Waterways
Centre for Freshwater Management

# A Summer Hydrological Budget for Lake Forsyth/Wairewa: Preliminary Findings

Summer Scholarship Report

***WCFM Report 2012-004***

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| REPORT: | WCFM Report 2012-004 |
| TITLE: | A summer hydrological budget for Lake Forsyth/Wairewa: Preliminary Findings |
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| DATE: | **28 March 2012** |

# Executive Summary

Lake Forsyth/Wairewa in Canterbury, New Zealand is a shallow eutrophic lake separated from the sea by the sand and gravel Kaitorete spit. The lake has historic cultural and community significance but has been susceptible to sporadic toxic algal blooms for ca. 100 years. Previous studies have indicated that phosphate in the lake sediments may be a contributing factor in the algal blooms. These sediments originate as catchment soils, transported into the lake by rivers, streams and direct runoff from the steep loess covered volcanic subcatchments. The purpose of this report was to formulate an indicative summer hydrologic budget for Wairewa, incorporating a moderate rainfall event. This budget will be used to underpin sediment and phosphate budgets for the lake catchment.

Stream gauging over 5 days, including a 60mm rain event, in December 2011 provided reliable input flow data for the two major rivers; the Okana and Okuti, and smaller streams along the north west side of the lake. Direct runoff from the two other subcatchments (the Northern and Southern regions) was assumed to occur only during rainfall, and estimated from land surface area and precipitation. Lake level data was available from the ECan monitoring site near the western end of the lake. Daily rainfall and evaporation data were available for the catchment, but no data were available for groundwater flow or seepage from the lake into the groundwater system. The latter was therefore estimated as the difference between known input flows and known output flows plus the change in lake volume.

Under dry conditions, input to the lake was dominated by the Okana and Okuti Rivers. However, direct precipitation onto the lake surface made similar contribution under the rainfall conditions occurring on the 6 & 7 Dec, 2011. Direct surface run off from the Northern and Southern subcatchments appears unlikely to be major input, even during the moderate rainfall event. Total surface water inputs to the lake increased by almost an order of magnitude (from 1750 to 13,000m$^3$/hr) during the moderate rainfall event.

The only outputs from the lake are evaporation from the lake surface and seepage to the shallow groundwater system through the bottom of the lake, or through the gravel barrier at the western end of the lake. Evaporation rates exceeded seepage rates under the dry conditions, but vice versa during the rainfall event. Total outputs were less than inputs for each of the 5 days monitored, and lake level rose consistently through this period.

There may be wave effects present during storm events, delaying the lake level response to the inflow of storm waters at the eastern end of the lake. It has not been possible to fully characterise the time delay of this wave, and this in turn limits the accuracy of the hydrologic budget and affects the estimation of seepage through the barrier to the ocean. Recommendations for addressing this and other limitations of this study are given.

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# Section 1 Introduction

## 1.1 Background & Research Aim

Situated on the southern side of Banks Peninsula (Canterbury, New Zealand) Lake Forsyth/Wairewa (Figure) is a shallow eutrophic lake, of cultural importance to Ngāi Tahu. The sedimentary history of the lake over the last 7000 years indicates a transition from a tidal embayment to a brackish coastal lake (Woodward and Shulmeister, 2005). From 1860 AD onwards, anthropogenic land use changes, including deforestation and an increase in grasslands within the lake catchment, have lead to an increase in sedimentation and nutrient levels within the lake, a reduction in lake water salinity and increasing levels of eutrophication. Salinity rose again after artificial opening of the lake commenced in the late 1800's. For at least 100 years, particularly in the summer, Wairewa has had sporadic toxic cyanobacteria algal blooms (Reid et al., 2004). Woodward and Shulmeister (2005) suggest that phosphorous from the catchment soils may be a contributing factor controlling the algal blooms. Catchment soils are transported into the lake via rivers, streams and direct surface runoff from the land. However the mechanism by which phosphorous is released from the lake sediments into the water column has yet to be determined (Webster-Brown et al., 2011).

The purpose of this study is to quantify surface water flow into the lake, and develop a preliminary lake water budget for summer 2011/2012. The hydrological budget will underpin future sediment and phosphorus budgets for this lake.

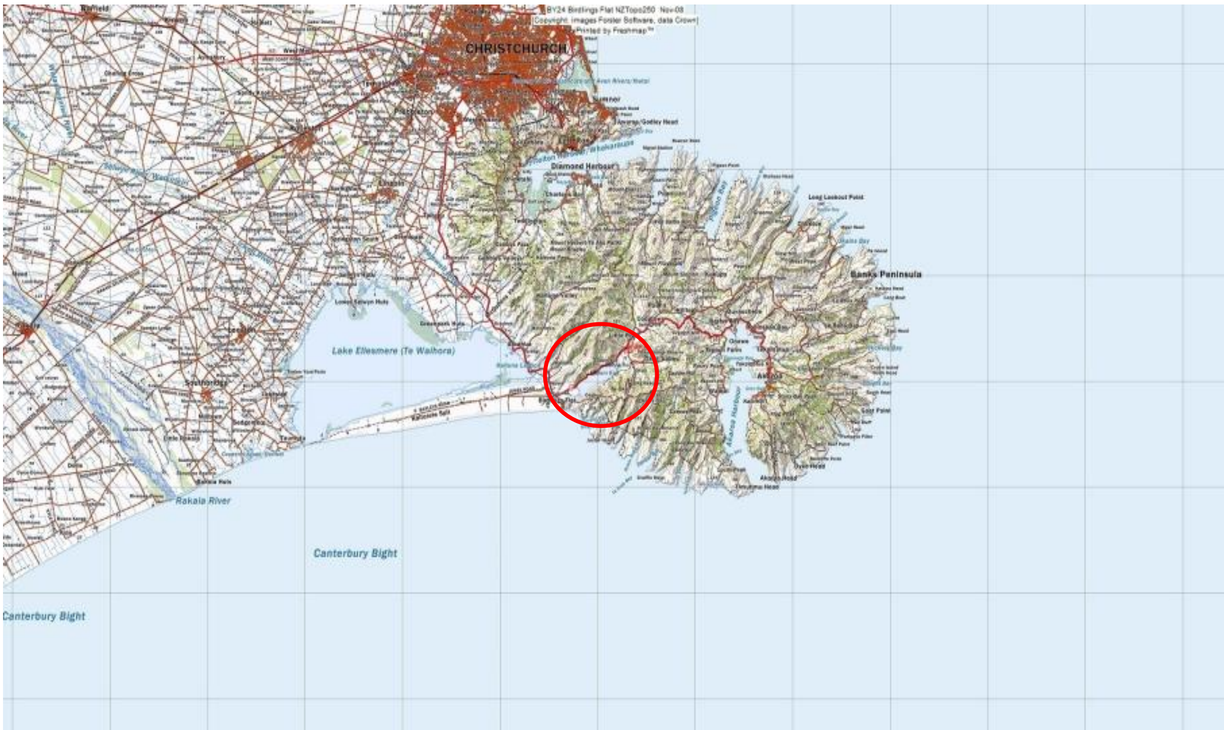



**Figure 1.** Location of Lake Forsyth/Wairewa on Banks Peninsula in Canterbury. Map reproduced from Freshmap (2005)

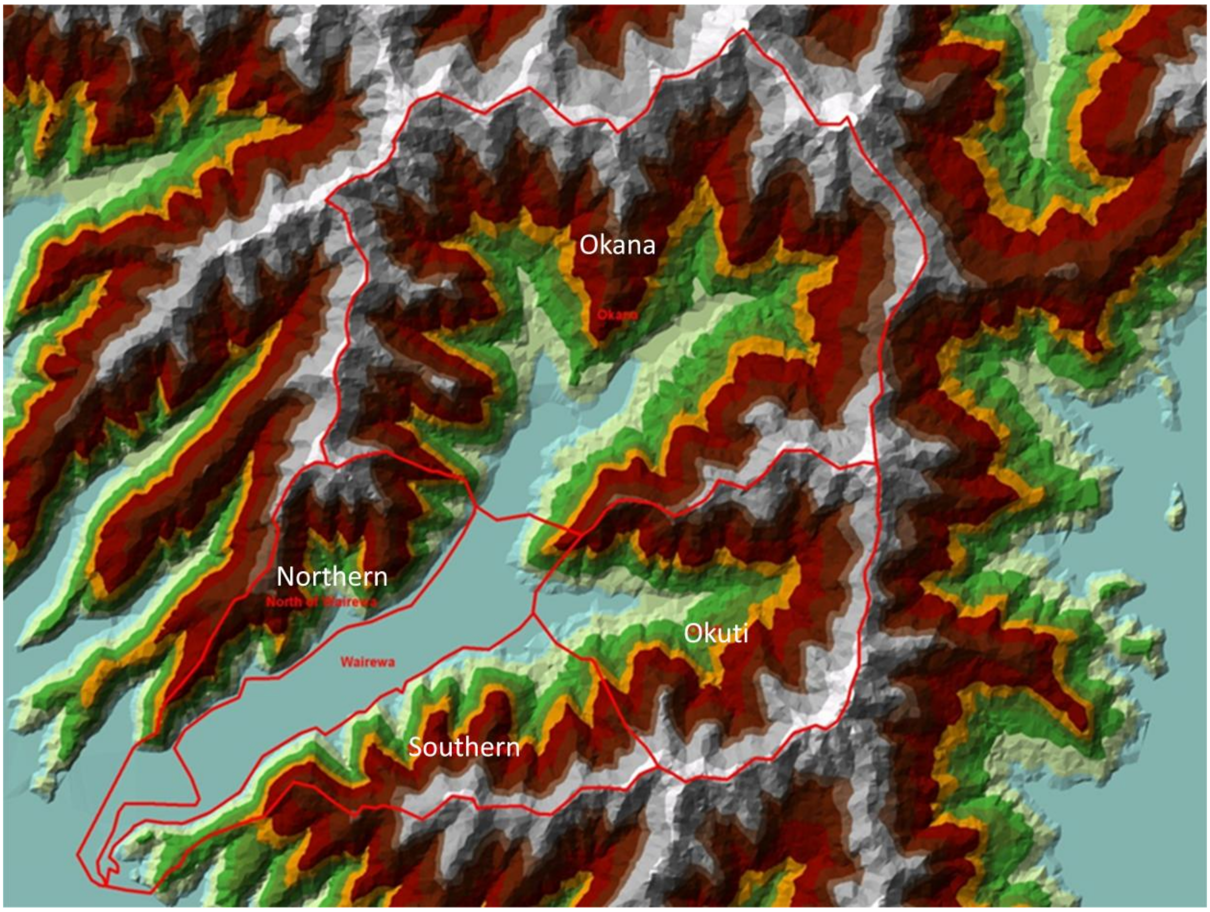



**Figure 2.** Individual surface water drainage boundaries within the Wairewa catchment, showing the four subcatchments (original image from Whyte, 2011).

## 1.2 Catchment characteristics

The hydrologic catchment area of the lake is 108km$^2$, which can be divided into four subcatchments (Figure 2); Okana (54km$^2$), Okuti (19.7km$^2$), the Southern region (13.3km$^2$) and the Northern region (11.2km$^2$) (Whyte, 2011).

### 1.2.1 Geology and Geomorphology

Wairewa lies within the Banks Peninsula volcanic complex. The basement lithologies within the Lake Forsyth hydrologic catchment have been mapped and described by Sewell et al (1993). The Northern, Okuti and the majority of the Okana regions are comprised of French Hill Formation of the Miocene Akaroa Volcanic group, with the remainder of the Okana region comprised of the Orton Bradley Formation from the Miocene Mt Herbert Volcanic Group. The Southern region is comprised of the Akaroa Volcanic Group, Mt Sinclair Formation.

The floor of the valley from the eastern end of the lake, to the bridge crossing the Okana River in Little River (NB. indicated as “Bridge” site on Figure 8), has been classified as Holocene saline sand, silt and peat of the Christchurch Formation. The remaining valley sediments at the eastern end of the lake are classified as valley fill and slopewash deposits from the Christchurch Formation. The barrier and Birdlings Flat areas at the western end of

the lake are classified as beach gravels of the Christchurch Formation (Sewell et al., 1993). At the time of writing, no soils data was available for the catchment on the Landcare Research online soils map. Thick loess deposits cover hills throughout the catchment, and are particularly evident in the Northern and Southern region subcatchments.

As well as the well defined rivers, streams and drainage channels in the catchment, catchment loess slopes have developed multiple erosion gullies. Hosking (1962) and Hughes (1972, 1970) noted that loess covered slopes on Banks Peninsula are prone to tunnel erosion, which collapse to form shallow gullies for surface runoff. Such shallow gullies can be seen in the Northern and Southern regions of the catchment (Figure 3 & 4). Hughes (1972) also noted that loess slopes with sparse vegetation, bare basement rock at the top and thick redistributed loess deposits on the lower slopes (as shown in Figures 3 & 4), are highly susceptible to both tunnel erosion and rapid overland flow of water and sediment, particularly on slopes with a NW to W aspect. This phenomenon was attributed to increased exposure to the effects of evaporation and wind.

### 1.2.2 Surface waters

Three main surface waterways in the catchment are the Okana and Okuti Rivers, which drain the largest two of the four subcatchments. Their flows combine just before entering the lake to form the short (ca. 1.5km long) Takiritawai River which flows into the lake through a flat, wetland area at the eastern end.

Smaller but more-or-less permanent streams within the Okana River catchment, draining hills on the north side of the catchment, include Catons Bay Stream and two unnamed streams in the Little River township; one which emerges near the Little River hotel (referred to here as “Hotel” stream) and one which joins the Okana River at the bridge on Kinloch Rd (referred to hear as “Bridge” stream).

The Northern region subcatchment (Figures 3 & 5) consists of partially vegetated, loess-soiled, steep slopes leading down to the SH75 highway, which separates the hill slopes from the lake. A drainage gully runs along the northern side of the SH75 highway with occasional pipe work allowing drainage under the road and through the lake embankment. Only one stream of note was observed from the slopes of the Northern region and this was sampled as “Eastern End” stream in this study.

The Southern region subcatchment (Figures 4 & 6) consists of relatively steep volcanic (predominantly basaltic) bedrock with loess soil up to ~100m above lake level, sparse vegetation and multiple eroded surface drainage channels. No access was available to this area during this study.

There is no permanent outflow from the lake at the surface. However the lake is opened to the sea through the gravel barrier at the western end at regular intervals (refer Appendix 2 for recent lake openings).

**Figure 3.** Multiple shallow gullies on the loess-covered slopes of the Southern region of Wairewa.

**Figure 4.** A lightly vegetated rip rap lake embankment in the Northern region of Wairewa's catchment (foreground), and the slopes of the Southern region on the far shore of the lake.

**Figure 5.** Looking towards the Northern Region, across the flats at the eastern end of the lake.

**Figure 6.** The Southern Region as viewed from Catons Bay.

# Section 2 Methods

## 2.1 Constructing a lake water budget

The catchment of any river, lake or body of water can be defined as the upstream area that contributes to open channel flow (Brutsaert, 2010). All waters within the catchment can then be defined as one of the following;

i) An input, being precipitation (P), inflowing groundwater ($G_{in}$) or inflowing surface water ($Q_{in}$) and maybe also a minor component from condensation

ii) An output; being evaporation (E), transpiration (T), outflowing groundwater ($G_{out}$) or outflowing surface water ($Q_{out}$)

iii) In storage (S), which is water held within lakes, streams, puddles, groundwater systems, flora and fauna (Todd and Mays, 2005)

The expression that describes the water budget for the lake, expressed in terms of the change in water storage (ΔS) is as follows;

$$\Delta S = P + (Q_{in} - Q_{out}) + (G_{in} - G_{out}) - E - T$$

Where water bodies flow out to the sea, via a river mouth, groundwater seepage, or lake drainage through permeable barriers, the ocean can also influence the overall water budget. The rise and fall of tides increases and decreases the volume of oceanic water opposing the seaward flow of freshwater. Low flow conditions within a river, lake or groundwater system can therefore lead to a reduction in the volume of outflow, or even intrusion of saline water into the freshwater body, the volume of which will be dependent on the height of the tide. Because Wairewa is a coastal lake with no surface outflow to the sea, any tidal component of the hydrologic budget would be included within the $G_{in}$ or $G_{out}$.

