Groundwater in the Okataina caldera:

Model of future nitrogen loads to Lake Tarawera

CBER Report 94

Prepared for Environment Bay of Plenty and
Lake Tarawera Ratepayers' Association

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1. Introduction

Protection and restoration of water quality are a major priority of the New Zealand government[1]. To support this objective, a monitoring and an action programme named "The Regional Water and Land Plan" was set up by the Environment Bay of Plenty Regional Council in February 2005 for the Rotorua lakes district[2]. Lake Tarawera is part of this programme. The plan includes a Tarawera River management plan developed originally by Bay of Plenty Catchment Commission (1985).

Currently water quality of Lake Tarawera is slightly worse than during the 1990s (Environment Bay of Plenty 1997). The Trophic Level Index (TLI), a measure of water quality, is 2.9 in Lake Tarawera. Environment Bay of Plenty wishes to reduce the TLI to 2.6, to improve the water quality of the lake. Actions have already been programmed to support this initiative, including sewage treatment[3].

Most of the water inflow to the lake is from groundwater. Nitrogen loads to the lake from groundwater are largely unknown as there is limited monitoring data. Development of highly productive pasture in the last 50 years, coupled with a residence time for the groundwater estimated on average to be c. 200 years, look likely to result in increasing nutrient loads to the lake with potential for deterioration of water quality.

The objective of this study was to assess current and future groundwater nutrient loads to Lake Tarawera, particularly nitrogen loads. Following a consideration of the Lake Tarawera catchment water balance, a hydrogeological model was created. Nitrogen discharge with groundwater to Lake Tarawera is assessed based on pre-development land use, current land use and scenarios of future land use, allowing conclusions to be made for priorities for the maintenance of lake water quality.

[1] See www.mfe.govt.nz
[2] See www.ebop.govt.nz
[3] See www.lernz.co.nz and the On-Site Effluent Treatment Regional Plan (2006) (www.ebop.govt.nz)

2. Geomorphology and Land Use

2.1 Okataina Volcanic Centre

The Okataina Volcanic Centre (OVC), located east of Lake Rotorua, has given rise to eight lakes (Figure 1) within the Okataina Caldera complex. Topography of the Okataina Volcanic Centre is marked by volcanic domes, plateaus, hills and plains. The eastern part of the study area is dominated by Maikati Dome (934 m), Mount Tarawera including Tarawera Dome (1,050m), Ruawahia Dome (1,111 m) and Wahanga Dome (1,047 m). The southern part of the OVC consists of plateaus and hills. The western and northern parts of the study area include hills and valleys bounded by the Rotorua and Rotoiti catchments. Ground elevations for the whole area range from 1,111 m at the Ruawahia Dome to 299 m on the edge of Lake Tarawera. The catchment area of the eight lakes is approximately 331 km^2 (Table 1).

The chronology of lake formation is described by Nairn (2002):

- Lake Okareka (formed circa 19,000 yr B.P.)

  The earliest formed lake of the Okataina Caldera complex is Lake Okareka. It is located at an altitude of 355 m on the eastern part of the caldera. The lake occupies an area of 3.34 km^2 in a valley eroded back into the ignimbrite plateau.

- Lake Tikitapu (Blue Lake) and Lake Rotokakahi. (Green Lake) (formed circa 13,300 yr B.P.)

  Located respectively at an altitude of 417 m and 394 m, these lakes were formed after damming of lava from a Rotorua ash eruptive episode. They occupy an area of 1.46 km^2 (Lake Tikitapu) and 4.52 km^2 (Lake Rotokakahi).

- Lake Okataina (formed circa 7000 yr B.P.)

  Lake Okataina was formed after lava flows of a rhyolite eruptive episode dammed the valley which formed from the eastern margin. The eroded walls of the Haroharo Caldera form the western margin of the lake. Lake Okataina has an area of 10.8 km^2.

- Lake Tarawera (formed circa 5000 yr B.P.)

  Around 2000 years after the formation of Lake Okataina, with Haraharo and Tarawera volcanoes erupted and lava flows delimited a basin which progressively filled with water to produce the Lake Tarawera. This lake has the largest area (41.65 km^2) and the lowest elevation (299 m) of the OVC lakes.

- Lake Rerewhakaaitu (formed circa 700 yr B.P.)

Lake Rerewhakaaitu was formed by a pyroclastic eruption that created a dam. The lake occupies an area of 5.3 km^2 and has an altitude of 438 m.

- Lake Rotomahana (formed circa 111 yr B.P.)

The present Lake Rotomahana was created by a series of hydrothermal explosions at the south-west of Mount Tarawera. Deep craters subsequently filled to form the current lake which has a water level of 335 m above mean sea level and an area of 8.99 km^2.

Most of the Okataina caldera complex is covered by forest (Table 1), especially on the northern and eastern parts, on the slopes of the volcanic domes. Pasture is concentrated in the southern caldera, around Lakes Rerewhakaaitu and Okaro. The western plains are farmed for beef, deer and sheep. Human presence in the study area is localized mainly around the lakes, in small towns such as Okareka and on the edge of the western edge of Lake Tarawera. Rotorua City is the nearest developed urban area, with a population of approximately 65,901 (Government census 2006).

Table 1 - Summary statistics for the lakes and land use for each surface catchment (Environment Bay of Plenty, 2003).

Lake	***Age (years BP)***	***Lake elevation (m)***	***Lake area (km^2)***	***Catchment area (km^2)***	***Surface catchment land cover (%) in 2003***				
					Indigenous forest	Exotic forest	Pasture	Wetlands	Urban
Rerewhakaaitu	700	438	5.3	37.0	7.2	15.2	75.3	2.3	0.0
Rotomahana	111	335	8.99	83.3	39.7	16.3	43.2	0.0	0.0
Rotokakahi	13,300	394	4.5	19.7	16.6	57.1	26.3	0.0	0.0
Tikitapu	13,300	417	1.46	6.2	79.2	17.3	3.5	0.0	0.0
Okareka	19,000	355	3.3	19.6	51.6	7.6	37.8	0.0	2.9
Okaro	800	412	0.33	3.89	2.1	6.3	90.6	0.0	0.0
Okataina	7,000	311	10.8	59.8	84.1	7.8	7.8	0.0	0.0
Tarawera	5,000	299	41.7	101.4	62.4	16.0	19.7	1.2	0.7
TOTAL			76.38	330.89					

Figure 1 - Topographic map (MapToaster Topo NZ 1:250,000) of the Okataina Volcanic Centre; east of Lake Rotorua.

2.2 Lake Tarawera surface catchment

The Lake Tarawera catchment (Figure 2) includes hills, volcanic domes and plateaus, with the lake being the lowest part of the catchment.

To the east, Lake Tarawera outlet is surrounded by domes that form the highest parts of the catchment. The high point to the south is Mount Tarawera, which is composed of several domes. To the north is Makatiti Dome (934 m elevation) which is part of the Okataina Volcanic Centre. Both have unstable slopes criss-crossed with thalwegs that can give rise to ephemeral streams and landslides after heavy rains.

The southern part of the Lake Tarawera catchment, linking Lake Rotomahana and Lake Tarawera, is gently sloping. This area includes areas with geothermal activity (Section 4.2). Two plateaus occur to the west, separated by the valley formed by Te Wairoa stream coming from Lake Rotokakahi.

The northern catchment includes a boundary of Mamaku Ignimbrite, erupted from the Rotorua caldera, with a gentle slope to Lake Tarawera, and a collapsed part of the OVC which has created a natural barrier between Lake Okataina and Lake Tarawera.

Land use in the Lake Tarawera catchment is dominated by indigenous forest (Figure 3). Scrub occurs on the northern and eastern slopes of the mountains. The western catchment of Lake Tarawera includes pasture, with sheep, beef and deer cattle and dairy land uses. Human habitation occurs around the western edge of the Lake Tarawera (Figure 2).

Table 2 shows a comparison of land use for Lake Tarawera catchment between 1986 (White and Cooper 1991), 1996 (Scholes 2000) and 2003 (Scholes 2005).

The area in pasture has increased between 1986, when pasture occupied 16% of the catchment land area, and 2003 when pasture occupied 21% of the catchment land area. This increase in pastoral land use is translated to an increase of nitrogen exports from 32.7 tonnes N/yr in 1986 to 35 tonnes N/yr in 2003, i.e. an increase of approximately 7% (Table 3). This calculation assumes mean nutrient yields of 0.25 tonnes N/km^2/yr for forest, 0.7 tonnes N/km^2/yr for the pasture and 0.29 tonnes N/km^2/yr for urban land use (Hamilton *et al*. 2006).

The increase of nitrogen export from the land shows how important the assessment options of future land use are to prevent deterioration of Lake Tarawera water quality.

Table 2 - Lake Tarawera catchment land use from 1986 (White and Cooper 1991) to 2003 (Scholes 2005).

	Lake Tarawera catchment land use					
	1986		**1996**		**2003**	
	Area (km^2)	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**
Indigenous forest	67	66	66	65	63.9	63
Exotic forest	17.2	17	16.2	16	15.2	15
Pasture	16.2	16	18.2	18	21.3	21
Urban	1	1	1	1	1	1
Total	101.4	100	101.4	100	101.4	100

Table 3 - Estimates of nitrogen export evolution for the different surfaces of the Lake Tarawera catchment from 1986 (White and Cooper 1991) to 2003 (Scholes 2005).

	Nitrogen export (tonnes N/yr)		
	1986	**1996**	**2003**
Indigenous forest	16.8	16.6	16
Exotic forest	4.2	4	3.8
Pasture	11.4	12.8	14.9
Urban	0.3	0.3	0.3
Total	**32.7**	**33.7**	**35**

Figure 2 - Lake Tarawera catchment topographic map.

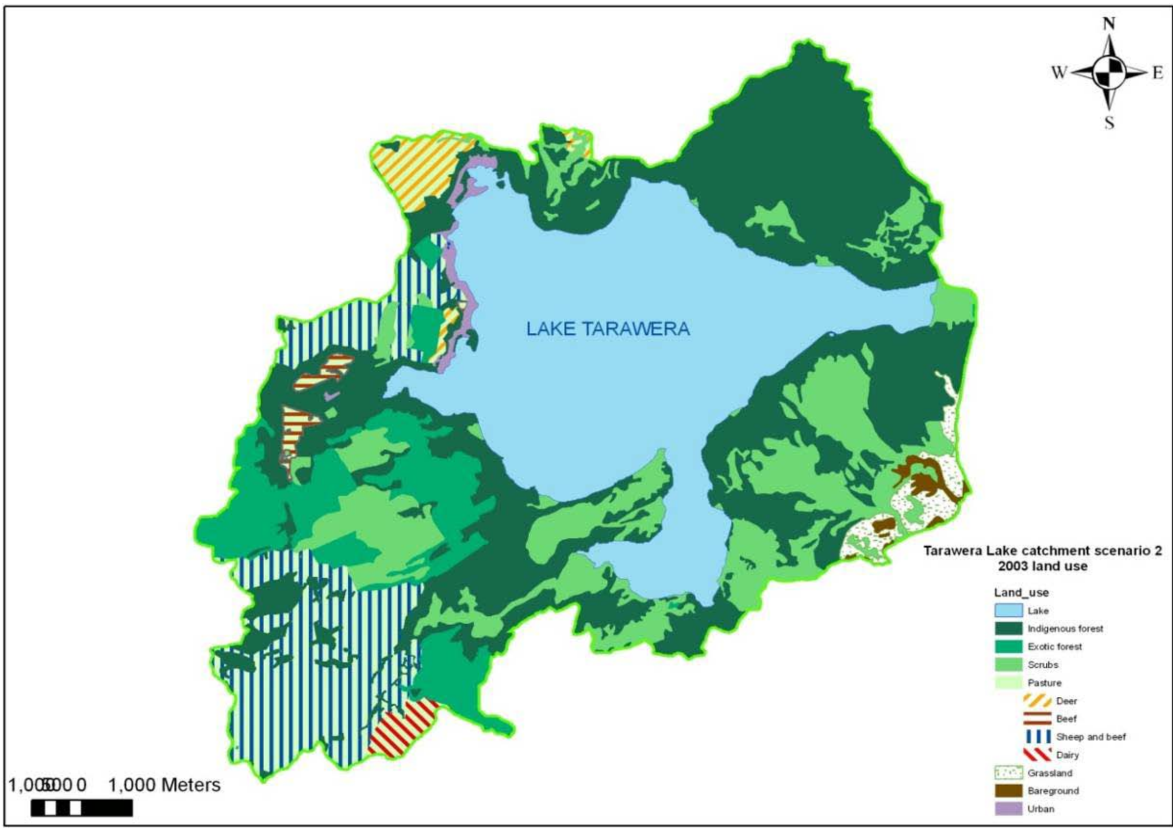

Figure 3 - Land use of the Lake Tarawera catchment in 2003.

3. Geology

3.1 Geological history and lithological description of the Okataina Caldera complex

The geology of the Okataina Caldera Complex (Figure 4) has been shaped by volcanic events. Calderas have been formed during the last 400,000 years, with two major and some smaller eruptions (Nairn 2002). Described here are the geological units that are most relevant to the hydrogeological model.

3.1.1 Whakamaru Ignimbrite

Early pyroclastic eruptions from the Okataina Volcanic Centre (OVC) were from multiple source calderas in the central Taupo Volcanic Zone (TVZ) at around 0.34 Ma. Termed the Whakamaru Group Pyroclastics, they form the basal units for groundwater aquifers in the Rotorua catchment. A period of frequent eruptions sent extensive ignimbrite sheets from a probable source in Maroa Caldera to the north (Wilson *et al*. 1995). In the Rotorua area, drillholes have penetrated at least 100 m of Rangitaiki Ignimbrite; part of the Whakamaru Group ignimbrites (Wilson *et al.* 1995; Nairn 2002). In general, the Whakamaru Group pyroclastics are non-welded to moderately welded with some jointing observed in the eastern margin of the Puhipuhi Basin in the OVC. The distinguishing feature of these ignimbrites is that they are dark grey, crystal-rich, with abundant, large and predominantly quartz crystals (Nairn 2002)

3.1.2 Matahina Ignimbrite

Matahina ignimbrite was erupted mainly from the eastern OVC around 0.28 Ma (Houghton *et al*. 1995) and can be divided into a basal pyroclastic fall deposit, with three overlying pyroclastic flow deposits. In the OVC area, the ignimbrite is commonly a compacted to moderately welded light brown tuff, with lithic rhyolite and vesiculated obsidian inclusions, and large devitrified pumice fragments. The unwelded basal plinian lapilli beds are about 2 m thick on the south shore of Lake Rotoma and up to 4 m thick at the east at Lake Rerewhakaaitu. Isolated areas also outcrop on the southeast shore of the Lake Rotomahana, just within Haroharo Caldera (Nairn 2002).

3.1.3 Pokopoko-Onuku Pyroclastics

Matahina ignimbrite is interbedded with the Pokopoko Pyroclastics and Onuku Pyroclastics. These layers have an estimated age of between 0.23 Ma and 0.28 Ma (Nairn 2002).

Pokopoko Pyroclastics are very coarse near Lake Okataina and Lake Okareka, signifying that the source is in close proximity, probably the vents within western OVC. Onuku Pyroclastics are largely pyroclastic flow and fall deposits with weak soil development interspersed between units, indicating that these deposits were laid down over time. They are made up of moderately compacted pumice-rich pyroclastic fall and flow units. The fall units are shower-bedded and are interspersed between pyroclastic flow units. The Onuku pyroclastics probably emanate from within OVC (Nairn 2002).

Pokopoko-Onuku pyroclastics include moderately compacted to welded pyroclastic flow components, are crystal-poor and exceed 120 m in depth near lakes Okareka, Tarawera and Okataina (Nairn 2002). The geology in groundwater drillholes at Mamaku Township, where drilling penetrated through about 15 m of Pokopoko pyroclastics (Wood 1985), indicates that pyroclastic flows did not go far west of the town. These deposits were later buried beneath the Mamaku Ignimbrite (Morgenstern et al. 2004).

3.1.4 Kaingaroa Ignimbrite

Kaingaroa ignimbrite erupted from nearby Reporoa Caldera at 0.23 Ma. The lower unit is sandy and grades up into a pumice-rich unit, with no visible contact or grading of lithics, and slight normal grading of pumice abundance. The lower unit is a non-welded to partially welded, pumice-rich sandy ignimbrite with two distinct pumice types. The upper unit is exposed around Kawerau, where it underlies Rotoiti Breccia. The upper unit is a non-welded, pumice-poor ignimbrite with localised, 0.5 m thick, fines-depleted pumice concentration zones, (Beresford and Cole 2000).

3.1.5 Mamaku Ignimbrite

Mamaku ignimbrite is generally considered to have erupted at 0.22 Ma from Rotorua Caldera (Healy 1964a; Healy 1964b; Briggs 1973; Wood 1992; Wilson *et al*. 1984; Houghton *et al*. 1995). It consists of three main subunits; lower, middle and upper (Milner *et al*. 2003). The upper and lower subunits are non-welded and predominantly fine-grained. On the north-western side of the OVC, the upper Mamaku ignimbrite, where it is at least 70 m thick, consists of a fine-grained ignimbrite containing devitrified pumice. The middle subunit is strongly welded with cooling joints that are 0.5 to 4 m wide (Milner *et al*. 2003).

3.1.6 Rotoiti Pyroclastics

Rotoiti pyroclastics appear to have erupted from fissures within the basement fracture zone at c.65 ka, as the first voluminous ignimbrite from the northern part of Haroharo Caldera, which collapsed as a result (Ewart and Healy 1965; Nairn 1981; Nairn 2002).

Rotoiti pyroclastics is a composite term for the entire Rotoiti eruptive sequence, including numerous, widespread, fall deposits (Rotoehu Tephra) underlying, intercalated and overlying climactic flow deposits (Rotoiti Ignimbrite; Nairn 2002). Rotoiti pyroclastics were erupted from the northern part of Haroharo Caldera, within OVC. Rotoiti Ignimbrite flow units are non-welded, are generally fine to coarse grained and crystal-rich, deposited mainly north and west of Haroharo Caldera and can measure up to 100 m thick. The widely dispersed and fine-grained Rotoehu Tephra is approximately 5 m thick on the western side of Lake Okataina. Crustal collapse within Haroharo Caldera likely occurred during and immediately after the Rotoiti eruption (Nairn 2002).

3.1.7 Huka Group Sediments

Huka Group sediments include reworked volcanic material, diatomaceous silts, interbedded gravels, and pyroclastic deposits from the frequently-active OVC (Nairn 2002). An 80 m maximum thickness of Huka Group sediments has been drilled in some geothermal and groundwater wells in the Lake Rotorua catchment, on the western side of the study area (Morgenstern et al. 2004).

Lake sediments were deposited after the eruption of Mamaku Ignimbrite. A large area of lake sediments marks the aerial coverage of the post-Mamaku and post-Rotoiti Ignimbrite higher stand shorelines in the Rotorua caldera (Marx in prep.).

3.1.8 Recent Okataina Rhyolites

Rhyolitic pyroclastic eruptions which formed calderas were followed by the Mangaone Pyroclastics sequence of eruptions between 45 ka and 28 ka. Haroharo and Tarawera volcanic complexes were formed in an intracaldera sequence in 11 separate eruptive episodes post-22 ka. Over the last 22 ka, about 80 km^2 of rhyolitic magma and 1 km^3 of basalt were erupted from 40 or more vents within the OVC (Nairn 1992; Nairn 2002). Eruptions occurred from a number of separate vents along underlying fissures defined by two north-east trending zones running almost parallel to each other (Nairn, 2002). Table 4 and 5 summarize the lava flows into eruptive episodes with their associated pyroclastic deposits.

3.1.9 Holocene alluvium

Alluvium laid down after 1886 has been recorded in the Lake Rotomahana and Lake Tarawera area. Deposits of Rotomahana Pyroclastics and the Tarawera Pyroclastics represented by remixed ash and scoria, has been found in drainage channels and at the bottom of the lakes (Nairn 2002).

