Waterways
Centre for Freshwater Management

Principal Sources of Summer Sediment to Lake Forsyth/Wairewa

Summer Scholarship Report

WCFM Report 2013-003

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TITLE: **Principal sources of summer sediment input to Lake Forsyth/ Wairewa**

PREPARED FOR: **Waterways Centre for Freshwater Management**

PREPARED BY: **Jordan Miller** (BSc Geography)

EDITED & REVISED BY: Professor Jenny Webster-Brown (WCFM)

REVIEWED BY: Dr Tom Cochrane (Civil and Natural Resources Engineering)

AFFILIATION: Waterways Centre for Freshwater Management
University of Canterbury & Lincoln University
Private Bag 4800
Christchurch
New Zealand

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Executive Summary

Lake Forsyth/Wairewa is a shallow eutrophic lake on the southern coast of Banks Peninsula, Canterbury, New Zealand. It has suffered from sporadic algal blooms over the last century, which have affected water quality and lake ecology. The high phosphorus content of the lake sediment has been identified as a key driver for the algal blooms. The purpose of this study was to quantify the volume of sediment entering Wairewa through tributary rivers and streams, and via direct runoff during storms, over the summer of 2012-13. The results will contribute to a concurrent assessment of sediment-associated phosphorus input to the lake.

There are only two permanent tributaries to Wairewa; the Okana and the Okuti Rivers. The remaining tributaries are all ephemeral, flowing only during heavy rainfall. Sampling and analysis for total suspended sediment (TSS) was carried out immediately following rainfall events on four occasions in December 2012 and January 2013. There were only three days when the daily rainfall exceeded 20 mm. Water loggers were installed in the Okuti and Okana Rivers and in Catons Culvert, to continuously record water level. This, combined with manual stream gauging, was used to calculate discharge. TSS loads delivered by these tributaries were then calculated for the 2 months of December and January, as 41,000 kg from the Okana River, 22,500 kg from the Okuti River, and < 850 kg from Catons Culvert.

To assess direct runoff from the steep eastern and western slopes of the catchment experimental rain simulations on bare and grassed soil collected from the lake catchment, on slopes of 5-30^{o} slopes and under rainfall intensities of 12 and 24 mm/hr, were conducted in the Fluid Mechanics Laboratory at the University of Canterbury. The volume of runoff from each simulation was recorded, and samples analyzed for TSS. On average, bare soil produced 14 times as much runoff as grassed soil, and bare soil runoff contained 96 times the TSS concentration of grassed soil runoff. It is not possible to calculate potential direct runoff sediment loads for the catchment, as the rainfall intensities and sediment attenuation rates are not known, but it is estimated that <2000 kg would have been mobilised from the eastern slopes of the catchment during a storm event in December. Catchment soils remained very dry for most of the summer, and therefore required extended periods of intense rainfall before they were able to generate direct runoff.

The largest sediment input to Wairewa over summer was therefore from the Okuti and Okana Rivers. Attempts to reduce the sediment input to the lake (and its phosphorous load) should focus on actions which can be taken in the catchments of these rivers.

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Section 1 Introduction

1.1 Background and Research Aim

Lake Forsyth/Wairewa is a shallow brackish lake that occupies the lower section of a coastal valley on the southern side of Banks Peninsula, on the east coast of the South Island, New Zealand (Fig. 1.1). The lake is separated from the Pacific Ocean at its southern end by the narrow Kaitorete Spit, an active gravel barrier beach that extends northwards for 30 km from southern end of Lake Ellesmere. The barrier developed over the last 8000 years through accumulation of the fluvial sediments that are transported northwards along the Canterbury Bight by long-shore drift (Woodward & Shulmeister, 2005). Lake Forsyth, however, hasn't always been cut off from the ocean; analysis of lake sediment cores has revealed that the lake used to be a tidal estuary with historical accounts indicating that a direct opening to the sea existed as recently as 1830 AD (Soons et al., 1997).

Anthropogenic land-use change from native forest to grassland throughout the Wairewa catchment since the mid-19th century has caused a dramatic increase in erosion, which has lead to large amounts of sediment and nutrients entering the lake through tributary streams and surface runoff. Since 1907 when the presence of surface algae was first reported in the Lyttelton Times, the lake has been subject to summer blooms of *Nodularia* and *Anabaena*, two genera of filamentous nitrogen-fixing cyanobacteria. The blooms are driven by high phosphorus, which is a limiting element for growth of cyanobacteria, and which enters the lake principally bound to sediment. While fertilizer application to the pastoral slopes of the lake could easily be assumed to be a contributing factor, the volcanic lithology of the catchment is the most likely source of most of the phosphorous (Woodward & Schulmeister, 2005; Lynn 2005).

Figure 1.1: Location of Lake Forsyth in relation to Christchurch City and Banks Peninsula (image from Google Maps, 2012)

The aim of this project was to quantify the contribution of sediment to the lake made by both direct stormwater runoff and tributary rivers/streams, during the 2012-13 summer period. This involved collecting samples from selected streams (shown in Fig. 1.2 below) after rainfall to analyse their suspended sediment content and simulating erosion on catchment soils using a rainfall simulator.

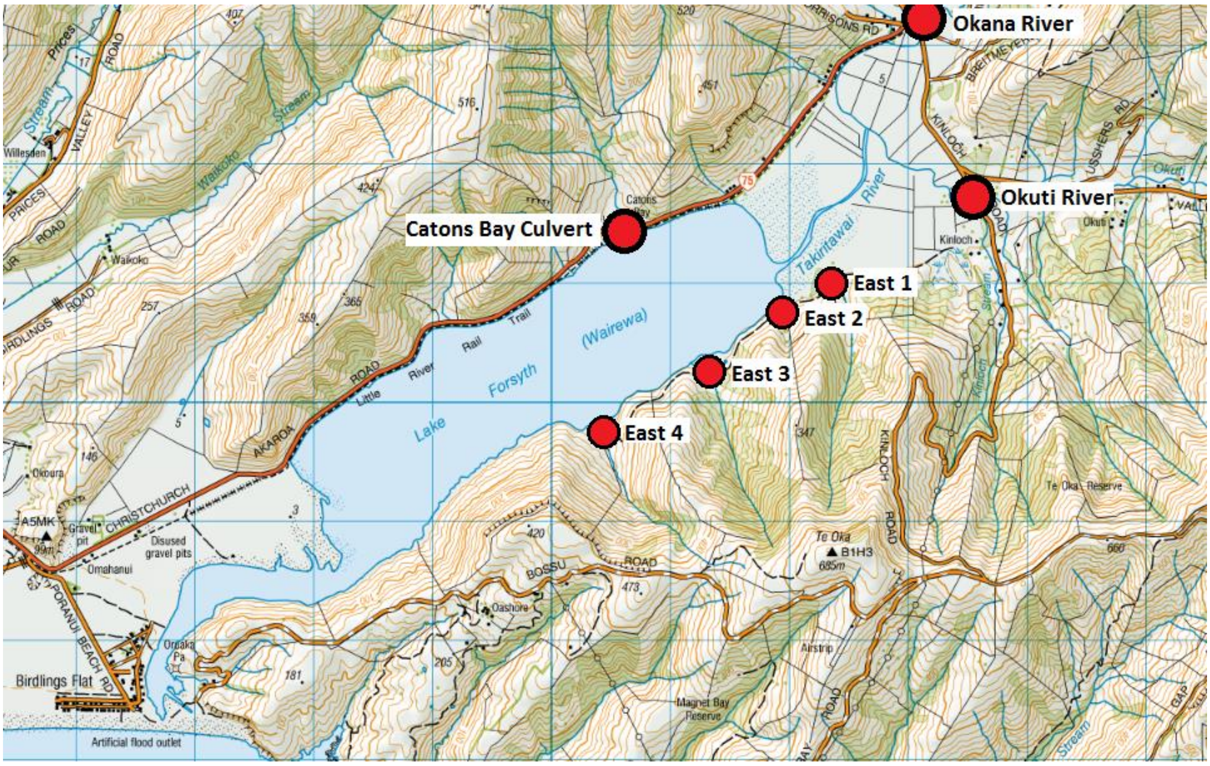


Figure 1.2: Topographic map showing the study area and sampling locations (map from LINZ, 2012)

1.2 Catchment Characteristics

Wairewa lies at the bottom of a valley with steep ridges running parallel to it on both the eastern and western sides, each reaching over 400 m in elevation. The catchment resides in the five million year old Banks Peninsula Volcanic Complex and the topography of the upper slopes is steep with rocky escarpments. The lower slopes are composed of smooth colluvium. Vegetation on both sides consists mainly of regenerating manuka scrub. The western slopes are more widely vegetated than those of the east (Fig 1.3). Tussock and pasture dominate the latter, particularly at the southern end of the lake, with the exception being two small valleys where pockets of both native and exotic forest exist. The grassed slopes are openly grazed by sheep and cattle. There is considerable erosion occurring on the lower slopes directly above the lake, especially on the steep land directly above the eastern lake edge. The settlement of Little River lies only a short distance north of the lake and Birdlings Flat sits atop the Kaitorete Spit at the southern end. State Highway 75 (Christchurch-Akaroa Road) follows the western shoreline and the Little River Rail Trail is an embanked gravel cycleway that sits between the road and the lake. The western shore

embankment is armoured with stone rip-rap (Fig. 1.4). A 4WD road runs halfway along the eastern shoreline from the northern end but access to the southern half can be gained only by foot.

