Lake Horowhenua Water Balance Assessment and Quantification of Uncertainties – 2019 Update

October 2019

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Horizons Regional Council

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1.0 Introduction

The Horowhenua Groundwater Management Zone is located in the south-west of the Horizons region and includes a number of surface water bodies that are dependent (in part) on groundwater to maintain flows in the tributary streams and levels within the lakes. The geological structure of the area means that groundwater and surface water are likely to be closely linked, however the exact contribution of groundwater to surface water bodies is poorly defined. This particularly applies to Lakes Horowhenua and Papaitonga and the groundwater fed streams that flow into the lakes.

This report provides an update to our previous report provided in 2014. Since 2014, further information regarding water use has become available and additional consents have been issued in the area, to authorise existing abstractions that had not been consented. This additional information is expected to provide a more accurate picture of the effect of groundwater abstraction on the lake water balance. In addition, some further information is available regarding surface water inflows to the lake.

A variety of water balances have been developed for the area prior to the 2014 PDP assessment, either focussing exclusively on Lake Horowhenua (Gibbs and White 1994), or providing water balances for the wider Horowhenua Groundwater Management Zone (Phreatos 2005) and (White, Raiber and Meihac, et al. 2010)) with specific assessments for Lake Horowehenua. None of these water balance estimates are consistent with one another particularly in terms of defining the groundwater proportion of lake inflows. Such inconsistency serves to highlight the uncertainty the water balance estimates.

Understanding the water balance and sources of inflows to the lakes is crucial to their successful management to ensure their long term health. The purpose of this report is to investigate the uncertainty within the various water balances and provide some quantification of the range of values possible for each component. In particular, the relative effect of current rates of groundwater abstraction within the Lake Horowhenua catchment on the groundwater component of the water balance for the lake is assessed.

Section 2 of this report describes the conceptual hydrogeological setting of Lake Horowhenua, and Section 3 details each of the different water balance components, in terms of the range of possible values and uncertainties. Section 4 recommends work to refine the water balance and the effects of groundwater abstraction on lake inflows is presented in Section 5. An interim framework for managing groundwater abstraction in the area is outlined in Section 6. Section 7 provides a summary and conclusions.

A map showing the location of Lake Horowhenua within the wider Horowhenua Groundwater Management Zone is provided in Figure 1, together with other key hydrological features.

2.0 Conceptual Hydrogeological Setting

The conceptual hydrogeological setting for Lakes Horowhenua and Papaitonga is relatively well established and largely governed by the underlying geological structure of the area.

Several previous reports have documented the geology of the area, which is shown in Figure 2. The key structure with regards to groundwater flow is the Levin Fault / Poroutawhao High, which runs approximately parallel to the coast just west of Lake Horowhenua. The lateral extent of this structure, where low permeability basement greywackes have been uplifted towards the groundwater seems open to some debate; the original fault trace extended some distance south of Lake Horowhenua (Phreatos 2005) but more recent work (White, Raiber and Della Pasqua, et al. 2010) seems to indicate that the area of significantly elevated basement strata only extends to the southern edge of Lake Horowhenua (Figure 3). Whilst these interpretations are not inconsistent (the fault trace may extend further south, but uplifted strata are further below the surface), they both have the same important implications regarding groundwater flow and the water balance for the areas of the lakes.

Figure 4 presents a conceptual figure of groundwater flow, based on a cross section line extending approximately from the Tararua Ranges in the east, through Lake Horowhenua and to the coast in the west. The figure indicates that groundwater in the area is recharged largely via rainfall (less evapotranspiration) with some additional recharge as seepage loss from rivers that occur in the east of the area as they emerge from the ranges. Groundwater flows westwards towards the coast and in the east of the area, close to the foot of the Tararua Ranges, the vertical hydraulic gradient is downwards. However, as westward flowing groundwater approaches the low permeability strata that make up the Poroutawhao High / Levin Fault it is forced upwards, resulting in the increasing groundwater pressures with depth (i.e. an upwards vertical gradient) observed in bores around Levin township. As deep groundwater is forced upwards it discharges into the shallow strata, which subsequently discharges into the lakes and the spring fed streams that flow into the lakes.

The extent to which low permeability basement strata is elevated by the Levin Fault does have an impact on groundwater flow as it will limit the proportion of deeper groundwater that can continue to flow westwards. Where the basement high is relatively deep, groundwater will be able to flow westwards without discharging into the lakes, but where the basement high occurs close to the ground surface, it will effectively block the majority of groundwater flow, forcing a large proportion of deeper groundwater to discharge into the shallow strata and subsequently into the lake.

As noted above, there is some uncertainty regarding the levels and elevation of the basement high. Consequently, this introduces uncertainty into the water balance assessments for the lakes because there is an unknown proportion of groundwater that may exit the groundwater catchment for the lakes as throughflow to the west.

3.0 Water Balance Assessments

A series of water balance assessments for Lake Horowhenua, and also for the wider groundwater management zone have been undertaken at several points in the past, including work by:

- Gibbs (1994), which included a water balance model and nutrient model of the lake inputs and outputs;
- Phreatos (2005), which covered a groundwater modelling study of the Horowhenua Groundwater Management Zone (GWMZ), including a water balance assessment of Lake Horowhenua; and
- GNS (2010), which involved a water balance study of the whole Horowhenua GWMZ, including Lake Horowhenua.

A summary of each of these three water balances is provided in Table 1 and a conceptual plan showing each of the water balance components is provided in Figure 5.

Table 1: Summary water balances (Lake Horowhenua)

Water balance component	Inputs (x 10^6 m^3/yr)			Outputs (x 10^6 m^3/yr		
	Gibbs	Phreatos	GNS	Gibbs	Phreatos	GNS
Rainfall (direct to lake)	3.32	3.2	3			
Urban runoff	*5.09*	*2.9*	-			
Rural runoff	-	*5.9*	-			
Total stream flows	*8.57*[1]	-	*27.6*[1]			
Total surface water inflows	13.66	8.8[2]	27.6[1]			
Direct groundwater discharge into lake	12.85	16[3]	6.9			
Evaporation from lake surface				2.34	2	2.2
Groundwater seepage from the lake				1.44		
Lake discharge into Hokio Stream				26.05	26	35.3
Total	**29.83**	**28**	**37.5**	**28.39**	**28**	**37.5**
Groundwater proportion of lake inflow:	43%	57%	70 %			

Notes:
1. Includes groundwater fed baseflow within the streams that flow into the lake
2. Excludes groundwater fed baseflow in streams draining into the lake
3. Includes groundwater fed baseflow in streams as well as direct groundwater discharge

Sections 3.1 to 3.7 discuss each of the water balance components in more detail including an assessment of the uncertainty within the long term average value of each component.

3.1 Inputs: Direct rainfall

Rainfall direct to the lake in all three studies has been derived based on an average annual rainfall value applied across the surface area of the lake (2.9 km^2). Neither the Gibbs nor Phreatos studies provide the source of their rainfall estimates but Gibbs indicates that average annual rainfall is 1,095 mm/year and Phreatos indicates that average annual rainfall is very similar (1,100 mm/year). GNS indicates that the source of their annual rainfall estimate is from a NIWA model, which indicates a mean annual rainfall of 1,113 mm/year. These are all very consistent values, and given that all three studies took place over different time periods, this consistency indicates that rainfall direct to the lake has not varied significantly.

The closest rainfall station to the lake is the Levin AWS station, which is currently operated by MetService. The record at this station extends from October 1991 to the present day and a copy of the annual total rainfall record up to 2014 is shown in Figure 6. Based on that data, the total annual average rainfall is approximately 1,065 mm/year, although from Figure 6 it is likely that this value is skewed by higher rainfall years, particularly prior to 2000 (i.e. between 1991 and 1998). The average annual rainfall since 2000 is approximately 994 mm/year.

Whilst water levels in the lake are controlled to some extent by the weir at the lake outlet, it will be possible for the levels to fall at times of high evaporation and lower rainfall. The surface area of the lake where direct rainfall can occur will therefore vary throughout the year, as water levels in the lake rise and fall.

It is worth noting that there are uncertainties and error bounds associated with rainfall measurements themselves, particularly with ‘tipping bucket’ gauges of the type used at the Levin AWS station. Typically these type of gauges underestimate the amount of rainfall, particularly during high rainfall events, and the underestimate can be around 10 % (Groisman & Legates, 1994). Table 2 summarises the different rainfall values and the possible range.

Table 2: Sources of rainfall data and range of values

Study	Source of data	Value (mm/yr)	Min (mm/yr)	Max (mm/year)	Cause of range	Resulting input to water balance (x 10^6 m^3/year)
Gibbs (1994)	?	1,095				3.32
Phreatos	?	1,100				3.2
GNS	NIWA model	1,113				3
PDP	Levin AWS weather station		994	1,171	Minimum value based on average data from 2000. Maximum value based on average of total data series + 10 % to account for underestimate due to undercatch effects.	2.88 to 3.39

3.2 Inputs: Urban runoff

Runoff into the Lake from the Levin urban area was estimated by a number of different methods across each of the different water balance estimates. The Gibbs study estimated urban runoff as 50 % of rainfall across the urban area, whereas the Phreatos study estimated runoff as 30 % of mean annual rainfall, based on flow in the Queen St drain that takes stormwater runoff from the Levin urban area. The GNS study does not define urban runoff as a separate component in their water balance.

Based on discussions with Horowhenua District Council (Joel Dykstra) we understand that approximately 60 % of stormwater runoff is directed into the Queen Street Drain, with the remaining 40 % of stormwater directed into the Domain Drain and the Makomako Road Drain. Stormwater runoff directed into these drains primarily consists of runoff from roading and commercial areas whereas stormwater runoff from residential areas is initially directed into soakpits, although overflow during high rainfall events (1 in 10 year events or greater) will be directed towards the Queen Street Drain, Domain Drain and Makomako Drains. The Queen Street drain also receives some flow from the rural areas that occur to the east of Levin.

Horowhenua District Council have recently installed continuous flow monitoring equipment into the Queen Street Drain and a plot of that data is presented in Figure 7a. Flow rates are recorded at five minute intervals. Rainfall data from the Levin AWS gauge is also shown, which demonstrate a clear relationship between rainfall and flow within the drain. The record is relatively short, covering around 9 months from September 2013 to May 2014 but it indicates that there was a consistent minimum flow within the drain between September and early December. One explanation of this consistent flow is that it may it may indicate errors in the flow monitoring equipment. Horowhenua District Council indicate that errors in the flow record could be up to 20%. However, alternatively, and more likely, the sustained flows reflect groundwater inflow to the drain. The plot of groundwater levels shown in Figure 7a is consistent with this explanation, where higher groundwater levels coincide with the period of sustained flow.

From the available data, the average daily flow in the Queen Street drain is around 5,500 m^3/day (63 L/s), and the median flow is 1,674 m^3/day (19.3 L/s). This value is generally consistent with the median value from monthly flow gauging in the Queen Street Drain at Lake Horowhenua by Horizons Regional Council, which indicates a median flow of around 30 L/s. However, much higher flows have been recorded, reaching more than 450 L/s at times of high rainfall. The total flow in the drain between the start of the record in September 2013 and May 2014 was 1.37×10^6 m^3. Based on the average flow rate, the total flow over a year in the drain would be around 2×10^6 m^3. Allowing for the 20 %

potential error in the flow record the total flow annual from the Queen Street Drain could range from 1.6 x 10^6 m^3 to 2.4 x 10^6 m^3.

The Queen Street Drain accepts 60 % of the stormwater runoff from the Levin urban area and therefore the total stormwater runoff may be in the range of 2.66 x 10^6 m^3/year to 4 x 10^6 m^3/year. However, a proportion of this runoff originates from the rural catchment to the east of Levin, so this range represents an upper limit to the urban runoff component of the water balance.

The data available from the Queen Street drain flow monitoring is only available from a short time period and therefore it may not represent average conditions. Some indication of how the data compares to average conditions can be made by comparing rainfall in the months where flow data in the Queen Street Drain has been collected to long term average rainfall. Figure 7b presents average monthly rainfall compared to rainfall that occurred between 2013 and 2014, and also shows the monthly total flows in the Queen Street Drains. Overall, rainfall in the period September 2013 to April 2014 was around 90 % (643 mm compared to 691 mm) of the average rainfall that would typically occur between September and April. Stormwater flows are directly proportional to rainfall and therefore long term average flows could be around 10 % greater, or between 2.66 x 10^6 m^3/year to 4.4 x 10^6 m^3/year. These values are broadly consistent with the estimates from the Gibbs and Phreatos studies.

Table 3: Sources of urban runoff data and range of values

Study	Source of data	Value	Min (x 10^6 m^3/year)	Max (x 10^6 m^3/year)	Cause of range	Resulting input to water balance (x 10^6 m^3/year)
Gibbs (1994)	Based on previous work (Brougham and Currie, 1976)	50 % of rainfall over Levin urban area				5.09
Phreatos (2005)	Queen Street drain flows	30 % of rainfall				2.9
GNS (2010)	-					-
PDP	Queen Street drain flows		2.66	4.4	Range based possible error estimates in flows measured in the Queen Street Drain.	2.66 to 4.4

3.3 Inputs: Rural runoff and total stream flows

Urban runoff makes up one part of overland flows into the lake, with the second part comprising flows in streams that rise in rural area and that drain into the lake. The flows in these streams are a combination of two components: baseflow and runoff. The distinction between these two components is important because baseflow represents an important part of the overall groundwater component of flows into the lake. Only the Phreatos study quantified rural runoff as a separate component of flow into the lake (5.9 x 10^6 m^3/year), although this study did not subsequently characterise baseflow in the streams. The Gibbs study and GNS study both calculated total flow into the lake as a combined component, presented as 8.57 x 10^6 m^3/year and 27.6 x 10^6 m^3/year respectively.

Figure 8a presents gauged total flows into the lake from the three different time periods when gauging took place (1975 to 1977, 2008 and 2012 to 2014). It indicates that flow into the lake is overwhelmingly dominated by inflows from the Arawhata Drain, the inflow at Lindsay Road and Patiki Stream. However, it is worth pointing out that the total is not always made up from flows at the same points. For example gauging in the 1970's did not always include an assessment of flows at Patiki Stream, which is one of the largest inflows. The most consistent measurements were taken in 2008 and since 2012, and the average total flow from those gaugings (excluding flows from Queen Street Drain) is around 310 L/s, or around 9.7 x 10^6 m^3/year. It is perhaps also worth noting that the higher values recorded in 2008 (which represent predominantly winter flows and was a relatively wet year) may skew the average flow calculation towards a higher value; average flow rates based on more recent gauging in 2012-2014 suggest an average total flow of around 190 L/s (6 x 10^6 m^3/year).

There is potential uncertainty in the flow rates due to measurement errors, and typically gauging is only accurate to around 8 %. Therefore, the average total streamflow could fall in the range 5.54 x 10^6 m^3/year to 10.4 x 10^6 m^3/year. That range compares favourably with the Gibbs estimate of 8.57 x 10^6 m^3/year.

It is also worth highlighting an additional area of uncertainty at this stage, which relates to the size of the surface water catchment. In the Gibbs (1994) and Phreatos (2005) studies the catchment area is given as 54 km^2, whereas the more recent 'Lake Horowhenua Review', prepared for Horizons in May 2011, indicates a total lake catchment of 61 km^2, of which the Levin urban area comprises 8.4 km^2. Assuming the 2011 Horizons figure is correct, the difference in rural areas represents an increase approximately of 15 % (an increase from 45.6 km^2 to 52.6 km^2). This change may imply that the Gibbs estimate of total stream flow should also increase by 15 %, to 9.85 x 10^6 m^3/year. This represents a combination of rural runoff during rainfall events and baseflow, as discussed below.

3.3.1 Rural runoff

Rural runoff in the Phreatos water balance was evaluated based on estimates from studies undertaken by Hort Research on the Manawatu Plains, which suggested that rural runoff represents around 10 % of rainfall (1,100 mm/year), or around 5.9 x 10^6 m^3/year. However, it is worth noting that there is an error in the water balance calculation in this study; rural runoff was calculated using the entire catchment area (54 km^2), which includes the Levin urban areas (reported by Phreatos as 9 km^2). Therefore, there is some double accounting for water because urban runoff was also calculated as a separate component.

A more consistent value for rural runoff should be around 5 x 10^6 m^3/year, based on the original total catchment area of 54 km^2 less 8.4 km^2 of urban area i.e. 45.6 km^2 and 10 % of annual rainfall (110 mm/yr). Alternatively, if the updated rural catchment area of 52.6 km^2 is used, the total runoff would be in the order of 5.8 x 10^6 m^3/year. This value of runoff would represent between 55% and 100 % of the range of total flows discussed above.

3.3.2 Baseflow

Ideally runoff and baseflow would be calculated based on a continuous flow record, where it is possible to separate the flow record into runoff and baseflow components. A continuous flow record was not available for the 2014 PDP study for the rural streams that drain into Lake Horowhenua, but some indication of likely baseflow rates can be determined from a comparison between gauged flows relative to rainfall events.

Figure 8b presents total flows from streams draining into the lake (excluding flows from the Queen Street drain) for the two years where regular flow records have been collected (2008 and 2013), together with rainfall, calculated as a total daily volume across 53 km^2 of rural catchment (i.e. 61 km^2 less 8 km^2 of the Levin urban area).

The purpose to Figure 8b is to show the flows relative to the timing of rainfall, which therefore provides some information on baseflow in the streams. Where there is very little antecedent rainfall, the flow will represent an estimation of baseflow, although this will vary depending on groundwater levels. For example, flows in March 2013 were gauged following a period of very little rainfall, and flows were approximately 11,750 m^3/day. Equally, flows gauged in January 2013 were around 6,307 m^3/day following relatively low rainfall, suggesting that summer baseflow falls in a range from around 6,000 m^3/day to around 12,000 m^3/day.

Baseflow in winter is likely to be higher due to higher groundwater levels and it is more difficult to identify periods of low rainfall in winter. However, gaugings in May 2013 and June 2013 show flows of between 15,000 m^3/day and 21,000 m^3/day, following periods of relatively low rainfall. Likewise, flows gauged in June 2008 were around 16,000 m^3/day following a period of limited rainfall.

A way of illustrating the effect of groundwater levels on flows is to plot groundwater levels compared to flows. Such a plot is shown in Figure 9a, where the groundwater level in bore 332033 (22.2 m deep) is plotted against the total flows gauged at or around the same time in 2008, when flows were gauged between April and September and represent a predominantly winter timeseries. Note that groundwater level measurements and gaugings did not always occur concurrently.

