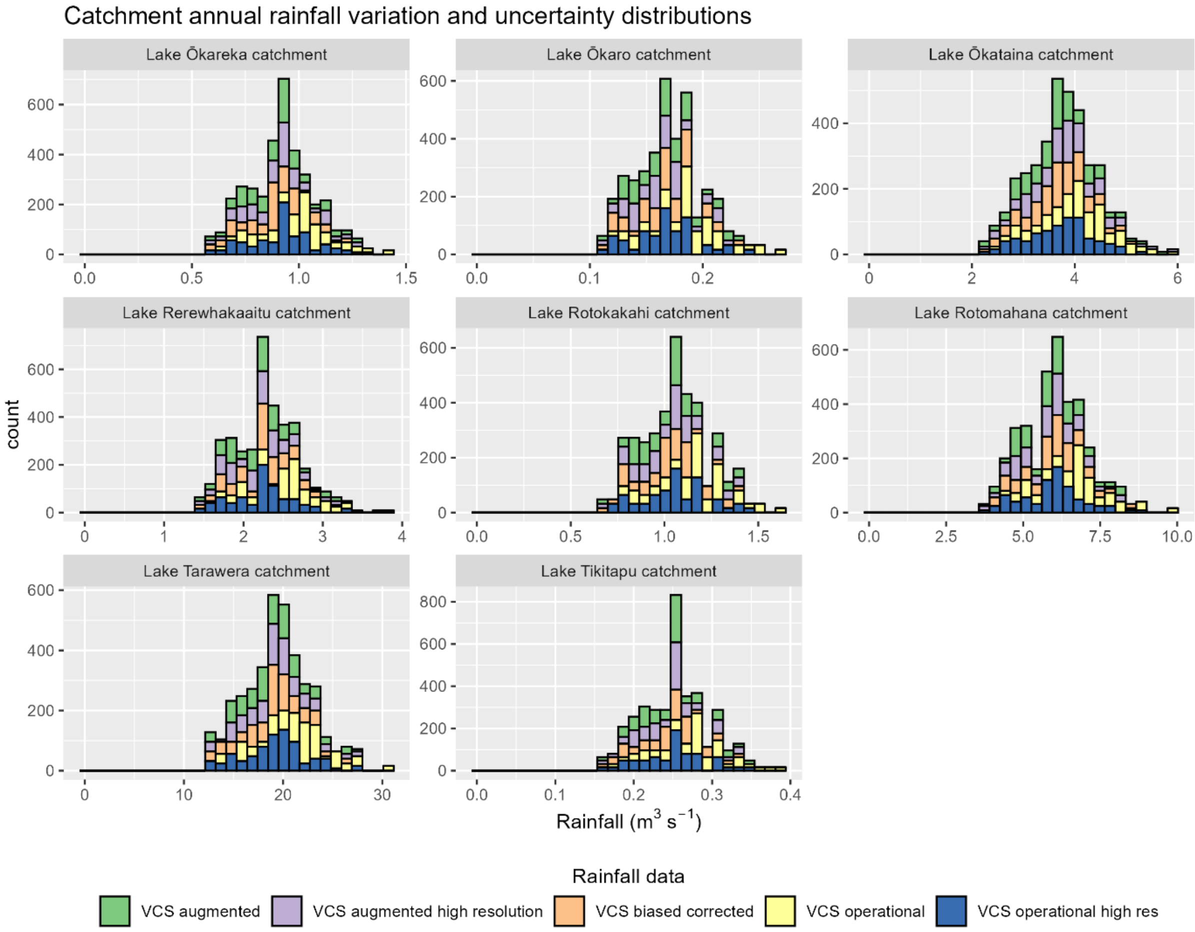


Figure C2

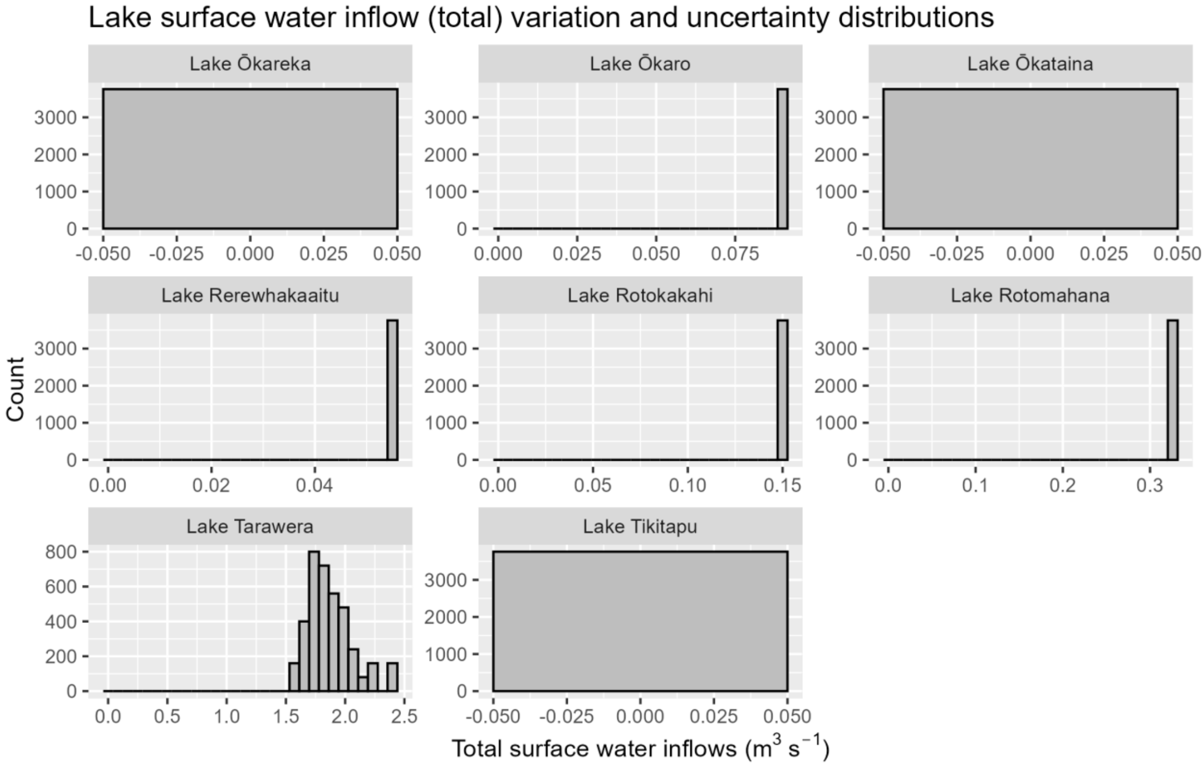


Figure C3

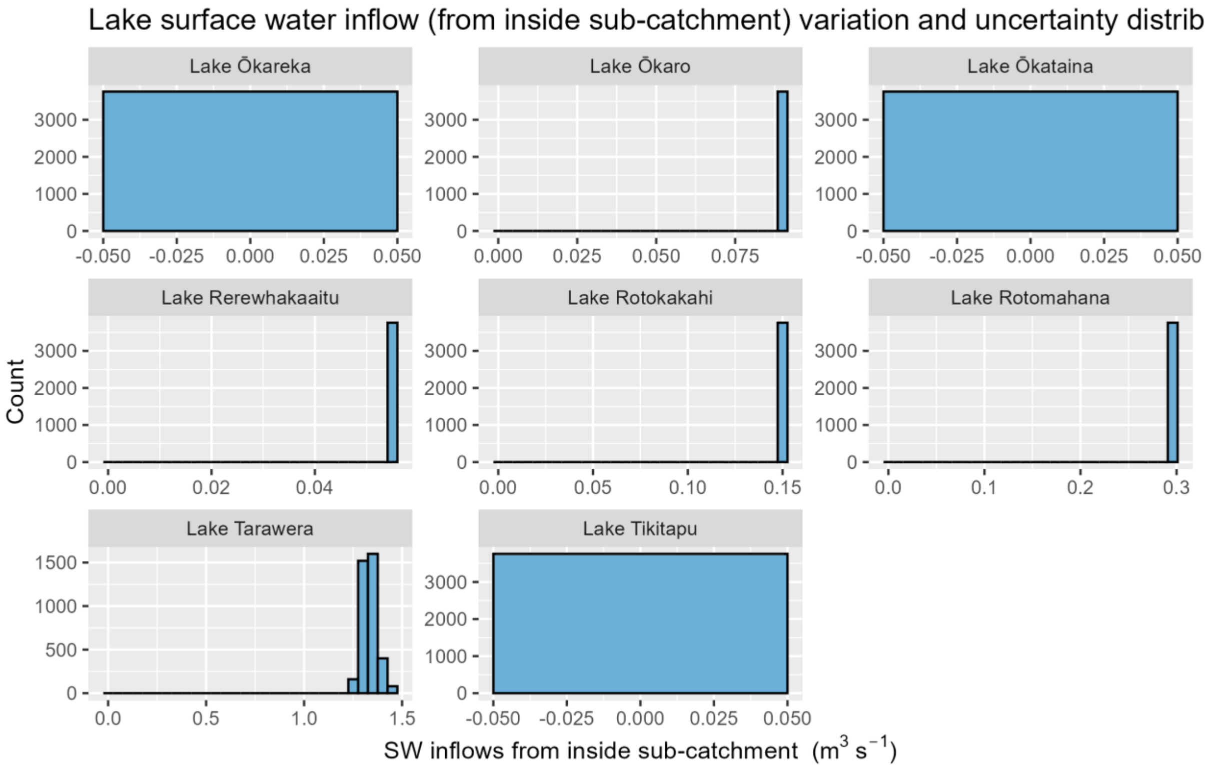


Figure C4

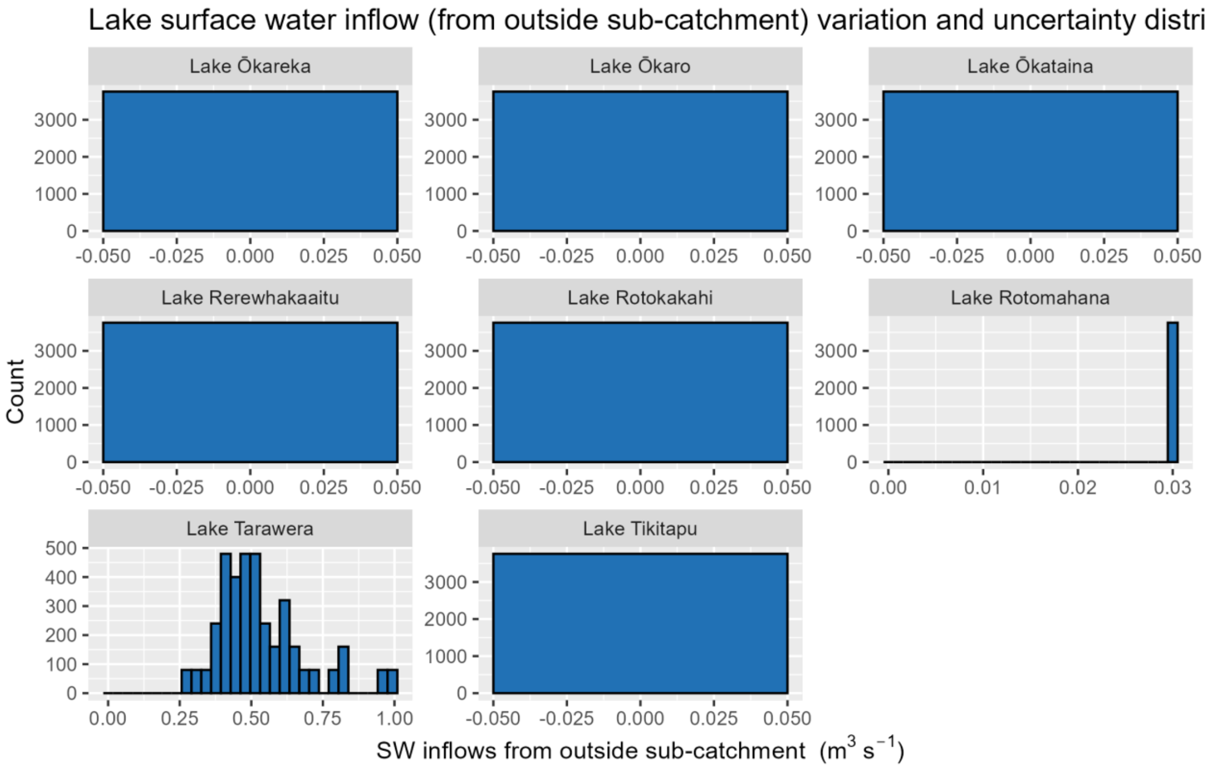


Figure C5

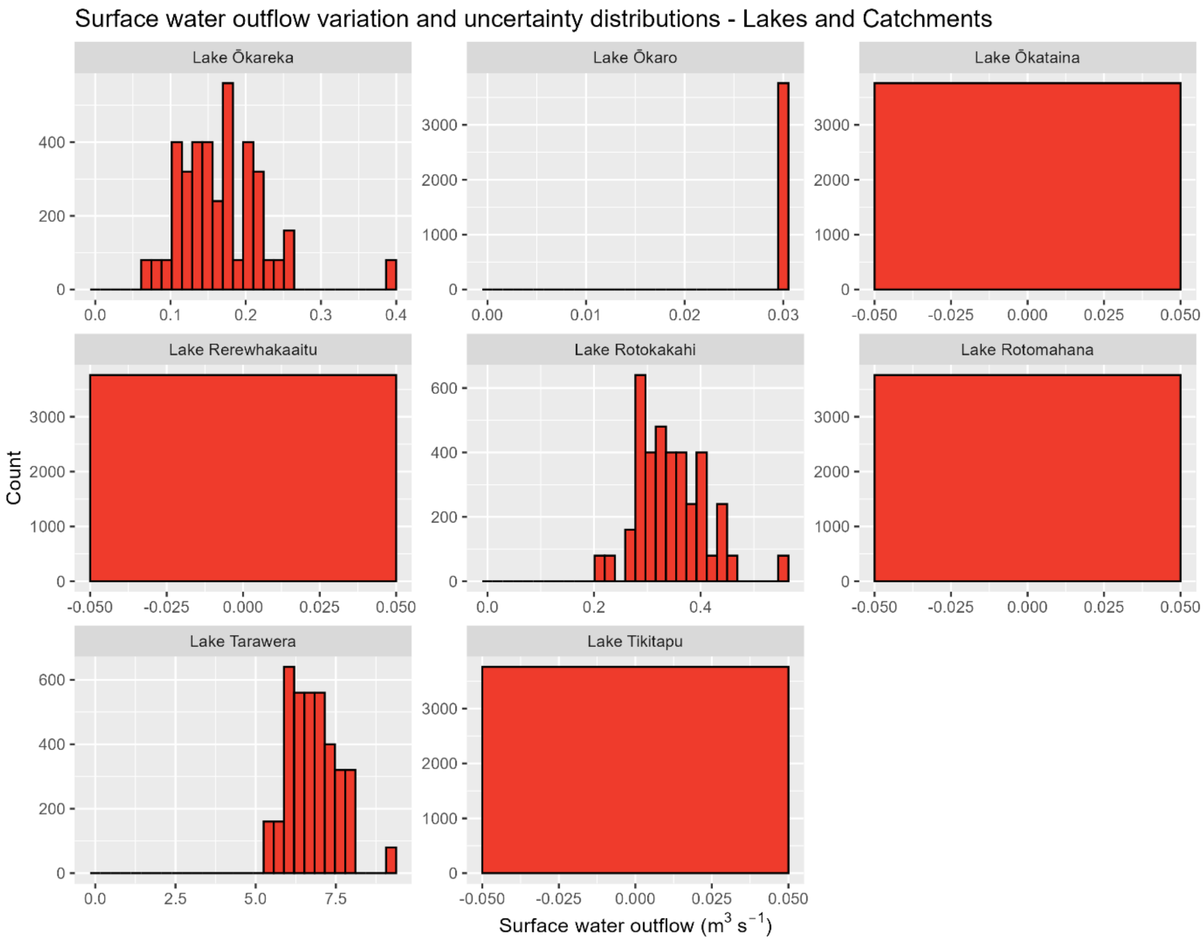


Figure C6

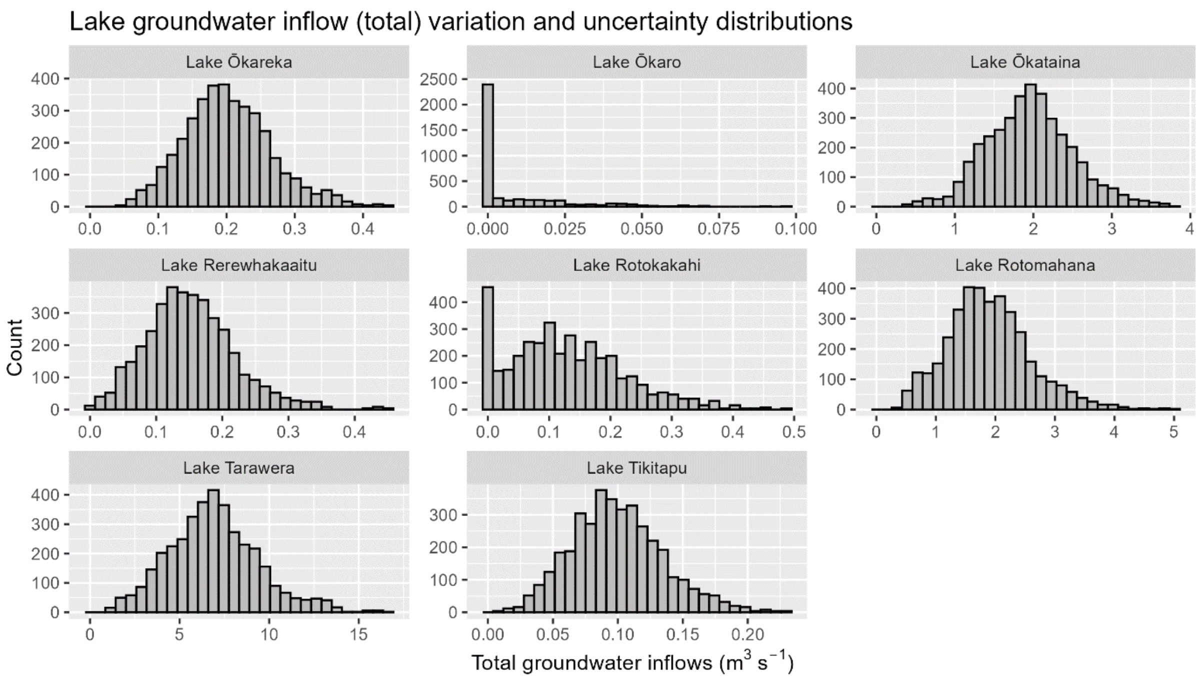


Figure C7

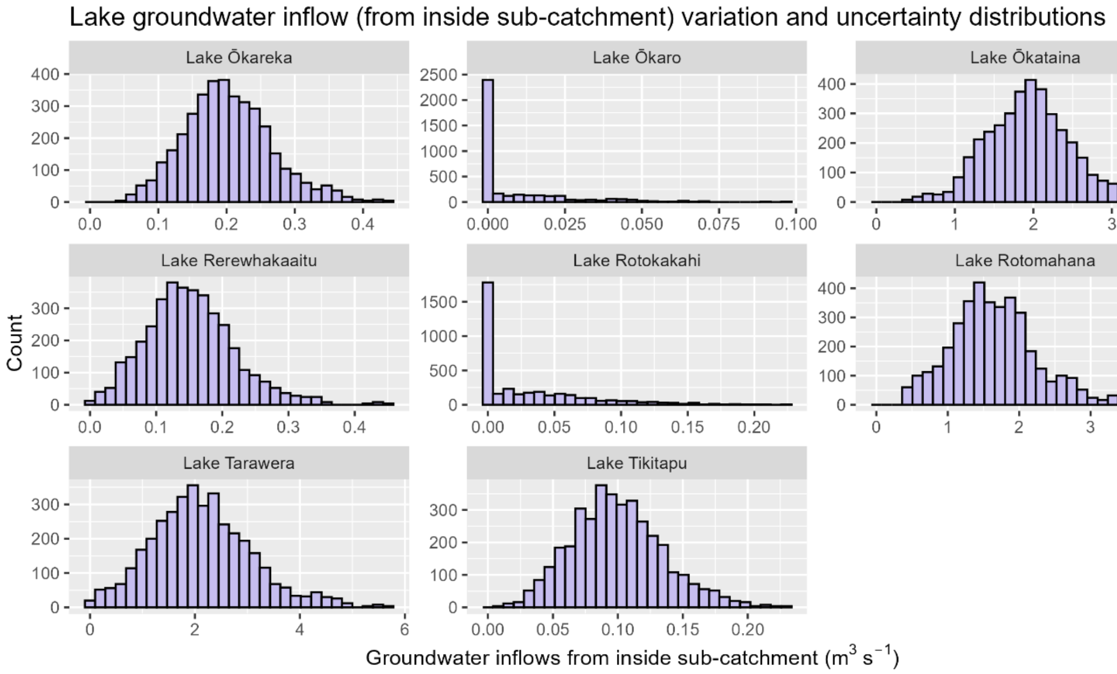


Figure C8

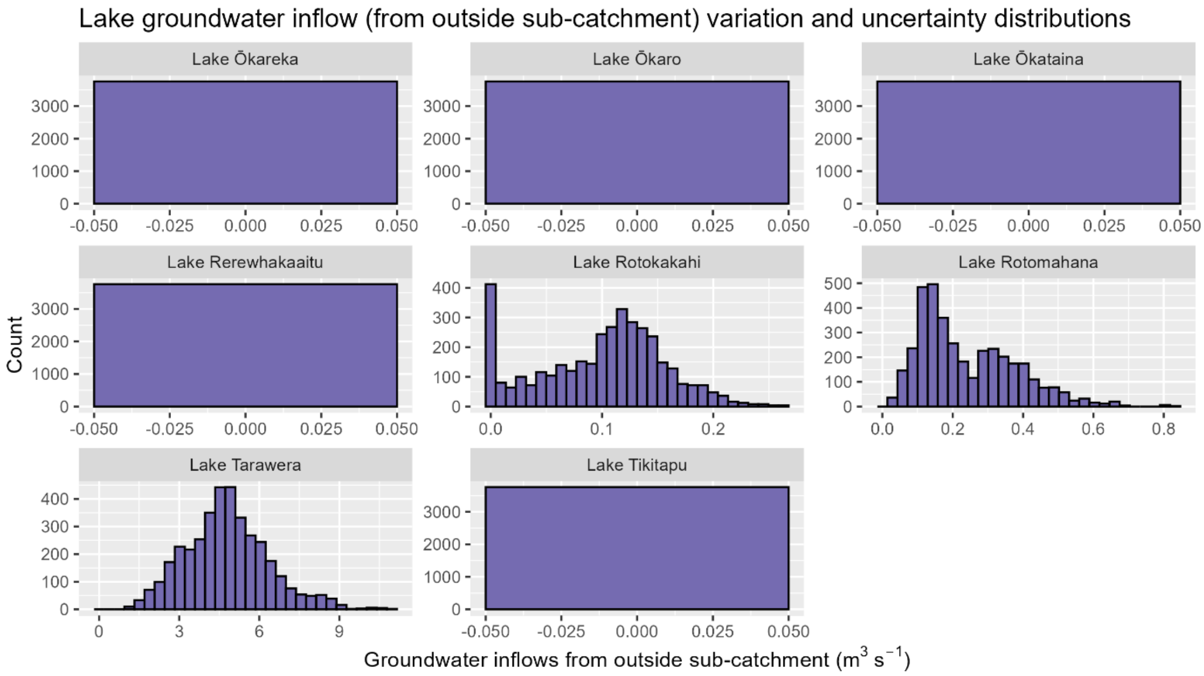


Figure C9

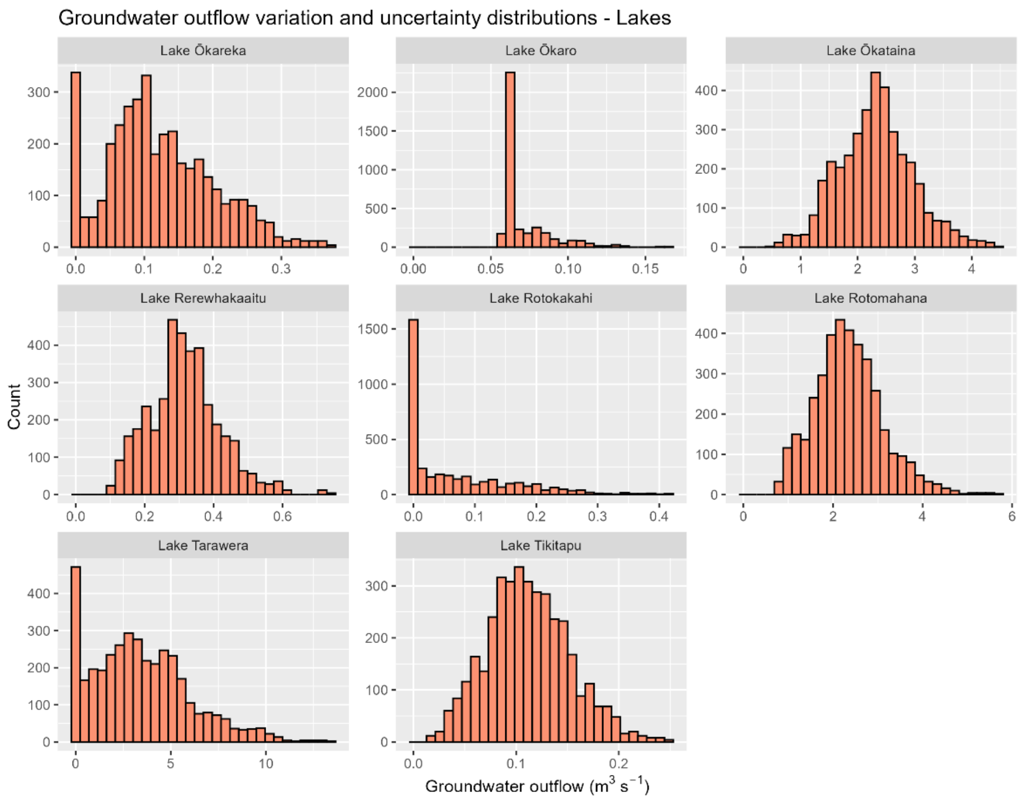


Figure C10

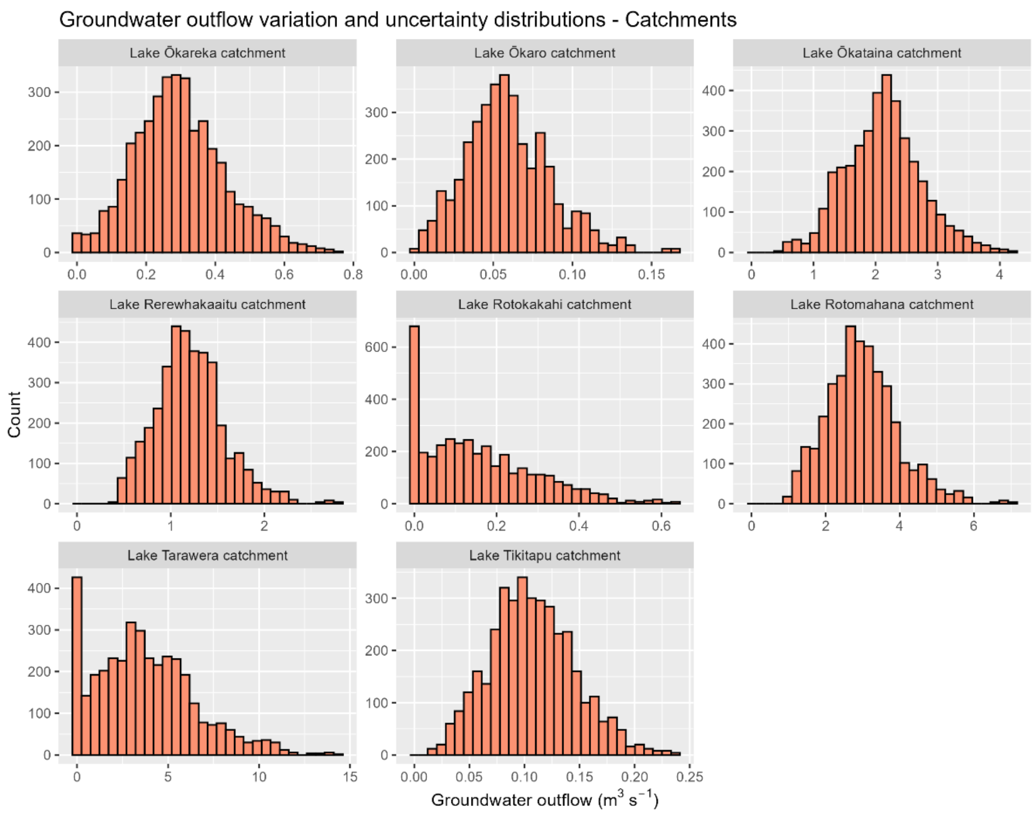


Figure C11

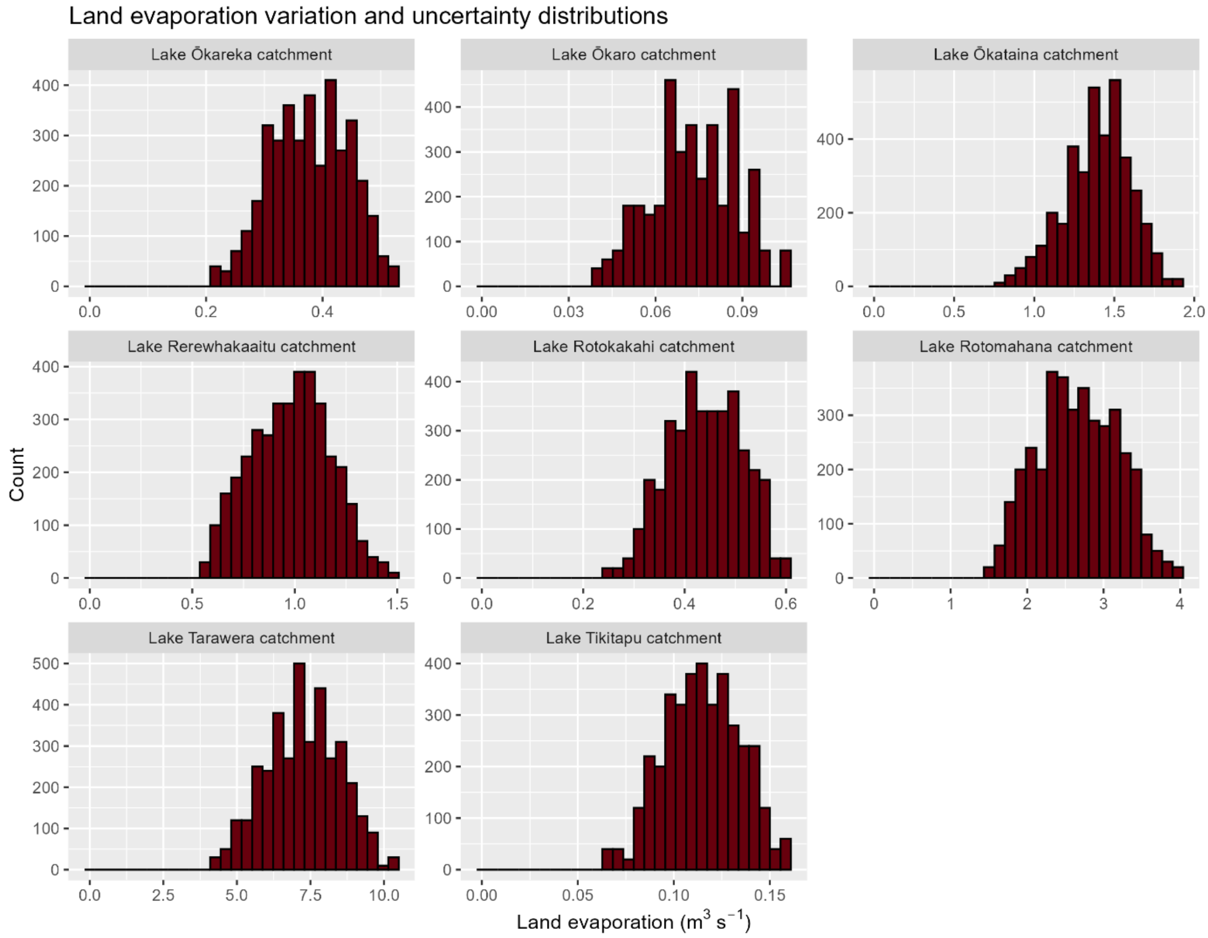
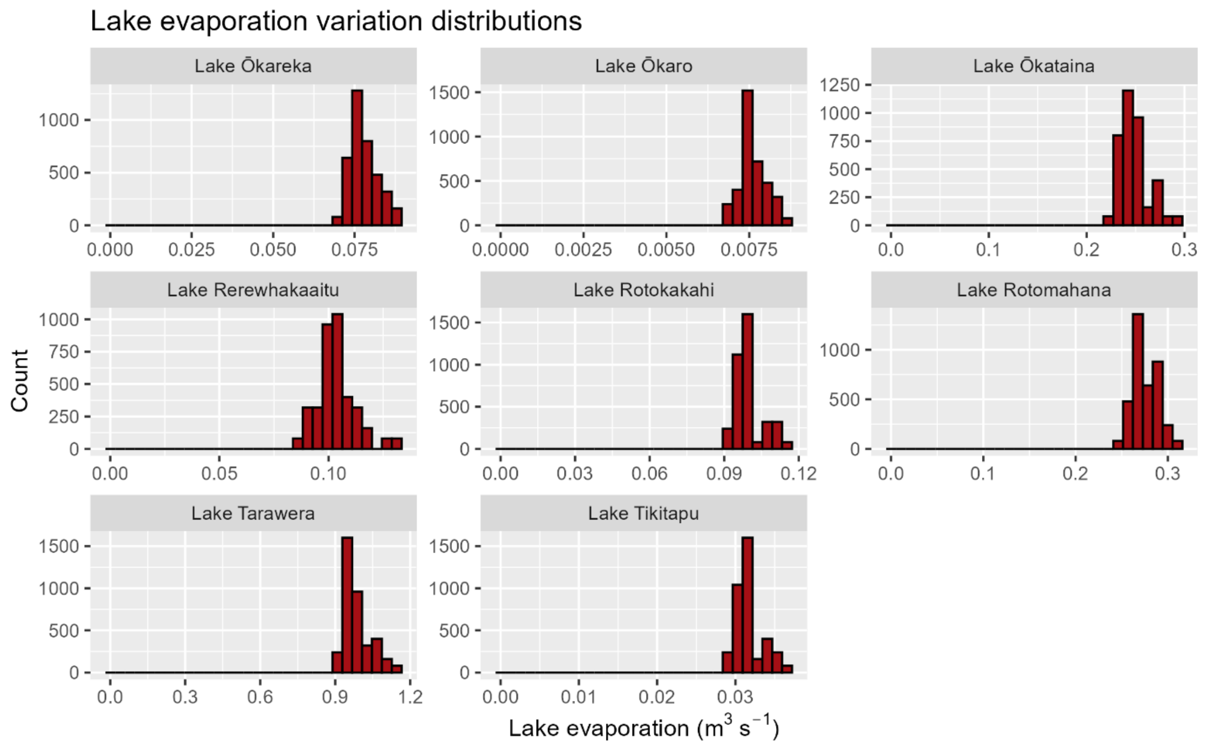


Figure C12



Appendix D: Annualised nutrient loads

Table D1

Lake Ōkareka loads from sub-catchment (current land uses)					
Land use/nutrient source	Land Use (%)	TN load (t y^{-1})	TP load (t y^{-1})	TN load (%)	TP load (%)
Agriculture - dry stock	22.07	6.74	0.59	44.99	59.41
Agriculture - lifestyle	3.39	1.21	0.08	8.07	8.15
Forest - exotic	14.87	0.53	0.03	3.54	2.68
Forest - native	33.29	1.46	0.05	9.77	4.80
Gorse/broom	-	1.59	0.00	10.59	0.00
Scrub/shrub	3.18	0.19	0.04	1.26	3.82
Unknown	0.67	0.04	0.01	0.27	0.81
Urban - infrastructure	4.04	0.28	0.02	1.89	2.43
Urban - parks	0.15	0.04	0.00	0.30	0.03
Wastewater	-	0.61	0.06	4.05	6.14
Water - lake or stream	17.23	2.29	0.12	15.26	11.73
Water - wetland	1.11	0.00	0.00	0.00	0.00
All sources	**-**	**14.98**	**0.99**	**-**	**-**