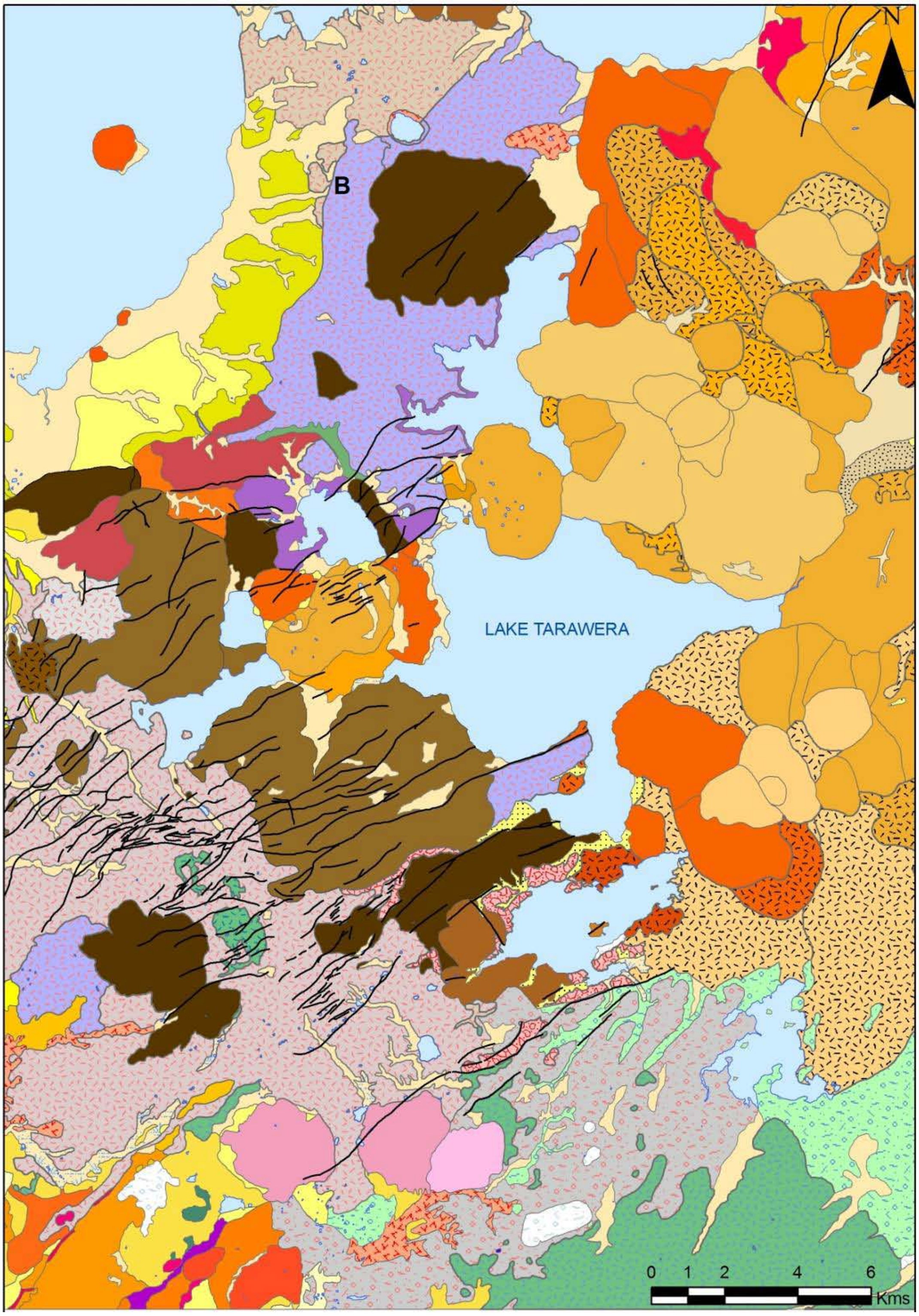

Figure 4 - Geological map of the Okataina Volcanic Centre (Nairn 2002).

Table 4 - Stratigraphy and chronology of Haroharo vent zone lavas and pyroclastics (Nairn 2002).

Eruptive Episode and Age	Lavas	Pyroclastics
Whakatane	*Makatiti dome*	} Minor pyroclastic eruptions
5 ka	*Haroharo dome*	
	Pararoa dome	
	Makatiti lava flows	*Makatiti pyroclastics*
	Rotokohu dome	*Pararoa pyroclastics*
	Okataina lava flow	*Rotokohu pyroclastics*
	Tapahoro dome	*Whakatane Tephra*
	Tapahoro lava flows	
	Rotoroniu lava flows	
		Te Whekau explosion brecchia
Mamaku	*Te Horoa dome*	*Te Horoa Pyroclastics*
7.5 ka	*Hainini dome*	
	Hainini lava flow	
	Te Matae lava flow	*Parewhaiti Pyroclastics*
	PArewhaiti dome	*Hainini Pyroclastics*
	Ruakokopu lava flow	
	?Otangimoana lava flow	*Mamaku Tephra*
	?Oruaroa lava flow	
	Waiti lava flow	
	Kaipara lava flow	
		?Otamuri Pyroclastics
Rotoma	*Te Pohue lava flows*	*Tuahu Pyroclastics*
9ka		*Rotoma Tephra*
	Rotoma lava flows	*Matutu Pyroclastics*
		Rotorua pyroclastics
Rotorua	*Trig 7693 lava B*	*Rotorua Tephra*
13.5ka		
Te Rere	*Haumingi lava flow*	*?Te whekau explosion breccias*
21ka	*Te Koutu lava flow*	*?Tapuaeharuru Pyroclastics*
	Tuarae lava flow	*?Te Haehaenga Pyroclastics*
	?Fenton's Mill lava flow	*explosion breccias from*
	?Northern dome (at Okareka)	*Rotokakahi*
	Trig 7693 lava A	*Te Rere tephra*

Table 5 - Stratigraphy and chronology of Tarawera Volcanic Complex lavas and pyroclastics (Nairn 2002).

Eruptive Episodes and Age	Lavas	Pyroclastics
Tarawera *1886 AD*	*Basalt dikes beneath* *1886 AD craters*	*Tarawera Pyroclastics* *Rotomahana Pyroclastics* *Rotomahana Tephra*
Kaharoa *0.7 ka*	*Ruawahia, Tarawera,* *Wahanga domes* *Green Lake plug* *Crater dome*	*Kaharoa Pyroclastics* *Kaharoa Tephra*
Waiohau *11 ka*	*Kanakana dome* *Pokohu lava flows* *Waikakareao lava flows* *Eastern dome*	*Waiohau Pyroclastics* *Waiohau Tephra* *Local pyroclastic deposits* *at Rotomahana*
Rerewhakaaitu *15 ka*	*Southern dome* *?Te Puha lava flow* *Western dome* *?Rotomahana dome*	*Rerewhakaaitu Pyroclastics* *(tuff cone)* *Rerewhakaaitu Tephra*
Okareka *18 ka*	*?Ridge dome* *Ridge lava flow* *Hawea lava flow* *Patiti Island*	*Okareka Tephra* *Scoria fall*

3.2 Tarawera geological model

Lake Tarawera’s catchment (Figure 2) is in the heart of the OVC and is underlain by all the geological units introduced in Section 3.1. A cross section built from the OVC geological map shows a possible repartition of these layers (Figure 5).

Pamer (pers. comm.) built a 3D model of the Okataina caldera complex from this cross section, drill holes, the geological map and digital elevation data (Figure 6 and Figure 7). This model is used here to simplify the Tarawera catchment into 3 general layers:

- Okataina rhyolites, which include all the different erupted pumices, old and recent;
- Pokopoko-Onuku Ignimbrites;
- Matahina Ignimbrite.

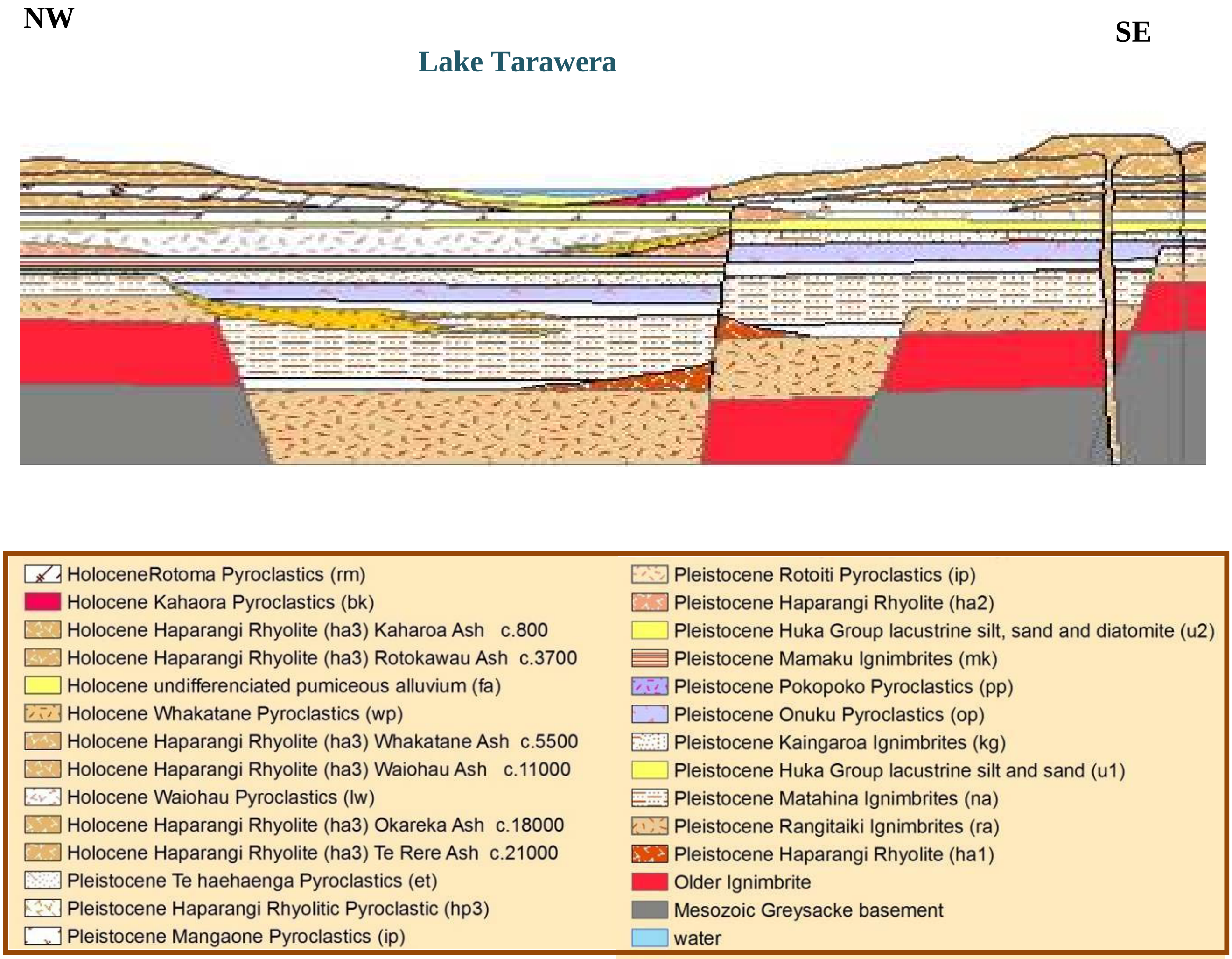

Figure 5 – Lake Tarawera catchment NW-SE cross section (New Zealand Geological Survey (1989).

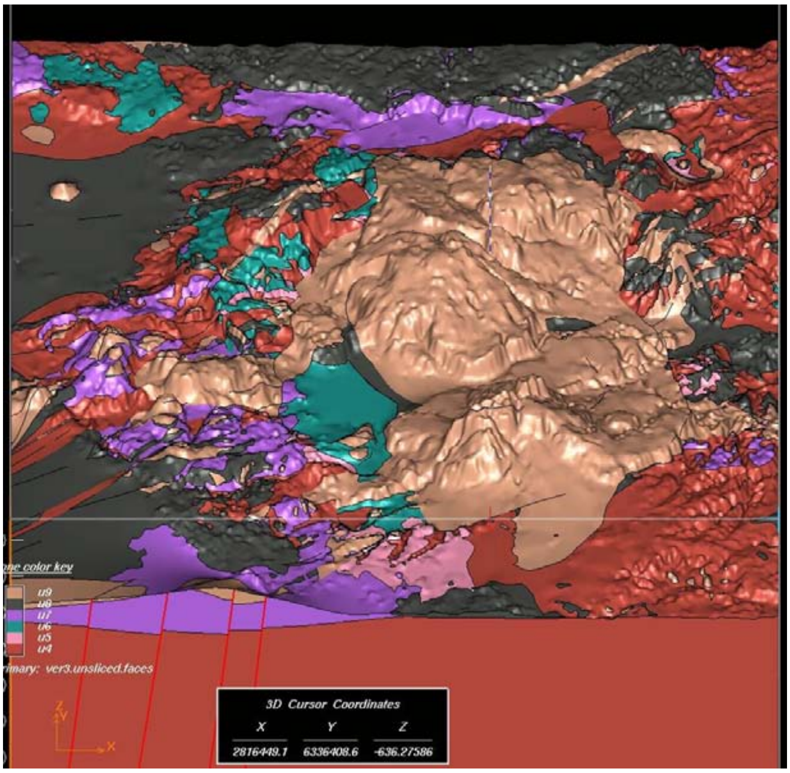

Figure 6 - Three-dimensional model of Okataina Caldera complex (Pamer pers. comm.).

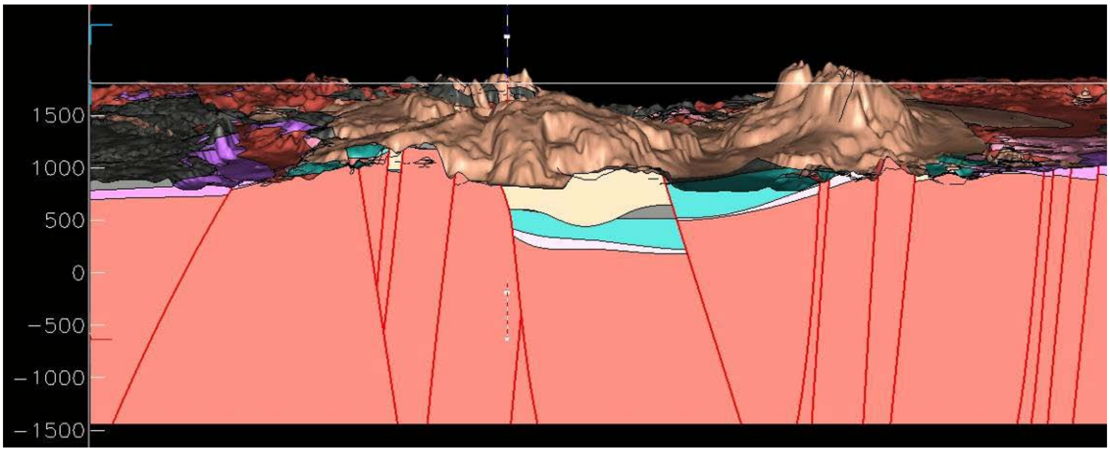

Figure 7 - North-south vertical geological cross section of the Lake Tarawera catchment (Pamer pers. comm.).

4. Hydrogeology

4.1 Aquifer layers

Groundwater resources in the catchment of the Okataina Volcanic Centre are poorly understood mainly because of the low demand for the groundwater and the predominantly forestry land use. Seven geological formations in the Lake Tarawera catchment have been identified as possible aquifers based on surface geology in the catchment and from a hydrogeological investigation in the neighbouring Lake Rotorua catchment. (White *et al*. 2004):

- Matahina Ignimbrite;
- Onuku – Pokopoko Pyroclastics;
- Old TVZ rhyolite lava;
- Mamaku Ignimbrite;
- Active TVZ rhyolite lava;
- Huka Group sediments;
- Holocene alluvium.

Some studies relate horizontal conductivity values for these geological units. Tracey (1986) showed that the degree of welding controls the hydraulic conductivity in an inverse manner. Densely welded material is more likely to contain cooling fractures giving rise to high bulk conductivities. Pumping test data from various ignimbrites indicate a high degree of uniformity and also fairly consistent values for transmissivity and storativity for ignimbrites. Highly jointed zones, densely welded zones and inter-ignimbrite contacts are the dominant and most efficient groundwater paths, whereas the poorly welded zones typically have very little groundwater flow, despite their high (50-60%) porosities. Hind (1986) thus estimated that densely welded ignimbrites have hydraulic conductivities of approximately 3×10^{-3} m/s and poorly welded ignimbrites of approximately 6×10^{-6} m/s.

The results of Reeves *et al*. (2005) coincide with this estimation. He assessed, from pump tests in the Lake Rotorua catchment, the Mamaku Ignimbrite hydraulic conductivity as 7×10^{-4} m/s (60 m/day) and Huka group sediments a hydraulic conductivity as 5.5×10^{-5} m/s (4.7 m/day).

Another study from Pang (1994) of groundwater in the lower Tarawera catchment reports estimated hydraulic conductivity of 60-100 m/day for greywacke, between 30-50 m/day for alluvium and between 10-50 m/day for sands and pumice, on the Rangitaiki Plains, south-east of the OVC.

Previously, two studies (Groundwater Consultants 1983, Groundwater Consultants 1984) of the Rangitaiki Plains assessed an average hydraulic conductivity of 70 m/day for the ignimbrites, 85 m/day for the pumice sands and 35 m/day for the coarse pumice gravels.

Continuity of the layers, seepage between them and the impact of faults on hydraulic conductivities and flow directions are unknown. Hydraulic conductivities of the water-bearing geological units in the OVC are assumed (Table 6) from observations in neighbouring catchments.

Table 6 - Estimated horizontal hydraulic conductivities of aquifers in the Lake Tarawera catchment.

Geological unit	Welding degree/ material	Assumed hydraulic conductivity ($m.d^{-1}$)
Matahina Ignimbrite	moderately compacted pumice	30
Pokopoko-Onuku	moderately compacted pumice	30
Kaigaroa Ignimbrite	sandy, partially welded pumice	20
Mamaku Ignimbrite (middle)	Strongly welded pumice	6
Okataina Rhyolites	Pumice	20
Huka Group sediments	Sandstones	4.7
Holocene alluviums	Alluvium	40

4.2 Geothermal features

The Okataina Lakes Complex is situated within the Haroharo Caldera. Beneath the caldera there is presumably an acidic magma chamber, with its upper surface within 3 km of the ground surface (Rogan 1982). This reservoir has contributed to geothermal activity, particularly close to the lakes (Figure 7).

Geothermal water has temperatures above 30 °C (Bioresearches Group Ltd 2003). These waters are oxidising and can dissolve minerals in rocks. Thus, the quantification of geothermal water inflows to the lakes is essential for the nutrient budget because these flows may carry a high nitrogen load (Bioresearches Group Ltd 2003).

Among the Okataina caldera lakes, Lake Tarawera and Lake Rotomahana are supplied by hot springs (Figure 8). Located on the southern shores of Lake Tarawera, the Tarawera geothermal area includes the Wairua Stream, the Rapatu Bay (Hot Water Beach) hot springs, Te Puha and Tarawera fumaroles. Data obtained from these springs indicates that they are hot (37-90^{o}C; Nairn 1974), with a flow estimated to be 0.1 m^3/s and would contribute approximately 0.41 tonnes per year of TN to the lake (Bioresearches Group Ltd 2003).

Two other flows supply the lake with hot water: Tarawera Peak/ Camp Stream and a spring 100 m north of a waterfall. These flows have been estimated as 0.1 m^3s^{-1} and contribute around 0.83 tonnes per year TN (Bioresearches Group Ltd 2003).

Surface hydrothermal activity in the Lake Rotomahana catchment occurs mainly along the western shore, where it extends north from the adjacent Waimangu thermal area, as boiling springs, geysers and fumaroles. Large upwellings of hot water in the lake indicate the location of major submerged hot springs 10-20 m offshore. Total heat flow from this area has not been estimated, but visual comparison with other measured areas suggests that this lake has the largest geothermal inputs of any of the Rotorua lakes (Timperley and Vigor-Brown 1986).

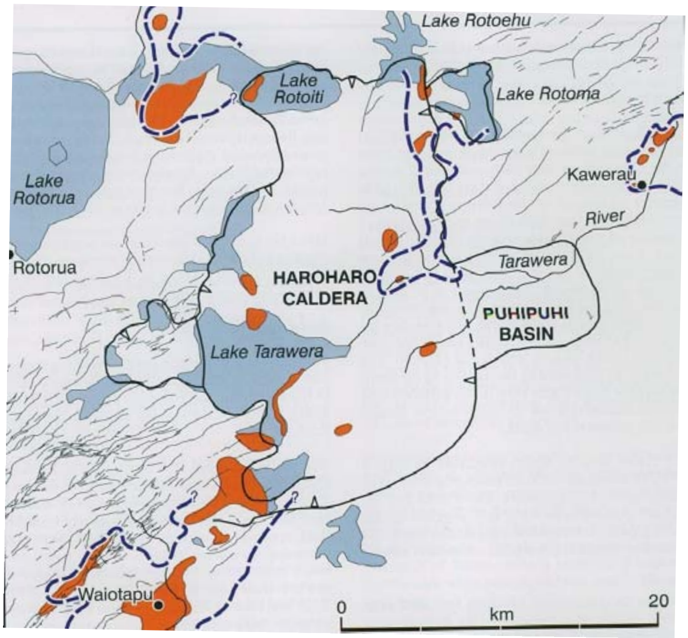

Figure 8 - Geothermal areas (in orange) in the OVC (Nairn, 2002).

5. Surface Hydrology

Figure 9 presents the surface inflow monitoring sites in the Lake Tarawera catchment and Lake Tarawera outflow. Flows are assessed from the Environment Bay of Plenty gauging flow database for measurements recorded between 1994 and 2003.