Figure 9a indicates a relationship between depth to groundwater and flows. Shallower groundwater levels tend to be associated with higher flows up to around 30,000 m^3/day. Note that the flows plotted in Figure 9a are those where there was relatively little antecedent rainfall, for example flows from April 2008 are omitted from the plot. The plot also indicates two outliers where high flows (> 30,000 m^3/day) occurred at lower groundwater levels, which likely represent the effects of rainfall runoff that may have occurred elsewhere in the catchment (i.e. not recorded at the Levin AWS gauge). Overall the plot suggests that winter baseflows could fall in the range 15,000 m^3/day to around 30,000 m^3/day, which is broadly similar to the range identified by comparing flows to rainfall events.

On average, the total surface water flows into Lake Horowhenua are around 310 L/s (26,670 m^3/day), based on gauging data between 2008 and 2014 and excluding flows from the Queen Street drain and the other Levin urban drains. Seasonally, the average summer flow is around 15,000 m^3/day, whereas the average winter flow is around 31,000 m^3/day.

Based on gaugings in rural streams indicating an average summer total flow of 15,000 m^3/day and a baseflow range of 6,000 m^3/day and 12,000 m^3/day (from gaugings in rural streams in January and March 2013 during periods of low rainfall) the baseflow component of summer average flows could therefore fall between 40 % and 80 % of summer flows.

Similarly, based on gaugings in rural streams indicating an average winter total flow of 31,000 m^3/day and winter baseflows ranging from 15,000 m^3/day and 30,000 m^3/day, the baseflow component of winter average flows could be in the range 50 % to 100 % of winter flows. However, an average winter baseflow of 100 % of flow is unlikely since some runoff would be expected, and in reality, the value is more likely to be towards the lower end of this range perhaps between 50 % and 75 % of total winter flows.

Conversely, therefore, the rural runoff component of the total streamflows could be between 20 % and 60 % of summer flows and 25 % and 50 % of winter flows. However, it is important to highlight that these estimates are based on very limited datasets. In addition, conceptually, little runoff would be expected during summer because high levels of evapotranspiration would result in a relatively high soil moisture deficit. The runoff components in summer are therefore likely to only occur during high rainfall events.

A long term average estimate of baseflow in the rural streams may therefore be between 45 % and 78 % of total flows (i.e. the average of the ranges of summer and winter baseflows), or between 2.5 x 10^6 m^3/year and 8.1 x 10^6 m^3/year, based on the range of total flow discussed earlier in Section 3.3 (5.5 x 10^6 m^3/year to 10.4 x 10^6 m^3/year)

However, because the sum of baseflow and runoff must equal the total flows, an upper limit to baseflow must be closer to 7.4 x 10^6 m^3/year or around 71 % of total flow. For example, using the lower end of the estimate of baseflow (2.5 x 10^6 m^3/year), implies a minimum estimate of runoff of 3 x 10^6 m^3/year, because the sum of baseflow and runoff must equal the minimum flow estimate of 5.5 x 10^6 m^3/year.

Likewise, if the minimum estimate of runoff is 3 x 10^6 m^3/year and the maximum total flow estimate is 10.4 x 10^6 m^3/year, then the upper limit of baseflow must be closer to 7.4 x 10^6 m^3/year (i.e. 10.4 minus 3).

Table 4 presents the different values used in the various studies to date and the range of values derived from the assessment above.

Table 4: Sources of baseflow, runoff and total flow estimates and range of values

Study	Source of data	Baseflow		Runoff		Total Flow		Resulting total flow input to water balance (x 10^6 m^3/yea)	Cause of range
		Min (x 10^6 m^3/year)	Max (x 10^6 m^3/year)	Min (x 10^6 m^3/yea)	Max (x 10^6 m^3 /year)	Min (x 10^6 m^3/year)	Max (x 10^6 m^3/year)		
Gibbs (1994)	Calibrated model providing total stream flow estimates					8.57	9.85	8.57 to 9.85	Change in catchment area
Phreatos (2005)	Soil moisture balances for Manawatu by HortResearch suggest 10 % of rainfall goes to runoff			4.95	5.8	-	-	5.9 to 6.75	Change in catchment area and error in original water balance
GNS (2010)	Gauged flows from 2008					27.6	27.6	27.6	
PDP (2014)	Gauged flows in streams draining into Lake Horowhenua from 2008 and 2012-2014	2.5 (45% of min value of total flow)	7.4 (71% of max value of total flow)	3 (based on minimum value of baseflow)	7.9 (76% of max value of total flow)	5.5	10.4	5.5 to 10.4	Range of average flow estimates and range of potential proportions of baseflow.

Ideally, continuous gauging on the major inflows to the lakes would help to refine estimates of rural runoff because flow records can then be accurately compared to rainfall records, allowing a reliable estimate of runoff and baseflow to be developed. Flow records could also be used to calibrate a rainfall runoff model of the catchment, which could also provide an estimate of recharge to groundwater.

Continuous gauging has been installed on the Arawhata Drain since 2017 and a plot of that data is shown in Figure 9b Whilst the dataset is relatively short, summer baseflow in the Arawhata Drain is around 70 L/s to 80 L/s, while baseflow in winter appears to be around 300 L/s. Median flows in the Arawhata Drain are around 185 L/s (5.8 x 10^6 m^3/year), which is generally consistent with the estimates provided in Table 4. Groundwater levels in a nearby shallow bore are also shown which illustrate the correlation between flows and groundwater levels and imply that flows in the Arawhata Drain are driven by groundwater discharges.

3.4 Inputs: Shallow and deep groundwater direct to the lake

The groundwater component from all the studies has been calculated as the balance between inputs to the lake, in the form of direct rainfall and stream flows (including groundwater fed baseflow), and outputs, in the form of outflows and evapotranspiration from the lake surface. The outflows exceed the inflows, and therefore there is an assumption that groundwater inputs must make up the difference.

There are effectively two methods to determine this difference:

- One option is to determine the sum of the values of each of the individual inputs to the water balance (i.e. rainfall, urban runoff and surface flows), and subtract these from the sum of the each of the individual outputs from the lake (i.e. flows in Hokio Stream and open water evaporation);
- Alternatively, groundwater inflows can be estimated based on the difference between gauged outflows from the lake (i.e. flows at Hokio Stream) and gauged inflows to the lake, including drains receiving urban runoff. This assessment is valid provided inflows and outflows are gauged on the same day, and the difference is taken for days where there is little, or no, rainfall over the lake.

It is important to recognise that these assessment methods calculate the net groundwater inflow. Actual groundwater inflow may be greater, with the extra inflow balanced by groundwater outflows.

Figure 10 presents the total of the gauged inflows and the gauged outflows, illustrating the large deficit that is presumed to be made up from groundwater flowing directly into the lake. This difference between inflows and outflows can be used to estimate the groundwater contribution direct to the lake. Note that the plot of total inflows compared to total outflows for 1976 to 1978 should be treated with caution because not all inflows were gauged at this time, although the largest inflows at Arawhata Stream were included.

Figure 10 indicates that the difference is reasonably consistent, except at very high flows, such as those recorded during August and September 2008. On average, excluding days with significant rainfall, the difference between inflows and outflows shown in Figure 10 is around 438 L/s, which equates to around 13.8 x 10^6 m^3/year. This value compares favourably with the estimate from the Gibbs and Phreatos studies. Inevitably there is some uncertainty associated with this value, in part due to uncertainties related to gauging measurements, which are up to 8 %. As a result, the uncertainties in the difference between the inflows and outflows could be up to 16 % (i.e. the errors are compounded).

An alternative means of estimating groundwater inflows is via a simple Darcy calculation.

- The lateral groundwater gradients in the area around the lake are in the order of 0.005 (12 m change in 2.5 km), based on the piezometric maps in the GNS report.
- The perimeter around the lake that may include inflowing groundwater (excepting the lake base) is approximately 8 km. The lake is around 2 m deep, but the effective aquifer thickness through which groundwater may flow to the lake is likely to be in the order of 5 m to 10 m. Therefore, the area through which groundwater may flow is in the range of 40,000 m^2 to 80,000 m^2.
- The hydraulic conductivity of the strata is unknown, but the strata comprise sands and gravels, where the typical hydraulic conductivity is in the range of 5 m/d to 100 m/d.

Based on these inputs, lateral groundwater flow to the lake could be in the range 0.365 x 10^6 m^3/year to 14.6 x 10^6 m^3/year. The upper end of the range is consistent with the difference between the surface water inflows and surface water outflows, which implies that the strata are likely to be permeable. Although there is also likely to be vertical seepage into the lake through the lake bed, but it is difficult to quantify this component without knowledge of groundwater pressures directly under the lake.

Table 5 presents the different values used in the various studies:

Table 5: Sources of estimates of direct groundwater inflows to the lake and range of values

Study	Source of data	Value	Min (x 10^6 m^3/year)	Max (x 10^6 m^3/year)	Cause of range	Resulting input to water balance (x 10^6 m^3/year)
Gibbs (1994)	Determined based on model and prior work as 60 % of land drainage	12.85				12.85
Phreatos (2005)	Value determined through water balance	16				16
GNS (2010)	Value determined through water balance	6.9				6.9
PDP (2014)	Comparison of inflows and outflows		11.6	16.0	Possible compounding errors in flow gauging.	11.0 to 16.0

3.5 Outputs: Open water evaporation

Open water evaporation is one component that can be relatively accurately assessed. Based on open water evaporation data from the Levin AWS climate station, the average long term open water evaporation across the lake surface of 2.9 km^2 is around 2.42 x 10^6 m^3/year, and varies within a range from 2.1 x 10^6 m^3/year to 2.8 x 10^6 m^3/year.

3.6 Outputs: Surface water outflow (Hokio Stream)

Estimates of surface water outflow have been made at Hokio Stream and used to define the major output for the water balance. Both the Gibbs and Phreatos studies used an average flow of around 800 L/s or around 26 x 10^6 m^3/year, but the GNS study based its water balance on a much higher flow of around 1,100 L/s. The GNS study indicates that its flow rate is taken from gauging at the Hokio at Moutere Bridge, downstream of the lake outlet, whereas both the other studies are based on flows gauged at the Lake Horowhenua outlet.

Figure 11 presents the gauged flows at the lake outlet as well as at the downstream Moutere Bridge site. Early data, between 1970 and 1976 is only available from the Moutere Bridge site, but some simultaneous gauging at both the Lake Horowhenua outlet and the Moutere Bridge site took place in 2008 and again in 2013. Where simultaneous gauging did place, the flows are very similar suggesting that there is no substantial gain in flow between the lake outlet and the Moutere Road Bridge.

Given the similarity in flows, an overall average of the gauged flows can be made, using both the data from the Moutere Bridge site (to represent earlier data), and the flows gauged at the lake outlet (to represent more recent data). Using all the data, the average flow is approximately 880 L/s. Therefore, it seems likely that the GNS study is based on an incorrect assessment of outflows of the Lake. The lowest flows from the lake typically occur during late summer (February to March) and the data available suggest that the lowest flows are in the order of 250 L/s. The highest flows typically occur during winter and are in the order of 1250 L/s.

A flow recorder has been installed at both the outlet of the lake and at the weir that controls lake levels and a copy of the flow record between May 2013 and March 2014 is presented in Figure 12. Between May 2013 and approximately late September 2013, the flow records at these sites are almost identical, but from September 2013, the record indicates a greater flow at the weir recorder site, with a reasonably consistent difference of around 750 L/s until January 2014. From January 2014 the difference in flow rates drops to around 250 L/s.

We understand that this difference is a result of weed growth in the channel (with the large increase coinciding with the time when weed growth increases in summer), which results in changes to the channel geometry and subsequently alters the rating curve that relates the river stage to flow. Based on the flow record from May 2013 until September 2013, average flows from the lake into Hokio Stream are in the order of 850 L/s.

Also plotted on Figure 12 are the gauged flows for the Hokio at Lake Horowhenua. In general, these appear to agree poorly with the flow recorder readings, particularly after September 2013. There is therefore some question as to what an accurate assessment of outflow from the lake may be, given the differences in various measurements and the available data suggest a range from 800 L/s to 880 L/s, or 25.2 x 10^6 m^3/year to 27.7 x 10^6 m^3/year. If potential gauging inaccuracies are also accounted for (in the order of 8 %), then this range could extend to 740 L/s to 950 L/s, or 23.33 x 10^6 m^3/year to 29.9 x 10^6 m^3/year.

3.7 Outputs: Groundwater seepage and throughflow

It is unclear whether there is seepage through base of the lake that enters groundwater. It is possible that seepage occurs, but given that the water budget for the lake is balanced with groundwater inflows it may be difficult to quantify. One possible method may be to evaluate groundwater levels around its western edge, since this is where seepage from the lake is most likely to occur. Seepage meter surveys on the lake floor could also clarify the direct groundwater input into the lake bed.

The water balances above also assume that the lake is the main sink for all surface water and groundwater in its catchment. However, it is possible that some groundwater flows beneath the lake and discharges at some point further west, either at the coastal boundary, or into surface water discharge points. Such a possibility is important with regards to the effect that groundwater abstractions may have on the lake, since they may not all intercept groundwater that otherwise flows into the lakes.

Quantifying such an effect may be possible based on a rainfall runoff model, which could also calculate groundwater recharge. If the long term recharge to groundwater is significantly larger than the estimates of groundwater discharge to the lakes, some groundwater must be leaving the catchment as throughflow.

3.8 Summary water balance

Table 6 presents a summary water balance, including the ranges discussed in Section 3.1 to 3.7.

Table 6: Summary water balances (Lake Horowhenua)

Water balance component	**Inputs (x 10^6 m^3/yr)**					**Outputs (x 10^6 m^3/yr)**				
	Gibbs	Phreatos	GNS	PDP Minimum estimate	PDP maximum estimate	Gibbs	Phreatos	GNS	PDP Minimum estimate	PDP maximum estimate
Rainfall (direct to lake)	3.32	3.2	3	2.88	3.39					
Urban runoff	5.09	2.9		2.6	4.4					
Rural runoff	-	*5.9*		*3*	*7.9*					
Rural baseflow	-	-		*2.5*	*7.4*					
Total rural flow (runoff + baseflow)	*8.57*			*5.5*	*10.4*					
Total surface flows (urban + rural):			*27.6*[1]	*8.1*	*14.8*					
Groundwater discharge direct into lake	12.85	16[2]	6.9	11.9	16.0					
Evaporation from lake surface						2.34	2	2.2	2.1	2.8
Groundwater seepage from the lake						1.44			?	?
Lake discharge into Hokio Stream						26.05	26	35.3	23.3	29.9
Total	**29.83**	**28**	**37.5**			**28.39**	**28**	**37.5**	**25.4**	**32.7**
Proportion of direct groundwater seepage into lake (not including stream baseflow)	43%		18%	36 % (11.9 of 32.7)	63 % (16.0 of 25.4)					

Notes: 1. The value of total flow from the GNS study includes urban runoff
2. Groundwater discharge into the lake in the Phreatos study must effectively include baseflow into spring fed streams that drain into the lake

We have reviewed the above information in regard to more recent flow gauging data available from Horizons since the previous PDP study in 2014 which indicates that the median inflows to the lake could be around 10 x 10^6 m^3/year. While this median is based on flow records taken during different time periods, it is within the range of 8.1 to 14.8 x 10^6 m^3/year given in the previous study and in Table 6 above. Therefore, we consider that the range of surface flow inputs to the lake previously used in 2014 still remains relevant. Figure 13 shows the flow data recently provided by Horizons. This shows that the lake outflows to the Hokio Stream are reasonably significant in comparison to the smaller but more numerous sources of inflow. The largest contributor to the lake inflows is the Arawhata Drain, which has a median flow of around 184 L/s.

Table 6 indicates that groundwater could potentially account for a large proportion of lake inflows. The direct groundwater contribution to the lake (i.e. excluding baseflow in the streams that flow into the lake) is likely to be in the order of 36 % to 63 %. If baseflow in the streams that feed into the lakes is included, that proportion would be greater.

It is worth highlighting that the values for each of the components provided above indicates the range of individual components and the groundwater seepage directly into the lake is based on the difference between gauged inflows and outflows, rather than the sum of each individual component. The difference between the gauged inflows and outflows provides a smaller range of possible groundwater seepage to the lake, perhaps implying a better definition of the potential range.

For example, the maximum value of groundwater seepage directly into the lake in Table 6 (16.0 x 10^6 m^3/year) based on the difference between gauged inflows and outflows is smaller than the sum of the minimum values of rainfall, urban runoff and surface water inflow (10.98 x 10^6 m^3/year) minus the maximum value of outputs from the lake (32.7 x 10^6 m^3/year minus 10.98 x 10^6 m^3/year = 21.72 x 10^6 m^3/year).

Likewise, the estimate of the minimum value of groundwater seepage direct to the lake (11.9 x 10^6 m^3/year) based on the difference between the gauged inflows and outflows is greater than the minimum estimate of outputs (25.4 x 10^6 m^3/year) less the sum of the maximum levels of each individual component (18.19 x 10^6 m^3/year) (25.4 x 10^6 m^3/year minus 18.73 x 10^6 m^3/year = 7.21 x 10^6 m^3/year).

One explanation for this discrepancy is that the maximum and minimum estimates for each component do not coincide, and therefore calculating the range of groundwater inflows based on those maximum and minimum is not a reasonable method.

4.0 Recommended work to constrain uncertainties

The discussion of the various water balances components in Section 3 has highlighted a variety of uncertainties with regards to the water balances.

There are several actions that could be undertaken to help refine the value of groundwater inflows to the lake. In approximate order of importance these include:

- Development of a rainfall, runoff and recharge model for the catchment once flow records are available to be used as a calibration point, together with an updated groundwater flow model;
- Assessment of recharge to the catchment to determine the proportion of groundwater that discharges into the lake, to that which may flow out of the catchment (which could be an output from a rainfall runoff model);
- Conducting a seepage meter survey within the lake to measure rates of groundwater inflow and lake water outflow; and
- Discussions with Horowhenua District Council stormwater managers to determine the likely amount of urban runoff and delineation of catchment sizes.

5.0 Effects of groundwater abstraction on lake inflows

The potential effects of groundwater abstraction on the lake health will vary seasonally, with the greatest effects occurring at times when high groundwater abstraction rates coincide with low inflows to, outflows from, the lake. Section 5.1 considers the abstraction rates that occur in the area, together with their seasonal variations. Section 5.2 presents a seasonal water balance, comparing the timing of abstraction to flows into and out of the lake.

5.1 Current groundwater abstraction

With regards to abstraction, there are two ways in which the data can be assessed:

- Annual allocated volumes (consented use); and
- Water use as a proportion of the total consented volume (actual use).