Table D2

Lake Ōkaro loads from sub-catchment (current land uses)					
Land use/nutrient source	Land Use (%)	TN load ($t\ y^{-1}$)	TP load ($t\ y^{-1}$)	TN load (%)	TP load (%)
Agriculture - dairy	15.67	1.13	0.13	29.04	22.29
Agriculture - dry stock	67.77	2.22	0.47	56.85	79.25
Agriculture - lifestyle	3.20	0.21	0.01	5.43	2.38
Forest - native	0.06	0.00	0.00	0.01	0.00
Gorse/broom	-	0.07	0.00	1.87	0.00
Urban - infrastructure	1.48	0.02	0.00	0.49	0.28
Urban - parks	2.74	0.15	0.00	3.88	0.14
Wastewater	-	0.04	0.00	0.95	0.62
Water - lake or stream	8.40	0.21	0.01	5.32	1.77
Water - wetland	0.69	−0.15	−0.04	−3.85	−6.74
All sources	-	**3.90**	**0.59**	-	-

Note: modelled negative "loads" represent nutrient removal by the wetland

Table D3

Lake Ōkataina loads from sub-catchment (current land uses)					
Land use/nutrient source	Land Use (%)	TN load (t y^{-1})	TP load (t y^{-1})	TN load (%)	TP load (%)
Agriculture - dairy support	1.03	1.46	0.15	6.36	10.53
Agriculture - dry stock	0.91	0.97	0.13	4.24	9.66
Agriculture - lifestyle	0.43	0.48	0.03	2.07	2.29
Forest - exotic	10.49	1.17	0.09	5.10	6.18
Forest - native	66.41	9.13	0.44	39.81	32.04
Geothermal	-	1.58	0.03	6.89	2.16
Gorse/broom	-	0.18	0.00	0.80	0.00
Scrub/shrub	0.11	0.02	0.01	0.09	0.43
Unknown	3.58	0.67	0.13	2.90	9.60
Urban - infrastructure	0.13	0.03	0.00	0.13	0.18
Wastewater	-	0.11	0.01	0.48	0.79
Water - lake or stream	16.92	7.14	0.36	31.13	26.13
All sources	**-**	**22.94**	**1.39**	**-**	**-**

Table D4

Lake Rerewhakaaitu loads from sub-catchment (current land uses)					
Land use/nutrient source	Land Use (%)	TN load ($t\ y^{-1}$)	TP load ($t\ y^{-1}$)	TN load (%)	TP load (%)
Agriculture - dairy	55.35	11.20	0.81	53.11	62.33
Agriculture - dairy support	1.25	2.30	0.06	10.89	4.68
Agriculture - dry stock	4.08	0.74	0.03	3.53	2.14
Agriculture - lifestyle	1.75	1.04	0.07	4.91	5.30
Forest - exotic	14.20	0.68	0.03	3.24	2.62
Forest - native	8.42	0.59	0.02	2.78	1.46
Gorse/broom	-	0.06	0.00	0.30	0.00
Unknown	2.50	0.24	0.05	1.12	3.63
Urban - infrastructure	1.51	0.09	0.01	0.43	0.58
Urban - parks	0.38	0.08	0.00	0.39	0.04
Wastewater	-	0.37	0.04	1.74	2.82
Water - lake or stream	10.56	3.70	0.19	17.54	14.40
Water - wetland	0.00	0.00	0.00	0.00	0.00
All sources	**-**	**21.09**	**1.30**	**-**	**-**

Table D5

Lake Rotokakahi loads from sub-catchment (current land uses)					
Land use/nutrient source	Land Use (%)	TN load (t y^{-1})	TP load (t y^{-1})	TN load (%)	TP load (%)
Agriculture - dairy	0.23	0.18	0.01	1.87	1.38
Agriculture - dry stock	25.13	3.83	0.59	38.68	68.23
Connections	-	0.71	0.02	7.21	2.58
Forest - exotic	38.70	1.34	0.07	13.54	7.77
Forest - native	11.92	0.51	0.02	5.14	1.91
Gorse/broom	-	0.28	0.00	2.82	0.00
Urban - infrastructure	0.89	0.06	0.01	0.61	0.59
Water - lake or stream	23.14	2.98	0.15	30.13	17.54
All sources	**-**	**9.89**	**0.86**	**-**	**-**

Table D6

Lake Rotomahana loads from sub-catchment (current land uses)					
Land use/nutrient source	Land Use (%)	TN load (t y^{-1})	TP load (t y^{-1})	TN load (%)	TP load (%)
Agriculture - dairy	13.28	29.57	3.20	31.07	15.51
Agriculture - dairy support	9.81	24.80	3.65	26.06	17.69
Agriculture - dry stock	7.16	5.18	0.60	5.45	2.91
Agriculture - lifestyle	0.91	1.32	0.09	1.39	0.43
Connections	-	3.88	0.16	4.08	0.79
Forest - exotic	14.76	2.15	0.11	2.26	0.52
Forest - native	33.91	6.10	0.20	6.41	0.96
Geothermal	-	13.44	11.93	14.12	57.77
Gorse/broom	-	0.61	0.00	0.64	0.00
Unknown	7.87	1.91	0.38	2.01	1.85
Urban - infrastructure	0.72	0.21	0.02	0.22	0.09
Urban - parks	0.01	0.01	0.00	0.01	0.00
Wastewater	-	0.07	0.01	0.08	0.04
Water - lake or stream	10.51	5.90	0.30	6.20	1.45
Water - wetland	1.06	0.00	0.00	0.00	0.00
All sources	**-**	**95.16**	**20.65**	**-**	**-**

Table D7

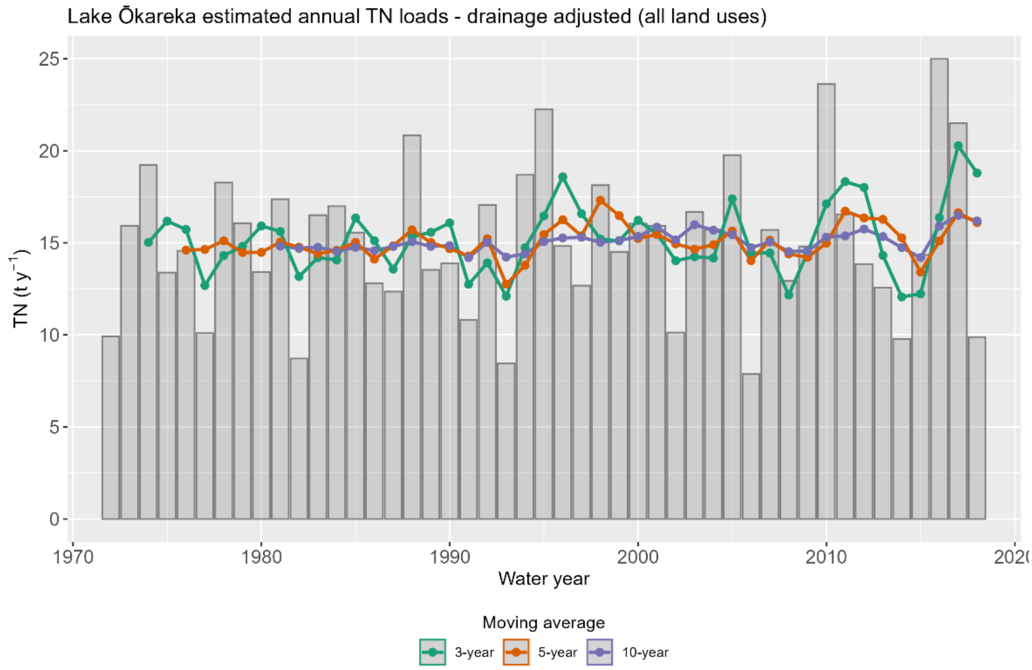
Lake Tarawera loads from sub-catchment (current land uses)					
Land use/nutrient source	Land Use (%)	TN load (t y^{-1})	TP load (t y^{-1})	TN load (%)	TP load (%)
Agriculture - dry stock	11.48	20.27	2.87	18.97	26.99
Agriculture - lifestyle	1.98	4.94	0.33	4.62	3.09
Connections	-	23.19	2.49	21.71	23.40
Forest - exotic	11.32	2.82	0.18	2.64	1.68
Forest - native	44.56	13.67	0.55	12.80	5.21
Geothermal	-	2.69	2.39	2.52	22.45
Gorse/broom	-	7.58	0.00	7.10	0.00
Scrub/shrub	0.30	0.12	0.03	0.12	0.29
Unknown	0.66	0.27	0.05	0.26	0.51
Urban - infrastructure	1.09	0.53	0.05	0.50	0.43
Urban - parks	0.01	0.03	0.00	0.03	0.00
Wastewater	-	2.84	0.28	2.66	2.67
Water - lake or stream	28.59	27.87	1.41	26.09	13.28
All sources	**-**	**106.82**	**10.65**	**-**	**-**

Table D8

Lake Tikitapu loads from sub-catchment (current land uses)					
Land use/nutrient source	Land Use (%)	TN load (t y^{-1})	TP load (t y^{-1})	TN load (%)	TP load (%)
Agriculture - dry stock	1.87	0.05	0.01	2.38	11.28
Forest - exotic	11.80	0.12	0.01	5.55	5.22
Forest - native	56.08	0.71	0.02	32.55	19.86
Gorse/broom	-	0.02	0.00	0.82	0.00
Urban - infrastructure	4.85	0.10	0.01	4.49	7.16
Urban - parks	0.80	0.07	0.00	3.15	0.33
Wastewater	-	0.17	0.02	7.98	15.01
Water - lake or stream	24.59	0.94	0.05	43.07	41.13
All sources	**-**	**2.19**	**0.12**	**-**	**-**

Figure D1

(a) Modelled load variation using best-estimate datasets and methods



(b) BOPRC lake monitoring data

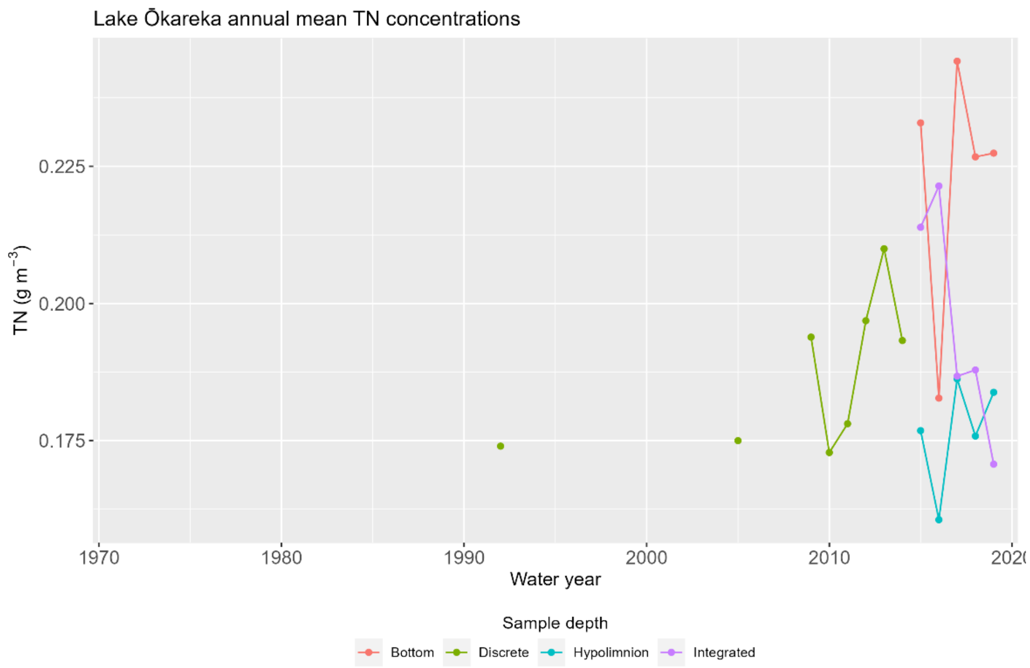
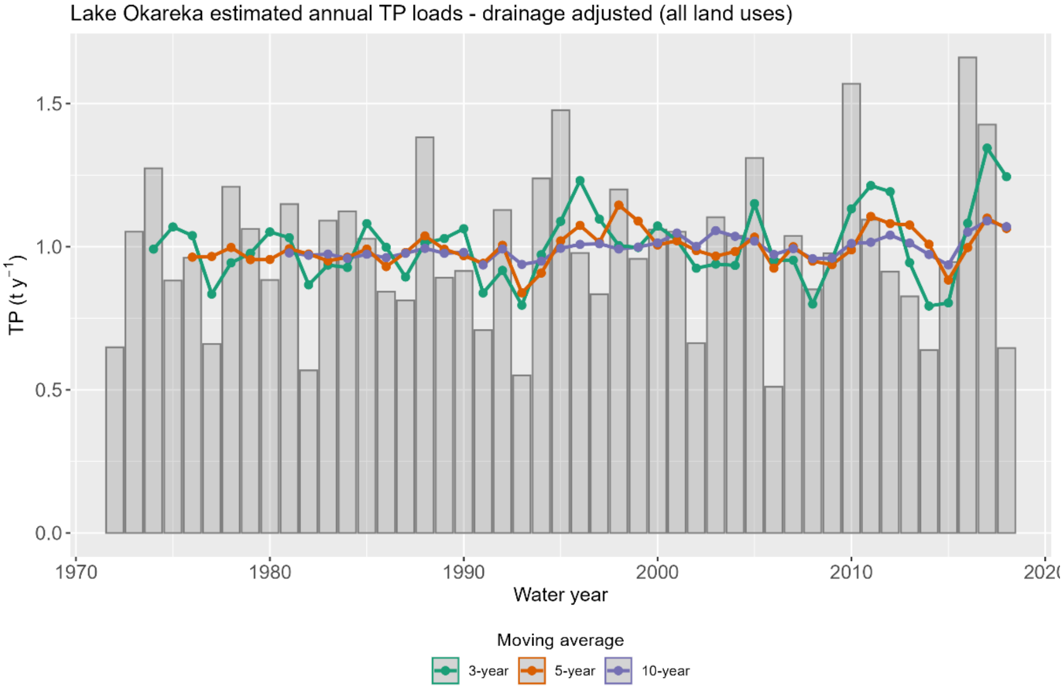


Figure D2

(a) Modelled load variation using best-estimate datasets and methods



(b) BOPRC lake monitoring data

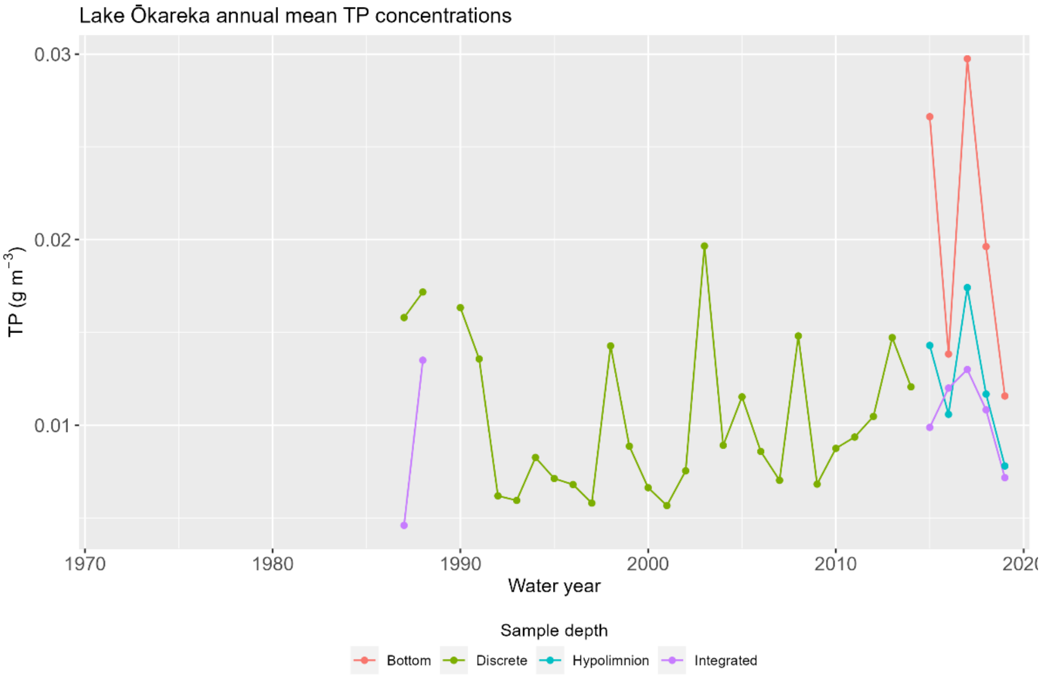
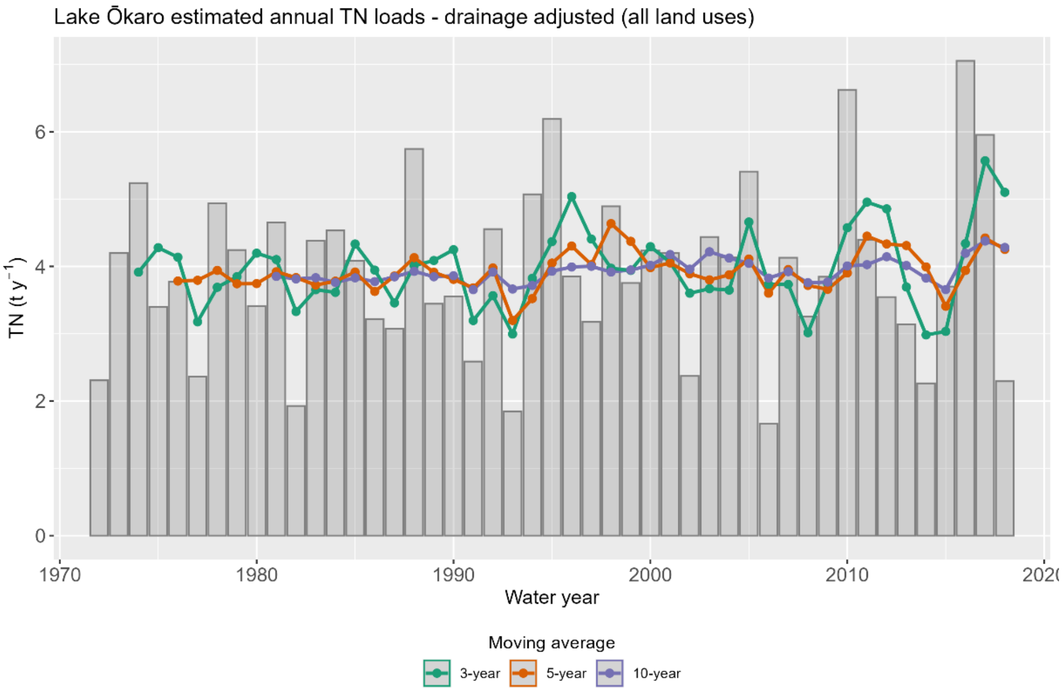


