RILEY CONSULTANTS

LAKE ROTOMAHANA OUTLET STUDY

Engineers and Geologists

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OUTLET STUDY

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Report Reference:	03108-A
Date:	7 April 2003
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Executive Summary

Study Outline

1. Lake Rotomahana was created in the 1886 Tarawera eruption. The lake occupies the Rotomahana hydrothermal eruption crater, with an area of 9 square kilometres, and a stored water volume of 480 million m³ above Lake Tarawera level.

2. The lake is contained by rhyolite rock and eruption debris which forms a barrier between the two lakes. Lake Rotomahana is about 39m higher than Lake Tarawera; with the barrier effectively forming a dam.

3. The brief for this study was to examine the safety of the barrier for various natural hazards. Breaching of the barrier if it occurred would release a very large volume of water into Lake Tarawera, raising lake levels about 7m. An extremely large flood would result down the Tarawera River. A hydrothermal eruption would also occur in the Lake Rotomahana geothermal field as a result of the drop in lake level.

Risk Assessment

4. An extreme wet period of greater than 1000 years return period was modelled to test the overtopping risk. The existing 600 diameter overflow pipe would be fully discharging, with 2m freeboard to the top of the barrier. This is acceptable.

5. Channels downstream of the pipe may erode with prolonged flows, and will require vigilant inspection during overflow periods.

6. Other hazards to the barrier of sliding, piping and liquefaction were examined and found to have a very low probability of occurrence. The width of the barrier and the non stratified well graded granular materials in the barrier mitigate this risk.

7. The risk of failure due to Seismic disruption or earthquakes is also low. Waves or seiches in the lake could result but are expected to pass over the barrier without major disruption, due to the low gradient on the downslope side.

8. Volcanic eruption is a risk, with eruption frequencies in the Mount Tarawera area at about 2000 – 2500 years.

9. Hydrothermal eruptions from reduction in water pressure or other events causing superheated water to turn into steam and to blow out a crater occur more frequently, and are the most likely event in the near future. Disruption to the barrier is unlikely, but property and lives would be at risk from eruptions in the lake area.

Recommendations

10. The Lake Rotomahana Dam should be considered as a large natural dam of High Potential Impact Classification under the NZSOLD Guidelines.

11. A Monitoring and Surveillance programme should be set up to provide assurance of safety.

12. Particular monitoring is necessary for detection of hydrothermal eruptions in the lake, to provide data on frequency.

13. An Emergency Action Plan should be prepared to allow appropriate actions to be taken if circumstances of concern arise.

Contents

Appendices

LAKE ROTOMAHANA OUTLET STUDY

1.0 Introduction

The following report has been prepared at the request of Steve Everitt on behalf of Environment Bay of Plenty (EBOP). It presents the results of a study into the risks posed by intrinsic or induced instability in the natural divide between Lake Rotomahana and Lake Tarawera.

2.0 Brief

This report is intended to provide the annual probability, along with any uncertainty, of the natural divide being breached as a consequence of various natural geophysical processes.

3.0 Literature Survey

The stability of the1886 eruption material that at present forms a barrier preventing Lake Rotomahana from flowing along its old course to Lake Tarawera has been considered in a number of reports that have been prepared over the past sixty-five years.

A review of relevant files was undertaken on 26 February 2003 at EBOP in Whakatane with the assistance of Steve Everitt.

Files have also been traced to the old Land and Survey Department in Hamilton (now LINZ) and the archives in Auckland. It is believed these contain borehole information following the installation of the overflow pipe in 1972 to approximately 1983. However, due to time and access constraints a review was not possible.

Some key references are listed below:

- Environment Bay of Plenty files 153015/1, 153015/2, 153016/1, 153016/2, 19/4/105, 212004/3
- "Tarawera" - by Ron Keam (1988)
- A report on the "Earthquake Hazards of the Bay of Plenty Region" undertaken by IGNS in 1999.

4.0 Site Examination

A site visit was undertaken on 27 February by Peter Riley and Ross Paterson of Riley Consultants Ltd., Professor Ron Keam of the University of Auckland, and Steve Everitt and Verna Arts from EBOP.

This involved a study walk from the shore of Lake Rotomahana to the shore of Lake Tarawera along the overflow section where the overflow pipe is installed. This is the low point on the barrier where overtopping is likely to occur. The overflow section continues down on to the 'pumice wash' and covers a distance of approximately 1600m.
We were particularly looking at vegetation cover, soil type and potential for erosion, as well as the pipe spillway itself and the valley where the pipe discharges.

The following is a list of some observations made:

- The overflow channel has an entrance level ~3m above present lake level (we estimate this overflow channel level to be at an RL of 342m).
- Approximately 4m above the level of the pipe there is an open area, which is grassed and slopes down over a ~50m width towards the pipe outlet.
- Above the pipe outlet a trench has been excavated in which a notch would form, should the barrier ever overtop.
- The pipe is nearly level, and can be seen through. The pipe diameter was confirmed at 0.6m (2ft).
- Some eroded banks are visible above the outlet on the right hand side showing pumicious sand with some gravel. There was some binding at the topsoil line but not much.
- Beyond the pipe outlet sinuous channels exist that have been cut into the barrier by flowing rain water. There is one main channel from the pipe outlet which is initially 0.5 – 1.0m wide. A few small pools exist in the channel at various points.
- The banks of the channel are standing vertically in places. They are composed of loose pumice sand and base flow ejecta material that is easily eroded. Large water flows of the order of several cumecs would cause substantial erosion to occur.
- Further towards Tarawera the channels reach 4-5m depth and 2m wide and obviously carry water at various times. There are occasional erosion holes in the bottom. There is rock in the channels as a residual deposit from the erosion of the debris from the base surge eruption.
- A borehole (we believe it to be BH5) was located approximately 4m below lake level of Rotomahana, on the flat slope above the channel.
- The vegetation is fairly open with grassy interludes and a substantial number of ti-trees ranging from 2-6m in height.

We also examined the section closer to Mt Tarawera, particularly near the Tarawera eruption memorial. This is the narrowest point between the lakes with a distance between them of only ~650m. Professor Ron Keam reported that water has been heard gurgling through cracks in the rock on the Rotomahana side in the past. The location of this is near the base of Mt Tarawera.

The climb up from Lake Tarawera is gradual but increasing in steepness, with erosion gullies into eruption materials of pumicious gravels and boulders. The eruption memorial is roughly the highest point on the track at 367m (30m above Lake Rotomahana). On the Lake Rotomahana side of the ridge is a deeply incised gully, which drains towards Lake Rotomahana. The vegetation is thicker here than along the overflow section.

On 26 February a brief site inspection of Lake Rerewhakaaitu was made from the roads encircling it. Levels and observations were taken and are discussed in Section 10.0.

5.0 Geology and Formation of the Barrier

The following section is largely from Prof. Ron Keam's notes, prepared after our site visit; and with the benefit of his extensive knowledge of the area.

5.1 Barrier Emplacement

The tephra infilling the former Kaiwaka stream valley between Lake Rotomahana and Lake Tarawera was emplaced within an interval of four or five hours on the morning of 10 June 1886 by the complex phreato-magmatic / hydrothermal eruptions at the site of Rotomahana – with perhaps some minor contributions from other craters along the rest of the Tarawera rift. At its thickest, near the edge of the Rotomahana crater, this material reached a depth of between 40 and 45 metres. The stratigraphy was initially described from a cross-section near the site of Te Ariki village as basal deposits consisting of blocks of rock, evidently derived from the rhyolite mass that occupied much of the eastern shoreline of the pre-eruption lake Rotomahana. Above this was a dry stratum that was a climactic base surge deposit (secondary pyroclastic flow), resulting from the initial hydrothermal explosion at Rotomahana. On top of that was a thick sequence of later pyroclastic flows, largely composed of sandy rhyolitic material derived from the country rock but with a substantial admixture of basalt lapilli. The basal blocks and the dry deposit were evidently both produced by the climactic initial explosion. They were emplaced in the order found because the blocks followed ballistic paths from their places of ejection, while the base surge material was first ejected upwards as an expanding fluidised mass which afterwards fell nearly vertically and then spread laterally in all directions from its region of impact with the land surface. Its path was longer and took longer to traverse than the path of the blocks. Because of its origin this pyroclastic flow was emplaced at hydrothermal eruption temperatures rather than volcanic eruption temperatures. It covered a disc of country with a radius of approximately 6 kilometres centred on the centre of the Rotomahana crater. The uppermost deposit, which is much thicker near the crater edge than the initial base surge deposit, covers a much more limited area, and thins more quickly with distance from the crater.

5.2 History of the Barrier

When first emplaced, the upper surface of the Kaiwaka valley infill was relatively smooth, perhaps with subdued surface manifestations of the wave-like structure, which characterises pyroclastic flows. However, a number of large pools of water on the surface of flat country lying just to the west of the barrier are visible in the first photographs taken on 15 June (1886).[1] There had been no significant rain between 10 and 15 June, so the water had a different origin. The only obvious source is pre-eruption Lake Rotomahana. Evidently much of this took no active part in the eruption and was simply bodily lifted and dispersed over the surrounding country. Because it was afterwards seen on the surface is not certain evidence that it was emplaced last - the volume of water was considerable and it could have been expressed onto the surface during compaction of the deposit as fresh material was added during the course of the eruption.

[1]See *Tarawera*, illustrations 18/3 (p.216), 29/12a (p.315). Both photographs by C. Spencer, 15 June 1886.

The upper surface of the barrier deposit sloped (and slopes) gently down to Rapatu Bay, almost 2 kilometres distant, beside the site of the overwhelmed village of Te Ariki. In most places the surface of the new deposit had a consistency like mud, and for months was to become the bane of explorers attempting to traverse it. It was originally reported that the surface was cracked as if by earthquakes and that the floors of individual cracks provided firm walking in the direction of Te Ariki.[2] It is considered that "earthquake" cracks were instead shallow erosion channels cut by the flow of former lake water that had fallen and been expressed in this locality and then moved downhill towards Rapatu Bay, and that it was the resulting alluvium on the channel floors that had provided the convenient pathways. On the afternoon of the same day, the Lake Tarawera rescue expedition reached the shoreline in Rapatu Bay. Its members reported that the lapping of the lake against the toe of the new deposit had already cliffed it and provided a narrow submerged beach where they were able to land. The cliffs were already about 10 metres high and unscaleable at the lake edge. However, there was a small stream of warm water issuing from a valley and debouching into the lake. Not knowing the full extent of the changes wrought at Rotomahana, they took this to be the buried Kaiwaka stream and ironically to some extent they were correct. It was undoubtedly former Rotomahana lake water deposited further up the slope and here emerging at the toe of the deposit after filtering through to its distal end. Headward erosion was occurring as a result of this "piping" and a couple of expedition members were able to follow up the little valley almost 300 metres and clamber up its walls sufficiently to enable them to see across the upper surface of the deposit and convince themselves that all the inhabitants of Te Ariki must have perished.

A good photograph looking down to Rapatu Bay on 27 July 1886 shows the barrier surface to have then been smooth, apart from a myriad of minor erosion ditches and fewer, more widely spaced, more deeply entrenched channels. Over the course of the next fifteen years, erosion of the deposit proceeded apace and produced a large delta of redeposited material that completely infilled the part of Rapatu Bay that had once extended in front of Te Ariki. The slope along the course of the former Kaiwaka stream provided the main access route for tourists seeking to satisfy their curiosity about the topographic changes at Rotomahana caused by the eruption. In 1903, when the "Government Round Trip" was inaugurated, this for a time became the regular route for guided parties. Photographs show that the valley fill had been eroded out to a considerable depth along much of its lower length, but that the floor of this had then been infilled again with alluvium so that the net level was perhaps 3 to 5 metres below the original level of the post-eruption surface. The upper parts of the slope were only slightly eroded, consistent with the local catchment being of very small extent.

By the 1930s and 1940s vegetation became re-established to the extent that when Ron Keam first visited the area in 1951 there was a more or less complete cover and one had to push through ti-tree scrub generally about 2 metres high when traversing the northern side of Lake Rotomahana. At the actual saddle, whose location was ill-defined, there was a coverage of grass between the ti-tree trees and walking in its near vicinity was consequently a little easier. In our visit vegetation had matured with sporadic ti-tree 7-10m high, and a lot of lower scrub. The pumice outwash fan was sparsely vegetated.

[2][Morgan, J.], *Otago Daily Times*, 18 June 1886, p.3 col.3; See also *Tarawera*, pp. 234-235

6.0 Hydrological Risk of Lake Rotomahana Barrier

6.1 Lake Characteristics

Lakes Rerewhakaaitu and Rotomahana are bounded on their northern sides by barriers of volcanic debris deposited by Mount Tarawera and the Rotomahana crater.

Lake Rerewhakaaitu has an area of 5 square kilometres, an elevation of approximately 435 metres, and a level range of about 2 metres. This lake is almost landlocked, but high lake levels can drain via twin culvert pipes to the Mangaharakeke Stream. The barrier between Lakes Rerewhakaaitu and Rotomahana has a crest level approximately 8 metres above the lowest ground level on the Mangaharakeke Stream side at Ash Pit Road.

Lake Rotomahana has an area of 9 square kilometres, an elevation of approximately 337 metres, and natural operating range of about 8 metres. This lake is landlocked, but very high lake levels can drain via a culvert pipe into Lake Tarawera. The barrier between Lakes Rotomahana and Tarawera has a crest level at the saddle of 344.7 metres, approximately 7.7 metres above the normal Rotomahana Lake level.

Lake Tarawera has an area of 41km², at an elevation of approximately 298 metres. This is 137 metres below the level of Rerewhakaaitu, and 39 metres below the level of Rotomahana. The barrier between Lakes Rotomahana and Tarawera is relatively narrow, permeable, and may be vulnerable to erosion in the event of overtopping.

The risks of the barrier failing due to overtopping erosion or slope instability are assessed as part of this study. Any sudden catastrophic failure of the barrier would result in a "dam-break" situation, with the contents of Lake Rotomahana discharging into Lake Tarawera, and potentially causing flooding along the lower Tarawera River.

6.2 Catchment Characteristics

Lake Rerewhakaaitu has a catchment area of 70 square kilometres including the lake. The catchment consists of part of the south-eastern slopes of Mount Tarawera, foothills in the vicinity of the Rerewhakaaitu settlement, and a relatively flat area at the foot of Mount Tarawera.

Lake Rotomahana has a catchment area of 83 square kilometres including the lake. The catchment consists of part of the south-western slopes of Mount Tarawera, and foothills in the vicinity of the Rotomahana Settlement.

The greater parts of both catchments are farmed, with the exception of the Mount Tarawera slopes which have native vegetation cover, and some plantation forestry in the Crater Road area.

Mount Tarawera has a maximum elevation of 1110 metres, and the foothills adjoining the lakes have a maximum elevation of approximately 600 metres.

6.3 Hydrology

The following hydrological records (refer Table 6.1) have been obtained for use in this study.

