greater WELLINGTON
REGIONAL COUNCIL
Te Pane Matua Taiao

Lake Wairarapa water balance investigation

Stage 1 report – interim findings and recommendations

M Thompson
D Mzila

Environmental Science Department

For more information, contact the Greater Wellington Regional Council:

Wellington	Masterton
PO Box	PO Box 41
T 04 384 5708	T 06 378 2484
F 04 385 6960	F 06 378 2146
www.gw.govt.nz	www.gw.govt.nz

GW/ESCI-T-15/47
ISBN: 978-1-927217-76-4 (online)

June 2015

www.gw.govt.nz
info@gw.govt.nz

Report prepared by:	M Thompson	Senior Environmental Scientist - Hydrology	
	D Mzila	Senior Environmental Scientist - Groundwater	
Report reviewed by:	N Boyens	Team Leader, Hydrology	
Report approved for release by:	G Sevicke-Jones	Manager, Environmental Science	**Date**: June 2015

The report may be cited as:

Thompson M and Mzila D. 2015. *Lake Wairarapa water balance investigation: Stage 1 report – interim findings and recommendations.* Greater Wellington Regional Council, Publication No. GW/ESCI-T-15/47, Wellington.

Contents

1. Executive summary

Lake Wairarapa is situated in the lower reaches of the Ruamahanga River catchment amongst an area of intensive agriculture. It is a shallow (~2.5 m at its deepest point), isothermal lake, of about 80 km^2 in area. While lake level has been monitored for several decades, little is known about other aspects of the lake hydrology.

This report describes work undertaken to better understand the water balance of Lake Wairarapa and develop a predictive model of lake water levels to assist with lake management. A spreadsheet model was developed using daily rainfall, inflow, outflow and evaporation data for the period November 2012 to September 2013. Initial model results suggested that tributary inflows were the dominant input to the lake throughout the year (and especially so in the winter) and outflow via the barrage gate was the dominant loss from the lake throughout most of the year. Evaporation matched, or slightly exceeded, barrage outflow for lake losses in peak summer while abstraction was estimated to comprise about 3-5% of total monthly losses in summer.

A comparison of modelled water level with observed water level showed reasonable prediction of the shape and timing of water level fluctuations, but systematic over-prediction of water levels during dry weather and the reverse during wetter spells when soils were saturated. Model fit was improved by making adjustments to inflow time series based on soil moisture conditions.

The adjusted model was used to estimate the magnitude of water level reductions that could be expected under scenarios of increased allocation. Every additional 40,000 m^3/day allocated (equivalent to the existing level of allocation) is predicted to result in a water level decline of 5 cm and, potentially, the exposure of an additional 50 m of the eastern shoreline of the lake. The environmental consequences of such changes are unknown but it is noteworthy that the target minimum lake level in summer (designed to maintain appropriate habitat quality for wader birds) is already difficult to achieve under the existing allocation regime.

Given the potential sensitivity of the lake to small changes in volume, it is recommended that no further water is allocated (either directly from the lake or its marginal drains) until more is known about likely impacts. With regard to managing existing takes, this study has shown that requiring a cease take when minimum target levels are not met (as has been stipulated in the past) is overly simplistic. A set of criteria based on a combination of lake level, trend in lake level and stream inflow conditions is suggested as an alternative approach that is more targeted towards periods of genuine water stress.

While this study has been informative, there remains considerable uncertainty in our understanding of the water balance and dynamic hydrological processes of Lake Wairarapa. More sophisticated modelling may be required to inform enduring allocation limits and assist with lake catchment land use scenario analyses.

2. Introduction

2.1 Purpose

The purpose of this report is to document work that was undertaken in 2012/13 to better understand the water balance of Lake Wairarapa and develop a predictive model of lake water levels. One of the objectives of the modelling study was to help provide a technical basis for reviewing the water allocation policy for Lake Wairarapa. This review is required as part of the wider Regional Plan review being undertaken by Greater Wellington Regional Council (GWRC).

2.2 In scope

The original scope of this study was set out in proposals developed by Mzila (2011). In summary, the study aimed to:

- Quantify hydrological and meteorological fluxes to and from Lake Wairarapa (with a focus on summer conditions when abstraction from the lake is occurring);
- Develop and calibrate a spreadsheet water balance model to replicate observed water level changes, and;
- Compare various allocation scenarios to make predictions about the impacts on water level of direct abstraction from the lake.

However, as the study progressed the scope changed, mainly as it became apparent that understanding some of the complexities of the lake water balance would require effort and resource beyond that available. In particular, quantifying the groundwater and drainage fluxes within the water balance was to prove elusive, and this constrained the scope of the predictive modelling and, to an extent, the ability to draw firm conclusions about hydrological alteration resulting from abstraction (see Discussion).

2.3 Out of scope

The extent to which future scenarios have been modelled has been constrained at this stage to simplistic representations of different rates of abstraction. No attempt is made in this report to consider scenarios where water balance components other than abstraction are varied (eg, varying barrage gate configurations or climate components through the season). It is noted that there are many wider questions regarding the management of Lake Wairarapa (as a potential water resource) that need to be addressed in the longer term. For example;

- What would be the effect of reducing the use of the barrage gates during non-flood periods? i.e. would the lake be in a more healthy or less healthy state if there was less intervention at the barrage?
- Could additional water be routed from the Ruamahanga River into the lake during non-flood periods to increase the water available for irrigation and to enhance the condition/health of adjoining wetlands?

3. Background

3.1 Hydrological setting

Lake Wairarapa is situated in the lower reaches of the Ruamahanga River catchment amongst an area of intensive agriculture. It is a shallow (~2.5 m at its deepest point – see Figure 3.1), isothermal lake, of about 80 km^2 in area. The lake and its associated marginal waterbodies, including Lake Onoke to the south, comprises the largest wetlands complex in the lower North Island. It is considered to be of both national and international importance due its significant cultural, ecological, recreational and natural character values A National Conservation Order for the lake was established in 1989 to protect outstanding wildlife habitat, particularly on the eastern shoreline. Nevertheless, over a century of development of adjacent farmland and associated drainage and flood control schemes has left the lake in a highly modified state, to the detriment of the ecosystem and many of the community-held values.

Tributaries of the lake include the Tauherenikau River and Otukura Stream on the north-eastern shore, the Waiorongomai River at the south-western end and a number of smaller streams which mostly enter the lake along its western shore. Drainage schemes along the southern and eastern shores – constructed to lower the underlying groundwater table (much of the soils are poorly drained) – also discharge into the lake. Due to the nature of its geology and geomorphology, the Wairarapa Valley is essentially a closed hydrogeological system in which all groundwater outflow occurs predominantly as discharge into the Ruamahanga River system or Lake Wairarapa. Pastoral land cover makes up just over 50% of the lake's catchment area and, while surrounding the lake on all sides, is predominantly located to the north and east.

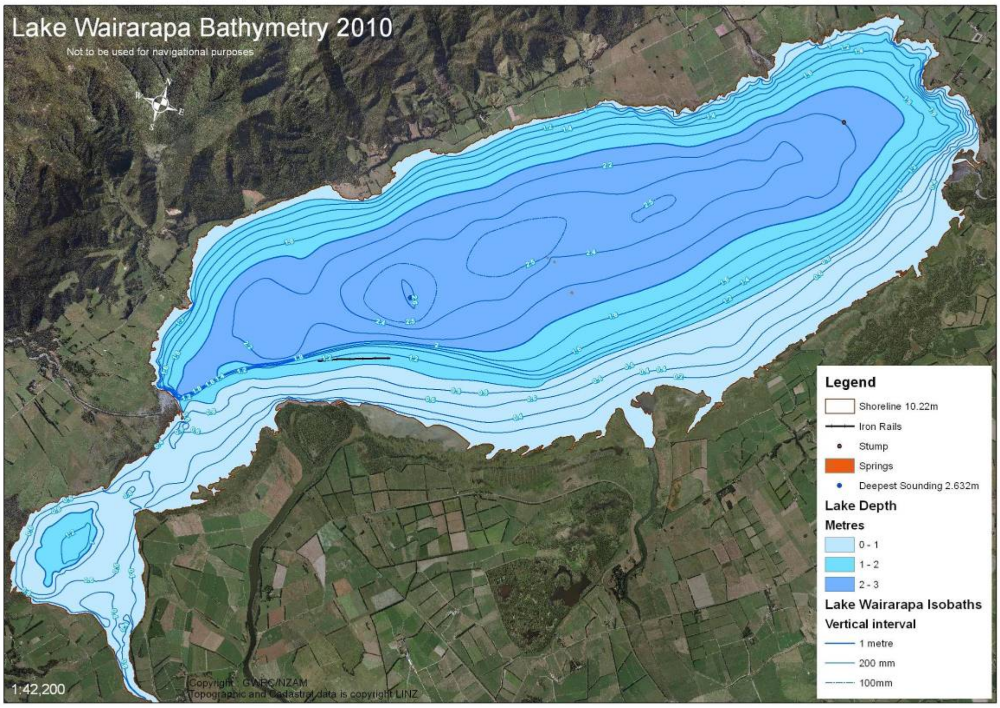


Figure 3.1: Lake Wairarapa bathymetry 2010

3.2 Managing lake levels to give effect to Water Conservation Order

Lake levels are controlled – to the extent possible – by the operation of the barrage at the south end of the lake. A resource consent held by GWRC sets the conditions of water level management based on an agreed regime. The six gates of the barrage can be manipulated individually, or together, by staff in GWRC's Masterton office. Outside of times when the lake and rivers are in flood, or the mouth of Lake Onoke is blocked, the barrage is operated in response to automated alarm triggers (ie, as water levels gradually get too high or low). This includes automatic daily openings of two of the six gates (the lateral gates) for one hour to allow fish to pass. The original fish pass is a permanent opening at the base of the barrage although it is suspected that the opening is ineffective and the barrage, when all the gates are closed, is a barrier to fish movements (Glova and Jellyman, 2003).