Depending on the volume and type of flora along the margins of a lake, transpiration can have an important role in the hydrologic budget. However, the northern margin of Wairewa is bounded predominantly by a sparsely vegetated rip rap embankment that supports SH75 (Figure 4), and sparsely vegetated gravels at the eastern end (Figure 5). The southern margin of the lake is bounded predominantly by steeply sloping, sparsely vegetated, loess-soiled slopes. The only areas with significant vegetation are the larger Okana and Okuti valleys, where it is anticipated that the use of river flow data would take account of most of the effects of transpiration. Therefore T has been removed from the water budget formula for Wairewa.

The only times that surface water flows out of the catchment is during anthropomorphic opening and natural, storm-inducedopenings through the gravel barrier. The flow volumes at these times will vary depending on the cross sectional area of the opening, and the level of water in the lake, with the flow typically decreasing over a few days as the lake level lowers and the barrier closes. This study concentrates on the water balance during normal (closed barrier) conditions. Outflowing surface water flows have not been quantified because the barrier was closed throughout the study.

## 2.2 Data collection

### 2.2.1 Precipitation (P)

The predominant source of climate data for the Banks Peninsula region is NIWA, through the National Climate Database. The locations of climate stations with a current record of precipitation are shown in Figure 7. Precipitation at each station is measured using a standard tipping bucket rain gauge (NIWA reports this as generally an OTA™ 0.2mm per tip gauge). All stations report precipitation data as daily amounts (09:00 to 09:00). The Akaroa and Lyttleton harbour stations are the only NIWA stations within 30km that provide hourly precipitation data. It is highly likely that, due to the mountain and valley terrain of Banks Peninsula, the wind direction, atmospheric conditions and orographic effects during rainfall events may create differences in the recorded onset and cessation of rainfall between gauges. Precipitation data within the Wairewa catchment is measured and reported as a daily figure from the Okuti rain gauge (agent number 4925), which is only 100m upstream of the gauging station used for this study on the Okuti River (as shown on Figure 8).

The direct contribution of precipitation to the lake volume (P in $m^3$) has been calculated by multiplying precipitation data by the surface area of the lake, to provide the volume of water directly added to the lake during that period.


**Figure 7.** NIWA climate monitoring stations in the vicinity of Wairewa (original map from Freshmap, 2005).

### 2.2.2 Surface Water Flow Gauging (Q)

Stream gauging was carried out between the 6th and 9th December 2011 at the sites indicated in Figure 8 and

Table 1. Gauging was carried out using the USGS "6 tenths" method outlined by Brassington (1998). The stream width was divided into multiple sections (or "stages") with the width of the section dependent on the gradient of the river bed (as the gradient of the river bed increased the width of the section decreased). The depth and average water velocity were measured for each section, with velocity measurements carried out over a period of 60 seconds, and at 0.6 ("6 tenths") of the total depth measured from the surface.

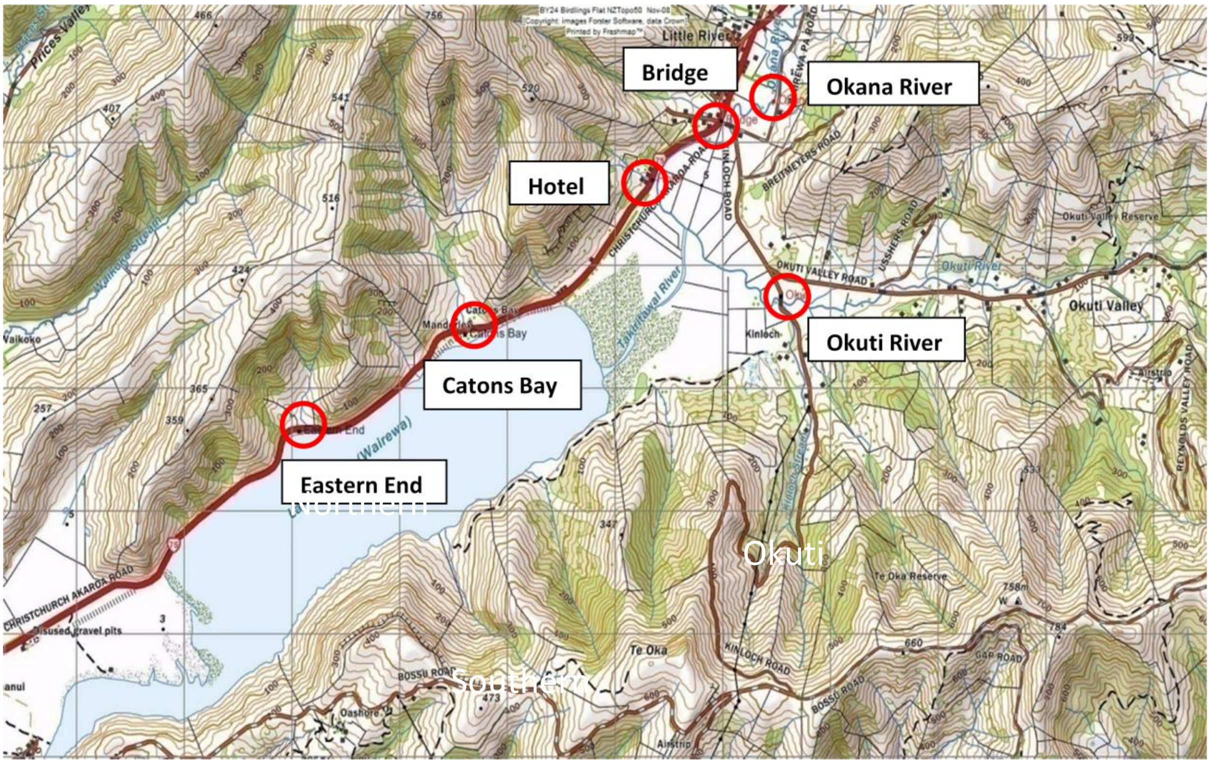



**Figure 8.** Location of sites used for flow gauging. GPS coordinates are shown in Table 1. (original map from Freshmap, 2005).

**Table 1.** Stream gauging site location GPS information.

| Site | NZTM | | NZGD (2000) | |
|---|---|---|---|---|
| Okana | E1582986 | N5153181 | E172 47.315 | S43 46.454 |
| Okuti | E1583472 | N5153341 | E172 47.678 | S43 46.368 |
| Bridge | E1583541 | N5151755 | E172 47.726 | S43 47.225 |
| Hotel | E1582346 | N5152701 | E172 46.837 | S43 46.712 |
| Catons Bay | E1580604 | N5151441 | E172 45.536 | S43 47.390 |
| Eastern end | E1579065 | N5150657 | E172 44.386 | S43 47.811 |

Current velocity and water depth readings were taken using a Global Water FP111 (Ser No 1024103407) flow probe. The flow probe measures current velocity to within 0.1$m^3$/sec, and depth measurement graduations were at 5mm intervals. Due to ripple height and water velocity causing the water level to rise up the depth measuring rod, measurements had an error of ±5mm.

The cross sectional area for each stage was calculated and multiplied by the average current velocity for that stage, to provide the instantaneous stage flow in $m^3$/sec. The sum of the flows for all of the stages provided the total flow for the river at that point. The calculation method is given in more detail, together with the raw gauging data (e.g. Table A1-A22) in Appendix 1.2.

The Okana and Okuti River gauging points were further from the lake than ideal, due to the difficulty in finding suitable conditions. Due to this distance, it is possible that groundwater flow from or to storage in this area and data (as shown in Figure 9) could alter the actual input from these rivers to the lake via the Takiritawai River.

Finally, due to the time taken to gauge each stream, and to travel between sites, the flows at sequentially gauged sites could be as much as 1.5hrs apart. The time between the first and last measurements required to calculate the complete surface flow input to the lake took up to 5hrs (Table 2). Therefore, to calculate simultaneous stream flows, for any point in time, the rate of change of flow for each stream over a relevant interval was calculated, allowing measured flows to be synchronised to the time of interest. Once synchronised, the cumulative runoff input for the various regions of the catchment could be estimated. The calculation method for time correction is further described in Appendix 1.5.

**Table 2.** Start time and date of each gauging at sites shown on Figure 8.

| **Gauging carried out on 6/12/11** | |
|---|---|
| Site | Time |
| Okana | 11:00 |
| Okuti | 12:50 |
| Catons Bay | no flow |
| Eastern end | no flow |
| Hotel | no flow |
| Bridge | no flow |

| **Gauging carried out on 7/12/11** | |
|---|---|
| Site | Time |
| Okana | 8:25 |
| *Okuti | 9:50 |
| Catons Bay | 11:20 |
| Eastern End | 13:00 |
| Hotel | 13:30 |
| Okana | 15:15 |
| *Okuti | 14:00 |

| **Gauging carried out on 8/12/11** | |
|---|---|
| Site | Time |
| Okana | 9:50 |
| Okuti | 10:40 |
| Bridge | 11:20 |
| Hotel | 11:45 |
| Catons Bay | 12:05 |
| Eastern End | 12:30 |
| Okana | 13:15 |
| Okuti | 14:05 |

| **Gauging carried out on 9/12/11** | |
|---|---|
| Site | Time |
| Okana | 10:25 |
| Okuti | 11:15 |
| Bridge | 11:45 |
| Catons Bay | 12:10 |

*Gauging unable to be undertaken at exact site; shifted 20m upstream

### 2.2.3 Direct runoff estimation

Unfortunately an accurate measurement of the direct surface runoff from the steep, loess slopes of the northern and southern subcatchments could not be made (with the exception of the Eastern End site stream which is within the northern catchment). During rainfall surface runoff can access the lake via the multitude of shallow, small erosion gullies, which are dry between rainfall events. The limited scope of this study, and access difficulties, precluded measurements of these flows during the 6-7 Dec rainfall event.

However, an initial estimate of the likely contribution of these subcatchments to the lake during periods of rain, was made from precipitation and subcatchment area. This has been done, using the following assumptions;

i) Direct runoff to the lake occurred only during the 24hr period of rain between 11:00 on 6/12/11 and 11:00 on the 7/12/11. Precipitation over this period was 60.8mm.

ii) Infiltration rates of between 0 and 50% have been considered, reflecting the low level of infiltration that might be expected in the steep sparsely vegetated terrain of these subcatchments, as well as the early summer conditions in which dry soils might favour infiltration as long as they remain hydrophilic.

iii) Land areas of 13.3km$^2$ for the Southern subcatchment, and 7.2 km$^2$ (11.2 km$^2$ less the area of the Eastern End Stream catchment which is ~4km$^2$) for the Northern subcatchment.

GIS modelling information from DHI Group in Whyte (2011) provided the above catchment area data, and slope information for the Northern (244.6m/km) and Southern (181.3m/km) regions.

### 2.2.4 Groundwater inflow and seepage (G)

Although no records of previous thorough groundwater studies have been found during the course of this investigation, some properties of the subsurface aquifer have been ascertained.

A seismic survey was carried out by Broadbent & Haines (1976) in the area indicated in Figure. Results from the survey indicate that the barrier area is comprised of three distinct layers. Layer 1 is up to 1m of surface soil/ loess with a compressional wave velocity of 0.2km/s. The middle layer, Layer 2, is comprised of water-saturated sand and gravel ranging in thickness from 0m to 37m; thickest against the cliffs in the region of a filled channel. The sand and gravel layer responded with compressional wave velocities of 2km/s. Layer 3, the basement layer, is comprised of Akaroa volcanic with compressional velocities of between 3-4km/s.

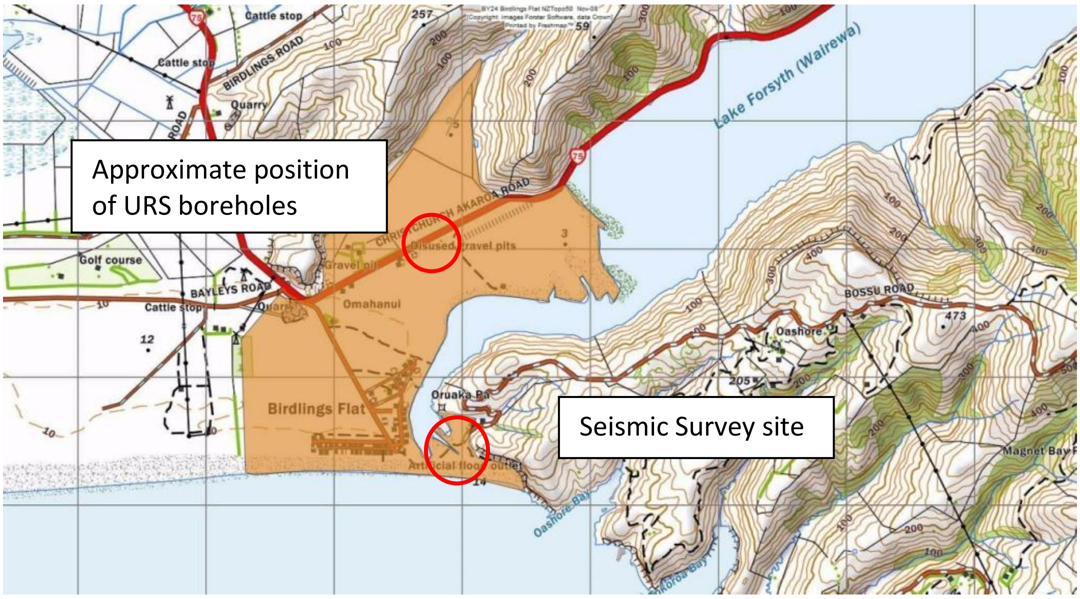



**Figure 9.** The area of sand and gravel at the western end of Wairewa (image modified from original Freshmap, 2005) showing the position of the previous seismic survey and the URS bores (Figure 10).

As part of the resource consent conditions for the disused Birdlings Flat Landfill site, Christchurch City Council (CCC) is required to undertake groundwater quality measurements annually; a task which has been delegated to URS New Zealand Ltd. Initial information from URS indicates the presence of 4 borehole wells within the gravels of Birdlings flat (approximate position shown in Figure 10). However, although permission has been granted by both URS and CCC to use the groundwater data, little useful analysis was able to be achieved in the time available. Water levels in the bores fluctuated between 4.09m and 5.65m below the surface. However, until the reference datum level and exact position of the boreholes can be ascertained, the direction of flow cannot be derived, or therefore the hydraulic gradient and the potential lake water seepage pathways through the barrier.


**Figure 10**. Approximate locations of URS boreholes at the Birdlings Flat Transfer Station (as supplied by URS New Zealand Ltd., 2012)

Instead the net amount of seepage into/out of the lake was estimated as the difference between the known lake inputs and outputs, that is not accounted for in the lake level, over any given period. Todd & Mays (2005) formula (Section 2.1) can be rearranged to;

$G = \Delta S - P + E - (Q_{in} - Q_{out})$

to calculate the groundwater component of a lake hydrologic budget. For the purposes of this study $Q_{out} = 0$ and can be removed from the equation, and G is the seepage losses to the ocean through the barrier, and/or water transferred to or from, and stored within, the areas identified in Figure 11.