Table 6.1 - Available Hydrological Data

Site Number	Site Name	Type	Period of Record	Source
15301	Lake Tarawera at Te Wairoa	Lake Level	1925 to 2003	EBOP
15308	Lake Rerewhakaaitu at Awaatua Bay	Lake Level	1952 to 1982	EBOP
15338	Lake Rotomahana at Crater Bay and Waimanpu landing	Lake Level	1924 to 2003	EBOP
861204	Whakarewarewa	Daily and automatic rainfall	1899 to 1997	NIWA Climate
861301	Rotorua Airport	Daily rainfall record	1963 to 1992	NIWA Climate
861301	Rotorua Airport	Daily raised pan evaporation	1972 to 1992	NIWA Climate
861303	Rotorua Airport AWS	Daily rainfall record	1982 to 2003	NIWA Climate
861303	Rotorua Airport AWS	Daily Penman estimated potential evapotranspiration	1991 to 2003	NIWA Climate
863401	Waiotapu Forest	Daily rainfall	1901 to 1997	NIWA Climate
864501	Kaiangaroa Forest	Daily rainfall	1929 to 1999	NIWA Climate

Rainfall records have been assessed at the combined Rotorua Airport sites (1963-2003, approx. Map. Ref. U16:010384) and at the Whakarewarewa (1899-1997, Map. Ref. U16:960327) and Waiotapu Forest (1963-2003, Map. Ref. U16:093155) sites. They have been compared over the concurrent period from 1964 to 1996, and show fairly close agreement on an annual basis with minimum, mean, and maximum annual rainfall totals of around 950mm, 1400mm and 2000mm respectively. Maximum monthly rainfalls do not vary significantly between the three sites, with a range of 340-360mm.

On this basis, and due to its closer proximity to the study area, the Waiotapu site (No.863401) has been chosen to assess the response of Lakes Rerewhakaaitu and Rotomahana.

Whilst there are some very long records above, the concurrent periods of rainfall, evapotranspiration, and lake level data are limited to the 1972 to 1982 period (inclusive).

This period of record has been used to calibrate the water balance model, which has been developed to simulate the lake response, in particular the nature of the seepage from Lake Rerewhakaaitu to Lake Rotomahana. For the period where raised pan evaporation data was collected, this has been converted to evapotranspiration by multiplying by a factor of 0.7 (Linsley, Kohler and Paulhus).

6.3.1 Design Approach

The 3-year rolling average 0.001 Annual Exceedance Probability (AEP) event (1000-year Average Recurrence Interval, ARI) has been chosen as a starting point for assessing the lake levels for Rotomahana, as described in the EBOP brief of 16 October 2002. Discussions with Peter Blackwood have confirmed that the hydrological risk shall be assessed within the water balance model as follows:

- Starting lake level equals 3-year rolling average 0.001 AEP event
- 12-month 0.001 AEP rainfall and evapotranspiration data applied to the calibrated water balance model with the above starting lake levels. Monthly totals to be weighted using the long-term mean distribution of rainfall and evapotranspiration as shown below in Figure 6.1.

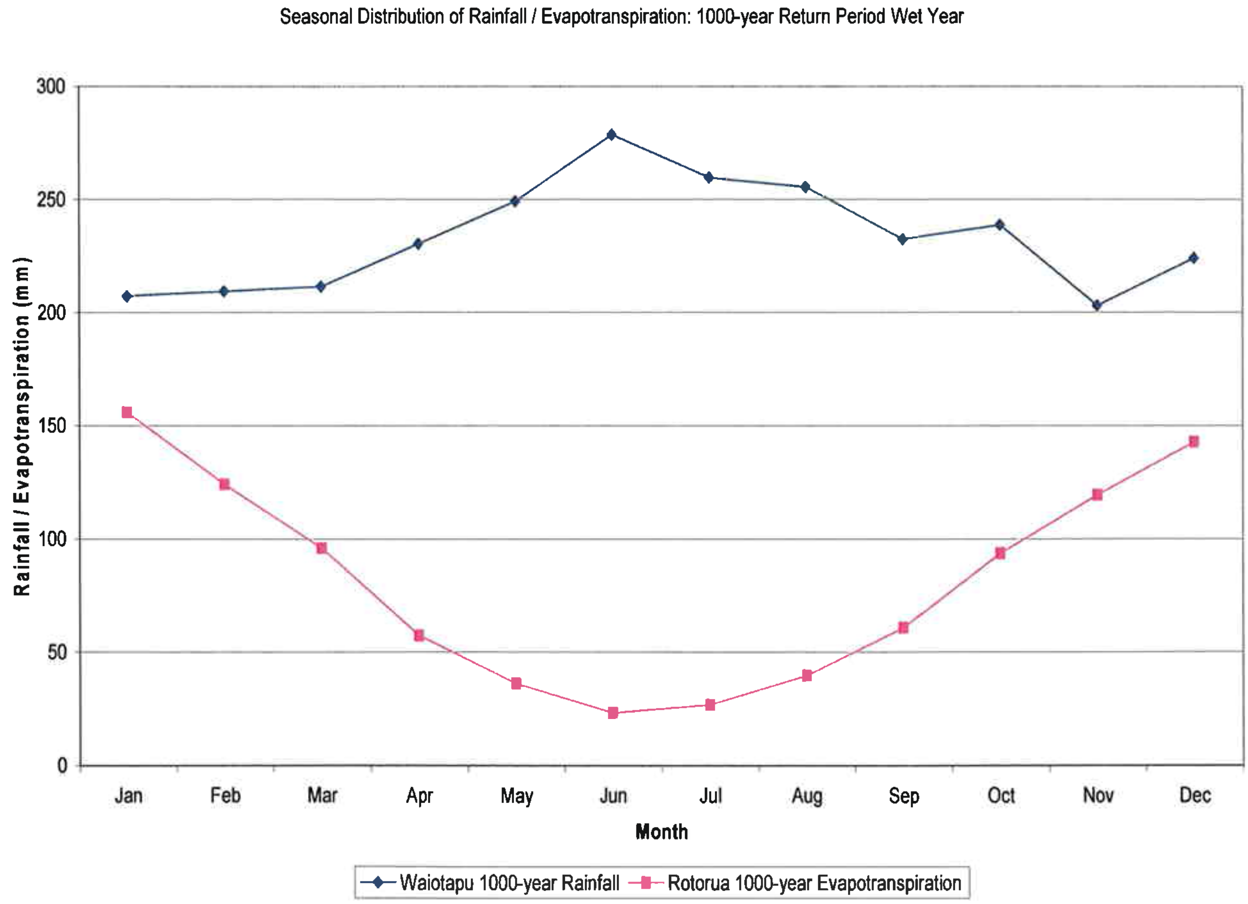


Figure 6.1: Seasonality of Rainfall and Evapotranspiration (0.001 AEP)

6.4 Water Balance Model

Simple water balance models were developed for both the Rerewhakaaitu and Rotomahana Lakes.

These models used Excel calculation spreadsheets, and included terms for catchment rainfall, evapotranspiration, soil moisture storage, and losses to groundwater; as well as lake seepage losses, evaporation, and culvert outflow drainage; and lake level versus storage relationships.

The data used for model calibration were the concurrent records from January 1972 to 1982, along with Waiotapu Forest rainfall, Rotorua Airport evapotranspiration, and Rerewhakaaitu and Rotomahana lake levels.

Lake evaporation was taken as equivalent to the estimated evapotranspiration (Linsley, Kohler and Paulhus). The available catchment soil moisture storage figure adopted was 75mm, and culvert flow versus lake level relationships were included for both lakes.

Lake Rerewhakaaitu has twin 1000mm diameter pipes at an assumed invert level of 436.5 metres (EBOP to confirm the invert level of this outlet). This level was adopted as it was consistent with long term lake levels, and gave very good results for the model calibration (refer Section 5).

Lake Rotomahana has a single 600 mm diameter outlet pipe of 150 metres length. The existing invert level is 340.43 metres, and an effective flow threshold level of 341.2 metres was adopted for the 1972 to 1982 calibration period, during which the culvert was assumed to be stoplogged forming a low weir at the culvert inlet.

The time interval adopted for the models was monthly. Effective catchment monthly rainfall was calculated as rainfall, less evapotranspiration, less the change in soil moisture storage.

The effective monthly rainfall was multiplied by the catchment area (excluding the lake), and a calibration factor was then applied to allow for losses to groundwater. The lake evaporation, seepage losses, and culvert outflows were then subtracted to give a change in lake storage volume. This change in volume was then related to the lake level for the previous month, using the lake level-storage relationship, to give the modelled lake level for the current month.

6.5 Model Calibration

To bring modelled levels into line with observed lake levels, a calibration factor of 0.2 was applied to allow for catchment losses to groundwater. Also an average lake seepage outflow of 0.32 cumecs was applied for Lake Rerewhakaaitu, and a net lake seepage outflow of 0.55 cumecs was applied for Lake Rotomahana. Allowing for the average seepage inflow from Rerewhakaaitu, the total average seepage outflow from Rotomahana is therefore estimated at 0.87 cumecs.

Appendix 1 shows the water balance model inputs and outputs for both Lakes Rerewhakaaitu and Rotomahana for the period from 1972 to 1982.

The Rotomahana lake levels over this period show a very good fit between recorded and modelled lake levels. The lake levels at the start and end of this period have been modelled, as have the overall amplitude and timing of rises and falls. The modelled results over the final 8 years of the period give an excellent fit, with typical variance in level of up to 0.2 metres. The fit for the first 2 years of the record was not as good, with peak levels underestimated by up to 0.4 metres.

The Rerewhakaaitu lake levels show a very good fit between recorded and modelled lake levels. The lake levels at the start and end of this period have again been modelled, as have the overall amplitude and timing of rises and falls. The modelled results over the first three years give a good fit, with peak levels overestimated by up to 0.4 metres. For the remaining 7 years of record a very good fit was achieved, with maximum variance in level of up to 0.2 metres.

Overall the model results reproduce actual lake levels with a very good level of precision, with overall model errors expected to be in the range of plus 0.2 to minus 0.4 metres for Lake Rotomahana, and plus 0.4 to minus 0.2 metres for Lake Rerewhakaaitu.

6.6 Modelling of Extreme Event

The Excel model was then used to estimate lake levels resulting from an extreme annual rainfall event superimposed on historically high starting lake levels. The extreme rainfall event chosen was a 1000-year return period annual rainfall distributed on an average seasonal monthly basis.

Waiotapu Forest rainfall and Rotorua Airport evapotranspiration figures were estimated for a 1000-year return period. Initial levels of 437.4 metres and 342.0 metres were chosen for Lakes Rerewhakaaitu and Rotomahana respectively. Agreement on these starting levels was reached with Peter Blackwood (EBOP) prior to modelling the extreme event.

Appendix 2 shows the water balance model inputs and outputs for both Lakes Rerewhakaaitu and Rotomahana for the 1000-year rainfall event. The maximum level produced for Lake Rerewhakaaitu was 437.6 metres, and for Lake Rotomahana was 342.5 metres.

In the case of Lake Rerewhakaaitu the 1000-year level lake level would be expected to surcharge the outflow culvert, but have a freeboard of approximately 0.4 metres with respect to the Ash Pit Road crest level of 438.0 metres. As Ash Pit Road has a long overflow length, and the barrier to Lake Rotomahana is some 6 metres higher, overtopping into Lake Rotomahana can not occur.

In the case of Lake Rotomahana, the 1000-year level lake level would be expected to surcharge the outflow culvert, but have a freeboard of approximately 2.2 metres with respect to the barrier crest level of 344.7 metres. The annual risk of overflow from Lake Rotomahana is less than the 0.001 AEP criteria set by the EBOP. Wind set-up, wave action, and culvert blockage are factors which could reduce barrier freeboard, but the 2.2 freeboard gives a margin for such events.

6.7 Hydrological Risk

The risk of overtopping therefore appears low. However, monitoring of the barrier will need to be increased at high lake levels.

7.0 Geotechnical Risk of the Barrier

The barrier separating Lake Rotomahana from Lake Tarawera can be considered as a natural dam. This dam is 45m high, and 2000m through at Lake Tarawera level; measured along the overflow channel. At the narrowest point of the barrier near the Tarawera Eruption Memorial, the dam is 67m high and 900m through at Lake Tarawera level. Sections through the barrier at these points are shown on drawing 03108-1.

7.1 Erosion Potential of the Barrier

7.1.1 Old Kaiwaka Stream Valley

The original Kaiwaka Stream had a low gradient through the barrier. Maori canoes could traverse the stream over some rapids. Given the length of the stream at about 2km, it is likely that the change in level along the stream would have been no more than two metres; and probably less than one metre.

Historical records indicate that the valley was flat-floored but quite steep sided. The explosion debris, including blocks of rhyolite from the sides of the eruption crater would have been emplaced into the stream valley filling it with granular material ranging from boulders through gravels and sands to silt size material. All of this would have been chaotically mixed. The material when deposited would have been 100° to 200° in temperature. This is of course not sufficient to weld the material.

Run off from heavy rainfall on the barrier has created stream channels on the downstream side. These have generally followed the old Kiawaka Steam Valley which would have been a natural depression resulting from consolidation of the volcanic surge debris.

The course of the stream has formed a classic profile which the steeper gradient at the top end just below the high point at about 3.4% gradient over the first 500m. This gradient then gradually flattens out and is about 2% down towards Lake Tarawera.

We examined the channels the stream is flowing in. At the top end the channels are very sinuous which creates a flatter gradient by making the stream course longer. The channels are also armoured at the bottom by boulders of rhyolite which have fallen from the banks with erosion. These form a very rough course. There is little evidence of erosion of the channel under present conditions.

At the lower end where the flows are much larger, the gradient is less and there are deposits of finer sandy materials.

Although there had been significant overnight rain, on the day of our visit no water was flowing in the streams.

We conclude that the stream is at a natural gradient in accordance with the flows that it is carrying. This concurs with the opinion of Jim Healey, Government geologist in his 1954 report.

It is particularly important to note that the gradient of the channel is low downstream of the pipe outlet. This low gradient has been created by the excavation of the pipe running out almost horizontally to join the channel systems. In the event that the pipe were to discharge, the initial flows would be over this low gradient section, reducing erosion potential.

In an overflowing event, frequent observations would need to be made of the channel down stream of the pipe to keep for evidence of the headward erosion of the channels. A monitoring schedule will be needed for high lake level events.

7.1.2 Narrow Section near Tarawera Memorial

This section of the barrier is about 650m across between Lake Rotomahana and Lake Tarawera. The track from the Rapatu Bay on Lake Tarawera to Lake Rotomahana crosses this section.

We went across this section and examined the ground on either side. The ground is rockier than further to the west with the ridge likely to be underlain by rhyolitic rock. The land also rises considerably with the Tarawera Memorial being about 25m above lake level. This high ridge continues along the barrier.

There are some deep erosion gullies on the Lake Rotomahana side but these are now heavily vegetated.

On the downstream Lake Tarawera side erosion gullies are also present but are similarly heavily vegetated and have no obvious erosion scars heading back towards lake Rotomahana.

At the time of our visit water courses were examined and no running water was observed. We consider there is negligible risk of breach in this section.

7.2 Breach Flood

None of the scenarios we have considered indicate that the barrier will be breached. As part of this report we have considered the effects of a breach of the barrier. The most likely breach scenario is by overtopping at the low point above the outlet pipe.

We have considered the infilled Kaiwaka Stream Valley as a dam. The height of this dam is 45m. The width of the dam in an upstream downstream direction is 2000m.

If this dam were to breach, the volume of water realesed from Lake Rotomahana would be in the order of 320 million m^3. (Refer to Appendix 3 – Lake Volume Curves)

We have calculated the peak outflow from this breach using the USBR Dam Safety Research Report: DSO – 1998 – 4 July 1998. This calculation, using the Froelich equation gives a flow of 19,000m^3/sec at the peak of the breaching. The breach time has been calculated at three and a half hours to develop. Effectively the lake would empty in about 4 hours from the time breaching was initiated.