5.1.1 Consented abstraction volumes

HRC records indicate that there are 20 currently consented groundwater abstractions within the estimated groundwater capture zone for Lake Horowhenua (Figure 14). Note that there are other consents in the surface water catchment, but these are on the opposite side of the Levin fault and are there less likely to affect the lake. The majority (15) of these consents (within the estimated groundwater capture zone) are for horticultural purposes (fruit and vegetables), with the remaining consents used for agriculture (two consents), industrial, processing and manufacturing (two consents) and recreational uses (one consent). Annual volume information is available for all 20 consents as specified on the Horizons database. The locations of the bores associated with the 20 consents are shown in Figure 14. The total annual allocated volume for the consents within the estimated Lake Horowhenua groundwater capture zone is around 2,083,021 m^3/year.

5.1.2 Estimates of actual use

Of the 20 consents within the capture zone for Lake Horowhenua, 10 have flow meter data available. To estimate the use on those consents which do not have metered water use data we have reviewed water use data for consents within the wider area around the lake as provided by Horizons.

Water use records are available for 32 consents within the wider area around the lake, of which six of these consents do not have a full water year (i.e. 1st July to 30th June) worth of available data. Ten remaining consents are within the Lake Horowhenua groundwater capture zone (Figure 15). The 26 consents within the overall Horowhenua district with at least one full water year of data cover a range of uses including:

- Horticulture (20 consents);
- Pasture consents (including recreational) (five consents); and
- Industrial (one consent).

Of the available water use data, the most comprehensive dataset available occurred during the 2017/2018 and 2018/2019 water years. As such, this data has been used for the following water usage estimates, including consents where no water use data is available. A summary of the average use by consent type per month for the 2017/2018 and 2018/2019 water years is provided in Figure 16. It indicates that groundwater abstraction predominantly occurs between late spring and early autumn (November to March), with minimal abstraction taking place in winter (July to August) for horticultural and pasture consents, whereas industrial usage is relatively stable year round. This timing of abstraction is important, since it indicates that the overwhelming majority of abstraction occurs during periods of lower inflows and outflows to the lake.

On average, the available data indicate that around 69 % of the total annual abstraction within the overall Horowhenua region occurs during summer (December to February). Abstraction during late summer (i.e. February to April) is also around 27 % of the total. The remaining 4% is used during winter and summer.

However, that 69 % is not distributed evenly between pastoral, horticultural and industrial consents. On average, pastoral consents take around 73 % of their annual total during summer (December to February), horticultural consents take around 67 % of their annual total during summer and industrial take around 22 % of their annual total during summer.

Of the 20 consents within the Lake Horowhenua groundwater capture zone, ten consents either have no water use data or do not have a full water year of data. For the consents with no water use data, actual usage estimates have been made based on the available monitoring data for each consent type in the wider Horowhenua region. The parameters used to estimate actual annual volumes and summer usage are summarised in Table 8 below.

Table 7: Parameters Used for Annual and Summer Usage Estimates

Consented Use	Average Annual Water Use during 2017/2018 and 2018/1029 Water Years (% of Consented Annual Volume)	Average Summer Water Use during 2017/2018 and 2018/1029 Water Years (% of Actual/Estimated Annual Use)
Horticulture	15 %	67 %
Pasture	23 %	73 %
Industrial	4 %	22 %

Notes:
1. *Percentages based on usage data from the wider Horowhenua Region,*

Based on the parameters provided in Table 8, the annual and summer water usage within the Lake Horowhenua groundwater capture zone is summarised in Table 9 below.

Table 8: Annual and Summer Usage Estimates for Groundwater Takes within the Lake Horowhenua Groundwater Capture Zone

Consented Use	Total Consented Annual Volume (m^3/year)	Metered Annual Use (m^3/year)	Estimated Actual Annual Use (m^3/year)[1]	Metered Summer Use (m^3/3 months)	Estimated Actual Summer Use (m^3/3 months)[1]
Horticulture	1,807,883	388,085	15,084	256,503	10,067
Pasture	98,140	2,078	6,452	2,905	5,428
Industrial	176,998	-	7,438	-	1,397
Total	**2,083,021**	**419,137**		**276,301**	

Notes: 1. Estimated use based on the parameters provided in Table 8, for consents where no metered use data is available

The information presented in Table 9 indicates that consented use over a year could be around 2,083,021 m^3, or around 66 L/s on average over a year. In summer, using the percentages from Table 8 the consented use could be up to 947,650 m^3 over around 90 days, or around 122 L/s.

However, actual use over the course of a full year may be much less, around 419,137 m^3 (13.3 L/s) or around 20% of the consented total on average. The total actual use in a 90 day summer (December to February) is around 66 % of the estimated actual annual use, or 276,301 m^3 (35.5 L/s).

Note that based on the available data, the total actual annual use varies from less than 10% of the consented total (2011/2012 water year) to a maximum of 22% of the consented total (2017/2018 water year). However, utilisation of individual annual volumes varies from around 5% up to around 70%.

5.1.3 Permitted use

There are around 388 bores within the Lake Horowhenua groundwater capture zone, of which 26 are part of a consent (as discussed in Section 5.1.1). Of the remaining 362 bores, 24 are within the Levin urban area and are expected to be unused. The final 338 bores are potentially used at rates between 1 m^3/day to 5 m^3/day (for both domestic use and stock use), with a likely average of around 3 m^3/day. Additional use due to permitted bores could therefore be in the order of 1,014 m^3/day. Assuming use is distributed evenly throughout the year, the total permitted use could be around 370,110 m^3/year, with around 91,260 m^3 being abstracted during summer.

Compared to the estimates of actual use under consented takes, the estimate of permitted use is large, and may be an overestimate.

Table 10 provides estimates of total abstraction from the Lake Horowhenua groundwater capture zone, including permitted takes.

Table 9: Estimated Annual Allocated Volume for groundwater takes with water use data in the Lake Horowhenua catchment

Consent Use	Consented Annual Volume (m^3/year)	Estimated consented use in summer (m^3/90 days)	Actual annual use (m^3/year)	Actual use in summer (Dec to Feb) (m^3/90 days) (see notes)
Horticultural consents	1,807,883	869,350	403,170	266,570
Pasture consents	98,140	32,040	9,516	8,333
Industrial consents	176,998	46,260	6,452	1,397
Permitted takes	370,110	91,260	370,110	91,260
Total	**2,453,131**	**1,038,910**	**789,247**	**367,561**

5.2 Groundwater abstraction compared to seasonal lake water balances

Figure 17 shows average monthly outflows from the lake (as gauged at Hokio Stream) compared to typical monthly water use. It indicates that the greatest abstraction rate typically occurs in December, January and February, which are also typically around one to two months before the period of lowest flows from the lake. On average, flows from the lake in February and March are between 335 and 407 L/s, although flows as low as 250 L/s have been recorded in both February and March.

Figure 18 displays the depth distribution of estimated annual groundwater usage, which indicates that the highest portion of water use is from bores in the 40 to 80 m depth range. Given the small portion of groundwater abstraction occurring at depths less than 20 m bgl, it is likely that stream depletion effects will be delayed and therefore, whilst the peak abstraction effect does not coincide with the lowest flows, the peak stream depletion effect may do so. As a result, the water balance has been undertaken assuming that the highest surface water influences from groundwater abstraction could coincide with the period of lowest flows from the lake (typically February and March).

Based on these data, the greatest impact from groundwater abstraction on the lake is therefore expected to occur in February and March.

Table 10 provides an indicative seasonal water balance for Lake Horowhenua, highlighting the relative importance of groundwater inflow to the lake (as a proportion of the total flow into the lake) during late summer (February to April, representing the time of lowest inflows to the lake) and winter. Note that abstraction effects over a period of 90 days are used because abstraction effects will take some to develop.

Table 10 also provides an indication of the relative proportion of groundwater abstraction compared to seasonal lake inflows, from both a consented view point and an actual use perspective.

Table 10: Indicative Average Seasonal Water Balance (Lake Horowhenua)

	Average Summer (February to April) (x 10^6 m^3/ 90 days)		**Winter (June to August) (x 10^6 m^3/ 90 days)**	
Water balance component (x 10^6 m^3/season (90 days))	**Inputs**	**Outputs**	**Inputs**	**Outputs**
Rainfall (direct to lake)	0.72		0.85	
Runoff from Levin (urban runoff)	0.77		0.98	
Rural Runoff	*0.17*		*1.52*	
Rural Baseflow	*1.0*		*1.21*	
Total surface flow (rural runoff + rural baseflow)	1.17		2.72	
Net Groundwater seepage into lake	1.59 (204 L/s)		5.51	
Total inflows	**4.25**		**10.06**	
Evaporation from lake surface		0.92		0.34
Lake discharge into Hokio Stream		3.33 (429 L/s)		9.72 (1,250 L/s)
Total outflows		**4.25**		**10.06**
Groundwater (baseflow + seepage) proportion of total lake inflow:	1.0 + 1.59 = 2.59 = 60 % of 4.25		66 % (6.27 of 10.06)	
Estimated **consented** groundwater use (including permitted use)	1.04 of 2.59= 40 % of total gw inflows or 24 % of total inflows (4.25)		-	
Estimated **actual** groundwater use (including permitted use)	0.37 of 2.59 = 14 % of total gw inflows, 9 % of total inflows		-	

The values in Table 10 were calculated based on the following assumptions:

- **Rainfall** is apportioned based on average monthly rainfall, which indicates that on average 23 % of annual rainfall occurs between December and February (summer), and 27 % of annual rainfall occurs in winter (June to August).
- **Urban runoff** is apportioned assuming that urban runoff is related to rainfall. Therefore, around 27 % of urban runoff would be expected to occur in winter. Slightly less than 23 % of urban runoff would occur in summer because there is some rainfall loss as surfaces 'wet out'. The summer urban runoff estimate was reduced by 5 % to account for this effect.
- **Total flows** were estimated based on gauged data (as opposed to continuous flow data). Typical summer flows range between 100 L/s and 200 L/s, whereas typical winter flows fall in the range 300 L/s to 400 L/s, although higher winter flows have been recorded. These values imply that between one third and one half of all flows occur in winter.
- Estimates of **rural runoff** (as a proportion of total flows) are based around measured values of evapotranspiration. Measured values of evapotranspiration indicate that EVT is likely to exceed rainfall during the summer resulting in soil moisture deficits. Given that runoff is a function of soil moisture and rainfall intensity, limited runoff may be expected in summer (set as between 10% and 20 % of total flows), whereas higher runoff may occur in winter (set as between 50 % and 60 % of total flows).
- **Baseflow** in the streams feeding the lake is set as the inverse of runoff. During the summer, flow is likely to be dominated by baseflow, whereas during winter, a relatively larger proportion of flows would be expected to result from runoff.
- **Open water evaporation** from the lake surface was determined as an average of available data from the Levin AWS weather station. On average, 37.82 % of open water evaporation occurs between December and February, whereas 14 % of open water evaporation occurs between June and August.
- **The lake discharge** was estimated based on gauged flows for summer and winter periods respectively. These indicate that average summer flows are in the range 250 L/s to 500 L/s, with the lowest flows typically occurring towards the end of summer and in early autumn (i.e. February to April), whereas average winter flows are in the order of 1000 L/s to 1,500 L/s, although gaugings indicate that higher winter flows do occur; and

- **Groundwater seepage** into the lake is calculated as the balance of inputs and outputs from the lake.

6.0 An interim framework for managing groundwater abstraction consents

6.1 Groundwater abstraction effects on lake health

Based on the most recent information obtained in 2019 regarding consented use in the catchment, both the consent and actual use estimates are higher than the previous 2014 study undertaken by PDP.

The information regarding the effects of groundwater abstraction indicate that consented groundwater abstraction could be a large proportion of summer groundwater inflows to the lake (40 %), and also a significant, albeit lesser, proportion of the total inflows to the lake in summer (24 %).

However, it is important to note that the groundwater seepage into the lake (as presented in Table 10) is calculated as the balance of inputs and outputs into the lake. Monitoring of the lake outflows indicate that summer flows can reduce to 250 L/s or less, which would result in a reduced estimate of groundwater seepage into the lake. Accordingly, at times of low lake outflow the effect of consented groundwater abstraction may be greater than 40 % of groundwater inflows to the lake. Further data collection is required before the upper limit of this effect can be quantified, however these data imply that if all users utilised their full annual volume the effect on groundwater inflows to the lake could be significant.

Based on usage data from the 2017/2018 and 2018/2019 water years most consented users do not utilise their full annual volume; based on metered data, typical annual use is around 20% of the consented annual total and most of that is used during summer. In terms of the inflows to the lake, the estimated actual groundwater use could amount to around 14 % of summer groundwater inflows to the lake, and around 9 % of the total inflows to the lake.

Based on previous work (Gibbs, 1994 and 2014) changes in the groundwater inflows to the lake can affect the lake health in three main ways:

- Estimates of the nutrient budget for the lake indicate that groundwater is the dominant source of nitrogen into the lake. Therefore, changes to the groundwater inflows to the lake will change the flux of nitrogen entering the lake, although given the currently high nitrogen concentrations this might not significantly alter the lake health;
- The lake level is controlled by the weir at the lake outlet on Hokio Stream, and overall, the lake level remains largely constant through the year (Figure 19). Therefore, changes to the inflows into the lake are

likely to affect the residence time of water within the lake, with lower inflows resulting in longer residence times, and higher inflows resulting in shorter residence times. Based on modelling by Gibbs (1994) the shortest residence time occurs in late winter / early spring and is around 30 days. The longest residence time occurs in late summer / early autumn and is around 95 days.

Modelling by Gibbs (1994) indicates that phosphorus concentrations in the lake correlate with the lake water residence time, with higher phosphorus concentrations coinciding with longer residence times. Given that the lake health is related to phosphorus concentrations in the lake, there is an inferred relationship between the lake health and residence times. Therefore any changes in the groundwater inflows may have an impact on lake health by changing lake residence times. It is important to note that the main source of phosphorus in the lake is from internal sources (i.e. lake sediments), rather than external inflows into the lake; and

- Gibbs also postulates that changes to the groundwater inflows could also affect lake health by releasing phosphorus into the lake. The phosphorus concentration in groundwater around the lake is generally very low (typically < 0.04 mg/L in bore 362003) which is thought to be partly because there are limited phosphorus sources within groundwater in the first place, but also because the shallow groundwater flowing into the lake is typically aerobic and travels through an iron rich gravel aquifer, which can adsorb phosphorus from groundwater. As a result there may be a large store of phosphorus bound up within the aquifer material under the lake.

  If groundwater pressures reduce beneath and around the lake, a possible result is that the wetting front of groundwater would effectively retreat. This could potentially result in higher pH lake water moving into the aquifer around the lake, which could result in phosphorus bound within the aquifer material being released into the lake. However, it is not clear exactly how this mechanism might operate, nor the degree to which the 'wetting front' for groundwater would have to retreat in order for the process to be initiated.

It is worth noting at this stage that whilst groundwater abstractions located some distance from the lake may not have a direct effect on the groundwater flowing directly into the lake, they will have an effect on the overall lake water balance, and the groundwater component of that balance. As discussed in Section 3.3, the baseflow in the streams that feed into the lake can be a significant proportion of their total flow. The strata from which groundwater is taken around the lake is demonstrably leaky and thus ultimately, both deep and shallow groundwater takes will source the majority of their take from shallow groundwater. Shallow groundwater will either flow directly into the lake, or provide a baseflow into the streams that drain into the lake. Therefore, groundwater abstractions within the Lake Horowhenua catchment will influence inflows into the lake.

The first process, whereby groundwater abstraction could reduce nitrogen inputs to the lake may not significantly affect the lake health. Algal growth within the lake is phosphorus limited in winter, but nitrogen limited in summer due to plant uptake of nitrate in the spring growth phase. A reduction in groundwater inflow may therefore not have an adverse direct effect on the water quality of the lake (Gibbs, 2014).

Lake water residence time is simply a function of the lake outflow and the lake volume. Since the lake level remains largely constant, then inflows must equal outflows. Therefore, any reduction in inflows must be reflected in a reduction in outflows and an increase in the lake residence time together with a reduction in the lake flushing rate.

The precise relationship between the lake flushing rate (i.e. lake residence time) and lake health is not clear. However, a theoretical modelling exercise by Gibbs (1991) indicated that flushing the lake with clean water resulted in a significant reduction in lake phosphorus concentrations, implying improved lake health.

Some indication of the possible effect may be gained through actual monitoring data. A plot comparing the lake residence time (based on gauged flow at Hokio Stream and a lake volume of 3.8 x 10^6 m^3) to total phosphorus concentrations from the Hokio Stream at Lake Horowhenua in 2013 and groundwater levels is shown in Figure 20. To some extent it shows some of the relationships discussed in Section 6.1, with some higher groundwater levels correlating with shorter residence times and lower phosphorus concentrations, for example in November 2013. However, that relationship is not consistently present, due to the complex nature of nutrient interactions within the lake.

The most important of the three mechanisms through which groundwater abstraction may affect lake health is somewhat uncertain. However, overall, it seems likely that increased groundwater abstraction will not improve the lake health.

6.2 Recommended management approach for groundwater abstractions

The effect from most individual groundwater abstractions is small and potentially delayed and therefore direct restrictions during the course of an irrigation season such as a groundwater level trigger approach to limiting abstraction effects on the lake are not appropriate. In the area around the lake, effects from groundwater abstractions on groundwater levels in individual bores are likely to be delayed in time to an extent that trigger levels may be ineffective. For example if a trigger level is breached, the effect of reducing nearby shallow abstraction may be rapid, but more distant, or deeper abstractions will take longer to have an effect, although their overall impact is equally important. The most appropriate approach in these situations is to develop an overall allocation limit which contributes to maintaining the lake health.

Such limits are not precisely determined and require qualitative judgements to be made. They should be determined through community consultation supported by technical data. Until that thorough consultative approach can be implemented there is a need for an interim approach for considering applications to abstract groundwater.

The consented volume of groundwater abstraction is large compared to groundwater inflows. On the face of the potential effect from consented volumes, there should be no more abstractions allowed from within the catchment of a lake that is experiencing adverse effects that are made worse by a lack of throughflow and an increase in residence time. However, based on water use data, it is also clear that the majority of users do not utilise their consented volumes.

Therefore, as consents approach their expiry date and come up for renewal, a review of the allocation allowance should be undertaken for each consent to ensure it reflects realistic use requirements, taking into account past water use records. Based on flow meter records to date, this assessment of realistic water use requirements has the potential to make a meaningful reduction in consented allocation and reduce the potential for groundwater allocation to affect the lake health.

The highest total annual use relative to the total consented volume (across all consents in the capture zone to Lake Horowhenua) since 2015/2016 was 22%. Whilst it is not yet possible to develop an allocation limit that is strictly linked to direct effects on the lake health, given the utilisation of consented takes, the allocation could be reasonably be reduced to a more realistic value that should represent a reduction for the lake catchment of at least 50% of the currently allocated volume, i.e. 50% of 2.45 million m^3/year, or 1.23 million m^3/year. However, that proposed value will need to be confirmed in consultation with the community.