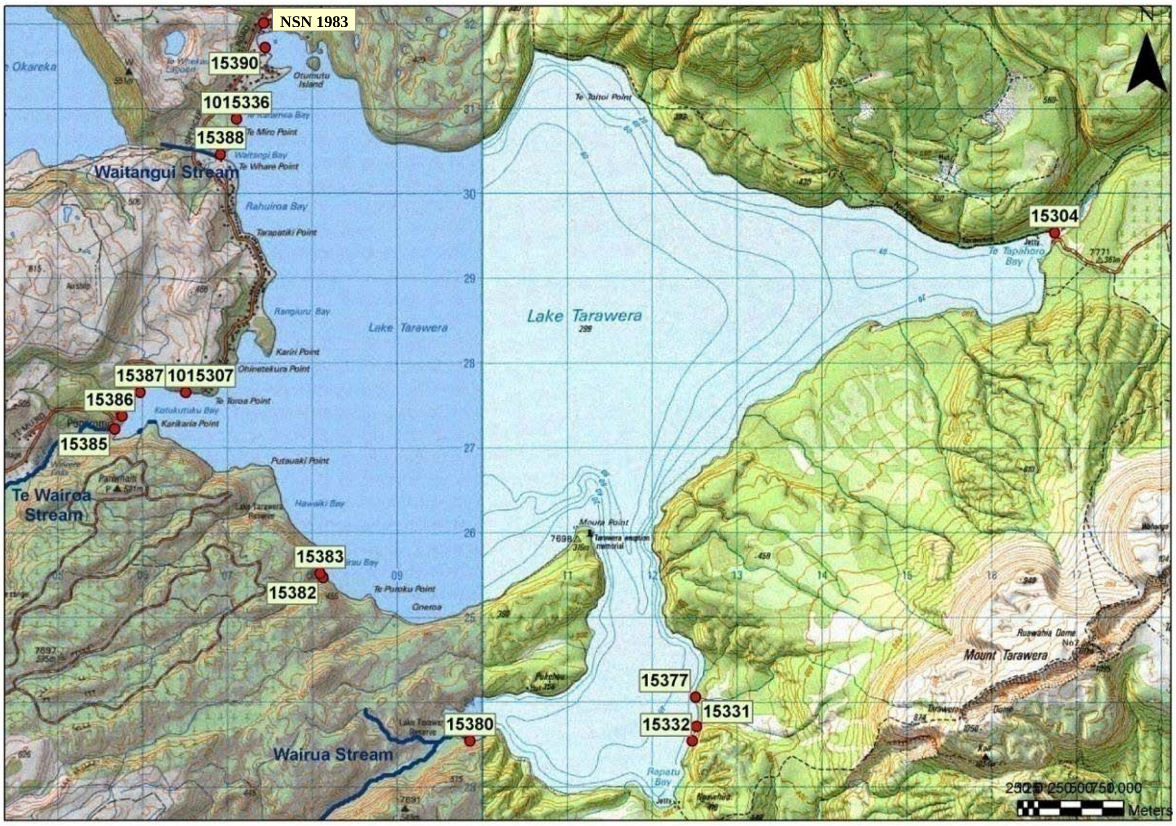

Figure 9 - Lake Tarawera surface flow monitoring sites

Three permanent streams are located in the Lake Tarawera catchment. Wairua Stream (site 15380, Figure 9), located on southern shores of Lake Tarawera, is a stream with geothermal activity and has an estimated flow of 208 L/s. The two other permanent streams are lake outlets: Te Wairoa from Lake Rotokakahi (site 15385, Figure 9) with an estimated flow of around 311 L/s and Waitangi Stream from Lake Okareka (site 15388, Figure 9) with an assessed flow of approximately 102 L/s.

Comparisons between gauging sites from 1987 (White and Cooper 1991), 1995-2003 (EBOP database) and 2006 (Hamilton *et al*. 2006) identified 12 springs around Lake Tarawera. However, the possible transient nature of some springs, their low flow or surrounding dense vegetation, prevents the identification of all springs.

The total surface water inflow to Lake Tarawera is estimated at 1760 L/s (Table 7). Table 7 summarises all the monitoring sites with their assessed flows. A mean flow for these streams is given, considering the same years for each stream. The main Twin Creeks stream (site 15383, Figure 9) has the highest inflow to the lake with 384 L/s. Some other streams, assumed permanent but impossible to gauge due to their low flows, are grouped as "total ungauged flows" in Table 7.

Table 7 - Assessed flows of the permanent streams and springs of Lake Tarawera.

RIVER/STREAM	***EBOP site number***	***FLOW (L s^{-1})***
Tarawera Peak and Camp stream	15377	64.5
Tarawera Peak Stream spring	15331	91
Tarawera Peak Stream rockslide	15332	173.5
Wairua Stream	15380	208
Te Puroku No. 1 (Twin Creeks)	15382	123
Te Puroku No. 2 (Twin Creeks)	15383	384
Te Wairoa Stream	15385	310.6
Jetty Stream (ramp 4)	15386	226
Orchard Stream	15387	15.6
Te Wairoa wharf spring	1015307	26.6
Waitangi Stream	15388	102.3
Waitangui spring	1015336	3.9
Te Whekau Stream	15390	19.5
Spencer Rd Ford Stream	NSN 1983	1.5
Total ungauged flows		10
TOTAL INFLOW TO LAKE TARAWERA		1760
TOTAL OUTFLOW (TARAWERA RIVER)	15304	7240

Lake Tarawera has only one outflow, via the Tarawera River (site 15304, Figure 8). This flow is estimated as 7,240 L/s (Hamilton *et al*. 2006).

Surface inflow represents only about a quarter (24 %) of the surface outflow. This means that the groundwater flow coming from the immediate catchment and coming from the seepage contributes greatly to lake recharge. This shows the importance of characterisation of the groundwater flux for the Lake Tarawera catchment; as well as for groundwater fluxes in the whole Okataina Caldera complex.

6. Water Budget

Determination of a water budget model in the study area is an essential step in deriving water flows. The water budget model suggested here is a schematic solution allowing assessment of water transfers between the OVC lakes and assessments of water flows between OVC catchments and catchments outside the study area.

The Okataina Caldera Complex water balance model aims to define the water balance for each lake catchment and assess the groundwater flows between catchments. The estimated flows will later be used for the lake water balances, in particular Lake Tarawera and further to assess nutrient inflows to Lake Tarawera.

6.1 Okataina Caldera water budget

The water balance of the Okataina Caldera lake catchments is expressed in terms of an equation relating the rate of change of storage in each lake to rainfall input, evaporation output, stream flow input/output and groundwater input/output for each lake catchment (Spigel and Viner 1992).

The equation is:

$$dV/dt = (Q_{GWin} - Q_{GWout}) + (\Sigma Q_{Surf.in} - \Sigma Q_{Surf.out}) + (Pc - Ec)Ac + (Pl - El)As \qquad (1)$$

Where:

dV/dt = rate of change in lake water volume over a period of time,

Q_{GWin} = ground water inflow,

Q_{GWout} = ground water outflow,

$\Sigma Q_{Surf.in}$ = sum of all surface inflows into the lake catchment,

$\Sigma Q_{Surf.out}$ = sum of all surface outflows from the catchment,

Pc = average rainfall on the catchment surface,

Ec = evaporation on the catchment surface,

Pl = average rainfall on the lake surface,

El = evaporation on the lake surface,

Ac = surface area of the catchment,

As = surface area of the lake.

The two most important terms for this project are the groundwater inflows and the groundwater outflows. The aim here is to define, for all the OVC lake catchments, each term of the equation to assess the local water balance and to gather all catchment water balances to obtain estimates of groundwater inflow and outflow for Lake Tarawera. The measurement periods and time steps are different for the datasets used in the water budget model. Therefore, the water budget calculations here are approximate.

6.1.1 Lake Rerewhakaaitu catchment

Records of lake level for Lake Rerewhakaaitu are available from Homestead Arm (Site Number 1015310), McIntosh *et al*. (2001). Lake levels are measured daily from 1992 to 2005. The water level at the Homestead Arm site can be used to estimate changes in lake volume using the relationship between lake level and volume (Figure 10) established by Ellery (2004).

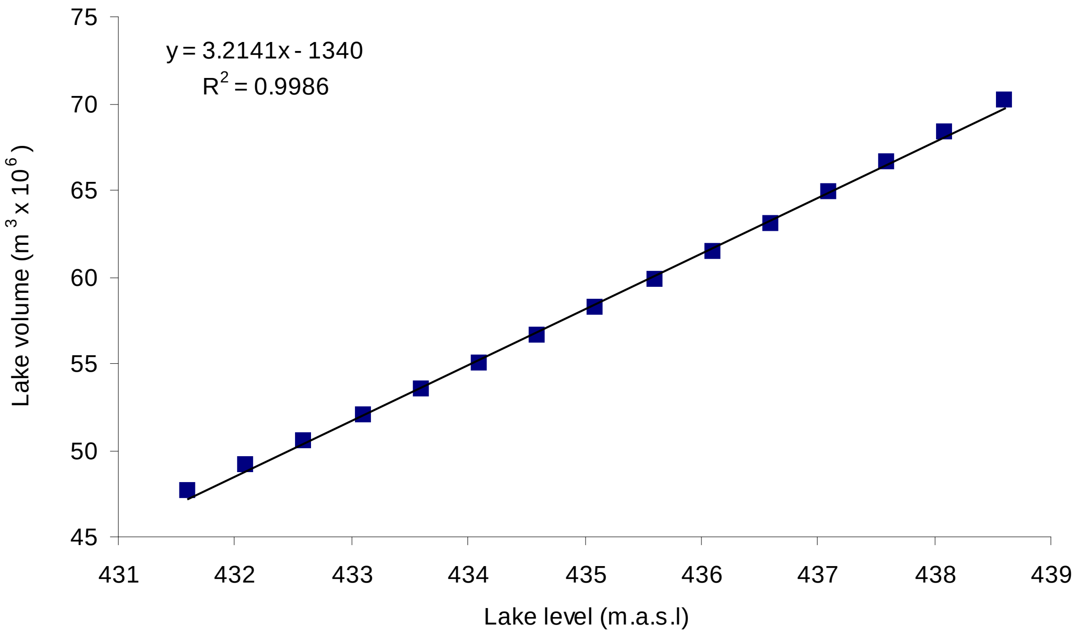

Figure 10 - Correlation between lake water level and lake volume for Lake Rerewhakaaitu.

No surface flow enters the Lake Rerewhakaaitu catchment. Stream flow out of the catchment does not normally occur, however when the lake level is high a drain out of the swampy area at the south-eastern corner of the lake takes overflowing water into the Mangaharakeke Stream. This flow is likely to be very close to zero in the long term. Therefore, $Q_{surf.in}$ and $Q_{surf.out}$ are estimated as zero.

Rainfall for Lake Rerewhakaaitu catchment was obtained from Climpacts software statistics. Climpacts was developed by the International Global Change Institute at The University of Waikatoin collaboration with National Institute of Water and Atmospheric Research (NIWA) and was originally used for weather prediction. For this study, Climpacts was used to generate rainfall isohyets for the year 2008 on a GIS layer corresponding to the catchment and the lake, to obtain a mean value for the whole catchment. Thus, the mean rainfall was estimated to 1,451 mm/year on the lake and 1,460 mm year on the catchment. Combining the lake and catchment area (approximately 5.3 + 37 km^2), the total rainfall inflow on the catchment was approximately 1,940 L/s.

Lake evaporation was estimated with daily total recorded data measurements from Rotorua Aero 2 (site number B86131) between January 1 of 1991 and December 31 of 2005. These data include vapour pressure, surface water temperature and wind for each record.
The lake evaporation was estimated using the following formula:

$$E=Min(0,((\frac{0.622}{1013.25})*330625152*W*(VP-(e^{(2.3026*(((7.5T)/(T+237.3))+0.7858)))))*(\frac{A}{2,258*10^9}))*-1 \qquad (2)$$

with:
E= evaporation (m^3/s)
W= wind (m/s)
VP= vapour pressure (mb)
T= surface water Temperature (°C)
A= area (m^2)

For the purposes of this report, it is assumed that these data measured at Rotorua Aero 2 are representative of the Lake Rerewhakaaitu area and the seven other lakes. These values are added for Lake Rerewhakaaitu with monthly surface water temperature measured by Environment Bay of Plenty. However, the lack of regular measurements limited the working period to the years 2003 and 2004. Evaporation for the lake was estimated as approximately 93 L/s over the period. Evaporation for the catchment was estimated as approximately 821 L/s, equivalent to 48% of the total catchment rainfall inflow (White *et al*. 2003).

Due to its perched nature, it is assumed that no groundwater inflows to the catchment. So, according to the Equation 1, groundwater outflow from the Lake Rerewhakaaitu catchment can be estimated from:

$$Q_{GWout} = Q_{Surf.in} - Q_{Surf.out} + (P\text{-}Ec)Ac + (P\text{-} El)As - dV/dt \qquad (3)$$

Groundwater outflow from the Lake Rerewhakaaitu catchment is estimated as approximately 1,021 L/s. This groundwater travels to the Lake Rotomahana catchment to the northwest and the Rangitaiki River catchment to the east.

6.1.2 Lake Okaro catchment

The rate of change for the Lake Okaro is calculated from a correlation of lake level and water volume estimated for this level. Lake Okaro levels were measured monthly at the Reserve by EBOP from 1992 to 2006. Water volume correlation (Figure 11) is obtained from Ellery (2004).

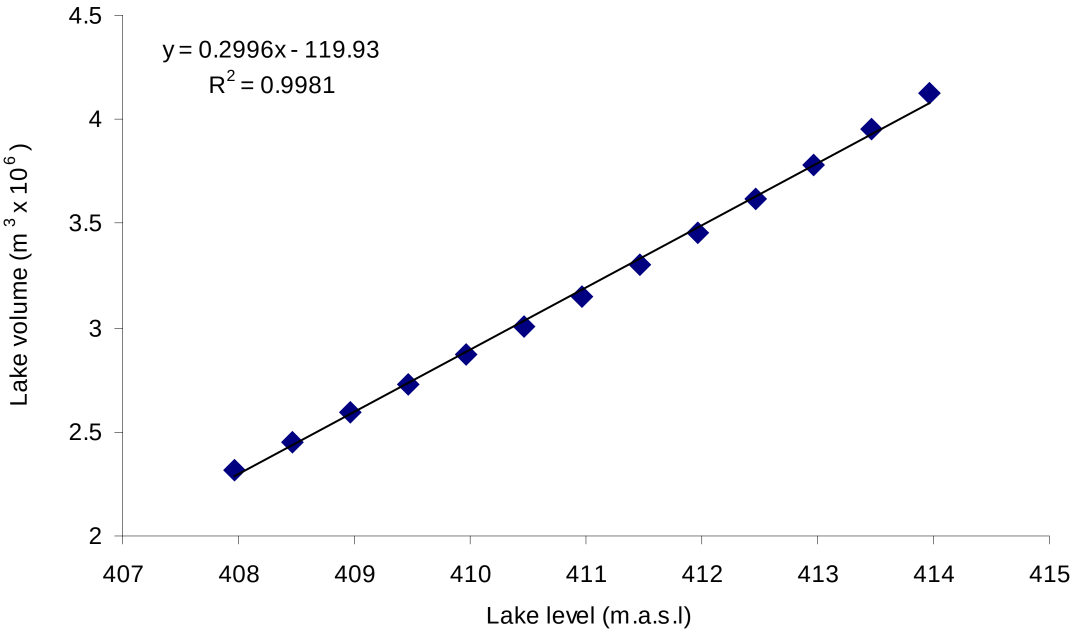

Figure 11 - Correlation between lake water level and lake volume for Lake Okaro**.**

With this correlation, no change is found in the water volume of Lake Okaro from 1992 to 2006.

No surface inflow reaches the Okaro catchment. Haumi Stream flows from Lake Okaro to Lake Rotomahana. Özkundakci and Hamilton (2008) assessed the Haumi Stream flow as 30 L s^{-1}.

Rainfall on Lake Okaro and the Lake Okaro catchment is assessed with Climpacts. Mean rainfall was estimated to be 1389 mm year^{-1} for the lake and 1445 mm year^{-1} for the catchment. Combining these values for lake and catchment areas (approximately 0.3+3.9 km^2), the rainfall inflow was estimated as approximately 189 L s^{-1}.

Evaporation includes evaporation from the lake and evaporation from the surface catchment. Evaporation from the lake was calculated with Equation 1. Data used for the surface water temperature are monthly measurements by EBOP, checked with the Rotorua Airport 2 station daily database to obtain a homogeneous monthly database. However, gaps in the data restrict the estimation to years to 2003 and 2004. The mean evaporation value obtained from Lake Okaro is equivalent to 6 L s^{-1} for this period. Evaporation from the catchment was estimated as 48% of the mean rainfall for the catchment area. Evaporation was therefore estimated as approximately 86 L s^{-1}.

Lake catchment geology mainly consists on alluvium lying on a low permeability geological layer; so it is assumed that no groundwater inflows into the catchment. Proximity with Lake Rotomahana catchment and surface connection between Lake Okaro and Lake Rotomahana allows the possibility of groundwater discharge from Lake Okaro and Lake Rotomahana. Estimated groundwater flow from Lake Okaro and Lake Rotomahana, using Equation 3, is approximately 67 L s^{-1}.

6.1.3 Lake Rotomahana catchment

The lake volume variation is calculated from 13 years (1992 – 2005) of daily level measures recorded at Crater Bay (site 15338) by EBOP and the relation between lake level and lake volume proposed by Ellery (2004), Figure 12.

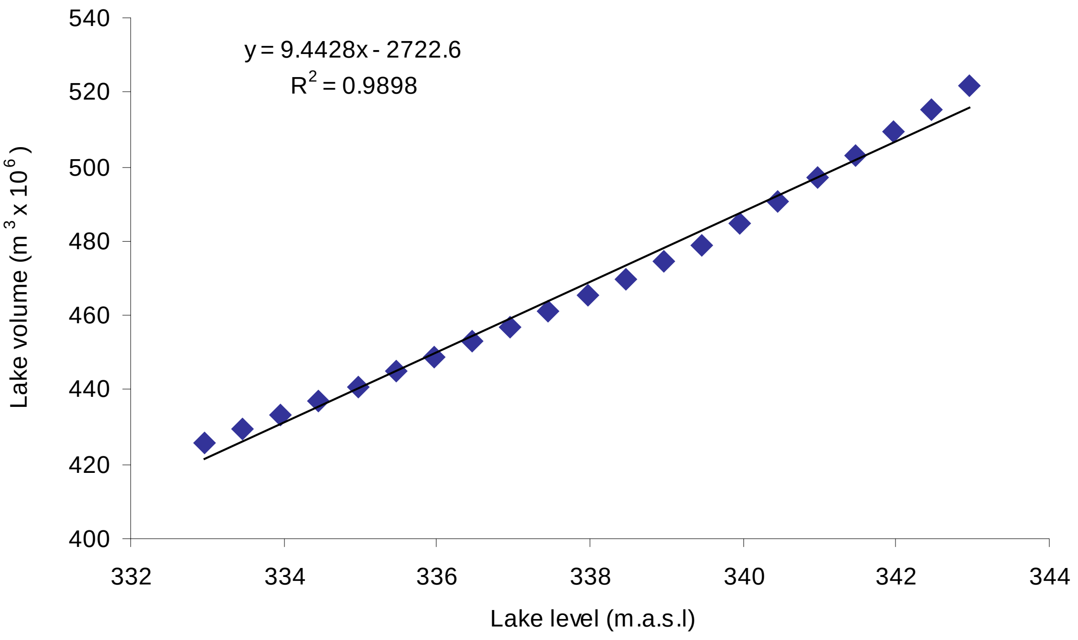

Figure 12 - Correlation between lake water level and lake volume for Lake Rotomahana**.**

The mean rate of lake volume change was estimated as equivalent to an inflow of 18 L s^{-1} between 1992 and 2005.

Surface flow into Lake Rotomahana is from Lake Okaro, via the Haumi Stream, discharging into an average flow of 30 L s^{-1}. No surface water outflow leaves the Lake Rotomahana catchment.

Rainfall for the Lake Rotomahana catchment was assessed using Climpacts software. The mean rainfall was estimated as approximately 1418 mm $year^{-1}$ for the lake and 1498 mm $year^{-1}$ for the catchment. These values over the lake and catchment areas (approximately 8.8+83.3 km^2) yield a rainfall inflow of approximately 4350 L s^{-1}.

Evaporation from the lake was calculated using Equation 2. Data used for the surface water temperature are monthly measurements from EBOP, checked with the Rotorua Airport 2 station daily database to obtain a homogeneous monthly database. However, gaps in some years restricted the estimation to the years 2003 and 2004. Mean evaporation from the lake in 2003 and 2004 averages approximately 213 L s^{-1}. Evaporation for the catchment was approximately 48% (White 2003) of the total catchment rainfall inflow i.e. approximately 1898 L s^{-1}.

Groundwater inflows to Lake Rotomahana from the Lake Okaro catchment and the Lake Rerewhakaaitu catchment are probable. Total inflow is discussed in Section 6.2.

Groundwater probably outflows to Lake Tarawera. A likely geological link occurs between Lake Rotomahana and Lake Tarawera (Figure 13), Lake Rotomahana has a higher elevation than Lake Tarawera and the water budget indicates relatively large groundwater losses from Lake Rotomahana. Groundwater outflow from Lake Rotomahana to Lake Tarawera was confirmed by the Lake Tarawera water budget (Section 6.3).

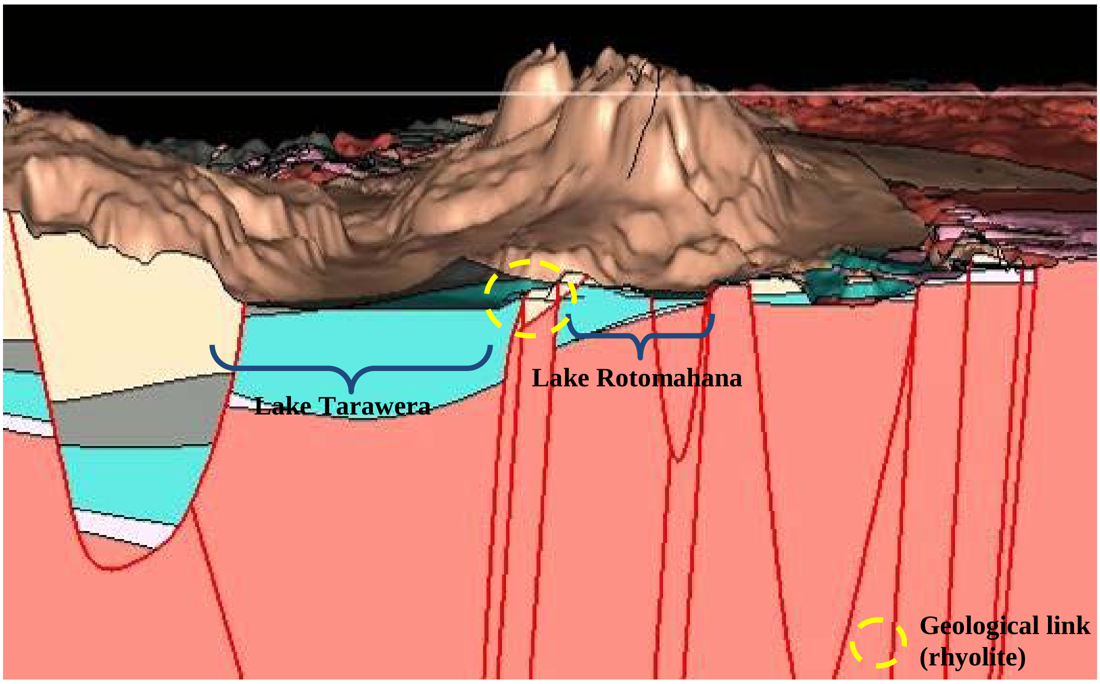

Figure 13 - Geological cross section between Lake Rotomahana and Lake Tarawera indicating the geological link between the two lakes (from the Earth Vision geological model of the OVC, Pamer, pers. comm.).