3.3 Barrage gates – flood control

The original purpose of the barrage gates was to prevent a flood backflow occurring from Lake Onoke to Lake Wairarapa, and to contain flood waters within the lower Ruamahanga channel. The barrage gates are closed for the majority of the time. The lower Ruamahanga River averages 10.0 m, using the Schemes datum, but in flood events can reach 12.5 m. The Lake Wairarapa level in contrast averages 10.2 m with a maximum level since the construction of the barrage gates of 12.2 m. Before the scheme, the maximum lake level on record is 13.65 m. The flood gates are used to maximise the benefit of flood storage and to achieve low lake levels for land use purposes.

The barrage also enables levels of Lake Onoke to be raised quickly to either overcome impending blockage of the Onoke outlet or to aid in the formation of a new opening.

3.4 More background

A fuller summary of historical catchment development that shapes the hydrological characteristics of the present day lake is given in Thompson (2011).

4. Methodology

4.1 General approach

The general approach of the water balance study has been guided by objectives developed by Mzila (2011) and, prior to that, advice provided by Horrell (2010).

The method so far has primarily comprised the development of a spreadsheet model capable of predicting water level changes. The water balance components used to predict lake level were either measured or estimated using GWRC monitoring site data. Some monitoring sites existed already and others were established specifically for the water balance study. Monitoring sites, data sets and the derivation of time series for each of the main components is described in more detail below.

4.2 Field work and data collection

The fieldwork and data collection programme comprised:

- Flow gaugings in the catchments of tributary rivers and streams, including several concurrent[1] gauging runs
- Installation of a rated stage-to-flow continuous (5 minute) record gauge site in Burlings Stream catchment
- Installation of two telemetered met sites (measuring rainfall, wind speed and direction, air temperature and humidity) on each of the eastern and western shores of the lake
- Installation and calibration of an Acoustic Doppler Current Profiler (ADCP) continuous flow measurement site at the lake outlet channel (just upstream from the barrage)
- Observation of lake levels using the existing site 'Burlings' on the western shore

All new and existing site data was archived and accessed from GWRC's Hilltop database. The maximum period of overlapping datasets that could be achieved was 01 November 2012 to 30 September 2013, almost a full year, and this defined the water balance and model development period.

All monitoring site locations are shown on Figure 4.1.

---

[1] Spot flow gaugings undertaken on the same day at several locations on a stream in order to measure the flow loss or gain occurring along the channel; this is especially helpful for understanding surface water/groundwater interactions.

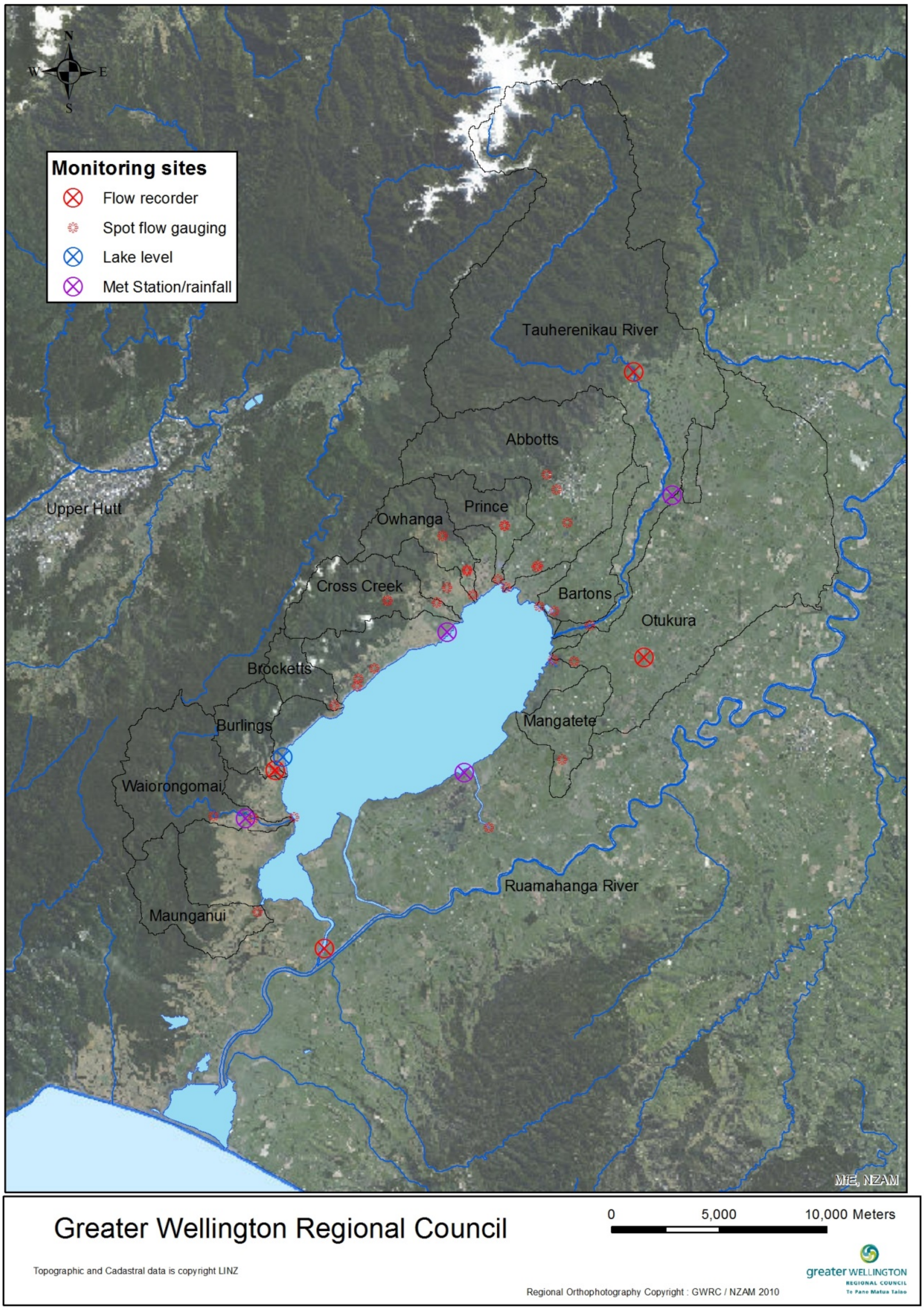


Figure 4.1: Location of hydrological and climate (met) monitoring sites

4.3 Water balance components

4.3.1 Inflows

(a) Rainfall

Daily rainfall data were obtained from Ota tipping bucket gauges at the two new lake shore met sites and two existing GWRC rainfall sites, ‘Tauherenikau at Racecourse’ to the northeast of the lake and ‘Waiorongomai at Matthews’ to the southwest (Figure 4.2). There are storage gauges at all sites with which to calibrate automated records.

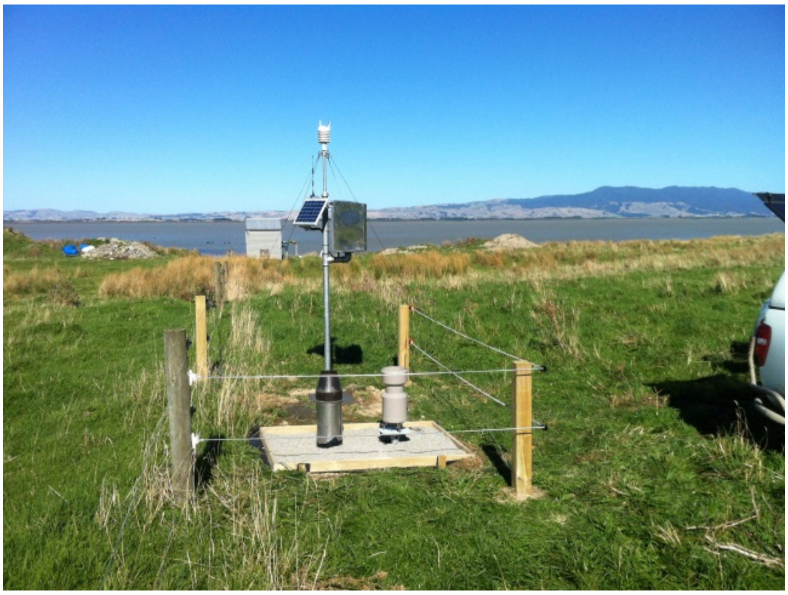


Figure 4.2: Recently installed GWRC met site on the western lake shore (an identical site was installed on the eastern shoreline); instrumentation includes tipping bucket and storage rain gauges, wind speed and direction, solar radiation and air temperature sensors

A comparison of cumulative rainfall plots for the four sites (Figure 4.3) shows that while the timing and duration of events across the sites is similar, the magnitude of rainfall is significantly higher in the west due to the orographic influence of the Rimutaka Range. However, given the fairly even distribution of the gauges around the lake, it was considered that a simple average of rainfall across the four sites would adequately represent lake rainfall; this daily average was used as an input to the water balance.

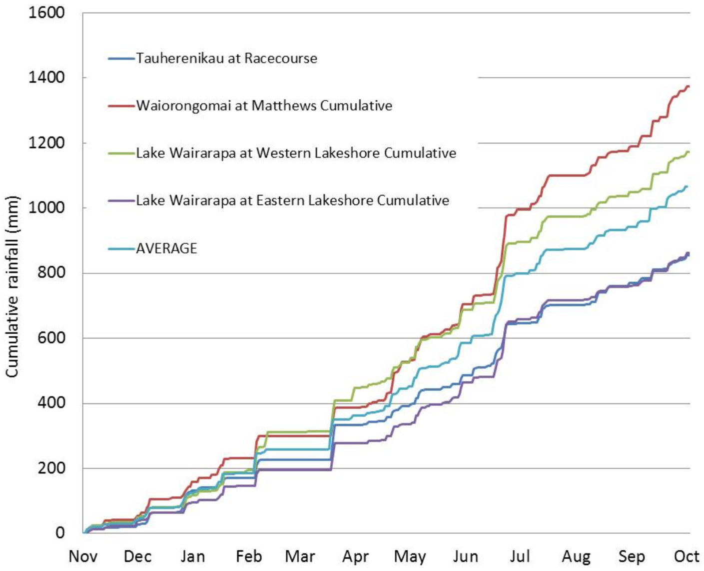


Figure 4.3: Cumulative rainfall for the period 01 November 2012 to 30 September 2013 at four sites around Lake Wairarapa

(b) Tributary channel inflow

There are 13 named tributary inflow channels to Lake Wairarapa; the catchments are shown in Figure 4.1. These catchments have a combined area of 488 km^2 (93% of the total lake catchment area) with catchments draining the Rimutaka and Tararua ranges to the west having roughly twice the area of the eastern lake catchments (314 km^2 compared to 173 km^2, respectively).