An allocation limit of 1.23 million m^3/year would still allow a possible opportunity for new abstractions to occur, provided they are subservient to (and fit within) the 1.23 million m^3/year consented allocation amounts. Such an arrangement can only occur with the agreement of existing consent holders, who would need to confirm that they will not utilise their full consented volume, so as to make it accessible to a new user.

Any such arrangements are best determined through a water user group so that all users are aware of the water management issues and are involved in developing the solution. Such a group should consider not only water abstraction issues but also land management methods to reduce nutrient losses from the land.

1. The total consented groundwater allocation should not exceed the proposed annual allocation, 1.23 million m^3/year;
2. Any application for new groundwater abstractions can only occur if:
    a. They have a low surface water depletion effect (as defined in policy 15-2C of the One Plan) on Lake Horowhenua or Lake Papaitonga, or the surface waterways that feed into the lakes; and
    b. They are subservient to (or receive transfers from) existing groundwater abstraction consents from within the catchment so no increase occurs in the total consented allocation.
    c. When applications are received to replace current consents they should be subject to a water efficiency check and the allocation of water should be defined in terms of peak pumping rates, daily volumes, annual volumes and perhaps monthly or seasonal values to constrain the volume of water allocated to realistic usage. The intention of this approach is to reduce the currently consented volumes to around 50% of the current allocation volume.

7.0 Conclusion

Excluding baseflow within the streams and springs, the potential range of proportions of groundwater inflow to the lake is in the order of 36 % to 62 % of total flows and this proportion would be greater if baseflow was included. This is a relatively high proportion, and implies that the lake may have a high dependency on groundwater to sustain its levels. There are several areas where additional monitoring may help to refine these estimates including monitoring shallow groundwater levels close to, and potentially directly beneath the lake.

Seasonally it seems likely that in summer, consented groundwater abstraction could account for a significant proportion of the total lake inflow (up to 24 %, or 40 % of groundwater inflows alone, based on average flow rates), although water use data suggests that in reality most consent holders rarely use their fully consented volume, and typically actual groundwater abstraction is likely to account for around 9 % of total inflows to the lake in summer and 14 % of groundwater inflows to the lake.

There is uncertainty around the mechanism through which groundwater abstraction affects lake health and in reality, any adverse effects are likely to be due to a combination of factors including changes to the lake residence time and changes to the rate of groundwater seepages into the lake. The most appropriate means to control any adverse effects on the lake due to groundwater abstraction is to develop an annual groundwater allocation limit for groundwater takes within the Lake Horowhenua catchment. This could be achieved based on a calibrated groundwater model of the area, in conjunction with a rainfall runoff model.

Such limits are best defined through community consultation supported by technical information and ongoing collection of monitoring data. Until these limits are defined and set an interim approach to consent applications should avoid any increase in the currently consented volume and should seek to reduce that volume as applications are received to replace or transfer existing consents. Based on the available data comparing consented volumes to actual metered water use, a reduction in the existing annual volume of at least 50% would be realistic and achievable without unduly restricting water use in the area.

8.0 References

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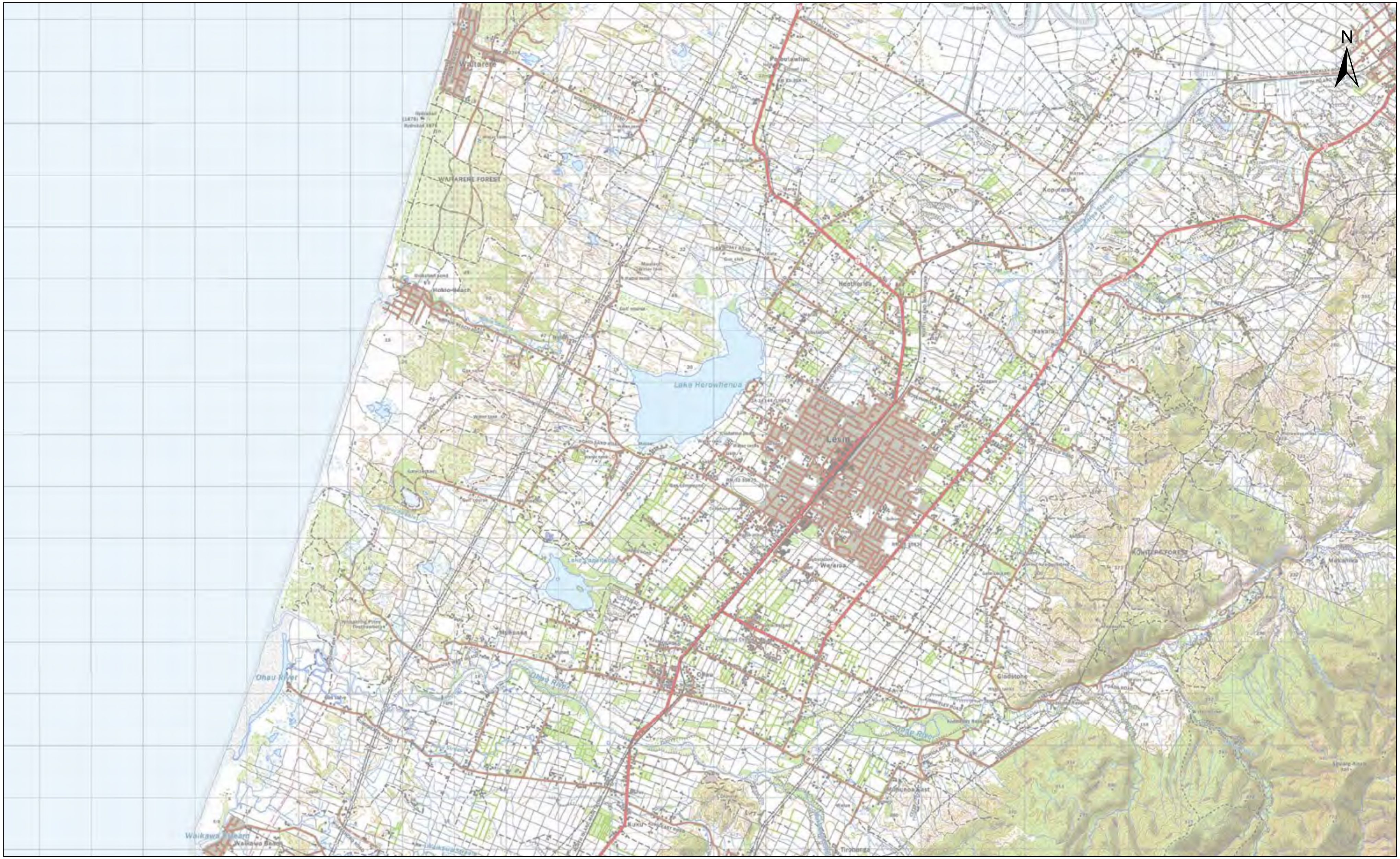
Appendix A
Figures



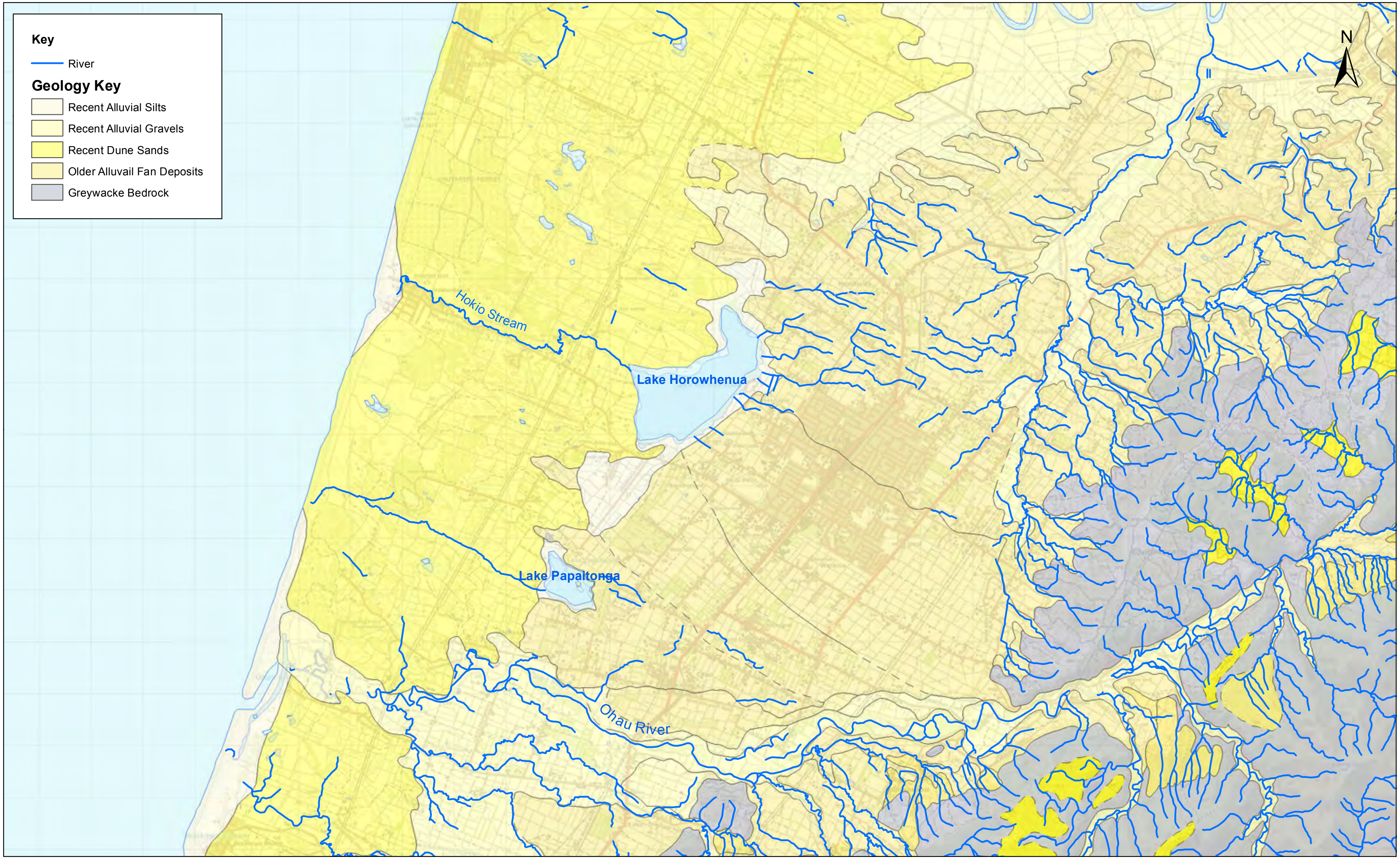
SCALE : 1:100,000 (A4)

0 1.25 2.5 5

Kilometers

SOURCE:
BACKGROUND IMAGE SOURCED FROM FRESHMAP

FIGURE 1 : LOCATION MAP



SOURCE:
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GEOLOGICAL DATA FROM GNS QMAP WELLINGTON

FIGURE 2 : GEOLOGICAL MAP

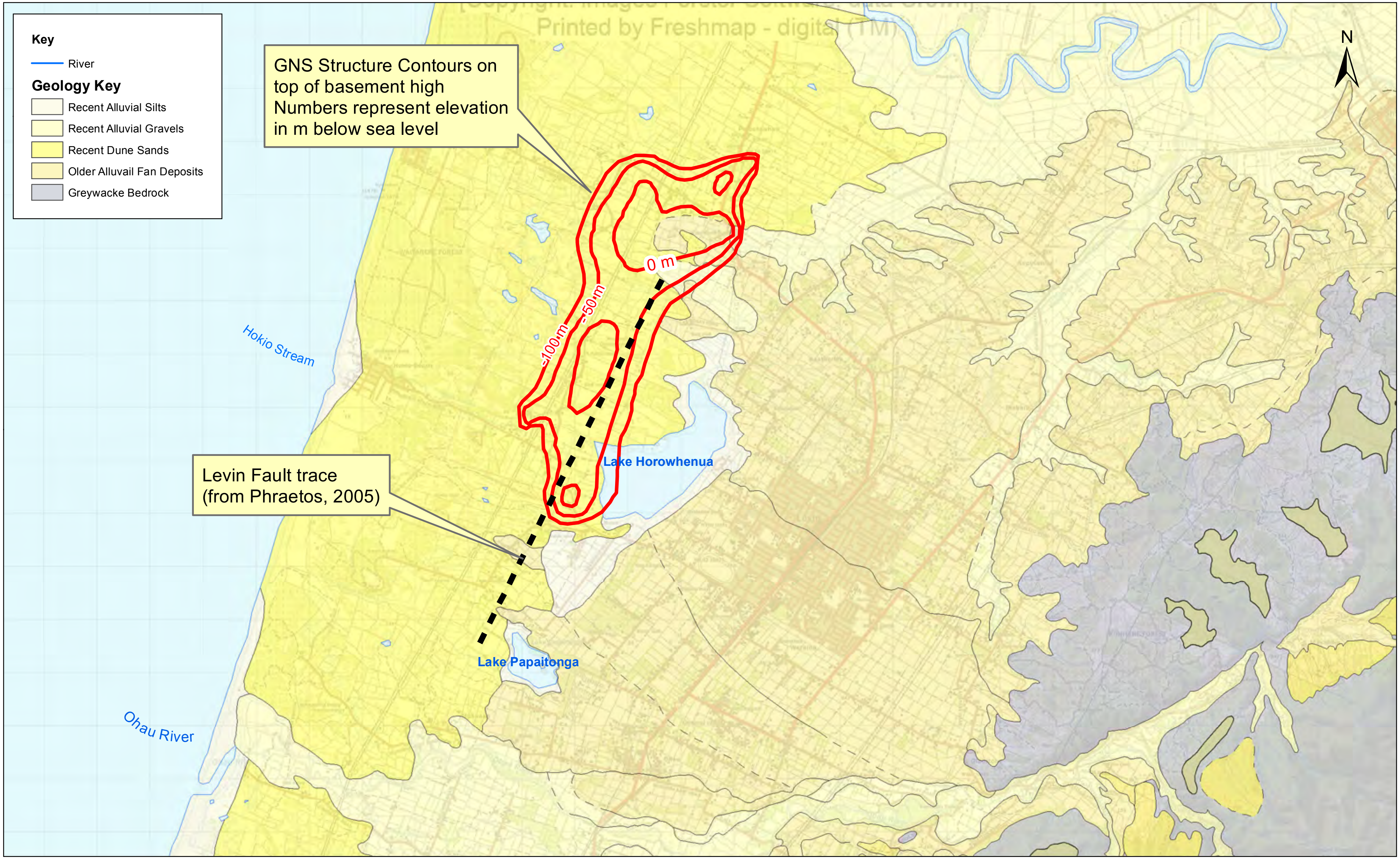

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FIGURE 3: LEVIN FAULT AND BASEMENT HIGH