Figure 1.3: North view along Wairewa, from the southwest end of the lake.

Figure 1.4: North view along the western shore of Wairewa. Stone rip-rap armours the western shoreline

1.2.1 Hydrology

The lake catchment is approximately 108 km², ranging in elevation from 840 m to sea-level. The lake is approximately 5.6 km² in area and has an average depth of only 2 m, with its deepest point being only 4 m. There are two small permanent rivers that feed directly into the northern end the lake; the Okana and Okuti. These converge in the swampy marsh a kilometre upstream of the lake, to form the Takiritawai River. The sub-catchment areas of the Okana and Okuti are 54.7 km² and 19.7 km² respectively (Whyte, 2011). There are several small tributary streams that drain the eastern and western slopes directly adjacent to the lake, of which Catons Bay Culvert is the only one named. For the purpose of identification in this study they have been named East 1, East 2, East 3 and East 4, and all are presumably spring-fed (Fig. 1.2). East 3 and East 4 flow on the surface for much of their journeys down their respective valleys but disappear to groundwater as soon as they reach the flat land at the lake edge. However, evidence of erosion and sediment deposition suggests surface flow does occur during heavy rainfall (Fig. 1.5). The Okana River has been known to flood the town of Little River, and on October 19th 2011, what was considered by locals to be the worst flood since the Wahine Storm of 1968 inundated the town (The Press, 2011).

Wairewa is highly turbid due to the prolific algal growth and re-suspension of bed sediments by waves generated by surface shear during strong winds. The only way the lake can drain naturally is via percolation through the gravels of the barrier beach. However, the lake is opened artificially during times of high rainfall to prevent flooding upstream of the lake as the rivers back up. A channel is excavated through the gravel beach to allow the lake to drain. Environment Canterbury has a lake level gauge on the western shoreline that triggers the need to drain. The lake is typically opened for two days to a week before it is closed again.

Figure 1.5: The dry stream channel of East 4 Stream from the bottom of the valley (near the lakeshore).

Although Berry & Webster-Brown (2012) counted the eastern shore of the lake as one single catchment (the 'southern region'), for this study the catchment has been further divided into five individual catchments.

1.2.2 Geology

Parent rock materials and major soil types of the catchment have been thoroughly studied and mapped. The Banks Peninsula is a five million year old volcanic complex with varying lithologies, however all of it can generally be described as 'basaltic' (Lynn, 2005). The eastern half of the catchment is mainly composed of the French Hill formation, part of the Akaroa Volcanic Group. The regolith is primarily volcanic derived. The western side of the lake is mainly composed of Mt Sinclair and Orton Bradley Formations which are part of the Mt Herbert Volcanic Group. Soil here is also a mix of loess and basalt derived soil. The loess that is found throughout the catchment, as well as the rest of Banks Peninsula, is a feature of the glaciations that have occurred over the last tens of thousands of years. Fine eroded sediments were blown eastwards from the Southern Alps and deposited on bare slopes. It is up to 20 m thick in some places, mainly under 150 m elevation, as it had long since eroded off the upper slopes and been re-deposited on the lower slopes (Boffa-Miskell, 2006). The valley floors are a mix of marine sand and silt and materials deposited over time from the upper slopes.

The closure of Lake Forsyth to the ocean through extension of the Kaitorete Spit is due to the natural process of long-shore drift. However the speed at which this process occurs has been increased through deforestation of major river catchments further south (Rakaia, Rangitata and Waitaki). Removal of forest and the subsequent increase in erosion lead to far more sediment entering the system than what naturally would, and in turn has caused the Kaitorete Spit to grow at a quicker rate (Environment Canterbury, 2003).

1.2.3 Weather

Annual precipitation varies significantly through the Lake Forsyth catchment. On the coast at Birdlings Flat the mean annual total is 635 mm while less than 10 km away in the Okuti Valley the figure is almost double, at 1232 mm. The head of the western valleys receive around 1800 mm (Lynn, 2005; NIWA, 2012). The Okuti Valley has a mean of 98 'wet' days (days with 1 mm or more precipitation) per year based on the last 30 years of NIWA data for the site. The site has a mean annual maximum 24 hour total of 95 mm, while the highest on record is 182 mm. As Banks Peninsula extends eastwards from the mainland, it lies prone to moist weather systems approaching from the south and east.

1.2.4 Anthropogenic Influence

Banks Peninsula was forested prior to human arrival. Podocarp and conifer-hardwood forests would have surrounded much of Lake Forsyth, with low scrub and tussock covering the higher ridges and peaks (Environment Canterbury, 2003;Boffa-Miskell, 2006). TeRoto o Wairewa has cultural significance to Ngai Tahu. The lake and the land surrounding it provided a wealth of resources to local Maori in time past. Eels, other native fish and waterfowl were abundant and forests and wetland flaxes adjacent to the lake provided material for building and weaving. It was those resources that first attracted Maori and the concept of mahinga kai is intertwined with the use of these resources, literally meaning "to

work the food”. Since the removal of forests and subsequent sedimentation and proliferation of algae, the biodiversity of the lake has been dramatically reduced. Though some deforestation occurred through uncontrolled Maori fires, deforestation on a large scale only occurred after the arrival of European Settlers in the 1830s. Whalers, who at the time had boat access to Wairewa as the ocean entrance was yet to close up, felled trees on the lake edge and rafted them back to whaling stations that had been established in the eastern bays of Banks Peninsula. In 1863 the first of five sawmills in the area was built at Little River and by 1895 all mill-able trees surrounding the lake had been removed (ECan, 2003). By 1920 as much as 99% of the original forest over the entire Banks Peninsula had been cleared (BoffaMiskell, 2006). In 1962, Mr Armstrong noted that in the latter half of the 19th century many of the streams in the catchment had begun to silt up as a result of the erosion that was occurring through the loss of trees, which provided stability to the steep slopes (Environment Canterbury, 2003). Forest was cleared to gain timber for construction of the nearby settlements and to clear land for pastoral development.

At present the lake catchment is highly developed. Currently the majority of the steep hill country surrounding the lake is only suitable for grazing sheep and beef, but there is some dairying on the valley floors. Present day forest cover has improved to approximately 15% more than the 1920’s cover.

1.3 Soil Infiltration and Overland Flow

Infiltration capacity is the rate at which water can enter the soil. Overland flow (stormwater runoff) occurs when the rainfall intensity exceeds the infiltration capacity of a soil. Different soils have different rates of infiltration and these are dependent on a range of factors including soil structure, vegetation cover and the existing water content in the soil. Soils with larger grain size (e.g., sand) typically allow higher rates of infiltration than fine soils such as clays. Loess is a mixture of sand, silt and clay, and typically has a maximum dry soil infiltration rate of around 200 mm/hr. Vegetation increases the infiltration capacity of soil as roots break down the soil structure and create macropores for quick drainage. Once a soil is saturated, its capacity for infiltration is reduced.

Berry & Webster-Brown (2012) made an estimate of surface runoff by selected an arbitrary average infiltration for catchment soils of 0-50%; an assumption based on a low level of infiltration due to the steep and sparsely vegetated slopes.

1.4 Surface Erosion

Surface erosion depends on rainfall, soil, slope and vegetation characteristics of the local topography. Active erosion is apparent on the bare eastern slopes directly above the lakeshore (Fig. 1.6). Historical aerial photography can provide an indication of the timeframe most of this erosion has been occurring. Surface erosion can generally be placed into four different categories, splash, sheet, rill and gully (Fletcher, 2007):

- Splash erosion is where soil particles are displaced by the force of rain drops as they impact the ground surface. The erodiblity of a soil through splash erosion is determined by a range of factors; vegetation cover, soil cohesion and rainfall intensity. Bare soil is most susceptible to splash erosion as it has no cover from vegetation to intercept raindrops.

- Sheet erosion occurs as soil particles are dislodged by overland flow. Occurrence of overland flow, as stated earlier, is a function of rainfall intensity and the infiltration capacity of soil. The erosive power of overland flow increases with slope. Vegetation reduces sheet erosion by slowing down overland flow and reducing its erosive power.