Most of the lake tributaries are un-gauged catchments (only the Otukura Stream and Tauherenikau River have permanent continuous flow recorders with good historical data and these are situated 5 km and 13 km, respectively, upstream of the lake shore); therefore, the general approach to estimating flow for these catchments has been to synthesise a flow record based on paired catchment analysis.

Early in the study it was recognised that flow loss to groundwater occurs in the lower reaches of the western tributaries. An attempt was made to quantify just the channel inflow to the lake by measuring or estimating flow at the lake shore (in the hope that shallow groundwater flow could then be quantified as a water balance model residual). Where insufficient lake shore data existed, concurrent gauging runs in some of the tributaries were undertaken to make the necessary flow adjustments to data from higher in the catchments. However, the density of data required to make robust assessments could not be achieved and the decision was made to simplify the inflow characterisation. Inflows to the water balance model were ultimately derived for sites in some catchments that were upstream of losing reaches and therefore were assumed to incorporate any subsequent shallow groundwater flow to the lake as well as channel flow.

Several rounds of spot flow gaugings on each main tributary were undertaken across a range of flows and results compared with coincident data from the nearest continuous flow recorders. For the western lake tributaries, the 'Pakuratahi River at Truss Bridge' site was found to offer the best correlation, while Bartons Lagoon outlet correlated well with the ‘Otukura Stream at Weir’ site and the lower Tauherenikau River and Otukura Stream flows could be estimated by adjusting their measured upstream site records. The results of paired site correlations are provided in Appendix 1.

Once a full set of synthetic mean daily flow records had been generated for each tributary they were simply added together to produce a single mean daily flow hydrograph that represents total channel input to the lake. An additional 10% of flow was added across the aggregated record to account for flows from minor tributaries and those catchments for which spot gauging data was too sparse to attempt a calibration exercise (including the Owhanga, Whakawiriwiri and Mangatete catchments). The 10% factor was consistent with the proportion of additional catchment area occupied by these other catchments.

(c) Groundwater

A constant groundwater discharge to the lake at a rate of 0.4 m^3/s was assumed for the study period based on the results of Wairarapa Valley groundwater modelling work undertaken by Gyopari and McAlister (2010). It is noted that this estimate was derived as a model residual (ie, the flux required to balance the lower valley groundwater model) and has not been substantiated through any specific measurement or assessment. This is a weakness of the current water balance modelling and will need to be addressed in subsequent studies; the installation of a shallow piezometer array around the lake in 2012 may help.

4.3.2 Outflows

(a) Lake outlet (barrage)

Lake outflows (and inflows during times of flow reversal) were measured directly in the barrage channel using a side-looking (ADCP). This unit was installed in September 2012 and calibrated with a boat mounted ADCP over several flow cycles (Figure 4.4).

Figure 4.4: ACDP installation on the left bank of the lake outlet channel (left) and calibration gaugings (right - barrage gate is in the background)

(b) Evaporation

Evaporation is a significant component of the water balance of most lakes, especially in summer. Factors that cause evaporation and also directly influence its intensity are weather variables such as air temperature, air moisture, atmospheric pressure, relative humidity, wind, and environmental variables such as water temperature and surface area of the lake.

Generally, the most accurate way to estimate evaporation is to use Class A pan evaporation measurements from a climate zone that is similar to the site of interest. Unfortunately, there are no Class A pan measurements available within what could be considered a representative area of Lake Wairarapa. Instead, this study relied on established theoretical methods for estimating evaporation from climate data. Several evaporation equations were trialled including those of Priestley-Taylor, MacMillan and Hargreaves but ultimately only the Penman Open Water method was considered suitable for the Lake Wairarapa environment. Penman combined the energy balance with the mass transfer method and derived an equation to compute the evaporation from an open water surface from standard climatological records of sunshine, temperature, humidity and wind speed. The Penman method is also referred to as the combination method and the equation is provided in Appendix 1.

In this study Penman Open Water evaporation was derived in two ways. The first involved calculating evaporation (using the equation in Appendix 1) from data collected from the shoreline GWRC met stations (see section 4.2) and floating water temperature thermometers attached to a stake located within the lake. The second way was to use NIWA daily estimates of Penman Open Water evaporation for the ‘Martinborough EWS’ weather station (Agent 21938), located about 15 km to the east of Lake Wairarapa. For both approaches evaporation depth was converted to a volume using a previously established functional relationship between lake stage and lake surface area.

The Penman Open Water evaporation daily time series generated from both approaches were generally comparable, although the NIWA weather station estimates fluctuated more on a daily basis and reached higher maximum values on the hottest days. Evaporation totals for the full period of monitoring (11 months) were 875 mm and 995 mm for the GWRC and NIWA methods, respectively. These were compared with an average annual evaporation of 1075 mm presented by Horrell (undated) for Lake Ellesmere − a similar lake in many respects including size, depth, setting and climate[2]. This comparison, while limited in extent, indicated that the NIWA weather station data was perhaps providing a closer approximation of actual evaporation for Lake Wairarapa than the GWRC data; the NIWA dataset was therefore used as a model input.

(c) Abstraction

The total maximum rate of abstraction directly from Lake Wairarapa and its marginal drains[3] is 0.604 m^3/s, spread across 11 consented activities. However,

---

[2] Horrell (undated) used both Class A pan measurements and nearby weather station derived data.

[3] Total maximum consented allocation from the lake catchment that is considered to be ‘lake depleting’ is about 1.8 m^3/sec. However, the effect of abstractions from tributaries in the wider lake catchment is assumed to have been incorporated in the tributary flow records.

several consents have conditions stipulating that pumping at the maximum rate can only occur for between 12 and 22 hours per day. Taking in to account these conditions, the maximum daily volume that can be abstracted (which is the more important value for this study) is 39,635 m^3/day.

Actual water use can only be determined from meter records and records coinciding with the period of model analysis were sparse. Of the 11 consented activities (some of which run more than one pump/meter), six meter records were available, accounting for approximately 40% of the daily consented volume. Although good quality data for these six consents were not available for the whole 2012/13 summer, the data were useful for extrapolating an actual use profile for the peak summer months.

The most complete meter data covered the period 13 December 2012 to 28 February 2013. These data were used to define the proportion of actual use to consented daily maximum for each day in the period and for each of the six available records. The proportion varied from 11% to 100% with an average of 55%. Under the assumption that the remaining five non-metered consents had a similar pattern of use, an estimate of total actual daily abstraction was made for the period 13 December to 28 February by scaling up the results from the metered data. For the periods prior to 13 December 2012 and after 28 February 2013, abstraction was assumed to occur at a rate of 55% of the total consented amount, based on the average use value discussed above. Zero abstraction was assumed on days with significant rainfall in these periods and irrigation was assumed to cease altogether at the end of April 2013 until the end of the modelling period.

4.3.3 Lake water level

Lake water levels have been measured continuously at ‘Burlings’ recorder site (Figure 4.1 and Figure 4.5) since 1953, although before 1976 the record is heavily influenced by construction work on the Ruamahanga diversion channel. Data is recorded at 15 minute intervals.

Figure 4.5: Burlings lake water level recorder located on the south western shore

4.4 Spreadsheet modelling of the water balance and lake level

4.4.1 Model set up

The water balance of Lake Wairarapa is described by the following equation:

$$\frac{dh}{dt} = P(t) - E(t) + Rin(t) - Rout(t) + Gnet(t) - Abst(t) \pm Bar(t) + \varepsilon(t)$$

Where:

h is the level of the lake and t is time,

P is the rate of rainfall over the lake,

E is the rate of lake evaporation,

Rin and $Rout$ are surface water inflow and outflow respectively,

$Gnet$ is the net groundwater flux,

$Abst(t)$ is water abstraction and

$Bar(t)$ is the inflow and outflow through the barrage gates

The final term $\varepsilon(t)$, represents uncertainties in the water balance arising from errors in the data or unquantified fluxes.

A water balance model was produced in Microsoft Excel and solved on a daily time step for the period 01 November 2012 to 30 September 2013. The length of the period was defined by the maximum available overlap of datasets required for the modelling. While the period usefully spanned a full summer and winter season, traditional calibration and validation of the model (that might have been possible with multiple years of data) could not be achieved. Model performance was therefore assessed more qualitatively by visual data fit.

4.4.2 Abstraction scenarios

Once a model that reasonably replicated observed water level changes had been developed, simple scenarios of increased abstraction were run to assess the extent to which lake levels were altered. This involved scaling up existing abstraction over the period of modelling by factors of two or more and assuming that, over the same period, all other influences on lake level (eg, operation of the barrage) held their observed behaviour. In this exercise, attention focused on water level changes in the summer period when abstraction for irrigation purposes is at its peak.

No attempt was made in this study to assess the impact of any predicted change in lake water level on lake values; this is a separate exercise. However, to give the results some context, predicted changes in lake water level are discussed in terms of shoreline impact by relating the depth change to lake shore bathymetry (ie, amount of additional shoreline exposure likely under various abstraction scenarios).

5. Results

In this section the measured and estimated water balance variables are presented, followed by the results of attempts to predictively model changes in the water level of Lake Wairarapa during the period November 2012 to September 2013.