6.1.4 Lake Tikitapu catchment

The water level database measured by EBOP at Tarawera Road (site 15347) between 1992 and 2005 was used to estimate changes in volume using the relationship between lake level and volume (Figure 14) established by Ellery (2004).

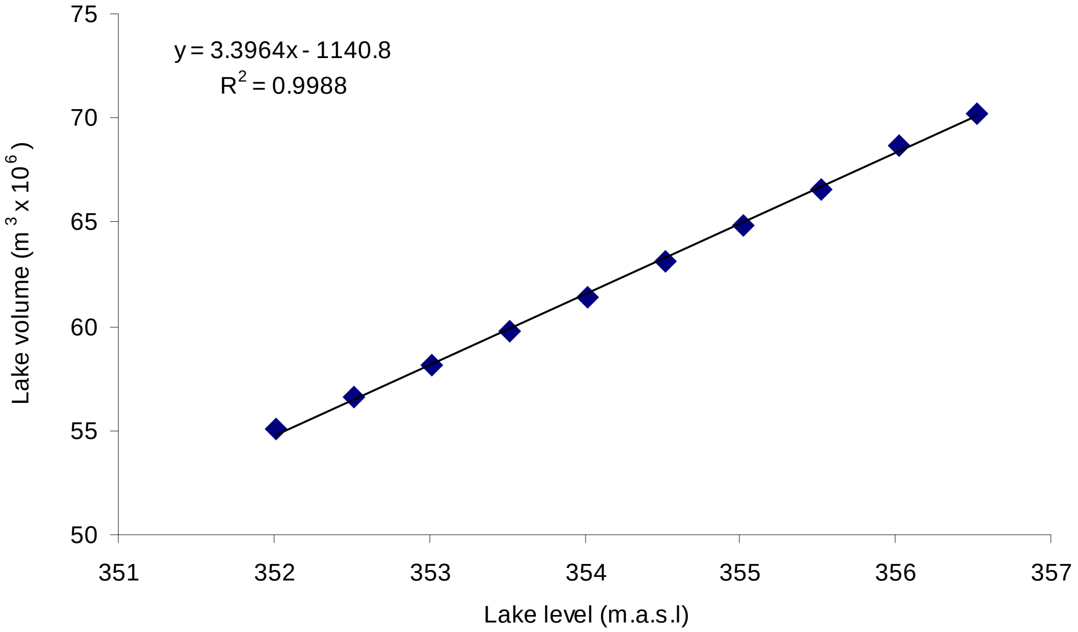

Figure 14 - Correlation between lake water level and lake volume for Lake Tikitapu.

The rate of change of Lake Tikitapu water volume is the equivalent an inflow of 2 L s^{-1} over the period 1992 to 2005.

Lake Tikitapu is at the highest elevation amongst the lakes in this part of the study area (417 m above sea level). Thus, no external surface flow comes from surrounding catchments. Despite the proximity of Lake Okareka and Lake Rotokakahi, no surface flows come out from the Tikitapu catchment.

Rainfall inflows for the lake and the catchment were estimated using Climpacts software. Average precipitations of 1568 mm $year^{-1}$ for the lake and 1678 mm $year^{-1}$ for the catchment were found. The total catchment surface area (approximately 1.4+6.2 km^2) gave a rainfall inflow of approximately 400 L s^{-1}.

Evaporation from the lake was calculated using Equation 2. Data used for the surface water temperature were measured monthly by EBOP and the measurement dates were checked against the Rotorua Airport weather daily database because no weather station exists close to Lake Tikitapu. A lack of data for several years restricted the calculations to the 2003 and 2004 years.

Average evaporation from the lake in this period was approximately 24 L/s. Evaporation for the catchment was estimated as approximately 48% (White 2003) of the total catchment rainfall inflow, i.e. approximately 159 L/s.

No surface flow exists between the catchment and the catchments of adjacent lakes. However, the water budget indicates a groundwater outflow from the catchment of approximately 215 L s^{-1}. This groundwater flow may go to the Lake Rotokakahi catchment (the nearest lake) and to the Lake Rotorua catchment (the lake at the lowest elevation).

6.1.5 Lake Rotokakahi catchment

The lake volume variation was calculated from 13 years (1992-2005) of daily water level measurements recorded at Te Wairoa Stream (site 15344) by Environment Bay of Plenty and the relation between lake level and lake volume proposed by Ellery (2004) for this lake (Figure 15).

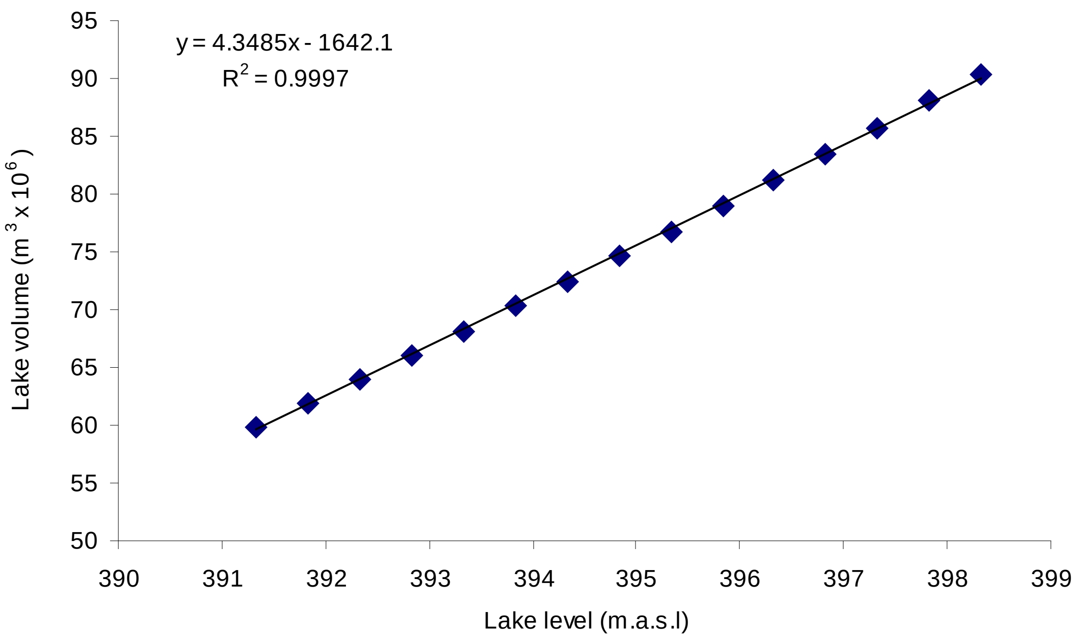

Figure 15 - Correlation between lake water level and lake volume for Lake Rotokakahi.

It was estimated the rate of water volume change for Lake Rotokakahi was equivalent to zero inflow over the period 1992-2005.

No surface flow comes in the lake catchment from other catchments. Lake Rotokakahi catchment is linked to the Lake Tarawera catchment via Te Wairoa Stream, with a flow assessed from EBOP gauging database (site number 15385) of 310.6 L s^{-1}.

Rainfall for the Lake Rotokakahi catchment was assessed with the Climpacts software. Mean rainfall was estimated as 1497 mm $year^{-1}$ for the lake and 1573 mm $year^{-1}$ for the catchment. Rainfall inflow was approximately 1176 L s^{-1} with lake and catchment areas of approximately 4.1 km^2 and 19.7 km^2, respectively.

Evaporation from the lake was calculated from the Equation 2. Data used for the surface lake temperature are measured monthly by EBOP. They were integrated with the Rotorua Airport weather station database to obtain monthly values for the years 2003 - 2004. Mean evaporation was estimated as approximately 56 L s^{-1} for Lake Rotokakahi in 2003 and 2004. Evaporation for the catchment was estimated as approximately 48% (White 2003) of the total catchment rainfall inflow, i.e. approximately 472 L s^{-1}.

The Lake Rotokakahi catchment possibly receives groundwater flow from the Lake Tikitapu catchment. Groundwater outflow is assumed to flow into to the Lake Tarawera catchment, due mainly to the presence of a surface link between these two catchments and possibly into the Waikato catchment situated at the south-western boundary of the Rotokakahi catchment. Partitioning of the flows is explained in Section 6.2.

6.1.6 Lake Okareka catchment

The lake volume variation was calculated in a period between 1992 and 2005 with daily level measures recorded at Acacia Road (site 15307) by EBOP and the lake level-lake volume relationship proposed by Ellery (2004) for this lake, Figure 16.

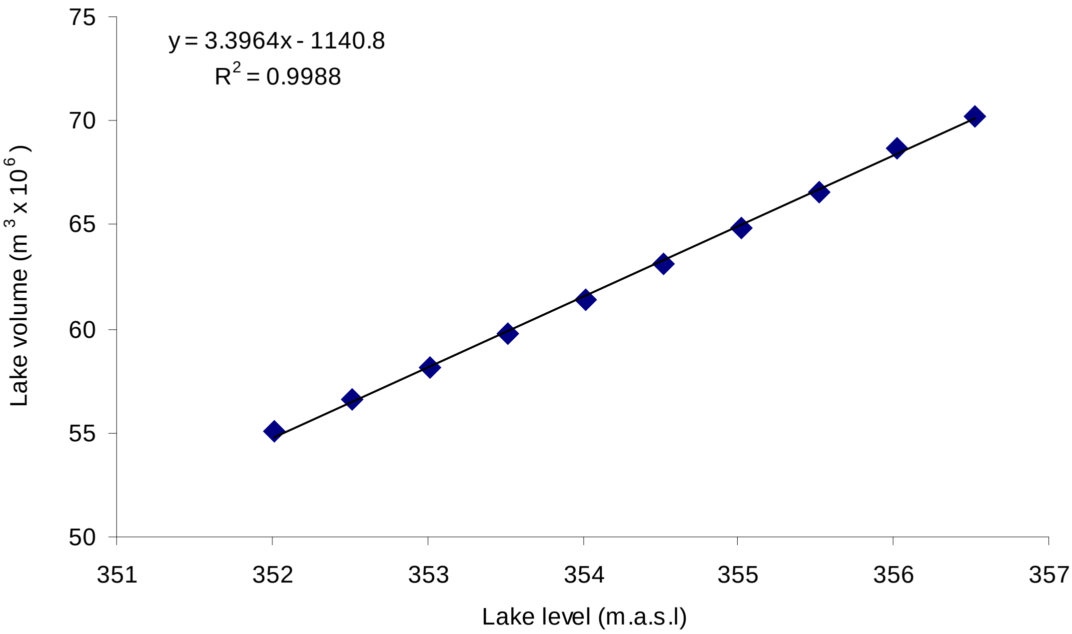

Figure 16 - Correlation between lake water level and lake volume for Lake Okareka. The lake volume change for Lake Okareka in the period 1992- 2005 was equivalent to an inflow of 1 L s^{-1}.

No surface inflows in the lake catchment are known. The only known surface outlet from the catchment is Waitangi Stream from Lake Okareka to nearby Lake Tarawera (Scholes and Bloxham 2007). Outflow from this stream was gauged monthly by EBOP during July 2003 to June 2005 and was estimated as 102 L s^{-1}.

Catchment rainfall was estimated using the Climpacts software for the year 2008. Rainfall was estimated as 1556 mm $year^{-1}$ for the lake and 1688 mm $year^{-1}$ for the catchment. This means an average precipitation for the whole catchment area of approximately 3.3 + 19.6 km^2 was estimated as approximately 1209 L s^{-1}.

Evaporation from the lake was calculated using Equation 2. Data used for the surface water temperatures are monthly measurements from the EBOP Rotorua lakes database in the period 2003 - 2004. The average evaporation from the lake found for these two years was estimated as 59 L s^{-1}. Evaporation for the catchment was estimated as approximately 503 L s^{-1} assuming evaporation of approximately 48% of the catchment rainfall inflow (White 2003).

Lake Okareka is the second highest lake of the region, after Lake Tikitapu. So it was assumed that the catchment doesn't receive groundwater from adjacent catchments. The catchment may discharge groundwater to the west to the Lake Rotorua catchment and to the east to the Lake Tarawera catchment. Equation 3 gives a groundwater outflow from the Lake Okareka catchment of 646 L s^{-1}.

6.1.7 Lake Okataina catchment

The rate of change of Lake Okataina volume was calculated from a correlation between lake level and water volume (Figure 17). Lake Okataina levels are measured daily at Tauranganui Bay (Site 15309) by EBOP from 1992 to 2006. Water volume correlation was obtained from Ellery (2004).

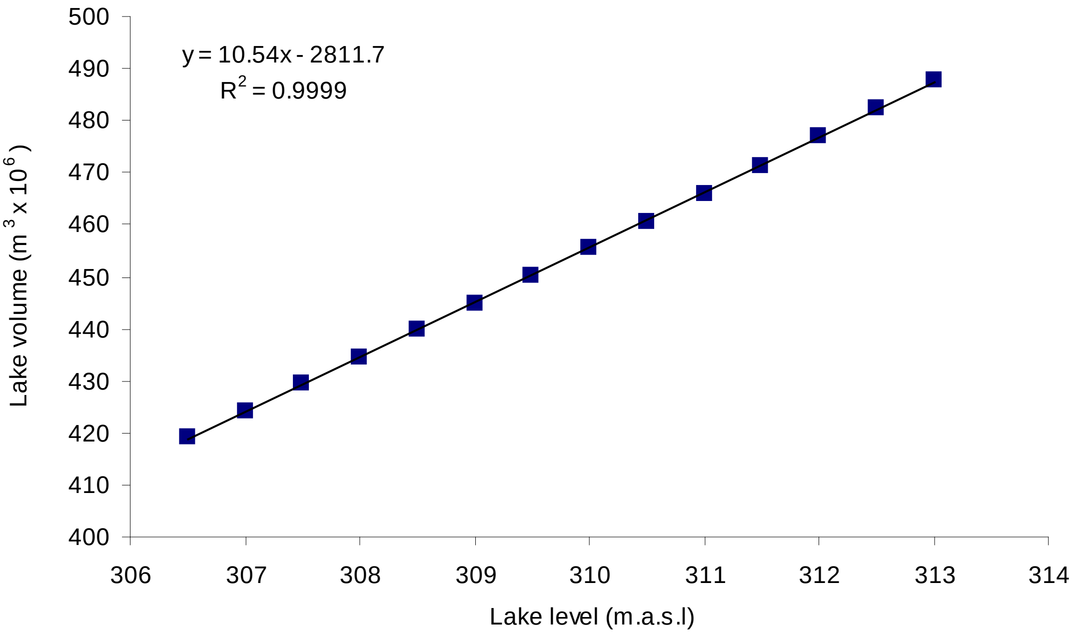

Figure 17 - Correlation between lake water level and lake volume for Lake Okataina.

The rate of change of the water volume for Lake Okataina was estimated as equivalent to an inflow of approximately 4 L s^{-1} for the period 1992 to 2006.

No surface water flows have been observed in the Lake Okataina catchment.

Rainfall in the Lake Okataina catchment was assessed with the Climpacts software and GIS layers of the catchment and the lake. The mean rainfall was estimated as 1764 mm $year^{-1}$ for the lake and 1958 mm $year^{-1}$ for the catchment. The combined lake and catchment areas (lake: 10.8 km^2 + catchment: 59.8 km^2) yields a rainfall inflow of approximately 4320 L s^{-1}.

Evaporation from the lake was calculated using Equation 2. Data used for the surface lake temperature were monthly measurements by EBOP in their Rotorua lakes database for 2003 and 2004. Average evaporation from Lake Okataina was estimated as 214 L s^{-1} for this period. Evaporation from the lake catchment was estimated as 1931 L s^{-1} assuming evaporation is 48% (White 2003) of the total catchment rainfall inflow.

The Lake Okataina catchment has a central position within the OVC. So without previous studies to give a concrete idea on the catchment connections, it was assumed that the Lake Okataina catchment is possibly linked by groundwater flow to the Lake Rotorua catchment, the Lake Rotoiti catchment and the Lake Tarawera catchment. Equation 3 allowed assessment of the groundwater outflow as approximately 2319 L s^{-1}. Estimation of the flow partition is addressed in Section 6.2.

6.1.8 Lake Tarawera catchment

Records of lake level for Lake Tarawera are available from Te Wairoa (site no. 15301), measured by EBOP with daily observations over the period 1992 to 2005. These data are used to estimate changes in volume using the relationship between lake level versus volume (Figure 18) established by Ellery (2004).

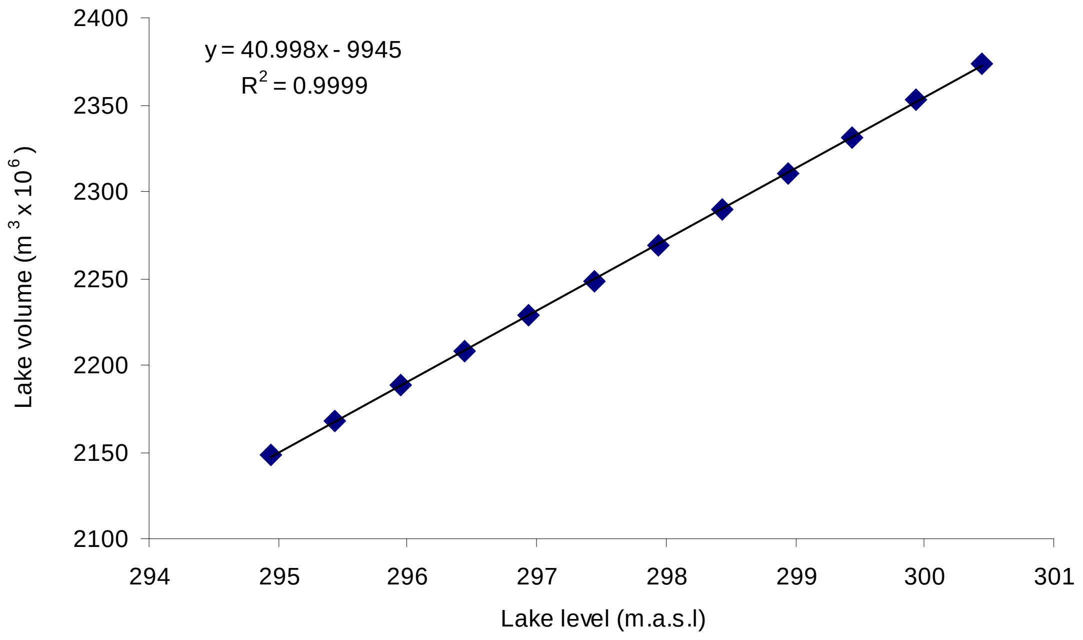

Figure 18 - Correlation between lake water level and lake volume for Lake Tarawera.

The rate of change of Lake Tarawera volume in the period 1992 to 2005 was estimated as an average inflow of 7 L s^{-1}.

Two streams flow into the Lake Tarawera catchment, Waitangi Stream and Te Wairoa Stream, for a total flow of approximately 434 L s^{-1}. The catchment outlet is the Tarawera River. With a flow estimated to 7240 L s^{-1} (Hamilton *et al*. 2006), it represents the only surface outflow from Okataina Caldera catchments.

Rainfall was assessed with the Climpacts software. Average rainfall on the lake was estimated as 1556 mm $year^{-1}$ and average rainfall on the catchment was estimated as 1649 mm $year^{-1}$. Rainfall on the 143.1 km^2 catchment was estimated as approximately 7204 L s^{-1}.

Evaporation from the lake was calculated using Equation 2. Data used for the surface lake temperature are monthly observations from the EBOP Rotorua lakes database over the period 2003 - 2004. Average evaporation from the lake is estimated as 887 L s^{-1}. Evaporation from the catchment was estimated as 2545 L s^{-1} assuming evaporation of 48% (White 2003) of the total catchment rainfall inflow.

The Lake Tarawera catchment may collect groundwater from Lakes Okataina, Okareka, Rotokakahi and Rotomahana catchments. Proportions of groundwater flow from each catchment to Lake Tarawera catchment are addressed in Section 6.2. Groundwater outflow from Lake Tarawera catchment is likely, via the Tarawera River valley.

6.2 Groundwater transfers between catchments

Darcy's law and water budgets were used to assess the groundwater transfers between OVC catchments and from OVC catchments to other catchments.

Groundwater flow between catchments (Q) was first estimated from the hydraulic gradient (Δh) between the lakes, transmissivity (T) of aquifer layers considered and the width of possible groundwater pathways between lakes. By the combination of these three parameters, an approximate value of the groundwater flow between two catchments was obtained with Darcy's law (estimated flow: $Q = T \times \Delta h \times w$). This procedure was applied to the OVC catchments, with assumptions on the direction of flow, to obtain estimated flow between catchments (Table 8). These distributions give an estimated groundwater outflow from Tarawera lake catchment of 918 L s^{-1}.

In order to consider all the possibilities between catchments, several scenarios varying the potential flow direction of groundwater between catchments were assessed (Table 9). These scenarios show that modification of one parameter causes an important change in the groundwater outflow from the Lake Tarawera catchment. Rainfall is a fundamental element of the model because an increase of rainfall by 10% multiplies the outflow by two and 10% less rainfall gives a negative value of groundwater outflow from Lake Tarawera.

Two scenarios (1 and 9) were consistent with the maximum groundwater outflow from Lake Tarawera of 1 m^3 s^{-1} suggested by White and Cooper (1991). The value of 918 L s^{-1} (i.e. scenario 1) was preferred because it is a more realistic for a groundwater flow transfer. This value implies that OVC lake catchments likely discharge groundwater towards the Lake Rotorua catchment and towards the Lake Rotoiti catchment.