This short time interval means that the level of Lake Tarawera would be raised by about 7m. Flows through its outlet of from 1500 to 4000m^3 /sec are likely to result. These figures would need to be checked by flood routing calculations.

The extreme consequences of such an event emphasize to the importance of managing the risk with civil engineering and monitoring, as would be done for any high hazard dam.

7.3 Groundwater Levels

The highest groundwater readings discovered in the files were taken on 13 December 1971 when Lake Rotomahana was close to its highest recorded level of 342m.

BH1 - 6.0m below ground surface

BH4 - 9.3m below ground surface

BH5 - 14.0m below ground surface

These levels establish the moderate permeability of the barrier. Of particular interest is the apparently steep gradient close to lake Rotomahana – see drawing 03108-1. Establishment of this profile is probably due to deposition of finer materials on the lake bed, decreasing permeability. The curved phreatic line also indicates a deep aquifer. The curved phreatic line also indicates a deep aquifer. Groundwater levels are also well below ground surface – also conducive to reducing piping risk.

One report on the barrier in 1948 refers to "one large spring just north of the launch landing, Lake Tarawera" and that judging by the colour of water it is "definitely an overflow or direct channel seepage from Rotomahana". No evidence of outflow from this source was found during our inspection.

7.4 Sliding of Barrier

The barrier is constructed of granular volcanic material of high frictional characteristics. Groundwater levels in the barrier are low with groundwater 5 to 7m below ground surface in the upper areas of the barrier close to Lake Rotomahana.

The surface slope of the barrier is also very low at about 1:33 down stream slopes. This is a very low angle for a dam; particularly one constructed of granular materials.

It is our opinion that there is no risk of slope failure of the crest of the barrier or of the barrier as a whole.

7.5 Piping Risk

International statistics on dam incidents indicate that 2% of embankment dams have experienced a piping incident. In New Zealand a number of piping incidents and failures have occurred in volcanic materials mostly within the Taupo Volcanic Zone.

Seepage and internal erosion may lead to piping and a breach of the barrier. For piping to occur, materials which are susceptible to piping need to be present. Hydraulic gradients also need to be high, with a continuity of susceptible materials through the section.

We have used an approach produced by recent research of piping for dams from Australian engineers to estimate the risks. Although the Rotomahana barrier is a natural dam the concept is applicable. In this the process of internal erosion and piping is broken up into four phases: initiation of erosion, continuation of erosion, progression to form a pipe and formation of a breach.

As well as this the following points are also relevent:

- The Rotomahana barrier has survived intact with a lake behind it for approximately 100 years. About 64% of piping failures on dams occur on first filling or in the first five years of operation.
- The rapid emplacement of infill material creates a mixed granular fill without stratification.
- Initiation of erosion is only likely at a free surface.
- Earlier groundwater monitoring, and our observations, show that groundwater is below ground level on the downstream side of the barrier.
- Hydraulic gradients are also low at 0.028 average for the overflow section and 0.06 average for the Tarawera memorial section. No dam has failed with a hydraulic gradient of <0.1.
- There are no obvious signs of any large seeps.

From these observations, our assessment of the risk of piping failure can be considered as very low. At times of high lake level, above 340m, inspections of the downstream side of the barrier should be made to look for evidence of seepage.

8.0 Volcanic and Geothermal Risks

The study area is in the Okataina Volcanic Centre located within the central Taupo Volcanic Zone in the North Island. Within this region volcanism has been overwhelmingly rhyolitic and concentrated in a number of caldera centres, such as Haroharo Caldera at Tarawera.

8.1 Volcanic Eruptions

In the last 25,000 years there have been 11 major eruptions identified in the geological record from the Okataina Volcanic Centre – or one every 2,000 to 2,500 years on average. Smaller events may well be more frequent but definitive information on such is lacking.

Table 8.0: Okataina Eruption

Eruption	Radiocarbon Age	Volume (cubic km)	Repose Period
Te Rere	20700	10.5	7000
Okareka	18000	10	3200
Rerewhakaaitu	14700	8	3900
Rotorua	13450	8	1500
Waihau	11250	18.5	2400
Rotoma	8860	15	3500
Mamaku	7390	21	1750
Whakatane	4830	19	2550
Rotokawau	3440	0.7	1900
Kaharoa	650	7.5	3100
Tarawera (1886)	64	2	540

Much larger eruptions such as the Matahina ignimbrites are also evident further back in the geological record producing 100's of cubic kilometers of erupted material.

The main sites of activity have been the Haroharo region north of L. Tarawera and the Mt Tarawera region. The average return period for the Tarawera complex is about 4000 years, but as is seen from the Kaharoa/Tarawera1886 gap that particular time interval was much less.

Only a local eruption event, such as the 1886 eruption of Tarawera, would be likely to cause a breach of the divide.

8.2 Geothermal Risk

The Rotomahana barrier lies within the boundary of the large region that stretches from the southern shore of the Ngutuahi arm of Lake Tarawera south-south-westwards to Waiotapu (and probably beyond to Reporoa), where there are wide-spread surface manifestations of hydrothermal activity. While distinct separated concentrations of surface activity exist, there are good reasons for believing that this whole region has connected or contiguous geothermal aquifers at relatively shallow depth. At some places here thermal activity is, or has been, among the most intense in the Taupo Volcanic Zone: hydrothermal eruptions have frequently occurred in historic times, and the geological record provides ample evidence that this pattern is a continuation of behaviour that has characterised the region for many thousands of years. Thus one needs to consider the risk of the Rotomahana barrier being breached either directly by a hydrothermal eruption at its location, or indirectly through a nearby hydrothermal eruption destabilising the barrier material. These two possibilities and also the consequences of sudden barrier overtopping are addressed in the following paragraphs.

8.2.1 Local Eruption

Hochstetter's pre-eruption map of Rotomahana and its environs[3] shows that hot springs cropped out alongside the Kaiwaka stream from its source in Rotomahana to below its confluence with the Awaporohe stream (from Rotomakariri lake) and at least as far as the start of the rapids along its course towards Te Ariki. By inferring distances from the map one sees that surface activity was manifest to at least 1 kilometre north-north-east of the northern end of the White Terraces. Therefore, part of the area that exhibited surface thermal activity before the 1886 eruption extends well beyond the northern boundary of the 1886 crater. Thus, in this vicinity the hydrothermal system at this site (namely that part under the present barrier) was sufficiently stable not to take part in the 1886 upheavals. It now has a load of pyroclastic material 40 to 45 metres thick lying on it, and this is likely to have enhanced its stability against a hydrothermal eruption at this location. In the absence of any present obvious manifestations of hydrothermal activity there, or anywhere else along the barrier, it would seem highly improbable that a hydrothermal eruption would occur in the barrier region itself unless this were part of a much larger event on a scale comparable to that of 1886.

[3] Hochstetter, F.von, and Petermann, A., *Geological and Topographical Atlas of New Zealand*, 1864

8.2.2 Non-Local Eruption

The Rotomahana / Waimangu area has a long history of hydrothermal eruptions since 10 June 1886 outburst. Only those in the near vicinity of the Rotomahana crater will be considered here.

Hydrothermal eruptions from places within the Rotomahana Crater continued for many weeks after 10 June 1886 eruption. Most of these were relatively small, but at times they reached significant proportions and were a danger to explorers in their close vicinity. On 8 July 1886 a party of four had been approaching the edge of the main crater when it burst into activity in the strongest recorded upheaval to disturb the area in the volcanic eruption aftermath. The party escaped uninjured but shaken by their experience.[4]

Late in July 1886 an outbreak occurred outside the Rotomahana Crater about 1 kilometre to the west-south-west of the saddle. Its site lay close to the pools of water appearing in the C. Spencer photographs that were used as illustrations 18/3 (p.216) and 21/12a (p.315) in *Tarawera*, and indeed illustration 34/2 (p.354) by photographer F.A. Coxhead, shows the new vent erupting. Between 10 June and when this formed, there had been some weak fumarolic activity in its near vicinity. It was regarded by S.P. Smith as having broken out close to the site of one of the lesser pre-eruption Rotomahana hot springs whose sinter apron was dark in colour. The new crater was therefore christened "Black Terrace Crater".[5] Its activity lasted a few weeks, at the end of which time it partly filled with water and hosted a small circular lakelet. In time, erosion of the barrier between Black Terrace Crater and the Rotomahana Crater led to the two amalgamating, and later the site was buried beneath an accumulation of sediments. Currently the site lies right at the lake edge where a main sediment wash debouches into Rotomahana.

The Rotomahana Crater rapidly filled, dominantly from rainfall within its catchment, and by 1900 the new Rotomahana lake was well formed. Although then probably about 5 - 8 metres lower in level than at present, its main features were well established and these can easily be recognised in photographs and identified in comparison with the modern natural scene. A length along about 1 kilometre of what became the lake's western shoreline had exhibited intense hydrothermal activity since 1886, and from 1901 (when visitor numbers increased as a result of Waimangu Geyser forming) there were several reports of geysers, small and large, breaking out there. Most of the rest of lake Rotomahana showed no sign of thermal activity beyond having a scattering of localities where bubbles of gas rose to the surface. Whether any water entering through the lake-bed at the sites where this gas enters is hot has not been determined, except along the western shoreline where the concentrations of vigorous onshore thermal springs have been matched by pronounced offshore thermal activities. Geysers appear from time to time close above the shoreline. They do not usually persist for intervals of the order of decades because of fluctuating lake levels on this time scale.[6] Their water supply fails if the lake falls too far, or the vents are submerged if the lake rises too far. These features generally do not suffer permanent failure, however, and usually revive if the lake returns to a favourable level.

Lake Rotomahana remained turbid until the 1940s, but had cleared by 1951. Apart from small fractures near its eastern extremity leading through to springs near Lake Tarawera, Rotomahana has been without a natural outlet, with its level being quite variable and responding in the expected way to natural meteoric influences.[7]

[4]See *Tarawera* pp. 261-262

[5] Smith, S.P., *The Eruption of Tarawera, New Zealand*, 1887, p.59

[6] See, e.g., Grange, L.I., *The Geology of the Rotorua-Taupo Subdivision*, 1937, p.38.

[7] Taken from G. Mair, his caption states: "The surplus waters of Lake Rotomahana running into the end of big rift at west of Tarawera Mt 100 feet below self sitting on the Pinnacle Rock."

Although a general rise in lake level has occurred during the last century, this has slowed and perhaps has now ceased, and there have been several periods during which falls in level have persisted for years. Falls in level reduce pressures on submerged hydrothermal discharge features and can induce hydrothermal eruptions. Whether or not one can attribute them to such falls in lake level is uncertain, but there have been two quite large hydrothermal eruptions from submerged localities close to Rotomahana's active western shoreline. The first was in 1926 when a small tsunami / surge was produced and caused some alarm at the time.[8] However, nothing further happened and the incident became largely forgotten. In June 1951 there was what seems to have been a larger eruption. Its vent seems to have been a little offshore in what is informally called "Fumarole Bay", and happened only a few weeks after the author (R.F.K) and E.F. Lloyd explored the thermally active onshore springs there. A description of this eruption has been published in *Tarawera*.[9]

There is every reason to believe that hydrothermal eruptions from time to time will occur again from similar localities within Rotomahana. With the energy content of the hydrothermal system being enormous – enough, indeed, to have produced the climactic event of the1886 eruption – one cannot put a reasonable limit on the magnitude of any individual event. The energy is there awaiting triggering from what could be an apparently inconsequential event or even continuous processes. The magnitude is determined by local conditions in the lake bed and substrata. The only consolation is that the history of hydrothermal systems indicates that small events are much more common than large events. But since there have been only two known significant hydrothermal eruptions in the last 100 years the information available is insufficiently reliable to forecast the likelihood of an event of any particular magnitude by statistical analysis. However, all is not lost. The chances are that there have been many quite small hydrothermal eruptions that have not been detected. If a relatively small event occurred offshore, the steam bubble produced might not have broken the surface of the lake. Even if it did, with large parts of the lake being unobserved for much of each day all signs could have disappeared before any person visited or saw the affected area. But an electronic monitoring system could be put in place to detect the events.

8.3 Consequential Hydrothermal Effects

The risk needs to be considered in the light of potential risk to the stability of the Rotomahana barrier. A sizeable hydrothermal eruption in Rotomahana lake can produce a tsunami, and the larger the eruption the larger the size of the tsunami. There is no reason to think the tsunami could not overtop the barrier. In more than 100 years no event on this scale has occurred. However, if such an overtopping event did occur its effects could possibly be estimated by comparison with studies of the effects of dam-overtopping or similar events elsewhere. We believe that overtopping would result only in a single substantial surge of water down into the present natural erosion channel. A lot of local slipping would probably occur but this would cease soon after the wave passed and the barrier would be left essentially intact (see section 9.4).

[8] Grange, L.I., *The Geology of the Rotorua-Taupo Subdivision*, 1937, p.129. The chart on p.38 of this publication shows that indeed a fairly rapid fall in level immediately preceded the outbreak.
[9] Keam, R.F., *Tarawera*, 1988, p.80

8.4 Effects of Sudden Lowering of Lake Rotomahana

In section 7.2 we have considered the direct effects of the (very unlikely) scenario of a breach flood occurring. But in addition to such direct effects there is one indirect effect which could be comparably destructive. This is the triggering of a large hydrothermal eruption by the sudden reduction of hydrostatic pressures on the bed of Rotomahana and on the walls of the lakes basin newly exposed as the lake drains in the course of a breach flood.

It has already been mentioned in section 8.2.2 above how even very small pressure drops can provide sufficient impetus to induce hydrothermal eruptions. The bigger the pressure drop, and the more sudden it is, the more likely it is that instability will be induced.

In June/July 1918, some fourteen months or so after the Frying Pan Flat eruption at Waimangu, the new hot lakelet confined in the crater, on the site of Frying Pan Flat was released, and in the course of a few hours its level dropped by several metres. A violent hydrothermal eruption occurred, throwing water and solid debris to an estimated height of 1000 feet, comparable indeed to the most spectacular eruptions of the old Waimangu Geyser.

The sudden dropping of Rotomahana by somewhere between 30 and 40 metres would almost certainly induce a violent hydrothermal eruption in the vicinity of the "Steaming Cliffs". There is no way of forecasting the magnitude of such an event, but it has a high probability of being the largest eruption of the Rotomahana hydrothermal system since its magma-induced triggering on 10 June 1886.

9.0 Seismic Events

9.1 Seismicity

Rotomahana lies within the 10-15km wide Taupo Fault Belt. This is a major tectonic feature of New Zealand and is characterised by active subsidence and extension.

According to the 1:250,000 Geological Map of Rotorua, there are two main sub parallel fault lines trending from southwest to northeast that run through the study area – the Paeroa fault and the Ngapouri Fault. Both are considered to be active.

It is encouraging for barrier stability that the faulting structure is along the barrier; and not across it.

The **Paeroa Fault** is a major structural feature of the Taupo Volcanic Zone. It is vertically displaced by as much as 600m. Towards Waimangu the fault zone consists of many discontinuous and arcuate fault traces, defining small grabens, and displaces Earthquake Flat Breccia by less than 10m. If we extrapolate from the geological map it appears to run through the north western extent of the barrier.

The **Ngapouri Fault** diverges eastward from the Paeroa Fault and trends northeast through the Rotomahana area. The northwest side is downthrown possibly by as much as 180m. Considerable thermal activity is associated with the Ngapouri Fault and there are many young hydrothermal explosion craters along it. The fault line is trending towards Mt Tarawea at the eastern end of the barrier, approximately along the south-east shoreline of Lake Rotomahana.