5.1 Climatic conditions during the model run period

Climatic conditions during the summer of 2012/13 were ideal for the water balance study. While the late spring and early summer months were typical, there was an extended dry spell from early February to mid-March that was highly unusual in a historical context and represented a period of significant water stress. Such conditions provided a useful reference point for the development of a water balance model as the variability in some components (especially tributary inputs) was reduced.

From mid-March 2013 onwards, rainfall became more frequent and sustained and by mid-April soil moisture deficits were falling quickly. By the end of May, soils were saturated and typical winter climate and hydrological conditions set in, although no significant flood events occurred thereafter.

5.2 Water balance – initial results

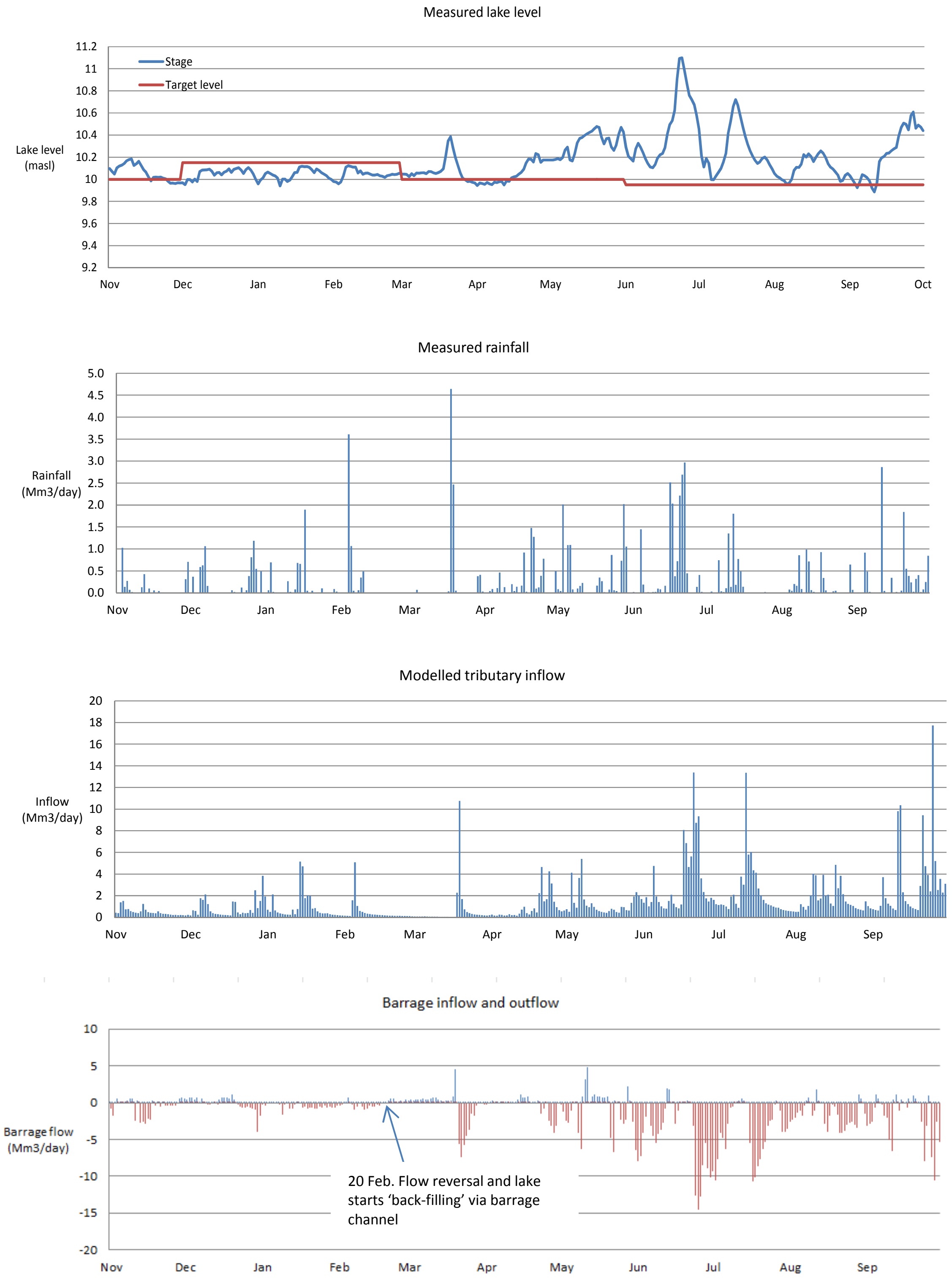
5.2.1 Daily fluxes or major water balance components

Figure 5.1 shows the measured mean daily water level of Lake Wairarapa (along with target levels stipulated in the lake management plan) for the period 01 November 2012 to 30 September 2013 and the measured or estimated daily time series for each of the major components of the lake water balance for the same period. Inflows to the lake are shown as positive fluxes (in blue) and losses from the lake are shown as negative fluxes (in red).

The following observations from Figure 5.1 are noteworthy:

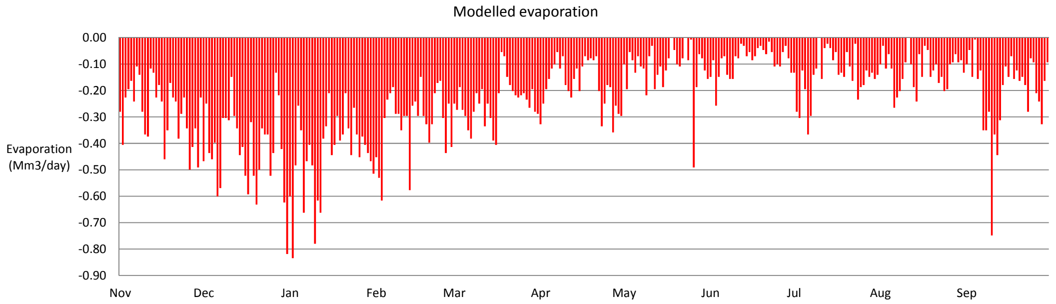
- While the target minimum lake level of 10.0 masl was generally achieved in early and late summer, the slightly higher mid-summer minimum target level of 10.15 masl generally could not be sustained; this is a common situation in many summers. In winter, all effort is normally made by GWRC flood managers to keep the lake down at 10.0 or 9.95 masl between unsettled periods of weather to allow headroom for flood storage; while this was generally achieved in 2012/13, frequent rainfall between mid-April to mid-June made it especially difficult.

- As would be expected, tributary inflows (both base flows and freshes) were highest in winter and were mirrored by slightly lagged losses of a similar magnitude from the lake via the barrage. Summer channel flow patterns were less predictable, as illustrated by fluxes observed during the six-week dry spell starting in February 2013 (highlighted in Figure 5.1). During this recession, the barrage gate was held open and the lake gradually emptied until around 20 February. At this point, flow naturally reversed in the barrage channel and the lake began backfilling from flows in the lower Ruamahanga River.



20 Feb. Flow reversal and lake starts 'back-filling' via barrage channel

Figure 5.1: Top graph: mean daily water level of Lake Wairarapa measured at 'Burlings' recorder site (along with target levels stipulated in the lake management plan) for the period 01 November 2012 to 30 September 2013. Bottom graphs: measured or estimated daily time series for rainfall, tributary inflows and barrage inflows. Gains are presented as positive fluxes (blue) and losses as negative fluxes (red). Units for the bottom graphs are millions of cubic metres per day (Mm^3/day).



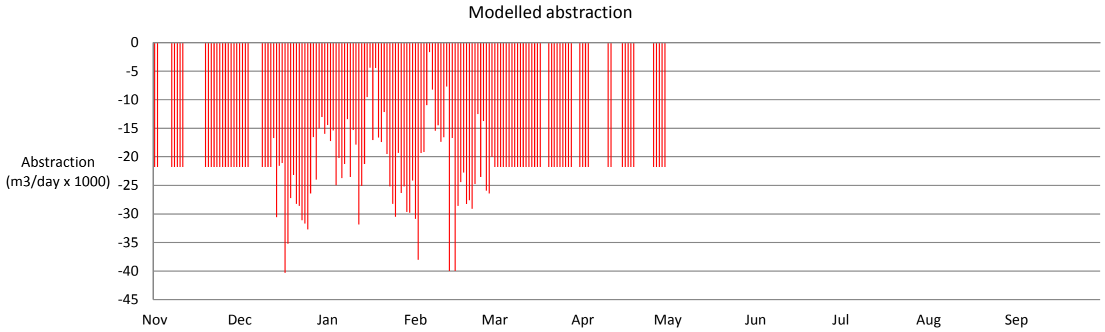


Figure 5.1 cont: Estimated daily time series for evaporation (top graph) and abstraction (bottom graph)

5.2.2 Monthly water balance

Table 5.1 shows the initial results for the monthly total flux for the primary water balance components for the period November 2012 to September 2013.

Table 5.1: Lake Wairarapa monthly total inflows and outflows (Millions of m^3) for the period 01 November 2012 to 30 September 2013

	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Seasonal pattern
Rainfall	3.3	6.5	4.7	5.6	8.1	7.0	10.5	16.6	5.8	5.4	9.7	
Stream inflow[1]	14.9	27.7	28.4	13.1	19.4	28.6	40.8	94.8	68.3	53.3	98.8	
Barrage Inflow	4.6	8.5	0.1	3.4	12.7	4.7	18.0	4.7	1.5	4.7	6.8	
Barrage Outflow	-20.7	-11.8	-14.8	-7.4	-31.1	-16.1	-46.2	-125.9	-122.5	-53.9	-66.3	
Evaporation	-8.3	-13.1	-13.7	-8.9	-7.6	-5.3	-3.5	-2.6	-4.4	-3.9	-6.2	
Abstraction	-0.4	-0.7	-0.6	-0.6	-0.6	-0.3	0.0	0.0	0.0	0.0	0.0	
Balance [modelled storage change + error]	**-6.6**	**17.1**	**4.0**	**5.2**	**0.9**	**18.5**	**19.6**	**-12.5**	**-51.2**	**5.6**	**42.9**	
Actual storage change[2]	**-5.9**	**-0.5**	**1.0**	**2.5**	**0.6**	**10.9**	**5.0**	**13.3**	**-16.5**	**-0.9**	**20.2**	

[1] Stream inflow includes constant assumed groundwater inflow of 0.4 m^3/sec or about 1 Mm^3 per month throughout the year

[2] Monthly storage change calculated from observed lake level and depth-dependent lake volume data.