- Rill erosion occurs when surface flow drains to natural low points, mainly where sheet erosion has incised a small channel into the slope. Positive feedback occurs as the low points act as preferential flow paths and are eroded by overland flow, further incising channels, increasing the volume and velocity of the water draining into them, which in turn increases the rate of erosion. Severe rill erosion can lead to gully erosion.

- Gully erosion is a severe form of rill erosion and can be placed into two types; deep rill and tunnel. Deep rill erosion is when water erodes the banks of rill channels, causing them to collapse and form wider gullies. Tunnel gullies form when water seeps into the soil and forms underground cavities, which eventually collapse inwards and form open gullies. Tunnel gullying usually occurs in areas where the soil is dry and desiccation cracks allow water to drain quickly into the subsurface.

Figure 1.6: Active erosion on the eastern shore of the lake.

1.5 The Phosphorus-Sediment Association

Phosphorus (P) is a limiting nutrient for algal growth in waterways, and high concentrations of P in over-nutrified waters (eutrophic) can result in uncontrolled growth of algae, or “algal blooms”. Inorganic P naturally occurs in high concentration in the basaltic soils of the Wairewa catchment. The Stewart-Akaroa soil (a mix of basalt and loess) that resides in the southern half of the Okuti Valley is particularly high in phosphorous, with almost 2500mg/kg (Lynn, 2005). Reynolds stream, a tributary of the Okuti River near the head of the Okuti Valley, drains this area and was found to have particularly high levels of dissolved phosphorus (Lynn, 2005).

The potential for P to be leached from the soil increases with P content in the soil, but only a fraction of the P transported into and along waterways is in dissolved form. P has a high affinity for minerals in soils, and binds strongly to soil particles being eroded from the land surfaces. Consequently much of the P transported to Wairewa is bound to the suspended sediment particle, providing a strong connection between the sediment load and the P load entering the lake.

Although P contributions to water bodies is mainly via surface flows, dissolved P can also be mobilised in subsurface (groundwater) flow, particularly in shallow groundwater which has a longer contact time with soil than surface flow (McDowell & Condron, 2004).

Section 2 Methodology

Both field measurements and laboratory experiments were undertaken in this investigation. Field work was required to collect stream flow samples and take stream discharge measurements. However the lack of rainfall in the field over the study period made it difficult to adequately characterise direct runoff using field sampling. Laboratory methods offered the chance to run experiments where storm runoff could be simulated and measured under controlled conditions.

2.1 Field Methods

2.1.1 Stream sample collection

Stream suspended sediment samples were collected following rainfall events in 1 L plastic containers, from the Okana and Okuti Rivers, Catons Culvert and East 1, 2, 3 and 4 (Fig. 1.2). Samples were collected as close as possible to peak flow of each stream after precipitation, relying on forecasting to know how long rainfall would last for and when the peak flow would occur.

2.1.2 Surface water gauging

The discharge of a river or stream (Q) is the volume rate of water flowing through a cross-sectional area of the channel perpendicular to the direction of flow and is measured in m^3/s (cumecs). Manual stream gauging was carried out on several occasions and permanent water level loggers were left in place over the entire study period. Odyssey 1.5 m conductive water level loggers were installed in Catons Bay Culvert (at SH75 Bridge), the Okana River (at SH75 Bridge) and the Okuti River (at Kinloch Road Bridge) and manual gauging was also conducted at these sites to obtain base flow Q values (Fig. 1.2).

To gauge Q the velocity-area method was used (Q=AV) where A is the cross-sectional area of the flow and V is the average velocity (Davie, 2002). Many depth measurements across the width of each channel were required to gain an accurate cross-sectional profile. The location of measuring was chosen to be as uniform as possible (in regard to width, depth, substrate size and flow direction). Accessibility also influenced the location of discharge measurements, and all the sites in this study were located within short distance of a road. As velocity is not even through the whole water column, velocity readings using a Global Water FP111 flow probe were taken at 0.6 of the depth where possible, to best represent the average velocity. The stream flows fastest just below the surface and is slowest at the bed where it is slowed by friction. Velocity measurements, taken with a Global Water FP111 flow probe, were averaged over 60 seconds and recorded to the nearest 0.1 m/s.

Water level loggers were installed and configured to record the water depth at 10 minute intervals so that a continuous record of the stream heights could be recorded (Fig. 2.1). Data from each logger was downloaded at each visit and used to produce a graph of the changing water height. At each study site, stream channel profiles were surveyed using fixed reference points to identify changes in the stream bed over the study period. This involved measuring the stream channel cross-section at a point, where there is a permanent structure to provide a reference point to identify long term changes.

Figure 2.1: Catons Bay Culvert with water level logger in dry conditions.

Figure 2.2: Weather station setup on Kinloch Farm in the Wairewa catchment.

Knowledge of the active channel and the inactive stream bed adjacent was required to calculate the A for high flows, as the river tops its channel and spreads laterally. Manual gauging data and water level data were used to produce a continuous flow rates (Q). Velocity measurements were undertaken during a range of flows to produce stream flow rating curves at each location

2.1.3 Precipitation

Precipitation data is important for developing the relationship between rainfall intensity and surface runoff. The primary source of precipitation data came from NIWA's online National Climate Database (Cliflo), as NIWA has operating rain gauges at Okuti Valley, Kaituna Valley and Magnet Bay. These record daily precipitation totals (24 hours from 0900 each day).

However, as the local Okuti Valley station records only 24-hour totals, no indication of local rainfall intensity was available, i.e. over what time period within the 24 hours did the rainfall occur. The nearest weather stations that report hourly precipitation totals are Akaroa and Lyttelton Harbour.

To address this issue, a small wirelesss weather station (Scientific Sales, model WS2083) weather station was set up in late December on Kinloch Farm, to record hourly rainfall totals (Fig. 2.2). This used a 0.2 mm tipping bucket as part of its rain gauge. This was set up to take hourly recordings of rainfall totals, meaning the hourly rainfall intensity could be obtained and related to the observed runoff. However, due to technical reasons the recorded data was unable to be used in this study.

2.2 Experimental Rainfall Simulations

The unpredictable and infrequent nature of rain over the study period created difficulty in obtaining field measurements of direct runoff and sediment yield. Accessibility to the eastern slopes of the lake also proved to be an obstacle. While creating field test plots on the slopes to the east of the lake would be the ideal option for investigating surface runoff, lack of a proper road on the eastern shore meant accessibility for transport of the required materials was an issue. The fact that this land is also a working farm meant that field testing was likely to not be the preferred option for the landowners. It was therefore easier to 'bring the field to the lab'. A rainfall simulator was used to simulate natural rainfall on small containers of soil collected from the field. Sediment yields and runoff volumes runoff were measures under various experimental conditions. The experiments were set up in the University of Canterbury's Fluid Mechanics Laboratory (Fig. 2.4).

2.2.1 Rainfall Simulator Setup

Four plastic containers (dimensions 670 mm long x 410 mm wide x 230 mm deep) were packed with soil taken from an erosion scarp off the side of the 4WD road at the north-eastern corner of the lake. It might be expected that soil samples collected from the field did not exactly replicate their natural structure, as disturbance was impossible to avoid when transferring them into the container using only a shovel. However, care was taken to ensure that the stratigraphy of the soil column was preserved as accurately as possible. The bottoms of the containers were lined with 10 cm of gravel and weed mat was cut to shape, placed atop the gravel and taped to the inner walls. The soil was then placed on top and compacted to near natural field conditions. The soil was levelled so it lay flush with the top walls of the container. Two 21 mm holes were drilled through the bottom of one end of each the containers and hoses inserted to allow drainage of infiltrating water (Fig.2.5).

Figure 2.4: Rain simulator set up in the UC Fluid Mechanics Laboratory.

Figure 2.5: Soil container with drainage hoses.

Two containers of bare soil and two of grassed soil, were prepared to replicate the typical surfaces found on the steep eastern slopes of the lake catchment. Once the containers had been filled and compacted to field conditions, they were left outside to dry and harden, in order to best replicate the 'baked' conditions of bare soil at the lake. The grassed containers were left outside under natural conditions to keep the grass alive. Plastic funnels were cut to shape and positioned on the downslope end of the containers. These extended down at 45° from the containers. Plastic covers were placed on top to prevent the falling water entering the funnel and being counted as runoff. After each test the funnels were cleaned to remove deposited sediment.

2.2.2 Rainfall simulator testing

The soil containers were tested under a range of rain intensities and slope angles. The rain simulator utilizes a sweeping action and water is released from two openings at either end of the crossbar. Water is pumped from a 1000 L tub at a pressure of 6 PSI. The simulations were run with filtered tap water. The number of sweeps per minute alters the volume of water falling, but not the velocity at which it falls. These are adjusted via the control box, which allows for 10 possible rainfall intensities (ranging from 12 to 119 mm/hr). Rain drops require a height of 1.8 m to accelerate to their terminal velocity so the simulator was set at a height of 2 m above the soil containers. The resulting rainfall drop size distribution and velocities produced by the rainfall simulator is comparable to natural rainfall. The platform on which the soil plots sit can be adjusted to be positioned at three different angles; 5°, 16° and 30°.