Table 8 - Estimation of the groundwater flow between OVC catchments and from OVC catchments to other catchments.

	Inflow from the other catchments (L s^{-1})	Outflow to the other catchments (L s^{-1})	Catchment linked	Lake level gradient Δh (m/m)	Width [1] (m)	Transmissivity T [2] (×10^{-3} $m^2.s^{-1}$)	Estimated outflow (L s^{-1})	Flow distribution (%)	Resulting flow distribution (L s^{-1})
Okataina	0	2319	Rotorua	33	8505	6.94	159	30	695
			Rotoiti	32	6330	6.94	302	55	1275
			Tarawera	12	5796	2.31	98	15	350
Okareka	0	544	Rotorua	175	5153	2.31	298	55	300
			Tarawera	56	4308	2.31	254	45	245
Tikitapu	0	215	Rotorua	137	2866	2.31	121	60	130
			Rotokakahi	23	3101	2.31	87	40	85
Rotokakahi	85	420	Waikato	-	-	-	400	45	210
			Tarawera	95	6294	2.31	494	55	210
Okaro	0	67	Rotomahana					100	67
Rerewhakaaitu	0	1021	East	-	-	-	-	30	320
			Rotomahana	103	12488	2.31	697	70	700
Rotomahana	767	3018	Tarawera	36	12661	2.31	917	100	3018
Tarawera	3823	**918**	East	-	-	-	-	100	**918**

(1) Value assessed by GIS.
(2) Transmissivity of the layers was generalised to the value suggested by White (2003) for the pumice (200 $m^2.d^{-1}$) and the ignimbrite (600 m^2d^{-1}).

Table 9 Groundwater outflow to the east from the Lake Tarawera catchment with scenarios for the OVC water balance.

	Scenario	***Outflow [1] (L s^{-1})***
1	Current model of flow discharges between the different catchments	**918**
2	No groundwater discharge outside OVC	**3848**
3	OVC groundwater discharge only to Northern lakes	**1993**
4	Scenario 1, but with 10% more rainfall	**2153**
5	Scenario 1, but with 10% less rainfall	**-286**
6	Scenario 2, but with 10% more rainfall	**5570**
7	Scenario 2, but with 10% less rainfall	**2151**
8	Scenario 3, but with 10% more rainfall	**3417**
9	Scenario 3, but with 10% less rainfall	**593**

(1) Groundwater outflow to the east through the Lake Tarawera catchment.

6.3 Lake Tarawera water budget

6.3.1 Water budget components

A water budget for Okataina Volcanic Complex allows assessment of the flow transfers between the Lake Tarawera catchment and the catchments of other lakes. The work here evaluates OVC catchment water flows required to obtain the Lake Tarawera water budget used for the groundwater flow model. The water budget is given in Equation 1, with flows from septic tanks included in the water balance.

The lake volume rate of change was estimated as equivalent to an inflow of 7 L s^{-1} (Section 6.1.8); lake rainfall is estimated by Climpacts to 2023 L s^{-1} and lake evaporation estimated as 887 L s^{-1}.

In total, stream and spring flow was estimated as 1760 L s^{-1} (Table 7) assumed inflowing to Lake Tarawera, with 413 L s^{-1} coming from outer streams: Waitangi stream and Te Wairua Stream. The estimated surface outflow was 7240 L s^{-1} through the Tarawera River.

The Lake Tarawera catchment is situated in a volcanically active area and an active geothermal area also occurs in the southern part of the catchment. Geothermal spring flow is estimated (Section 4.2 and Section 5) as 250 L s^{-1}. However, these flows are possibly only a component of the geothermal inputs. Sheppard (1986) showed, using chloride as a tracer, that flow from geothermal springs entering Lake Tarawera should total 1270 L s^{-1}. Considering geothermal spring flow of 250 L s^{-1}, then geothermal groundwater inflows were estimated as 1020 L s^{-1}.

Groundwater inflows can be divided into three categories: groundwater inflows from catchments outside the Lake Tarawera catchment, groundwater coming from the rainfall recharge and geothermally influenced groundwater. Groundwater flow to the Lake Tarawera catchment was estimated for the Okataina Volcanic Complex water budget as 3823 L s^{-1} (Table 8).

Groundwater coming from rainfall was estimated from the recharge of the catchment. Considering a rainfall equivalent of 5302 L s^{-1} and an evaporation rate of 48% for the catchment, the resulting rainfall inflow was 2757 L s^{-1}. The difference between this flow and the estimate derived from stream flow gauging (see above) can be attributed to the groundwater flow from the topographic catchment which totals 1409 L s^{-1}. Geothermally-influenced groundwater flow was estimated previously as 1020 L s^{-1}.

Only one groundwater outflow from Lake Tarawera catchment was considered to the east catchment, through the Tarawera River catchment. The water balance for the Okataina Volcanic Centre was therefore used to estimate groundwater outflow as 918 L s^{-1} (Table 8).

Assuming 2.8 people per household and 104 households around Lake Tarawera[4] with a mean effluent flow value of 250 L/person/day (Hamilton *et al*. 2006), the septic tank outflows to Lake Tarawera were estimated to be 0.84 L s^{-1}.

6.3.2 Water budget

Table 10 summarises the water budget for Lake Tarawera. A comparison was also done with the water budget of White and Cooper (1991). The first water budget in Section 6.3.1 gives a water excess of 918 L s^{-1}. This difference accounts for the stream flow value used. Indeed, the stream flow estimate deals with the streams coming into the lake but also with springs. The origin of the water in the springs and of several streams comes from groundwater surface outflow, which means that some water in this water budget was counted twice.

Because it was not possible to determine which part comes from the immediate catchment groundwater and which part comes from the external groundwater inflow, the excess of water was removed from the external inputs to obtain the adjusted Lake Tarawera water budget. This proposition was supported by the location of the springs, on the south and west part of the catchment, where spring flow may be supported by groundwater flow from other catchments. The proposed Lake Tarawera water budget was consistent with the estimates of White and Cooper (1991).

[4] http://www.mfe.govt.nz/publications/ser/gentle-footprints-may06/gentle-footprintsmay06.pdf

Table 10 - Lake Tarawera water budget.

	Water budget, section 6.3.1 (L s^{-1})	***Comparison with values suggested by White and Cooper (1991)(L s^{-1})***	***Adjusted Lake Tarawera water budget (L s^{-1})***
Outputs			
Tarawera River			
- surface	7240	6800	7240
- subsurface	918	0 – 1375	918
Lake Evaporation	887	910	887
Total	**9045**	**7710 – 9085**	**9045**
Inputs			
Rainfall on lake	2023	2080	2023
Septic tank effluent	1	3	1
Geothermally- influenced groundwater	1020	1272	1020
Immediate catchment			
- stream flow	1348	1650	1348
- groundwater (non-geothermal)	1409	382	1409
Externally derived			
- stream flow	413	322	413
- groundwater (non-geothermal)	3824	2004 – 3378	2838
Total	**10038**	**7713 – 9087**	**9052**
Lake volume rate of change	+7		+7

The Lake Tarawera water balance shows that surface inflows (stream flows and rainfall on lake) contribute only 42 % of the lake recharge. Therefore, groundwater is the main inflow to the lake but the nutrient concentrations carried by these flows are unmeasured. Future definition of a groundwater model of the Lake Tarawera catchment will help to assess the nutrient loads by groundwater inflows to the lake.

7. Lake Tarawera Groundwater Flow Model

7.1 Lake Tarawera sub-catchments

Assessment of water transfers in the Okataina Caldera complex showed that the Lake Tarawera catchment is connected to the adjacent catchments by underground water flows. In order to identify, characterise and quantify these groundwater inflows and outflows, it was necessary to define the supply areas for the lake. The lack of piezometric data and precise studies on the aquifers and the geological units in the Lake Tarawera catchment mean that catchment areas are estimated from geology, topography and spring flows.

Seven sub-catchments were defined in the Lake Tarawera catchment (Figure 19).

Sub-catchment 1 is on Haparangi rhyolites in the eastern part of the catchment. This sub-catchment has an area of 20.7 km^2; indigenous forest is the sole land use, and the sub-catchment has no permanent streams (Section 2 and Section 5).

Sub-catchment 2 is in the southern part of the Lake Tarawera catchment mainly on the rhyolite and alluvium geological layers. The area of this catchment links Lake Rotomahana with Lake Tarawera. Several springs and geothermal sources are present in this sub-catchment (Table 7 and Section 4.2). Total discharge to the lake for streams in this sub-catchment is approximately 329 L s^{-1}. Considering a mean annual rainfall recharge of 1497 mm yr^{-1}, this means a minimum recharge area of 6.91 km^2. This value is larger than estimated for the catchment area (5.4 km^2). Therefore seepage from Lake Rotomahana to Lake Tarawera is likely.

Sub-catchment 3 uses the boundaries of the old TVZ rhyolites and includes the Mamaku Ignimbrite. It encompasses the major part of the pasture land use in the Lake Tarawera catchment, for an area of 43.7 km^2. Two major cold spring inflows can be found on this area (Table 7) for a total flow of 507 L s^{-1}.

Sub-catchment 4 includes the 21 ka-old and 15 ka-old rhyolite layers, with an area of 8.6 km^2. Several springs are present in this area, and have a total surface flow of 404.4 L s^{-1} (Table 7).

Sub-catchment 5 is the smallest sub-catchment, with an area of 2.8 km^2, and includes Pokopoko ignimbrites and alluviums with relatively high transmissivity. The urban area is included in this sub-catchment. It is assumed that Mamaku Ignimbrite does not belong to this catchment. Two known springs discharge to Lake Tarawera from this catchment. The total flow was assessed to be less than 21 L s^{-1} (Table 7).

Sub-catchment 6 includes the boundary of the 7.5 ka-old rhyolite layer and has an estimated area of 3.8 km^2. This geological unit must be distinguished to link Lake Okataina and Lake Tarawera. Unfortunately, no gauged flows are recorded by EBOP for this area.

Sub-catchment 7 is located on the north-eastern part of the Lake Tarawera catchment, on the 7.5 ka-old rhyolite layer. The area of this sub-catchment is 16.8 km^2. Indigenous forest is the sole land use and spring flows are unknown – maybe springs occur in this area, but no springs are identified.

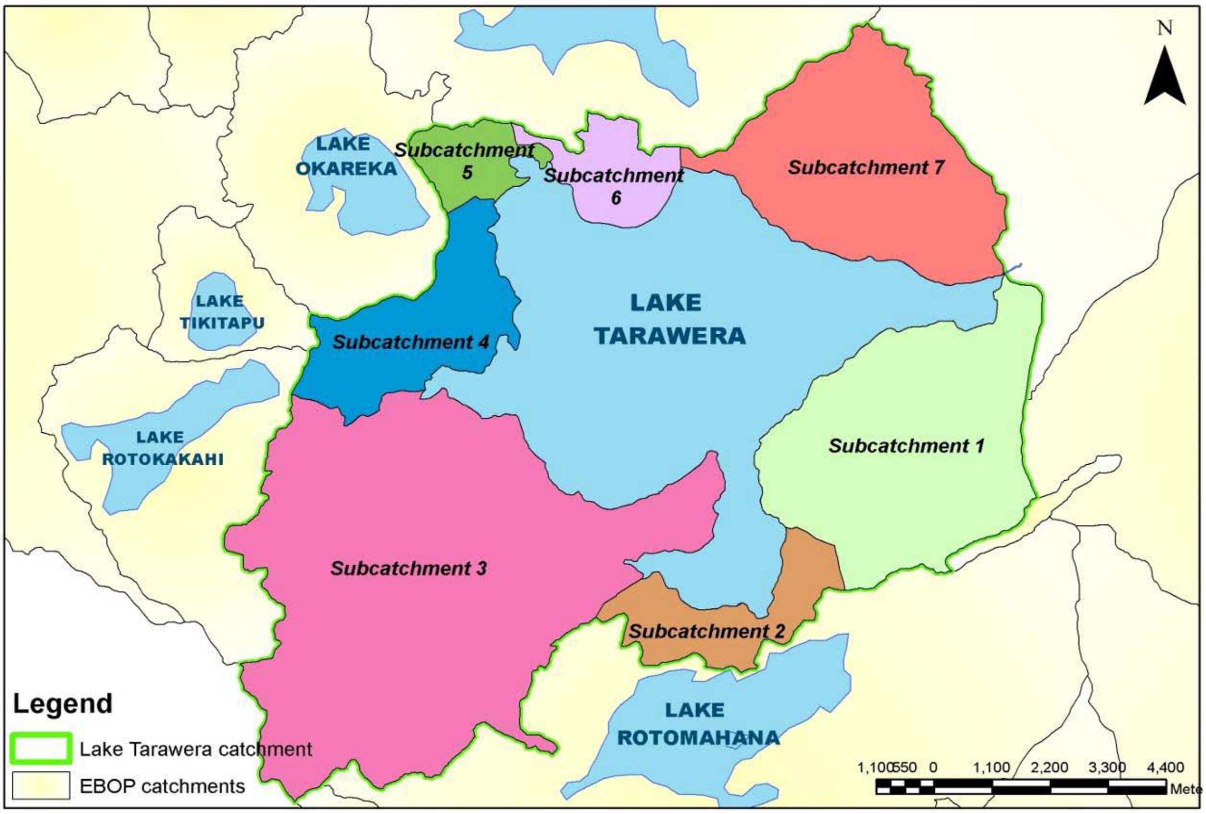

Figure 19 – Location of Lake Tarawera subcatchments.

7.2 Conceptual model

7.2.1 Initial properties of the proposed model

The groundwater flow model using Finite Element subsurface FLOW system (FEFLOW) software was developed for the Lake Tarawera surface catchment. One layer was used to simplify the model running. This layer was made of rhyolite units and is partitioned into two to improve FEFLOW performance.

- *Layer dimensions*

The top of the layer was defined from a digital terrain model (DTM) at a 25 m interval. This DTM was converted by GIS ArcMap into a points shape file and integrated into the model as topographic elevation. The bottom of the model is the lowest bathymetry value of the lake, i.e. 213 m above sea level. The layer was partitioned at an elevation of 100 meters below ground surface.

- *Layer properties*

Mean horizontal hydraulic conductivity Kxx used for the layer was 2.3×10^{-4} m s^{-1} (20 m day^{-1}, Section 4). For the two other dimensions, a transverse hydraulic conductivity (Kyy) of 2.3×10^{-4} m s^{-1} i.e. the value used to the Lake Rotorua groundwater flow model (White *et al*. 2007) and a vertical hydraulic conductivity Kzz (i.e. 2.3×10^{-5} m s^{-1} assuming Kzz = 0.1 Kyy. This factor limits the vertical seepage and promotes the horizontal flow.

Storativity and storage compressibility are unknown. Therefore it is assumed the same values applied as used by White *et al*. (2007) for both of the layers of 0.2 and 0.0001, respectively in the initial simulations.

7.2.2 Boundary conditions and inflows

Rainfall, proximity to the other lakes, presence of permanent streams, external groundwater inflows are all elements which need to be defined in the model.

- *Rainfall inputs*

Rainfall was estimated for each sub-catchment by Climpacts software and corrected by the evaporation to estimate groundwater recharge in the sub-catchments (Table 11).

Table 11 - Average rainfall recharge for Lake Tarawera sub-catchments.

	Average Rainfall ($mm\ yr^{-1}$)	*Range ($mm\ yr^{-1}$)*	*Rainfall recharge ($\times 10^{-4}\ m.day^{-1}$)*
Sub-catchment 1	1795.7	178.4	23.6
Sub-catchment 2	1496.8	43.8	19.7
Sub-catchment 3	1551.3		20.4
Sub-catchment 4	1625.1	88.2	21.4
Sub-catchment 5	1691.8	52.5	22.2
Sub-catchment 6	1708.7	43.9	22.5
Sub-catchment 7	2000.5	175.9	26.3

- *Head conditions*

Few piezometric level measurements are observed in the Lake Tarawera catchment. Therefore, a map of initial head distribution cannot be developed in the catchment. To estimate an initial head elevation, a random value of 400 m has been assigned for the initial head elevation. The model calibration (Section 7.5) allows adjustment of the values. A constant head boundary was defined for the edge of the lake, i.e. elevation of 299 m.

- *Stream inflows*

The three permanent streams inflows (Waitangi Stream, Te Wairoa Stream and Wairua Stream) are defined as Cauchy conditions and described by a 1D extrapolation of their heads between Lake Tarawera and their sources.

- *Groundwater inflows*

Groundwater inflows from surrounding catchments have been represented by the injection well condition as FEFLOW does not allow definition of an external inflow into a defined system. Three rows of injection wells (one for each slice i.e. ground level, 100 m below ground level and 213 m above sea level) along the presumed common boundary are used in the model to represent this flow. The number of wells was defined from the number of mesh elements around the boundary. For example:

- groundwater inflow from the Lake Rotomahana catchment was represented by 420 (3x140) wells. With a total flow of 3018 L s^{-1} (Table 8), the flow for each well was approximately 620 m^3 day^{-1}.
- groundwater inflow from Lake Rotokakahi catchment was represented with 150 (3x50) wells, with flow of 120 m^3 day^{-1} for each well (i.e. 210 L s^{-1} in total, Table 8).

- groundwater incoming from the Lake Okareka catchment was represented with 240 (3x80) wells, with a flow of 88 m^3 day^{-1} for each well (i.e. 245 L s^{-1} in total, Table 8).
- groundwater flow from the Lake Okataina catchment was represented with 300 (3x100) wells with a flow of 100 m^3 day^{-1} for each well (i.e. 350 L s^{-1} in total, Table 8).

7.3 Introduction to the FEFLOW software

FEFLOW (Finite Element subsurface FLOW system) is an interactive groundwater modelling system developed by WASY[5]. It incorporates several options such as a three dimensional areal and cross sectional view, fluid density-coupled or uncoupled, variably saturated layers, transient or steady state for flow, mass and heat transport with or without one or multiple free surfaces.

The model was developed in 2 steps. First, a 2D finite element mesh of the study area was generated according to geometrical properties, with the number of mesh elements and the kriging method defined by the user. The software also allows a manual refinement in targeted areas. In the second step, a three dimensional pattern of the study area, the type of model (flow with or without transport) and then the hydrogeological properties are added.

7.4 Model build

Table 12 summarises the FEFLOW model input data.

Table 12 - Data used for the Lake Tarawera hydrogeological model.

Rainfall recharge ***(10^{-4} m.d^{-1})***		***Aquifer properties***		***Seepage (from)***	
Subcatch 1:	11.3	Initial head conditions	(m)	Rotomahana	
Subcatch 2:	9.5	lake boundary	299	number of wells	420
Subcatch 3:	9.8	whole catchment	400	flow (m^3 d^{-1} $well^{-1}$)	620
Subcatch 4:	10.3	Transfer conditions for		Rotokakahi	
Subcatch 5:	10.7	Waitangi Stream		number of wells	150
Subcatch 6:	10.8	Te Wairoa Stream		flow (m^3 d^{-1} $well^{-1}$)	120
Subcatch 7:	12.7	Hydraulic conductivity:	(10^{-4} m s^{-1})	Okareka	
		Kxx	3.47	number of wells	240
		Kyy	3.47	flow (m^3 d^{-1} $well^{-1}$)	88
		Kzz	0.35	Okataina	
		Storativity	0.2	number of wells	300
		Storage compressibility	0.0001	flow (m^3 d^{-1} $well^{-1}$)	100

[5] www.wasy.de

The model (Figure 20) uses 75358 mesh elements and was run as steady state.

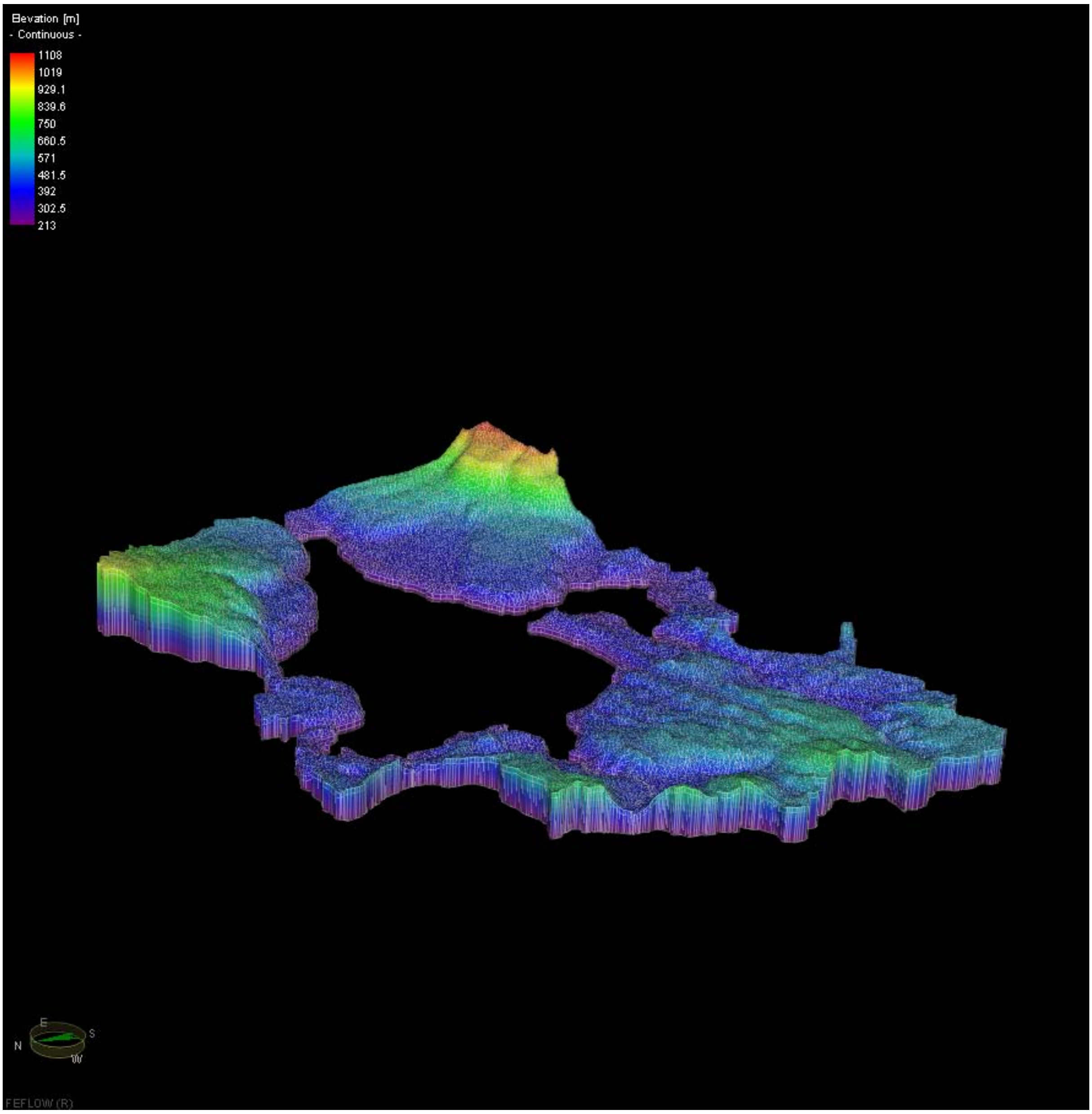

Figure 20 - 3D view of the Lake Tarawera catchment groundwater flow model.