The Rotomahana fault appears to be a northeastern extension of the Ngapouri fault trending ENE between the Ngapouri fault and the northern shore of Lake Rerewhakaaitu. We consider this to be far away enough to not have any adverse impact on the barrier in terms of rupturing.

Only minor extensional and transcurrent faulting is associated with the northeast trending 1886 Tarawera rift.

No lineaments typical of fault rupture were observed on the barrier during the site visit (the existing channels are interpreted to be erosion rills). Any prior to 1886 would have been covered by the Tarawera eruption material. However, we do note that the local trend of southwest to northeast faults is the same orientation as the overland flowpath.

Movement on a fault through the barrier is unlikely. If it did occur, the thick deposits of well graded non cohesive sands and gravels are likely to control any seepage along the fault line as they do now in the barrier.

9.2 Earthquake Size and Return Period

The following information comes from a report 'Earthquake Hazards in the Bay of Plenty Region' by IGNS in 1999. This shows an earthquake greater than 6 on the Modified Mercalli intensity scale once every 1000 years for the Paeroa fault and every 3300 for the Ngapouri Fault.

Table 9.2: Seismic Sources

	Fault Length (km)	Ave. Displ. (m)	Slip Rate (mm/yr)	Depth (km)	Est. Eartquake (M_w)	Ave. Recurrence (yrs)
Paeroa	28	2.0	2.0	8	6.4	1000
Ngapouri	18	1.0	0.3	8	6.2	3300

9.3 Site Response

According to the Modified Mercalli intensity scale an earthquake of the size expected from the Paeroa and Ngapouri faults would result in loose material being dislodged from sloping ground.

A ground rupture through the Rotomahana barrier with an average displacement as predicted above (1-2m) may provide a passage for water to exploit. However, it is likely the loose cohesionless volcanic material will fill into any significant crack that develops.

9.4 Seiching

The shaking motion of earthquakes can produce a periodic oscillation (seiching) in lakes with waves traveling back and forth. The period is determined by the resonant characteristics of the basin as controlled by its physical dimensions. These periods range from a few minutes to an hour or more.

Small seiches have been observed at Lake Rotomahana before which may have originated from hydrothermal eruptions in 1981. There is no reason to believe a large seiche could not occur and result in overtopping of the barrier.

Overtopping would result in a single or several substantial surge of water down into the present natural erosion channel. A lot of local erosion would undoubtedly occur but this would cease soon after the wave passed with the barrier left essentially intact. Similar seismically generated seiches on Hebgen Dam in Montana, USA from a magnitude 8 earthquake, overtopped the dam and caused no damage.

9.5 Liquefaction

Because of the coarse nature of the pumice wash and the low groundwater level we considered liquefaction of the barrier material to have a low probability, and low risk compared with other hazards.

10.0 Risk Assessment of Lake Rerewhakaaitu

This section considers whether water could be rapidly be released from Lake Rerewhakaaitu, approximately 100 metres higher than Rotomahana, and discharge into Rotomahana, increasing loading on the barrier between it and Lake Tarawera.

10.1 Geomorphology

Lake Rerewhakaaitu fills the former head of a valley which once drained down toward Lake Rotomahana. The valley was blocked by eruptions from Mt Tarawera with the last significant event about 700 years ago. A shallow lake has resulted, which can overspill into the Rangataiki river catchment. Lake volume storage for Rerewhakaaitu is given in Appendix 3.

The nature of the material in the Rerewhakaaitu barrier deposit could be observed in road cuttings just to the north. The land surface from Mt Tarawera down to Lake Rerewhakaaitu and Lake Rotomahana is a major avalanche deposit evidently emplaced during the Kaharoa eruption ~700 years ago. This has been covered with a relatively thin coating of 1886 eruption ejecta, largely basaltic ash and Rotomahana debris. All this area is now farmed or in pine forest. It presents a smooth curving slope to the lakes which fills and blocks the former valley.

10.2 Drainage

Lake Rerewhakaaitu also has no natural outlet, but surplus overflow now occurs via a man made drain across flat farmland to the south to the headwaters of tributaries of the Rangitaiki River. At the time of our visit this channel was dry, and the amount of vegetation growing in the drain indicates that little water has found its way from the lake by this route for some time. Since there is no other surface discharge channel it is evident that seepage and evaporation can cope with inflow for substantial periods. The catchment of Rerewhakaaitu includes some of the southern slopes of Tarawera mountain and a small area south, southwest and west of the lake.

A ridge on the northern side of the lake prevents surface outflow to the north, but beyond the ridge there is a long slope at 100m height over 4km to Lake Rotomahana. The elevation of the divide (which is relatively level here) for a distance of perhaps 300 metres, is about 8m above the level of Rerewhakaaitu. The transverse distance through this divide, from the lake edge to ground surface where this falls again to lake level, is about 500 metres.

Seepage flows would be expected down the original valley, northwards into the Rotomahana catchment through the material in the 'gap'. This will contribute substantially to Lake Rotomahana inflows.

Degradation of the barrier has not occurred in the approximately 700 years that has elapsed since the Kaharoa eruption occurred, and indicates that it is relatively stable. No evidence of overtopping in this time was noticed during the inspection. Following the avalanche deposit surface with the eye down the valley to the north reveals that it is resistant to erosion. The only sign of readjustment by flowing water was cross-sectional undulations with amplitude of 1-2 metres and wavelength about 20 metres; the alternate shallow troughs and ridges running longitudinally downslope. There was no deep channeling observed. Certainly a lot of the 1886 deposit here appears to have been washed off, but the matrix of the avalanche containing large rhyolite boulders that everywhere protrude through its surface is clearly resistant to erosion. Overflow from Lake Rerewhakaaitu to the southeast along the drain, or over the flat farmland through which the drain flows, will easily be able to cope with any sudden deposit of water from localised high intensity rainfall events without overtopping of the northern barrier. Thus, this open route, together with the evident resistance to erosion of the barrier material in the unlikely event of overtopping indicates that any sudden discharge of Rerewhakaaitu lake water down into Rotomahana resulting from high intensity rainfall events in the Rerewhakaaitu catchment is highly improbable.

The Rerewhakaaitu Saddle is about 8m above Lake level at time of our visit. ie Lake 435m, saddle 443m. Outflow will start with a rise of 0.5m, to 435.5m. Road at overflow will overtop at 437m with a large capacity above this. Excess flows will go out down the tributary of the Rangitaiki River. This leaves a margin of 6m, which would be adequate for overtopping safety by NZSOLD dam safety criteria.

11.0 Conclusions

<u>Physical Situation</u>

11.1 The Rotomahana barrier is part of a large hydraulic system of ground water flows from Lake Rerewhakaaitu down to Lake Rotomahana and from Lake Rotomahana to Lake Tarawera.

11.2 Natural volcanically placed barriers impound both Lake Rerewhakaaitu and Lake Rotomahana.

11.3 These barriers have resisted erosion since emplacement by volcanic eruption. They remain in good condition with no evidence of erosion.

11.4 Rotomahana barrier has a pipe outlet constructed in its crest. This outlet is in poor condition. The pipe is open but the inlet needs clearing work done and a reinstatement of the facilities.

11.5 Seiching in the lake could occur. An earthquake or fault displacement could cause a small seich in the lake. A more likely cause would be a hydrothermal eruption. The barrier could easily be overtopped but is unlikely to have major erosion. The downstream slope is at low gradient, and would require long consistent flows to erode.

Potential Hazards

11.6 Lake Rerewhakaaitu is part of the Lake Rotomahana catchment and is 98m above it. The lake is also retained by volcanic debris. The barrier is 8m above normal lake levels with no significant risk of overtopping or failure, as an adequate overflow path exists. Groundwater from the lake will contribute substantially to Rotomahana inflows.

11.7 The 1000 year flooding event at Lake Rotomahana will increase the lake levels to about 2m above the inlet of the pipe outlet. Our calculations indicate that the lake level will be about 2m below the crest of the barrier in a 1000 year event.

11.8 Erosion channels on the downstream side of the barrier appear to have reached an erosion equilibrium for present flows. Channel beds have been armoured with rhyolitic boulders eroded from the eruption debris. High flows through the outlet pipe could cause additional erosion. Monitoring will be necessary to check this.

11.9 A theoretical breach scenario has been examined. Should this barrier overtop initiating a breach, the barrier would erode in about 3.5 hours, releasing a peak flow of 19,000m^3/sec. Total released volume to Lake Tarawera would be 410 million m^3. Lake Tarawera levels would be raised by about 7m.

11.10 Sliding of the barrier is not considered possible.

11.11 Development of a piping failure has a low probability.

11.12 Repeat volcanic eruptions are possible in the Mt Tarawera area, at about 2000-2500 year intervals.

11.13 Hydrothermal eruptions are more frequent, and as they could originate in the Rotomahana crater, are more likely to be damaging. Two significant ones have occurred in the last 100 years. Monitoring is recommended to define this risk.

11.14 Seismic risk is considered low as fault alignment is generally sub-parallel to the barrier, and consequences of any anticipated movement would be low.

12.0 Recommendations

12.1 The Lake Rotomahana barrier is effectively a large natural dam. The Potential Impact Classification under the NZSOLD classification would be High.

12.2 A monitoring program should be set up for the Lake Rotomahana barrier to comply with NZSOLD recommendations for High Potential Impact classification dams.

12.3 An Emergency Action Plan should also be prepared, to allow any possible future effects to be considered and acted upon as necessary.

12.4 Lake Rerewhakaaitu is held in by a similar natural dam, but whose failure would be of lower potential impact. A monitoring procedure should also be prepared for this lake.

12.5 A geophone monitoring system should be installed in Lake Rotomahana to collect data on the size and frequency of hydrothermal incidents beneath the lake waters. This should be coupled with a geophone on shore for correlation purposes. Remote monitoring could provide warning of impending magmatic eruptive events, but not for hydrothermal eruptions.

12.6 We would be pleased to provide any further assistance as required.

Acknowledgements

Professor Ron Keam

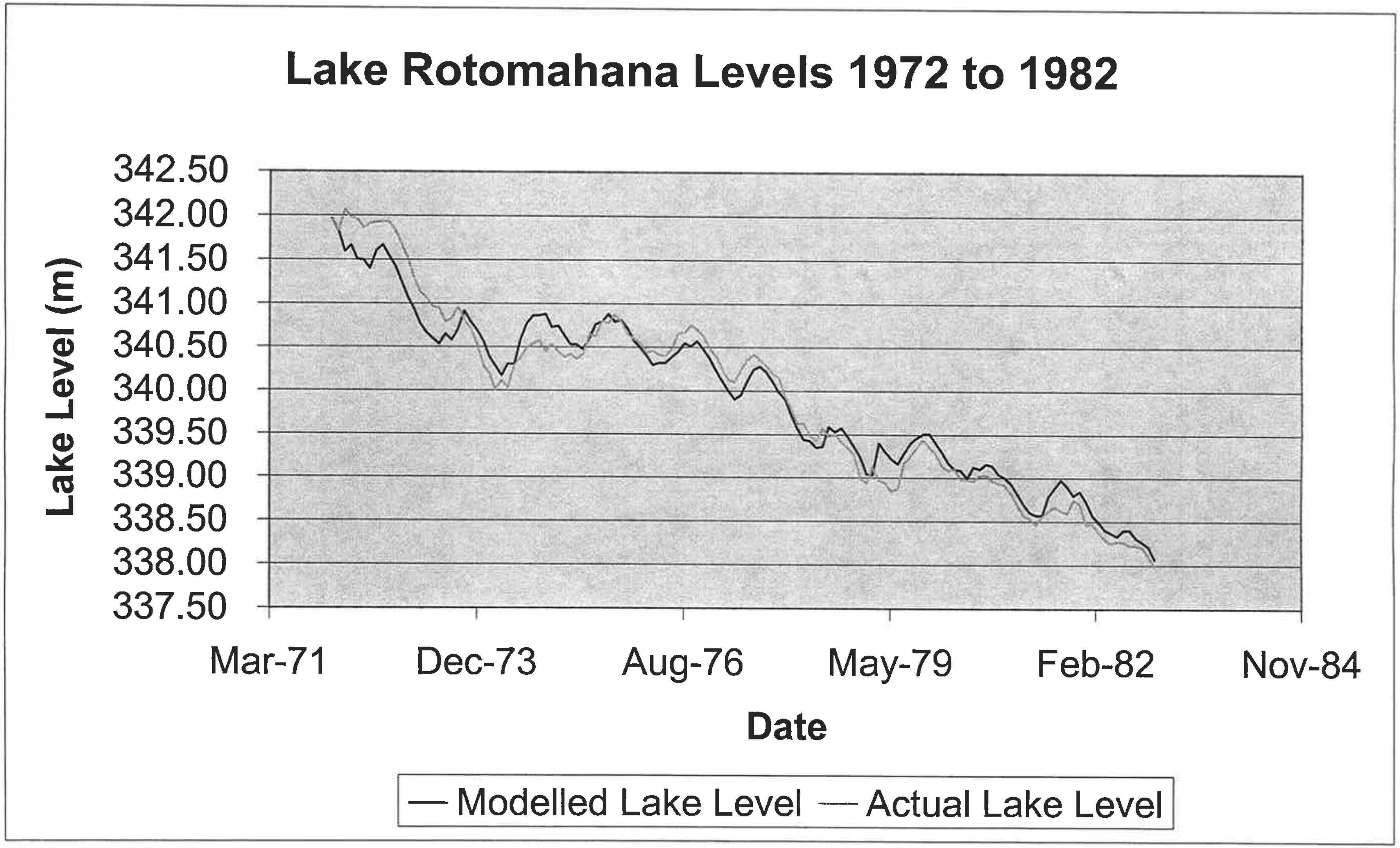
Chapters 5, 8.3, 8.4, 10.2

National Museum – Te Papa – for photos.