Figure D3

(a) Modelled load variation using best-estimate datasets and methods



(b) BOPRC lake monitoring data

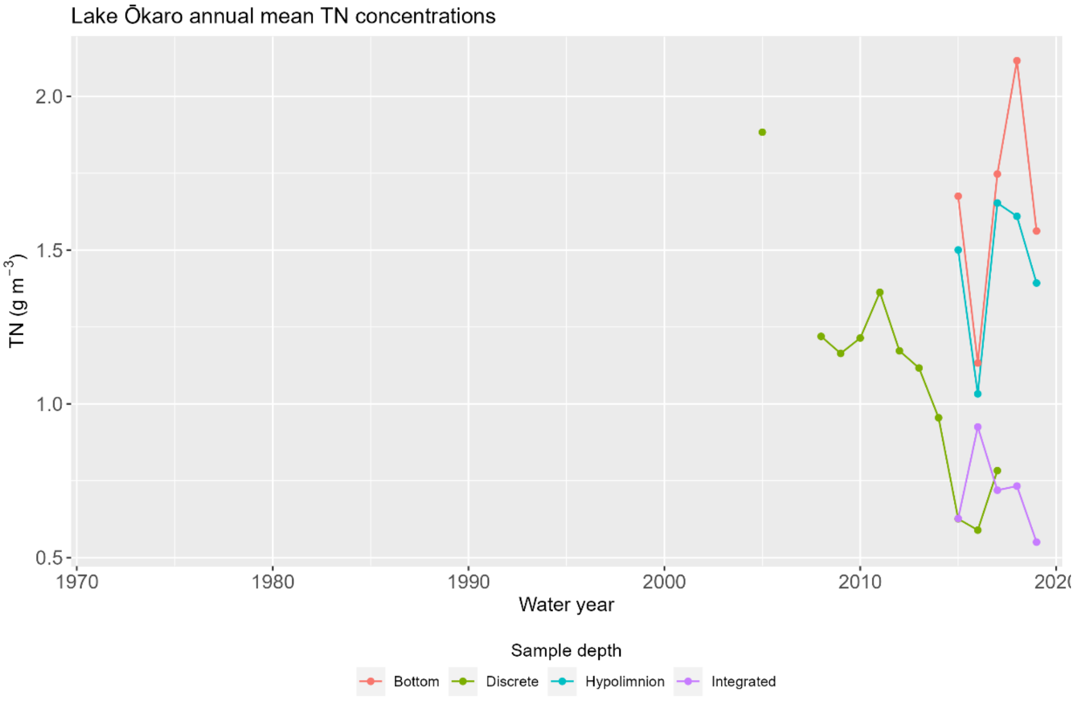
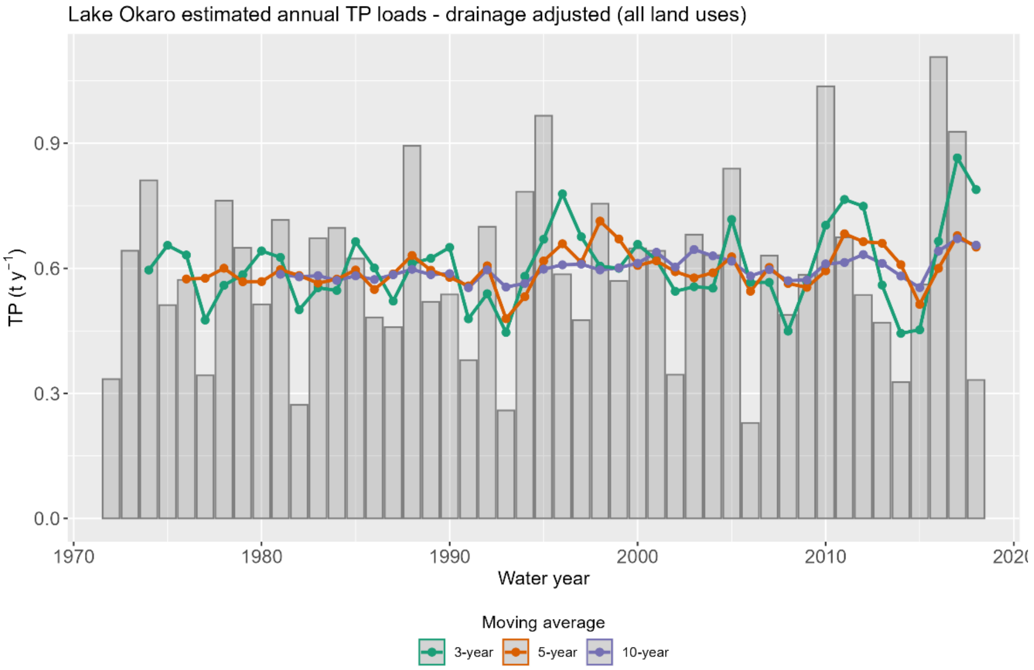


Figure D4

(a) Modelled load variation using best-estimate datasets and methods



(b) BOPRC lake monitoring data

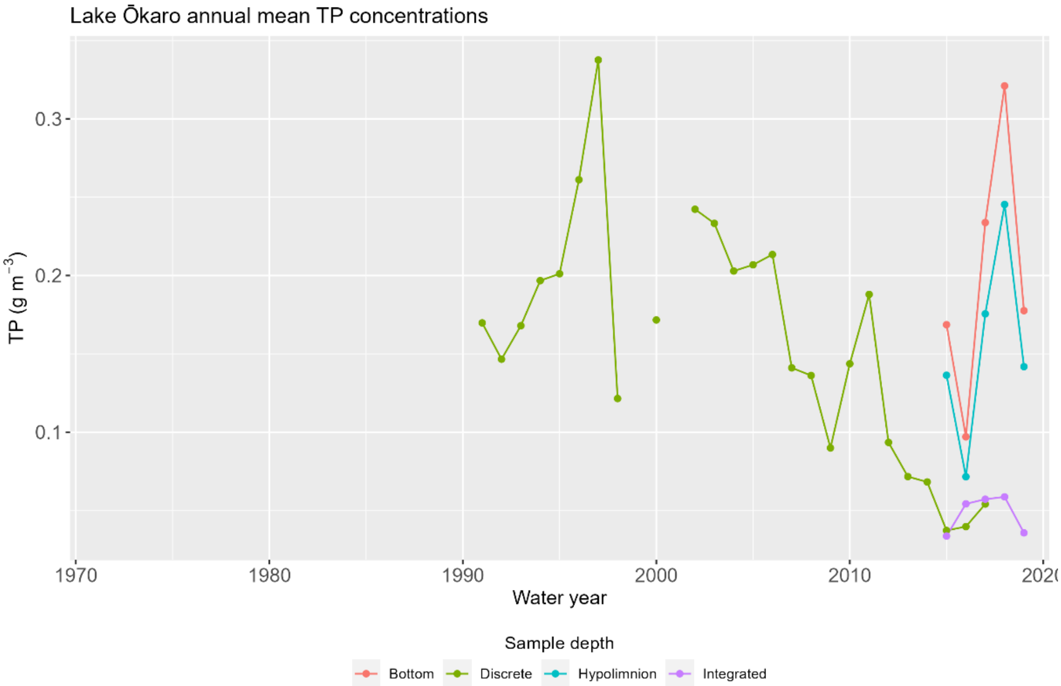
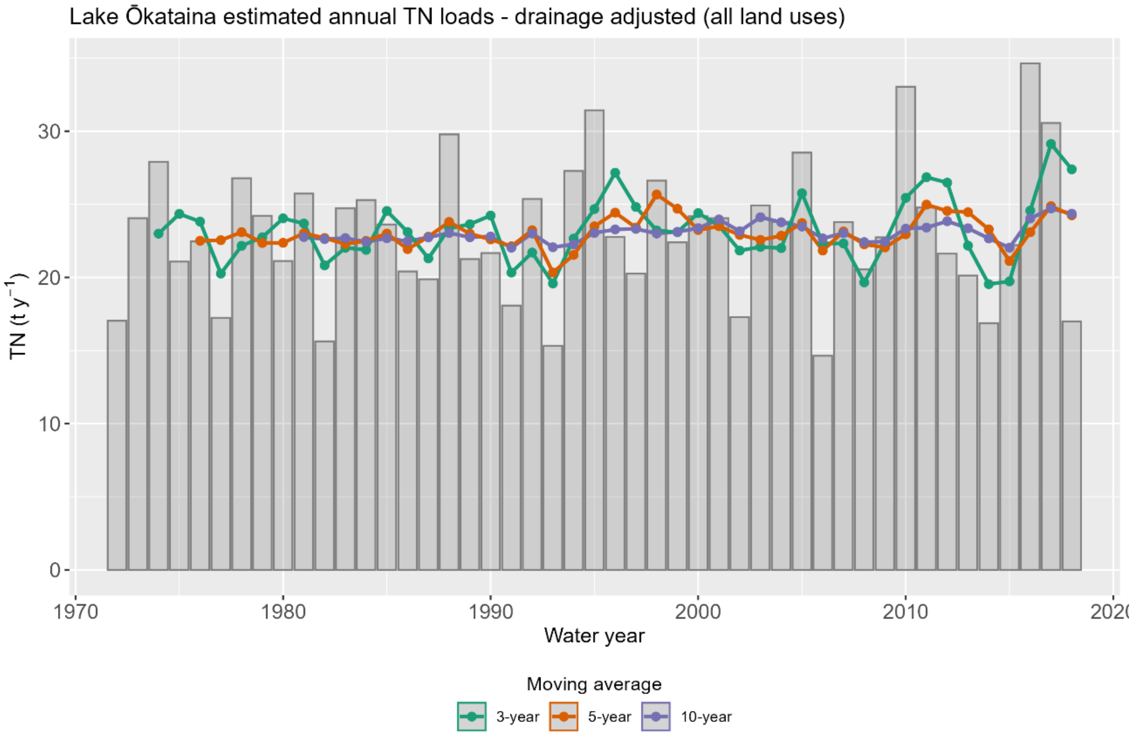


Figure D5

(a) Modelled load variation using best-estimate datasets and methods



(b) BOPRC lake monitoring data

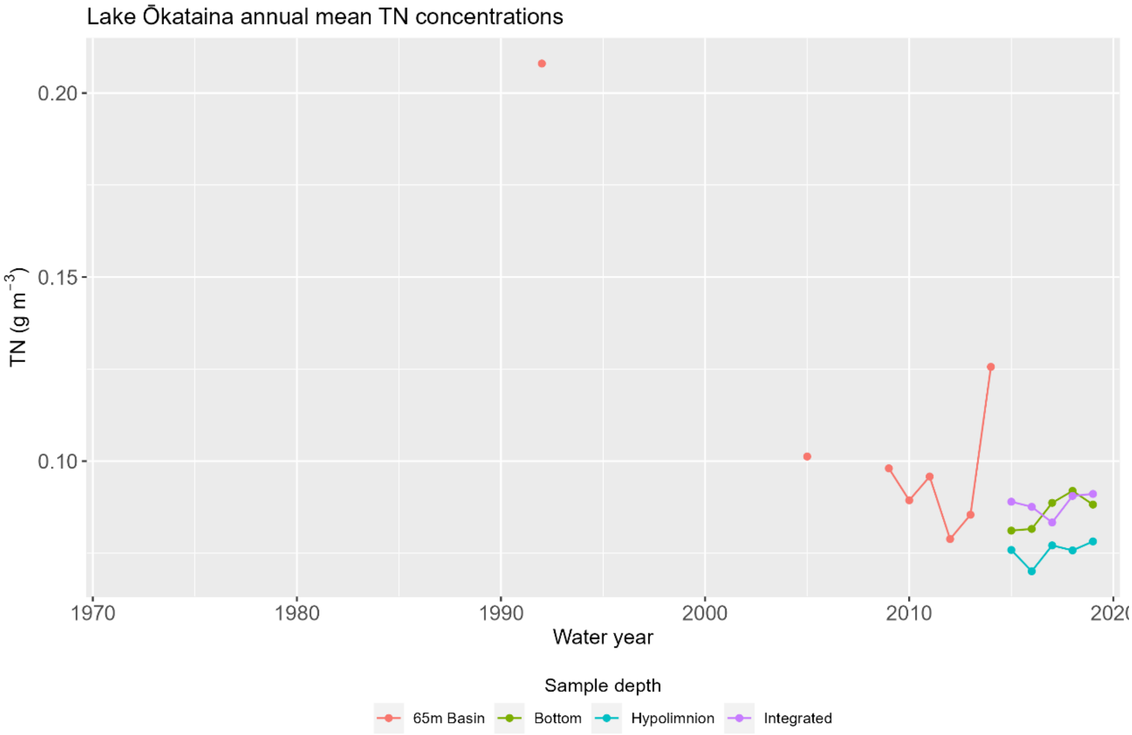
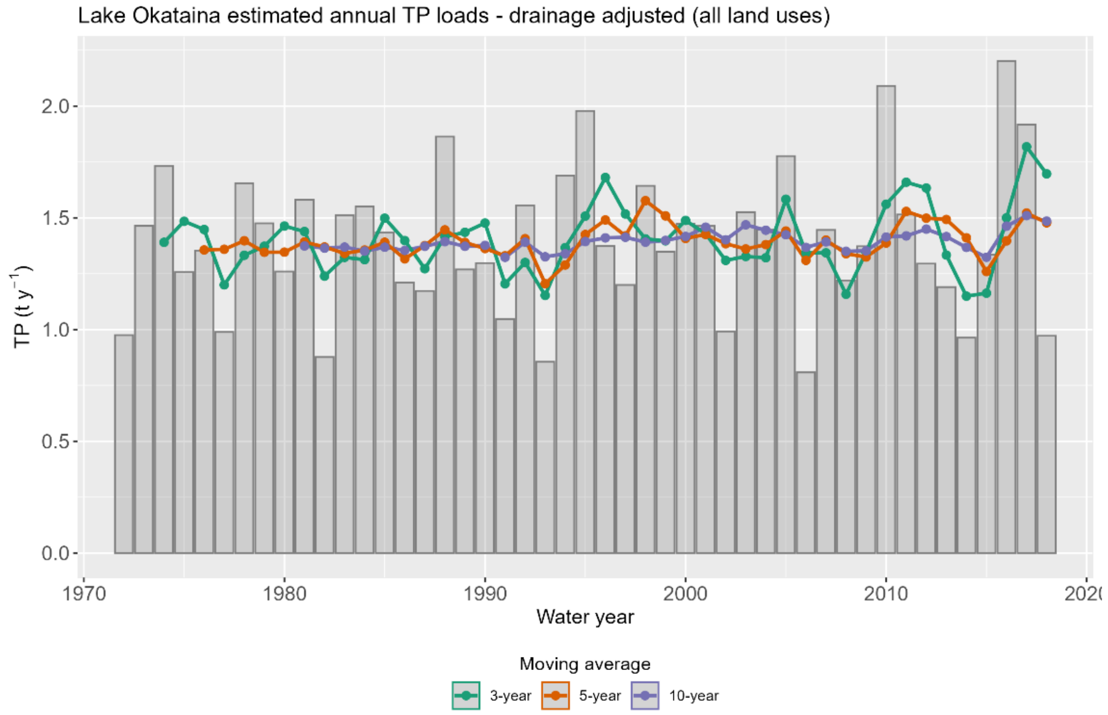


Figure D6

(a) Modelled load variation using best-estimate datasets and methods



(b) BOPRC lake monitoring data

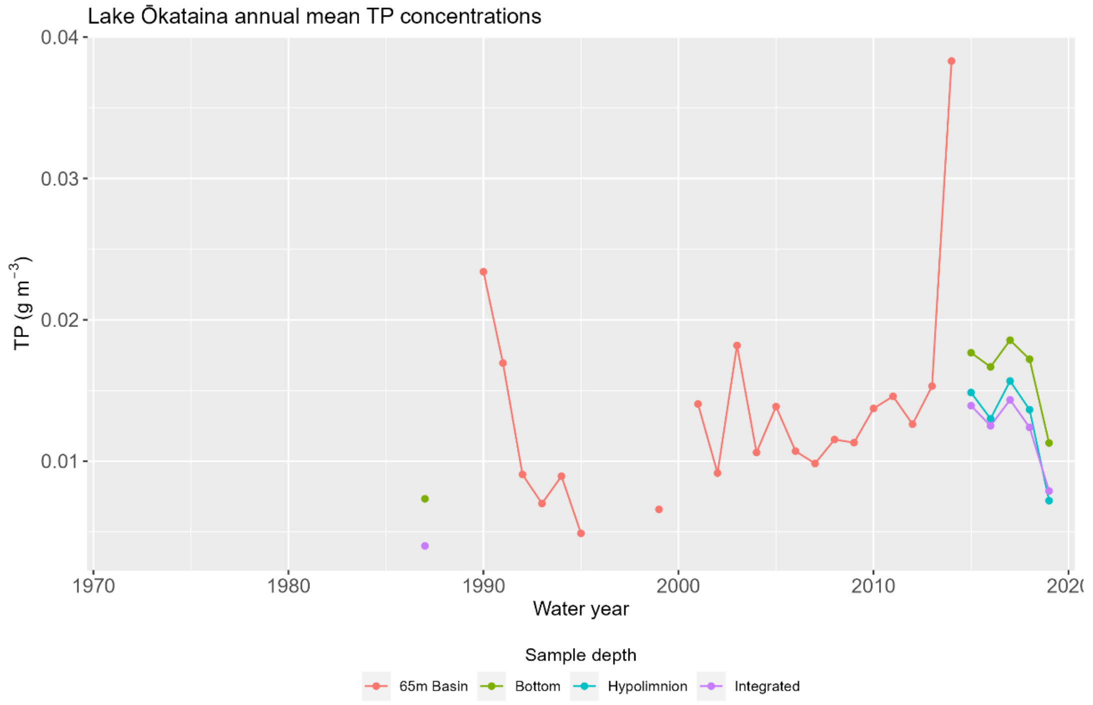
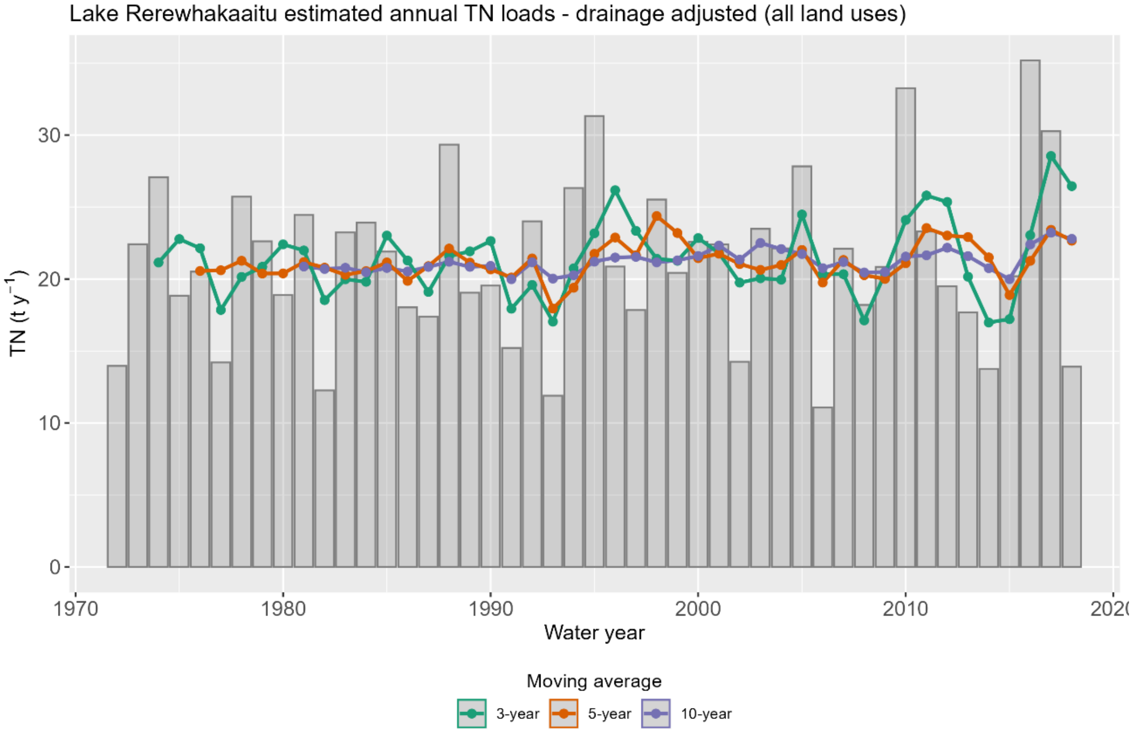