7.5 Model running

The model was calibrated by changing one or several parameters of the model to obtain the piezometric head elevation observed in known head elevations in the catchment. Five piezometric head elevations were used to calibrate the Lake Tarawera catchment groundwater model:

- Lake Rotomahana water level (335 m) on the southern boundary of the Lake Tarawera catchment;

- EBOP bore hole situated on the south-western part of the Lake Tarawera catchment. The piezometric level measured in July 2008 is 486 m;
- Lake Rotokakahi water level (494 m) on the western boundary of the Lake Tarawera catchment;
- Lake Okareka water level (355 m) on the north-western boundary of the Lake Tarawera catchment;
- Lake Okataina water level (311 m) on the northern boundary of the Lake Tarawera catchment.

Calibration considered local geology boundaries around the observation points. The southern part of the catchment represented by the sub-catchment 2 is formed of alluvium and rhyolites. Calibration of the hydraulic conductivity for the sub-catchment 2 concludes on a value of 2 $\times10^{-4}$ m day^{-1}.

For the western part of the Lake Tarawera catchment, a value of 0.06 $\times10^{-4}$ m day^{-1} obtains a head elevation of 490 m representing the water level of Lake Rotokakahi. The presence here of old TVZ rhyolites, that are probably more welded and less fractured, could explain this low hydraulic conductivity value.

On the north-western part of the Lake Tarawera catchment, presence of alluvium and possibly Pokopoko Ignimbrite implies a higher hydraulic conductivity than defined for the rhyolite (Table 6). Hydraulic conductivity after calibration was 0.22 $\times10^{-4}$ m day^{-1}.

Calibration of the sub-catchment 6 assuming Lake Okataina is linked through the groundwater system with Lake Tarawera suggests a hydraulic value of 2.5 $\times10^{-4}$ m day^{-1} to approximately match the level of Lake Okataina.

For the bore hole on the south-western part of the Lake Tarawera catchment, a value of 0.17 $\times10^{-4}$ m day^{-1} obtains a head elevation of 490 m.

As no other observation points exist on the catchment, the last value of 0.17 $\times10^{-4}$ m day^{-1} was assumed to be more representative of the hydraulic conductivity of the rhyolite layer for the Lake Tarawera catchment than the previous value of 0.2 $\times10^{-4}$ m day^{-1} (Table 12). This value was assigned to rest of the model area.

7.6 Steady state solution

7.6.1 General results

Results of head elevations after calibration of the Lake Tarawera catchment groundwater model are shown on the Figure 21.

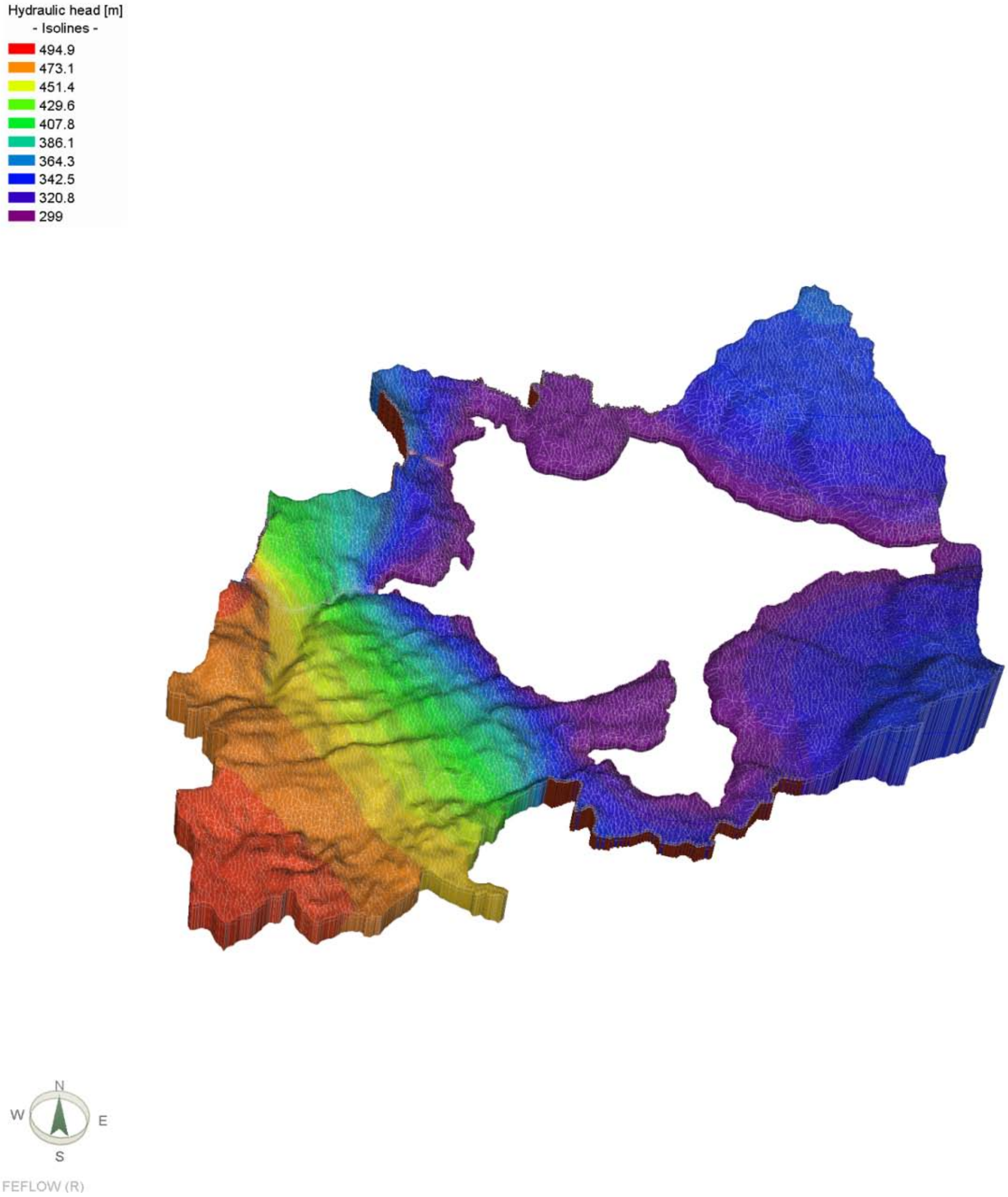

Figure 21 - Head elevation in the Lake Tarawera catchment. Elevations are represented by colours and the inset shows the elevation scale.

Head elevation after calibration was between 299 m and 494 m. Groundwater levels are highest in the south west.

7.6.2 Estimated groundwater flow properties

Groundwater flow is directed towards Lake Tarawera. Groundwater velocities are highest in sub-catchment 2 with a flow velocity of 2.1m day^{-1}. The mean flow velocity value for other catchments is estimated as 0.1m day^{-1}.

7.6.3 Water budget analysis

The calibrated Lake Tarawera groundwater model was used to calculate the water budget for each surface sub-catchment. The water budget analysis program, integrated in FEFLOW, calculates the catchment flow entering and exiting the sub-catchments, including groundwater recharge and well discharge and flow in from model boundary conditions (e.g., head condition of the lake boundary and transfer condition for the wells).

Table 13 - Water budget calculation for Lake Tarawera sub-catchments.

Surface Sub-catchment	Rainfall recharge to groundwater ($\times 10^4$ $m^3.d^{-1}$)	Calculated groundwater seepage entering into the sub-catchment (well flow) ($\times 10^4$ $m^3.d^{-1}$)	Calculated direct groundwater discharge to Lake Tarawera ($\times 10^4$ $m^3.d^{-1}$)	Imbalance ($\times 10^4$ $m^3.d^{-1}$)
Sub-catchment 1	2.4	0	1.5	+0.9
Sub-catchment 2	0.5	26.2	28.8	-2.1
Sub-catchment 3	4.3	1.1	5.3	+0.1
Sub-catchment 4	0.9	1.2	3	-0.9
Sub-catchment 5	0.3	1.2	0.6	+0.9
Sub-catchment 6	0.4	2.4	3.1	-0.3
Sub-catchment 7	2.1	0.7	1.5	+1.3
TOTAL	**10.9**	**32.8**	**43.8**	

Influence of the groundwater seepage is noticed in sub-catchment 2 where the model assumptions underestimate inflow by about 2.1m^3 s^{-1}.

Total direct groundwater discharge to Lake Tarawera was estimated as 43.8×10^4 m^3 day^{-1} or 5.1 m^3 s^{-1}. Previous assessment by the numerical Lake Tarawera water balance (Section 6.3.2) indicates a groundwater recharge of 5.2 L s^{-1}. A difference of 0.1 m^3 s^{-1} is reasonable for this model.

8. Land Use Scenarios

One of the objectives of this project was to simulate and evaluate the consequences of land use changes on the Lake Tarawera nutrient budget. For this, five scenarios were designed to give a range of nutrient loads. Two other scenarios were added after investigation of the consequences of current and future land use on nutrient discharge to Lake Tarawera.

Values used for the nitrogen discharge to the lake from land use are summarized in Table 14. Nitrogen loss coefficients to the lake were taken from the Rotorua and Rotoiti Lakes Action Plan (2004). A mean thickness of the rhyolite layer under each land use was also defined for the model units.

Table 14 - Nitrogen export to Lake Tarawera and land use.

Land Use	*N Loss to Lake Tarawera ($kg.ha^{-1}.yr^{-1}$)*	*Nitrogen rate set up in the model ($\times10^{-5} mg.l^{-1}d^{-1}$)*
Indigenous Forest	4	0.7
Exotic Forest	3	0.8
Deer cattle farming	15	4.1
Beef cattle farming	30	8.2
Sheep and Beef cattle farming	25	6.8
Dairy farming	40	11
Grassland	12	1
Bare ground	5	0.8
Urban *	25	13.7

*the "urban" row groups the exports coming from stormwater, sewage and septic tanks

Transport of nitrogen was simulated by the FEFLOW model. The longitudinal and transverse dispersivity are those of Hong (pers. comm.) i.e. 70 m and 3 m, respectively. It was assumed that molecular diffusion and sorption are negligible. It was also assumed that denitrification doesn't occur in the aquifer, so a zero-order kinetic reaction was preferred.

The porosity value will influence the travel time of the groundwater in the system. Travel time for the Lake Tarawera catchment was expected to be in a range of 100 years to 200 years to be consistent with the size and the geology of the catchment. Test simulations were done using the current land use and 4 different porosity values: 0.01, 0.03, 0.2 and 0.5. Porosity values 0.01 and 0.5 will give a range for the lowest travel time and the highest travel time (Figure 22). The porosity values of 0.03 and 0.2 are suggested by Stevenson *et al*. (1994) for the rhyolites in the Okataina Volcanic Centre.

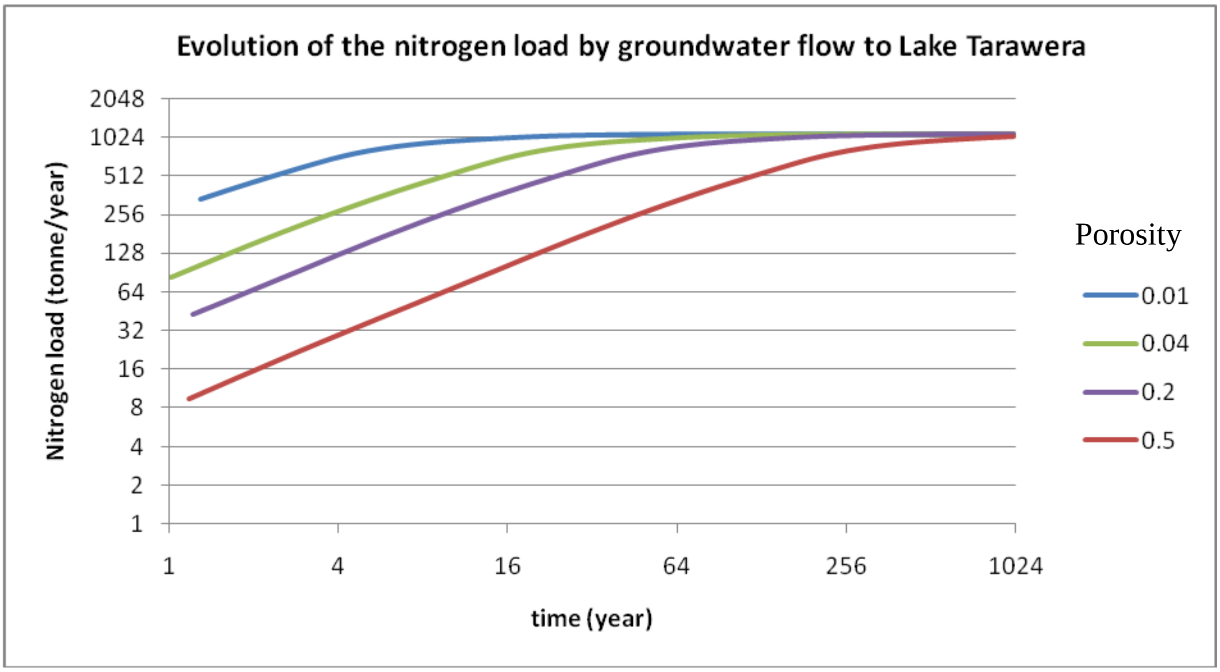

Figure 22 - Travel time of the nitrogen in the Lake Tarawera catchment for different porosity values. The minimum travel time obtained with the lowest porosity is estimated around 50 years. The more consistent results are obtained with a porosity of 0.03: steady state for the nitrogen concentration is obtained around 170 years. Thus this value was used for the model porosity.

Land use scenarios and effluent scenarios were made in four steps, considering four time periods. The first step consisted of running a model assuming an initial "natural" concentration of nitrogen (scenario 1) in the soil close to zero, i.e. 10^{-7} g ml^{-1}. The model was run over a period of 300 years aiming for steady state conditions.

The second step starts from the steady state results of the first step, with the current land use scenario. Scenario 2 was then run over a period of 50 years. This step simulates the changes of nutrient load attributed to pasture development, to compare with the estimate of the current nitrogen load.

The third step starts from estimated nitrogen loading to Lake Tarawera catchment in years beyond current loading. The third step was run over a period of 250 years to estimate the evolution of nitrogen loading to Lake Tarawera for the different scenarios. The period of 250 years was chosen to aim at steady-state conditions in Lake Tarawera catchments.

Scenario 1 : Pre-historic land use

The first scenario suggests a catchment without humans, like the land could be 5000 years ago, after the formation of the lake. This was represented in the model by a catchment exclusively covered by indigenous forest i.e. the whole 101.4 km^2 of the Lake Tarawera catchment covered with forest (Figure 23).

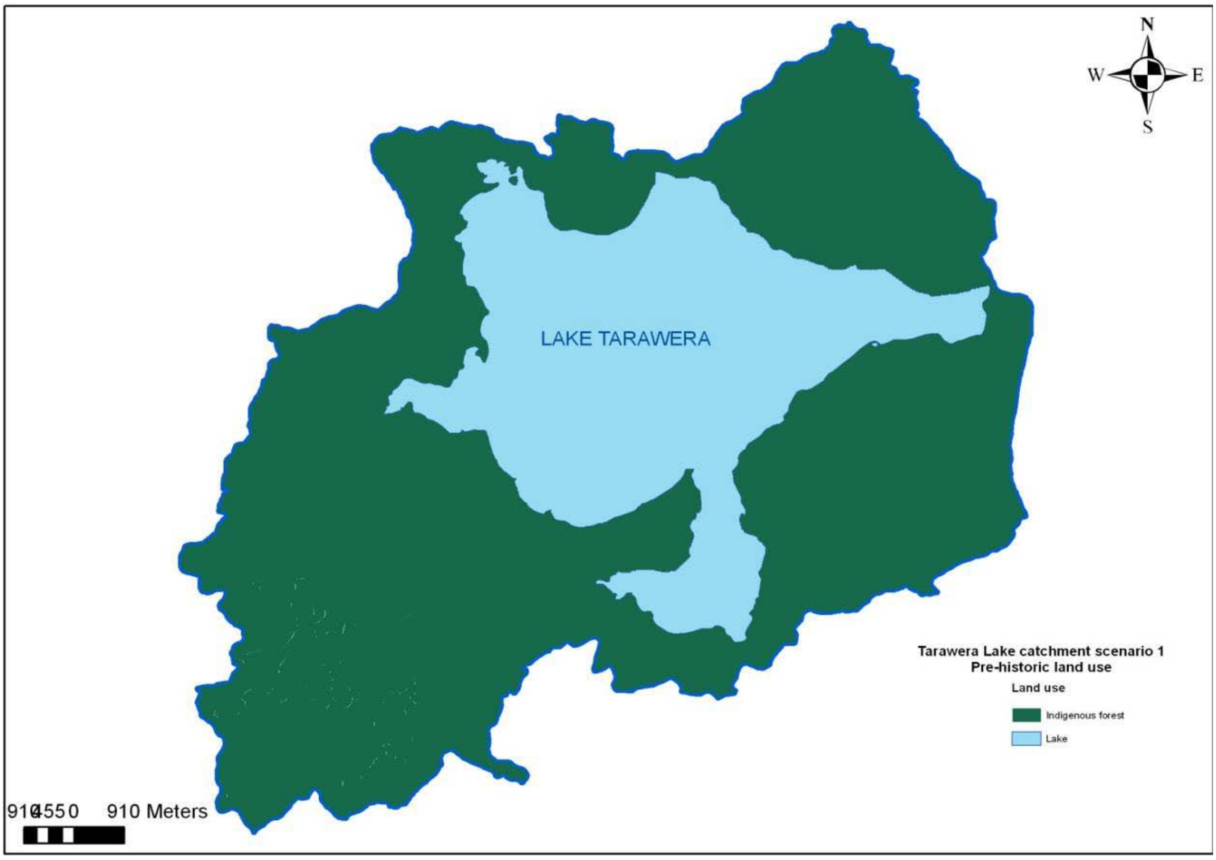

Figure 23 - Lake Tarawera catchment land use scenario 1: pre-historic land use.

Few data describe the groundwater quality inflowing from the surrounding catchments. To characterize the nitrogen concentration incoming from these catchments, two cases are applied:

- *Simulation 1a: Prehistoric land use and high nitrogen input at the boundary*

The first case "a" considers that groundwater seepage from the surrounding catchment has the same nitrogen loading as nitrogen concentration with forest, i.e. 0.45g d^{-1}. The simulation ran over a period of 300 years to ensure the system reached steady state conditions for nitrogen flow. Figure 24 shows the nitrogen evolution at time zero (i.e. forest land use began at time zero) for the prehistoric scenario.

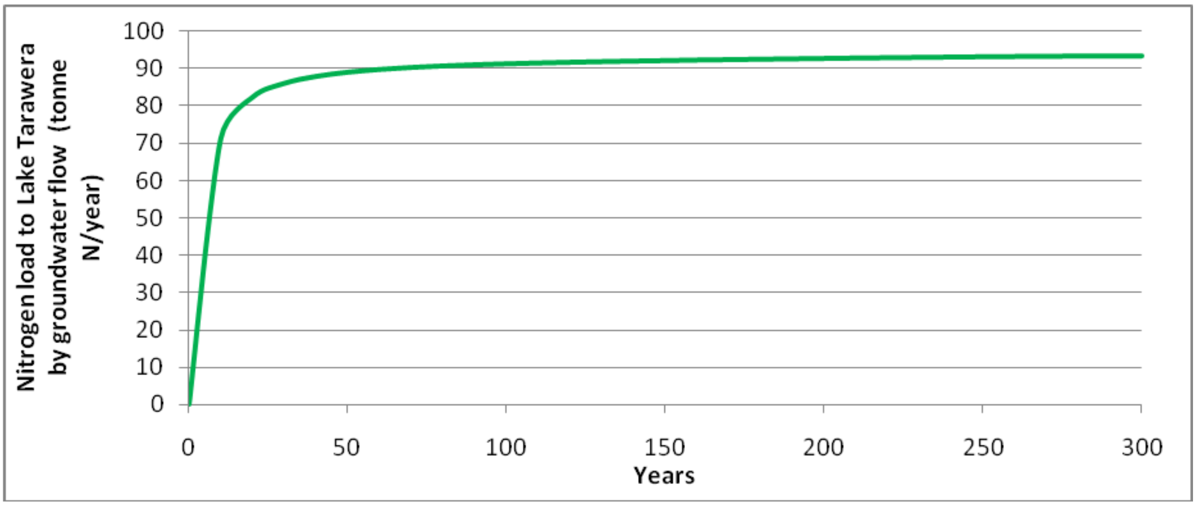

Figure 24 - Nitrogen evolution in the Lake Tarawera catchment scenario 1a: prehistoric land use and high nitrogen input at the boundary.