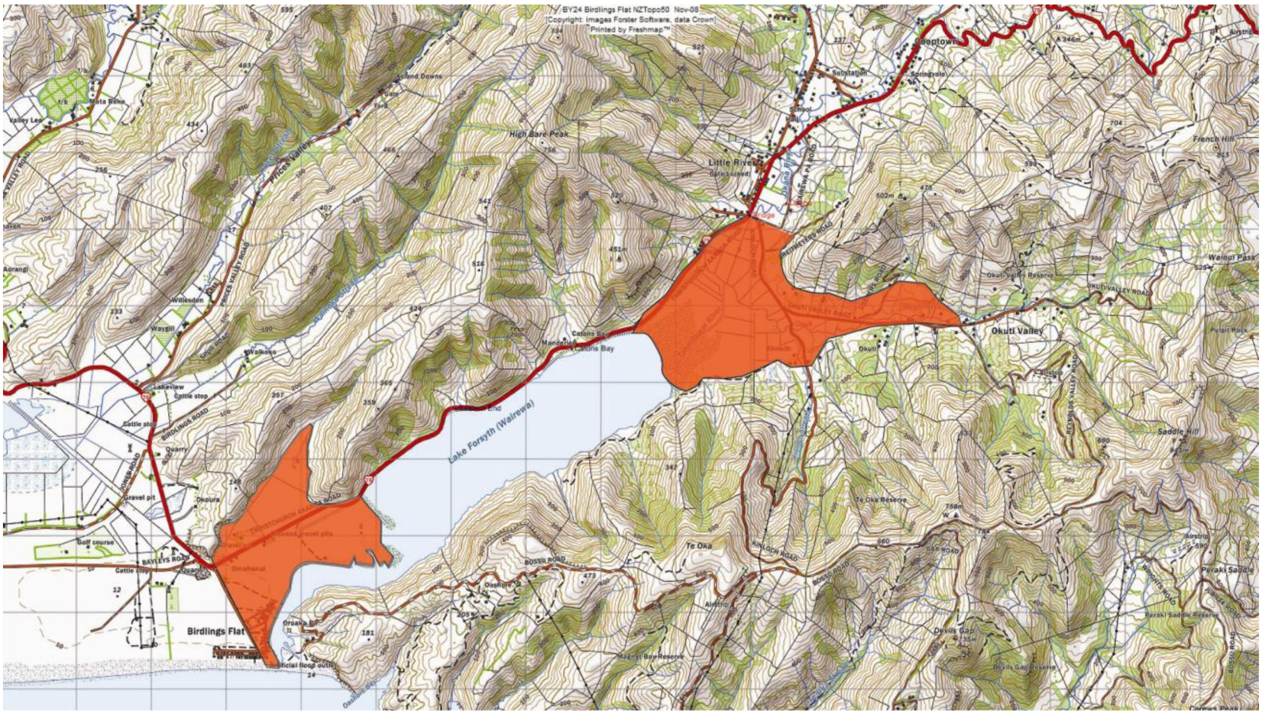



**Figure 11.** Areas of likely groundwater storage within the Wairewa catchment

### 2.2.5 Evaporation (E)

In its simplest form, evaporation can be considered as the transformation of water from its solid to gaseous state (water to vapour). In order to measure evaporation, atmospheric data measurements of surface and atmospheric temperature, long and short wave (incoming and outgoing) solar radiation and relative humidity and wind velocity/ direction are used.

Climate data within the catchment area is gathered by NIWA through the online National Climate Database (CliFlo). The closest climate station to the catchment area that physically measures evaporation data is in Akaroa (agent number 36593, see Figure 7). This is 12.7km from the Wairewa catchment, over mountainous terrain, which limits the applicability of this data. However, the CliFlo database also provides daily Penman open water evaporation estimates from the modelled Virtual Climate Network (VCSN). The VCSN utilises the ANU Spline interpolation model to produce a grid of 11491 stations around New Zealand. The closest Virtual station (agent number 21049) is positioned 2km from the Okuti rain gauge

(Figure 7), and provides estimates from 01 Jan 1960 to the present day. These evaporation estimates have been used in this study, as reported as mm/day (09:00 to 09:00).

To evaluate losses due to evaporation (E in $m^3$), an unlimited source of water surface is assumed, and evaporation data have been multiplied by the lake surface area.

**2.2.6 Lake volume change (ΔS)**

Environment Canterbury maintains a continual record of water level from a fixed calibrated recorder, on the northern side of the lake, near the mouth of the Eastern End Stream. This provides lake level measurements in millimetre increments at 15 minute intervals. The volume of water represented by each millimetre of lake level change has been calculated by Joyce (2011) from GIS and the bathymetry data captured by Irwin and May (1979), and is described in Appendix 3. The table of lake volume vs change in lake level (mm) has been used in conjunction with 15 minute lake level values provided by Environment Canterbury, to calculate the change in lake volume (ΔS in $m^3$) throughout the period of this study.

As noted by Hoffman et al (2008), water levels can vary over the surface of a lake in response to various atmospheric and hydrologic conditions. Wind blowing on a lake can force water to one end or side of the lake, for example. Cessation of the wind will cause the water will slop back to the other end, where the energy is reflected back, sending a wave in the opposite direction. The same effect can be caused by changes of atmospheric pressure. River inputs and high levels of precipitation in one area of the lake can also cause a plug of water to enter at one end of the lake, which is then transmitted by a wave towards the lake's discharge. Due to the long length of the lake, the potential for these variations will need to be considered when analysing short term fluctuations.

# Section 3 Results

## 3.1 Precipitation

Table 3 lists the daily precipitation data used within this study. The data is from the Okuti rain gauge, agent number 4925 on the National Climate Database. The rainfall event on the 6/12/11 was a moderate rainfall for summer, of just over 60cm in a 24hr period.

**Table 3.** Daily rainfall figures (mm) from the Okuti rain gauge, from NIWA (2012)

| Date | 4/12/11 | 5/12/11 | 6/12/11 | 7/12/11 | 8/12/11 | 9/12/11 | 10/12/11 |
|---|---|---|---|---|---|---|---|
| 04/12/11 | 0 | 0 | 51.7 | 9.1 | 0 | 0 | 0 |

## 3.2 Surface water flows

### 3.2.1 Flows from river gauging data

The flows calculated from river gauging during the period 6th - 9th December 2011 are provided in Table 4 (raw data and the calculation method is given in Appendix 1.2). Gauging began before rainfall in this catchment, on 6/12/11.

**Table 4.** Stream flows calculated from gauging carried out at each site

| **Gauging carried out on 6/12/11** | | |
|---|---|---|
| Site | Time | Flow ($m^3$/sec) |
| **Okana** | 11:00 | 0.293 |
| **Okuti** | 12:50 | 0.192 |
| **Catons Bay** | | 0.00 |
| **Eastern end** | | 0.00 |
| **Hotel** | | 0.00 |
| **Bridge** | | 0.00 |

| **Gauging carried out on 7/12/11** | | |
|---|---|---|
| Site | Time | Flow ($m^3$/sec) |
| **Okana** | 8:25 | 1.391 **+** |
| **Okuti *** | 9:50 | 2.827 |
| **Catons Bay** | 11:20 | 0.387 |
| **Eastern End** | 13:00 | 0.023 |
| **Hotel** | 13:30 | 0.026 |
| **Okana** | 15:15 | 1.625 |
| **Okuti *** | 14:00 | 1.447 |

| **Gauging carried out on 8/12/11** | | |
|---|---|---|
| Site | Time | Flow ($m^3$/sec) |
| **Okana** | 9:50 | 0.522 |
| **Okuti** | 10:40 | 0.515 |
| **Bridge** | 11:20 | 0.013 |
| **Hotel** | 11:45 | 0.006 |
| **Catons Bay** | 12:05 | 0.069 |
| **Eastern End** | 12:30 | 0.004 |
| **Okana** | 13:15 | 0.487 |
| **Okuti** | 14:05 | 0.523 |

| Gauging carried out on 9/12/11 | | |
|---|---|---|
| Site | Time | Flow ($m^3$/sec) |
| **Okana** | 10:25 | 0.425 |
| **Okuti** | 11:15 | 0.411 |
| **Bridge** | 11:45 | 0.007 |
| **Catons Bay** | 12:10 | 0.036 |

***+** Recalculated from CSA as 2.007 $m^3$/sec (refer Appendix 1.4)*

** Alternate upstream site used for safety reason (refer Appendix 1.2)*

The 7/12/11 8:25 Okana data point in Table 4 seems unlikely to be correct as the river was observed to be running faster at this time than at 15:15 on the same day. In addition, the CSA (cross sectional area) data indicates that the river CSA was greater at 8:25 than at 15:15. Recalculation of flow based on the CSA (refer Appendix 1.4) gave a value of 2.007 $m^3$/sec.

### 3.2.2 Time-synchronised flows & hydrographs

Time-synchronised flows have been calculated to correct for the different times at which gauging occurred at the different sites. The calculation method is described in Appendix 1.5 and results are shown in Table 5.

These data have been used to provide hydrographs for the gauged rivers and streams (Figure 12). Note that the peak flows may have occurred earlier, and may have been greater, than have been measured due to the frequency of the gauging. More frequent gauging through the rising flow period would have been useful, but was not practical.

**Table 5.**Time-synchronised summary of gauged flow ($m^3$/sec)

| Flows synchronised to 11:00 on 6/12/11 | |
|---|---|
| **Okana** | 0.293 |
| **Okuti** | 0.192 |
| **Catons Bay** | 0.000 |
| **Hotel** | 0.000 |
| **Bridge** | 0.000 |
| **Eastern End** | 0.000 |

| Flows synchronised to 08:25 on 7/12/11 | |
|---|---|
| **Okana** | 2.007 |
| **Okuti** | 2.649 |
| **Catons Bay** | 0.424 |
| **Hotel** | 0.027 |
| **Bridge** | 0.013 |
| **Eastern End** | 0.027 |

| Flows synchronised to 15:15 on 7/12/11 | |
|---|---|
| **Okana** | 1.625 |
| **Okuti** | 1.034 |
| **Catons Bay** | 0.337 |
| **Hotel** | 0.025 |
| **Bridge** | 0.008 |
| **Eastern End** | 0.022 |

| Flows synchronised to 09:50 on 8/12/11 | |
|---|---|
| **Okana** | 0.591 |
| **Okuti** | 0.567 |
| **Catons Bay** | 0.069 |
| **Hotel** | 0.007 |
| **Bridge** | 0.013 |
| **Eastern End** | 0.005 |

| Flows synchronised to 13:15 on 8/12/11 | |
|---|---|
| **Okana** | 0.487 |
| **Okuti** | 0.521 |
| **Catons Bay** | 0.069 |
| **Hotel** | 0.006 |
| **Bridge** | 0.013 |
| **Eastern End** | 0.004 |

| Flows synchronised to 10:25 on 9/12/11 | |
|---|---|
| **Okana** | 0.425 |
| **Okuti** | 0.428 |
| **Catons Bay** | 0.038 |
| **Hotel** | 0.000 |
| **Bridge** | 0.008 |
| **Eastern End** | 0.000 |

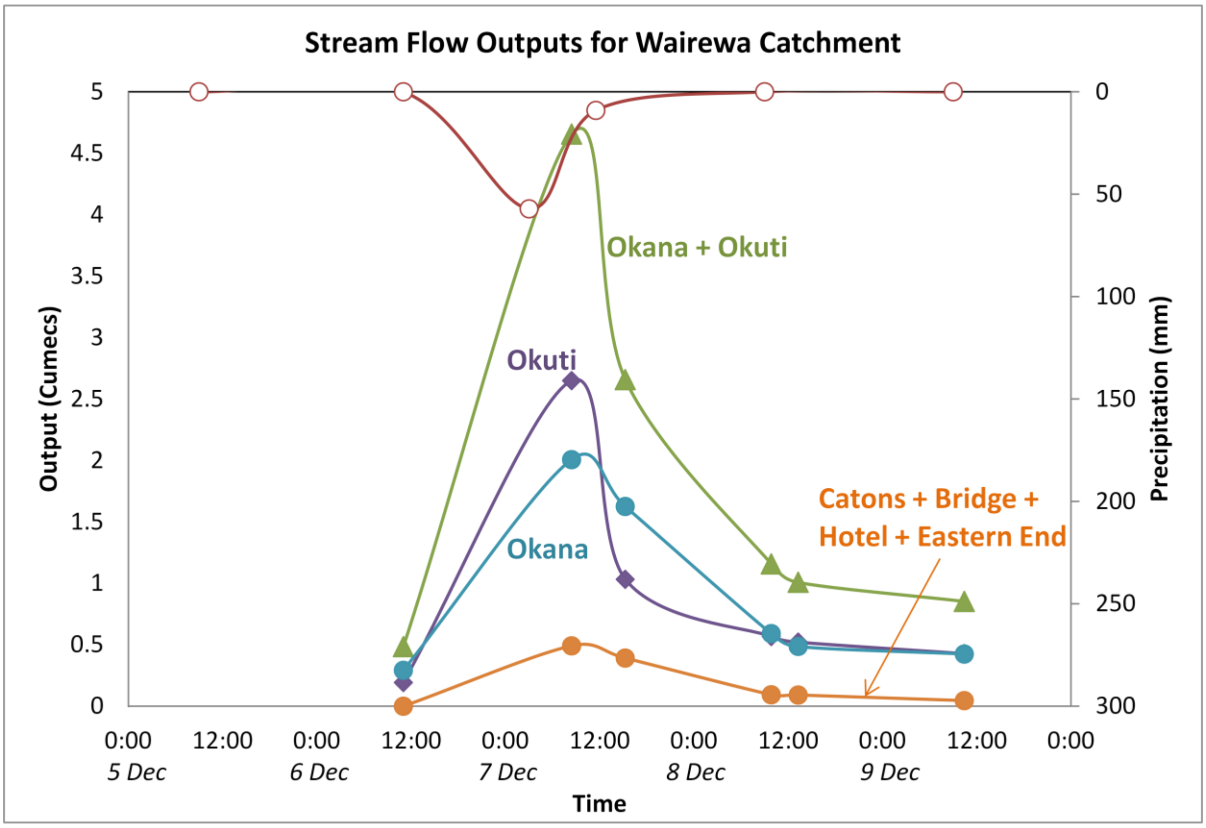



**Figure 12.** -Hydrographs for river and stream flows,with time-synchronised flow estimates shown with symbols, 6-9 December 2011.

These data clearly show the important contribution of the Okana and Okuti Rivers, when considering surface water flows into Wairewa. Before the period of rainfall they made up 60% and 40% of the total surface flows respectively. During the rainfall period they made up 39% and 52% respectively (i.e., 90% of the total surface flows); the remainder was comprised of Catons Bay Stream (8%) and the Eastern End, Bridge and Hotel site streams (0.25-0.5%) which had not been flowing before the rainfall began.

### 3.2.3 Direct surface runoff

As noted in the method, direct runoff from the Northern and Southern regions could not be gauged and has instead been assessed from land surface area and precipitation rates (refer Section 2.2.3). For these conditions, the Northern catchment (omitting that part drained by Eastern End Stream) might be expected to have shed an average of 0.51 - 0.25 $m^3$/sec, for 0 - 50% infiltration respectively, for the rainfall period. The Southern catchment might be expected to have shed 0.94 to 0.47 $m^3$/sec, for 0 - 50% infiltration, over this same period.

This method of runoff estimation was checked for general credibility and likely infiltration rates, by comparing such estimates for the river dominated Okana and Okuti subcatchments to the more accurate gauged flow data average for this period. The best agreement was observed for assumed conditions of 0% infiltration in the Okuti, where the direct runoff estimate of 1.4 $m^3$/sec agreed to within 15% of the average flow measured in the Okana over the rainfall period (1.6 $m^3$/sec). However, for the Okuti, the direct runoff estimate for 50% infiltration (1.9 $m^3$/sec) was the closer to the average gauged flow (1.4 $m^3$/sec).

Consequently 0% infiltration was assumed for the Southern catchment, with a similar aspect to the Okuti, and 50% for the Northern Catchment with a similar aspect to the Okana.

From this estimate it does appear that the Northern and Southern subcatchments make a minor contribution only to the surface runoff entering the lake, and then only during a period of rainfall. The maximum contribution, during rain, is likely to be <25% from these catchments; >75% from the Okana (incl. Catons Bay stream) and Okuti catchments.

## 3.3 Evaporation

Evaporation and atmospheric data from the Virtual Climate station VCSN (agent number 21049) used in this study, are provided in Table 6. As expected, evaporation was at a minimum during the rainfall event, (0.9-1.33mm).

**Table 6.** VCSN pressure and penman open water evapotranspiration (PET) estimates for Wairewa, 05-10 Dec 2011 (data compiled from NIWA, 2011).

| Date | MSL pressure (hPa) | PET (mm) |
|---|---|---|
| **05/12/11** | 1010.5 | 3.6 |
| **06/12/11** | 1008.5 | 0.9 |
| **07/12/11** | 1003.6 | 1.3 |
| **08/12/11** | 1012.0 | 1.2 |
| **09/12/11** | 1024.2 | 4.1 |
| **10/12/11** | 1028.5 | 3.1 |

## 3.4 Seepage estimation

An initial estimation of seepage losses to groundwater has been made. The first step was to construct a partial lake water budget for each day of the study period (from Q, E, P and ΔS as described above), then calculate the seepage loss as the amount required to balance the budget. An instantaneous lake level response to river inputs has been assumed (i.e., no wave-like effects in the lake) and the results of this calculation are given in Table 6. Further details of the calculation are given in Appendix 1.6.