Two containers were tested at a time, each positioned directly underneath the two openings. Each test was one hour in duration. 1L plastic jars were used to collect the surface runoff as soon as it began, and as required, every 10 minutes afterward. Filtered and unfiltered runoff was also collected in 50 ml test tubes to analyze TP and DRP. These were frozen as soon as possible after collection to preserve them for later analysis.

2.2.3 Rain gauge calibration

Nine 180 mm x 180 mm plastic tubs were placed uniformly across the platform to record the actual distribution of rainfall the simulator was producing. They were left for 15 minutes under 24 mm/hr rain intensity. Six rain gauges were positioned across the platform in order to gauge the actual amount of water that was being received by the soil plots. The total volume of rainfall collected in each tub was used to produce a distribution of rainfall for the whole platform. From this, each soil container was calculated to receive approximately 6500 ml/hr (at 24 mm/hr intensity) and this was assumed to be spread evenly across the surface area of the container.

2.3 Total Suspended Sediments

Stream and rainfall simulator water samples were analyzed for total suspended sediments (TSS) using the standard EPA method (APHA, 1995). Pre-weighed GFC filters (pore diameter size 0.45 µm) were used to separate suspended sediment from the water. A known volume of sample was filtered, e.g. 100 ml, with the amount depending on the anticipated sediment load. The filters were dried at 105°C overnight to remove moisture and then weighed again. The following equation was used to calculate the total suspended sediment concentration:

$$\text{TSS (mg/L)} = \frac{((\text{Sediment-bearing Filter} - \text{Filter}) - \Delta\ \text{Blank Filter}) \times 1{,}000{,}000}{\text{Sample volume}}$$

To determine "Δ Blank Filter", 500 ml, 250 ml and 50 ml blank tests were run with de-ionized water to measure the weight of fibres that washed through the filter during the filtration process. Note that TSS does not take into account solids that are too heavy to be suspended or particles that are too small to be caught in the filter.

Section 3 Results and Discussion

3.1 Surface Water Flows

3.1.1 Manual Gauging

Manual stream gauging of the Okana and Okuti Rivers and Catons Culvert was done on four days during November and January (Table 3.1). The river was gauged at base flow on November 28th and January 16th, while stormflow was gauged on November 30th and twice on January 17th. The highest flows were gauged on January 17th, when the Okuti River was at 0.725 m^3/s and the Okana River was at 0.572 m^3/s. Otherwise flows never deviated far from base flow. Catons Culvert remained dry for the majority of the study period, but had a slow flow when gauged on 30 November. All other ephemeral tributaries remained dry or contained only a trickle of water on these gauging days.

Table 3.1. Manual flow gauging results (Q, in m^3/sec).

Date	Catons	Okuti	Okana
28/11/12	Dry	0.305	0.262
30/11/12	0.04	0.431	0.307
16/1/13	Dry	0.187	0.289
17/1/13 am	Dry	0.316	0.341
17/1/13 pm	Dry	0.725	0.572

3.1.2 Water Level Loggers

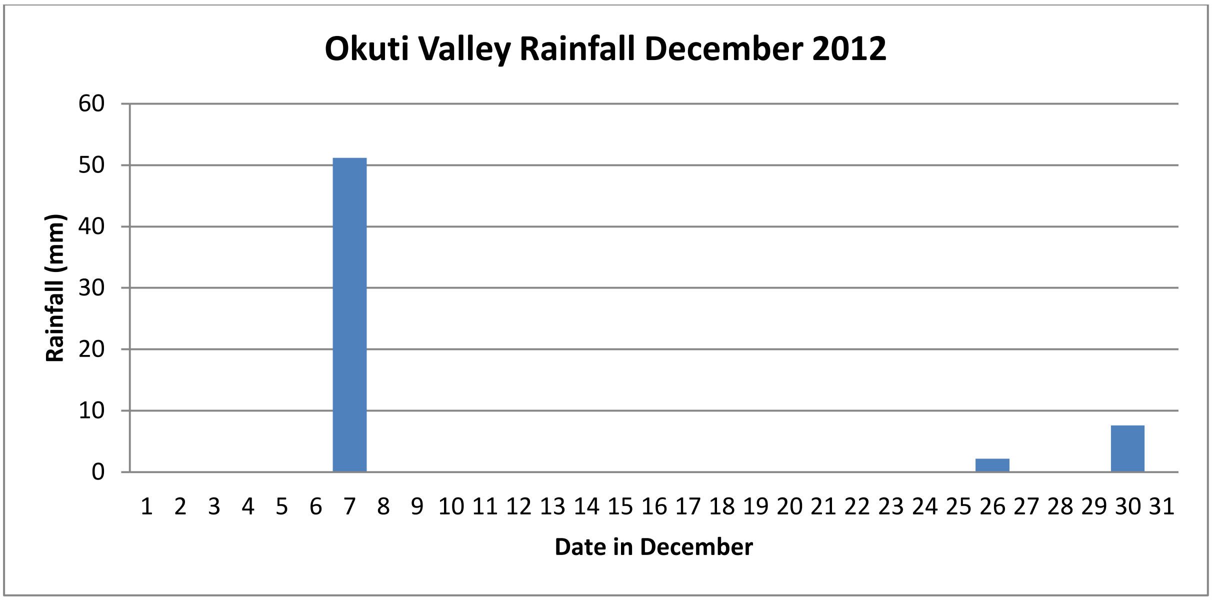
Water level loggers were able to capture continuous water level data, when flows could not be gauged manually. Using recorded water level and the water depth profile and velocities from the gauging described above (extrapolated when necessary for storm events), a continuous discharge record for each stream can be calculated.

The only major storm flow to occur over the study period was on December 7th. This day had by far the highest flow in all tributaries, with the Okuti River peaking at 1.75-2 m^3/s and the Okana River peaking at 3.0 - 3.5 m^3/s. Catons Culvert reached approximately 0.15 m^3/s. For the rest of December, the Okuti and Okana Rivers remained close to base flow and Catons Culvert recorded only two brief flows, each around 0.04 m^3/s.

During the entire month of January and through the first week of February, the Okuti and Okana Rivers barely rose above base flow at all, both flowing very consistently at around 0.3-0.4 m^3/s. During January, Catons Culvert had flow on only four occasions, each lasting less than 24 hours and peaking at approximately 0.05 m^3/s. On each occasion the channel filled rapidly, going from dry to having at least 25 cm of water in 20 minutes.

3.1.3 Rainfall monitoring

From the NIWA operated rain gauges at Okuti Valley, precipitation data was compiled for this study (Fig 3.1). The record shows daily precipitation totals, taken over 24 hours from 0900 each day. The largest rain event was on 7th December 2012, with just over 50 mm in 24 hours. Additional smaller events occurred in early and mid-January.



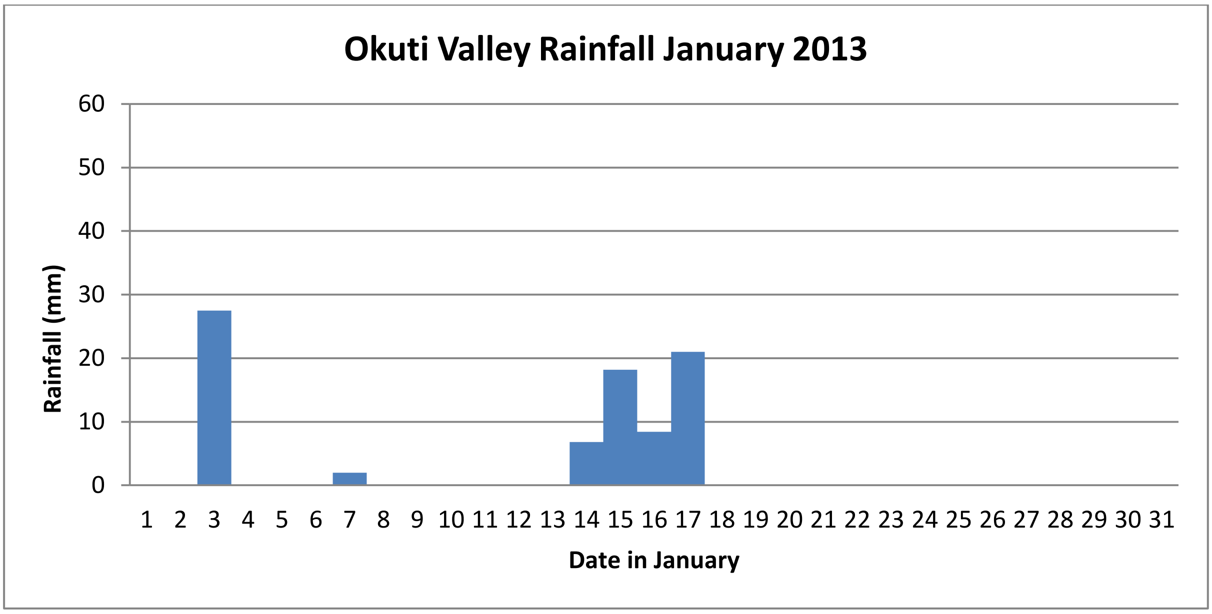


Figure 3.1. NIWA rain gauge data for the Okuti Valley, for the period of December 2012 and January 2013.