APPENDIX 1

WATER BALANCE MODEL

Calibration Data


Lake Rotomahana Levels 1972 to 1982
342.50
342.00
341.50
341.00
340.50
340.00
339.50
339.00
338.50
338.00
337.50
Lake Level (m)
Mar-71
Dec-73
Aug-76
May-79
Feb-82
Nov-84
Date
Modelled Lake Level
Actual Lake Level

Lake Rotomahana Water Balance Model
Calibration 1972 to 1982

Month	Cumm. Change Lake Volume (m^3)	Modelled Lake Level metres RL	Actual Lake Level metres RL	Catchment Rainfall (mm)	Catchment Evapotrans. (mm)	Intermediate If Statement	Soil Root Zone Storage (mm)	Effective Rainfall (mm)	Evaporation (mm)	Seepage Loss (m^3/s)	Rainfall less Evapotrans (mm)	Culvert Outflow (m^3/s)
Jan-72	-	341.96	341.96	57	120	12	12	0	120.0	0.55	-63	0
Feb-72	- 1,992,600	341.82	341.84	55	115	-48	0	0	115.0	0.55	-60	0.52
Mar-72	- 5,306,040	341.59	342.07	283	76	75	75	132	76.0	0.55	207	0.52
Apr-72	- 4,262,880	341.67	341.98	62	55	75	75	7	55.0	0.55	7	0.4
May-72	- 6,558,680	341.51	341.96	141	36	75	75	105	36.0	0.55	105	0.47
Jun-72	- 6,703,520	341.50	341.86	70	27	75	75	43	27.0	0.55	43	0.4
Jul-72	- 8,142,520	341.40	341.91	256	26	75	75	230	26.0	0.55	230	0.4
Aug-72	- 5,130,920	341.61	341.93	134	34	75	75	100	34.0	0.55	100	0
Sep-72	- 4,176,520	341.67	341.93	98	61	75	75	37	61.0	0.55	37	0.47
Oct-72	- 5,939,760	341.55	341.93	107	71	75	75	36	71.0	0.55	36	0.47
Nov-72	- 7,726,800	341.43	341.83	93	98	70	70	0	98.0	0.55	-5	0.4
Dec-72	- 10,234,200	341.25	341.68	98	122	46	46	0	122.0	0.55	-24	0.4
Jan-73	- 12,912,600	341.07	341.52	74	138	-18	0	0	138.0	0.55	-64	0
Feb-73	- 14,914,200	340.93	341.28	17	120	-103	0	0	120.0	0.55	-103	0
Mar-73	- 17,266,800	340.77	341.14	67	75	-8	0	0	75.0	0.55	-8	0
Apr-73	- 18,764,400	340.67	341.06	105	58	47	47	0	58.0	0.55	47	0
May-73	- 19,767,000	340.60	340.97	74	33	75	75	13	33.0	0.55	41	0
Jun-73	- 20,631,200	340.54	340.94	146	16	75	75	130	16.0	0.55	130	0
Jul-73	- 18,962,800	340.65	340.79	45	29	75	75	16	29.0	0.55	16	0
Aug-73	- 20,007,600	340.58	340.83	164	29	75	75	135	29.0	0.55	135	0
Sep-73	- 18,220,200	340.70	340.96	228	38	75	75	190	38.0	0.55	190	0
Oct-73	- 15,123,800	340.92	340.82	51	89	37	37	0	89.0	0.55	-38	0
Nov-73	- 16,891,400	340.80	340.71	100	96	41	41	0	96.0	0.55	4	0
Dec-73	- 18,281,000	340.70	340.54	95	137	-1	0	0	137.0	0.55	-42	0
Jan-74	- 20,084,600	340.57	340.29	15	159	-144	0	0	159.0	0.55	-144	0
Feb-74	- 22,806,200	340.39	340.19	103	110	-7	0	0	110.0	0.55	-7	0
Mar-74	- 24,294,800	340.28	340.01	69	93	-24	0	0	93.0	0.55	-24	0
Apr-74	- 25,936,400	340.17	340.12	231	44	75	75	112	44.0	0.55	187	0
May-74	- 24,021,400	340.30	340.04	87	29	75	75	58	29.0	0.55	58	0
Jun-74	- 24,066,600	340.30	340.28	253	23	75	75	230	23.0	0.55	230	0
Jul-74	- 20,018,200	340.58	340.37	196	22	75	75	174	22.0	0.55	174	0
Aug-74	- 17,302,600	340.77	340.49	151	33	75	75	118	33.0	0.55	118	0
Sep-74	- 15,919,800	340.86	340.54	107	44	75	75	63	44.0	0.55	63	0
Oct-74	- 15,846,000	340.87	340.58	141	73	75	75	68	73.0	0.55	68	0
Nov-74	- 15,653,200	340.88	340.45	21	103	-7	0	0	103.0	0.55	-82	0
Dec-74	- 17,816,800	340.73	340.54	241	127	75	75	39	127.0	0.55	114	0
Jan-75	- 17,639,200	340.74	340.44	98	123	50	50	0	123.0	0.55	-25	0
Feb-75	- 19,289,800	340.63	340.38	105	104	51	51	0	104.0	0.55	1	0
Mar-75	- 20,706,400	340.53	340.42	145	72	75	75	49	72.0	0.55	73	0
Apr-75	- 20,749,800	340.53	340.36	71	46	75	75	25	46.0	0.55	25	0
May-75	- 21,580,400	340.47	340.42	169	27	75	75	142	27.0	0.55	142	0
Jun-75	- 19,626,400	340.61	340.64	174	17	75	75	157	17.0	0.55	157	0
Jul-75	- 17,315,400	340.77	340.63	101	24	75	75	77	24.0	0.55	77	0

Aug-75	-	16,908,400	340.79	340.80	139	27	75	75	112	27.0	0.55	112		0
Sep-75	-	15,668,400	340.88	340.77	61	53	75	75	8	53.0	0.55	8		0
Oct-75	-	16,903,600	340.79	340.87	146	75	75	75	71	75.0	0.55	71		0
Nov-75	-	16,639,400	340.81	340.80	102	99	75	75	3	99.0	0.55	3		0
Dec-75	-	17,993,600	340.72	340.64	53	127	1	1	0	127.0	0.55	-74		0
Jan-76	-	20,085,200	340.57	340.60	128	96	33	33	0	96.0	0.55	32		0
Feb-76	-	21,222,800	340.50	340.55	113	101	45	45	0	101.0	0.55	12		0
Mar-76	-	22,540,400	340.41	340.44	64	83	26	26	0	83.0	0.55	-19		0
Apr-76	-	24,137,000	340.30	340.46	156	50	75	75	57	50.0	0.55	106		0
May-76	-	23,765,000	340.32	340.41	90	30	75	75	60	30.0	0.55	60		0
Jun-76	-	23,762,600	340.32	340.40	121	18	75	75	103	18.0	0.55	103		0
Jul-76	-	22,736,800	340.39	340.48	114	20	75	75	94	20.0	0.55	94		0
Aug-76	-	21,925,200	340.45	340.66	157	34	75	75	123	34.0	0.55	123		0
Sep-76	-	20,423,400	340.55	340.67	92	56	75	75	36	56.0	0.55	36		0
Oct-76	-	20,992,200	340.51	340.76	169	71	75	75	98	71.0	0.55	98		0
Nov-76	-	20,085,400	340.57	340.71	94	96	73	73	0	96.0	0.55	-2		0
Dec-76	-	21,529,000	340.48	340.63	100	115	58	58	0	115.0	0.55	-15		0
Jan-77	-	23,089,600	340.37	340.49	53	125	-14	0	0	125.0	0.55	-72		0
Feb-77	-	25,163,200	340.22	340.40	86	104	-18	0	0	104.0	0.55	-18		0
Mar-77	-	26,750,800	340.12	340.25	66	93	-27	0	0	93.0	0.55	-27		0
Apr-77	-	28,419,400	340.00	340.13	59	55	4	4	0	55.0	0.55	4		0
May-77	-	29,809,000	339.90	340.10	166	31	75	75	64	31.0	0.55	135		0
Jun-77	-	29,072,400	339.96	340.24	173	18	75	75	155	18.0	0.55	155		0
Jul-77	-	26,809,000	340.11	340.36	158	16	75	75	142	16.0	0.55	142		0
Aug-77	-	24,855,000	340.25	340.42	109	28	75	75	81	28.0	0.55	81		0
Sep-77	-	24,352,800	340.28	340.36	73	48	75	75	25	48.0	0.55	25		0
Oct-77	-	25,183,400	340.22	340.29	58	81	52	52	0	81.0	0.55	-23		0
Nov-77	-	26,816,000	340.11	340.19	65	103	14	14	0	103.0	0.55	-38		0
Dec-77	-	28,583,600	339.99	340.16	147	122	39	39	0	122.0	0.55	25		0
Jan-78	-	29,784,200	339.91	339.94	10	151	-102	0	0	151.0	0.55	-141		0
Feb-78	-	32,478,800	339.72	339.80	42	126	-84	0	0	126.0	0.55	-84		0
Mar-78	-	34,660,400	339.57	339.62	48	95	-47	0	0	95.0	0.55	-47		0
Apr-78	-	36,509,000	339.44	339.62	143	48	75	75	20	48.0	0.55	95		0
May-78	-	36,783,600	339.42	339.49	50	35	75	75	15	35.0	0.55	15		0
Jun-78	-	37,852,200	339.35	339.43	83	18	75	75	65	18.0	0.55	65		0
Jul-78	-	37,730,800	339.36	339.57	219	20	75	75	199	20.0	0.55	199		0
Aug-78	-	34,420,200	339.59	339.48	56	31	75	75	25	31.0	0.55	25		0
Sep-78	-	35,250,800	339.53	339.50	126	39	75	75	87	39.0	0.55	87		0
Oct-78	-	34,605,800	339.57	339.41	82	83	74	74	0	83.0	0.55	-1		0
Nov-78	-	36,040,400	339.47	339.35	79	112	41	41	0	112.0	0.55	-33		0
Dec-78	-	37,763,000	339.36	339.27	88	122	7	7	0	122.0	0.55	-34		0
Jan-79	-	39,494,600	339.24	338.99	7	163	-149	0	0	163.0	0.55	-156		0
Feb-79	-	42,324,200	339.04	338.94	191	89	75	75	27	89.0	0.55	102		0
Mar-79	-	42,432,200	339.03	339.12	341	58	75	75	283	58.0	0.55	283		0
Apr-79	-	37,122,400	339.40	338.97	47	49	73	73	0	49.0	0.55	-2		0
May-79	-	38,566,000	339.30	338.94	35	25	75	75	8	25.0	0.55	10		0
Jun-79	-	39,783,200	339.22	338.84	44	18	75	75	26	18.0	0.55	26		0
Jul-79	-	40,590,000	339.16	338.87	150	17	75	75	133	17.0	0.55	133		0
Aug-79	-	38,850,200	339.28	339.17	164	32	75	75	132	32.0	0.55	132		0

Sep-79	-	37,134,200	339.40	339.25	144	47	75	75	97	47.0	0.55	97	0
Oct-79	-	36,251,200	339.46	339.35	157	68	75	75	89	68.0	0.55	89	0
Nov-79	-	35,558,600	339.51	339.44	157	95	75	75	62	95.0	0.55	62	0
Dec-79	-	35,508,600	339.51	339.36	110	127	58	58	0	127.0	0.55	-17	0
Jan-80	-	37,087,200	339.40	339.27	88	110	36	36	0	110.0	0.55	-22	0
Feb-80	-	38,710,800	339.29	339.13	70	103	3	3	0	103.0	0.55	-33	0
Mar-80	-	40,433,400	339.17	339.08	115	78	40	40	0	78.0	0.55	37	0
Apr-80	-	41,526,000	339.10	339.10	117	41	75	75	41	41.0	0.55	76	0
May-80	-	41,660,800	339.09	338.98	35	32	75	75	3	32.0	0.55	3	0
Jun-80	-	43,015,000	338.99	338.98	159	19	75	75	140	19.0	0.55	140	0
Jul-80	-	41,108,600	339.12	338.96	65	19	75	75	46	19.0	0.55	46	0
Aug-80	-	41,439,400	339.10	339.03	127	32	75	75	95	32.0	0.55	95	0
Sep-80	-	40,604,000	339.16	339.03	99	53	75	75	46	53.0	0.55	46	0
Oct-80	-	40,934,800	339.14	338.96	76	76	75	75	0	76.0	0.55	0	0
Nov-80	-	42,360,400	339.04	338.93	139	100	75	75	39	100.0	0.55	39	0
Dec-80	-	42,857,800	339.00	338.92	124	110	75	75	14	110.0	0.55	14	0
Jan-81	-	43,950,200	338.93	338.81	94	123	46	46	0	123.0	0.55	-29	0
Feb-81	-	45,636,800	338.81	338.68	57	79	24	24	0	79.0	0.55	-22	0
Mar-81	-	47,260,400	338.70	338.57	62	58	28	28	0	58.0	0.55	4	0
Apr-81	-	48,650,000	338.60	338.53	114	45	75	75	22	45.0	0.55	69	0
May-81	-	49,129,000	338.57	338.46	88	30	75	75	58	30.0	0.55	58	0
Jun-81	-	49,174,200	338.57	338.56	209	14	75	75	195	14.0	0.55	195	0
Jul-81	-	45,958,800	338.79	338.62	141	23	75	75	118	23.0	0.55	118	0
Aug-81	-	44,576,000	338.89	338.67	151	36	75	75	115	36.0	0.55	115	0
Sep-81	-	43,264,600	338.98	338.62	63	50	75	75	13	50.0	0.55	13	0
Oct-81	-	44,380,800	338.90	338.59	86	94	67	67	0	94.0	0.55	-8	0
Nov-81	-	45,878,400	338.80	338.75	186	91	75	75	87	91.0	0.55	95	0
Dec-81	-	45,161,400	338.85	338.70	74	103	46	46	0	103.0	0.55	-29	0
Jan-82	-	46,848,000	338.73	338.46	37	140	-57	0	0	140.0	0.55	-103	0
Feb-82	-	49,200,600	338.57	338.47	149	101	48	48	0	101.0	0.55	48	0
Mar-82	-	50,194,200	338.50	338.39	73	63	58	58	0	63.0	0.55	10	0
Apr-82	-	51,529,800	338.41	338.30	101	51	75	75	33	51.0	0.55	50	0
May-82	-	52,017,000	338.37	338.25	61	26	75	75	35	26.0	0.55	35	0
Jun-82	-	52,609,600	338.33	338.27	118	17	75	75	101	17.0	0.55	101	0
Jul-82	-	51,631,400	338.40	338.27	83	21	75	75	62	21.0	0.55	62	0
Aug-82	-	51,581,400	338.40	338.23	42	39	75	75	3	39.0	0.55	3	0
Sep-82	-	52,935,600	338.31	338.22	81	49	75	75	32	49.0	0.55	32	0
Oct-82	-	53,599,600	338.26	338.21	106	79	75	75	27	79.0	0.55	27	0
Nov-82	-	54,382,600	338.21	338.10	59	126	8	8	0	126.0	0.55	-67	0
Dec-82	-	56,411,200	338.07	337.98	65	121	-48	0	0	121.0	0.55	-56	0

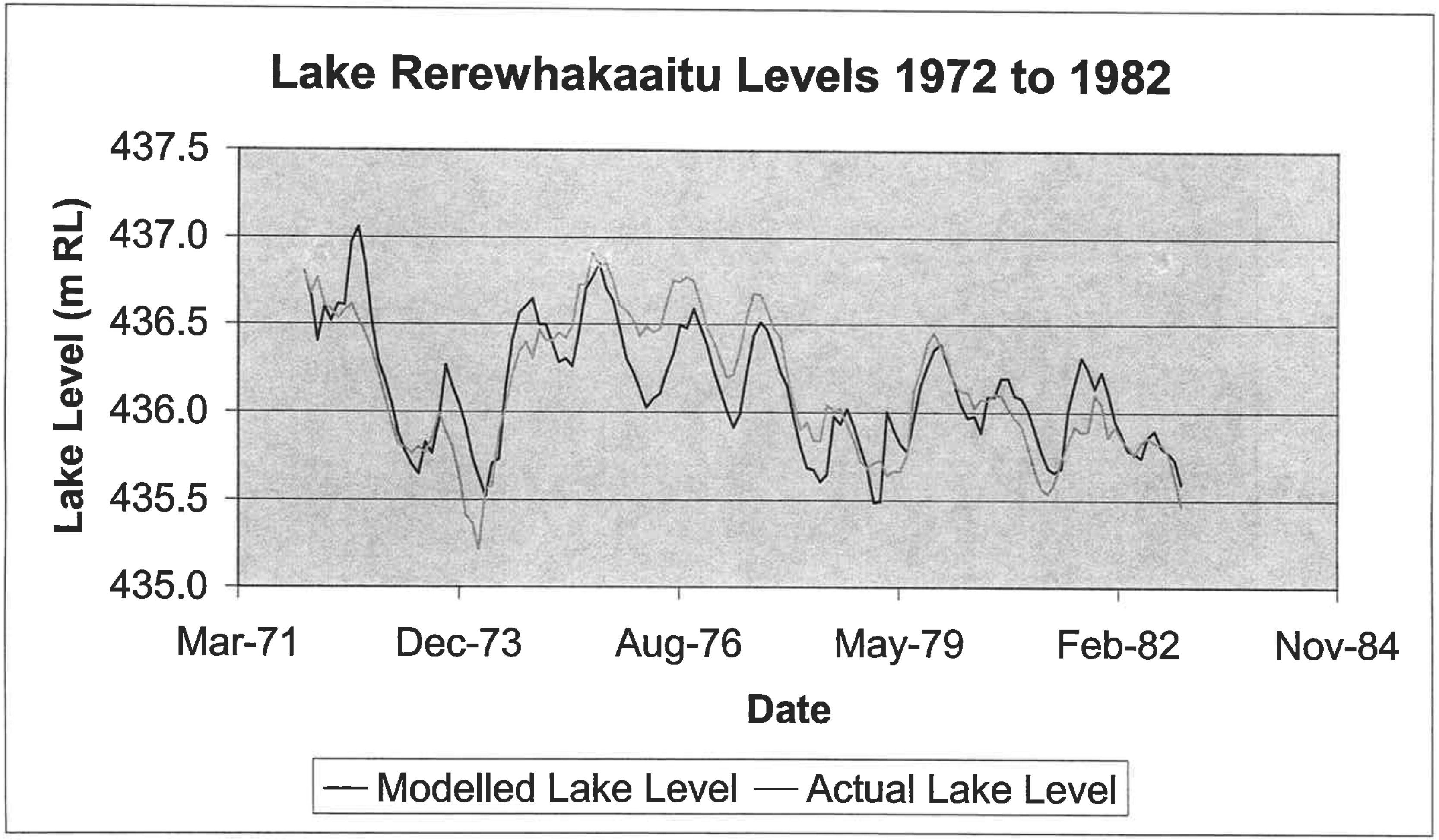
Lake Rotomahana Water Balance Model
Input Data for Calibration