**Table 7.** Estimation of seepage loss to groundwater, from 9:00 to 9:00 for the days shown in Dec 2011. Details of the calculation method is given in Appendix 1.6. All units in $m^3$/day.

| Date | Lake level change (ΔS) | River Input ($Q_1$) | Direct Surface Runoff ($Q_2$) | Evaporation from lake (E) | Rainfall on lake (P) | Seepage loss |
|---|---|---|---|---|---|---|
| **5-6$^{th}$** | 18168 | 41904 | 0 | 19621 | 0 | 4120 |
| **6-7$^{th}$** | 339134 | 248616 | 51480 | 5450 | 313093 | 268533 |
| **7-8$^{th}$** | 286541 | 200318 | 51480 | 7981 | 55865 | 13070 |
| **8-9$^{th}$** | 49112 | 85579 | 0 | 7367 | 0 | 29100 |

### 3.4.1 The possible effect of variable lake levels within Wairewa

Seepage losses have been estimated assuming a lake level which is constant over the lake, and responds instantly to changes in river input. However, if there are wave effects in the lake, then measurement of lake level change at a single point (the ECan monitoring site) may not be representative, experiencing a delayed response to river flow changes.

The potential effect of a delayed response in lake level on the seepage estimation calculation was assessed. It was found that allowing for even a 6hr delay in lake level response resulted in a positive inflow of groundwater to the lake in the period of 7-8 Dec. The magnitude of this groundwater inflow increased as the delay period increased (e.g., to 24 hrs). This appear to contradict other indications of seepage flow as, even under dry conditions, seepage estimations showed a net outflow from the lake to the groundwater system.

Therefore there is no evidence form this work that lake levels varied significantly from point to point for the lake over the period of 5 – 9 December 2011. However, this is far from conclusive and further work is needed to reliably establish the presence or absence of such an effect, and to take this into account in the calculation of a water budget for the lake.

# Section 4 Discussion

## 4.1 An indicative water budget for Wairewa

An indicative water budget for Wairewa for dry and moderate rainfall summer conditions can be constructed from the collected data (Figure 13a&b). Input is dominated by the river inputs; the Okana and Okuti Rivers, under dry conditions. However, direct precipitation onto the lake surface will make similar contribution under the type of rainfall conditions occurring on the 6 & 7 Dec, 2011. Direct surface run off from the northern and southern subcatchments are unlikely to be major input, even during moderate rainfall.

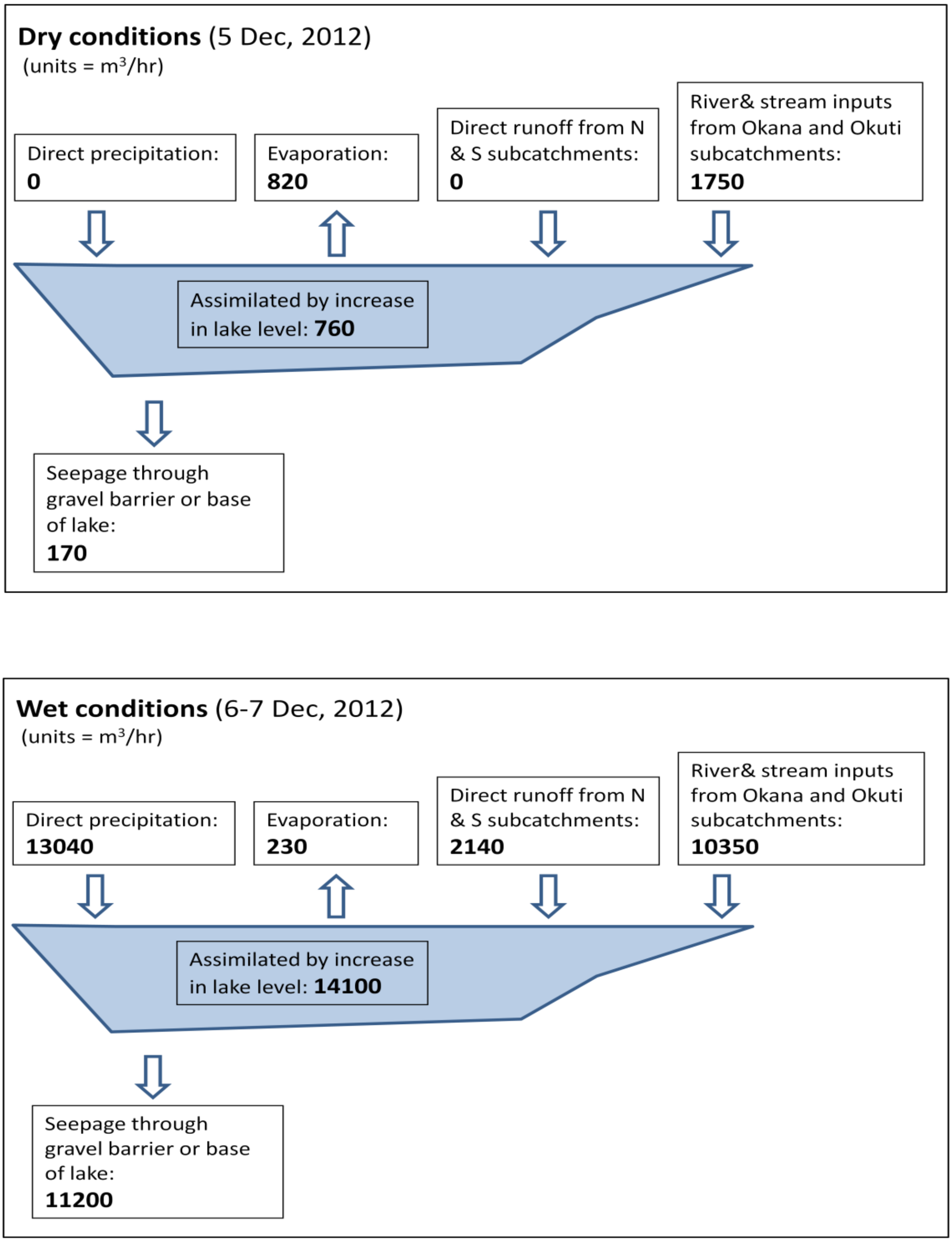
The only outputs from the lake are evaporation from the lake surface and seepage to the shallow groundwater system through the bottom of the lake, or through the gravel barrier at the western end of the lake. Evaporation exceeded seepage under the dry conditions, but vice versa during the rainfall event. Outputs were less than the inputs for the whole fo the 5 day study period, and lake level rose consistently.

This is an indicative water budget for the study period only. Although it may be of relevance to general summer conditions at the lake, it cannot be extrapolated into an annual water budget. It could also be greatly refined through improved data collection and manipulation, as indicated below. However, some useful observations concerning the possible presence of variations in lake level can be made. For example, over the period of the 5$^{th}$ to the 9$^{th}$ December 2011 western lake levels continuously rose against the beach barrier at the westerm end of Wairewa. This would increase the volume of water pressing against the gravels of the barrier, increasing the volume of seepage to the ocean through the barrier.

The analysis of seepage to groundwater assuming an instantaneous lake level response for inputs from the rivers indicates that seepage is highest during the period of highest river flow, not at the highest lake level. However if the seepage rates during 6$^{th}$ – 7$^{th}$ December rainfall are not considered, the seepage rate continues to rise as lake level increases. This trend indicates an instantaneous response to rainfall rather than river inputs, and may reflect the presence of lake levels varying across the surface of the lake at one time.

It can be seen at the start of the study the lake had a minor output via seepage to groundwater (170 $m^3$/hr) even after a sustained period without rain. The seepage increased during 6-7 December while rain was falling on the lake (11,000 $m^3$/hr), but returned to a low level again within 24hrs of the end of the rainfall event (1200 $m^3$/hr).

a)




b)



**Figure 13** A preliminary water budget for Wairewa over a 24 hr period, for 5-6$^{th}$ Dec 2011 for dry conditions (a), and for 6-7$^{th}$ Dec for moderate rainfall conditions (b).

## 4.2 Limitations of this study

### 4.2.1 Representativeness of gauging data

The stream and river gauging data collecting in this study are deemed as accurate and reliable as might be gained without a permanent gauging station set up on the river. They

represent early summer conditions for the catchment, with both dry, and moderate rainfall conditions covered by the data. A reliable contribution to the indicative summer water budget has been constructed. Several improvements to the river gauging would have been useful however. More frequent gauging, preferably continuous gauging of the rivers during the rainfall event would have allowed total water volumes and average event flows to be calculated, and maximum flow to be determined.

Recommendation:

Seasonal, or preferably continuous monitoring of river flow in the Okana and Okuti Rivers for at least one year. Access to, and characterisation of, the shallow gully system on the northern and southern sub catchments, and gauging of representative flows during rainfall events where possible. Improved interpretation of the rapidly changing flow conditions (with the more frequent measurements of velocity and water level volume that can be gained using a permanent gauging site) would have enabled a better indication of total water volume and average flow for the rain event to be calculated.

#### 4.2.2 Wave effects on lake level

To test for the presence of a wave, the analysis applied a delay in lake level response of 6 to 24 hours, relative to the rivers entering the eastern end of the lake, due to the datasets of evaporation and rainfall being daily values. Once a delay of even 6 hrs was applied to the river inputs, seepage outflow from the lake reversed immediately following the rainfall which seems unlikely. Even under dry conditions a continuous seepage appears to occur. However the possible presence of wave effects and their effect on seepage calculations needs to be assessed.

Recommendation:

Use of lake bathymetry data to calculate the time taken for river inputs to travel through the lake, to the lake level gauge. The installation of a lake level monitor at the eastern end of the lake would allow a direct comparison of lake level changes between the eastern end and the lake level gauge, allowing identification of variations in lake levels.

#### 4.2.3 Evaporation measurement

Evaporation is difficult to measure. The use of the VCSN evaporation measurements assumes that evaporation within a closed valley catchment is the same as at the modelled station. This assumption limited the accuracy of the calculated $\Delta S$ during the period of the study. The provision of daily evaporation also limits the ability to quantify the effect of tides on lake level over shorter timescales. Two high and two low tides during a ~24hr period require tighter constraints on the inputs and outputs to the lake than are available with daily data.

Recommendation:

Weather stations capable of long term recording of all atmospheric data required for evaporation measurement could be installed to calibrate actual evaporation within the catchment with the VCSN readings.

### 4.2.4 Precipitation measurement

The use of daily precipitation measurements for this study limited the degree of flow analysis that could be achieved during the rainfall event. Future stream gauging carried out during rain events could utilise the onsite portable rain gauges (from the University of Canterbury Engineering department) to obtain higher precision rain data at lake level.

### 4.2.5 Groundwater measurement

Few data are available for groundwaters in the catchment, requiring flow to or from groundwater to be estimated as the remaining water from the hydrological balance for the lake. This does not differentiate between flows to and from the two key storage areas indicated in Figure 4, and seepage to the ocean through the barrier. If hydraulic gradient, water level and transmissivity data can be obtained for each of the groundwater areas within the lake catchment, a higher level of reliability in seepage rate derivation could be achieved.

Recommendation:

Accurate measurement of the URS borehole positions (Figure 10) would allow analysis of the water level data obtained from their annual reports to indicate the flow paths of groundwater for variations in lake level. Further longer term studies can also be carried out utilising the URS boreholes for flowpath analysis. If the borehole drilling data can be located through URS it may also be possible to carry out pump testing to ascertain transmissivity data for the gravels. Local landowners may be contacted for permission to utilise auger holes within the area as either a stand-alone project to acquire permeability data (especially in the peat area at the western end of the lake) or as part of the pump testing.

# Section 6 References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# Appendix 1 Stream Gauging Data & Calculations

## A1.1 Weather conditions observed

Stream gauging was carried out over the period 6th to 9th December 2011. The main points of note during gauging were:

6th December

- Sporadic heavy rainfall along State Highway 75 from 08:00 until turning into the Wairewa catchment area at Birdlings flat. No rainfall was noted within the catchment until 11:30.

7th December

- Rainfall ceased at 11:00

8th December

- No rain all day.

9th December

- No rain all day.

## A1.2 Raw gauging data and flow calculations

### A1.2.1 Flow calculation

Calculation of the flow (Q) at each stage is Q = Cross Sectional Area (CSA) x Average Velocity Where:

CSA = depth x width, and where a gradient is present on the river bed, the CSA is the sum of the CSA of the largest possible rectangle and of the remaining right angled triangle (Figure A1).

The overall flow of the stream (Q) is then calculated as:

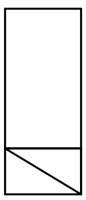

**Figure A1.** Schematic cross section of a single stage with a gradient at the base, as used to calculate the CSA.

## A1.2.2 Stream gauging and flow data tables

Tables A1 to A22 give the raw data from each of the undertaken stream gauging, and the calculated stream flow.

**Table A1.** Stream gauging data for the Okana site at 11:00 on 06/12/11

| **Stream gauging data for the Okana site at 11:00 on 06/12/11** | | | | | |
|---|---|---|---|---|---|
| Stage | Distance (m) | Depth (m) | Velocity (m/s) | CSA $m^2$ | Stage Flow ($m^3$/sec) |
| 0 | 0 | 0.540 | 0.05 | 0.16875 | 0.0084375 |
| 1 | 0.3 | 0.585 | 0.1 | 0.17175 | 0.017175 |
| 2 | 0.6 | 0.560 | 0.1 | 0.14025 | 0.0210375 |
| 3 | 0.9 | 0.375 | 0.2 | 0.1125 | 0.0225 |
| 4 | 1.2 | 0.310 | 0.2 | 0.0930 | 0.0186 |
| 5 | 1.5 | 0.285 | 0.2 | 0.0855 | 0.012825 |
| 6 | 1.8 | 0.275 | 0.1 | 0.0825 | 0.012375 |
| 7 | 2.1 | 0.250 | 0.2 | 0.0750 | 0.01125 |
| 8 | 2.4 | 0.250 | 0.1 | 0.0870 | 0.01305 |
| 9 | 2.7 | 0.290 | 0.2 | 0.0900 | 0.018 |
| 10 | 3.0 | 0.280 | 0.2 | 0.0870 | 0.0174 |
| 11 | 3.3 | 0.290 | 0.2 | 0.0870 | 0.0174 |
| 12 | 3.6 | 0.280 | 0.2 | 0.0840 | 0.0168 |
| 13 | 3.9 | 0.280 | 0.2 | 0.0840 | 0.0168 |
| 14 | 4.2 | 0.270 | 0.2 | 0.0810 | 0.0162 |
| 15 | 4.5 | 0.250 | 0.2 | 0.0750 | 0.015 |
| 16 | 4.8 | 0.250 | 0.2 | 0.0750 | 0.015 |
| 17 | 5.1 | 0.250 | 0.2 | 0.0750 | 0.01125 |
| 18 | 5.4 | 0.250 | 0.1 | 0.0780 | 0.0078 |
| 19 | 5.7 | 0.260 | 0.1 | 0.0780 | 0.0039 |
| 20 | 6.0 | 0.220 | 0 | 0.0550 | 0 |
| 21 | 6.25 | 0.000 | 0 | | |
| **Total** | | | | 1.9653 | 0.2928 |