Figure D7

(a) Modelled load variation using best-estimate datasets and methods



(b) BOPRC lake monitoring data

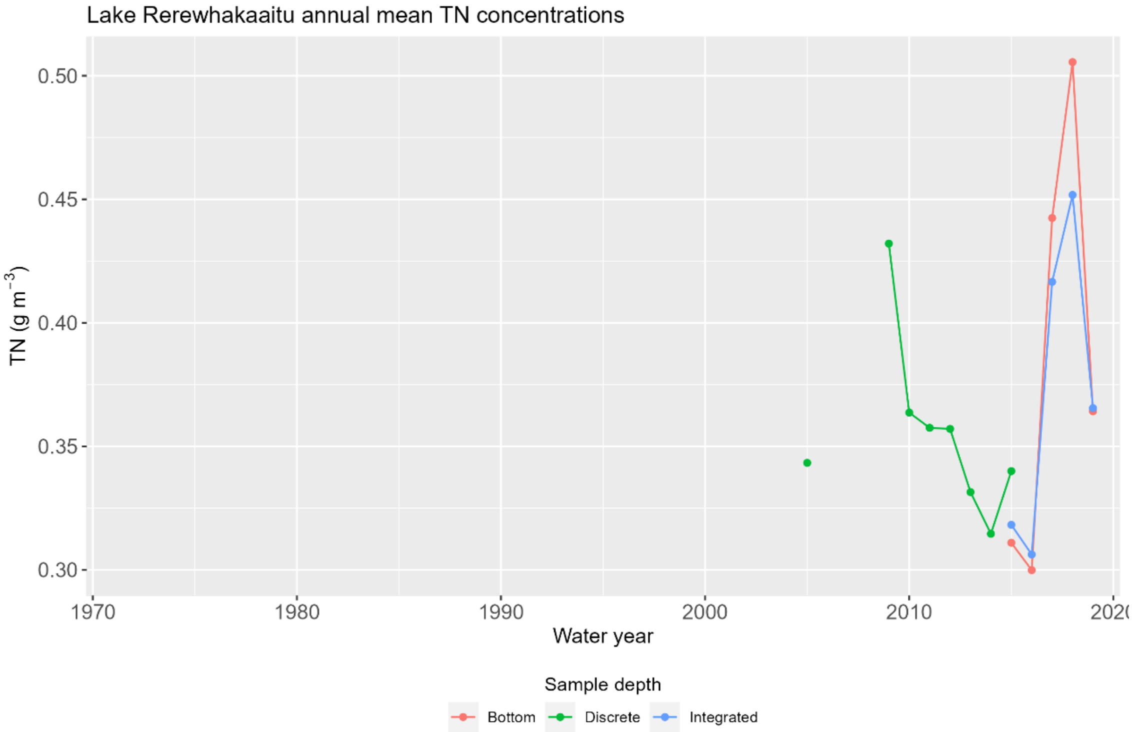
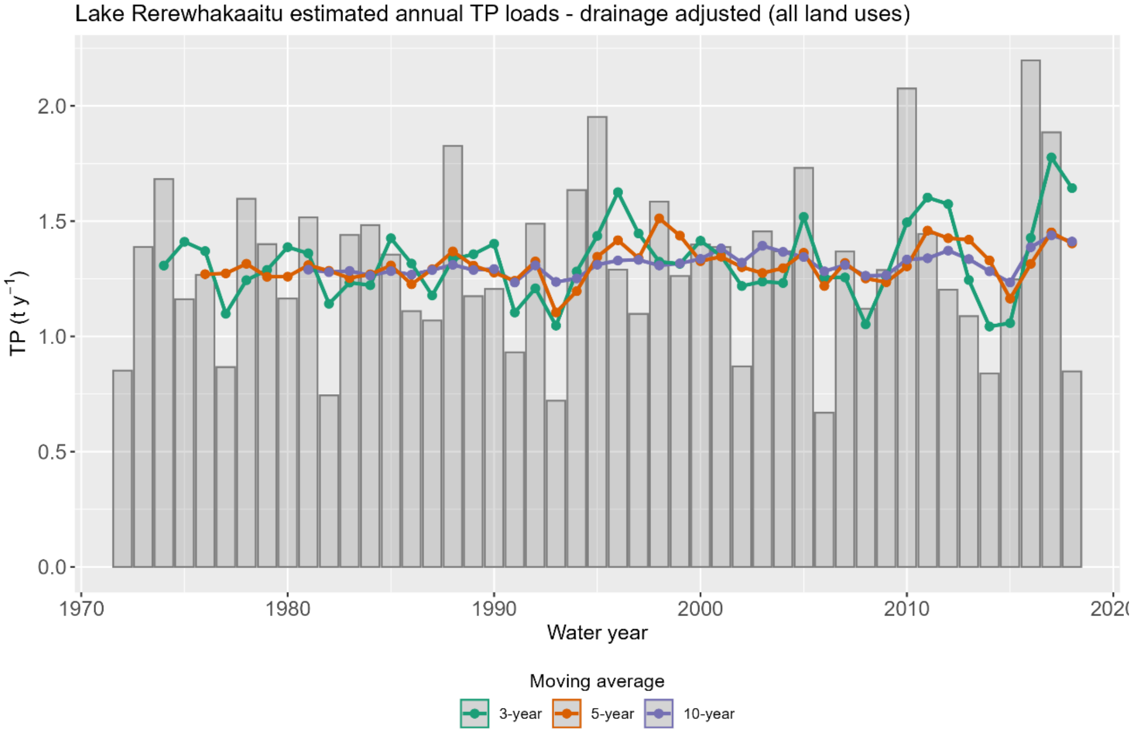


Figure D8

(a) Modelled load variation using best-estimate datasets and methods



(b) BOPRC lake monitoring data

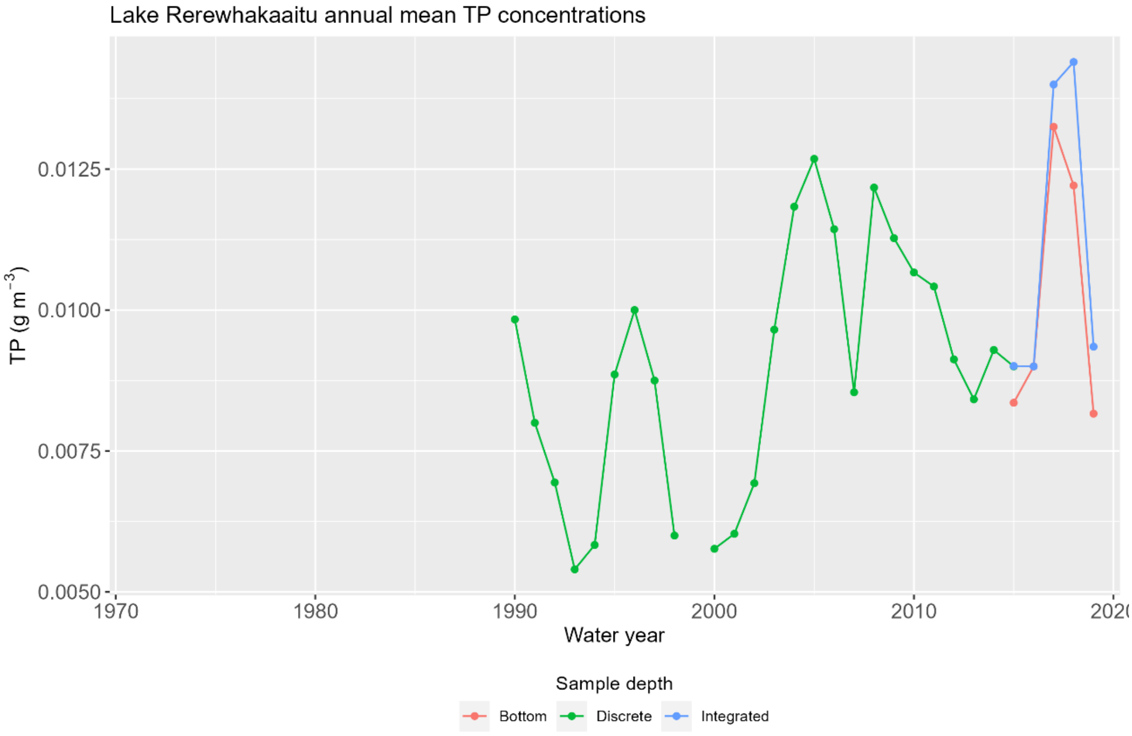
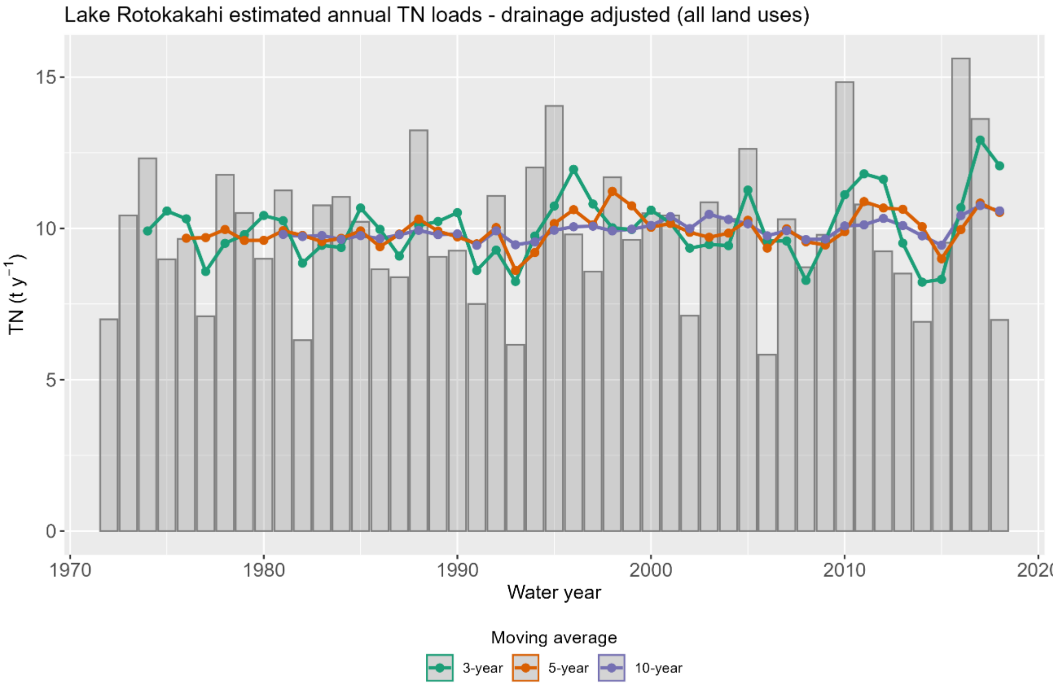