The main features in Table 5.1 are:

- Tributary inflows were the dominant input to the lake throughout the year, especially so in the winter. 'Backflow' into the lake via the barrage channel was similar to tributary inflows during March (due to high Ruamahanga River levels downstream)
- Barrage outflow was the dominant loss from the lake throughout most of the year and especially so in winter; in July, water loss through the barrage was almost double the total lake inputs (indicating a net reduction in lake level through this month)
- Evaporation matched, or slightly exceeded, barrage outflow for lake losses in peak summer while abstraction was estimated to comprise about 3-5% of total monthly losses in summer.

The 'Balance' term in Table 5.1 represents the sum of the water balance components for each month. This term incorporates both net monthly storage changes in the lake as well as any model errors. For example, if the lake level was exactly the same at the start and end of each month and all inputs and outputs were perfectly measured, the monthly balance would be zero.

At face value, the positive balance values between December and May indicate increasing lake storage and level in these months. The balance becomes negative for the months of June and July indicating storage losses and net lake level declines and then reverts to storage gains again during August and September.

However, a comparison of the monthly balance values with actual monthly storage changes derived from observed lake level data (see final row of Table 5.1) shows some significant differences (especially in December, May to July and September). This suggests one or more of the water balance components has been poorly quantified. The next section explores model fit and performance in more detail.

5.3 Lake level predictions

5.3.1 Initial model run

Figure 5.2 compares predicted lake level from the initial model run with observed lake level (for the period November 2012 to September 2013). While the model predicts the timing and shape of fluctuations in lake level quite well throughout the year, during the first half of the model period there appears to be a systematic over-prediction that results in a discrepancy between modelled and observed levels of more than 0.5 m by mid-May 2014. After this point, the modelled and observed levels begin to converge again indicating a switch to model under-prediction. During August there is a period of good agreement before the model again begins to over-predict in September as a wet spell sets in.

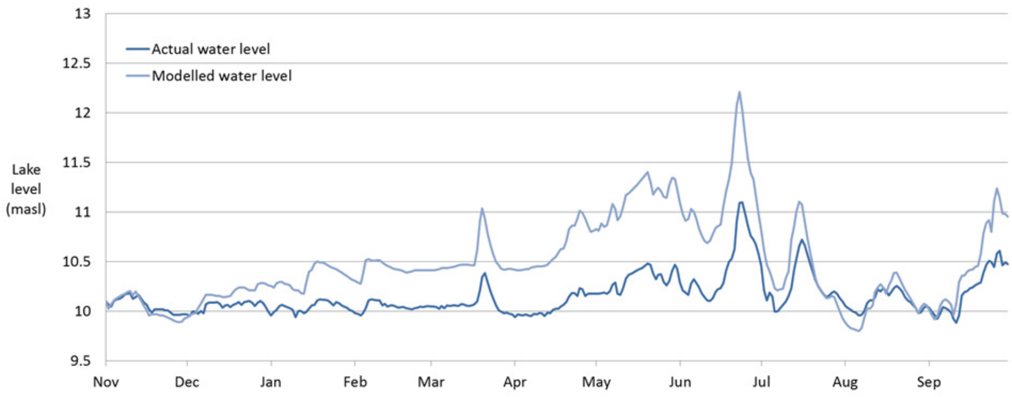


Figure 5.2: Comparison of measured ('Burlings') and predicted lake levels from initial model run

The generally poor model fit suggests that either one or more components of the water balance (quantified in Table 5.1) have not been accurately characterised or that there is a significant component of the water balance that has not been captured, or both. Conceptually, it is thought most likely that the largest errors, relative to the overall water balance, probably lie within the modelled tributary inflows; this is by far the largest water balance input and was heavily reliant on modelling rather than direct measurement. Small errors in the estimation of individual catchment inflows can lead to relatively large discrepancies in total flow volumes when aggregated, especially during freshes. To further explore the possible reasons for poor model performance the pattern of model error relative to the range of actual lake levels was plotted (Figure 5.3).

Figure 5.3 highlights the three distinct model phases just discussed; over-prediction between December 2012 and June 2013, under-prediction through June until the end of July and then over-prediction in August and September. The over-prediction through the summer appears to be fairly systematic with the overall error building through small but constant incremental errors during dry periods and more substantial positive errors as freshes come through. This pattern is consistent with a systematic over-estimation of inflows based on the correlation modelling, although errors relating to other water balance components could be contributing (eg, assumed constant groundwater discharge to the lake or modelled evaporative losses).

Also plotted on Figure 5.3 is the soil moisture deficit (SMD) measured at a climate station just to the northeast of the lake ('Kahutara'). The SMD trace shows deficits of 100mm or more for most of the summer and early autumn before a rapid reduction to zero (soil saturation) by the start of June. The start of the zero deficit period coincides almost exactly with the beginning of the period in which the model switches from over- to under-prediction. One interpretation of this is that once soils become saturated there is a new and significant component of inflow to the lake that has not been captured by the model – overland runoff and shallow drainage. This could include significant volumes of water removed during wet winter spells from adjacent farmland by pumped drainage schemes (eg, the Wairio Block)[4].

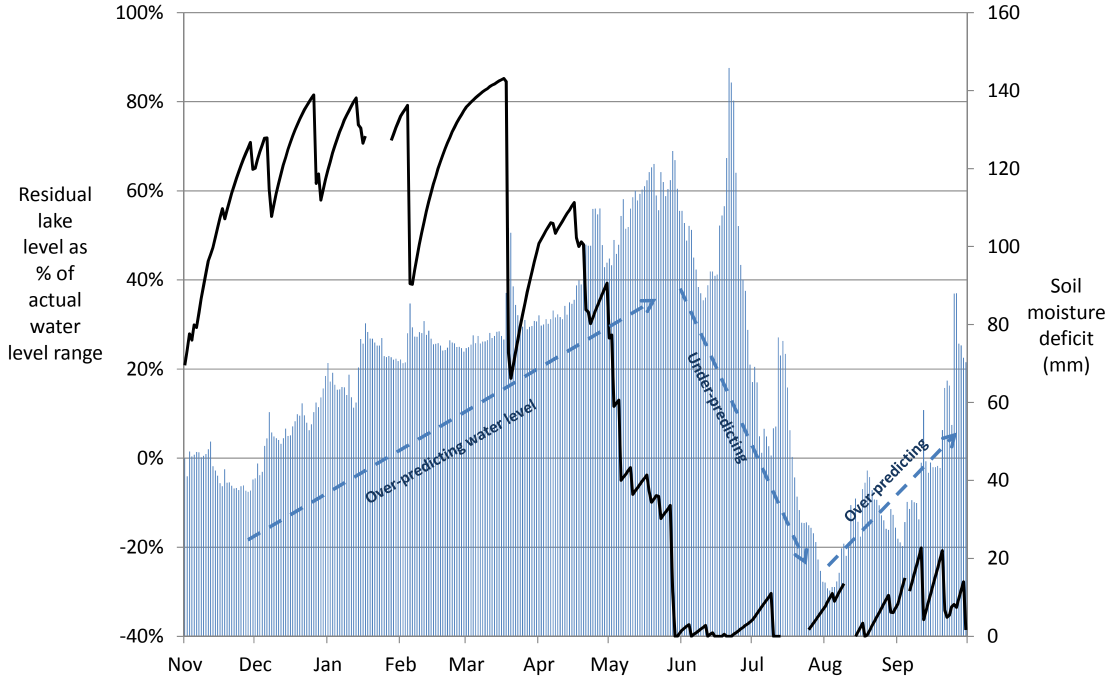


Figure 5.3: The blue bars show model residual lake level (ie, predicted daily water level minus actual level) expressed as a percentage of the range of actual water levels. The black line shows the daily soil moisture deficit (mm) measured at the 'Kahutara' climate site (Agent Number 2624 – source: NIWA Climate Database).

From mid-August 2013 there was a constant, albeit small, soil moisture deficit corresponding with a period in which the model returned to over-predicting water levels. This may indicate a return to conditions where shallow drainage was a less important component of the water balance.

5.3.2 Improving model fit

Thoroughly testing the reliability of the input datasets or investigating and quantifying other potential components of the lake water balance was not within the scope of this study. Rather an attempt was made to improve model fit by adjusting the existing input variables, an exercise that could also reveal more about where errors lie.

The systematic nature of the accumulating model errors and apparent relationship between model performance and soil moisture status led to the development of several conditional rules to trial in subsequent model runs. These rules focused on reducing tributary inflows during freshes and increasing tributary inflows when there was no (or a very small) soil moisture deficit. Through iteration the rules that were found to achieve the best visual model fit throughout the model period were:

- If the mean daily tributary inflow was greater than 1Mm^3/day then reduce by 30%

---

[4] Effort is currently being made (as of July 2014) to quantify drain inputs but results are not yet available to inform this study.

- If the mean daily tributary inflow was greater than 4Mm^3/day then reduce by 25%
- If the soil moisture deficit was less than 5mm then increase tributary inflow (as a surrogate for drainage inflow under saturated soil conditions) by a factor of 30%

The lake level prediction resulting from application of the rules above is shown in Figure 5.4.