Initial Soil Moisture (mm)	Catchment Area Excluding Lake (km^2)	Lake Area (km^2)
75	74	9

Lake Level metres RL	Lake Volume m^3
337.0	-
343.0	87,000,000

Culvert Flow Coeff	Net Seepage Loss (m^3/s)	Soil Moisture Storage (mm)
1	0.55	75

Lake Level (m3/s)	Culvert Outflow (m3/s)
335.0	0.00
341.2	0.00
341.4	0.40
341.6	0.47
341.8	0.52
342.0	0.59
342.2	0.66
342.4	0.74
342.6	0.79
342.8	0.84
343.0	0.9
343.2	0.95
343.4	1.00
343.6	1.05
343.8	1.10
344.0	1.15
344.2	1.20
344.4	1.25



Lake Rerewhakaaitu Levels 1972 to 1982
437.5
437.0
436.5
436.0
435.5
435.0
Lake Level (m RL)
Mar-71
Dec-73
Aug-76
May-79
Feb-82
Nov-84
Date
Modelled Lake Level
Actual Lake Level

Lake Rerewhakaaiti Water Balance Model
Calibration 1972 to 1982

Month	Cumm. Change Lake Volume (m^3)	Modelled Lake Level metres RL	Actual Lake Level metres RL	Catchment Rainfall (mm)	Catchment Evapotrans. (mm)	Intermediate If Statement	Soil Root Zone Storage (mm)	Effective Rainfall (mm)	Evaporation (mm)	Seepage Loss (m^3/s)	Rainfall less Evapotrans (mm)	Culvert Outflow (m^3/s)
Jan-72	-	436.80	436.80	57	120	12	12	0	120.0	0.32	-63	0
Feb-72	- 1,144,440	436.66	436.68	55	115	-48	0	0	115.0	0.32	-60	0.4
Mar-72	- 3,310,680	436.40	436.77	283	76	75	75	132	76.0	0.32	207	0.1
Apr-72	- 1,648,320	436.60	436.61	62	55	75	75	7	55.0	0.32	7	0
May-72	- 2,351,760	436.52	436.58	141	36	75	75	105	36.0	0.32	105	0.1
Jun-72	- 1,550,400	436.61	436.53	70	27	75	75	43	27.0	0.32	43	0
Jul-72	- 1,605,840	436.61	436.58	256	26	75	75	230	26.0	0.32	230	0.1
Aug-72	1,445,520	436.97	436.62	134	34	75	75	100	34.0	0.32	100	0.1
Sep-72	2,156,880	437.06	436.52	98	61	75	75	37	61.0	0.32	37	0.6
Oct-72	438,240	436.85	436.45	107	71	75	75	36	71.0	0.32	36	1
Nov-72	- 2,335,200	436.52	436.35	93	98	70	70	0	98.0	0.32	-5	0.4
Dec-72	- 4,226,440	436.29	436.22	98	122	46	46	0	122.0	0.32	-24	0
Jan-73	- 5,175,880	436.18	436.08	74	138	-18	0	0	138.0	0.32	-64	0
Feb-73	- 6,325,320	436.04	435.93	17	120	-103	0	0	120.0	0.32	-103	0
Mar-73	- 7,669,760	435.88	435.81	67	75	-8	0	0	75.0	0.32	-8	0
Apr-73	- 8,539,200	435.78	435.80	105	58	47	47	0	58.0	0.32	47	0
May-73	- 9,133,640	435.70	435.77	74	33	75	75	13	33.0	0.32	41	0
Jun-73	- 9,589,080	435.65	435.81	146	16	75	75	130	16.0	0.32	130	0
Jul-73	- 8,078,520	435.83	435.77	45	29	75	75	16	29.0	0.32	16	0
Aug-73	- 8,619,960	435.77	435.85	164	29	75	75	135	29.0	0.32	135	0
Sep-73	- 7,019,400	435.96	436.00	228	38	75	75	190	38.0	0.32	190	0
Oct-73	- 4,428,840	436.27	435.89	51	89	37	37	0	89.0	0.32	-38	0
Nov-73	- 5,448,280	436.15	435.81	100	96	41	41	0	96.0	0.32	4	0
Dec-73	- 6,257,720	436.05	435.65	95	137	-1	0	0	137.0	0.32	-42	0
Jan-74	- 7,297,160	435.92	435.42	15	159	-144	0	0	159.0	0.32	-144	0
Feb-74	- 8,846,600	435.74	435.36	103	110	-7	0	0	110.0	0.32	-7	0
Mar-74	- 9,711,040	435.63	435.21	69	93	-24	0	0	93.0	0.32	-24	0
Apr-74	- 10,660,480	435.52	435.57	231	44	75	75	112	44.0	0.32	187	0
May-74	- 9,098,920	435.71	435.58	87	29	75	75	58	29.0	0.32	58	0
Jun-74	- 8,884,360	435.73	435.89	253	23	75	75	230	23.0	0.32	230	0
Jul-74	- 5,573,800	436.13	436.03	196	22	75	75	174	22.0	0.32	174	0
Aug-74	- 3,271,240	436.41	436.21	151	33	75	75	118	33.0	0.32	118	0
Sep-74	- 1,976,680	436.56	436.34	107	44	75	75	63	44.0	0.32	63	0
Oct-74	- 1,672,120	436.60	436.40	141	73	75	75	68	73.0	0.32	68	0
Nov-74	- 1,277,560	436.65	436.30	21	103	-7	0	0	103.0	0.32	-82	0
Dec-74	- 2,517,000	436.50	436.47	241	127	75	75	39	127.0	0.32	114	0.1
Jan-75	- 2,528,640	436.50	436.41	98	123	50	50	0	123.0	0.32	-25	0
Feb-75	- 3,483,080	436.38	436.41	105	104	51	51	0	104.0	0.32	1	0
Mar-75	- 4,307,520	436.28	436.45	145	72	75	75	49	72.0	0.32	73	0
Apr-75	- 4,134,960	436.30	436.42	71	46	75	75	25	46.0	0.32	25	0
May-75	- 4,514,400	436.26	436.49	169	27	75	75	142	27.0	0.32	142	0
Jun-75	- 2,787,840	436.47	436.73	174	17	75	75	157	17.0	0.32	157	0
Jul-75	- 791,280	436.71	436.73	101	24	75	75	77	24.0	0.32	77	0

Aug-75	-	234,720	436.77	436.91	139	27	75	75	112	27.0	0.32	112	0.2
Sep-75		433,440	436.85	436.83	61	53	75	75	8	53.0	0.32	8	0.2
Oct-75	-	770,400	436.71	436.85	146	75	75	75	71	75.0	0.32	71	0.4
Nov-75	-	1,358,640	436.64	436.75	102	99	75	75	3	99.0	0.32	3	0.2
Dec-75	-	2,652,480	436.48	436.61	53	127	1	1	0	127.0	0.32	-74	0.1
Jan-76	-	4,111,120	436.31	436.58	128	96	33	33	0	96.0	0.32	32	0
Feb-76	-	4,780,560	436.23	436.52	113	101	45	45	0	101.0	0.32	12	0
Mar-76	-	5,550,000	436.13	436.43	64	83	26	26	0	83.0	0.32	-19	0
Apr-76	-	6,474,440	436.02	436.49	156	50	75	75	57	50.0	0.32	106	0
May-76	-	6,032,880	436.08	436.45	90	30	75	75	60	30.0	0.32	60	0
Jun-76	-	5,782,320	436.11	436.47	121	18	75	75	103	18.0	0.32	103	0
Jul-76	-	4,757,760	436.23	436.62	114	20	75	75	94	20.0	0.32	94	0
Aug-76	-	3,895,200	436.33	436.75	157	34	75	75	123	34.0	0.32	123	0
Sep-76	-	2,510,640	436.50	436.74	92	56	75	75	36	56.0	0.32	36	0
Oct-76	-	2,692,080	436.48	436.77	169	71	75	75	98	71.0	0.32	98	0
Nov-76	-	1,757,520	436.59	436.75	94	96	73	73	0	96.0	0.32	-2	0
Dec-76	-	2,596,960	436.49	436.63	100	115	58	58	0	115.0	0.32	-15	0
Jan-77	-	3,501,400	436.38	436.48	53	125	-14	0	0	125.0	0.32	-72	0
Feb-77	-	4,690,840	436.24	436.40	86	104	-18	0	0	104.0	0.32	-18	0
Mar-77	-	5,610,280	436.13	436.30	66	93	-27	0	0	93.0	0.32	-27	0
Apr-77	-	6,574,720	436.01	436.20	59	55	4	4	0	55.0	0.32	4	0
May-77	-	7,384,160	435.91	436.22	166	31	75	75	64	31.0	0.32	135	0
Jun-77	-	6,706,600	436.00	436.36	173	18	75	75	155	18.0	0.32	155	0
Jul-77	-	4,746,040	436.23	436.54	158	16	75	75	142	16.0	0.32	142	0
Aug-77	-	3,019,480	436.44	436.68	109	28	75	75	81	28.0	0.32	81	0
Sep-77	-	2,390,920	436.51	436.67	73	48	75	75	25	48.0	0.32	25	0
Oct-77	-	2,770,360	436.47	436.58	58	81	52	52	0	81.0	0.32	-23	0
Nov-77	-	3,714,800	436.35	436.47	65	103	14	14	0	103.0	0.32	-38	0
Dec-77	-	4,734,240	436.23	436.43	147	122	39	39	0	122.0	0.32	25	0
Jan-78	-	5,438,680	436.15	436.22	10	151	-102	0	0	151.0	0.32	-141	0
Feb-78	-	6,973,120	435.96	436.05	42	126	-84	0	0	126.0	0.32	-84	0
Mar-78	-	8,222,560	435.81	435.90	48	95	-47	0	0	95.0	0.32	-47	0
Apr-78	-	9,287,000	435.69	435.95	143	48	75	75	20	48.0	0.32	95	0
May-78	-	9,381,440	435.67	435.84	50	35	75	75	15	35.0	0.32	15	0
Jun-78	-	9,940,880	435.61	435.84	83	18	75	75	65	18.0	0.32	65	0
Jul-78	-	9,600,320	435.65	436.04	219	20	75	75	199	20.0	0.32	199	0
Aug-78	-	6,847,760	435.98	436.01	56	31	75	75	25	31.0	0.32	25	0
Sep-78	-	7,227,200	435.93	436.02	126	39	75	75	87	39.0	0.32	87	0
Oct-78	-	6,490,640	436.02	435.93	82	83	74	74	0	83.0	0.32	-1	0
Nov-78	-	7,325,080	435.92	435.84	79	112	41	41	0	112.0	0.32	-33	0
Dec-78	-	8,319,520	435.80	435.73	88	122	7	7	0	122.0	0.32	-34	0
Jan-79	-	9,318,960	435.68	435.68	7	163	-149	0	0	163.0	0.32	-156	0
Feb-79	-	10,928,400	435.49	435.71	191	89	75	75	27	89.0	0.32	102	0
Mar-79	-	10,896,840	435.49	435.73	341	58	75	75	283	58.0	0.32	283	0
Apr-79	-	6,632,280	436.00	435.64	47	49	73	73	0	49.0	0.32	-2	0
May-79	-	7,471,720	435.90	435.67	35	25	75	75	8	25.0	0.32	10	0
Jun-79	-	8,147,160	435.82	435.67	44	18	75	75	26	18.0	0.32	26	0
Jul-79	-	8,508,600	435.78	435.76	150	17	75	75	133	17.0	0.32	133	0
Aug-79	-	6,944,040	435.97	436.13	164	32	75	75	132	32.0	0.32	132	0