The steady state flow of nitrogen for prehistoric land use and high nitrogen input at the boundary was estimated as 94 tonnes N year^{-1}.

- *Simulation 1b: Prehistoric land use and low nitrogen input at the boundary*

The second case "b" considers the nitrogen concentration from Lake Rotomahana (with the highest groundwater flow seepage to Lake Tarawera catchment) with a nitrogen concentration in groundwater seepage of 0.2g d^{-1}. The simulation was run over a period of 300 years to ensure the system reached steady state conditions for nitrogen flow. The steady state flow of nitrogen for prehistoric land use and low nitrogen input at the boundary was estimated as 66 tonnes N year$^{\mathbf{-1}}$.

Scenario 2 : Current land use

This scenario simulates the current Lake Tarawera catchment land use (Figure 25).

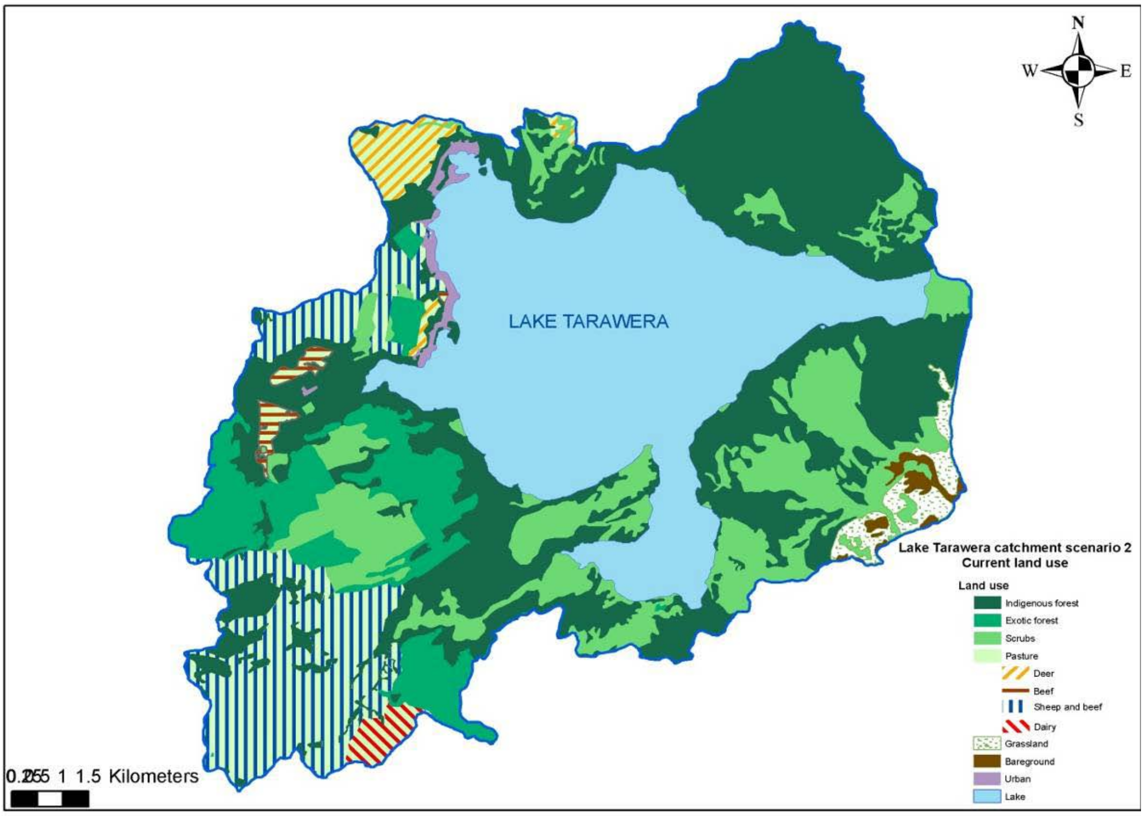

Figure 25 – Lake Tarawera catchment land use scenario 2: current land use.

Current land use areas include dairy pasture on the southern part, sheep and beef pasture on the south and western parts, a deer farm on the north-western and beef pasture on the western part of the Lake Tarawera catchment.

Steady state conditions from the two previous cases were used as initial conditions for this scenario. The model was run first over a period of 50 years to simulate development of farm activity until now then over a period of 300 years so that contaminant flow reaches steady state conditions. The two cases were simulated successively; calculated nitrogen loads to Lake Tarawera are shown in Figure 26 and Figure 27.

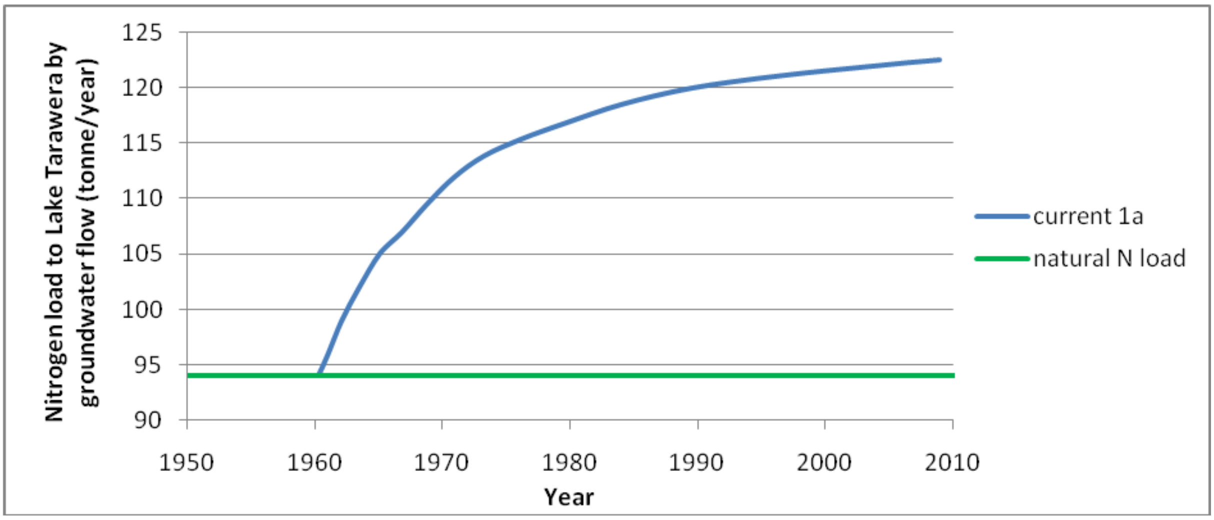

Figure 26 - Nitrogen concentration distribution observed at the surface of the Lake Tarawera catchment after the current land use scenario model was run over a period of 50 years.

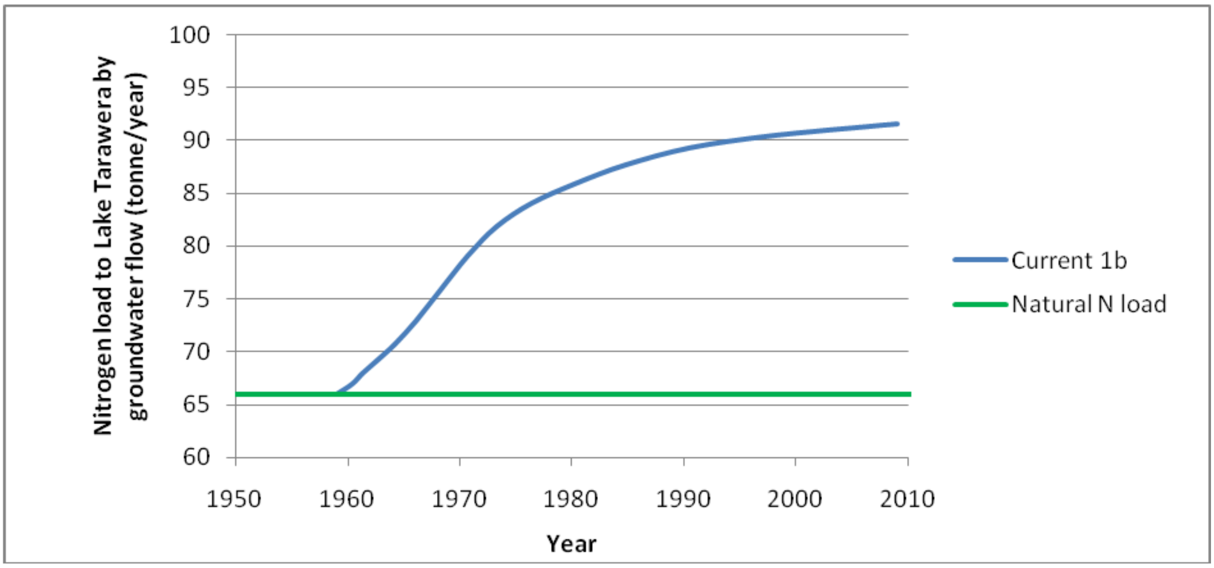

Figure 27 - Nitrogen concentration distribution observed at the bottom of the Lake Tarawera catchment after the current land use scenario model was run over a period of 50 years.

After 50 years, most of the nitrogen export flux from pasture reached the edge of Lake Tarawera for the surface layer. Higher concentrations of nitrogen were measured under the dairy pasture. The two simulations show the:

- importance of the groundwater seepage;
- importance of pasture land use in controlling the nitrogen discharge to Lake Tarawera.

Simulation of nitrogen exports from current land use over 300 years is shown in the Figure 28 and Figure 29. Steady state of nitrogen load by groundwater flow to Lake Tarawera was estimated as 127 tonnes N year^{-1} for the case “a” and 95 tonnes N year^{-1} for the case “b”. EBOP (2008) estimated from a numerical nitrogen balance for the Lake Tarawera the steady state of nitrogen load from current land use as 92 tonnes N yr^{-1}. Results of nitrogen load steady state from the two considered cases show that the case “b” result (i.e. 95 tonnes N yr^{-1}) is most consistent with EBOP (2008). Case “b” was used for the other scenarios.

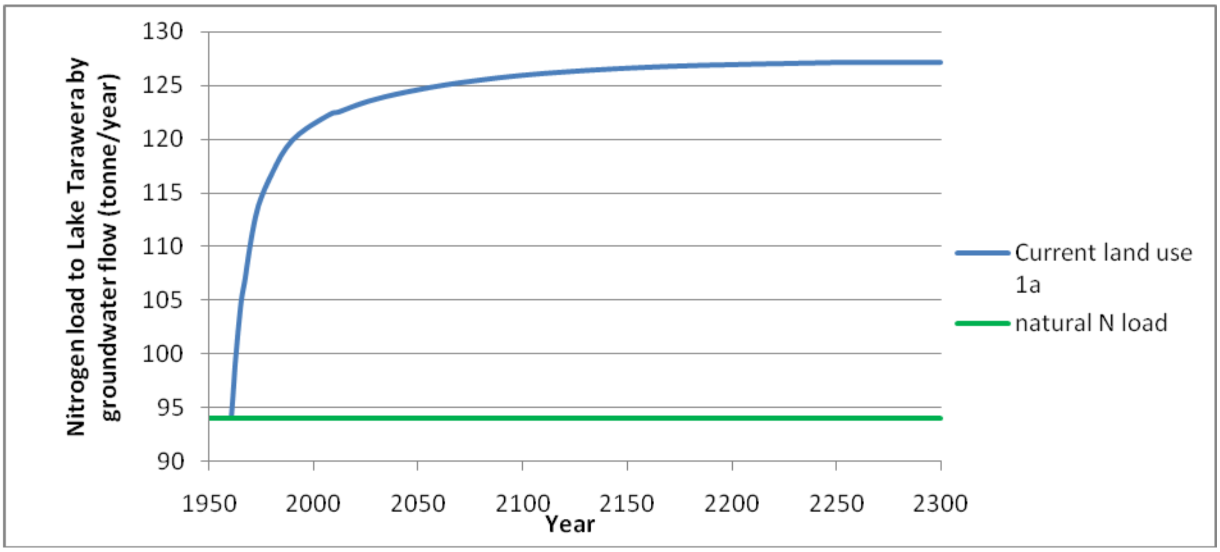

Figure 28 - Evolution of the nitrogen load by groundwater flow to Lake Tarawera for the current land use over a period of 300 years.

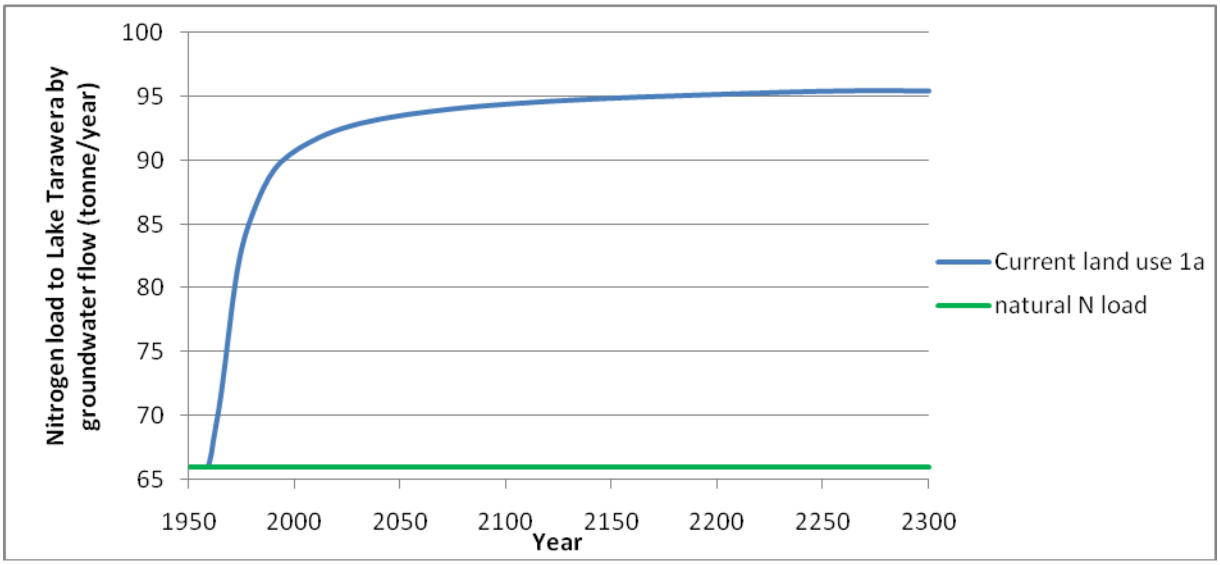

Figure 29 - Evolution of the nitrogen load by groundwater flow to Lake Tarawera for the current land use over a period of 300 years.

Scenario 3: Cattle farming extension

This first hypothetical land use scenario starts with the results of the current land use simulation, case “b”. In this scenario, all pasture was used for cattle farming. Figure 30 shows the proposed land use model.

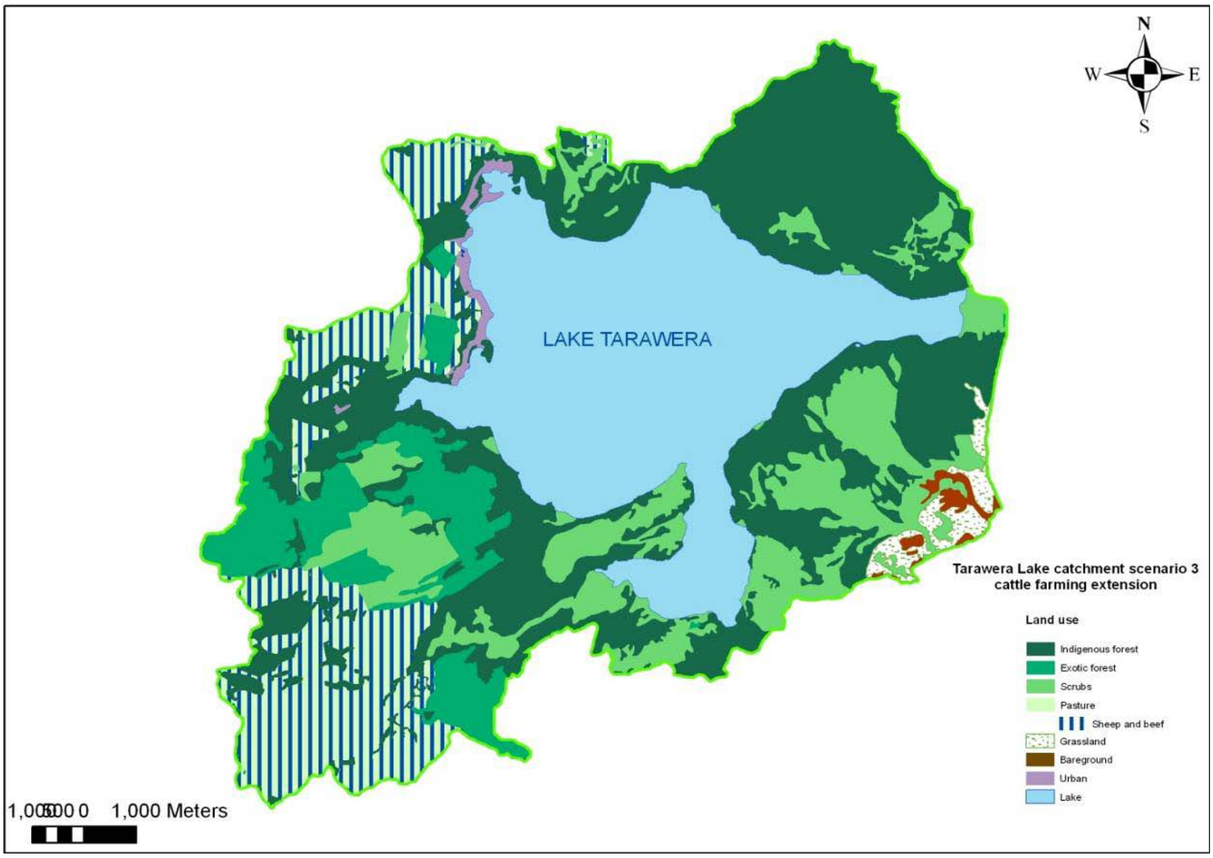

Figure 30 - Lake Tarawera catchment scenario 3 proposed land use (cattle farming extension).

The model was run over a period of 250 years. Figure 31 shows the evolution of the nitrogen load to Lake Tarawera.

A change of pasture to cattle farming affects the nitrogen load by groundwater to Lake Tarawera. The nitrogen load after 300 years was estimated as about 108 tonnes N year^{-1} i.e. 13% higher than the result from the current land use. Therefore the increase of nitrogen export from changing the deer farm into cattle pasture more than outweighs the decrease of nitrogen load resulting from the change of dairy farming to cattle farming.

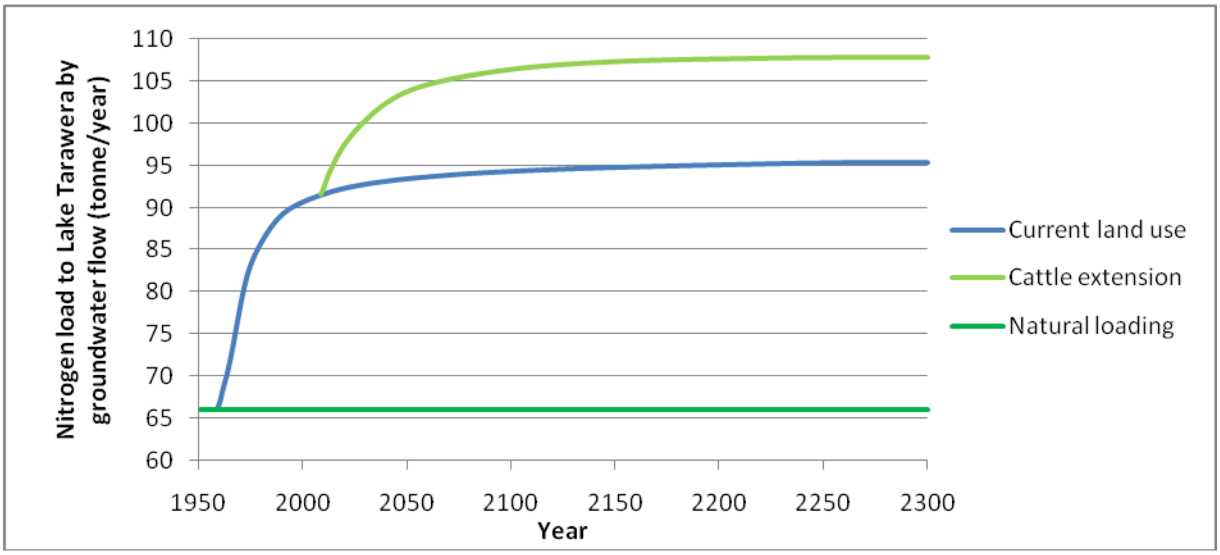

Figure 31 - Evolution and comparison between the nitrogen load by groundwater flow to Lake Tarawera from the cattle farming extension scenario and from the current land use scenario, over a period of 300 years.

Scenario 4: Dairy extension

The fourth scenario assesses conversion of all pasture to dairy farming. This is the worst likely case for nitrogen discharge from current pastoral land.