3.2 Surface Water Sediment content

3.2.1 Base flow readings

Base flow TSS readings were taken on 28th November and again on the 14th and 15th January (Table 3.2). The Okana and Okuti Rivers are the only two permanently flowing tributaries to Wairewa. The data showed both rivers have very little suspended sediment under base flow conditions.

Table 3.2. TSS concentrations (mg/L) in the main tributaries of Wairewa.

Date	Catons	Okuti	Okana
a) Base flow conditions			
28/11/12	-	5	4
14/1/13	-	7	3
15/1/13	-	7	4
b) Storm conditions			
30/11/12	5	4	10
7/12/12	383	59	7
16/1/13	-	8	5
17/1/13	-	37	22

3.2.2 Storm flow readings

TSS concentrations in four rainfall events were measured over the study period (Table 3.2). The highest sediment load captured was in Catons Culvert on December 7th, which was 383 mg/L; this was one of only two times Catons Culvert was observed to have a flow. The Okuti and Okana Rivers recorded almost no rise in TSS during rain events on 30 November and 16 January. The TSS in the Okana River seems to be particularly unresponsive to rainfall; the highest TSS reading (on Jan 17th) was only four times that of TSS at base flow. TSS in the Okuti River did rise substantially in two rainfall events; Dec 7th and Jan 17th.

3.3 Experimental Runoff and Sediment Yield Determinations

The rainfall simulations produced a large dataset from which relationships between rainfall, slope, runoff and TSS could be obtained. Table 3.3 provides results for all simulations conducted. On average, for all for the simulations, bare soil produced 14 times as much runoff as grassed soil (ranged from 4-33 times), and the sediment concentration in each runoff sample was 96 times greater (ranged from 2-233 times).

Table 3.3. Rainfall simulation experimental result for TSS concentrations and run-off volume, and derived values for erosion per mm of runoff, and total sediment loss.

Rainfall (mm/hr)	**Slope** (°)	**TSS** (mg/L)	**Runoff** (mL)	**Runoff** (mm)	**Erosion** (g/mm_{runoff})	**Total Sediment** (g)
Bare Soil						
Expt 1.						
12	5	1500	1000	3.64	0.41	1.5
12	16	2726	1800	6.55	0.75	4.9
12	30	6260	470	1.71	1.7	2.9
24	16	8634	4900	17.82	2.37	42.3
24	16	12482	5650	20.55	3.43	70.5
24	30	10198	4490	16.33	2.8	45.8
24	30	11720	5870	21.35	3.2	68.8
Expt 2						
12	5	2989	1000	3.64	0.82	3.0
12	16	3472	1700	6.18	0.95	5.9
12	30	5652	470	1.71	1.6	2.7
24	16	9091	4420	16.07	2.50	40.2
24	16	11260	5900	21.45	3.1	66.4
24	30	13854	4710	17.13	3.8	65.3
24	30	11919	5990	21.78	3.3	71.4
Grassed						
Expt 1						
12	5	0	0	0	0	0
12	16	283	130	0.47	0.08	0.04
12	30	1388	650	2.36	0.38	0.90
24	16	389	670	2.44	0.11	0.26
24	16	641	830	3.02	0.18	0.53
24	30	760	2380	8.65	0.21	1.80
24	30	1162	2500	9.09	0.32	2.90
Expt 2						
12	5	0	0	0	0	0
12	16	317	110	0.40	0.09	0.04
12	30	1288	830	3.02	0.35	1.07
24	16	153	610	2.22	0.04	0.09
24	16	531	720	2.62	0.15	0.38
24	30	1484	1710	6.22	0.41	2.50
24	30	3263	1910	6.95	0.89	6.20

Slight differences were found between the duplicate bare and grassed experiments, due to slight differences in the soil and grass characteristics of each surface, which was unavoidable

when setting them up. For 12 mm/hr rainfall on the grassed containers, significant runoff did not occur until a slope of at least 16°, on which it still took 34 minutes to begin and only produced 130 ml after one hour. Runoff on bare soil began almost immediately in all simulations. Bare soil on 30° slope under 24 mm/h rainfall produced the most runoff, at approximately 6,000 ml.

From the rainfall simulation experiment results, the infiltration rates of grassed and bare surfaces can also be calculated (Table 3.4). These will depend on the saturation values of the soils prior to precipitation, because as explained earlier, this affects their ability to accommodate more moisture. At 24 mm/hr on a 30° slope, bare soil can be expected to have an infiltration capacity of between 8-29%. This is significantly less than the 66-69% that can be expected on a grassed surface in the same intensity and slope settings.

Table 3.4. Rain infiltration into bare and grassed soil experiments.

Input volume (ml/hr)	Slope (°)	% of rain that infiltrated
Bare soil		
3,250	5	85
3,250	16	73
6,500	16	20
6,500	30	18
Grassed soil		
3,250	5	100
3,250	16	98
6,500	16	91
6,500	30	68

3.4 Sediment Load Calculations

The data obtained from river and streamflow measurements and from the rain-simulated storm runoff experiments can be compared and used to estimate the relative contribution of suspended solids delivered to Wairewa over summer.

3.4.1. Direct runoff sediment transport

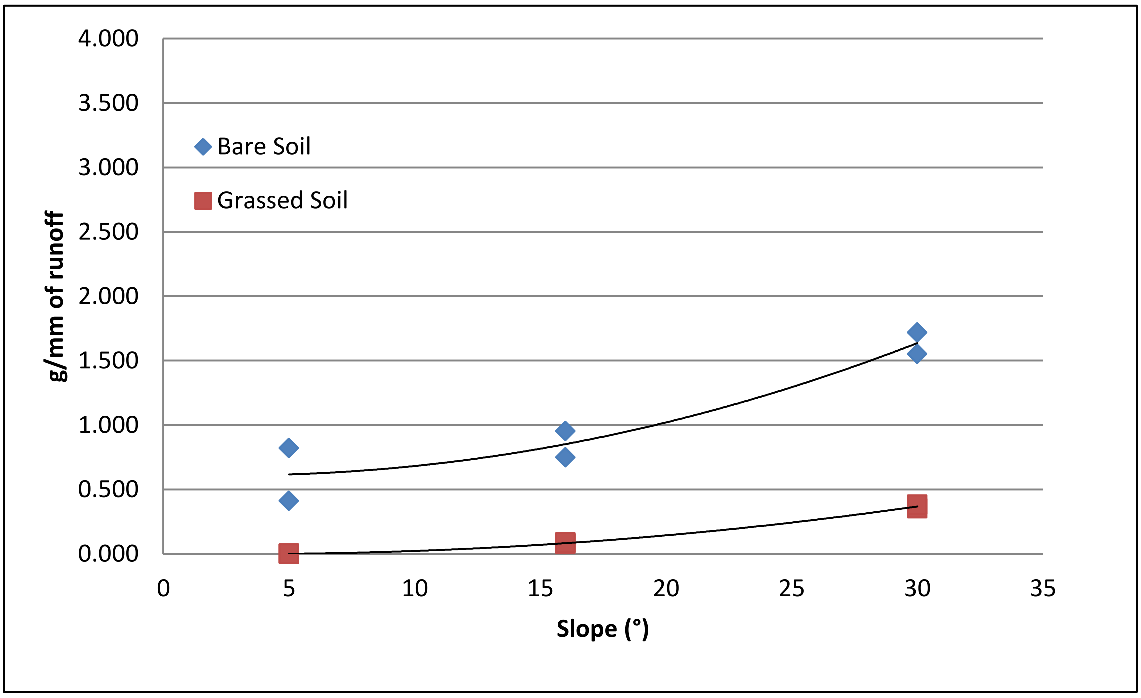
The eastern slopes of the lake are of particular interest for direct runoff contributions to lake sediments, as this is where most of the erosion seems to be occurring (Fig 3.2). The results from the small scale experimental simulations can be used to produce an estimation of rates of soil loss in volume per area or in volume per amount of rainfall, i.e. kg/mm or kg/m^2. By calculating the erosion rate per depth of runoff (g/mm) that occurred on different slopes under the same rainfall intensity, a relationship can be developed so that land slope can be used as a proxy for the amount of erosion likely to occur at steeper slopes under that rainfall intensity, on the lake edge (Fig 3.3).