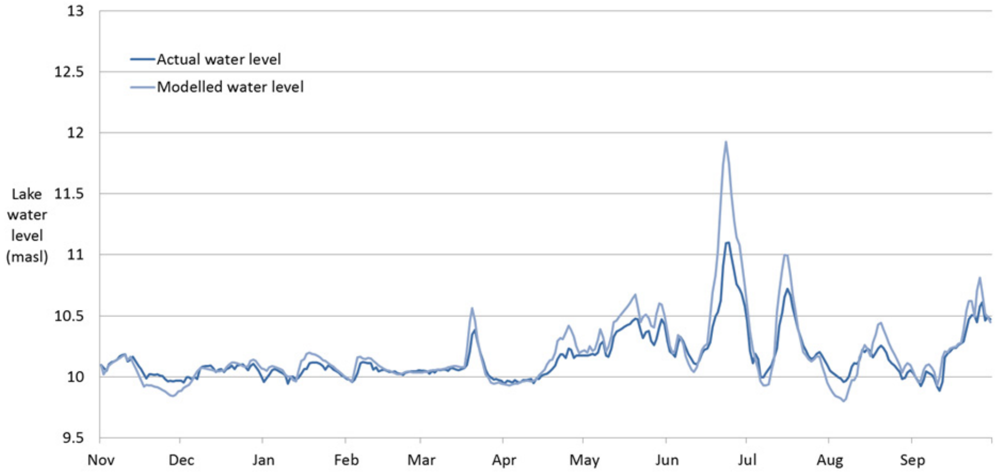


Figure 5.4: Comparison of measured ('Burlings') and predicted lake levels from the final model run incorporating conditional rules (see text) to adjust the tributary inflow time series

Compared with early runs, the adjusted model provides a better prediction of lake levels, particularly during the summer months when hydrological variability and the overall magnitude of fluxes is lower. The accuracy of predictions reduces somewhat during the winter as the lake hydrology becomes more dynamic and flows increase but is still considered reasonable for all but the largest freshes; for example, the peak lake level for the largest inflow event of the year (in July) was over-predicted by almost one metre.

Overall, the adjusted model offers a reasonable basis on which to proceed with making initial assessments of increased allocation. However, there are clear limitations (discussed further in sections 6 and 7) that need to be considered when using the model outputs.

5.3.3 Sensitivity analysis

Sensitivity analysis showed that a large rainfall reduction (45%) was required to change the standard deviation in lake levels by 150%. Only a 9% change in stream flow was required to change lake levels by the same amount while a 15% change in evaporation was required. These results indicate lake levels are most sensitive to changes in stream flow and, to a lesser extent, evaporation.

5.3.4 Allocation scenarios

To assess the potential impact of increased abstraction on lake level several scenarios were tested. The initial abstraction profile was retained as a status quo scenario and then daily abstraction volumes were increased in several increments of 40,000 m^3/day to represent higher allocation limits[5]. Figure 5.5 shows the results of four scenarios with abstraction rate increasing from the status quo of 39,635 m^3/day to 160,000 m^3/day.

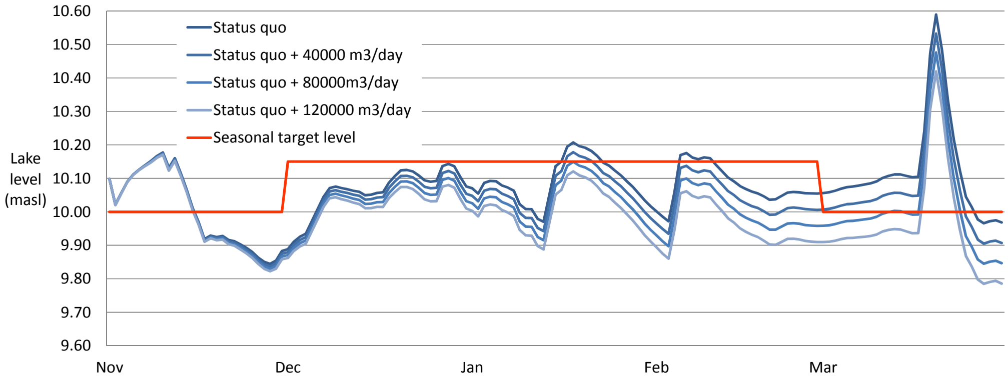


Figure 5.5: Lake level predictions under various allocation scenarios

The main features of Figure 5.5 are:

- The relationship between increasing allocation and declining lake level is roughly linear and proportional with the magnitude of impact steadily accumulating as the season progresses.
- During the critical part of the 2012/13 summer (the zero-rainfall period in February and March) the reduction in lake level for each increment of additional abstraction is about 0.05 m (5 cm).
- The maximum reduction in lake level (ie, the difference between abstraction scenarios of status quo 39,635 m^3/day and 160,000 m^3/day) reaches close to 0.2 m (20 cm) in mid-March.

It is also notable that any increase in abstraction makes the already difficult task of trying to achieve the mid-summer minimum lake level even harder.

The observations above are made under the assumption that all other factors (in addition to allocation) that affect lake level remain unchanged between scenarios. This is a significant point because, for example, it is possible that the impacts of alternative allocation regimes could be managed to some extent by operating the barrage gate in a different manner to that which occurred over the 2012/13 summer.

---

[5] Noting that the incremental increases were adjusted to reflect more likely actual abstraction patterns using the same relationship between actual use and consented abstraction determined for the status quo.

6. Discussion

6.1 Model performance

This study has succeeded in quantifying some previously un-measured components of the Lake Wairarapa water balance; in particular, dynamic gains and losses via the barrage channel, evaporative losses and tributary inflows. However, initial attempts to predict the lake level demonstrated that there remains significant uncertainty in the water balance data and that our understanding of hydrological processes needs further improvement.

Nevertheless, the pattern of model errors was informative and indicated that the model performs reasonably well in stable dry weather conditions but is less reliable when freshes move through the system, particularly during the wetter months. This is consistent with the model being more sensitive to changes in tributary inflow than any other component. The pattern of errors also suggested that soil moisture status and shallow groundwater level in land surrounding the lake may be an important driver of fluxes that are not adequately captured by the model. It is certainly known that the lake receives significant additional water from shallow sub-surface and overland drainage when soils are saturated but it is also conceivable that the lake loses water to shallow groundwater during summer months (causing the lake level model to over-predict by a small margin at these times).

Ultimately, the apparent relationships between the magnitude of tributary inflows, soil moisture status and the extent of model error allowed the development of some static rules to adjust the model to a better fit. Since the overall aim of the water balance and lake level modelling is to compare relative change in lake behaviour under differing abstraction scenarios (rather than precisely simulate all individual water balance components) this ‘black box’ approach was deemed adequate. The end result was a model that satisfactorily replicated changes in lake level for the 2012/13 period although, to achieve this, some fresh flows had to be down-scaled by up to 30% while some winter base flows had to be scaled up by about the same proportion.

With regard to model refinement, attention should focus primarily on improving the tributary inflow dataset. Many of the tributary catchments had gauging data that was only just adequate for paired catchment analysis and the strength of correlations could be improved with more effort, particularly in capturing higher flows. Further analysis of shallow groundwater levels and pump drainage scheme data may also help to better understand the extent of these potential fluxes. The generally good agreement of results from several methods for estimating evaporation indicates that significant improvement to this dataset could only potentially be achieved by making actual at-site measurements with Class A pans. A higher density rain gauge network could be established but is unlikely to yield improved results given the relative insensitivity of lake level change to rainfall. Barrage inflows and outflows were measured with an ADCP unit that was periodically calibrated during the study period with favourable results so no significant refinement of this component can be expected.

Validation of the performance of the model (and the adjustment rules) on an independent time period should be undertaken prior to any further refinement of water balance datasets.

6.2 Interpreting the results of the abstraction scenarios

A full assessment of the implication of reduced lake levels under increased abstraction regime is outside the scope of this report. However, the following are some preliminary thoughts on how the model results could assist.

The eastern shore of the lake is a nationally important site for wader birds. The shallow bed gradient and reduced fluctuation in water levels (resulting from barrage control) has created conditions, including the establishment of a native marsh turf, that are favoured by several wader bird species. Robertson and Heather (1999) found that wader birds were most abundant when lake levels were between 9.95 and 10.30 masl, with numbers dropping off significantly below and above these thresholds, respectively. These findings support the existing lake management plan and target minimum levels.

It follows that perhaps the most significant potential impact of increased allocation is a change in the eastern lakeshore inundation patterns and a subsequent reduction in the quality of wader bird habitat. Using the bathymetric survey data shown in Figure 3.1, the change in lake levels shown in Figure 5.5 can be translated into changes in the lateral extent of exposed shoreline. For example, it is estimated that for a reduction in lake level of 5 cm (caused by an additional allocation of 40,000 m^3/day) approximately 50 m of eastern shoreline could be exposed. If abstraction rates were to double from the status quo, about 100 m of shoreline may be exposed (Figure 6.1).

Figure 6.1: Lake Wairarapa viewed from north to south along the eastern shoreline. Distances from the shoreline are indicated for the purposes of putting the potential additional shoreline exposure under allocation scenarios into context

Overall, it is uncertain whether the scale of lake level reductions and shoreline exposures likely under increased allocation scenarios is environmentally meaningful. While the general lake level preferences of existing wader birds are reasonably well understood, there are unknowns primarily associated with the extent to which shoreline ecosystems (turf marshes, invertebrates, etc) and dependent bird communities would adapt to any summer reductions. There are also factors relating to natural processes like lake sedimentation that will influence the actual degree to which shoreline exposure results from increased abstraction.

7. Conclusions and recommendations

A water balance model for Lake Wairarapa has been developed and successfully calibrated for the summer of 2012/13. Summer allocation scenarios have been tested and the likely impacts on lake levels quantified. While further work is needed to translate the findings into firm conclusions regarding environmental consequence, it is considered that enough has been learned to inform recommendations about allocation management for Proposed Natural Resources Plan. These recommendations, including an interim allocation limit, are set out below.