Sep-79	-	5,397,480	436.15	436.24	144	47	75	75	97	47.0	0.32	97	0
Oct-79	-	4,480,920	436.26	436.39	157	68	75	75	89	68.0	0.32	89	0
Nov-79	-	3,708,360	436.35	436.45	157	95	75	75	62	95.0	0.32	62	0
Dec-79	-	3,421,800	436.39	436.38	110	127	58	58	0	127.0	0.32	-17	0
Jan-80	-	4,336,240	436.28	436.30	88	110	36	36	0	110.0	0.32	-22	0
Feb-80	-	5,275,680	436.17	436.16	70	103	3	3	0	103.0	0.32	-33	0
Mar-80	-	6,270,120	436.05	436.12	115	78	40	40	0	78.0	0.32	37	0
Apr-80	-	6,914,560	435.97	436.12	117	41	75	75	41	41.0	0.32	76	0
May-80	-	6,831,000	435.98	436.03	35	32	75	75	3	32.0	0.32	3	0
Jun-80	-	7,606,440	435.89	436.08	159	19	75	75	140	19.0	0.32	140	0
Jul-80	-	5,915,880	436.09	436.07	65	19	75	75	46	19.0	0.32	46	0
Aug-80	-	5,917,320	436.09	436.11	127	32	75	75	95	32.0	0.32	95	0
Sep-80	-	5,036,760	436.20	436.10	99	53	75	75	46	53.0	0.32	46	0
Oct-80	-	5,038,200	436.20	436.02	76	76	75	75	0	76.0	0.32	0	0
Nov-80	-	5,867,640	436.10	435.97	139	100	75	75	39	100.0	0.32	39	0
Dec-80	-	5,995,080	436.08	435.93	124	110	75	75	14	110.0	0.32	14	0
Jan-81	-	6,572,520	436.01	435.80	94	123	46	46	0	123.0	0.32	-29	0
Feb-81	-	7,546,960	435.89	435.67	57	79	24	24	0	79.0	0.32	-22	0
Mar-81	-	8,486,400	435.78	435.57	62	58	28	28	0	58.0	0.32	4	0
Apr-81	-	9,295,840	435.68	435.54	114	45	75	75	22	45.0	0.32	69	0
May-81	-	9,494,280	435.66	435.60	88	30	75	75	58	30.0	0.32	58	0
Jun-81	-	9,279,720	435.69	435.73	209	14	75	75	195	14.0	0.32	195	0
Jul-81	-	6,599,160	436.01	435.83	141	23	75	75	118	23.0	0.32	118	0
Aug-81	-	5,304,600	436.16	435.92	151	36	75	75	115	36.0	0.32	115	0
Sep-81	-	4,064,040	436.31	435.89	63	50	75	75	13	50.0	0.32	13	0
Oct-81	-	4,659,480	436.24	435.89	86	94	67	67	0	94.0	0.32	-8	0
Nov-81	-	5,528,920	436.14	436.10	186	91	75	75	87	91.0	0.32	95	0
Dec-81	-	4,752,360	436.23	436.04	74	103	46	46	0	103.0	0.32	-29	0
Jan-82	-	5,726,800	436.11	435.86	37	140	-57	0	0	140.0	0.32	-103	0
Feb-82	-	7,071,240	435.95	435.92	149	101	48	48	0	101.0	0.32	48	0
Mar-82	-	7,660,680	435.88	435.86	73	63	58	58	0	63.0	0.32	10	0
Apr-82	-	8,440,120	435.79	435.81	101	51	75	75	33	51.0	0.32	50	0
May-82	-	8,590,560	435.77	435.76	61	26	75	75	35	26.0	0.32	35	0
Jun-82	-	8,790,000	435.75	435.83	118	17	75	75	101	17.0	0.32	101	0
Jul-82	-	7,801,440	435.86	435.86	83	21	75	75	62	21.0	0.32	62	0
Aug-82	-	7,514,880	435.90	435.83	42	39	75	75	3	39.0	0.32	3	0
Sep-82	-	8,290,320	435.81	435.82	81	49	75	75	32	49.0	0.32	32	0
Oct-82	-	8,543,760	435.77	435.77	106	79	75	75	27	79.0	0.32	27	0
Nov-82	-	8,887,200	435.73	435.62	59	126	8	8	0	126.0	0.32	-67	0
Dec-82	-	10,051,640	435.59	435.47	65	121	-48	0	0	121.0	0.32	-56	0

Lake Rerewhakaaiti Water Balance Model
Input Data for Calibration

Initial Soil Moisture (mm)	Catchment Area Excluding Lake (km^2)	Lake Area (km^2)
75	65	5
Culvert Flow Coeff	**Seepage Loss (m^3/s)**	**Soil Moisture Storage (mm)**
1	0.32	75

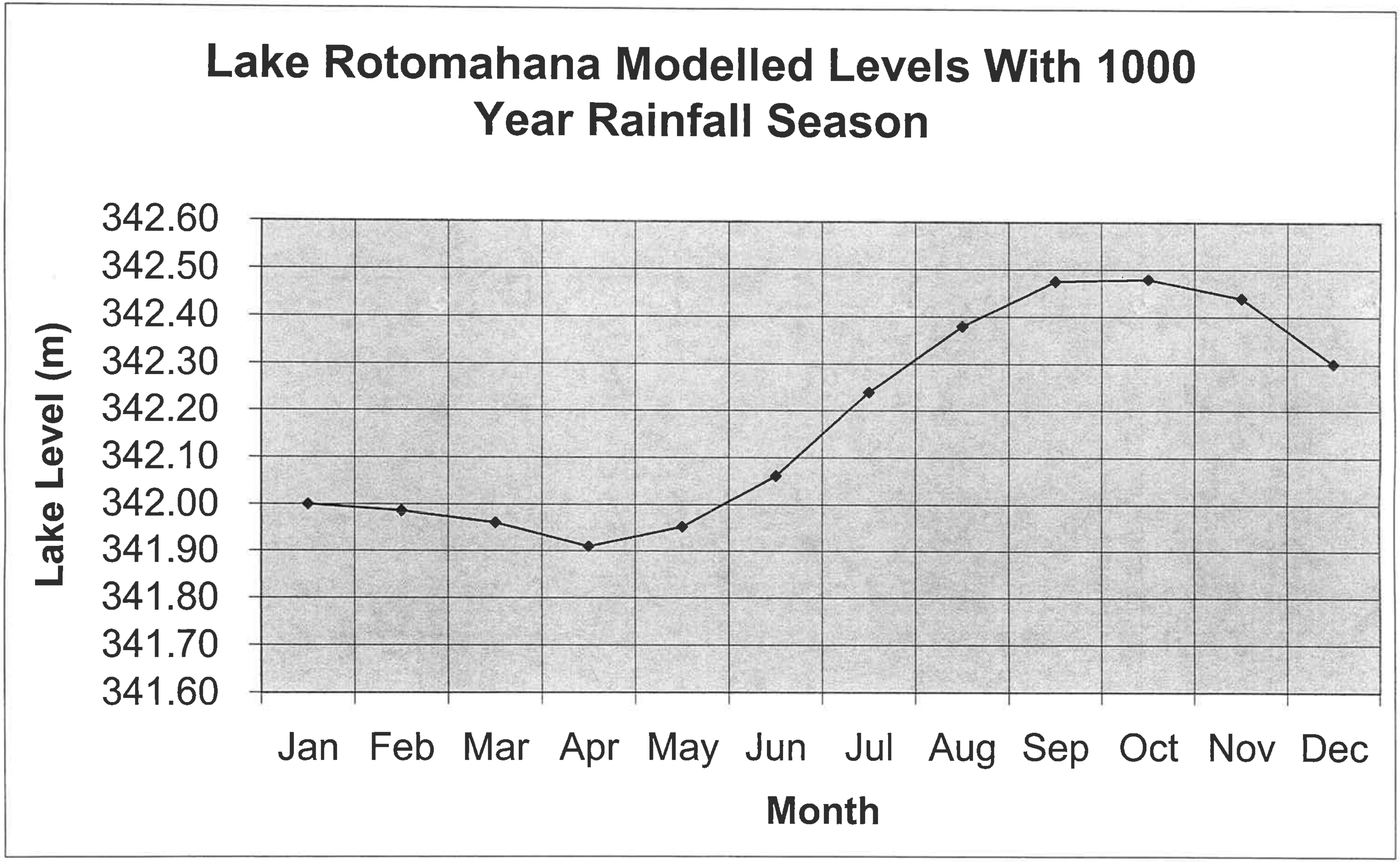
Lake Level metres RL	Lake Volume m^3
435.0	-
438.0	25,000,000

Lake Level (m3/s)	Culvert Outflow (m3/s)
400	0
436.5	0
436.6	0.1
436.7	0.2
436.8	0.4
436.9	0.6
437	1
437.1	1.15
437.2	1.5
437.3	1.7
437.4	1.9
437.5	2.1
437.6	2.3
437.7	2.45
437.8	2.6
437.9	3.3
438	4.0
438.1	4.2
438.2	4.4
438.3	4.6
438.4	4.8
438.5	5.0

APPENDIX 2

WATER BALANCE MODEL

1000 Year Extreme Event


Lake Rotomahana Modelled Levels With 1000 Year Rainfall Season
Lake Level (m)
342.60
342.50
342.40
342.30
342.20
342.10
342.00
341.90
341.80
341.70
341.60
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month

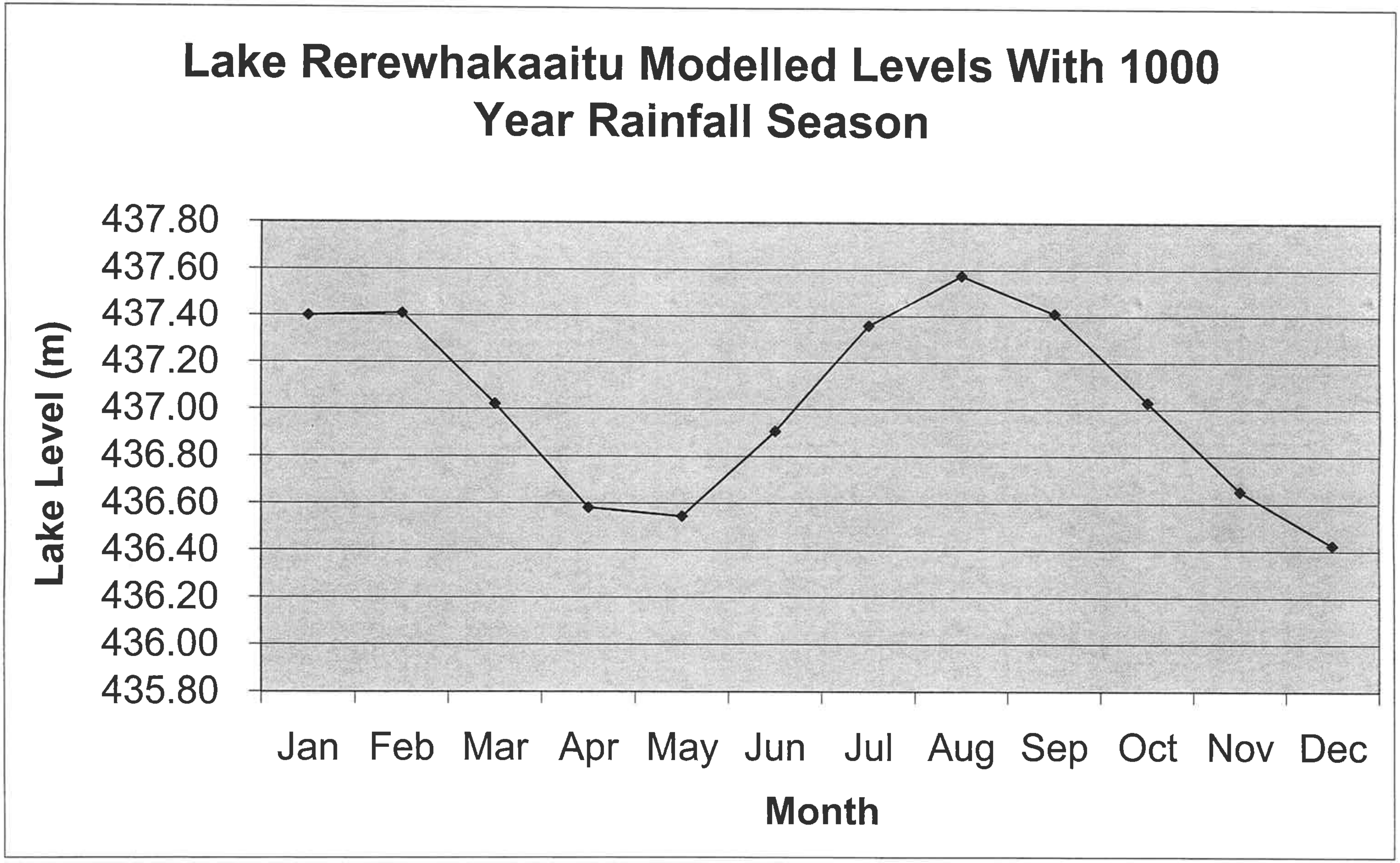
Lake Rotomahana Water Balance Model
1000 Year Rainfall Season

Month	Cumm. Change Lake Volume (m^3)	Modelled Lake Level metres RL	Catchment Rainfall (mm)	Catchment Evapotrans. (mm)	Intermediate If Statement	Soil Root Zone Storage (mm)	Effective Rainfall (mm)	Evaporation (mm)	Seepage Loss (m^3/s)	Rainfall less Evapotrans (mm)	Culvert Outflow (m^3/s)
Jan	-	342.00	207	156	75	75	51.3	156.0	0.55	51.3	0
Feb	- 203,950	341.99	209	124	0	0	160.4	124.0	0.55	85.4	0.8
Mar	- 560,057	341.96	212	96	0	0	115.5	96.0	0.55	115.5	0.8
Apr	- 1,309,920	341.91	230	57	0	0	173.4	57.0	0.55	173.4	0.8
May	- 682,998	341.95	249	36	0	0	213.2	36.0	0.55	213.2	0.8
Jun	892,311	342.06	279	23	0	0	255.5	23.0	0.55	255.5	0.8
Jul	3,474,821	342.24	260	27	0	0	232.7	27.0	0.55	232.7	0.8
Aug	5,513,545	342.38	255	40	0	0	215.5	40.0	0.55	215.5	0.9
Sep	6,883,982	342.47	232	61	0	0	171.5	61.0	0.55	171.5	1
Oct	6,947,148	342.48	239	94	0	0	144.7	94.0	0.55	144.7	1
Nov	6,374,442	342.44	203	119	0	0	84.1	119.0	0.55	84.1	1
Dec	4,359,406	342.30	224	143	0	0	81.1	143.0	0.55	81.1	1

Lake Rotomahana Water Balance Model
Input Data for 1000 Year Rainfall Season

Initial Soil Moisture (mm)	Catchment Area Excluding Lake (km^2)	Lake Area (km^2)	Lake Level metres RL	Lake Volume m^3
75	74	9	337.0	-
Culvert Flow Coeff	**Net Seepage Loss (m^3/s)**	**Soil Moisture Storage (mm)**	343.0	87,000,000
1	0.55	75		

Lake Level (m^3/s)	Culvert Outflow (m^3/s)
335.0	0.00
340.1	0.00
340.3	0.10
340.5	0.20
340.7	0.30
340.9	0.40
341.1	0.50
341.3	0.60
341.5	0.70
341.7	0.75
341.9	0.80
342.1	0.90
342.3	1.00
342.5	1.10
342.7	1.20
342.9	1.30
343.1	1.40
343.3	1.50


Lake Rerewhakaaitu Modelled Levels With 1000 Year Rainfall Season
Lake Level (m)
437.80
437.60
437.40
437.20
437.00
436.80
436.60
436.40
436.20
436.00
435.80
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month

Lake Rerewhakaaiti Water Balance Model
1000 Year Rainfall Season

Month	Cumm. Change Lake Volume (m^3)	Modelled Lake Level metres RL	Catchment Rainfall (mm)	Catchment Evapotrans. (mm)	Intermediate If Statement	Soil Root Zone Storage (mm)	Effective Rainfall (mm)	Evaporation (mm)	Seepage Loss (m^3/s)	Rainfall less Evapotrans (mm)	Culvert Outflow (m^3/s)
jan	-	437.40	207	156	75	75	51.3	156.0	0.32	51.3	0
feb	94,497	437.41	209	124	0	0	160.4	124.0	0.32	85.4	1.9
mar	- 3,147,109	437.02	212	96	0	0	115.5	96.0	0.32	115.5	1.9
apr	- 6,822,019	436.58	230	57	0	0	173.4	57.0	0.32	173.4	1
may	- 7,122,863	436.55	249	36	0	0	213.2	36.0	0.32	213.2	0
jun	- 4,114,439	436.91	279	23	0	0	255.5	23.0	0.32	255.5	0
jul	- 344,266	437.36	260	27	0	0	232.7	27.0	0.32	232.7	0.6
aug	1,459,439	437.58	255	40	0	0	215.5	40.0	0.32	215.5	1.7
sep	102,552	437.41	232	61	0	0	171.5	61.0	0.32	171.5	2.1
oct	- 3,083,795	437.03	239	94	0	0	144.7	94.0	0.32	144.7	1.9
nov	- 6,232,652	436.65	203	119	0	0	84.1	119.0	0.32	84.1	1
dec	- 8,139,548	436.42	224	143	0	0	81.1	143.0	0.32	81.1	0.1