Erosion seems to be confined to within 200 m of the lake edge, particularly at the northern end where slippage is evident on either side of the 4WD road. Using Google Earth to estimate the total areas of bare and grassed soil within this margin (Fig. 3.2) provides estimates of 51,000 m^2 and 45,000 m^2 respectively. While this is a very crude method for measuring small-scale slips and scarps at such small resolution, it is a valid approach for an initial assessment – one that can be later checked by on-site measurements. The surface area of each simulation container was 0.275 m^2. By dividing the bare soil and grassed soil areas (51,000 m^2 and 45,000 m^2) by the container area (0.275 m^2) and multiplying the outcome by the g sediment/mm runoff value calculated for each of the rain simulations, a very rough estimate of erosion can be calculated for the whole eastern side of the of the lake under different rainfall and slope conditions (Table 3.5).

Figure 3.2: The area of the eastern lake edge used in the calculation of sediment loss (Google Earth, 2013).

Note that the values in Table 3.5 assume a uniform slope across the whole area. From satellite photography it is impossible to assess the exact slope of the land (an accurate calculation of areas of equal slope would require GIS), but some of the slopes on the eastern shoreline are much steeper than the assumed maximum of 30°. The exponential relationship between slope and erosion means that some areas of land will therefore contribute far more storm runoff than is indicated in Table 3.5. Sediment loss rates will also be entirely dependent on the pre-existing moisture content of the soil. If the soil is already close to saturation after hours or days of light rain, then runoff will occur more rapidly with the onset of a heavy downpour, and transport more sediment. However if the catchment is very dry, as it was for most of the study period, it will take very heavy rainfall or hours of persistent drizzle before saturation is reached and runoff occurs.

a) 12 mm rainfall



b) 24 mm rainfall

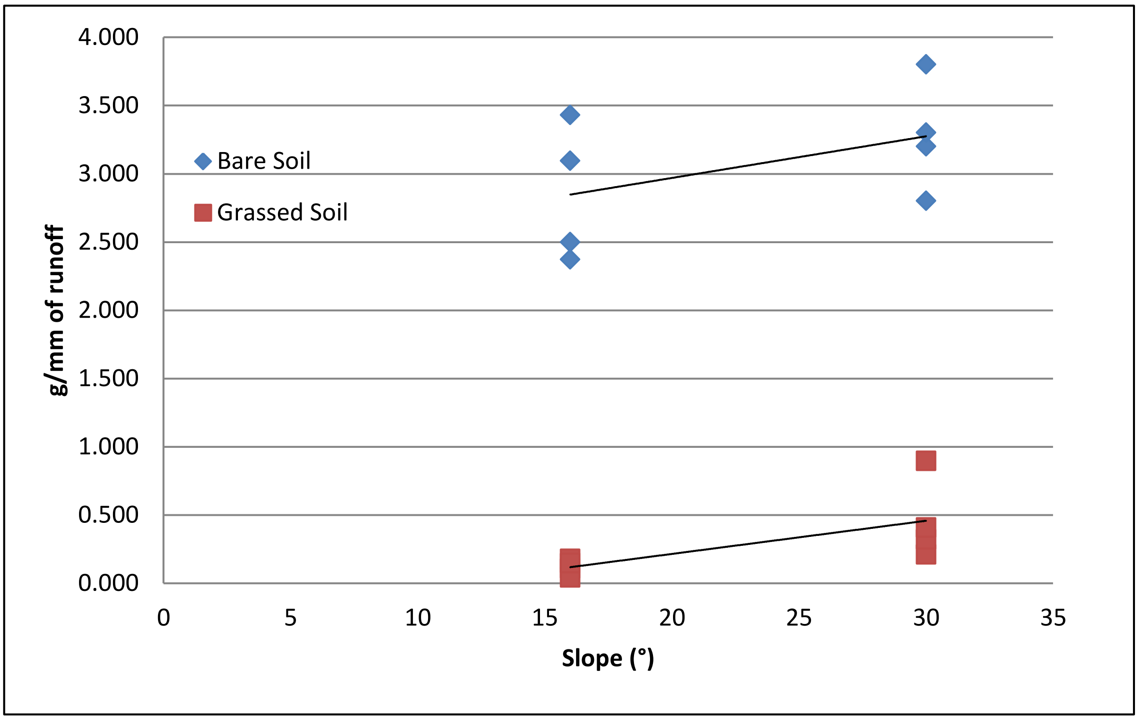


Figure 3.3. The relationship between erosion (g sediment/mm rainfall) and slope, for bare and grassed surfaces under a) 12 and b) 24 mm/hr rainfall

Furthermore, the laboratory experiments only measure sheet erosion and not rill (concentrated flow) erosion. Field observations indicate that there would be areas of concentrated flows which would produce higher erosion rates. The values in Table 3.5 would therefore be best considered as minimum estimates of sediment loss, except for the fact not all of this eroded sediment will actually reach the lake; a large portion of it will probably be deposited further down the slopes.

Table 3.5: Estimated erosion rates for the eastern lake shore, for selected rainfall intensities and slopes.

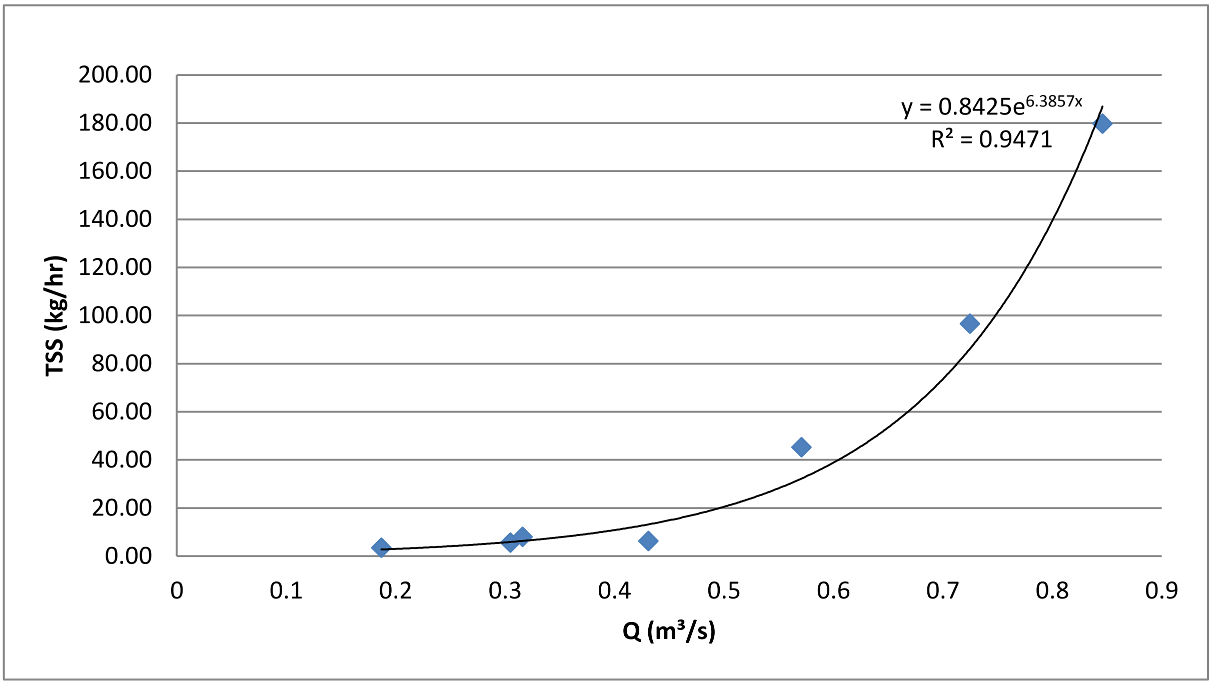
Rain Intensity (mm/hr)	**Slope** (°)	**Eastern Shoreline Total sediment loss** (kg/hr)
Bare Soil Area (51,000 m²)		
12	5	400
12	16 -30	500 – 1000
24	16	7600 – 12,700
24	30	10,300 – 13,000
Grassed Soil Area (45,000 m²)		
12	5	0
12	16 - 30	0 – 90
24	16	20 - 200
24	30	300 - 1000

The experimental runoff results indicate that sediment will likely only be lost from these slopes during rainfall events with an intensity of 12 mm/hr or greater. Over the 2 month study period (December 2012 and January 2013), the highest daily total rainfall was 51 mm which occurred on Dec 7th, and the only other significant rainfall was 28 mm on Jan 3rd. As the Okuti Valley rain gauge doesn't record hourly totals, Akaroa AWS data was used to assess rainfall intensity and this showed that this rarely exceeded 5 mm/hr, peaking at 8 mm/hr on Dec 7th. It is therefore clear that these rainfall intensities were probably not enough to cause significant storm runoff or sediment erosion from these slopes over the study period.