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Kilometers

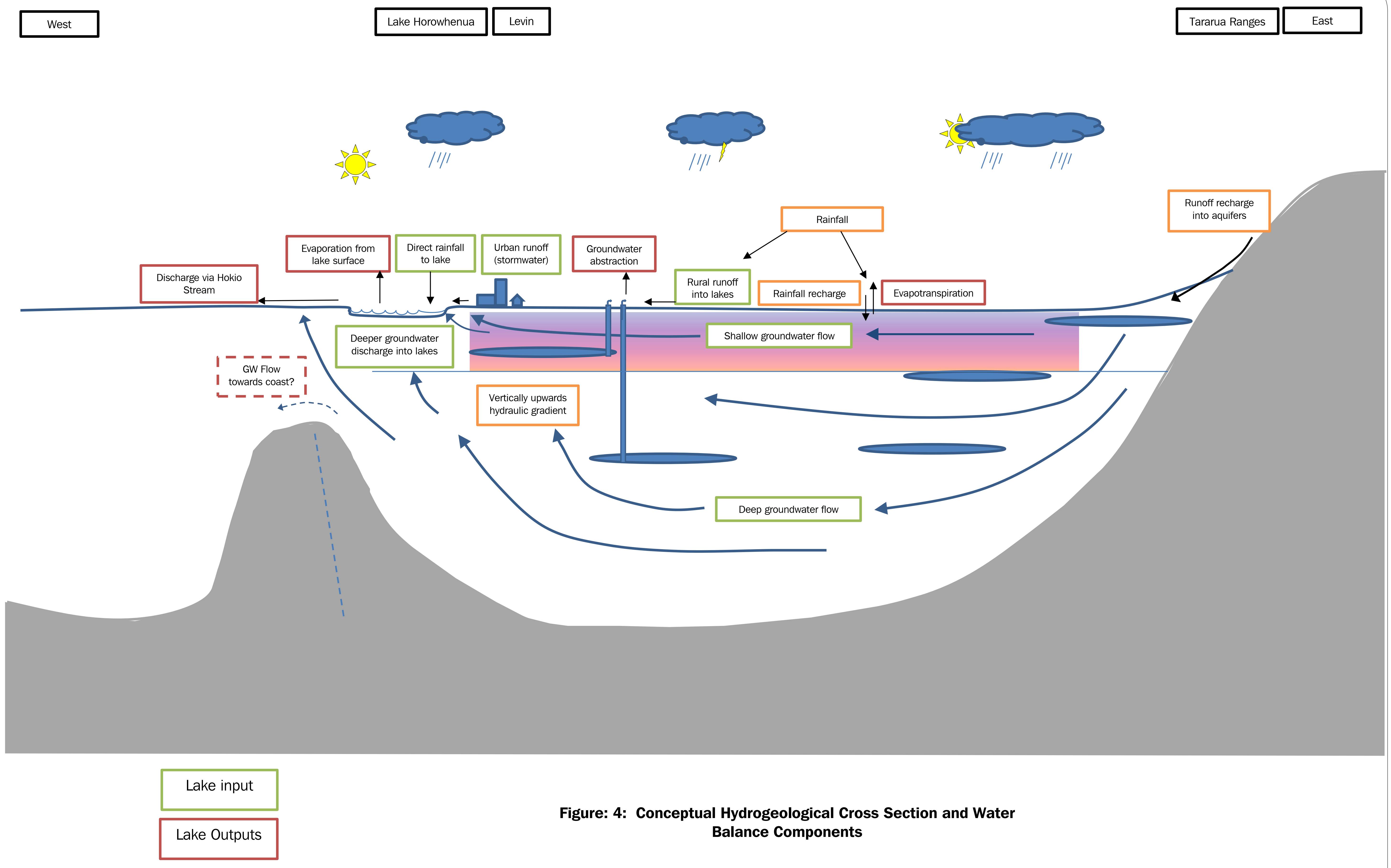


Figure: 4: Conceptual Hydrogeological Cross Section and Water Balance Components

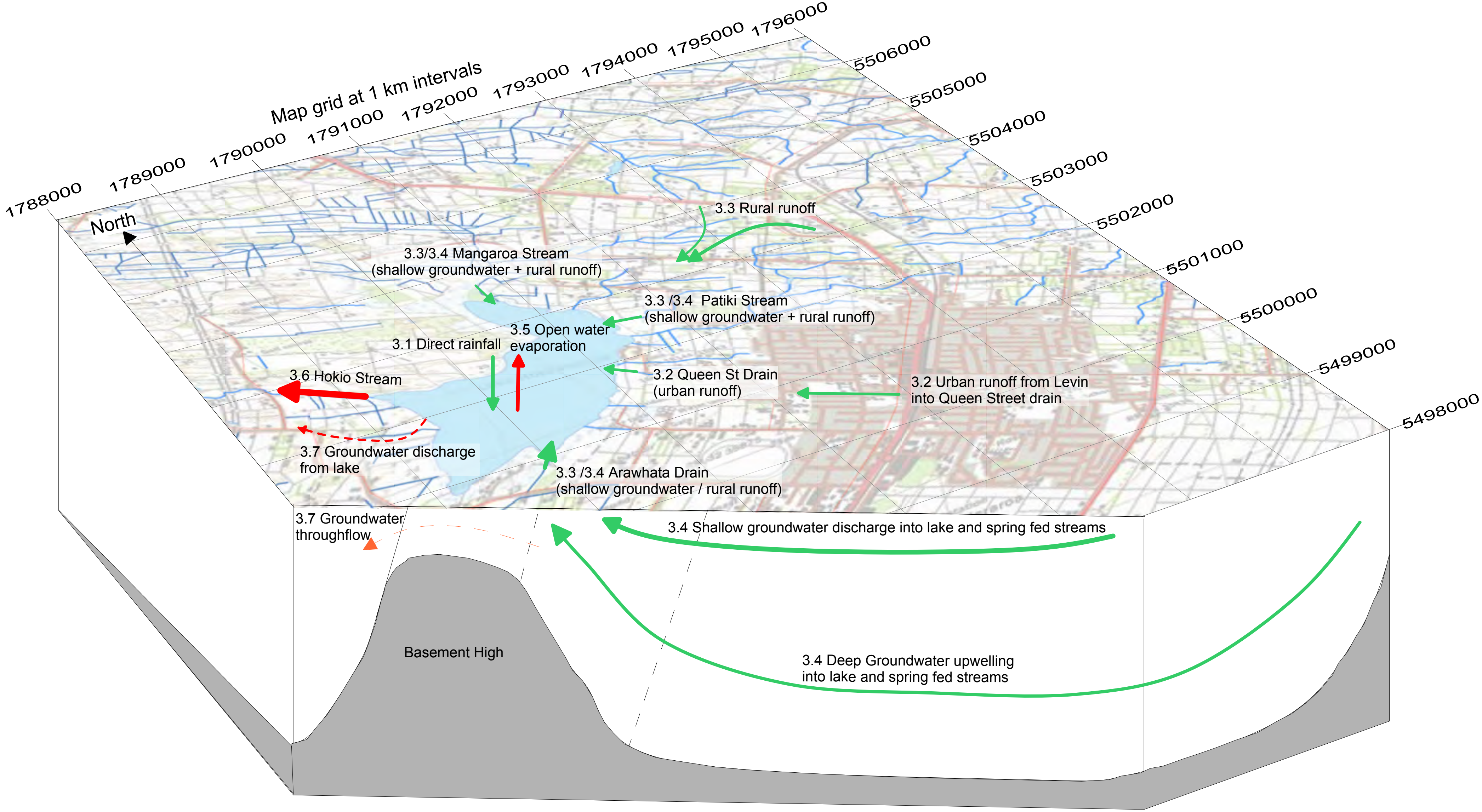


Figure 5: Map of water balance components for Lake Horowhenua (numbers adjacent to components refer to relevant section in report)

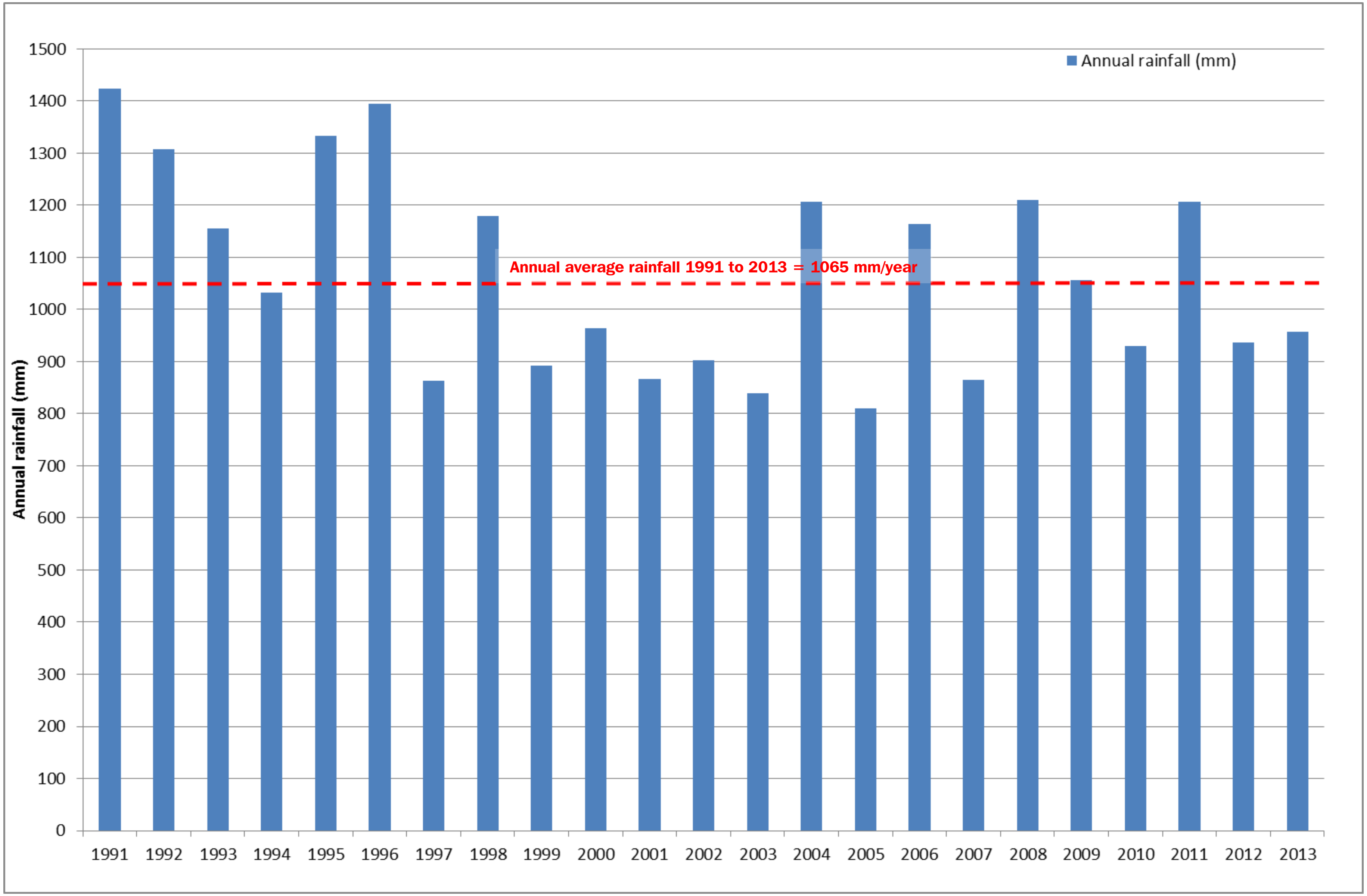


Figure 6: Annual rainfall totals at the Levin AWS weather station

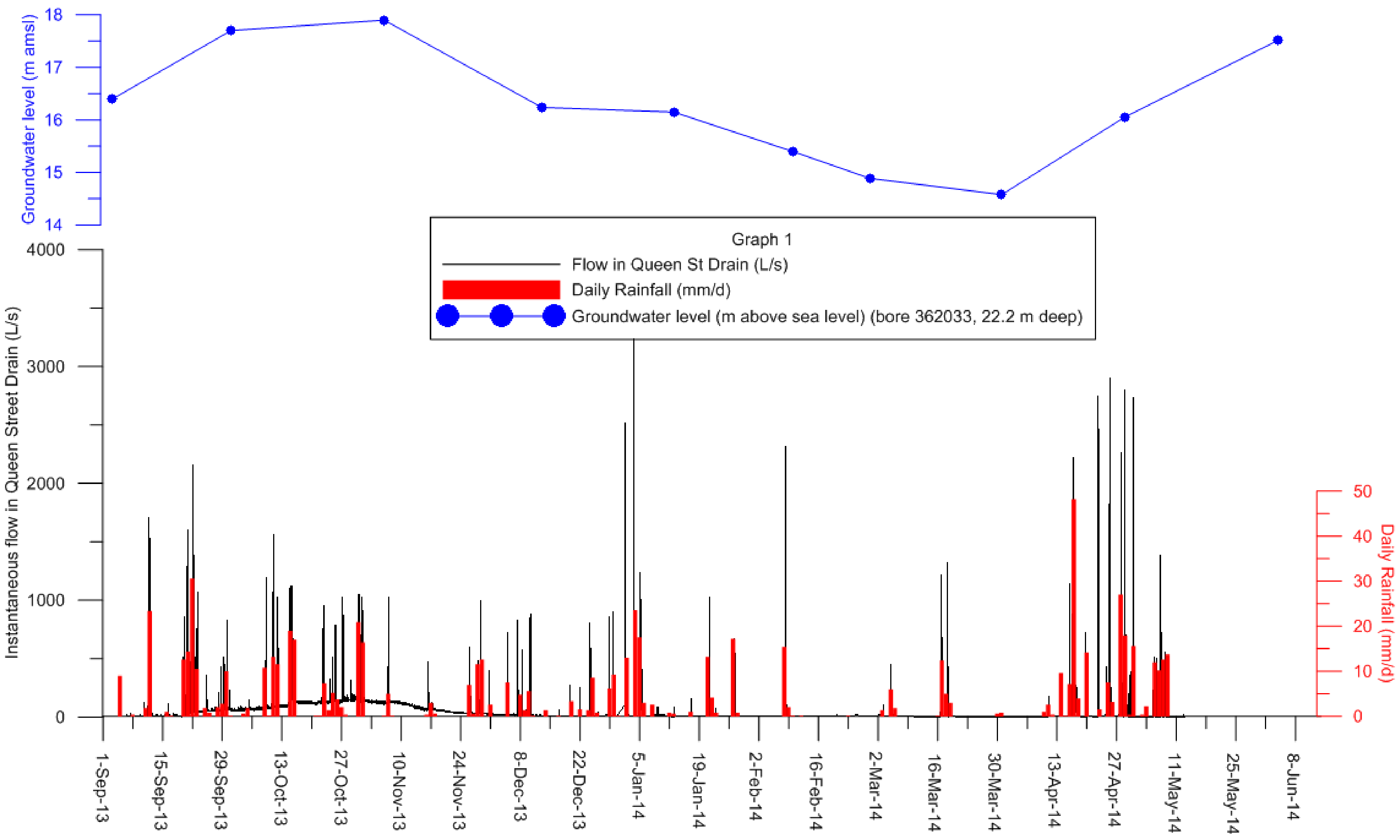


Figure 7a: Continuous flows measured in Queen Street Drain compared to daily total rainfall at Levin AWS and groundwater levels in bore 362033 (22.2 m deep)

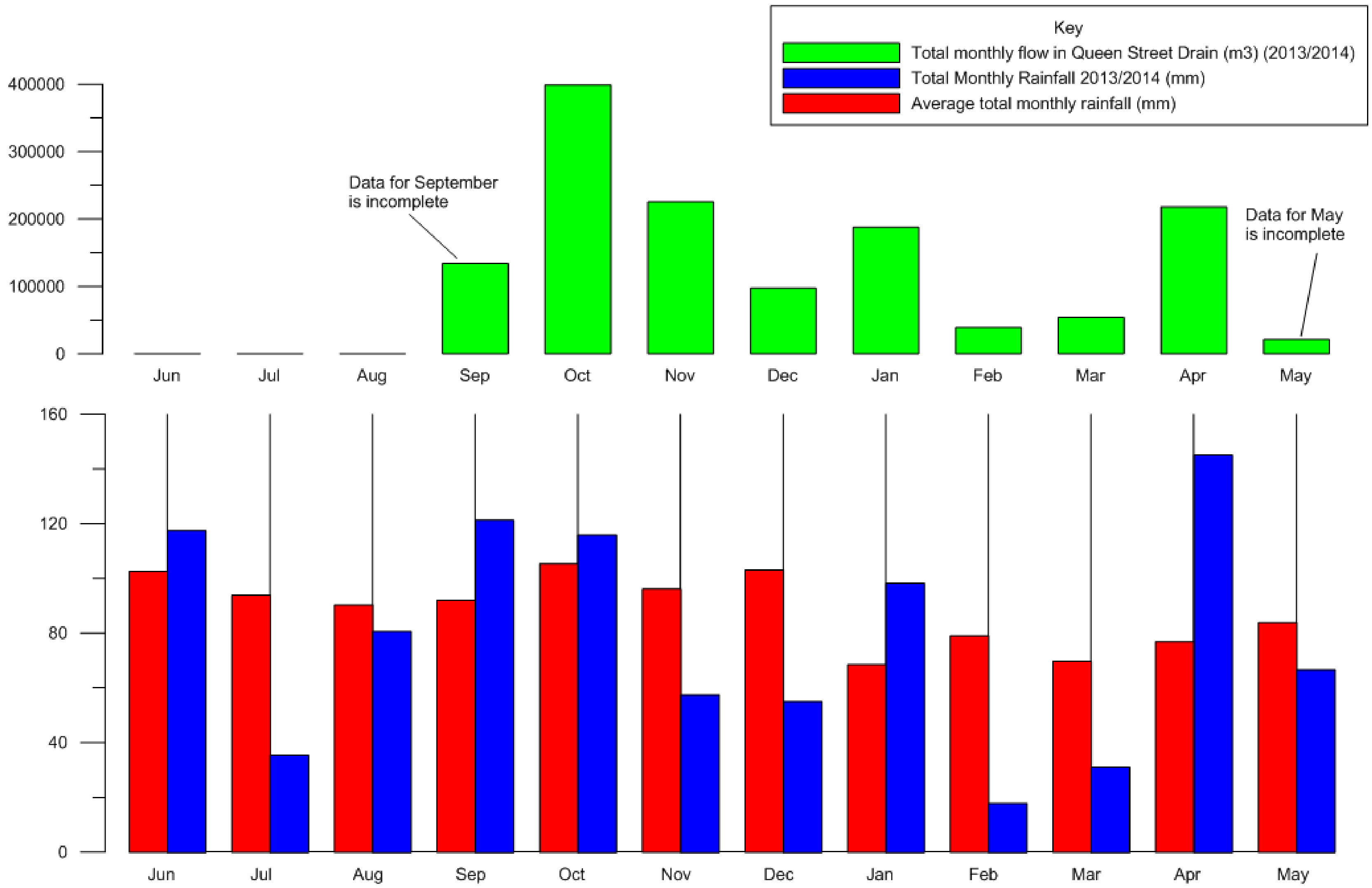


Figure 7b: Total monthly flows in the Queen Street Drain compared to rainfall

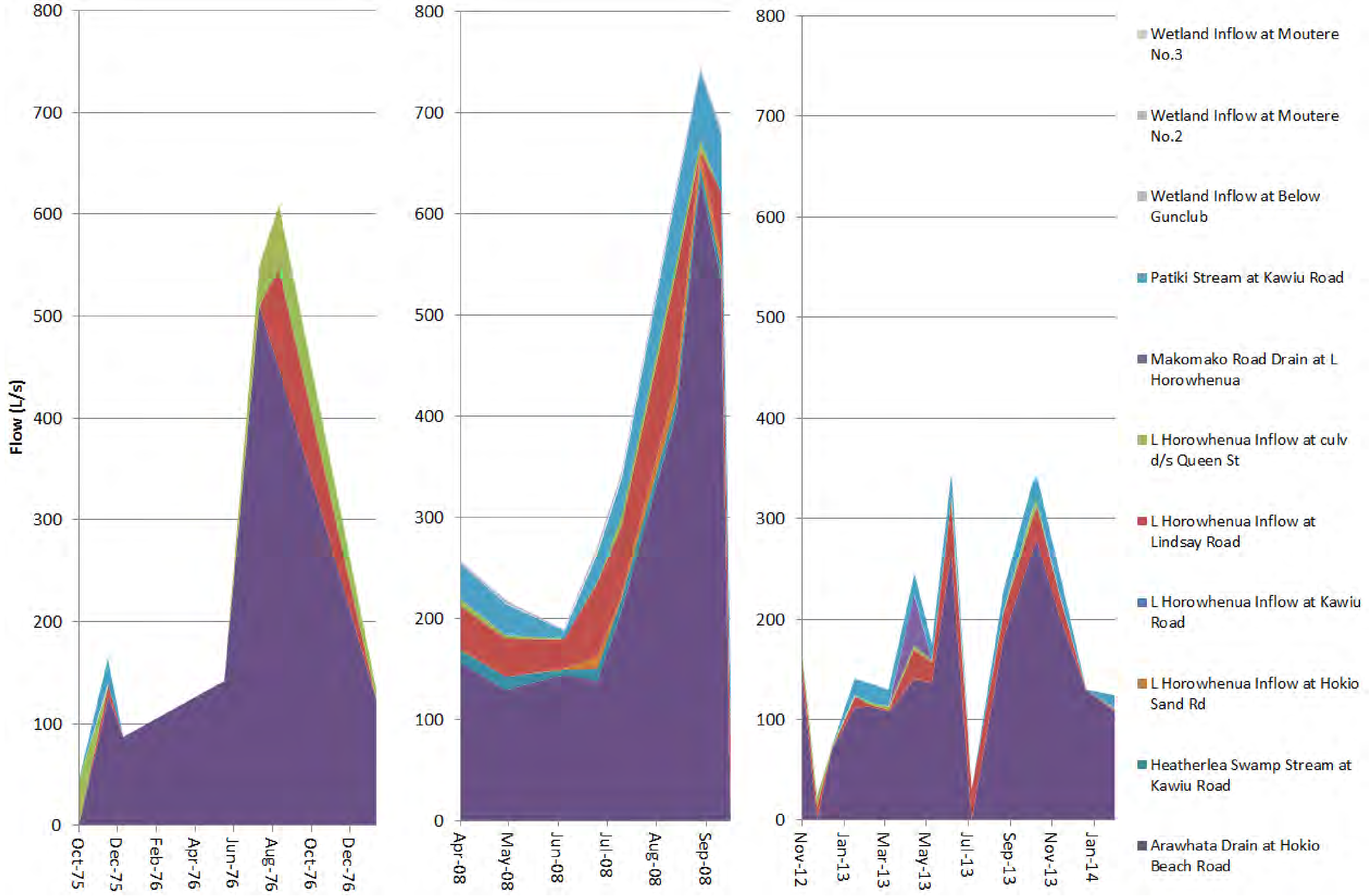


Figure 8a: Total inflows (gauged) excluding flows gauged in the Queen Street Drain. Note that no gauging occurred in the Arawhata Drain in July 2013, resulting in the apparent drop in flows.