Figure D9

(a) Modelled load variation using best-estimate datasets and methods

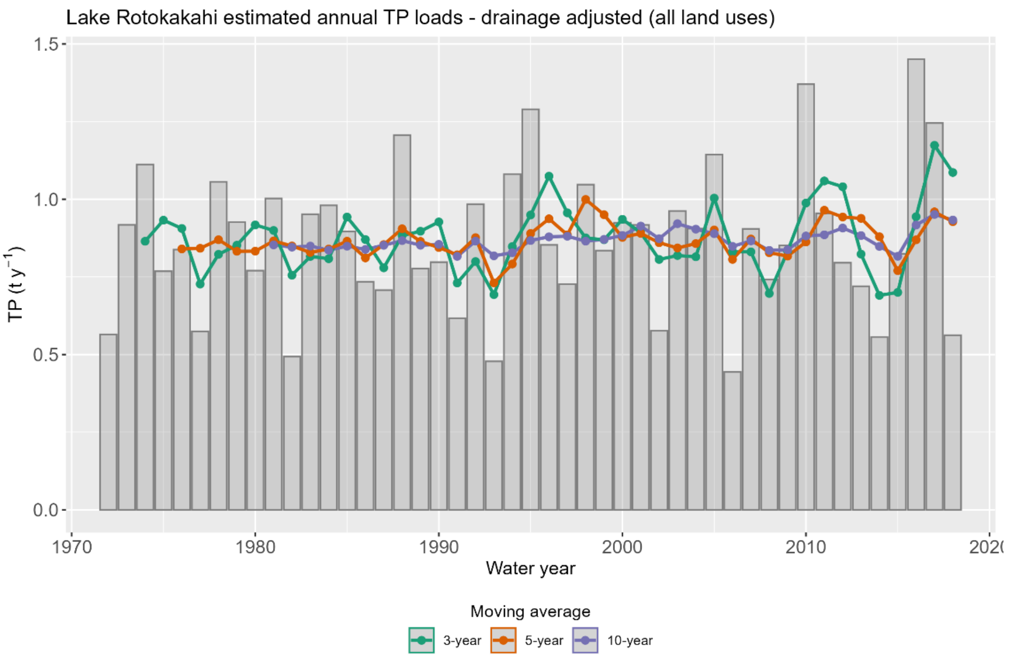


(b) BOPRC lake monitoring data

Not available for Lake Rotokakahi

Figure D10

(a) Modelled load variation using best-estimate datasets and methods

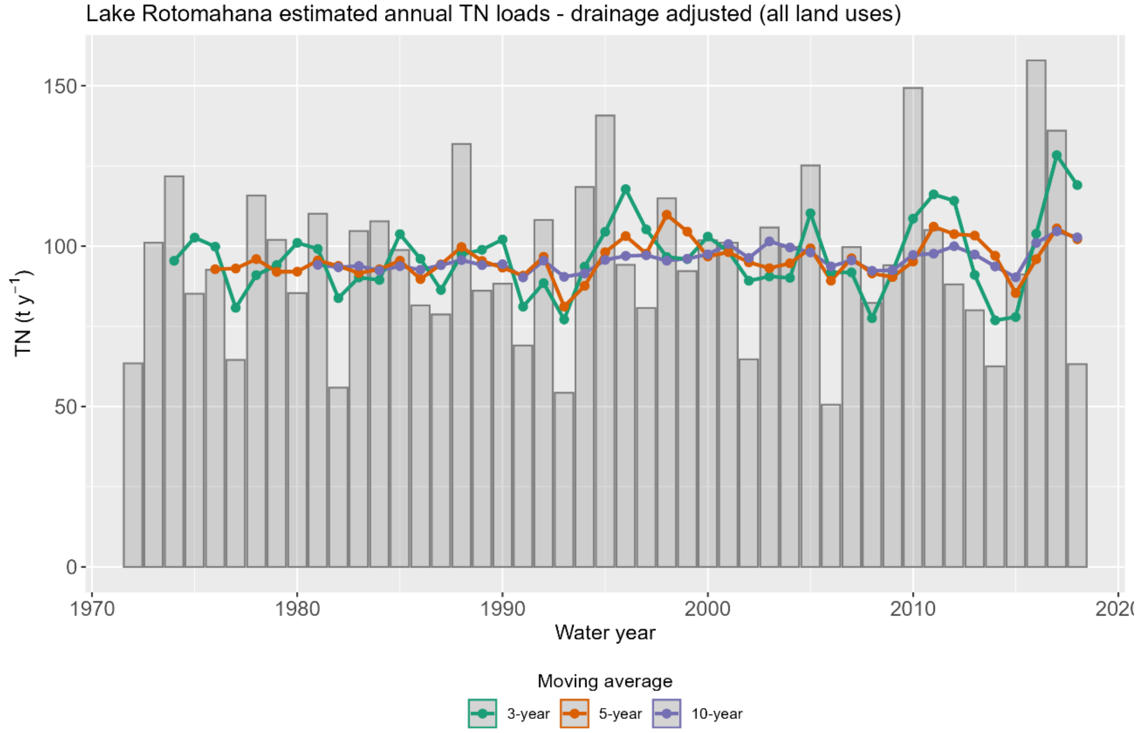


(b) BOPRC lake monitoring data

Not available for Lake Rotokakahi

Figure D11

(a) Modelled load variation using best-estimate datasets and methods



(b) BOPRC lake monitoring data

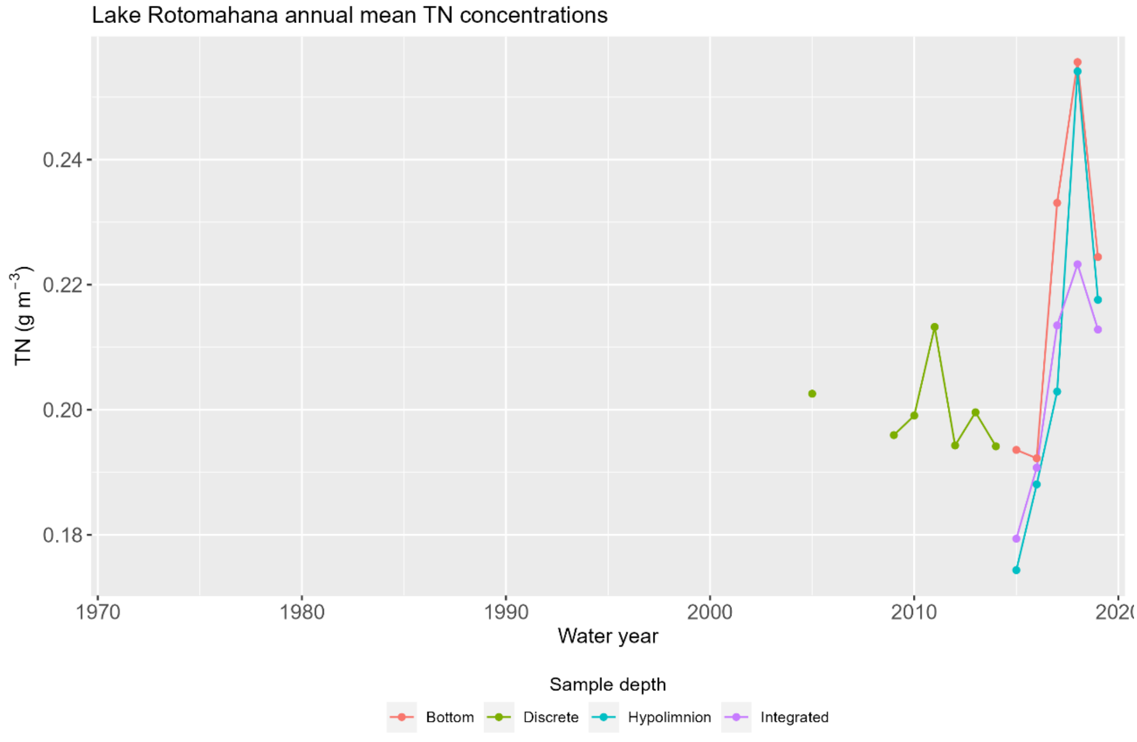
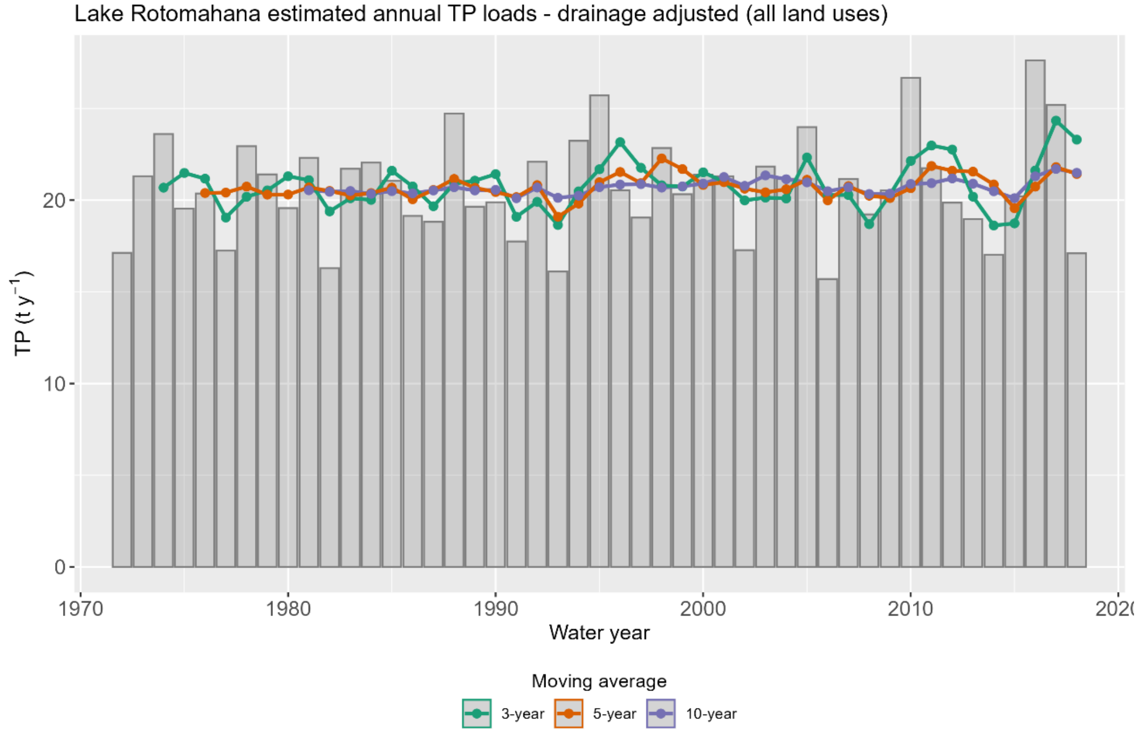


Figure D12

(a) Modelled load variation using best-estimate datasets and methods



(b) BOPRC lake monitoring data

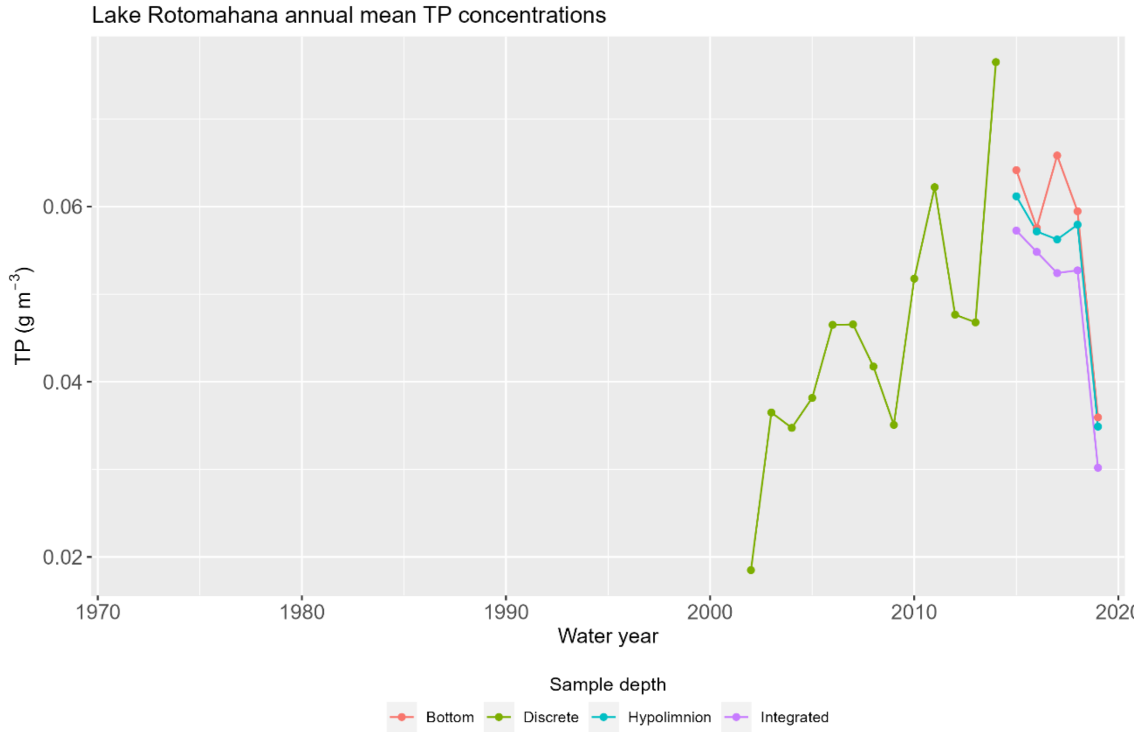
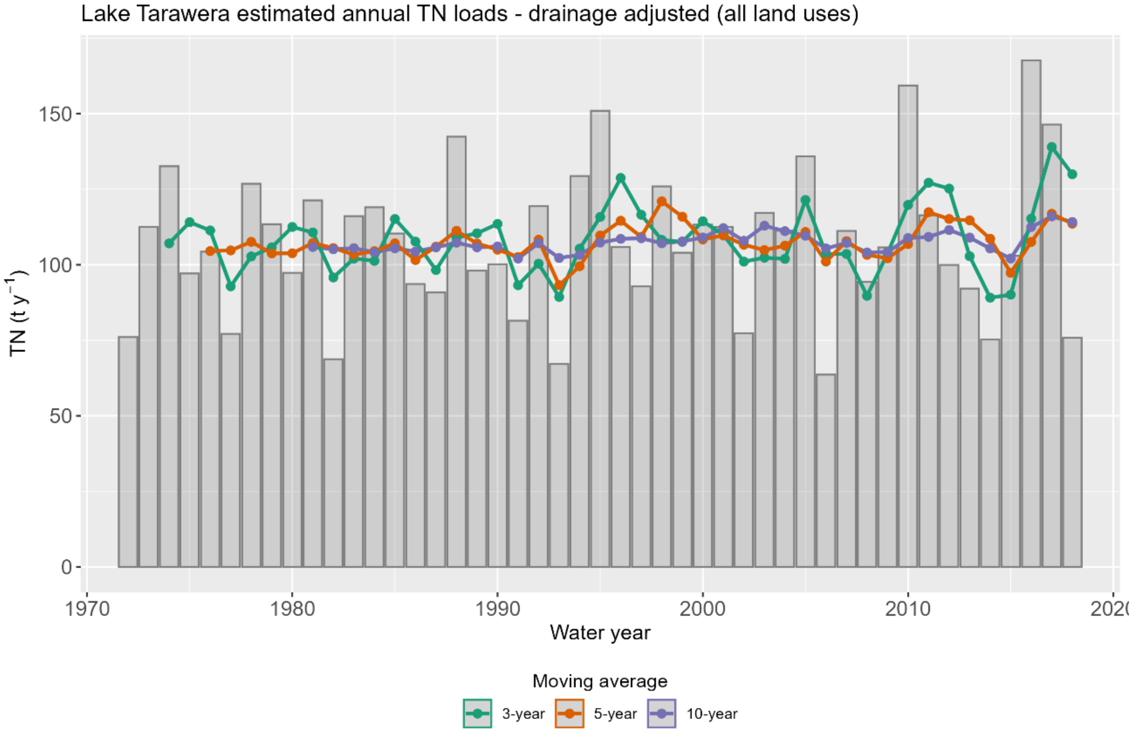


Figure D13

(a) Modelled load variation using best-estimate datasets and methods



(b) BOPRC lake monitoring data

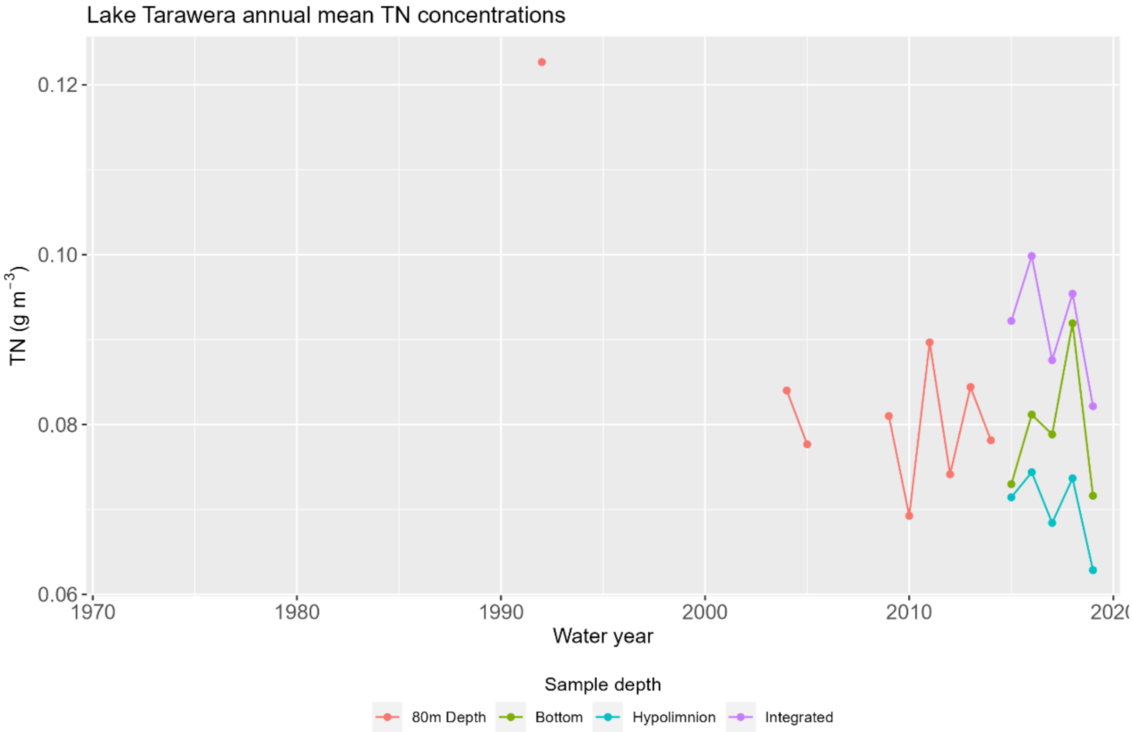
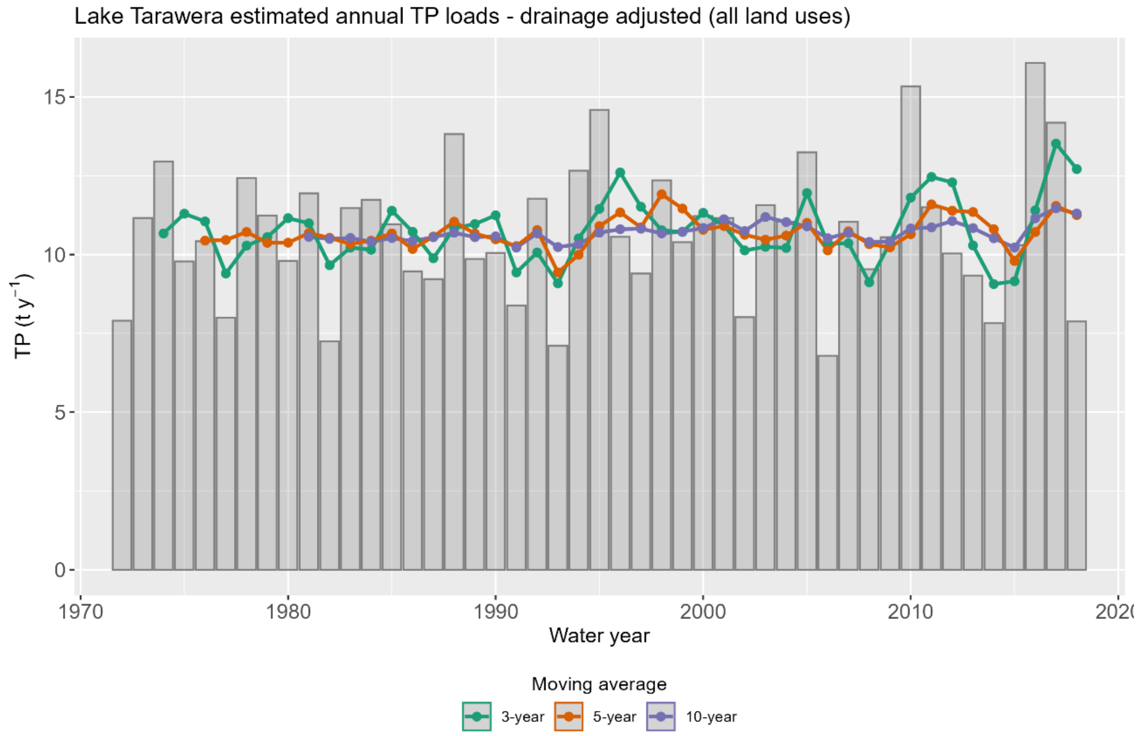


Figure D14

(a) Modelled load variation using best-estimate datasets and methods



(b) BOPRC lake monitoring data

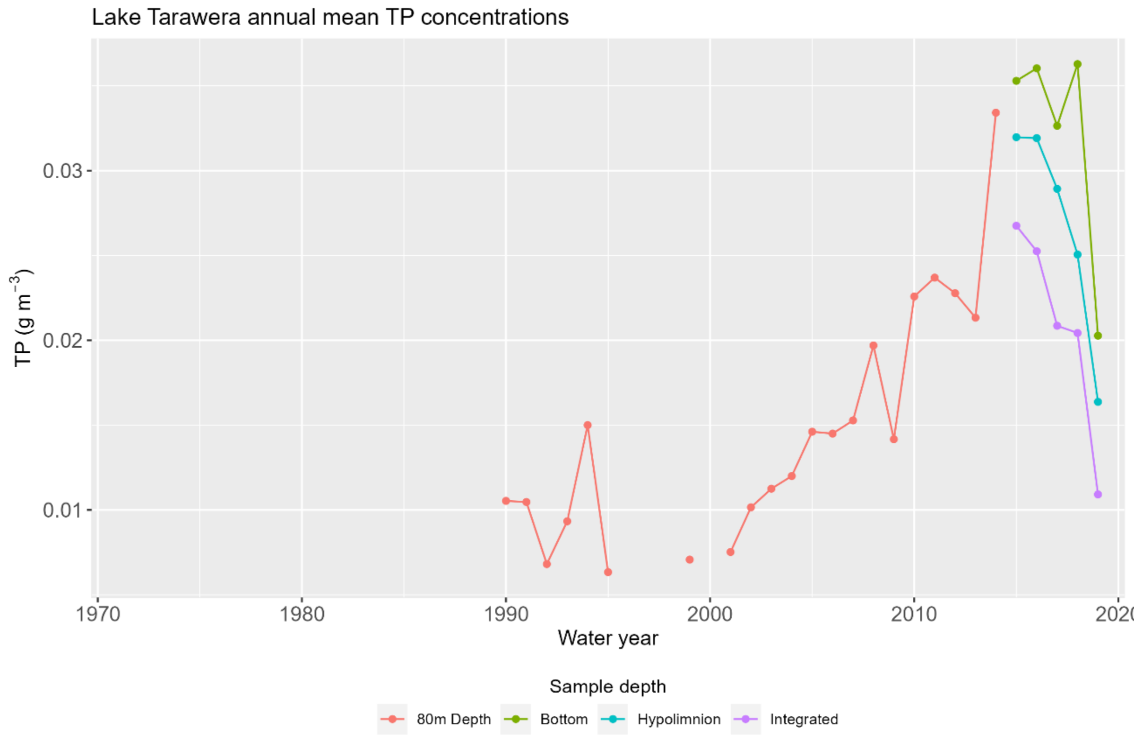
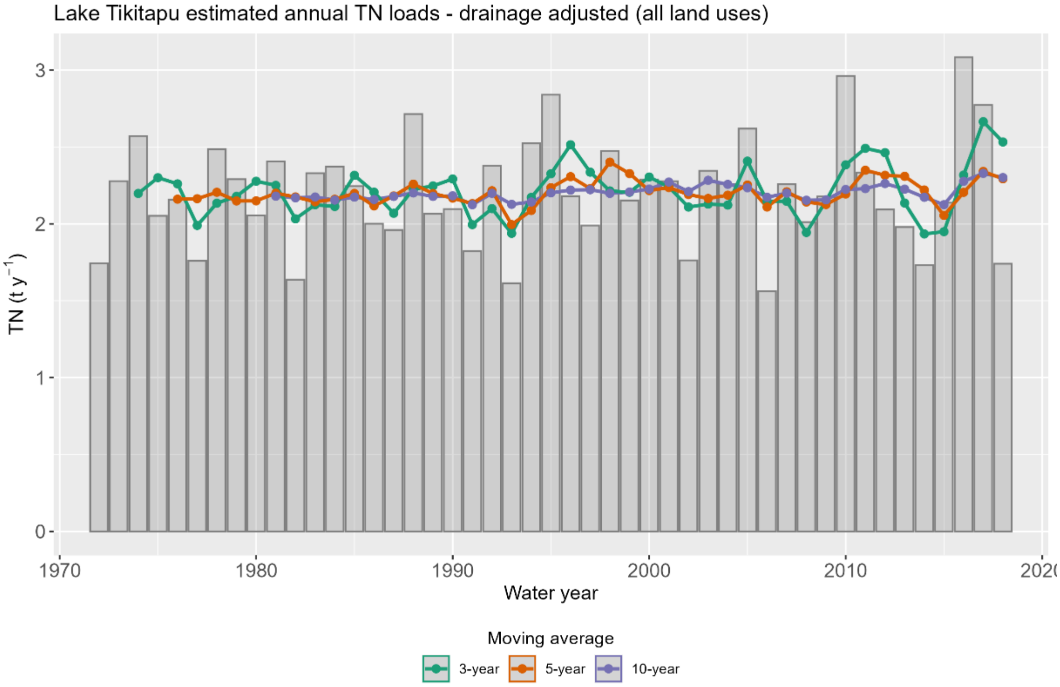