7.1 Recommended interim allocation limit for lake

It is recommended that the interim limit for allocation of water directly from Lake Wairarapa (and its marginal drains) is 0.6 m^3/s or 39,635 m^3/day. This equates to the existing (as at 15 November 2014) level of consented allocation from the lake and therefore represents a cap on any new takes. It also implies that the interim limit for allocating ‘lake depleting’ water from tributaries and groundwater in the wider lake catchment should equate to the existing level of consented allocation (1.8 m^3/sec).

The limit is informed by the preliminary findings in this report that the lake water level is likely to be relatively sensitive to increases in allocation; small changes in volume can potentially lead to quite large shoreline exposures. The recommended limit is not based on an explicit assessment of the environmental consequence of shoreline recessions due to increased allocation. It simply reflects the line of reasoning that any increase in allocation would be difficult to justify given the existing difficulty that is sometimes experienced in meeting summer minimum target levels, the likely sensitivity of the lake levels to abstraction and the lack of information about environmental consequences. It is considered prudent to adopt a precautionary approach until alternative allocation scenarios can be debated in the context of overall Lake Wairarapa management.

7.2 Recommended management of existing abstractions

In addition to setting an allocation limit, it is recommended that existing water takes are managed to prevent them exacerbating lake level reductions in times of summer water stress.

Currently, consents to take water directly from the lake are subject to cease take conditions when the lake is below target minimum levels. However, these conditions leave water users with a very low security of supply over summer months because the lake is so frequently below target levels (on average, 65 days per summer). This situation, combined with some doubt as to whether being below target levels represents a genuine period of water stress, has led to GWRC exercising discretion as to whether cease take conditions are enforced.

A change in approach is recommended to provide more certainty. Rather than being based on the single premise of maintaining a minimum target level, it is recommended that existing takes be restricted or required to cease in accordance with the status of all of the following:

- minimum target lake levels,
- trend in lake level over the preceding five days, **and**
- flow in the Tauherenikau River relative to its specified minimum flow

If the lake level is below its seasonal minimum target level **and** has been trending downwards for at least five days **and** the Tauherenikau River is at or below its minimum flow, then direct abstraction from the lake should cease. The reason for requiring all three conditions to be met simultaneously, rather than just one (such as the target lake level), is to ensure that restrictions are only imposed in the event of genuine high water stress in the lake and its catchment. The artificially managed nature of water levels in Lake Wairarapa, along with the complex influence of levels in Lake Onoke and the Lower Ruamahanga River, means that there are times when tributary rivers to the lake are below minimum flow and/or target lake levels are not met **but** lake levels are rising. Likewise, there are times when there is a relatively good river flow into the lake but seasonal minimum target lake levels have still not been achieved. At such times it is considered inappropriate to restrict abstraction from the lake because neither represent periods of genuine catchment water stress.

With regard to security of supply, the recommended criteria would have resulted in cease take situations in eight of the past 20 years and for an average of three days in those years. The maximum number of days of cease take would have been eleven days (1995/96).

7.3 Recommended further work to refine understanding

There are several areas where further hydrology work may be useful to help refine our understanding of the dynamic lake water balance:

- A fuller assessment of shallow groundwater bore monitoring data may shed more light on the nature of shallow subsurface flow to and from the lake
- Consideration of more sophisticated flow modelling for the lake tributaries. For example, it may be possible to calibrate models like TopNet with existing spot gauging data to provide a more reliable inflow time series (rather than relying on synthetic time series based on flow correlations).
- Consultation with ecologists and other interested parties to determine the likely actual consequence of increased summer shoreline exposures

Any further work should be planned with catchment-wide management objectives in mind. An important consideration for any further hydrological model development will be requirements for potentially coupling with water quality and biological models to provide integrated lake systems model.

Acknowledgements

Graeme Horrell from NIWA reviewed an early version of this report and is thanked for his helpful comments.

References

Glova G and Jellyman D. 2003. *Monitoring of fish movements at the Lake Wairarapa barrage gates.* NIWA Client Report: CHC2002-038 Prepared for Wellington Regional Council.

Gyopari M and McAlister D. 2010. *Wairarapa Valley groundwater resource investigation: Lower Valley catchment hydrogeology and modelling*. Greater Wellington Regional Council, Technical Publication No. GW/EMI-T-10/75.

Horrell G. 2010. *Lake Wairarapa Water Allocation.* Letter of advice prepared by NIWA for Greater Wellington Regional Council, dated 16 December 2010. WGN_DOCS#818919, Greater Wellington Regional Council, Wellington.

Horrell G. Undated. *Evidence prepared for a hearing on the matter of an application by Te Runanga o Ngai Tahu and Department of Conservation to amend the Water Conservation Order on Lake Ellesmere.* http://www.ecan.govt.nz/publications/Plans/lake-ellesmere-wco-submitter-evidence-ecan-graeme-horrell-170511.pdf

Mzila D. 2011. *Proposal to investigate Lake Wairarapa water balance.* Unpublished internal memo, WGN_DOCS#974727, Greater Wellington Regional Council, Wellington.

Robertson H and Heather B. 1999. Effect of water levels on the seasonal use of Lake Wairarapa by waders. *Notornis*, 46: 79–88 (1999).

Thompson M. 2011. *Lake Wairarapa catchment hydrology.* Unpublished internal report prepared as background information for a fieldtrip organised by the New Zealand Hydrological Society, WGN_DOCS#997375, Greater Wellington Regional Council, Wellington.

Thompson M. 2013. *Lake Wairarapa: tributary flow modelling*. Unpublished internal memo,WGN_DOCS#1160463, Greater Wellington Regional Council, Wellington.

Appendix 1: Modelling lake tributary inflows

Conceptual understanding of tributary inflow

For the purposes of summer water balance modelling the catchment area of Lake Wairarapa is calculated as 525 km^2. This excludes the Ruamahanga River catchment as this catchment only contributes flow to the lake in times of high flood (via the Oporua Spillway)

There are 13 named tributary inflow channels to Lake Wairarapa; these are shown in Figure 4.1 of the main report and listed in Table A1. These catchments have a combined area of 488 km^2 (93% of the total lake catchment area) with catchments draining the Rimutaka and Tararua ranges to the west having roughly twice the area of the eastern lake catchments (314 km^2 compared to 173 km^2, respectively). The most persistent (year round) and substantial base flows are from the Tauherenikau River, the Otukura Stream and Bartons Lagoon Outlet; these are all located around the north eastern margin of the lake. The streams around the western lake margin that emerge from steep catchments in the Rimutaka Range are flashy systems; winter base flows are maintained but they are prone to drying up completely in their lower reaches in mid-summer where the channels pass over permeable gravels. It is expected that most of this ‘lost’ flow reaches the lake relatively quickly as diffuse shallow groundwater discharge.

During summer, there does not appear to be any significant channelised base flow input to the lake south of the Otukura Stream on the eastern margin. This side of the lake is characterised by very flat farmland, marshlands and lagoons with few distinct flowing outlets. The two main streams on the eastern margin, the Mangatete Stream and Whakawiriwiri Stream, are essentially stagnant arms of the lake during dry weather summer conditions (even though they have a combined catchment area of about 73 km^2). Little flow is observed discharging during dry weather summer conditions from the Boggy/Matthews/Wairio Lagoon complexes to the south east.

In addition to the rivers and streams listed in Table A1, there are many minor unnamed streams around the lake; about 20 can be identified on a 1:50,000 scale topographic map, three quarters of which are small gully streams on the western lake margin. In total these streams comprise only 7% of the lake catchment area and flow contribution is probably even less than this proportion because they do not penetrate back into the higher rainfall areas of the ranges.

During winter it is known that significant volumes of water start flowing into the lake through the myriad small surface drains as well as via the pumped drainage schemes; water is periodically pumped from farmland on the eastern margin (eg, Wairio block) into drains and lagoons connected to the lake. However, data on the extent of these winter flows is not yet available.

Flow derivation

Table A1 shows the method of flow derivation for each of the primary lake tributary catchments. Generally flow was estimated for a location as close to the lake shore as practically possible by either adjusting a continuous flow record from the same catchment or by paired catchment analysis. A full record of spot flow gauging results is provided in Table A2 and the correlation results from paired catchment analysis are shown in Figure A1 and Table A2.

Table A1: Primary tributaries of Lake Wairarapa and flow estimate information

Tributary name	**Catchment area (km^2)**	**Method of flow estimate for lake inflow***
Manganui Stream	16.8	$\textit{Manganui flow} = 0.41[\textit{PTB}] – 0.057$
Wairongomai River	28.3	$\textit{Waiorongomai flow} = 0.67[\textit{PTB}] – 0.065$
Burlings Stream	10.4	Continuous recorder site established in January 2013 with some infilling of data prior to that based on correlation with Pakuratahi River
Brocketts Stream	7.2	$\textit{Brocketts flow} = 0.18[\textit{PTB}] + 0.005$
Cross Creek	18.4	$\textit{Cross Creek flow} = 0.37\ [\textit{PTB}] – 0.015$
Owhanga Stream	13.5	Included in lumped estimate for ‘rest of lake catchment’
Prince Stream	10.9	$\textit{Prince flow} = 0.07[\textit{PTB}] – 0.025$
Abbots (Otauria) Creek	51.5	$\textit{Abbots flow} = 0.46[\textit{PTB}] – 0.042$
Bartons Lagoon Outlet	13.1	$\textit{Bartons flow} = 1.02[\textit{OW}]^{0.245}$
Tauherenikau River	144.2	$\textit{Tauherenikau flow} = 1.33[\textit{TG}] – 1.548$
Otukura Stream	99.6	$\textit{Otukura flow} = 2.18[\textit{OW}] + 0.247$
Mangatete Stream	12.6	Included in lumped estimate for ‘rest of lake catchment’
Whakawiriwiri Drain	61.0	Included in lumped estimate for ‘rest of lake catchment’
Other minor tributaries	37.0	Included in lumped estimate for ‘rest of lake catchment’
TOTAL LAKE CATCHMENT	525.0	