**Table A2.** Stream gauging data for the Okana site at 08:25 on 07/12/11

| Stream gauging data for the Okana site at 08:25 on 07/12/11 | | | | | |
|---|---|---|---|---|---|
| Stage | Distance (m) | Depth (m) | Velocity (m/s) | CSA | Stage Flow ($m^3$/sec) |
| 0 | 0 | 0.020 | 0 | | |
| 1 | 0.3 | 0.020 | 0 | 0.006 | 0 |
| 2 | 0.6 | 0.400 | 0.1 | 0.063 | 0.00315 |
| 3 | 0.9 | 0.530 | 0 | 0.1395 | 0.006975 |
| 4 | 1.2 | 0.640 | 0.2 | 0.1755 | 0.01755 |
| 5 | 1.5 | 0.780 | 0.4 | 0.213 | 0.0639 |
| 6 | 1.8 | 0.750 | 0.3 | 0.2295 | 0.080325 |
| 7 | 1.95 | 0.700 | 0.4 | 0.10875 | 0.038063 |
| 8 | 2.1 | 0.600 | 0.5 | 0.0975 | 0.043875 |
| 9 | 2.4 | 0.570 | 0.5 | 0.1755 | 0.08775 |
| 10 | 2.7 | 0.530 | 0.6 | 0.165 | 0.09075 |
| 11 | 3.0 | 0.530 | 0.5 | 0.159 | 0.08745 |
| 12 | 3.3 | 0.500 | 0.4 | 0.1545 | 0.069525 |
| 13 | 3.6 | 0.510 | 0.3 | 0.1515 | 0.053025 |
| 14 | 3.9 | 0.560 | 0.4 | 0.1605 | 0.056175 |
| 15 | 4.2 | 0.560 | 0.5 | 0.168 | 0.0756 |
| 16 | 4.5 | 0.560 | 0.4 | 0.168 | 0.0756 |
| 17 | 4.8 | 0.560 | 0.5 | 0.168 | 0.0756 |
| 18 | 5.1 | 0.560 | 0.3 | 0.168 | 0.0672 |
| 19 | 5.4 | 0.550 | 0.3 | 0.1665 | 0.04995 |
| 20 | 5.7 | 0.530 | 0.5 | 0.162 | 0.0648 |
| 21 | 6.0 | 0.530 | 0.4 | 0.159 | 0.07155 |
| 22 | 6.3 | 0.520 | 0.5 | 0.1575 | 0.070875 |
| 23 | 6.6 | 0.510 | 0.3 | 0.1545 | 0.0618 |
| 24 | 6.9 | 0.520 | 0.2 | 0.1545 | 0.038625 |
| 25 | 7.2 | 0.510 | 0.2 | 0.1545 | 0.0309 |
| 26 | 7.4 | 0.510 | 0 | 0.102 | 0.0102 |
| 27 | 7.6 | 0.170 | 0 | 0.068 | 0 |
| **Total** | | | | 3.94925 | 1.391213* |

* Refer Appendix 1.4

**Table A3.** Stream gauging data for the Okana site at 15:15 on 07/12/11

| **Stream gauging data for the Okana site at 15:15 on 07/12/11** | | | | | |
|---|---|---|---|---|---|
| Stage | Distance (m) | Depth (m) | Velocity (m/s) | CSA | Stage Flow ($m^3$/sec) |
| 0 | 0 | 0.030 | 0 | | |
| 1 | 0.2 | 0.080 | 0 | 0.011 | 0 |
| 2 | 0.3 | 0.030 | 0 | 0.0055 | 0 |
| 3 | 0.4 | 0.000 | 0 | 0.0015 | 0 |
| 4 | 0.5 | 0.070 | 0 | 0.0035 | 0 |
| 5 | 0.6 | 0.100 | 0.1 | 0.0085 | 0.000425 |
| 6 | 0.7 | 0.405 | 0.1 | 0.02525 | 0.002525 |
| 7 | 0.9 | 0.540 | 0.4 | 0.0945 | 0.023625 |
| 8 | 1.2 | 0.730 | 0.2 | 0.1905 | 0.05715 |
| 9 | 1.5 | 0.800 | 0.5 | 0.2295 | 0.080325 |
| 10 | 1.8 | 0.720 | 0.4 | 0.228 | 0.1026 |
| 11 | 2.1 | 0.620 | 0.5 | 0.201 | 0.09045 |
| 12 | 2.4 | 0.560 | 0.6 | 0.177 | 0.09735 |
| 13 | 2.7 | 0.510 | 0.6 | 0.1755 | 0.1053 |
| 14 | 3.0 | 0.500 | 0.7 | 0.1515 | 0.098475 |
| 15 | 3.3 | 0.490 | 0.5 | 0.1485 | 0.0891 |
| 16 | 3.6 | 0.490 | 0.5 | 0.147 | 0.0735 |
| 17 | 3.9 | 0.520 | 0.5 | 0.1515 | 0.07575 |
| 18 | 4.2 | 0.530 | 0.5 | 0.1575 | 0.07875 |
| 19 | 4.5 | 0.520 | 0.5 | 0.1575 | 0.07875 |
| 20 | 4.8 | 0.510 | 0.5 | 0.1545 | 0.07725 |
| 21 | 5.1 | 0.520 | 0.5 | 0.1545 | 0.07725 |
| 22 | 5.4 | 0.500 | 0.5 | 0.159 | 0.0795 |
| 23 | 5.7 | 0.500 | 0.5 | 0.15 | 0.075 |
| 24 | 6.0 | 0.460 | 0.5 | 0.156 | 0.078 |
| 25 | 6.3 | 0.460 | 0.4 | 0.138 | 0.0621 |
| 26 | 6.6 | 0.450 | 0.4 | 0.1365 | 0.0546 |
| 27 | 6.9 | 0.460 | 0.3 | 0.1365 | 0.047775 |
| 28 | 7.1 | 0.450 | 0.1 | 0.091 | 0.0182 |
| 29 | 7.2 | 0.240 | 0 | 0.0345 | 0.001725 |
| 30 | 7.5 | 0.050 | 0 | 0.0435 | 0 |
| **Total** | | | | 3.61875 | 1.625475 |

**Table A4.** Stream gauging data for the Okana site at 09:50 on 08/12/11

| **Stream gauging data for the Okana site at 09:50 on 08/12/11** | | | | | |
|---|---|---|---|---|---|
| Stage | Distance (cm) | Depth (cm) | Velocity (m/s) | CSA | Stage Flow (Cumecs) |
| 0 | 0 | 0.290 | 0 | | |
| 1 | 0.2 | 0.400 | 0 | 0.069 | 0 |
| 2 | 0.4 | 0.450 | 0 | 0.085 | 0 |
| 3 | 0.5 | 0.610 | 0 | 0.053 | 0 |
| 4 | 0.6 | 0.610 | 0.1 | 0.061 | 0.00305 |
| 5 | 0.7 | 0.640 | 0.2 | 0.0625 | 0.009375 |
| 6 | 0.9 | 0.670 | 0.2 | 0.131 | 0.0262 |
| 7 | 1.1 | 0.600 | 0.2 | 0.127 | 0.0254 |
| 8 | 1.3 | 0.540 | 0.2 | 0.114 | 0.0228 |
| 9 | 1.5 | 0.420 | 0.3 | 0.096 | 0.024 |
| 10 | 1.8 | 0.380 | 0.2 | 0.12 | 0.03 |
| 11 | 2.1 | 0.365 | 0.2 | 0.11175 | 0.02235 |
| 12 | 2.4 | 0.360 | 0.2 | 0.10875 | 0.02175 |
| 13 | 2.7 | 0.350 | 0.3 | 0.1065 | 0.026625 |
| 14 | 3.0 | 0.350 | 0.3 | 0.105 | 0.0315 |
| 15 | 3.3 | 0.400 | 0.3 | 0.1125 | 0.03375 |
| 16 | 3.6 | 0.390 | 0.3 | 0.1185 | 0.03555 |
| 17 | 3.9 | 0.380 | 0.3 | 0.1155 | 0.03465 |
| 18 | 4.2 | 0.380 | 0.3 | 0.231 | 0.0693 |
| 19 | 4.5 | 0.400 | 0.2 | 0.117 | 0.02925 |
| 20 | 4.8 | 0.390 | 0.3 | 0.1185 | 0.029625 |
| 21 | 5.1 | 0.365 | 0.3 | 0.11325 | 0.033975 |
| 22 | 5.4 | 0.370 | 0.2 | 0.11025 | 0.027563 |
| 23 | 5.7 | 0.365 | 0.2 | 0.11025 | 0.02205 |
| 24 | 6.0 | 0.360 | 0.2 | 0.10875 | 0.02175 |
| 25 | 6.3 | 0.370 | 0 | 0.1095 | 0.01095 |
| 26 | 6.45 | 0.360 | 0 | 0.05475 | 0 |
| 27 | 6.5 | 0.170 | 0 | 0.01325 | 0 |
| 28 | 6.65 | 0.080 | 0 | 0.01875 | 0 |
| 29 | 6.7 | 0.050 | 0 | 0.00325 | 0 |
| **Total** | | | | 2.7365 | 0.591463 |

**Table A5.** Stream gauging data for the Okana site at 13:15 on 08/12/11

| Stream gauging data for the Okana site at 13:15 on 08/12/11 | | | | | |
|---|---|---|---|---|---|
| Stage | Distance (m) | Depth (m) | Velocity (m/s) | CSA | Stage Flow ($m^3$/sec) |
| 0 | 0 | 0.280 | 0 | | |
| 1 | 0.1 | 0.150 | 0 | 0.0215 | 0 |
| 2 | 0.2 | 0.070 | 0 | 0.011 | 0 |
| 3 | 0.3 | 0.110 | 0 | 0.009 | 0 |
| 4 | 0.4 | 0.420 | 0 | 0.0265 | 0 |
| 5 | 0.5 | 0.580 | 0 | 0.05 | 0 |
| 6 | 0.7 | 0.650 | 0.1 | 0.123 | 0.00615 |
| 7 | 1 | 0.650 | 0.2 | 0.195 | 0.02925 |
| 8 | 1.2 | 0.600 | 0.2 | 0.125 | 0.025 |
| 9 | 1.4 | 0.515 | 0.2 | 0.1115 | 0.0223 |
| 10 | 1.7 | 0.415 | 0.2 | 0.1395 | 0.0279 |
| 11 | 2.0 | 0.380 | 0.2 | 0.11925 | 0.02385 |
| 12 | 2.3 | 0.370 | 0.2 | 0.1125 | 0.0225 |
| 13 | 2.6 | 0.360 | 0.2 | 0.1095 | 0.0219 |
| 14 | 2.9 | 0.340 | 0.2 | 0.105 | 0.021 |
| 15 | 3.2 | 0.390 | 0.2 | 0.1095 | 0.0219 |
| 16 | 3.5 | 0.400 | 0.2 | 0.1185 | 0.0237 |
| 17 | 3.8 | 0.400 | 0.2 | 0.12 | 0.024 |
| 18 | 4.1 | 0.390 | 0.3 | 0.1185 | 0.029625 |
| 19 | 4.4 | 0.400 | 0.2 | 0.1185 | 0.029625 |
| 20 | 4.7 | 0.390 | 0.2 | 0.1185 | 0.0237 |
| 21 | 5.0 | 0.370 | 0.3 | 0.114 | 0.0285 |
| 22 | 5.3 | 0.380 | 0.2 | 0.1125 | 0.028125 |
| 23 | 5.6 | 0.360 | 0.2 | 0.111 | 0.0222 |
| 24 | 5.9 | 0.370 | 0.2 | 0.1095 | 0.0219 |
| 25 | 6.2 | 0.380 | 0.2 | 0.1125 | 0.0225 |
| 26 | 6.5 | 0.360 | 0 | 0.111 | 0.0111 |
| 27 | 6.6 | 0.130 | 0 | 0.0245 | 0 |
| 28 | 6.7 | 0.080 | 0 | 0.0105 | 0 |
| 29 | 6.75 | 0.050 | 0 | 0.00325 | 0 |
| **Total** | | | | 2.638 | 0.486725 |

**Table A6.** Stream gauging data for the Okana site at 10:25 on 09/12/11

| Stream gauging data for the Okana site at 10:25 on 09/12/11 | | | | | |
|---|---|---|---|---|---|
| Stage | Distance (m) | Depth (m) | Velocity (m/s) | CSA | Stage Flow ($m^3$/sec) |
| 0 | 0 | 0.260 | 0 | | |
| 1 | 0.1 | 0.230 | 0 | 0.0245 | 0 |
| 2 | 0.2 | 0.370 | 0 | 0.03 | 0 |
| 3 | 0.3 | 0.400 | 0 | 0.0385 | 0 |
| 4 | 0.4 | 0.445 | 0 | 0.04225 | 0 |
| 5 | 0.5 | 0.585 | 0 | 0.0515 | 0 |
| 6 | 0.6 | 0.590 | 0 | 0.05875 | 0 |
| 7 | 0.7 | 0.620 | 0.1 | 0.0605 | 0.003025 |
| 8 | 0.9 | 0.640 | 0.2 | 0.126 | 0.0189 |
| 9 | 1.1 | 0.590 | 0.2 | 0.123 | 0.0246 |
| 10 | 1.4 | 0.480 | 0.2 | 0.1605 | 0.0321 |
| 11 | 1.7 | 0.400 | 0.2 | 0.132 | 0.0264 |
| 12 | 2.0 | 0.375 | 0.2 | 0.11625 | 0.02325 |
| 13 | 2.3 | 0.365 | 0.2 | 0.111 | 0.0222 |
| 14 | 2.6 | 0.360 | 0.2 | 0.10875 | 0.02175 |
| 15 | 2.9 | 0.350 | 0.2 | 0.1065 | 0.0213 |
| 16 | 3.2 | 0.370 | 0.2 | 0.108 | 0.0216 |
| 17 | 3.5 | 0.385 | 0.2 | 0.11325 | 0.02265 |
| 18 | 3.8 | 0.380 | 0.2 | 0.11475 | 0.02295 |
| 19 | 4.1 | 0.385 | 0.2 | 0.11475 | 0.02295 |
| 20 | 4.4 | 0.395 | 0.2 | 0.117 | 0.0234 |
| 21 | 4.7 | 0.380 | 0.2 | 0.11625 | 0.02325 |
| 22 | 5.0 | 0.360 | 0.2 | 0.111 | 0.0222 |
| 23 | 5.3 | 0.355 | 0.2 | 0.10725 | 0.02145 |
| 24 | 5.6 | 0.360 | 0.1 | 0.10725 | 0.016088 |
| 25 | 5.9 | 0.345 | 0.2 | 0.10575 | 0.015863 |
| 26 | 6.2 | 0.360 | 0.1 | 0.10575 | 0.015863 |
| 27 | 6.4 | 0.350 | 0 | 0.071 | 0.00355 |
| 28 | 6.5 | 0.345 | 0 | 0.03475 | 0 |
| 29 | 6.6 | 0.110 | 0 | 0.02275 | 0 |
| 30 | 6.7 | 0.080 | 0 | 0.0095 | 0 |
| 31 | 6.8 | 0.010 | 0 | 0.0045 | 0 |
| **Total** | | | | 2.51825 | 0.425338 |

**Table A7.** Stream gauging data for the Okuti site at 12:50 on 06/12/11

| **Stream gauging data for the Okuti site at 12:50 on 06/12/11** | | | | | |
|---|---|---|---|---|---|
| Stage | Distance (m) | Depth (m) | Velocity (m/s) | CSA | Stage Flow ($m^3$/sec) |
| 0 | 0 | 0.135 | 0 | | |
| 1 | 0.3 | 0.163 | 0.1 | 0.0447 | 0.002235 |
| 2 | 0.6 | 0.180 | 0.2 | 0.05145 | 0.007718 |
| 3 | 0.9 | 0.153 | 0.3 | 0.04995 | 0.012488 |
| 4 | 1.2 | 0.150 | 0.4 | 0.04545 | 0.015908 |
| 5 | 1.5 | 0.180 | 0.4 | 0.0495 | 0.0198 |
| 6 | 1.8 | 0.210 | 0.5 | 0.0585 | 0.026325 |
| 7 | 2.1 | 0.210 | 0.4 | 0.063 | 0.02835 |
| 8 | 2.4 | 0.200 | 0.3 | 0.0615 | 0.021525 |
| 9 | 2.7 | 0.200 | 0.2 | 0.06 | 0.015 |
| 10 | 3.0 | 0.225 | 0.2 | 0.06375 | 0.01275 |
| 11 | 3.3 | 0.220 | 0.4 | 0.06675 | 0.020025 |
| 12 | 3.6 | 0.210 | 0.2 | 0.0645 | 0.01935 |
| 13 | 3.9 | 0.170 | 0.2 | 0.057 | 0.0114 |
| 14 | 4.2 | 0.190 | 0.2 | 0.054 | 0.0108 |
| 15 | 4.5 | 0.130 | 0.05 | 0.048 | 0.006 |
| 16 | 4.8 | 0.120 | 0 | 0.0375 | 0.000938 |
| 17 | 5.1 | 0.050 | 0 | 0.0255 | 0 |
| **Total** | | | | 0.7095 | 0.192263 |