Figure D15

(a) Modelled load variation using best-estimate datasets and methods



(b) BOPRC lake monitoring data

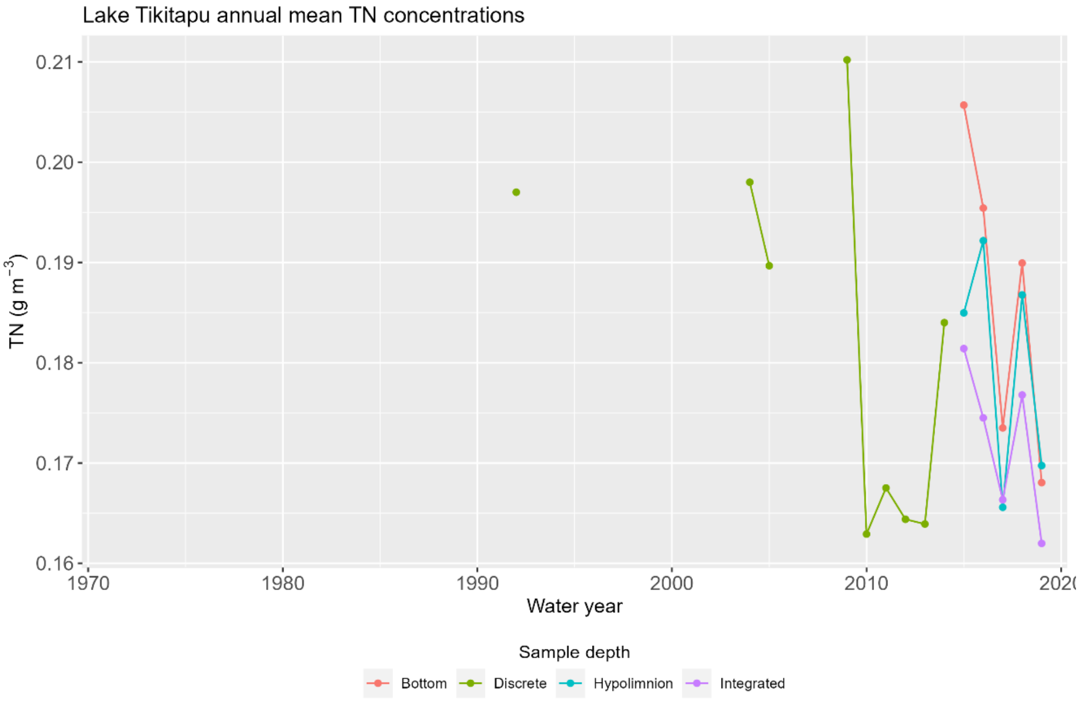
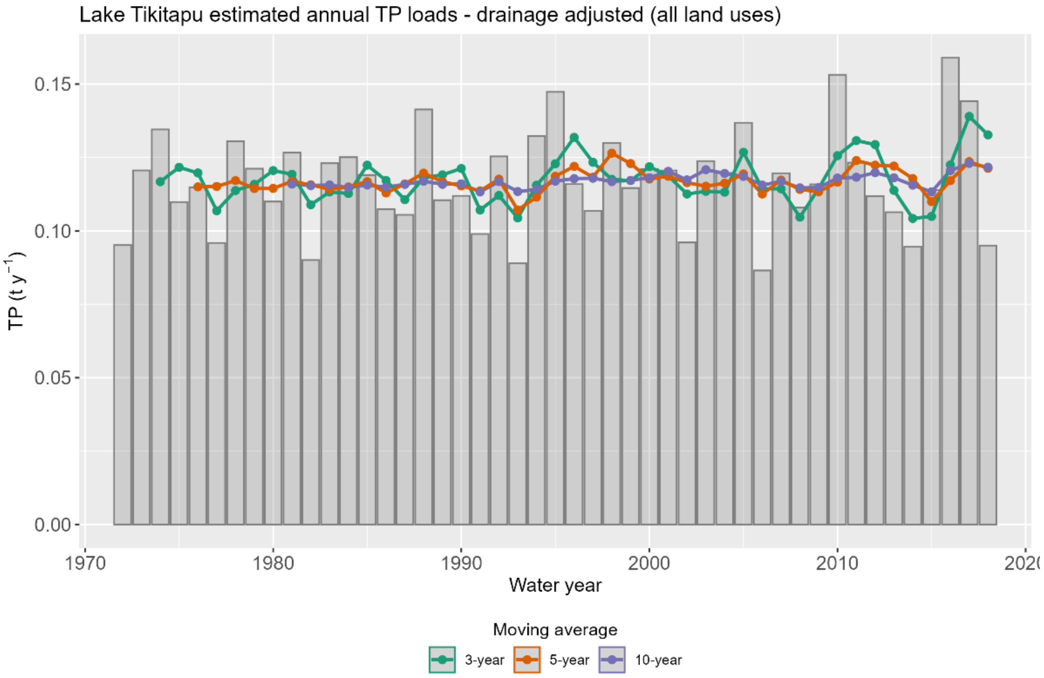


Figure D16

(a) Modelled load variation using best-estimate datasets and methods



(b) BOPRC lake monitoring data

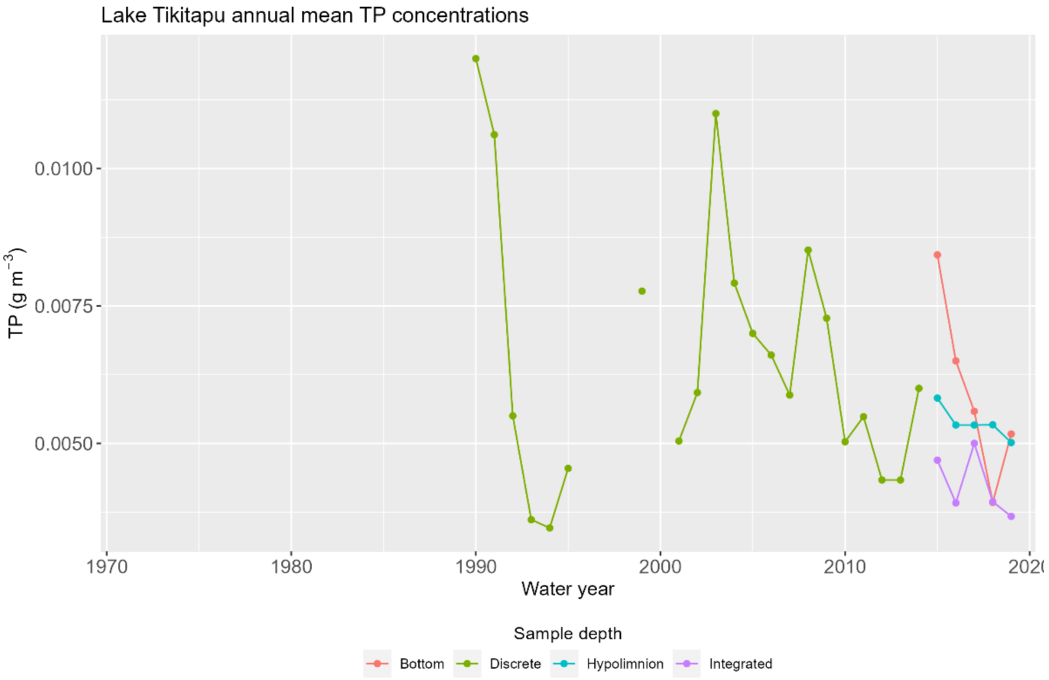


Table D9

Lake Ōkareka nutrient loads: land use scenarios Summary statistics (t y^{-1})	Nitrogen			Phosphorus		
	TN all native	TN current	TN all agriculture	TP all native	TP current	TP all agriculture
Mean	6.51	15.15	35.13	0.31	1.00	3.04
Median	6.53	15.20	35.25	0.31	1.01	3.05
95% CI lower limit	5.06	10.25	22.17	0.25	0.65	1.83
95% CI upper limit	7.87	20.43	47.20	0.37	1.38	4.40
Minimum	4.37	7.87	16.07	0.23	0.51	1.35
Maximum	9.53	25.47	62.05	0.41	1.70	5.43
Uncertainty and variability	± 46%	± 68%	± 77%	± 35%	± 70%	± 78%

Figure D17

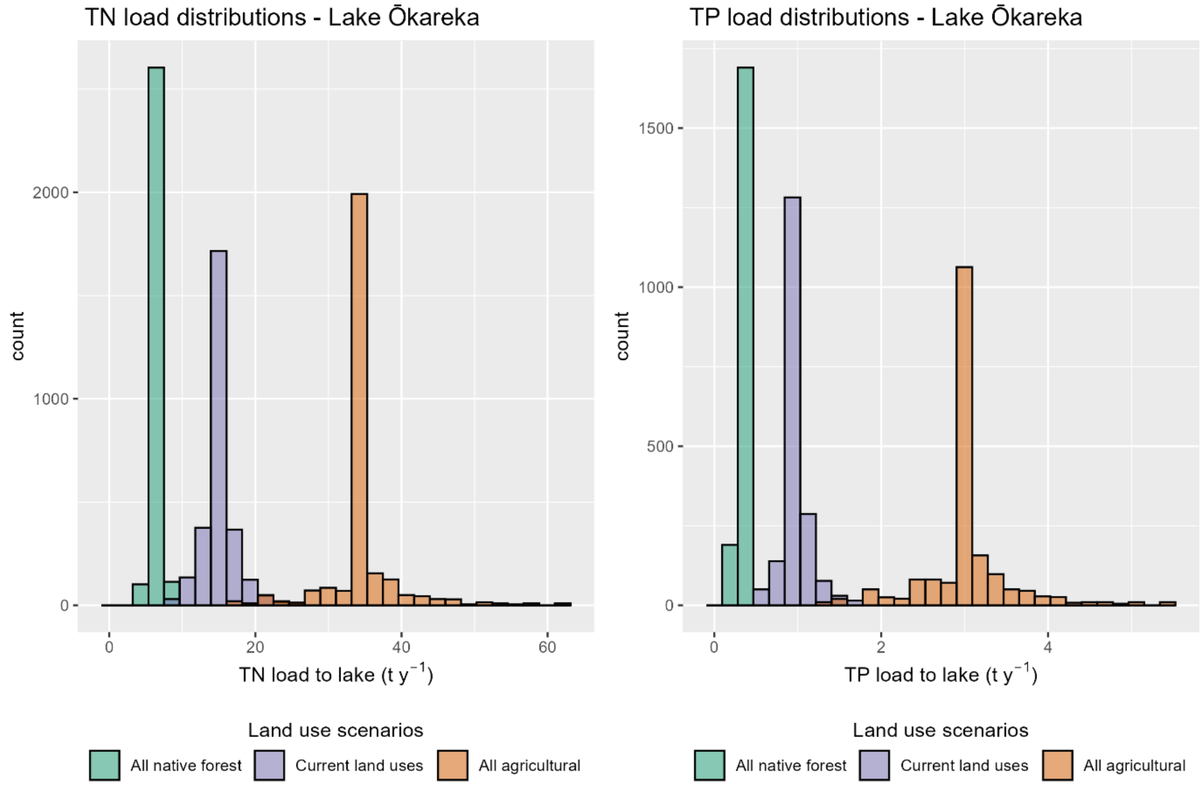


Table D10

Lake Ōkaro nutrient loads: land use scenarios

Summary statistics (t y^{-1})

	Nitrogen			Phosphorus		
	TN all native	TN current	TN all agriculture	TP all native	TP current	TP all agriculture
Mean	0.84	3.91	6.73	0.00	0.59	0.56
Median	0.84	3.90	6.72	0.00	0.59	0.56
95% CI lower limit	0.54	2.29	4.05	-0.01	0.33	0.31
95% CI upper limit	1.10	5.82	9.05	0.01	0.89	0.85
Minimum	0.40	1.66	2.82	-0.01	0.23	0.22
Maximum	1.45	7.05	12.21	0.02	1.11	1.05
Uncertainty and variability	± 73%	± 80%	± 81%	± 3300%	± 86%	± 86%

Figure D18

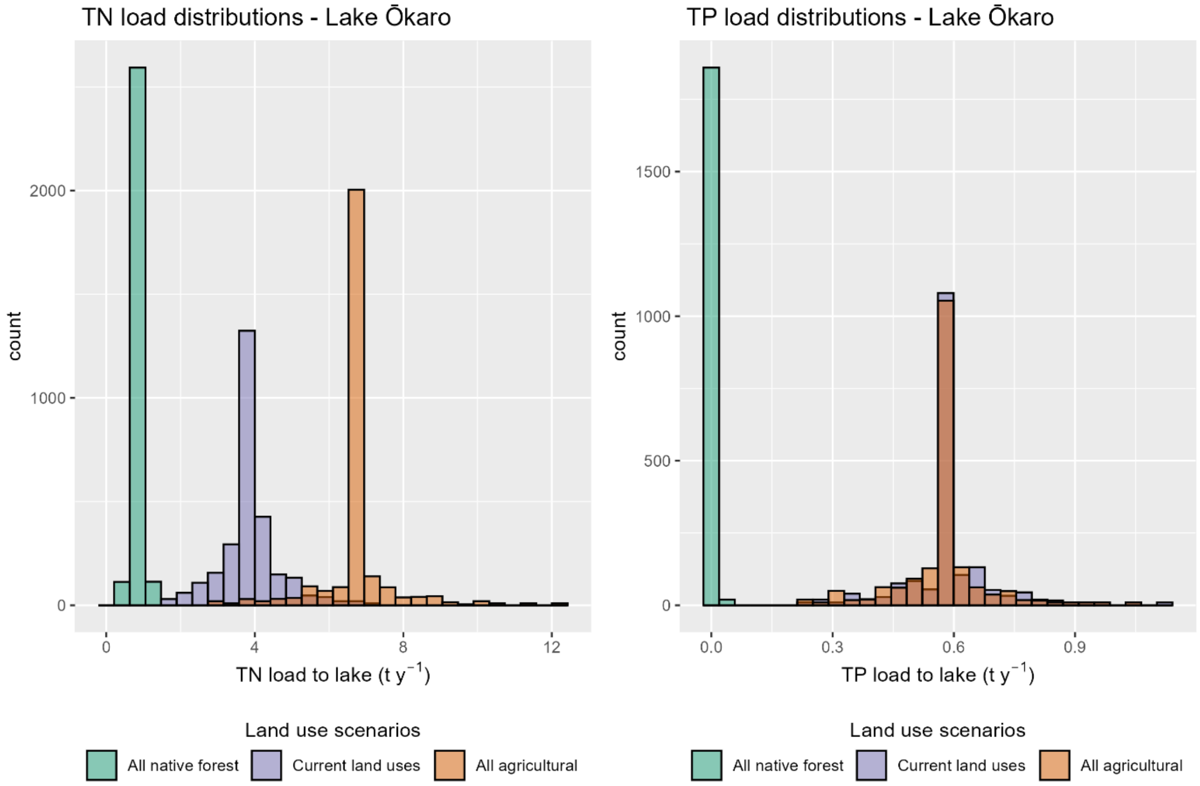


Table D11

Lake Ōkataina nutrient loads: land use scenarios

Summary statistics (t y^{-1})

	Nitrogen			Phosphorus		
	TN all native	TN current	TN all agriculture	TP all native	TP current	TP all agriculture
Mean	20.92	23.44	116.55	0.83	1.42	9.98
Median	21.06	23.45	117.81	0.84	1.43	10.09
95% CI lower limit	16.18	17.75	74.29	0.65	0.99	5.88
95% CI upper limit	25.18	28.53	154.52	1.03	1.88	14.42
Minimum	13.62	14.64	51.47	0.57	0.81	4.19
Maximum	31.70	36.32	212.58	1.21	2.30	18.51
Uncertainty and variability	± 52%	± 55%	± 82%	± 46%	± 62%	± 85%