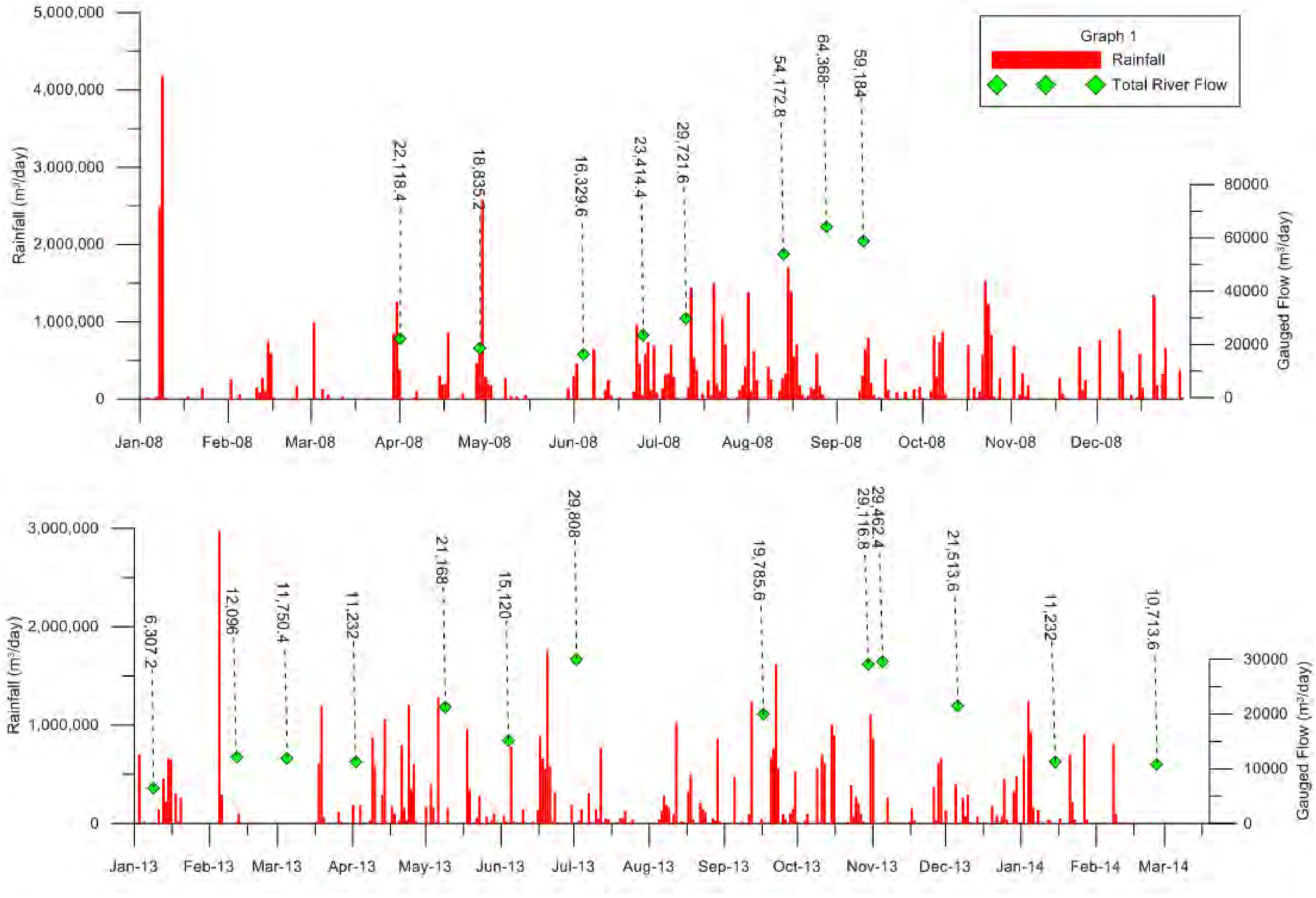


Figure 8b: Daily rainfall and gauged total flows into the catchment for 2008 and 2013/2014

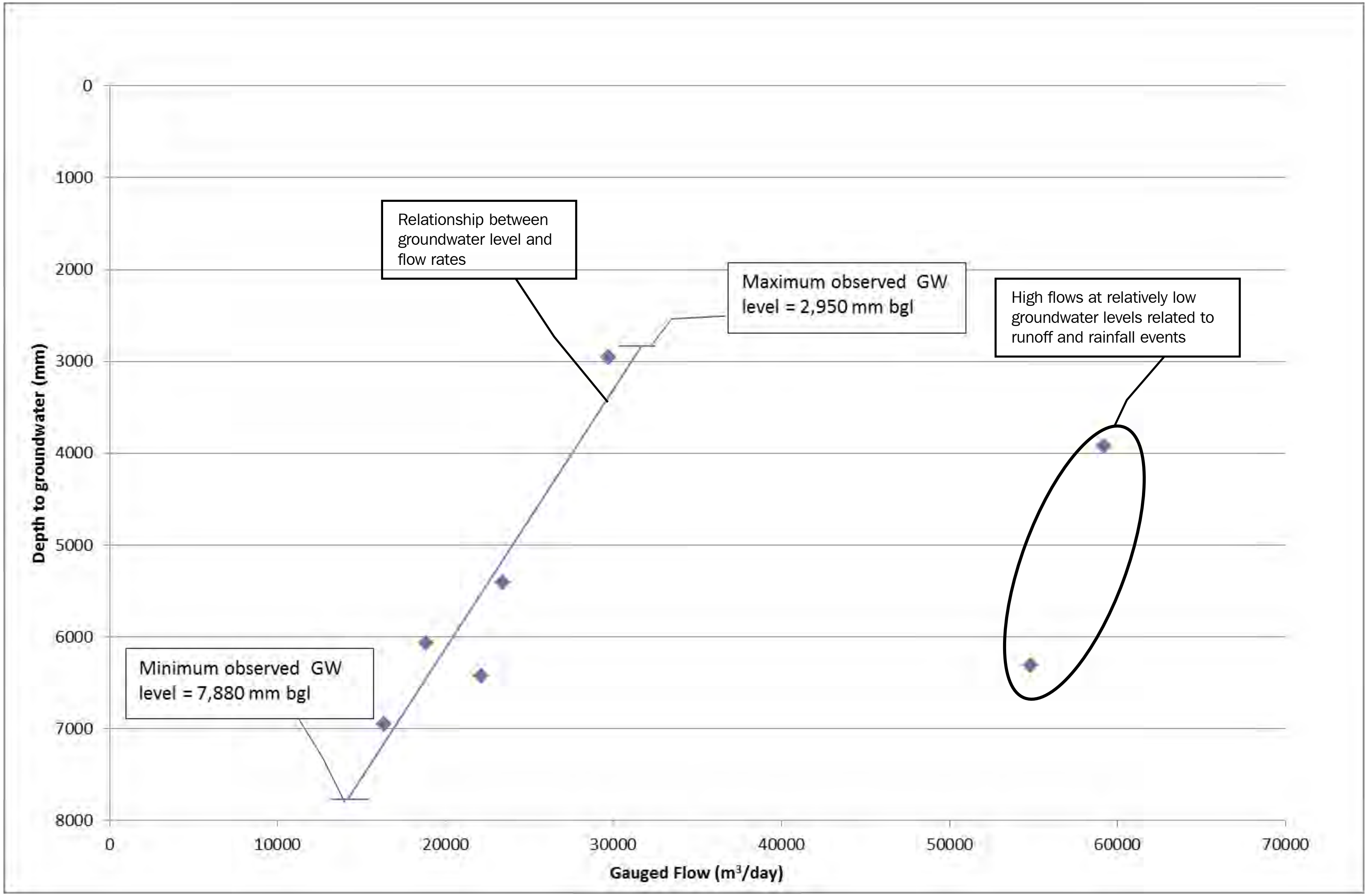


Figure 9a: Depth to groundwater compared to gauged flows in 2008 (April to September)

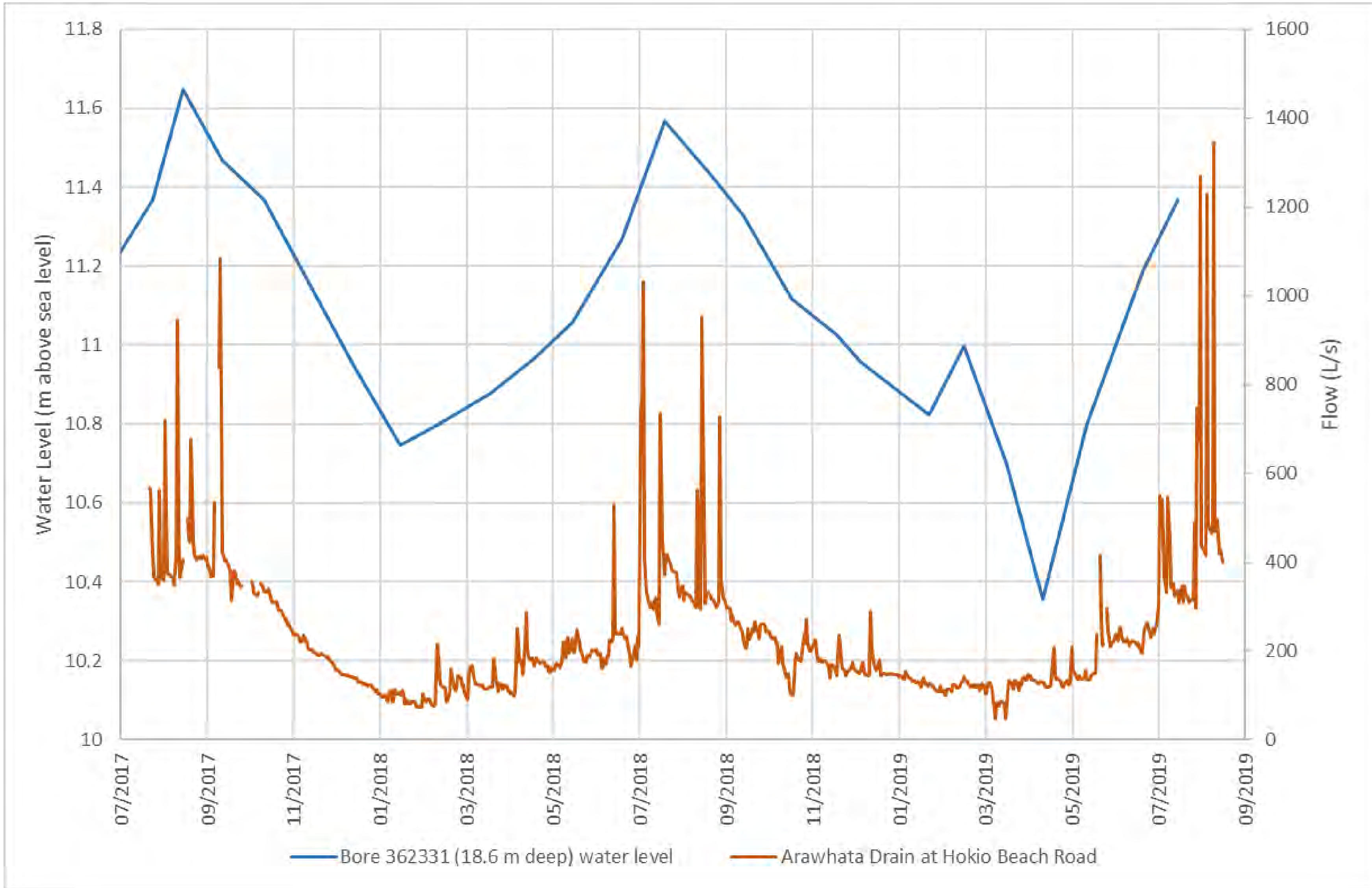


FIGURE 9B: FLOW RECORD IN ARAWHATA DRAIN AT HOKIO BEACH ROAD BETWEEN JULY 2017 AND AUGUST 2019

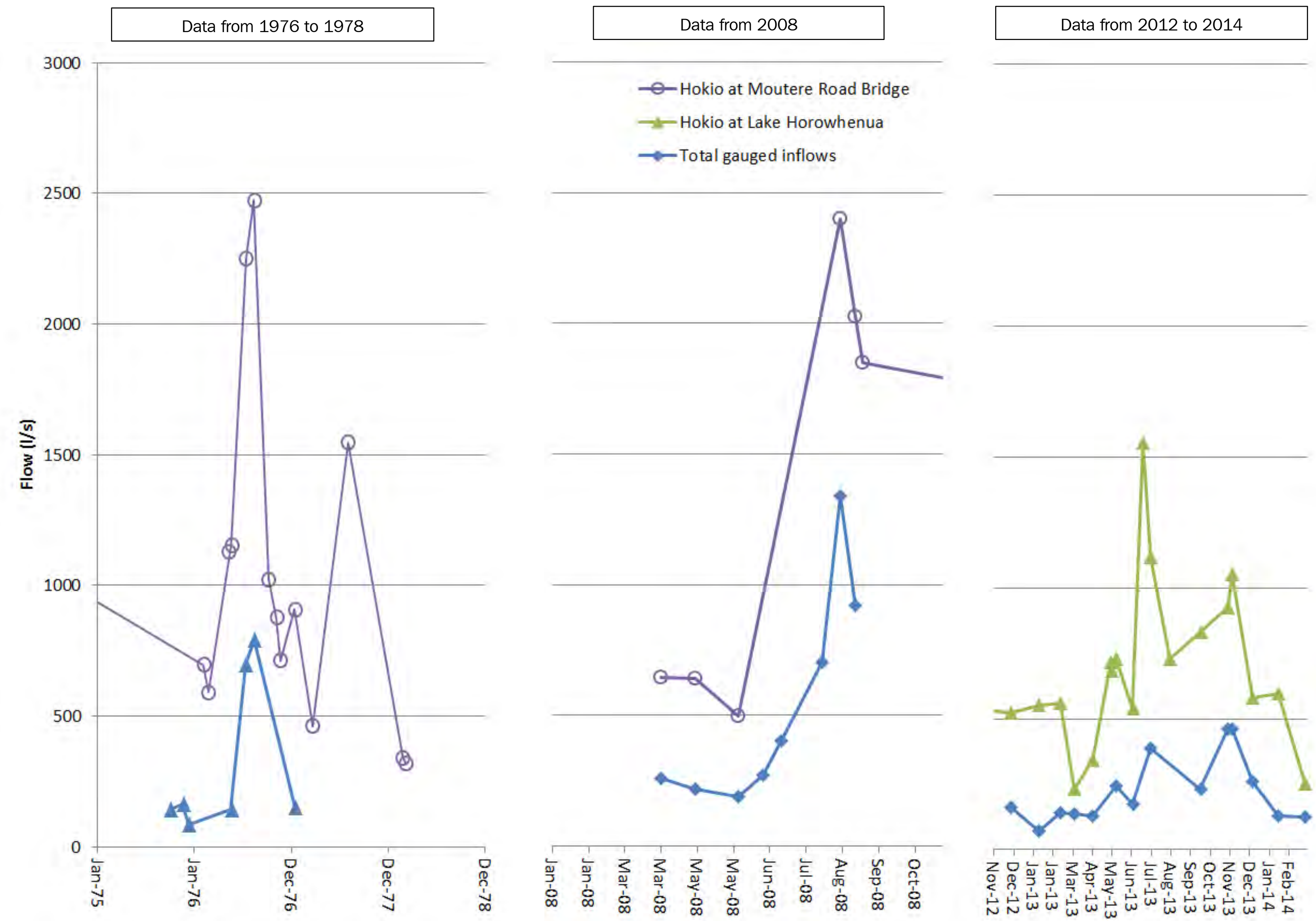


Figure 10: Total inflows to the lake compared to total outflows. Note that flows out of the lake were gauged at Moutere Bridge between 1975 and 2008, but since 2012 gauging has been at the lake outlet, although some overlap has also occurred.