**Table A8**. Stream gauging data for the alternate Okuti site (Okuti section) at 10:20 on 07/12/11

| **Stream gauging data for the alternate Okuti site (Okuti section) at 10:20 on 07/12/11** | | | | | |
|---|---|---|---|---|---|
| Stage | Distance (m) | Depth (m) | Velocity (m/s) | CSA | Stage Flow ($m^3$/sec) |
| 0 | 0 | 0.680 | 0.2 | | |
| 1 | 0.3 | 0.705 | 0.3 | 0.20775 | 0.051938 |
| 2 | 0.6 | 0.710 | 0.5 | 0.21225 | 0.0849 |
| 3 | 0.9 | 0.740 | 0.5 | 0.2175 | 0.10875 |
| 4 | 1.2 | 0.740 | 0.6 | 0.222 | 0.1221 |
| 5 | 1.5 | 0.750 | 0.5 | 0.2235 | 0.122925 |
| 6 | 1.8 | 0.800 | 0.6 | 0.2325 | 0.127875 |
| 7 | 2.1 | 0.790 | 0.7 | 0.2385 | 0.155025 |
| 8 | 2.4 | 0.820 | 0.4 | 0.2415 | 0.132825 |
| 9 | 2.7 | 0.820 | 0.5 | 0.246 | 0.1107 |
| 10 | 3.0 | 0.810 | 0.5 | 0.2445 | 0.12225 |
| 11 | 3.3 | 0.810 | 0.7 | 0.243 | 0.1458 |
| 12 | 3.6 | 0.800 | 0.3 | 0.2415 | 0.12075 |
| 13 | 3.9 | 0.810 | 0.5 | 0.2415 | 0.0966 |
| 14 | 4.2 | 0.800 | 0.8 | 0.2415 | 0.156975 |
| 15 | 4.5 | 0.770 | 0.6 | 0.2355 | 0.16485 |
| 16 | 4.8 | 0.760 | 0.7 | 0.2295 | 0.149175 |
| 17 | 5.1 | 0.750 | 0.5 | 0.2265 | 0.1359 |
| 18 | 5.4 | 0.760 | 0.6 | 0.2265 | 0.124575 |
| 19 | 5.7 | 0.750 | 0.6 | 0.2265 | 0.1359 |
| 20 | 6.0 | 0.770 | 0.5 | 0.228 | 0.1254 |
| 21 | 6.3 | 0.780 | 0.5 | 0.2325 | 0.11625 |
| 22 | 6.6 | 0.770 | 0.5 | 0.2325 | 0.11625 |
| 23 | 6.9 | 0.760 | 0.3 | 0.2295 | 0.0918 |
| 24 | 7.2 | 0.740 | 0.1 | 0.225 | 0.045 |
| 25 | 7.5 | 0.720 | 0 | 0.219 | 0.01095 |
| 26 | 7.7 | 0.630 | 0 | 0.135 | 0 |
| 27 | 7.8 | 0.160 | 0 | 0.0395 | 0 |
| **Total** | | | | 5.0795 | 2.507775 |

**Table A9.** Stream gauging data for the alternate Okuti site (small stream) at 14:00 on 07/12/11

| **Stream gauging data for the alternate Okuti site (small stream) at 14:00 on 07/12/11** | | | | | |
|---|---|---|---|---|---|
| **Stage** | Distance (m) | Depth (m) | Velocity (m/s) | CSA | Stage Flow ($m^3$/sec) |
| **0** | 0 | 0.100 | 0.1 | | |
| **1** | 0.2 | 0.120 | 0.3 | 0.022 | 0.0044 |
| **2** | 0.4 | 0.040 | 0.5 | 0.016 | 0.0064 |
| **3** | 0.6 | 0.170 | 0.5 | 0.021 | 0.0105 |
| **4** | 0.8 | 0.220 | 0.7 | 0.039 | 0.0234 |
| **5** | 1 | 0.210 | 0.6 | 0.043 | 0.02795 |
| **6** | 1.2 | 0.170 | 0.8 | 0.038 | 0.0266 |
| **7** | 1.4 | 0.210 | 0.9 | 0.038 | 0.0323 |
| **8** | 1.6 | 0.170 | 0.7 | 0.038 | 0.0304 |
| **9** | 1.8 | 0.200 | 0.6 | 0.037 | 0.02405 |
| **10** | 2 | 0.110 | 0.6 | 0.031 | 0.0186 |
| **11** | 2.2 | 0.030 | 0.2 | 0.014 | 0.0056 |
| **12** | 2.4 | 0.000 | 0 | 0.003 | 0.0003 |
| **total** | | | | 0.242 | 0.1658 |

**Table A10.** Stream gauging data for the alternate Okuti site (Okuti section) at 14:20 on 07/12/11

| Stream gauging data for the alternate Okuti site (Okuti section) at 14:20 on 07/12/11 | | | | | |
|---|---|---|---|---|---|
| Stage | Distance (m) | Depth (m) | Velocity (m/s) | CSA | Stage Flow ($m^3$/sec) |
| 0 | 0 | 0.470 | 0.1 | | |
| 1 | 0.3 | 0.480 | 0.3 | 0.1425 | 0.0285 |
| 2 | 0.6 | 0.480 | 0.3 | 0.144 | 0.0432 |
| 3 | 0.9 | 0.470 | 0.3 | 0.1425 | 0.04275 |
| 4 | 1.2 | 0.500 | 0.4 | 0.1455 | 0.050925 |
| 5 | 1.5 | 0.530 | 0.3 | 0.1545 | 0.054075 |
| 6 | 1.8 | 0.540 | 0.3 | 0.1605 | 0.04815 |
| 7 | 2.1 | 0.540 | 0.4 | 0.162 | 0.0567 |
| 8 | 2.4 | 0.540 | 0.3 | 0.162 | 0.0567 |
| 9 | 2.7 | 0.530 | 0.4 | 0.1605 | 0.056175 |
| 10 | 3.0 | 0.510 | 0.4 | 0.156 | 0.0624 |
| 11 | 3.3 | 0.510 | 0.4 | 0.153 | 0.0612 |
| 12 | 3.6 | 0.500 | 0.4 | 0.1515 | 0.0606 |
| 13 | 3.9 | 0.490 | 0.5 | 0.1485 | 0.066825 |
| 14 | 4.2 | 0.490 | 0.5 | 0.147 | 0.0735 |
| 15 | 4.5 | 0.480 | 0.4 | 0.1455 | 0.065475 |
| 16 | 4.8 | 0.460 | 0.5 | 0.141 | 0.06345 |
| 17 | 5.1 | 0.460 | 0.5 | 0.138 | 0.069 |
| 18 | 5.4 | 0.460 | 0.5 | 0.138 | 0.069 |
| 19 | 5.7 | 0.460 | 0.5 | 0.138 | 0.069 |
| 20 | 6.0 | 0.470 | 0.5 | 0.1395 | 0.06975 |
| 21 | 6.3 | 0.450 | 0.3 | 0.138 | 0.0552 |
| 22 | 6.6 | 0.480 | 0.5 | 0.1395 | 0.0558 |
| 23 | 6.9 | 0.480 | 0.4 | 0.144 | 0.0648 |
| 24 | 7.2 | 0.470 | 0.4 | 0.1425 | 0.057 |
| 25 | 7.5 | 0.470 | 0.2 | 0.141 | 0.0423 |
| 26 | 7.8 | 0.440 | 0 | 0.0455 | 0.00455 |
| 27 | 7.9 | 0.410 | 0 | 0.0425 | 0 |
| 28 | 8.0 | 0.270 | 0 | 0.034 | 0 |
| **Total** | | | | 3.1885 | 1.28165 |

**Table A11.** Stream gauging data for the Okuti site at 10:40 on 08/12/11

| Stream gauging data for the Okuti site at 10:40 on 08/12/11 | | | | | |
|---|---|---|---|---|---|
| Stage | Distance (m) | Depth (m) | Velocity (m/s) | CSA | Stage Flow ($m^3$/sec) |
| 0 | 0 | 0.205 | 0 | | |
| 1 | 0.1 | 0.240 | 0 | 0.02225 | 0 |
| 2 | 0.2 | 0.250 | 0.1 | 0.0245 | 0.001225 |
| 3 | 0.4 | 0.260 | 0.2 | 0.051 | 0.00765 |
| 4 | 0.7 | 0.240 | 0.4 | 0.075 | 0.0225 |
| 5 | 1.0 | 0.240 | 0.6 | 0.072 | 0.036 |
| 6 | 1.3 | 0.250 | 0.7 | 0.0735 | 0.047775 |
| 7 | 1.6 | 0.290 | 0.5 | 0.081 | 0.0486 |
| 8 | 1.9 | 0.280 | 0.8 | 0.0855 | 0.055575 |
| 9 | 2.2 | 0.320 | 0.6 | 0.09 | 0.063 |
| 10 | 2.5 | 0.280 | 0.5 | 0.09 | 0.0495 |
| 11 | 2.8 | 0.280 | 0.4 | 0.084 | 0.0378 |
| 12 | 3.1 | 0.300 | 0.4 | 0.087 | 0.0348 |
| 13 | 3.4 | 0.290 | 0.4 | 0.0885 | 0.0354 |
| 14 | 3.7 | 0.220 | 0.4 | 0.0765 | 0.0306 |
| 15 | 4.0 | 0.210 | 0.3 | 0.0645 | 0.022575 |
| 16 | 4.3 | 0.220 | 0.2 | 0.0645 | 0.016125 |
| 17 | 4.6 | 0.170 | 0 | 0.0585 | 0.00585 |
| 18 | 4.9 | 0.170 | 0 | 0.051 | 0 |
| 19 | 5.2 | 0.080 | 0 | 0.0375 | 0 |
| **Total** | | | | 1.27675 | 0.514975 |

**Table A12.** Stream gauging data for the Okuti site at 14:05 on 08/12/11

| **Stream gauging data for the Okuti site at 14:05 on 08/12/11** | | | | | |
|---|---|---|---|---|---|
| Stage | Distance (m) | Depth (m) | Velocity (m/s) | CSA | Stage Flow ($m^3$/sec) |
| 0 | 0 | 0.185 | 0 | | |
| 1 | 0.2 | 0.235 | 0 | 0.042 | 0 |
| 2 | 0.5 | 0.220 | 0.3 | 0.06825 | 0.010238 |
| 3 | 0.8 | 0.230 | 0.4 | 0.0675 | 0.023625 |
| 4 | 1.1 | 0.220 | 0.6 | 0.0675 | 0.03375 |
| 5 | 1.4 | 0.240 | 0.6 | 0.075 | 0.045 |
| 6 | 1.7 | 0.270 | 0.5 | 0.0765 | 0.042075 |
| 7 | 2.0 | 0.260 | 0.8 | 0.0795 | 0.051675 |
| 8 | 2.3 | 0.280 | 0.7 | 0.081 | 0.06075 |
| 9 | 2.6 | 0.270 | 0.6 | 0.0825 | 0.053625 |
| 10 | 2.9 | 0.280 | 0.4 | 0.0825 | 0.04125 |
| 11 | 3.2 | 0.270 | 0.5 | 0.0825 | 0.037125 |
| 12 | 3.5 | 0.270 | 0.6 | 0.081 | 0.04455 |
| 13 | 3.8 | 0.210 | 0.4 | 0.072 | 0.036 |
| 14 | 4.1 | 0.190 | 0.3 | 0.06 | 0.021 |
| 15 | 4.4 | 0.150 | 0.3 | 0.051 | 0.0153 |
| 16 | 4.7 | 0.175 | 0 | 0.04875 | 0.007312 |
| 17 | 4.9 | 0.160 | 0 | 0.0335 | 0 |
| 18 | 5.0 | 0.140 | 0 | 0.015 | 0 |
| 19 | 5.1 | 0.050 | 0 | 0.0095 | 0 |
| **Total** | | | | 1.1755 | 0.523275 |

**Table A13.** Stream gauging data for the Okuti site at 11:15 on 09/12/11

| **Stream gauging data for the Okuti site at 11:15 on 09/12/11** | | | | | |
|---|---|---|---|---|---|
| Stage | Distance (m) | Depth (m) | Velocity (m/s) | CSA | Stage Flow ($m^3$/sec) |
| 0 | 0 | 0.165 | 0 | | |
| 1 | 0.1 | 0.205 | 0 | 0.037 | 0 |
| 2 | 0.2 | 0.195 | 0.1 | 0.04 | 0.002 |
| 3 | 0.3 | 0.210 | 0.1 | 0.081 | 0.0081 |
| 4 | 0.4 | 0.210 | 0.2 | 0.021 | 0.00315 |
| 5 | 0.7 | 0.200 | 0.3 | 0.0615 | 0.015375 |
| 6 | 0.85 | 0.190 | 0.4 | 0.02925 | 0.010238 |
| 7 | 1.0 | 0.200 | 0.5 | 0.03075 | 0.0123 |
| 8 | 1.3 | 0.240 | 0.5 | 0.066 | 0.033 |
| 9 | 1.6 | 0.240 | 0.4 | 0.072 | 0.0324 |
| 10 | 1.9 | 0.230 | 0.8 | 0.0705 | 0.0423 |
| 11 | 2.2 | 0.280 | 0.6 | 0.0765 | 0.05355 |
| 12 | 2.5 | 0.240 | 0.5 | 0.078 | 0.0429 |
| 13 | 2.8 | 0.240 | 0.5 | 0.072 | 0.036 |
| 14 | 3.1 | 0.220 | 0.4 | 0.069 | 0.03105 |
| 15 | 3.4 | 0.250 | 0.5 | 0.0705 | 0.031725 |
| 16 | 3.7 | 0.190 | 0.3 | 0.066 | 0.0264 |
| 17 | 4.0 | 0.190 | 0.3 | 0.057 | 0.0171 |
| 18 | 4.3 | 0.170 | 0.1 | 0.054 | 0.0108 |
| 19 | 4.6 | 0.160 | 0 | 0.0495 | 0.002475 |
| 20 | 4.8 | 0.150 | 0 | 0.031 | 0 |
| 21 | 4.9 | 0.130 | 0 | 0.014 | 0 |
| **Total** | | | | 1.1465 | 0.410863 |

**Table A14.** Stream gauging data for the Catons Bay site at 11:20 on 07/12/11

| **Stream gauging data for the Catons Bay site at 11:20 on 07/12/11** | | | | | |
|---|---|---|---|---|---|
| Stage | Distance (m) | Depth (m) | Velocity (m/s) | CSA | Stage Flow ($m^3$/sec) |
| 0 | 0 | 0.050 | 0 | | |
| 1 | 0.2 | 0.090 | 0.1 | 0.028 | 0.0014 |
| 2 | 0.4 | 0.070 | 0.1 | 0.016 | 0.0016 |
| 3 | 0.6 | 0.100 | 0.1 | 0.017 | 0.0017 |
| 4 | 0.8 | 0.150 | 0.9 | 0.025 | 0.0125 |
| 5 | 0.9 | 0.370 | 1 | 0.026 | 0.0247 |
| 6 | 1.0 | 0.420 | 1.2 | 0.0395 | 0.04345 |
| 7 | 1.1 | 0.410 | 1.3 | 0.0415 | 0.047725 |
| 8 | 1.2 | 0.440 | 1.5 | 0.0425 | 0.0595 |
| 9 | 1.3 | 0.440 | 1.5 | 0.044 | 0.066 |
| 10 | 1.4 | 0.420 | 1 | 0.043 | 0.05375 |
| 11 | 1.5 | 0.420 | 0.9 | 0.042 | 0.0399 |
| 12 | 1.6 | 0.280 | 0.5 | 0.035 | 0.0245 |
| 13 | 1.7 | 0.210 | 0.1 | 0.0315 | 0.00945 |
| 14 | 1.8 | 0.130 | 0 | 0.017 | 0.00085 |
| 15 | 1.9 | 0.080 | 0 | 0.0105 | 0 |
| 16 | 2.0 | 0.020 | 0 | 0.005 | 0 |
| **Total** | | | | 0.4635 | 0.387025 |