3.4.2. Sediment transport in streams and rivers

Stream discharge (Q) and TSS concentrations can be used to derive a relationship between volume of flow and the volume of sediment being transported. The Okuti and Okana Rivers both have quite strong relationships between these variables; as flow increases so too does TSS (Fig 3.4). Using these relationships the TSS of the peak flows recorded by water level loggers can be estimated.

a) Okuti River



b) Okana River

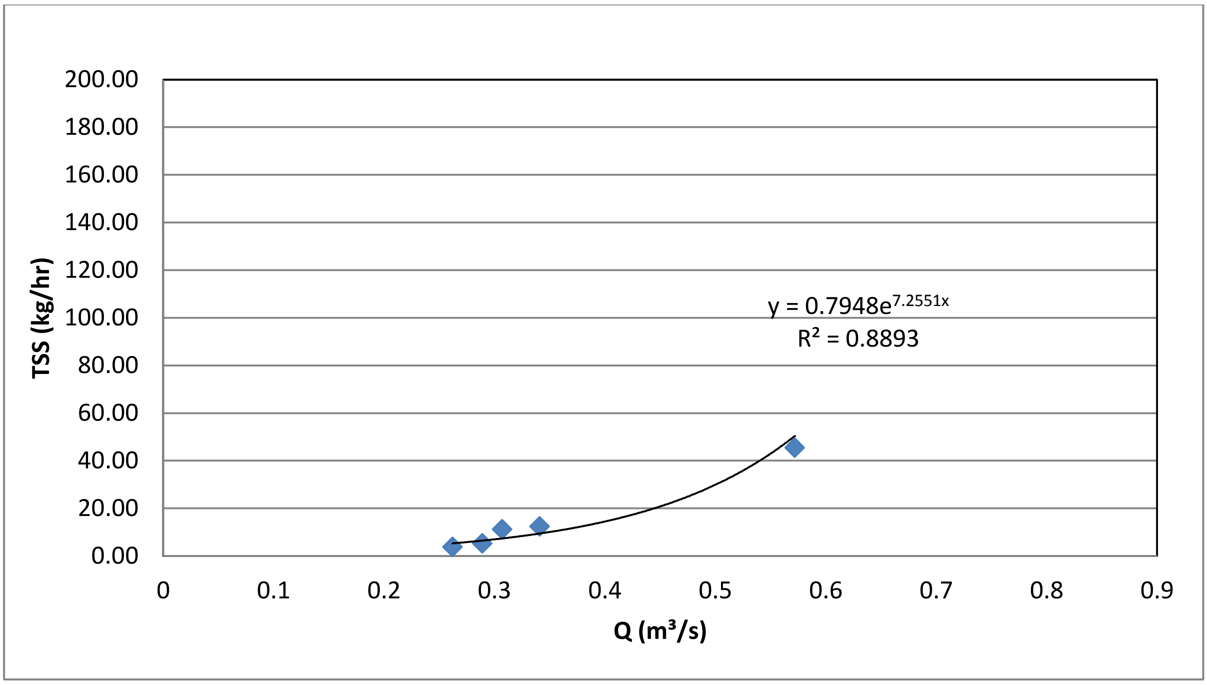


Figure 3.4: The relationship between stream discharge (Q) and TSS concentration in the a) Okuti River and b) Okana Rivers.

As stated earlier, water velocity was not recorded by the water level loggers, and stream discharge is therefore derived from rating curves based on the manual gauging. On Dec 7th, the Okuti River water level peaked at a height of 72.5 cm (Fig 3.5), corresponding to a discharge of between 1.75 and 2 m^3/s. Using the Q-TSS relationship in Figure 3.3, the volume of sediment likely to be transported at that peak flow will be in the order of 900 kg/hr. By accounting for the duration of the ascending and descending limbs of the hydrograph, up from and back down to base flow (8 and 20 hours respectively), the amount of sediment transported down river during this storm flow would have been ca. 13,200 kg. Using this same calculation method, the Okana would likely have been flowing between 3 and 3.5m^3/s during this event, with a suspended sediment load of 2,150 kg/hr and a total of 35,100 kg sediment carried over the entire storm flow period.

Catons Culvert sediment load is harder to estimate due to its ephemeral flow regime. As confirmed by water level logger data (Fig 3.5), the TSS sample of 383 mg/L on Dec 7th was collected on the steeply rising limb of the storm hydrograph. The high TSS concentration reflects the scouring effect a sudden pulse of water would have as it picks up loose sediments within the channel. Had Catons Culvert been sampled for on the descending limb of the hydrograph, several hours later, the value would likely have been much lower, and more data is needed to make a precise estimate of a summer sediment output form this small catchment. However, assuming an average of 383 mg/L over the 4 hr period of intense rainfall as indicated in the hydrograph (11.00-15.00), and the observed peak flow of 0.15 m^3/sec, this corresponds to approximately 830 kg of sediment delivered in this event.

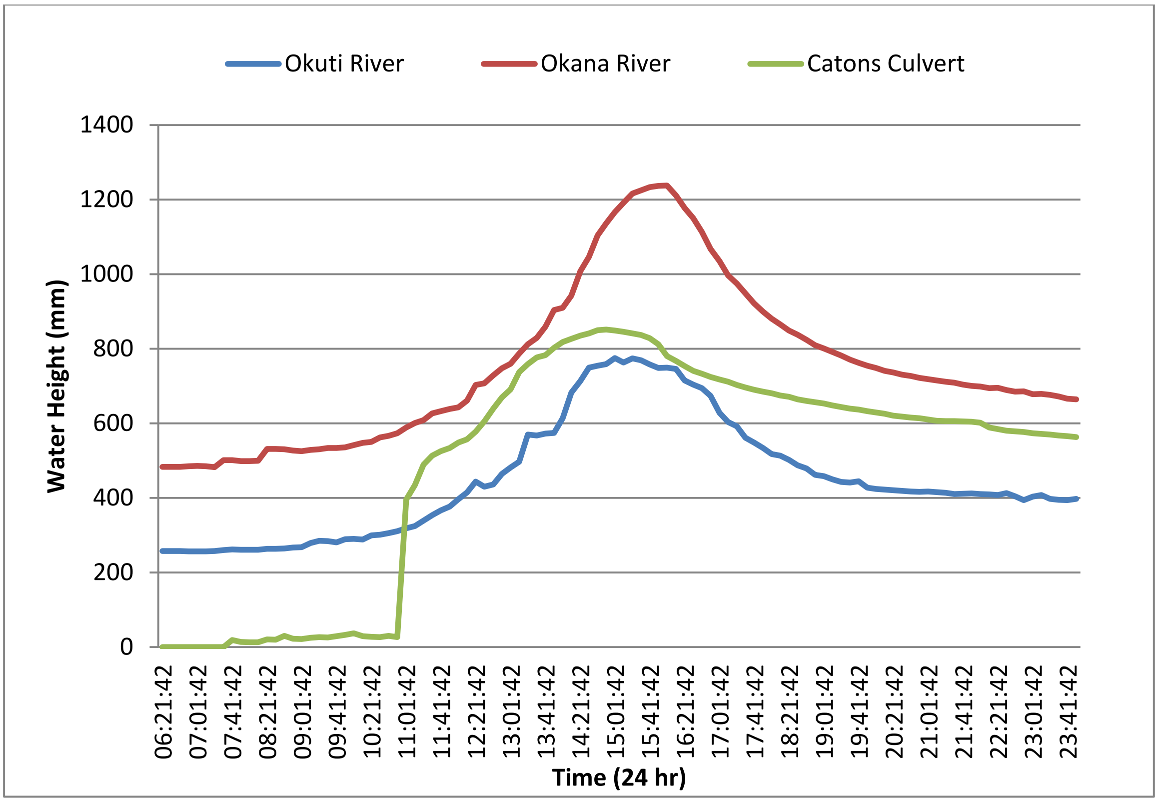


Figure 3.5. Water level logged for the three main tributaries of Wairewa, between 0600 and 2400 hrs on 7th December, 2012.

Because the Okuti River stayed at baseflow for the rest of December and for the whole of January, the base flow sediment load can be reliably estimated for a consistent river flow of 0.31 m^3/s and TSS value of 5.5 kg/hr. Therefore the amount of sediment washed through into the lake during December was ca. 18,000 kg, the majority of which was associated with the Dec 7th storm flow, and in January was 4,500 kg (total 22,500 kg).

Likewise, loads for the Okana River can be estimated as river flow did not deviated far from base flow after the Dec 7thstormflow. The Okana River delivered a December sediment load of ca. 38,000 kg, and a January load of 3,000 kg (total 41,000 kg); the lower base flow sediment contribution from this catchment reflecting the lower TSS content under base flow conditions. This is likely to reflect the morphology of the catchment. Despite draining a larger catchment, the Okana River has a shallower gradient than the Okuti River, and is slower and less turbulent. Suspended solids are more likely to settle out than remain suspended, and this is evident in the channel bed material, which consists mainly of fine silty sediment, compared to the cobbles which make up the Okuti River's bed. However, while the Okana River may carry less suspended sediment per litre of water, the sheer volume of water flowing through the river ensures a sediment load is transported into the lake. Also, due to its larger catchment size, the Okana River is more capable of producing flows of extreme magnitude, as was seen in August 2011 when it inundated Little River.