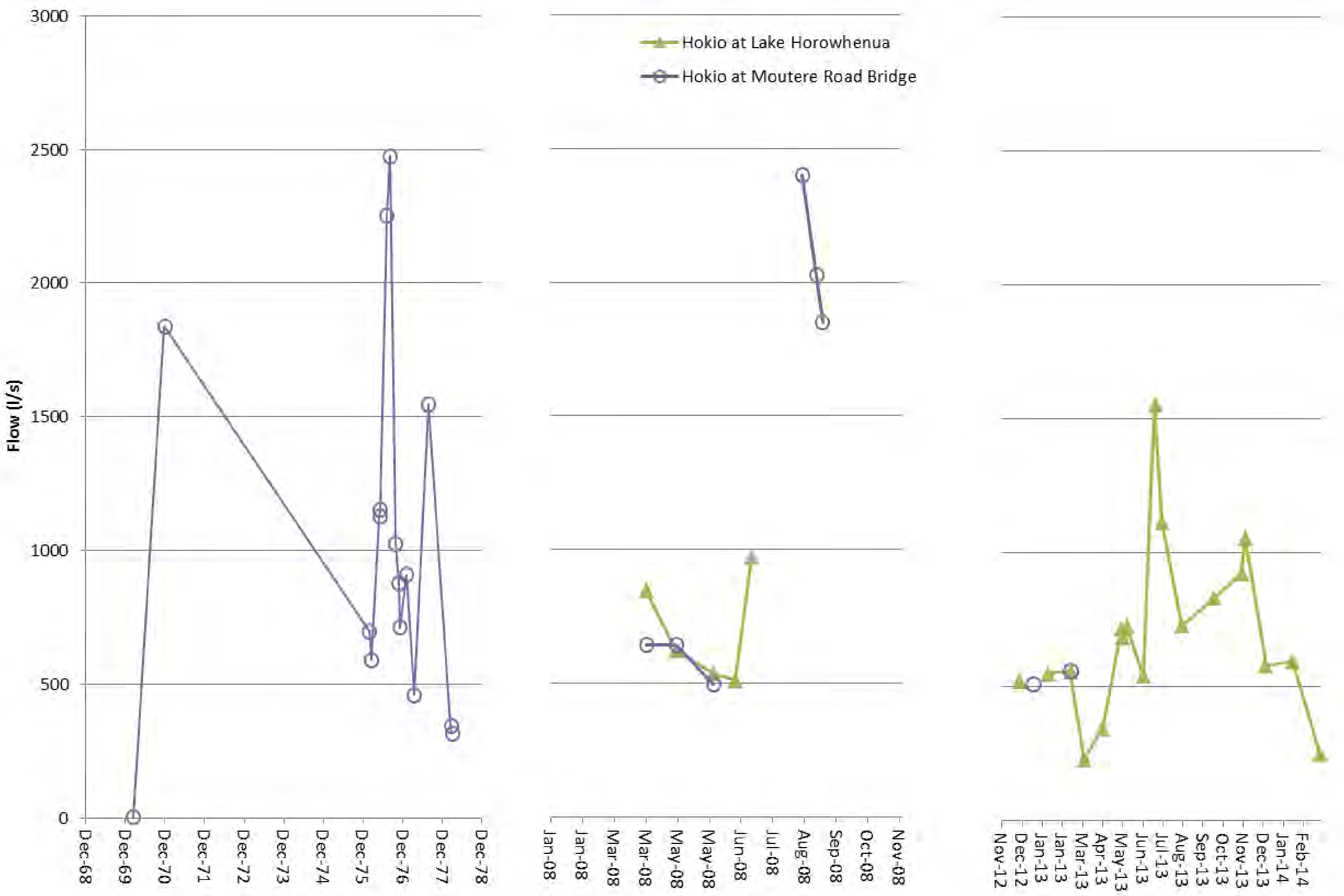


Figure 11: Gauged flows at Lake Horowhenua for the Hokio at Lake Horowhenua and the Hokio at Moutere Bridge for different times

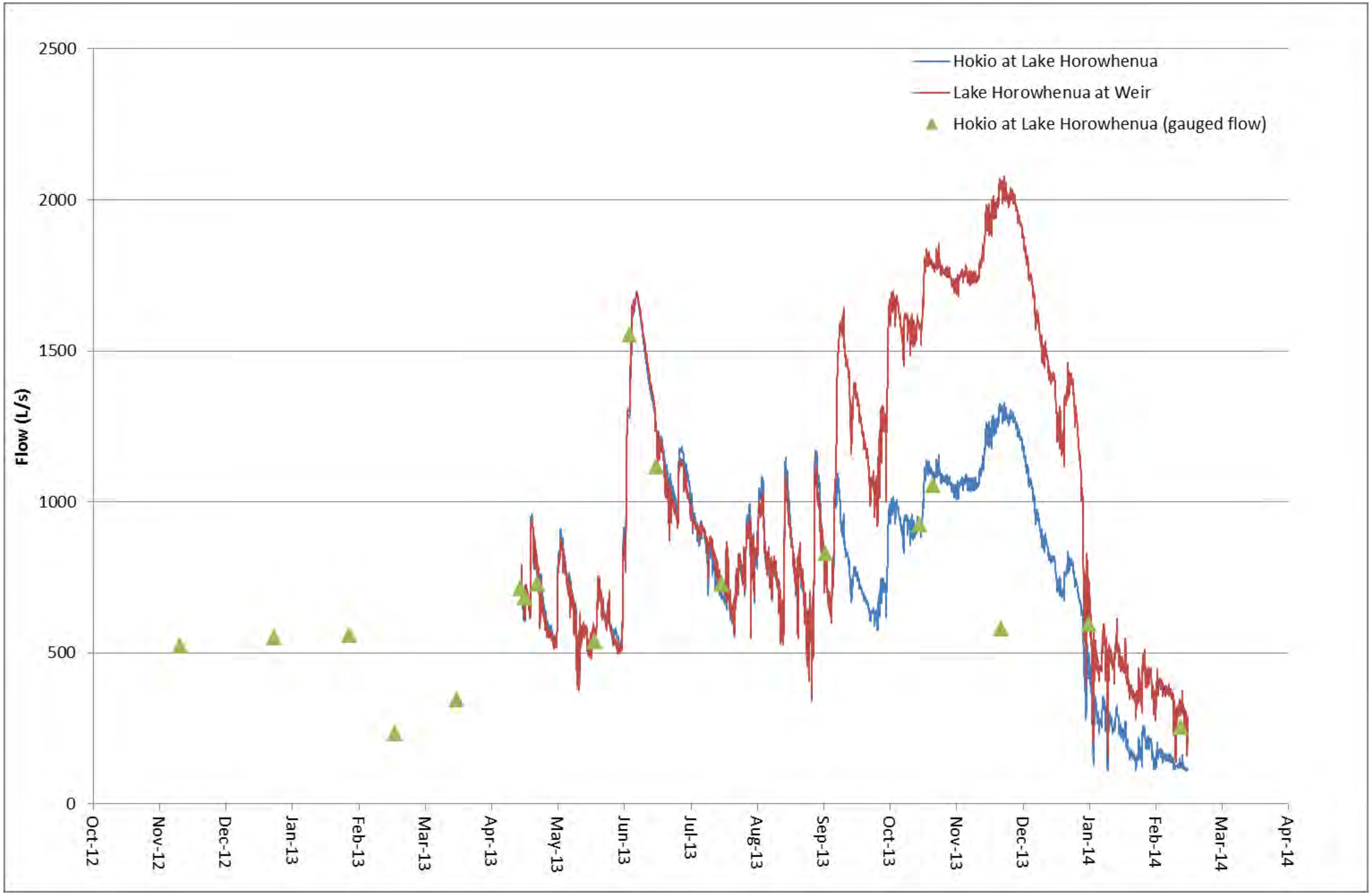


Figure 12: Recorded flows at Lake Horowhenua outlet compared to gauged flows

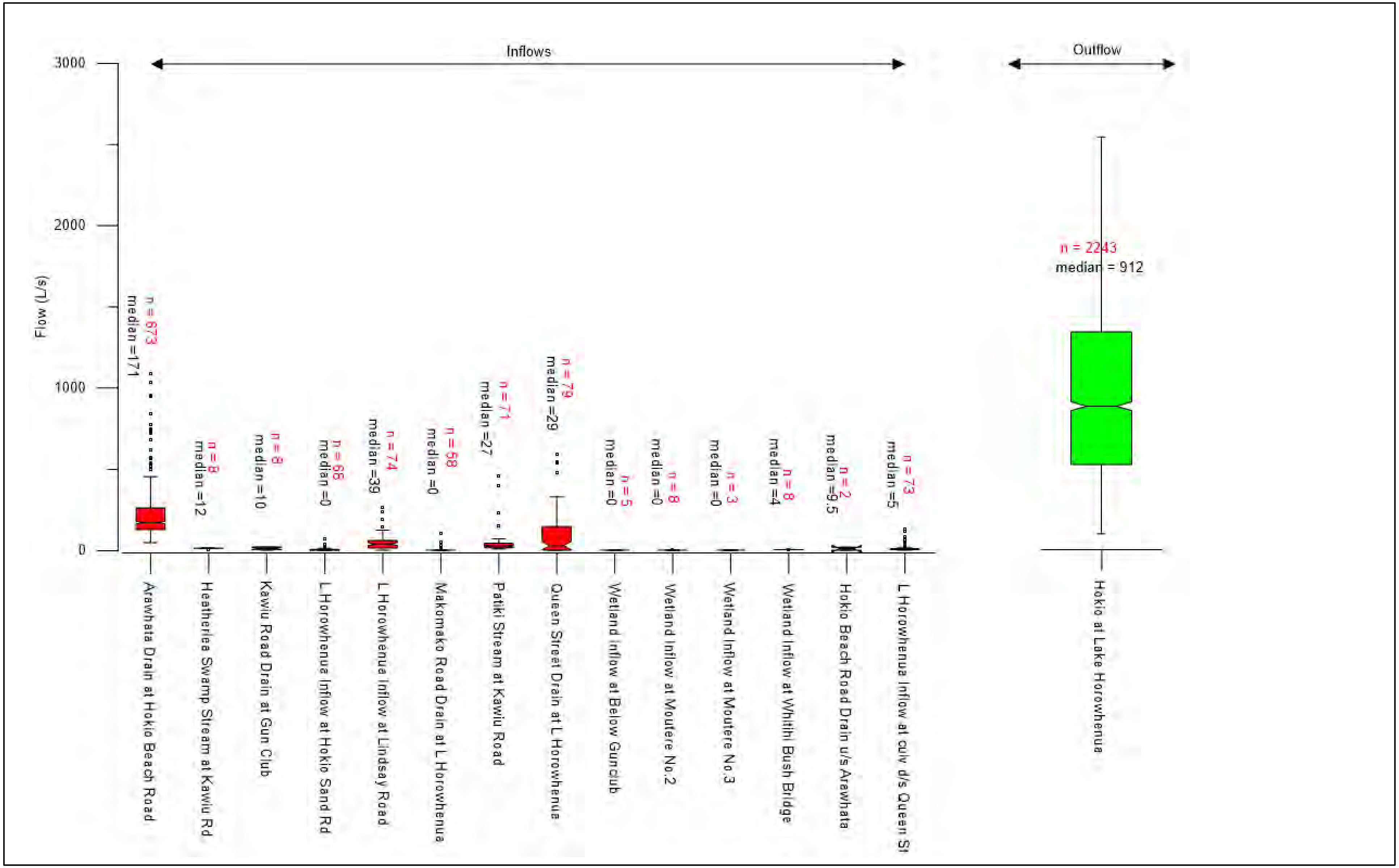
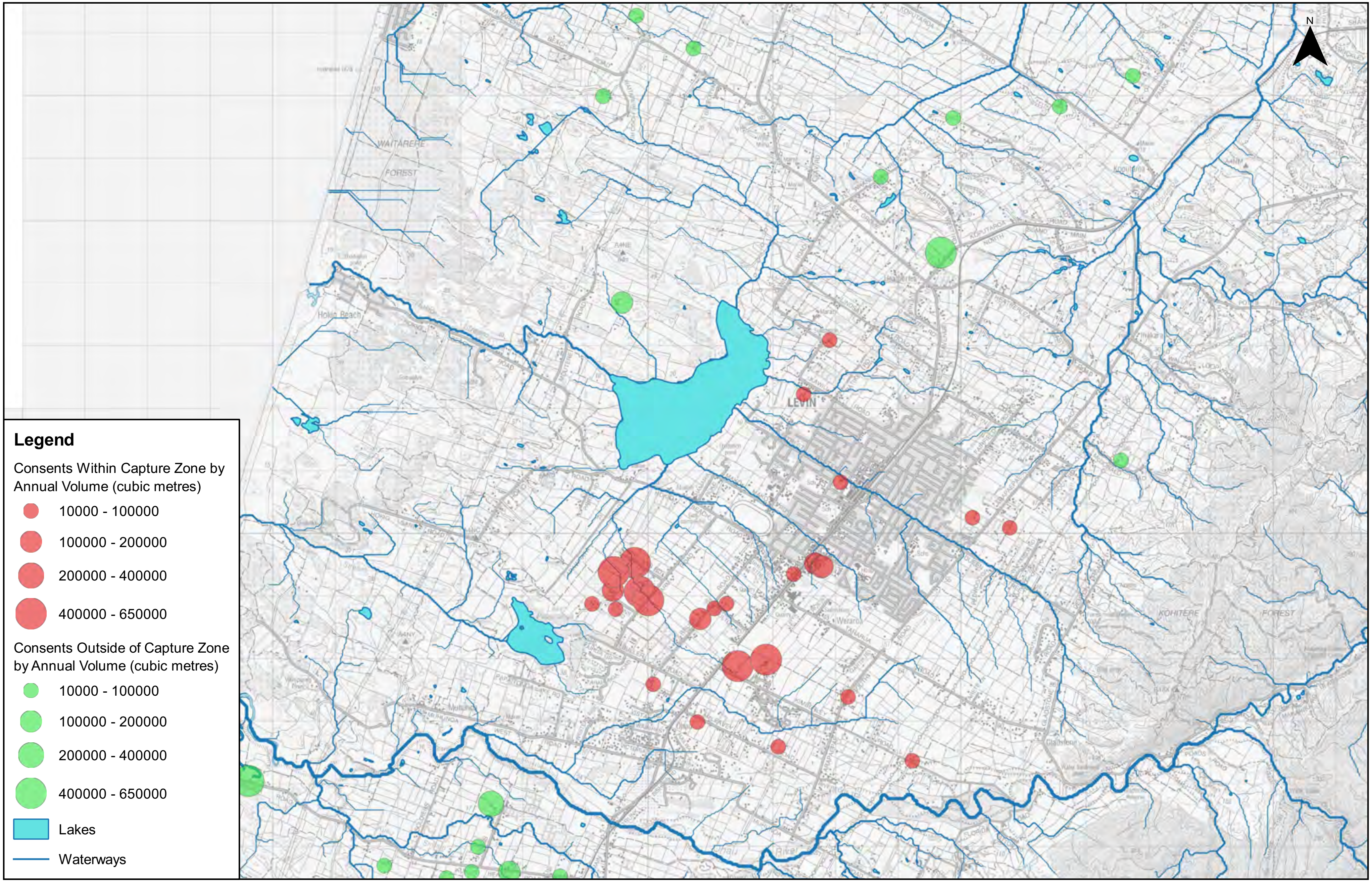


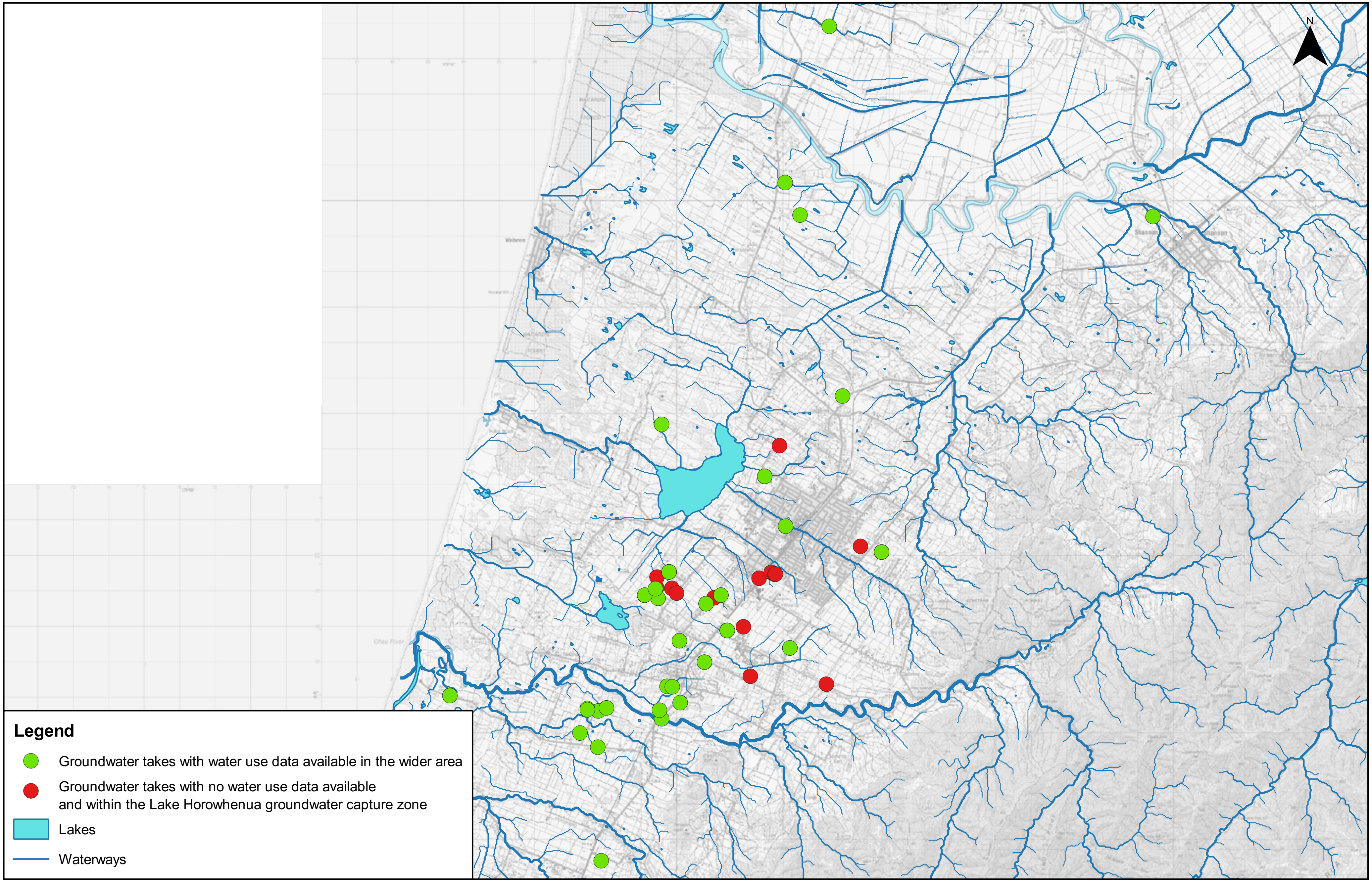
FIGURE 13: FLOW STATISTICS FOR SURFACE WATER INFLOWS AND OUTFLOWS OF LAKE HOROWHENUA



Note: Locations of features shown above are approximate.
Background image from LINZ Topo50 map.

FIGURE 14: LOCATION OF CONSENTS WITHIN LAKE HOROWHENUA GROUNDWATER CAPTURE ZONE

1 0 1 2 3 km



Note: Locations of features shown above are approximate.
Background image from LINZ Topo50 map.