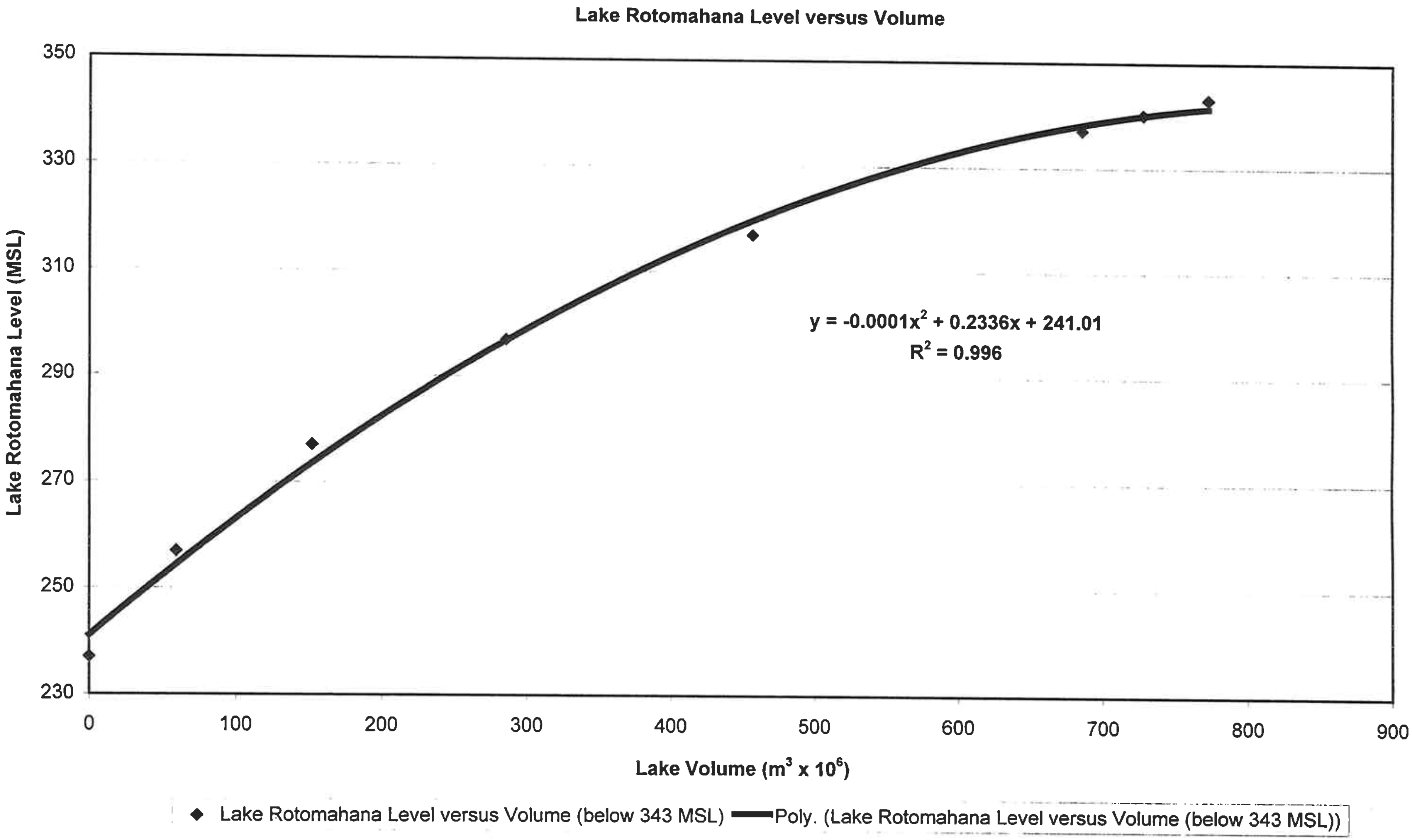
Lake Rerewhakaaiti Water Balance Model
Input Data for 1000 Year Rainfall Season

Initial Soil Moisture (mm)	Catchment Area Excluding Lake (km^2)	Lake Area (km^2)	Lake Level metres RL	Lake Volume m^3
75	65	5	435.0	-
Culvert Flow Coeff	Seepage Loss (m^3/s)	Soil Moisture Storage (mm)	438.0	25,000,000
1	0.32	75		

Lake Level (m^3/s)	Culvert Outflow (m^3/s)
400	0
436.5	0
436.6	0.1
436.7	0.2
436.8	0.4
436.9	0.6
437.0	1.0
437.1	1.15
437.2	1.5
437.3	1.7
437.4	1.9
437.5	2.1
437.6	2.3
437.7	2.45
437.8	2.6
437.9	3.3
438.0	4.0
438.1	4.2
438.2	4.4
438.3	4.6
438.4	4.8
438.5	5.0

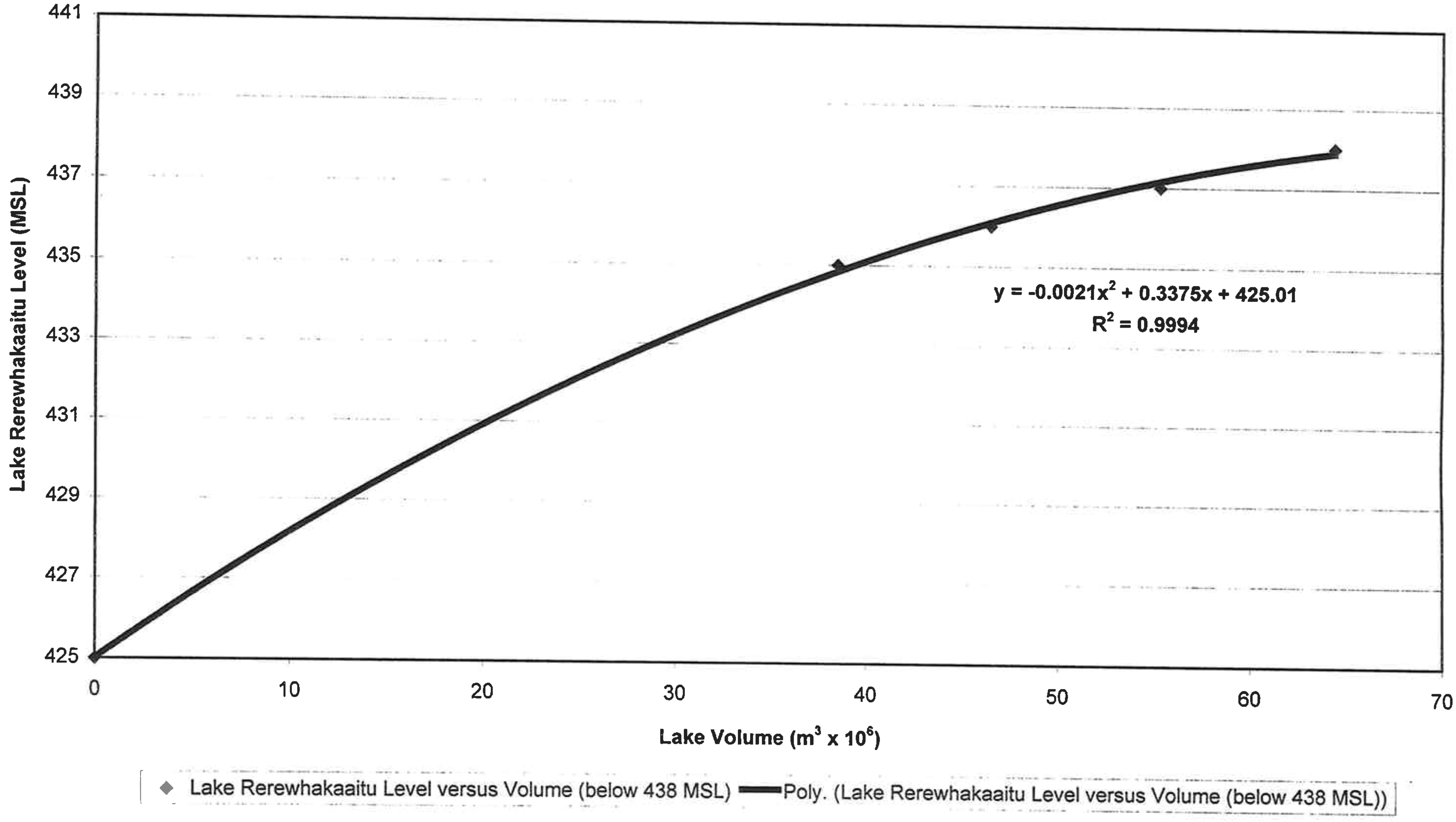
APPENDIX 3

LAKE VOLUME CURVES



Lake Rotomahana Level versus Volume
350
330
310
290
270
250
230
Lake Rotomahana Level (MSL)
0
100
200
300
400
500
600
700
800
900
Lake Volume (m3 x 106)
y = -0.0001x2 + 0.2336x + 241.01
R2 = 0.996
Lake Rotomahana Level versus Volume (below 343 MSL)
Poly. (Lake Rotomahana Level versus Volume (below 343 MSL))

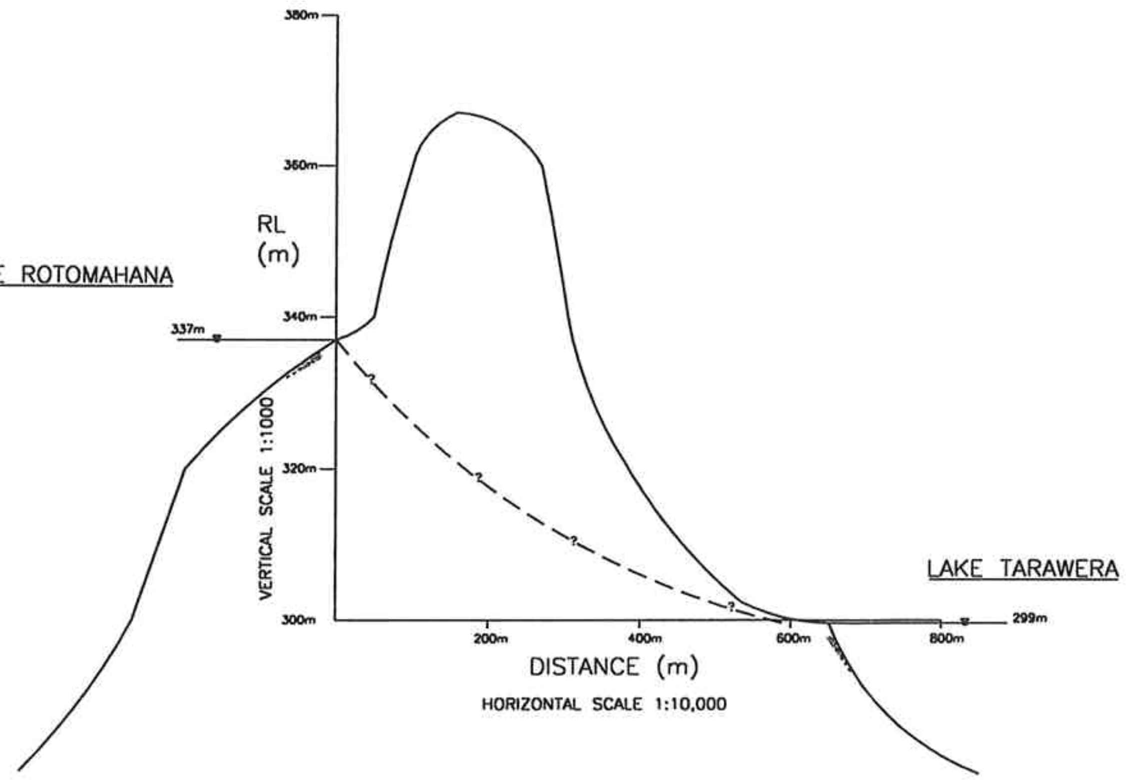
Lake Rerewhakaaitu Level versus Volume



APPENDIX 4

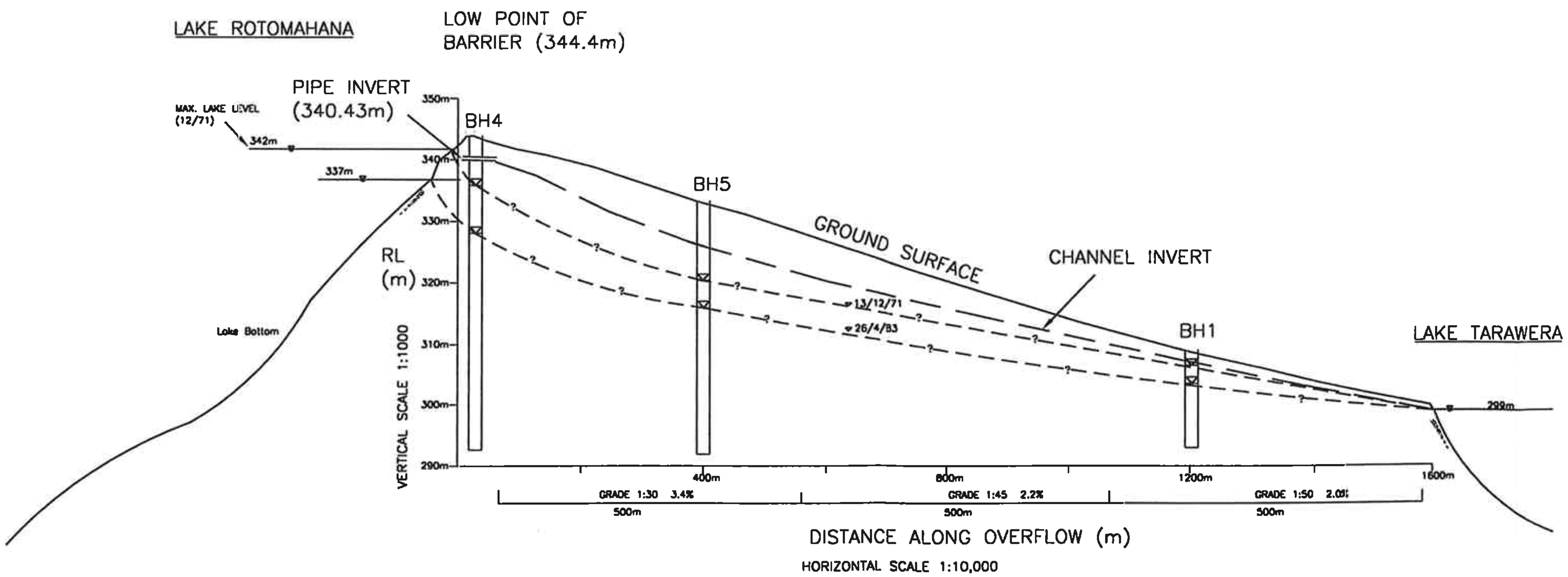
ROTOMAHANA BARRIER SECTIONS

RILEY CONSULTANTS LTD. P.O.Box 100 253 North Shore Mail Centre Auckland Ph +64-9-489 7872 Fax 489 7873



SHORTEST WIDTH CROSS SECTION NEAR TARAWERA ERUPTION MEMORIAL

NOTE:
10 TIMES VERTICAL EXAGERATION



OVERFLOW LONGSECTION

REV:	AMENDMENT:	BY:	DATE:

SCALES: AS SHOWN — DRAWN: RDP — CHECKED: PBR

TITLE:

LAKE ROTOMAHANA OUTLET STUDY

ROTOMAHANA BARRIER

SECTIONS

RILEY CONSULTANTS LTD
Engineers and Geologists

DATE: MARCH 2003 — DRAWING No.: 03108-1

ACENZ