Finally, rainfall isn't uniform throughout the Wairewa catchment. The different tributaries therefore can respond differently to passing storms.This was particularly evident on December 7th, when Catons Culvert responded faster to rainfall than the both the Okuti and Okana Rivers (Fig 3.4). Between 10.50am and 11.00am Catons Culvert flow rose from 0.05 to 0.15 m^3/s, more than tripling in flow. The Okuti and Okana experienced far slower rises, each reaching peak flow approximately four hours after Catons Culvert. This also reflects the time it takes for water to drain through the larger catchments.

Section 4 Conclusions and Recommendations

4.1 Principal Sediment Inputs to Wairewa in Summer 2012-13.

During the generally low rainfall conditions, and low flows in the rivers at this time of this study, the Okana and Okuti Rivers provided a constant input of suspended sediment to Wairewa. Under summer base flow conditions these rivers would be expected to deliver to the lake approximately 4500-5000 kg/month via the Okuti River, and 3000 kg/month via the Okana River (Table 4.1). Little or no sediment would be delivered via other tributaries or direct runoff from the steep eastern or western slopes of the catchment under low rainfall conditions.

Evidence of the critical role of intense rainfall events in the delivery of sediment to lake has been found in this study. Over 48,000 kg of sediment were delivered to the lake, via the Okuti and Okana Rivers, during a single 50 mm rain event on the 7th December 2012 (Table 4.1). Hence over 75% of the sediment delivered to the lake during the two month period of this study, was delivered in a single rainfall event.

The sediment contribution made by direct runoff from the steep eastern slopes on Dec 7th has been estimated assuming an average slope of 16°, intense rainfall within a 4 hr period (i.e., an intensity of 12 mm/hr), using the data in Table 3.5. The contribution from Catons Culvert is a similarly rough estimate (refer Section 3.5.2) due to the lack of flow data for this stream.

Even given these uncertainties, it can be concluded that the Okana and Okuti Rivers contributed most (>95%) of the 65 tonnes of sediment delivered to Wairewa over this two month period in summer.

Table 4.1 Summary of estimated sediment load (kg) delivered to the lake for December-January 2012-13.

Event	Okuti River	Okana River	Catons culvert	Direct runoff
December base flow	4,800	2,900	0	0
January base flow	4,460	2,980	0	0
December 7th rainfall	13,200	35,100	830?	<2000?
TOTAL	**22,460**	**40,980**	830?	<2000?

4.2. The Role of Vegetation in Preventing Sediment Loss.

Experimental rainfall simulation on vegetated and bare soil, under a regime of variable slope and rainfall intensity, confirmed the important role of vegetation (grass) in reducing both runoff volume and soil loss. Large areas of bare soil currently make up more than half of the surface area of the steep eastern slopes of the Wairewa catchment, due to past erosion of the loosely compacted loess deposits. This area is therefore capable of producing large

quantities of runoff with a very high sediment concentrations during heavy rainfall events. However mobilised sediment doesn't necessarily make it the whole way to the lake from where it was eroded from. By comparison, bare soil makes up a small proportion of the Okuti and Okana sub-catchments.

Revegetation and restablisation of the eroded bare eastern slopes would therefore prevent sediment input to the lake from this part of the catchment. However, the overall analysis of sediment inputs form all subcatchments (Table 4.1) suggests that, in terms of relative input to Wairewa, this would not significantly decrease the amount of sediment entering the lake.

4.3 Limitations of This Study.

The biggest challenge for this study was the lack of rainfall (required to obtain runoff data) during the study period. Summer is Canterbury's driest season and there was no guarantee that any rain would fall during the study period. Summer 2012-13 was typically hot and dry, with daytime temperatures often topping 30°C. January 2013 was Christchurch's sunniest on record. The warm temperatures and long dry spells between rainfall events meant that catchment soil remained very dry through the study period. The rain that did fall was well within the infiltration capacity of most soils and wasn't enough to cause extensive storm runoffor sediment mobilisation through. Although it was good to have had the December rainfall event to sample, more such events would have allowed more representative data to be collected.

Another challenge was the logistics of obtaining samples during and after rainfall. Instantaneous rainfall data wasn't available, so weather forecasts were used to dictate the timing of field sampling. The distance from Christchurch to Wairewa is 60 km, which made a quick response to actual rainfall difficult and an impediment to visiting the field study site "just in case". More data relating to conditions of rising, peak and falling water flows would have been useful.

The lack of rainfall intensity data for the catchment was a shortcoming. Without this data, it is impossible to know whether any of the rainfall events measured would have been intense enough to mobilise sediment from the steep eastern (or western) slopes of the catchment.

Finally, this study related only to summer conditions and is not representative of annual water flow and sediment transportation conditions.

4.4 Recommendations for Future Work

To provide a better analysis of sediment inputs to the lake on an annual basis, the following should be considered;

- GIS and LIDAR mapping of catchment topography to provide a more accurate assessment of slope conditions

- An extended study period, capturing data from the more frequent and more intense winter and springtime storms
- Location of an onsite weather station capable of measuring rainfall intensity
- Installation of automatic water sampling system on the key tributaries to collect TSS samples over high flow events.
- Development and calibration of an erosion model for the Wairewa catchment to identify critical sources of sediment and benefits of best management practices in the catchment.

If combined with an informed assumption regarding the mode of transport of P in the tributaries and direct runoff entering the lake (e.g., 70% of P is bound to suspended sediment), this type of research can provide an initial estimation of amount of P that might be entering Wairewa via surface flow. However, when seeking a solution to the eutrophication problems that have plagues this lake, a thorough determination of a P budget for this catchment is also warranted (e.g., Waters 2013, *in prep*).

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References

APHA (1995) *Standard Methods for the Examination of Water and Wastewater*, Total Suspended Solids Dried at 103°-105° C, Method 2540D, p. 2-56. Published by American Public Health Association, American Water Works Association, & Water Pollution and Control Federation.

Berry, N. & Webster-Brown, J. (2012) *A summer hydrological budget for Lake Forsyth/Wairewa: preliminary findings*, WCFM Report 2012-004, 54 p.

Boffa Miskell Ltd (2006) *Banks Peninsula landscape description and characterisation*, Section B, Banks Peninsula Landscape Study, 27 p.

Davie, T. (2002) *Fundamentals of hydrology*, 2nd edition, Routledge fundamentals of physical geography series, p. 78-89.

Environment Canterbury (2003) *The Okana River: assessment of water quality and ecosystem monitoring, July 1992 to May 2002 and water quality implications for Lake Forsyth/Wairewa*, Technical Report No. U03/20, Environment Canterbury, Christchurch, New Zealand

Fletcher, D. (2007) *Soil erosion control on Banks Peninsula: A bioengineering approach*, University of Canterbury ENNR429 final year project, 56 p.

Land Information New Zealand (LINZ) (2013) *Birdlings Flat*, NZTopo50-BY24, downloaded from http://www.linz.govt.nz/topography

Lynn, I. (2005) *Lake Wairewa/Lake Forsyth: potential sources of phosphorus to the lake*, Wairewa Report Series

McDowell, R. & Condron, L. (2004) *Estimating phosphorus loss from New Zealand grassland soils*, New Zealand Journal of Agricultural Research, 47:2, 137-145

NIWA (2012) *National climate database*, National Institute of Water and Atmospheric Research, accessed online from http://cliflo.niwa.co.nz/ between 29/11/2012 and 21/02/2013

Soons, J., Schulmeister, J. & Holt, S. (1997) *The Holocene evolution of a well nourished gravelly barrier and lagoon complex, Kaitorete 'Spit', Canterbury, New Zealand*, Marine Geology 138, p. 69-90.

Waters, A.S. (2013 *in prep*) *Phosphorus Loading to Lake Forsyth/TeRoto o Wairewa: Preliminary Results for a Lake Phosphorus Budget.* WCFM Report 2014-006.

Woodward, C. & Shulmeister, J. (2005) *A Holocene record of human induced and natural environmental change from Lake Forsyth (Te Wairewa), New Zealand,* Journal of Paleolimnology, 34: 481–501

Whyte, G. (2011) *Wairewa Lake Forsyth Hydrodynamic Modelling*. Presentation for Christchurch City Council. DHI Group.

Waterways Centre for Freshwater Management
University of Canterbury & Lincoln University
Private Bag 4800
Christchurch
New Zealand

Phone +64 3 364 2330
Fax: +64 3 364 2365

www.waterways.ac.nz