FIGURE 15: LOCATION OF CONSENTS WITH AVAILABLE WATER USE DATA WITHIN LAKE HOROWHENUA GROUNDWATER CAPTURE ZONE

1 0 1 2 3 km

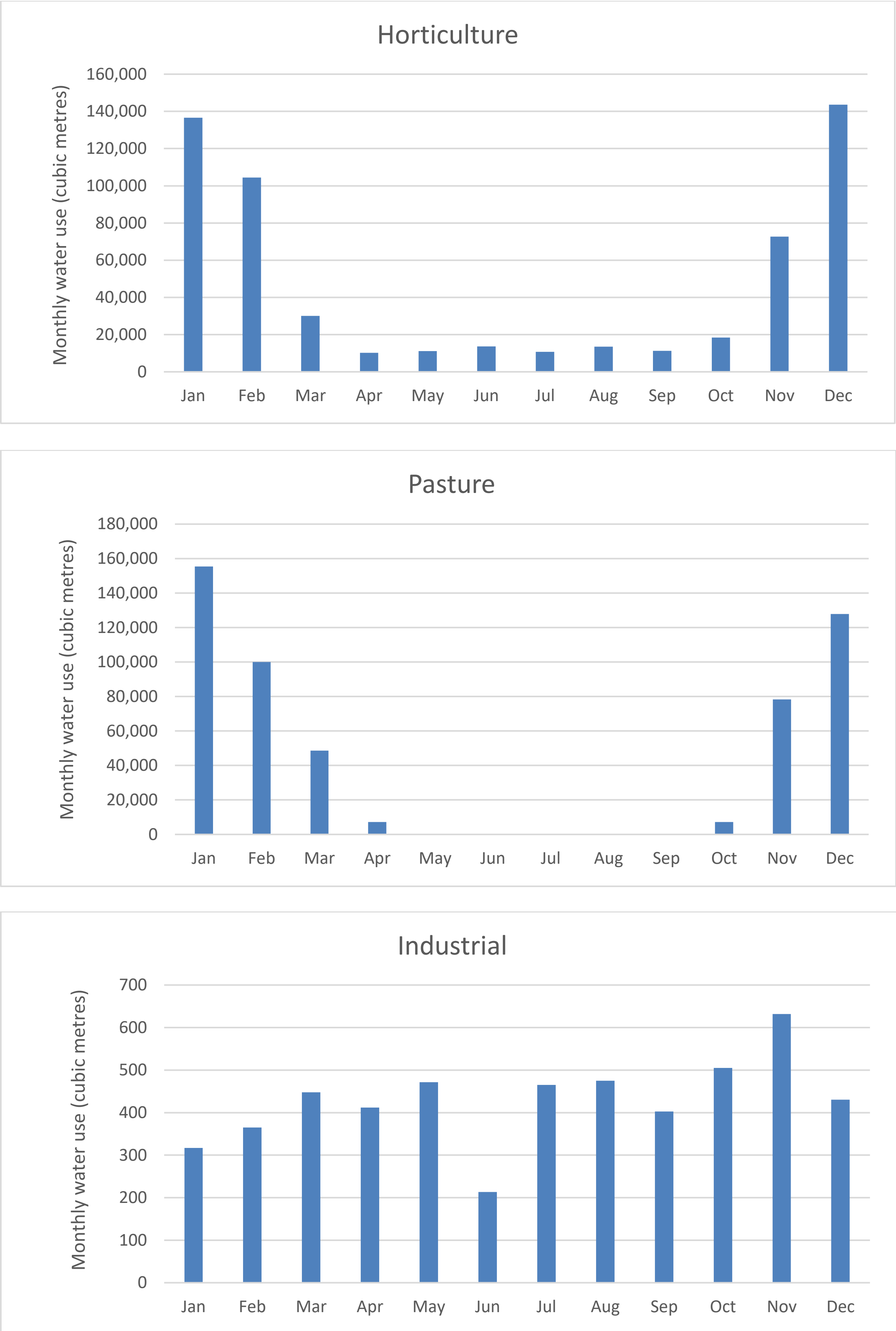


FIGURE 16: AVERAGE WATER USE PER MONTH BY CONSENTED USE

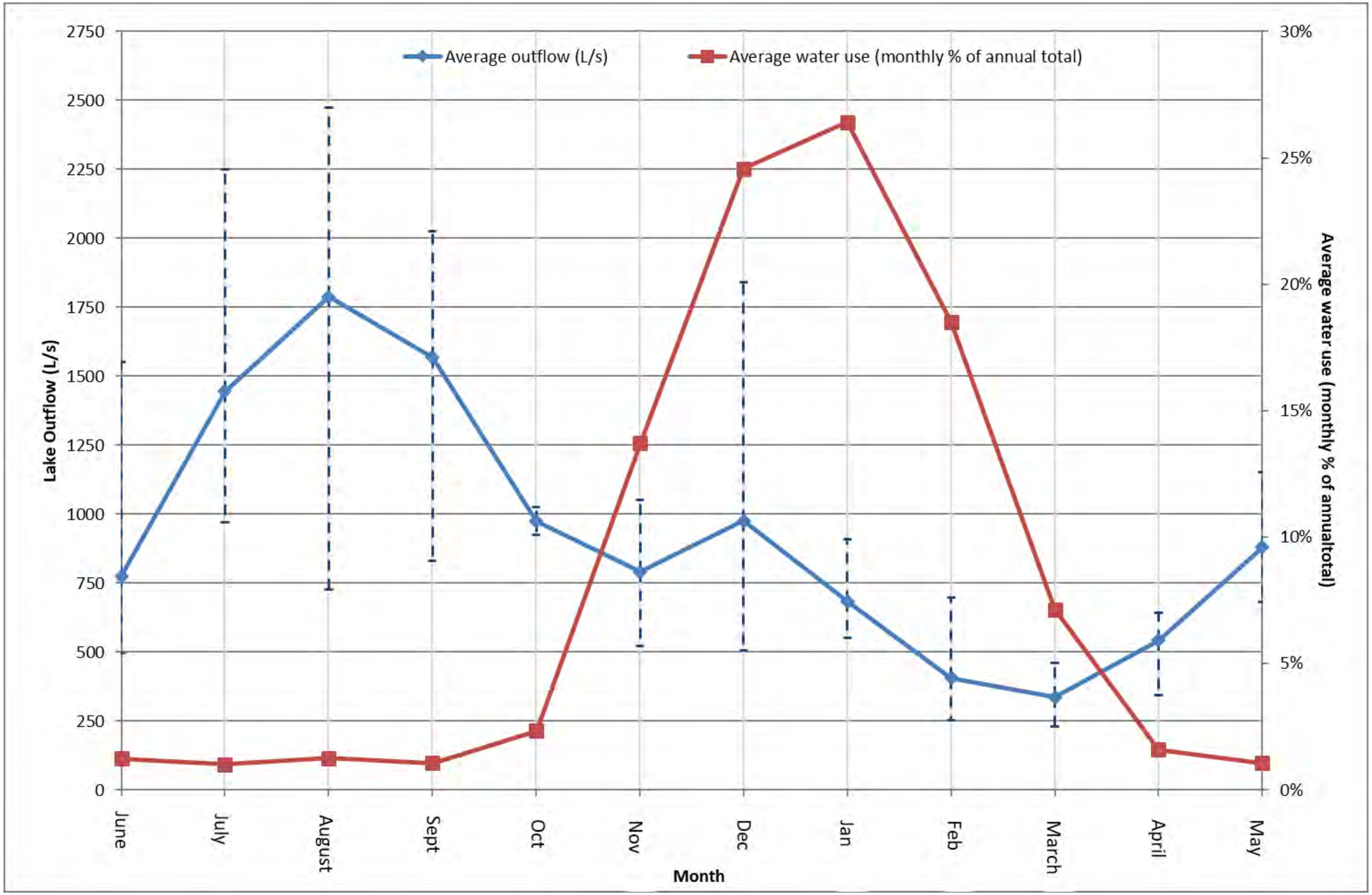


Figure 17: Relative monthly abstraction compared to average lake outflows (dashed lines indicate maximum and minimum flow rates)

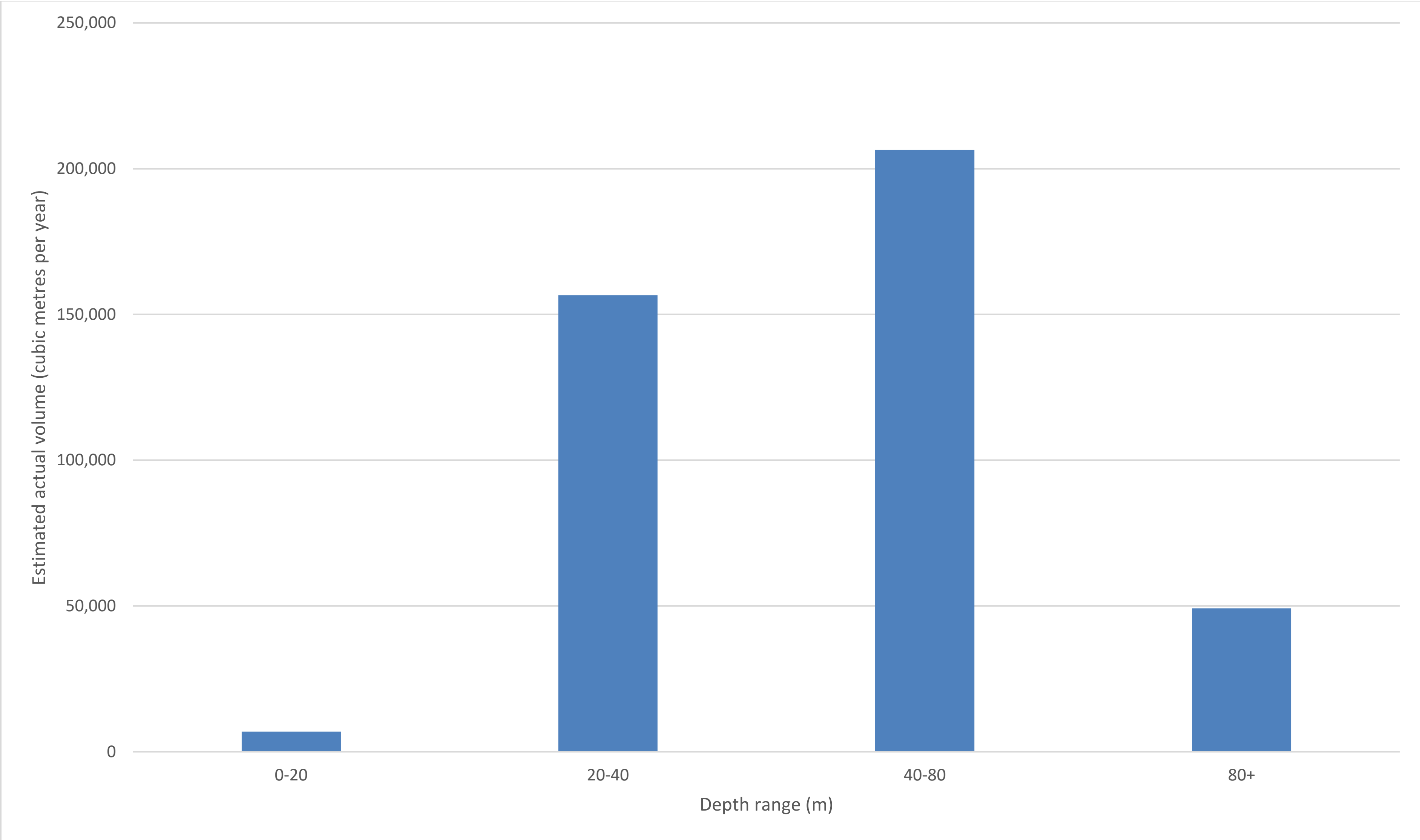


FIGURE 18: ESTIMATED ANNUAL WATER USAGE BY BORE DEPTH

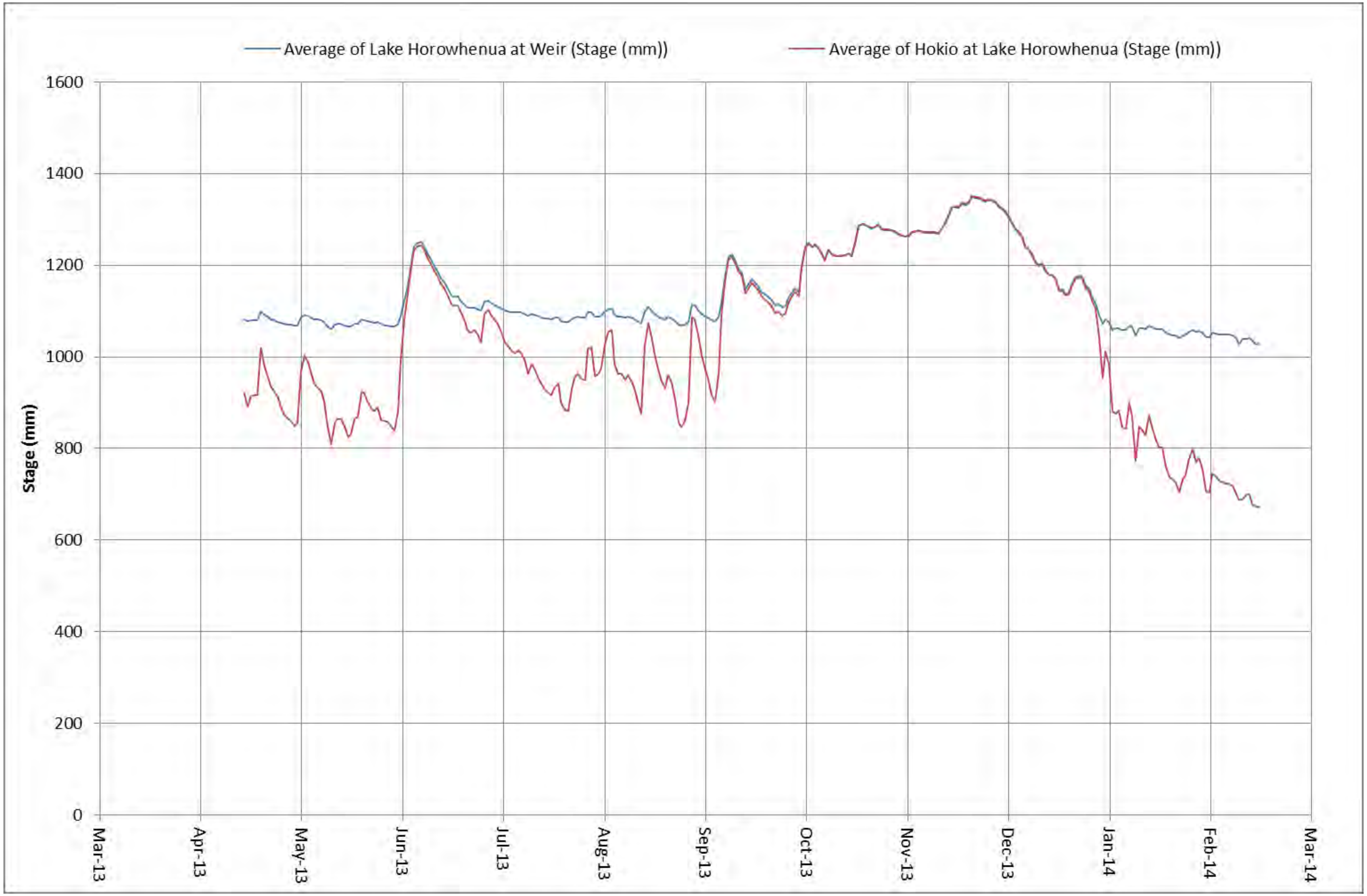


Figure 19: Lake Stage (mm)- Blue line represents lake level above the weir

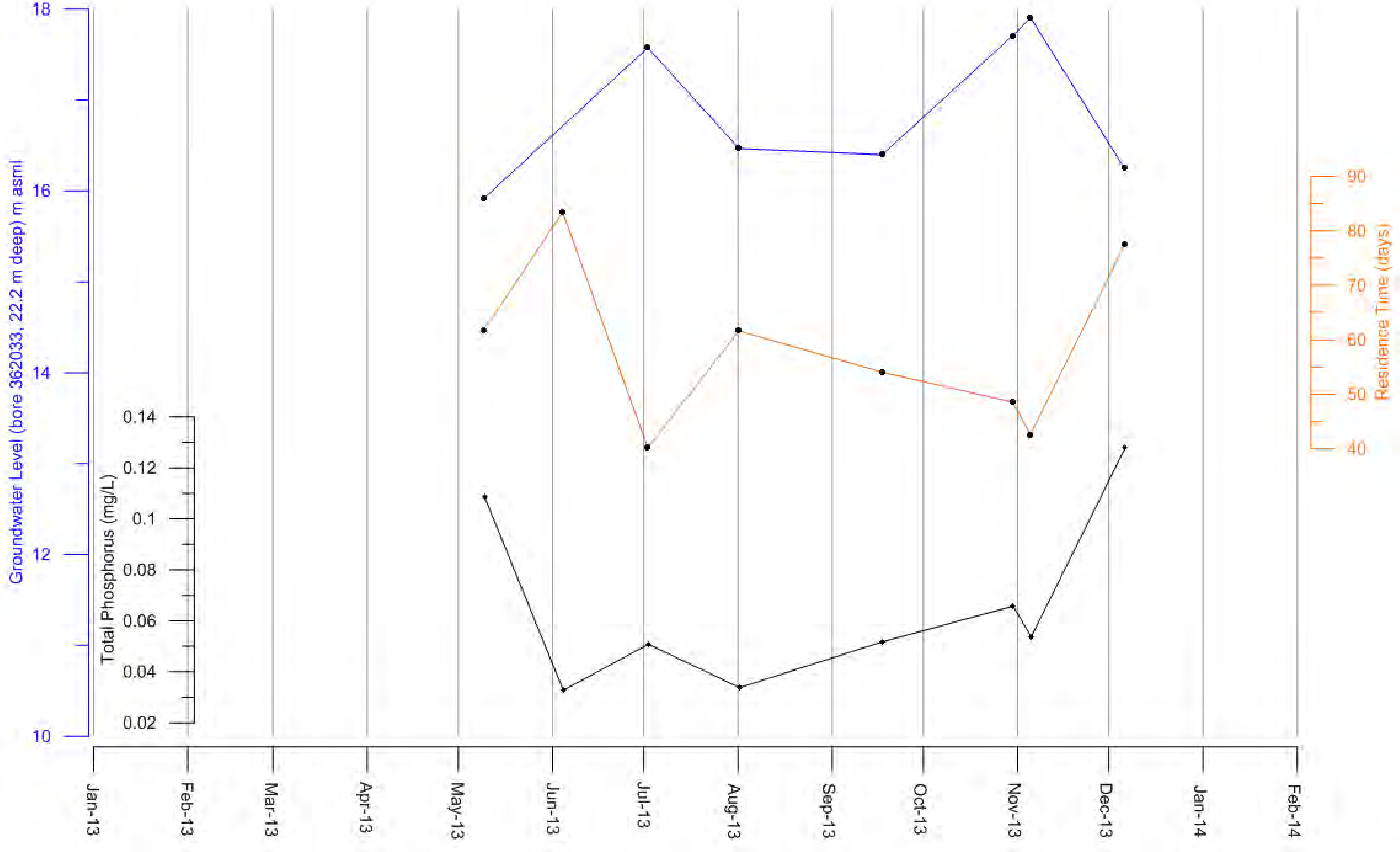


Figure 20: Groundwater levels, lake residence time and phosphorus concentrations for 2013/2014

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