* **PTB** = Pakuratahi River at Truss Bridge, **OW** = Otukura Stream at Weir and **TG** = Tauherenikau River at Gorge

Table A2: Spot gauging and recorder data (grey shaded) used to estimate flow contributions to lake from primary tributaries (see correlation plots in Figure A1

Date	Tauherenikau at Gorge	Otukura at Weir	Pakuratahi at Truss Bridge	Abbots Creek at SH2 Bridge	Bartons Lagoon Outlet	Otukura Stream at Lake Shore	Waiorongomai at Forest Park	Brocketts Stm at Western Lake Road	Goodings Stream at Western Lake Road	Cross Creek at Western Lake Road	Prince Stream at Western Lake Rd	Manganui at Papatahi Rd
26/7//2000	4.62	0.407	0.513		0.967							
12/03/2009	2.374	0.222	0.48		0.762							
14/12/2009			1.4				0.735					
12/03/2010							0.2					
21/04/2010			0.2				0.074					
22/04/2010	1.654	0.129	0.22		0.454	0.616		0.039	0.007	0.031		0.066
26/04/2010			0.23				0.075					
6/05/2010			0.325				0.081					
1/06/2010							1.182					
7/09/2010			4.56				3.016					
24/02/2011	1.808	0.053	0.339		0.581		0.11	0.051	0.005	0.072		0.048
6/03/2012	12.88	0.613	1.588	0.724						0.577	0.084	
14/08/2012	4.221	1.452	1.62		1.17	3.58						
15/08/2012	4.945	1.191	1.725					0.438	0.082	0.719	0.152	0.525
19/09/2012	4.536				1.01							
12/12/2012		0.136			0.574							
31/01/2013	1.45	0.05	0.285	0.077	0.5	0.42	0.135			0.089		0.068
27/02/2013	1.04	0.065	0.25	0.068			0.144	0.042	0.001	0.067	0	0.029
22/04/2013		0.225			0.733							
22/07/2013		0.863			0.888							
24/07/2013	4.52	0.82	0.86			1.705	0.734	0.184	0.057	0.39	0.029	0.418
30/01/2014			0.59	0.238								
18/02/2014			0.47	0.165								
15/04/2014			2.01	0.845				0.262	0.058	0.597	0.08	0.875
20/06/2014			0.915	0.39				0.155	0.041	0.326	0.021	0.256

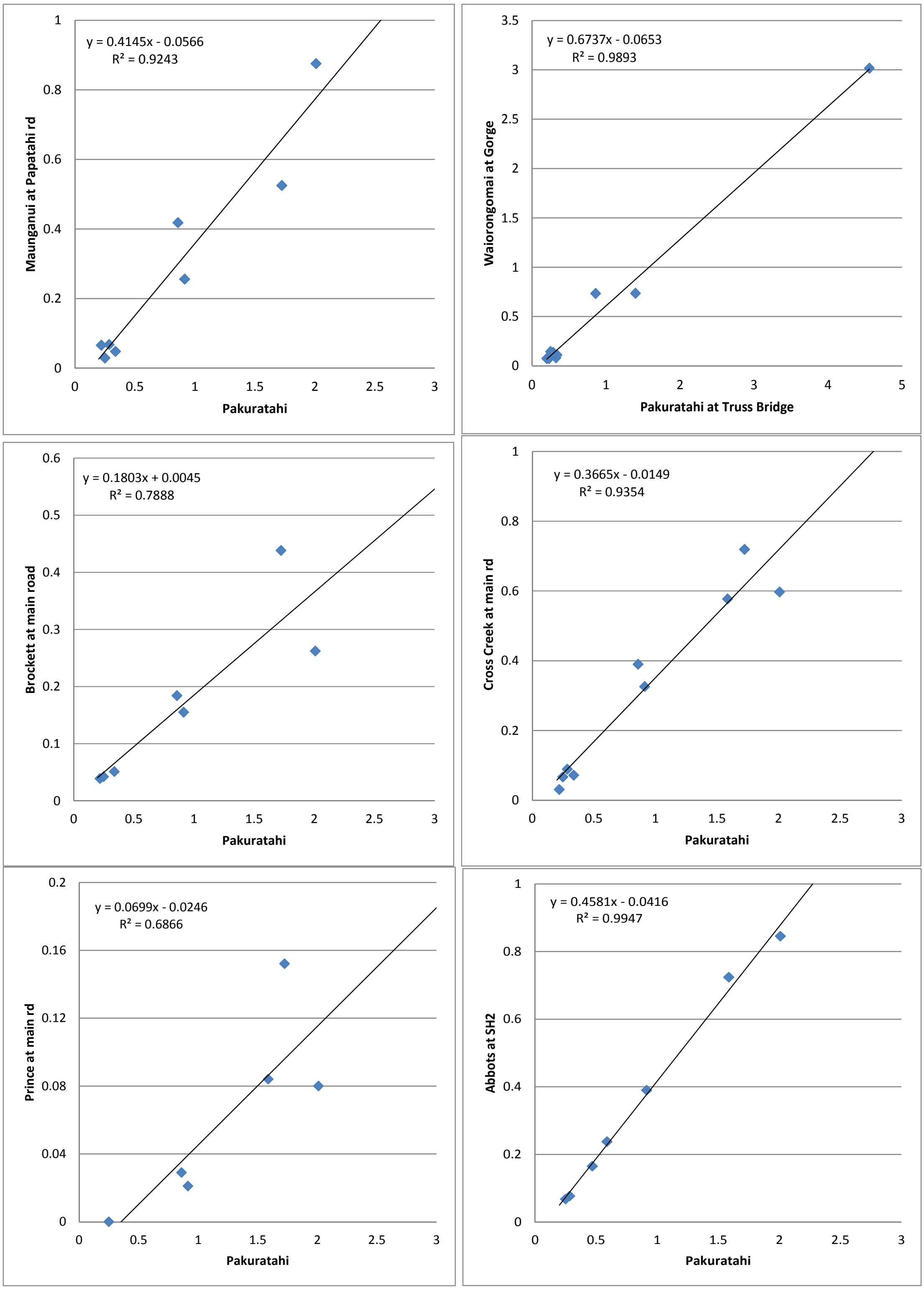


Figure A1: Paired catchment analysis results; correlation between spot flow gaugings at various lake tributary locations and corresponding (same time) flow at the chosen nearby site (in most cases, the Pakuratahi River at Truss Bridge). All units are m³/sec.

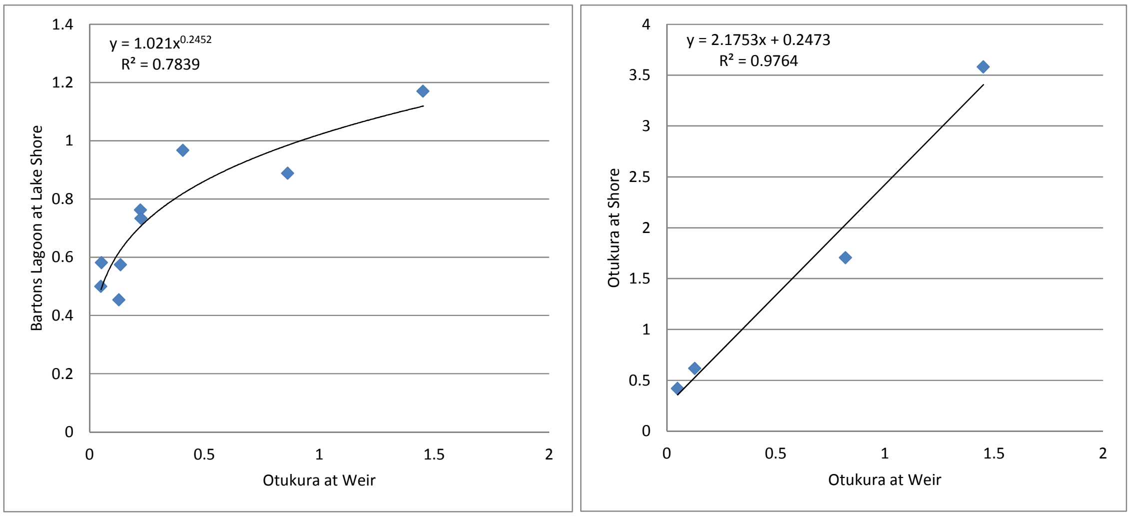


Figure A1 continued: Paired catchment analysis results; correlation between spot flow gaugings at various lake tributary locations and corresponding (same time) flow at the chosen nearby site. All units are m^3/sec.

Appendix 2: Penman evaporation calculations

Evaporation was calculated using the Penman method as follows:

$$Evap = \frac{\Delta}{\Delta + \gamma} \frac{R_n - Q}{\rho \lambda} + \frac{\gamma}{\Delta + \gamma} f(U_a)(e_s - e_a)\Delta\lambda \qquad (1)$$

Δ is the slope of the vapor pressure-temperature curve at the mean air temperature. T is the mean air temperature in ^{o}C

$$\Delta = 0.20(0.00738T + 0.8072)^7 - 0.000116 \qquad (2)$$

λ = the latent heat of vaporization of water at the mean air temperature in MJ / kg

$$\lambda = 2.501 - 0.002361T \qquad (3)$$

γ is the psychrometric constant for this temperature and pressure in kPa / oC.

$$\gamma = 0.00163 \frac{P}{\lambda} \qquad (4)$$

P is the atmospheric pressure in kPa at this field elevation (*H*)

$$P = 101.3 - 0.01055H \qquad (5)$$

$R_n = R_{nl} + R_{ns}$ (*net solar radiation*, R_n = *net longwave radiation,* R_{nl} *+net shortwave radiation,* R_{ns})

$$f(U_a) = 0.26(1 + 0.54U_a) \qquad (6)$$

e_s is the saturation vapor pressure in kPa at the mean air temperature,

e_a is the actual vapor pressure for this temperature and relative humidity in kPa.

$$e_a = (RH)(e_s)/100 \qquad (7)$$

U_a is the wind speed referenced to 2m above ground surface