Figure D19

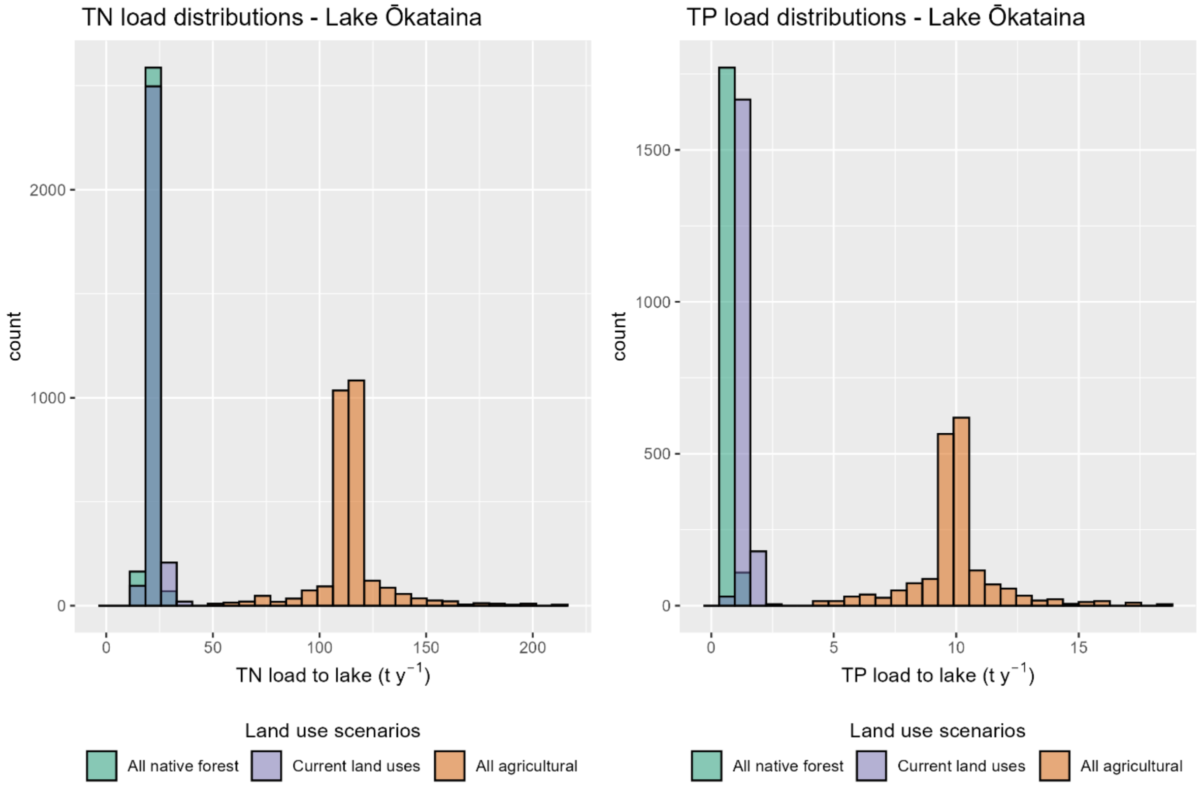


Table D12

Lake Rerewhakaaitu nutrient loads: land use scenarios

Summary statistics (t y^{-1})

	Nitrogen			Phosphorus		
	TN all native	TN current	TN all agriculture	TP all native	TP current	TP all agriculture
Mean	6.92	21.18	29.51	0.33	1.31	2.49
Median	6.93	21.15	29.62	0.33	1.31	2.49
95% CI lower limit	5.77	13.90	19.29	0.28	0.85	1.53
95% CI upper limit	7.98	29.43	38.92	0.37	1.83	3.55
Minimum	5.23	11.07	14.46	0.27	0.67	1.15
Maximum	9.31	35.30	50.78	0.41	2.20	4.37
Uncertainty and variability	± 34%	± 67%	± 72%	± 26%	± 68%	± 76%

Figure D20

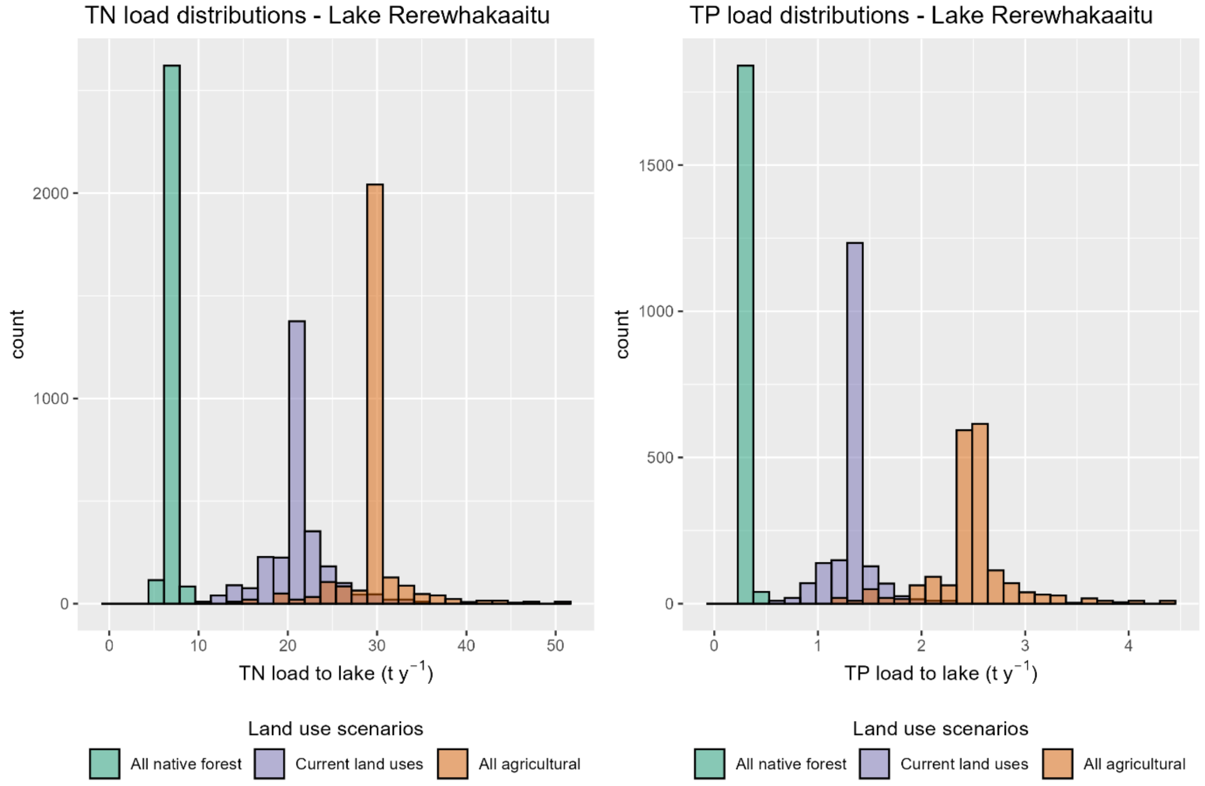


Table D13

Lake Rotokakahi nutrient loads: land use scenarios Summary statistics (t y^{-1})	Nitrogen			Phosphorus		
	TN all native	TN current	TN all agriculture	TP all native	TP current	TP all agriculture
Mean	6.98	9.90	32.99	0.29	0.86	2.78
Median	6.98	9.89	32.94	0.29	0.86	2.77
95% CI lower limit	5.37	7.11	20.90	0.23	0.56	1.67
95% CI upper limit	8.38	12.66	43.47	0.36	1.20	4.04
Minimum	4.62	5.82	15.31	0.21	0.44	1.23
Maximum	10.28	15.61	57.76	0.40	1.45	4.94
Uncertainty and variability	± 47%	± 58%	± 75%	± 39%	± 68%	± 78%

Figure D21

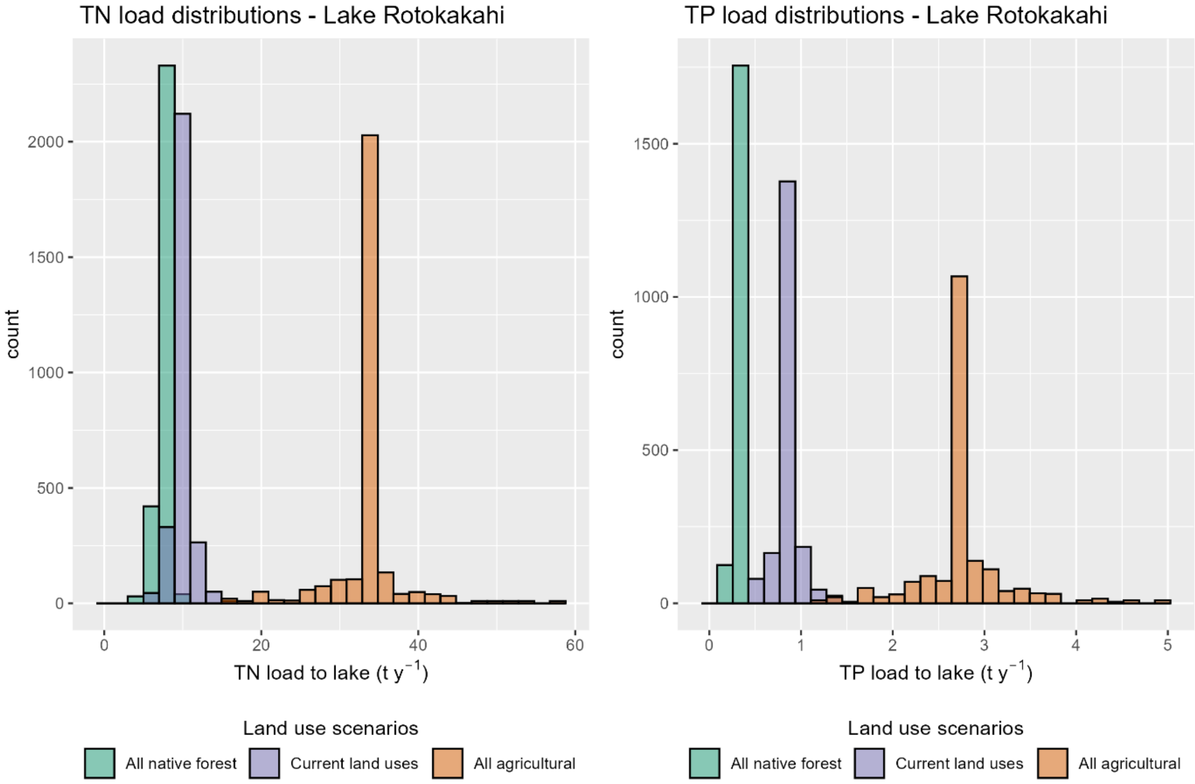


Table D14

Lake Rotomahana nutrient loads: land use scenarios

Summary statistics (t y^{-1})

	Nitrogen			Phosphorus		
	TN all native	TN current	TN all agriculture	TP all native	TP current	TP all agriculture
Mean	39.79	95.49	170.25	12.99	20.68	25.47
Median	39.76	95.28	169.98	12.98	20.66	25.43
95% CI lower limit	31.58	63.45	109.48	12.67	17.11	19.86
95% CI upper limit	46.98	131.87	223.46	13.35	24.73	31.82
Minimum	27.79	50.60	81.38	12.54	15.70	17.67
Maximum	56.61	158.12	294.69	13.60	27.65	36.36
Uncertainty and variability	± 42%	± 66%	± 73%	± 5%	± 34%	± 43%

Figure D22

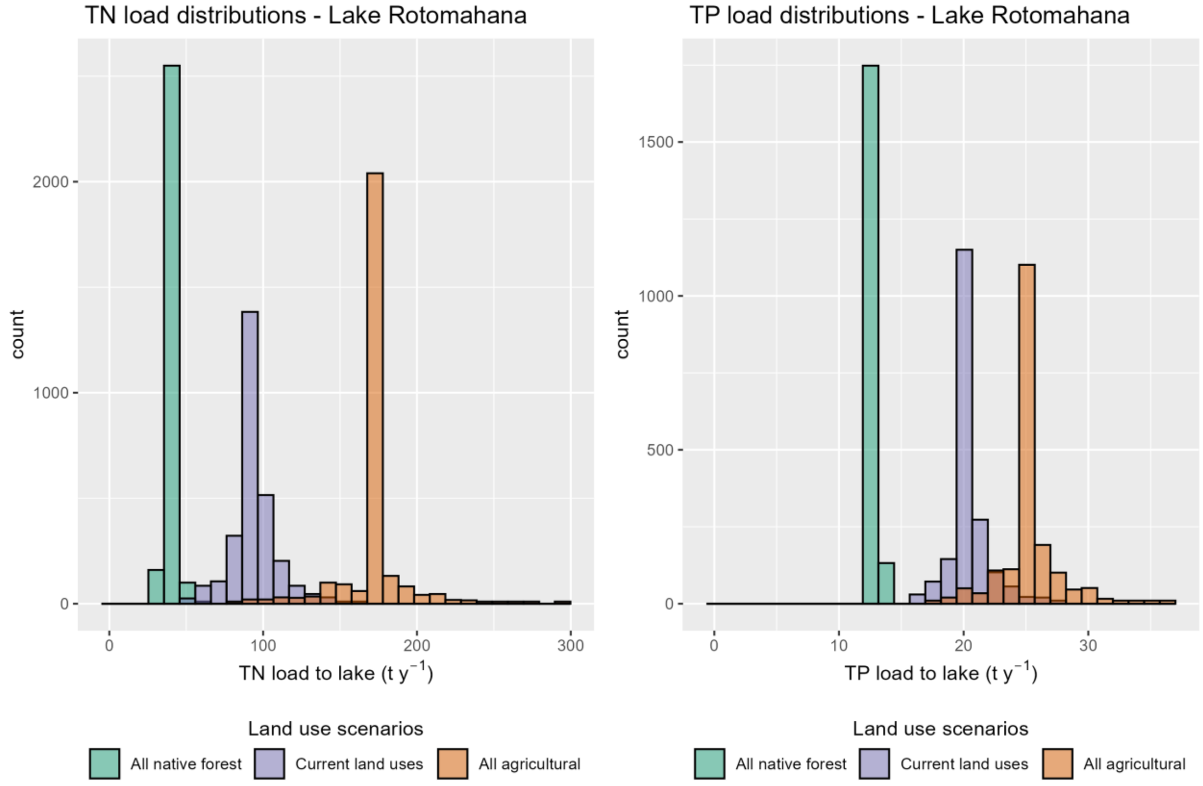


Table D15

Lake Tarawera nutrient loads: land use scenarios

Summary statistics (t y^{-1})

	Nitrogen			Phosphorus		
	TN all native	TN current	TN all agriculture	TP all native	TP current	TP all agriculture
Mean	79.70	106.89	262.17	7.41	10.65	24.87
Median	79.65	106.82	262.08	7.40	10.65	24.84
95% CI lower limit	61.03	77.19	169.81	6.00	7.88	16.08
95% CI upper limit	97.45	135.08	350.09	9.00	13.79	34.80
Minimum	52.41	63.53	127.25	5.45	6.78	12.60
Maximum	117.95	167.63	451.48	10.14	16.08	42.02
Uncertainty and variability	± 48%	± 57%	± 72%	± 37%	± 51%	± 69%

Figure D23

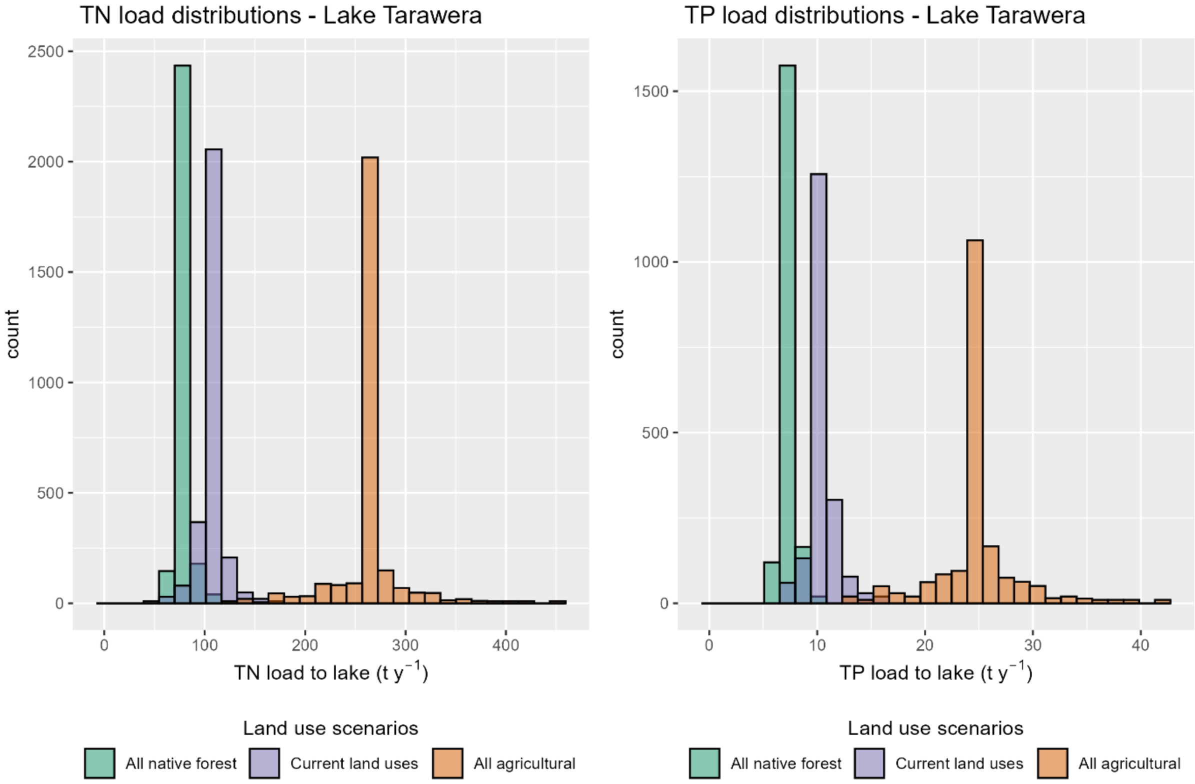


Table D16

Lake Tikitapu nutrient loads: land use scenarios

Summary statistics (t y^{-1})

	Nitrogen			Phosphorus		
	TN all native	TN current	TN all agriculture	TP all native	TP current	TP all agriculture
Mean	2.08	2.19	9.65	0.10	0.12	0.82
Median	2.08	2.19	9.68	0.10	0.12	0.83
95% CI lower limit	1.69	1.76	6.22	0.09	0.10	0.50
95% CI upper limit	2.43	2.59	12.78	0.12	0.14	1.18
Minimum	1.51	1.56	4.61	0.08	0.09	0.38
Maximum	2.88	3.08	16.76	0.13	0.16	1.46
Uncertainty and variability	± 38%	± 41%	± 74%	± 28%	± 36%	± 77%

Figure D24