**Table A15.** Stream gauging data for the Catons Bay site at 12:05 on 08/12/11

| **Stream gauging data for the Catons Bay site at 12:05 on 08/12/11** | | | | | |
|---|---|---|---|---|---|
| Stage | Distance (m) | Depth (m) | Velocity (m/s) | CSA | Stage Flow ($m^3$/sec) |
| 0 | 0 | 0.060 | 0.2 | | |
| 1 | 0.1 | 0.120 | 0.8 | 0.012 | 0.006 |
| 2 | 0.2 | 0.140 | 0.8 | 0.013 | 0.0104 |
| 3 | 0.3 | 0.210 | 1.4 | 0.0175 | 0.01925 |
| 4 | 0.4 | 0.250 | 0.8 | 0.023 | 0.0184 |
| 5 | 0.5 | 0.160 | 0.3 | 0.0205 | 0.011275 |
| 6 | 0.6 | 0.130 | 0 | 0.0145 | 0.002175 |
| 7 | 0.7 | 0.110 | 0 | 0.012 | 0.0018 |
| 8 | 0.8 | 0.070 | 0 | 0.009 | 0 |
| 9 | 0.9 | 0.030 | 0 | 0.005 | 0 |
| **Total** | | | | 0.1265 | 0.0693 |

**Table A16.** Stream gauging data for the Catons Bay site at 12:10 on 09/12/11

| **Stream gauging data for the Catons Bay site at 12:10 on 09/12/11** | | | | | |
|---|---|---|---|---|---|
| Stage | Distance (m) | Depth (m) | Velocity (m/s) | CSA | Stage Flow ($m^3$/sec) |
| 0 | 0 | 0.050 | 0 | | |
| 1 | 0.1 | 0.080 | 0.2 | 0.0065 | 0.00065 |
| 2 | 0.2 | 0.110 | 0.5 | 0.0095 | 0.003325 |
| 3 | 0.3 | 0.140 | 0.8 | 0.0125 | 0.008125 |
| 4 | 0.4 | 0.155 | 1.1 | 0.01475 | 0.0118 |
| 5 | 0.45 | 0.120 | 0.7 | 0.006875 | 0.006188 |
| 6 | 0.5 | 0.100 | 0.1 | 0.0055 | 0.0022 |
| 7 | 0.6 | 0.090 | 0 | 0.0095 | 0.003325 |
| 8 | 0.7 | 0.090 | 0 | 0.009 | 0 |
| 9 | 0.8 | 0.070 | 0 | 0.008 | 0 |
| 10 | 0.85 | 0.020 | 0 | 0.00225 | 0 |
| **Total** | | | | 0.077875 | 0.035613 |

**Table A17**. Stream gauging data for the Eastern End site at 13:00 on 07/12/11

| **Stream gauging data for the Eastern End site at 13:00 on 07/12/11** | | | | | |
|---|---|---|---|---|---|
| Stage | Distance (m) | Depth (m) | Velocity (m/s) | CSA | Stage Flow ($m^3$/sec) |
| 0 | 0 | 0.090 | 0.7 | | |
| 1 | 0.1 | 0.190 | 0.4 | 0.014 | 0.0077 |
| 2 | 0.2 | 0.210 | 0.2 | 0.02 | 0.006 |
| 3 | 0.3 | 0.210 | 0.2 | 0.021 | 0.0042 |
| 4 | 0.4 | 0.130 | 0.1 | 0.025 | 0.00375 |
| 5 | 0.45 | 0.130 | 0.1 | 0.0065 | 0.00065 |
| 6 | 0.5 | 0.000 | 0 | 0.00325 | 0.000163 |
| 7 | 0.6 | 0.100 | 0.1 | 0.005 | 0.0005 |
| 8 | 0.7 | 0.070 | 0 | 0.0085 | 0.000425 |
| **Total** | | | | 0.10325 | 0.023388 |

**Table A18.** Stream gauging data for the Eastern End site at 12:30 on 08/12/11

| **Stream gauging data for the Eastern End site at 12:30 on 08/12/11** | | | | | |
|---|---|---|---|---|---|
| Stage | Distance (m) | Depth (m) | Velocity (m/s) | CSA | Stage Flow ($m^3$/sec) |
| 0 | 0 | 0.020 | 0 | | |
| 1 | 0.1 | 0.080 | 0.2 | 0.005 | 0.0005 |
| 2 | 0.2 | 0.080 | 0.1 | 0.008 | 0.0012 |
| 3 | 0.3 | 0.080 | 0.2 | 0.008 | 0.0012 |
| 4 | 0.4 | 0.050 | 0.2 | 0.0065 | 0.000975 |
| 5 | 0.5 | 0.050 | 0 | 0.005 | 0.0005 |
| **Total** | | | | 0.0325 | 0.004375 |

**Table A19.** Stream gauging data for the Hotel site at 13:30 on 07/12/11

| Stream gauging data for the Hotel site at 13:30 on 07/12/11 | | | | | |
|---|---|---|---|---|---|
| Stage | Distance (m) | Depth (m) | Velocity (m/s) | CSA | Stage Flow ($m^3$/sec) |
| 0 | 0 | 0.150 | 0.2 | | |
| 1 | 0.1 | 0.100 | 0.3 | 0.0175 | 0.004375 |
| 2 | 0.2 | 0.150 | 0.3 | 0.0125 | 0.00375 |
| 3 | 0.3 | 0.170 | 0.6 | 0.016 | 0.0072 |
| 4 | 0.4 | 0.190 | 0.3 | 0.018 | 0.0054 |
| 5 | 0.5 | 0.170 | 0.1 | 0.018 | 0.0036 |
| 6 | 0.6 | 0.140 | 0 | 0.0155 | 0.000775 |
| 7 | 0.7 | 0.140 | 0 | 0.014 | 0.0007 |
| 8 | 0.8 | 0.110 | 0 | 0.0125 | 0 |
| **Total** | | | | 0.124 | 0.0258 |

**Table A20.** Stream gauging data for the Hotel site at 11:45 on 08/12/11

| Stream gauging data for the Hotel site at 11:45 on 08/12/11 | | | | | |
|---|---|---|---|---|---|
| Stage | Distance (m) | Depth (m) | Velocity (m/s) | CSA | Stage Flow ($m^3$/sec) |
| 0 | 0 | 0.070 | 0 | | |
| 1 | 0.1 | 0.080 | 0.1 | 0.0075 | 0.000375 |
| 2 | 0.2 | 0.090 | 0 | 0.0075 | 0.000375 |
| 3 | 0.3 | 0.090 | 0 | 0.009 | 0 |
| 4 | 0.4 | 0.115 | 0.1 | 0.01025 | 0.000513 |
| 5 | 0.5 | 0.100 | 0.2 | 0.01075 | 0.001613 |
| 6 | 0.6 | 0.090 | 0.1 | 0.0095 | 0.001425 |
| 7 | 0.7 | 0.090 | 0.1 | 0.009 | 0.00135 |
| 8 | 0.78 | 0.080 | 0 | 0.0068 | 0.00034 |
| **Total** | | | | 0.0703 | 0.00599 |

**Table A21.** Stream gauging data for the Hotel site at 11:20 on 08/12/11

| Stream gauging data for the Hotel site at 11:20 on 08/12/11 | | | | | |
|---|---|---|---|---|---|
| Stage | Distance (m) | Depth (m) | Velocity (m/s) | CSA | Stage Flow ($m^3$/sec) |
| 0 | 0 | 0.160 | 0.1 | | |
| 1 | 0.05 | 0.220 | 0.2 | 0.0095 | 0.001425 |
| 2 | 0.1 | 0.240 | 0.2 | 0.0115 | 0.0023 |
| 3 | 0.2 | 0.240 | 0.2 | 0.024 | 0.0048 |
| 4 | 0.3 | 0.230 | 0.1 | 0.0235 | 0.003525 |
| 5 | 0.4 | 0.230 | 0 | 0.023 | 0.00115 |
| 6 | 0.5 | 0.200 | 0 | 0.0215 | 0 |
| **Total** | | | | 0.113 | 0.0132 |

**Table A22.** Stream gauging data for the Bridge site at 11:20 on 09/12/11

| **Stream gauging data for the Bridge site at 11:20 on 09/12/11** | | | | | |
|---|---|---|---|---|---|
| Stage | Distance (m) | Depth (m) | Velocity (m/s) | CSA | Stage Flow ($m^3$/sec) |
| 0 | 0 | 0.100 | 0 | | |
| 1 | 0.1 | 0.190 | 0.1 | 0.0145 | 0.000725 |
| 2 | 0.2 | 0.180 | 0.2 | 0.0185 | 0.002775 |
| 3 | 0.3 | 0.205 | 0 | 0.01925 | 0.001925 |
| 4 | 0.4 | 0.190 | 0 | 0.01975 | 0.001975 |
| 5 | 0.5 | 0.160 | 0 | 0.0175 | 0 |
| 6 | 0.6 | 0.135 | 0 | 0.01475 | 0 |
| **Total** | | | | 0.10425 | 0.0074 |

## A1.3 River cross section area (CSA) profiles.

Each of the river CSA profiles has been compiled from the data in tables 7 to A19.
Depth = 0 is the height of the river and has not been normalized to represent a fixed height above base of river.

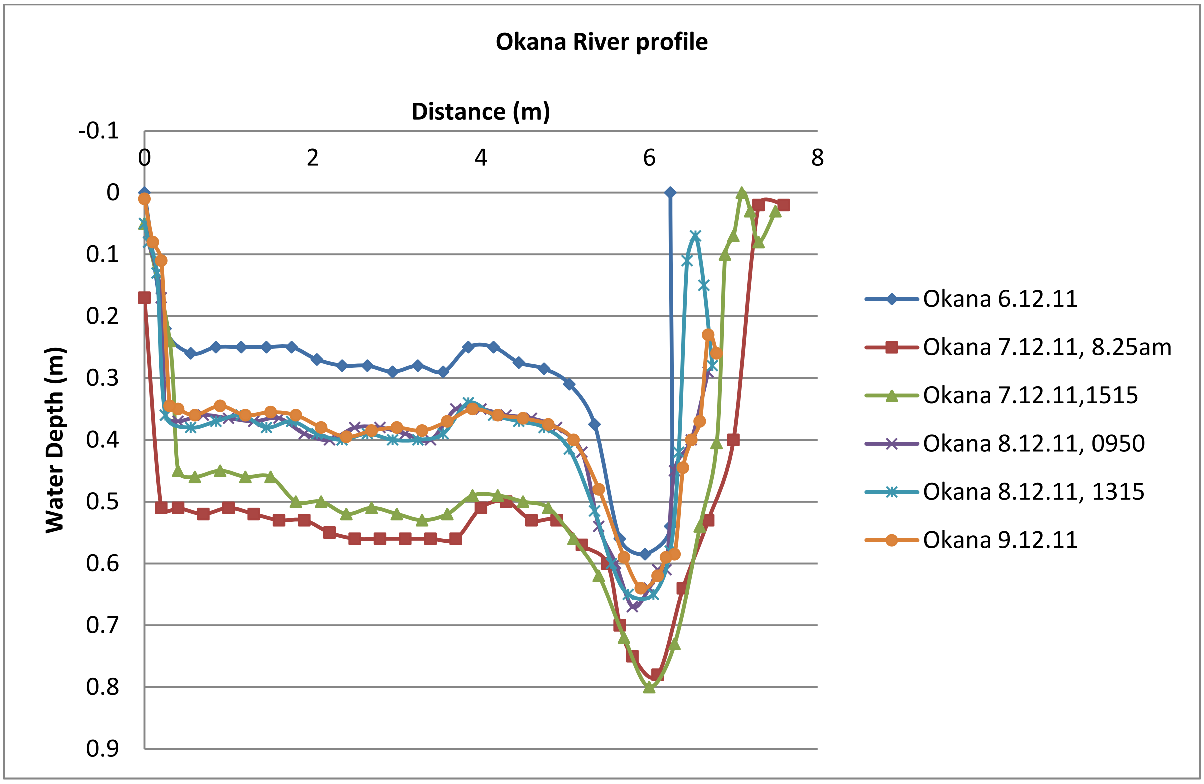


**Figure A2.** Okana River cross sectional profile, shown with the true right bank on the left of the graph (i.e. looking upstream).

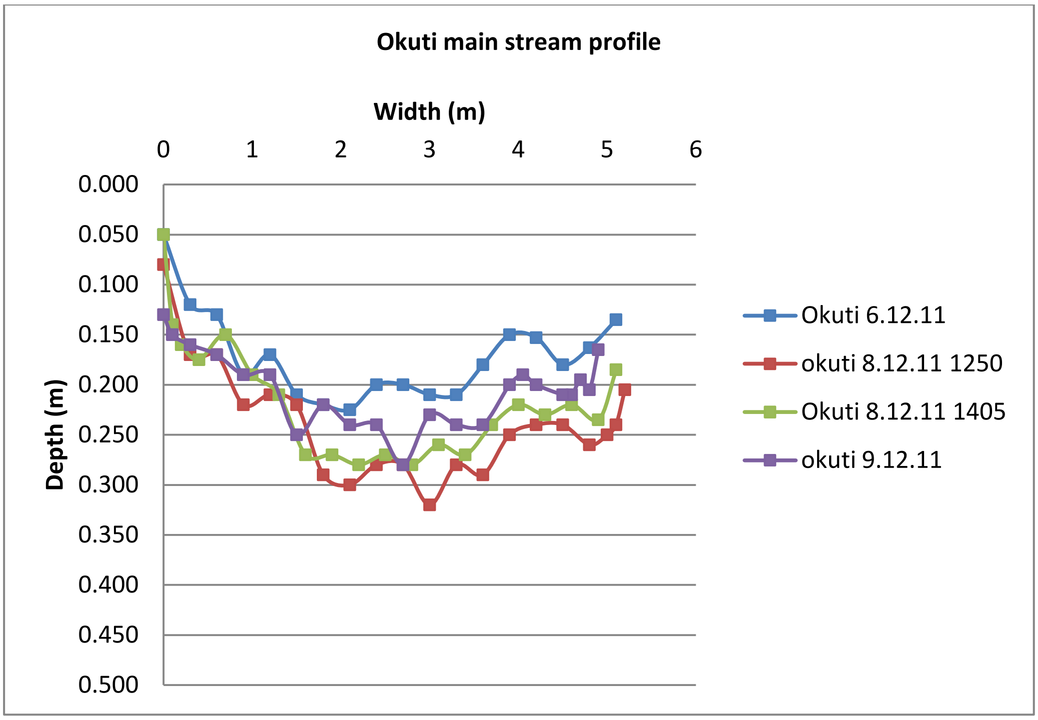


**Figure A3.** Okuti main stream cross sectional profile, with the true right bank to the left of the graph.

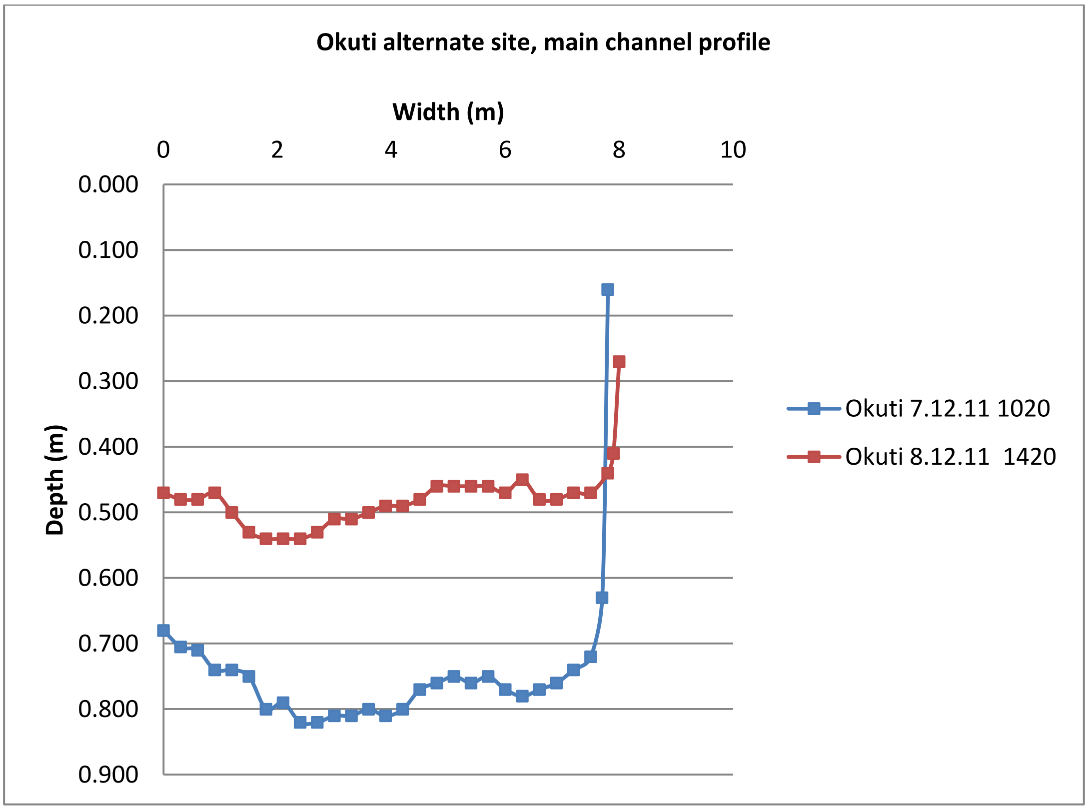


**Figure A4.** Okuti alternate site, main channel profile, true left bank on the left side of graph

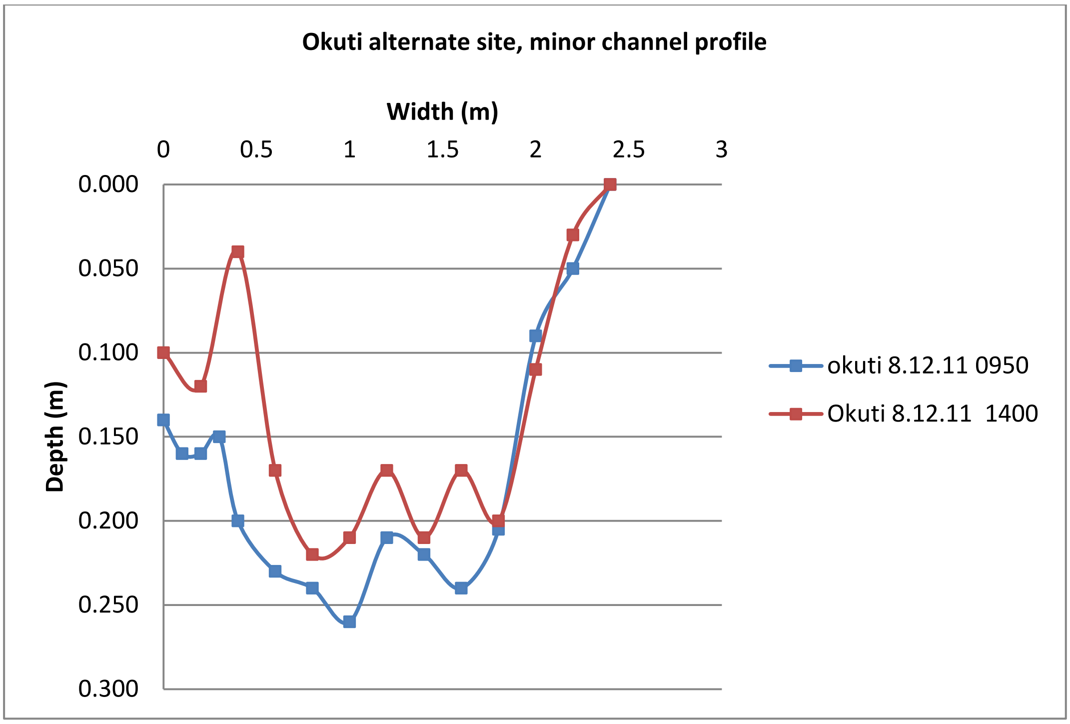


**Figure A5.** Okuti alternate site, minor channel profile, true left bank is to the left of the graph.

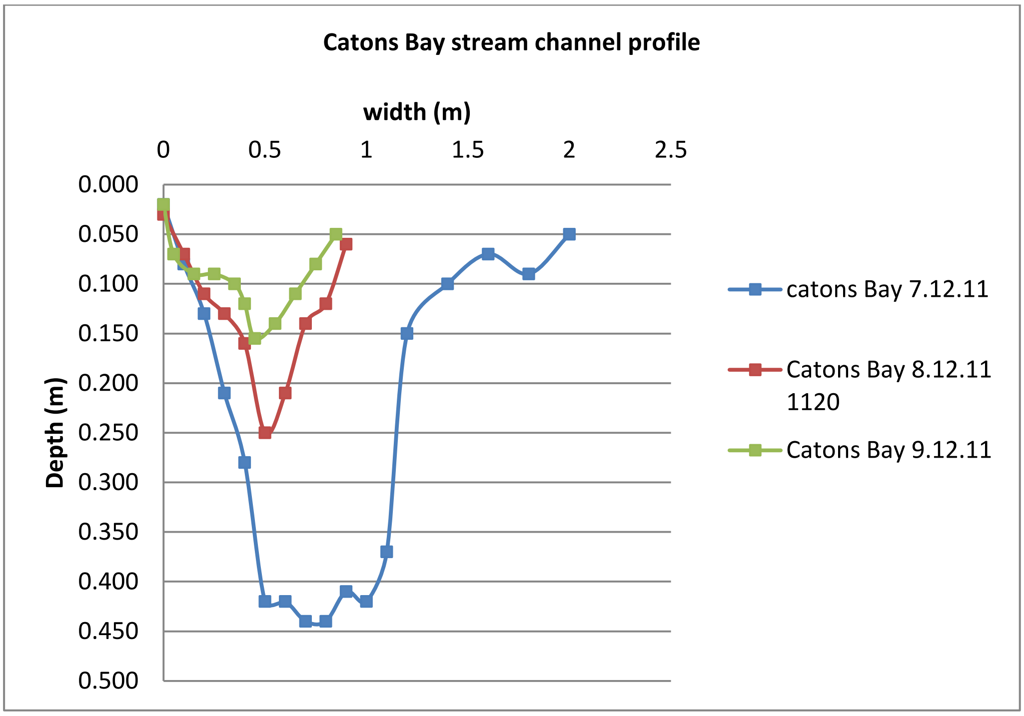


**Figure A6.** Catons Bay stream channel profile, true right bank shown to the left of the graph

## A1.4 Recalculation of Okana River flow for 08:25 on 7th December

An alternative Okana River site had to be used for this (and the 15:15) gauging, for safety reasons. The flow velocity was too dangerous for waded measurement. Site selected 20 metres upstream requiring 2 gauging points due to tributary stream entering the river from the true left, 5 metres below alternate site.

During the period of data collection it was noted visually (from turbulence and river level on the bank) and physically (flow strength against the legs of the author) that the flow of the Okana River should have been at its highest during the 08:25 gauging session. However the calculated flows indicate the highest flow during the 15:15 gauging session.

Due to the height of the river and the strength of the flow during the 08:25 gauging session correct positioning of the flow meter was very difficult, and multiple instances of the meter counter detaching were noted. Velocity measurements were retaken when detachment of the counter was noted, however short term detachments of the meter counter may have gone undetected. This could cause the velocity readings to be under estimated. It was therefore decided to recalculate the 08:25 flow, to provide an flow that was more representative of the CSA.

The CSA and flow data from Table A23 was used to provide an equation for a calibration relating CAS to flow (Figure A7).

**Table A23.** CSA and Flow data used to calculate the expected flow at 08:25 on 7/12/11

| **Okana** | | | |
|---|---|---|---|
| | Time | CSA | Flow |
| 7/12/2011 | 15:15 | 3.61875 | 1.625 |
| 8/12/2011 | 9:50 | 2.7365 | 0.592 |
| 8/12/2011 | 13:15 | 2.638 | 0.487 |

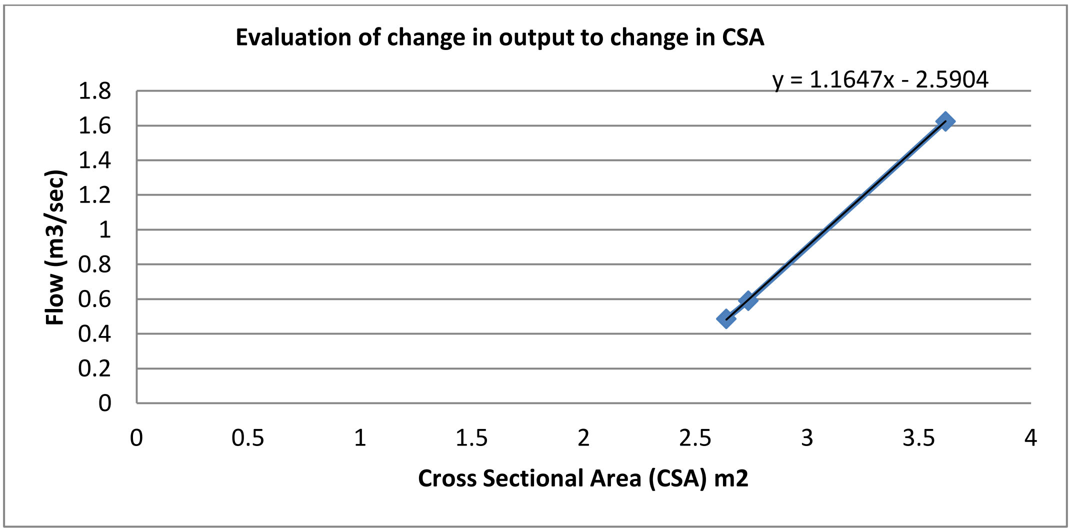


**Figure A7.** Graphical analysis of expected flow from cross sectional area.

Substitution of the 08:25 CSA (3.95$m^2$) into the formula from Figure A7 indicates that the correct flow should be:

Q = (1.164 x 3.95) – 2.590 = 2.007 $m^3$/sec

## A1.5 Time-synchronisation for gauging measurements

Due to the time required to travel between sites and conduct the stream gauging there is a large time difference between the first and last measurements to capture the overall inputs to the lake. In order to evaluate the inputs to the lake during the period of the study, it was deemed necessary to correct each of the measurements to the times of the Okana gauging. The assumption was made that where data was not available to indicate a rising or falling trend for that particular location, the overall trend could be used.

For example, for the Okana;

The rate of change was then multiplied by the difference between the Okana 08.25 gauging and the 09.50 Okuti gauging. In this case due to the period being a rising stage, the result was subtracted from the 09:50 Okuti gauging:

08:25 *Okuti flow = Okuti 09:50 flow – (rate of change x time difference)*

Therefore:

08:25 *Okuti flow* = 2.827 – (0.0000348 x 5100) = 2.64952$m^3$/sec

This method was utilised to align all of the flows to the Okana gauging times for each of the days.

## A1.6 Seepage estimation calculation

In order to quantify the volume of water lost from the lake as either a transfer to groundwater storage or seepage through the barrier to the sea, the hydrological balance formula is rearranged to:

$G = \Delta S - P + E - Q_{1,}$

Where:

P = Daily precipitation (mm) from the Okuti rain gauge

E = Evaporation measurement (mm) from the VCSN network

ΔS = Change in lake level. The sum of each 15 minute period, multiplied by its respective volume change from Table A27 in Appendix 3:

$Q_1$ = combined river and stream flow input over a 24hr period. This has been calculated as the average over the respective 24hr interval, but taken to be from 11:00 to 11:00 to allow for the timing of the gauging.

$Q_2$ = direct runoff from the Northern and Southern regions. The estimated runoff has been equally divided between the two 24hr periods in which active rain occurred (6-7 and 7-8$^{th}$ December).

Other than for $Q_1$, data is for a 9:00 to 9:00 interval.

# Appendix 2 Recent Lake Barrier Openings

Data regarding the openings of the Wairewa to the sea are collated by the Banks Peninsula Waterways Contract Manager within CCC. Table A24 provides the opening and closing dates and times for the period 31/05/10 to 2/09/11. It should be noted that only the opening times are reported by the contractor; the closing times have been estimated from the lake level graphs and not from physical observations.

**Table A24** Wairewa barrier opening and closing data

| **Event** | **Opening** | | | **Closing** | | |
|---|---|---|---|---|---|---|
| | Date | Time (approx) | Lake Level (m) | Date | Time (Approx) | Lake Level (m) |
| **1** | 31/05/2010 | 13:00 | 2.8 | 6/6/2010 | 12:00 | 1.4 |
| **2** | 10/06/2010 | 15:00 | 2.3 | 13/06/2010 | 12:00 | 1.5 |
| **3** | 28/06/2010 | 12:00 | 3.1 | 2/07/2010 | 06:00 | 1.9 |
| **4** | 13/07/2010 | 09:30 | 3.21 | 18/07/2010 | 09:30 | 1.23 |
| **5** | 10/08/2010 | 07:30 | 2.67 | 12/08/2010 | 06:00 | 1.9 |
| **6** | 13/08/2010 | 10:00 | 1.95 | 16/08/2010 | 08:00 | 1.4 |
| **7** | 08/07/2011 | 11:00 | 2.1 | 12/07/2011 | 08:00 | 1.25 |
| **8** | 26/08/2011 | 16:00 | 2..3 | 02/09/2011 | 18:00 | 1.2 |

# Appendix 3 Calculation of lake volume change from lake levels

**Table A25.** The calculated per millimetre volume change for each 10mm change in lake level between -2.6m and +3.9m.

| Contour Elevation | Contour Elevation | Volume per 1mm level change |
|---|---|---|
| **m** | m | $m^3$/mm |
| **From** | To | |
| **-2.6** | -2.5 | 0.73 |
| **-2.5** | -2.4 | 0.88 |
| **-2.4** | -2.3 | 1.03 |
| **-2.3** | -2.2 | 1.20 |
| **-2.2** | -2.1 | 1.37 |
| **-2.1** | -2.0 | 1.55 |
| **-2** | -1.9 | 1.74 |
| **-1.9** | -1.8 | 1.95 |
| **-1.8** | -1.7 | 4.80 |
| **-1.7** | -1.6 | 13.88 |
| **-1.6** | -1.5 | 20.69 |
| **-1.5** | -1.4 | 22.38 |
| **-1.4** | -1.3 | 24.08 |
| **-1.3** | -1.2 | 25.80 |
| **-1.2** | -1.1 | 27.55 |
| **-1.1** | -1.0 | 29.31 |
| **-1** | -0.9 | 31.10 |
| **-0.9** | -0.8 | 32.90 |
| **-0.8** | -0.7 | 34.73 |
| **-0.7** | -0.6 | 59.28 |
| **-0.6** | -0.5 | 111.92 |
| **-0.5** | -0.4 | 126.77 |
| **-0.4** | -0.3 | 141.44 |
| **-0.3** | -0.2 | 158.32 |
| **-0.2** | -0.1 | 484.94 |
| **-0.1** | 0 | 1079.37 |
| **0** | 0.1 | 1826.77 |
| **0.1** | 0.2 | 2411 |
| **0.2** | 0.3 | 2981 |
| **0.3** | 0.4 | 3322 |
| **0.4** | 0.5 | 3659 |
| **0.5** | 0.6 | 4003 |
| **0.6** | 0.7 | 4305 |

| Contour Elevation | Contour Elevation | Volume per 1mm level change |
|---|---|---|
| m | m | $m^3$/mm |
| From | To | |
| **0.7** | 0.8 | 4541 |
| **0.8** | 0.9 | 4722 |
| **0.9** | 1.0 | 4926 |
| **1.0** | 1.1 | 5091 |
| **1.1** | 1.2 | 5222 |
| **1.2** | 1.3 | 5370 |
| **1.3** | 1.4 | 5537 |
| **1.4** | 1.5 | 5867 |
| **1.5** | 1.6 | 5977 |
| **1.6** | 1.7 | 6055 |
| **1.7** | 1.8 | 6139 |
| **1.8** | 1.9 | 6226 |
| **1.9** | 2.0 | 6391 |
| **2.0** | 2.1 | 6604 |
| **2.1** | 2.2 | 6697 |
| **2.2** | 2.3 | 6790 |
| **2.3** | 2.4 | 6930 |
| **2.4** | 2.5 | 7121 |
| **2.5** | 2.6 | 7377 |
| **2.6** | 2.7 | 7554 |
| **2.7** | 2.8 | 7727 |
| **2.8** | 2.9 | 7886 |
| **2.9** | 3.0 | 8374 |
| **3.0** | 3.1 | 8433 |
| **3.1** | 3.2 | 8480 |
| **3.2** | 3.3 | 8533 |
| **3.3** | 3.4 | 8589 |
| **3.4** | 3.5 | 8672 |
| **3.5** | 3.6 | 8739 |
| **3.6** | 3.7 | 8818 |
| **3.7** | 3.8 | 8891 |
| **3.8** | 3.9 | 8968 |
| **3.9** | 4.0 | 9101 |

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