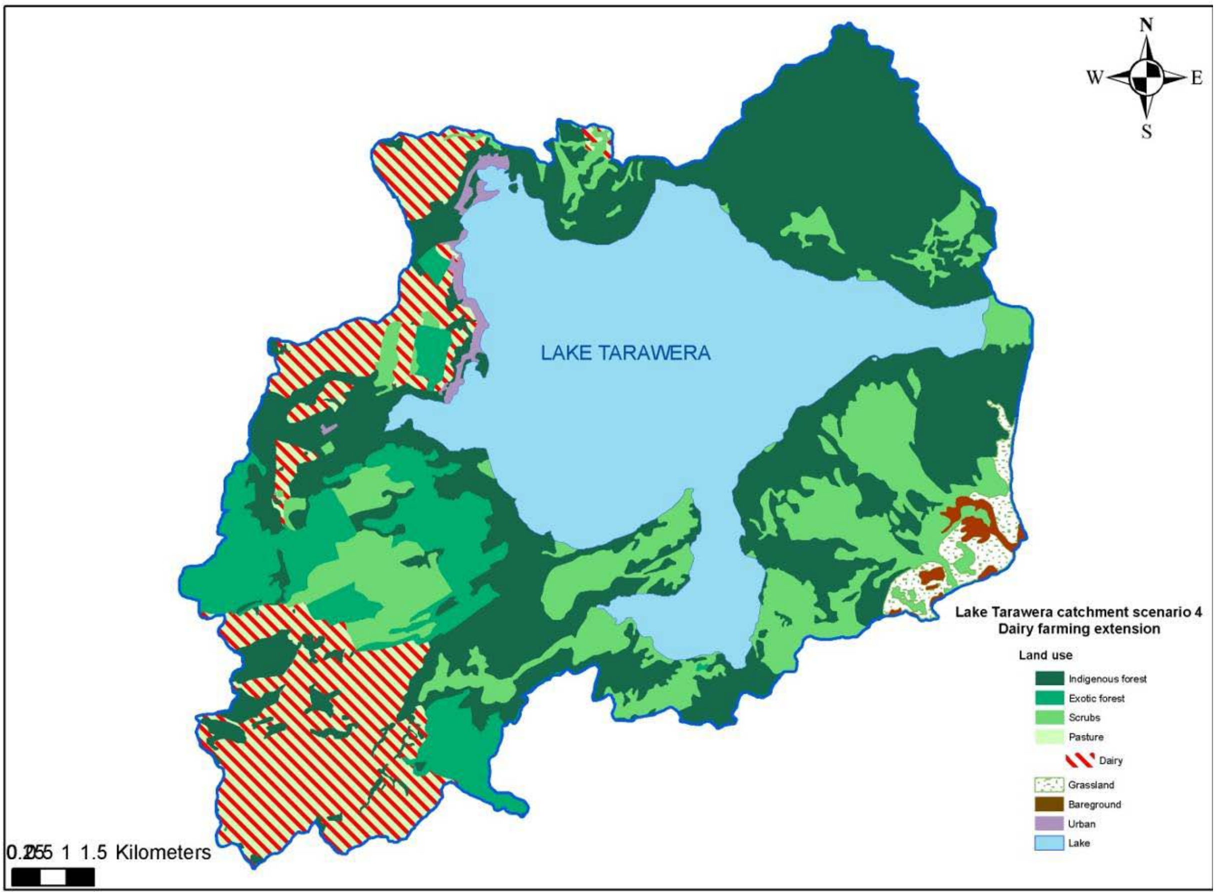

Figure 32 - Lake Tarawera catchment land use scenario 4: dairy extension.

Evolution of nitrogen load from this simulation and comparison with current land use is shown in the Figure 33.

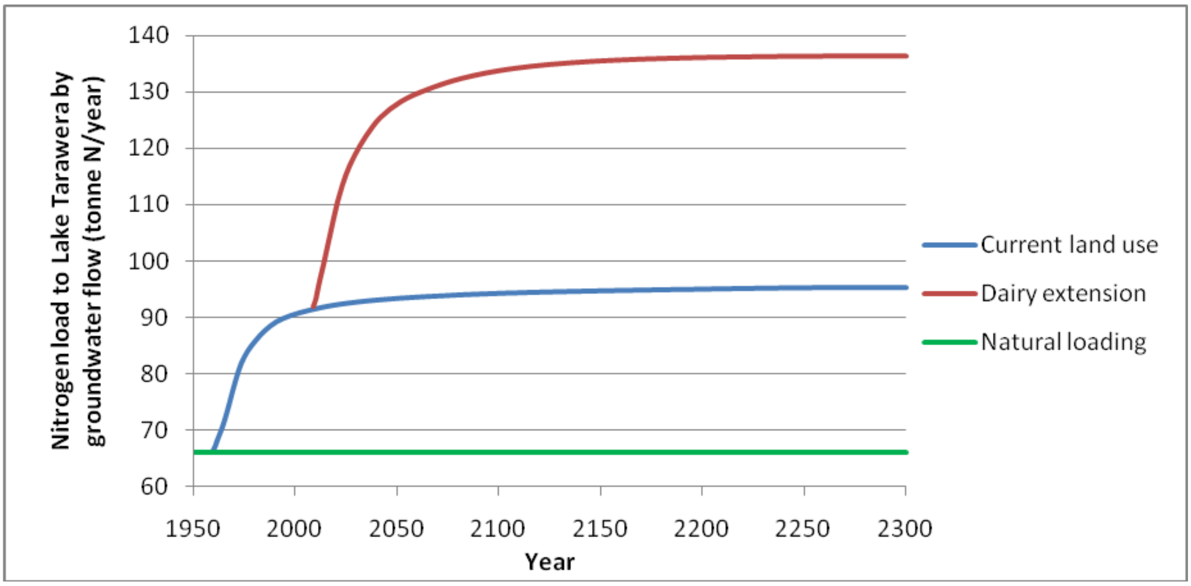

Figure 33 - Nitrogen load in groundwater flow to Lake Tarawera from the dairy farming extension scenario and from the current land use scenario over a period of 250 years.

Pasture change to dairy activity increases the nitrogen load by groundwater flow to Lake Tarawera. The maximum load of nitrogen by groundwater flow to Lake Tarawera was estimated as 136 tonne N year^{-1} with scenario 4.

Pasture change into dairy pasture is the worst case for the Lake Tarawera water quality, increasing by 43% the nitrogen load by groundwater flow compared to the current land use in the next 250 years and by 106% the nitrogen load by groundwater flow compared to the natural load.

Reduction nitrogen use or conversion of the farm activities to low use of nitrogen is possible and will help to protect Lake Tarawera water quality. However, nitrogen also enters Lake Tarawera from the urban area and treatment of the urban effluent should decrease the nitrogen load by groundwater to Lake Tarawera.

9. Septic Tanks

Scenario 5 : Tourist development (with pasture retirement)

Scenario 5 assesses how an increase of the population around the lake will impact the nutrient budget of Lake Tarawera. Scholes (2004) estimated a “natural” increase in the population around the Rotorua lakes by 9.8% by 2026, excluding potential development of tourist activity.

The simulation used for scenario 5 considers the urban area will be twice the current area, and imagines a tourist development will occur around the hot pools at the southern part of the Lake Tarawera and the population will be ten times the current population. Development of the urban area implies a development of urban infrastructures. Wallace (Lake Tarawera working party, 2006) suggests a conversion of the deer farm to a recreational “eco-park”. This concept is included in the simulation, assuming the deer farm is converted to an eco-park without animal grazing.

The value used for the nitrogen export from the urban area considers ten times the current population and was estimated as 13.3 kg N ha^{-1} $year^{-1}$. Figure 34 shows the proposed future Lake Tarawera catchment land use for scenario 5.

The simulation was run from the current land use over a period of 50 years thenrun over a period of 250 years to reach steady state conditions. Nitrogen load by groundwater flow to Lake Tarawera wass estimated (Figure 35).

Despite conversion of the deer farm to an eco-park, nitrogen flow generated by the population increase was higher than the current land use. Nitrogen load by groundwater flow to Lake Tarawera could reach 103 tonnes N yr^{-1} in 250 years, which means an increase of 8% for the nitrogen load to Lake Tarawera.

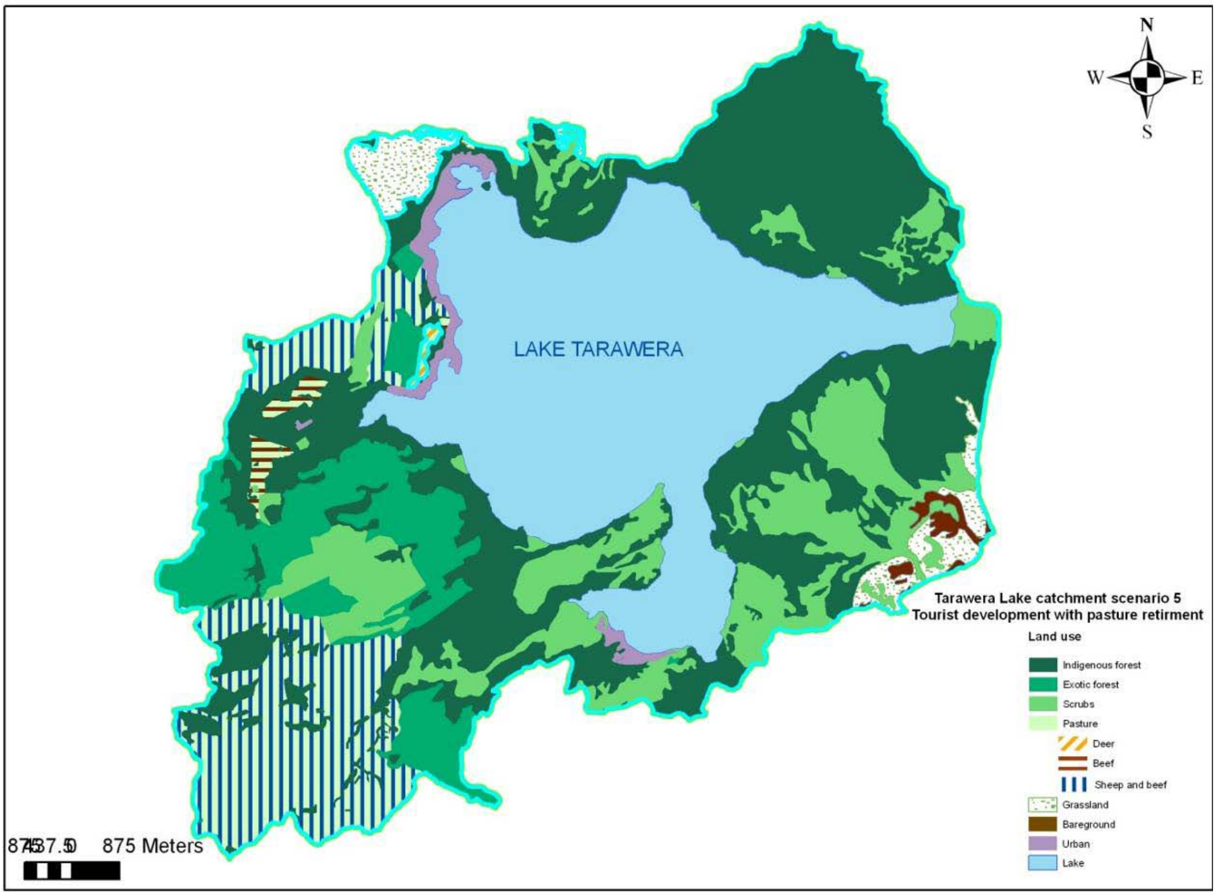

Figure 34 - Lake Tarawera catchment land use for the scenario 5: tourist development with pasture retirement.

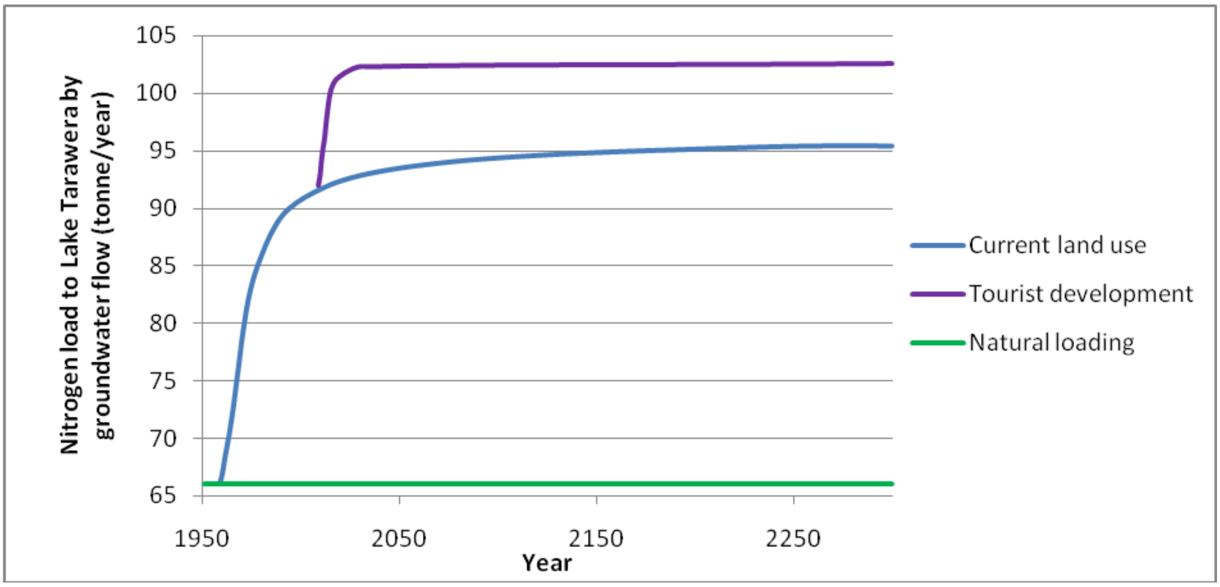

Figure 35 - Evolution of the nitrogen load by groundwater flow to Lake Tarawera for scenario 5.

Scenario 6 : On-site effluent treatment

The *On-site Effluent Treatment Regional Plan 2006* (EBOP 2006) imposes, for Lake Taraweraby 2014, a maximal discharge in total nitrogen (TN) of 15g m^{-3} in treated wastewater and a maximum effluent flow of 2 m^3 d^{-1}.

Assuming 2.8 people per household and 104 households around Lake Tarawera (Government census 2006) with a mean effluent flow value of 250 L/person/day (Hamilton *et al*. 2006) and the nutrient concentration of 15g m^{-3}, the leaking outflow from the urban area is estimated as 0.40 tonnes N yr^{-1}. Added to the sewage and the stormwater exports in nitrogen, the new nitrogen export value used for this scenario was estimated as 1.45 kg/ha/yr.

This simulation started from the current land use scenario results and the value of the urban area nitrogen export to groundwater was changed. The model was then run over a period of 250 years to reach steady state conditions for nitrogen load to Lake Tarawera. Figure 36 shows the nitrogen load results for this simulation.

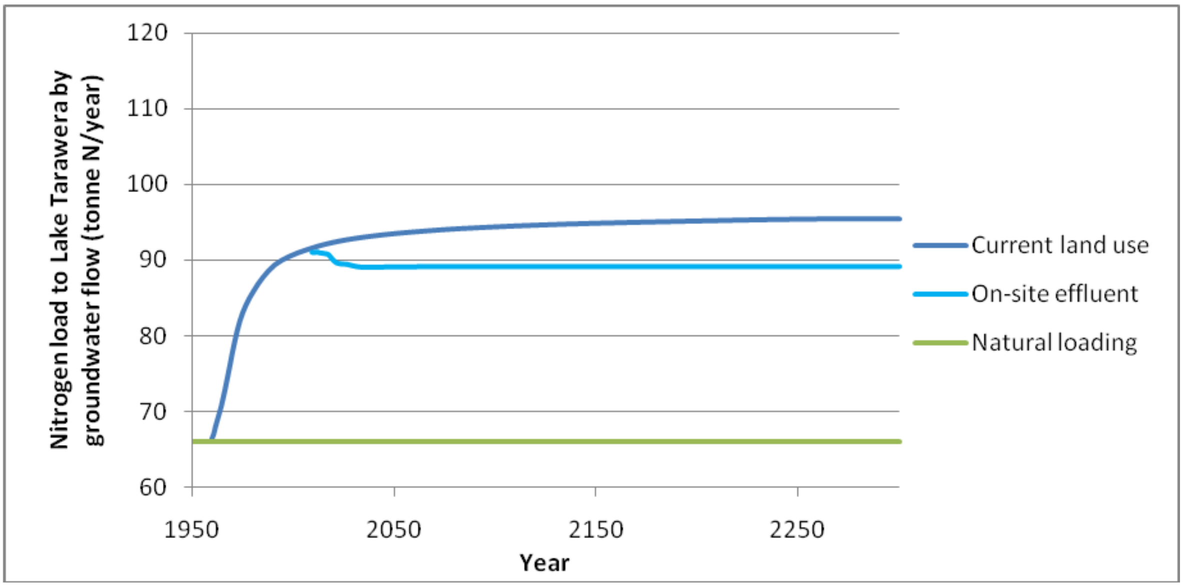

Figure 36 - Evolution of the nitrogen load by groundwater flow to Lake Tarawera considering a on-site effluent treatment.

Evolution of the nitrogen load by groundwater flow to Lake Tarawera showed a slight decrease of the nitrogen load to Lake Tarawera with on-site effluent treatment. Nitrogen export from urban area was estimated to reduce the nitrogen groundwater leakage into the lake by 6 % to an estimated value of 89 tonne N $year^{-1}$.

Scenario 7: Wastewater treatment plant

Another way to reduce nitrogen export from groundwater flow to Lake Tarawera is to treat wastewater from the urban area.

A wastewater treatment plant for effluent from the Tarawera urban area was suggested for this scenario. The location of the plant, in this scenario, is southwest of the urban area i.e. in the Lake Tarawera catchment, not too far from the urban area but not in forest.

The wastewater treatment plant was assumed to remove 70% of the nitrogen from the incoming wastewater and discharge the treated water directly to groundwater.

The model was run from the current land use scenario, from the current date. This scenario includes stormwater nitrogen export of 0.71 kg N ha^{-1} $year^{-1}$. The wastewater treatment plant was represented as a flow boundary condition with a constant flow of 12 mg L^{-1}. The new simulation was run over a period of 250 years to reach steady state conditions for contaminant flow.

Figure 37 shows the results for the nitrogen load by groundwater flow to Lake Tarawera for scenario 7.

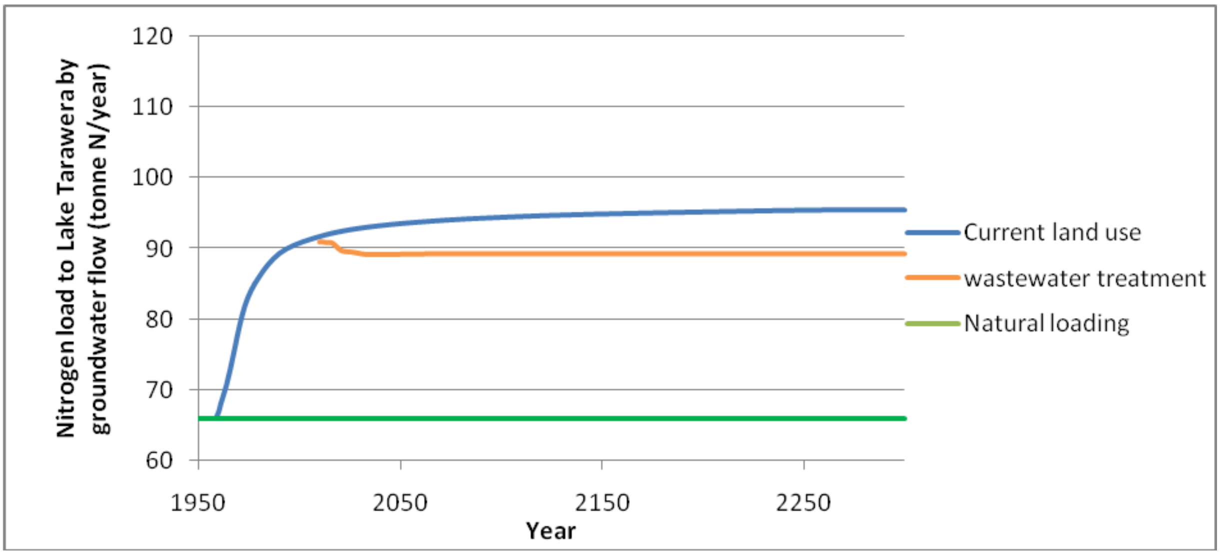

Figure 37 - Evolution of the nitrogen load by groundwater flow to Lake Tarawera considering a wastewater treatment plant.

Results were similar to these found for the septic tank solution. Treatment of sewage decreased the nitrogen load in groundwater flow to Lake Tarawera slightly, to an estimate of 89 tonnes N $year^{-1}$

Scenarios 6 and 7 allowed reducing the nitrogen load to Lake Tarawera. However, wastewater treatment is just a part of the solution to the problem of Lake Tarawera water quality. The really effective answer to the lake water quality problem remains a reduction of the nitrogen loads from the pasture. This solution would involve a reduction of the farm area or a change of their use to low nitrogen uses. The objective of EBOP to improve Lake Tarawera water quality by reducing the TLI to 2.6 implies a change in agricultural land use in the Lake Tarawera catchment by reducing agricultural land area or reducing agricultural land use intensity.

10. Information gaps and recommendations

This report identifies some issues and uncertainties that should be considered for future studies on groundwater in the Lake Tarawera catchment.

- The Okataina Volcanic Centre water budget was based on possible connections between the lake catchments. Lake Tarawera catchment is likely connected to four other lake catchments but no information exists to assess the connection between some lake catchments. Some studies should be undertaken to verify these links.

- It is necessary to improve the geological and hydrogeological knowledge of the catchment. For this a drill-hole campaign should be planned around the lake. Figure 38, and Table 15, describe the proposed priority sites. Thus, better data will be obtained for the layer properties and will allow the future definition of a model based on real hydrogeological properties.

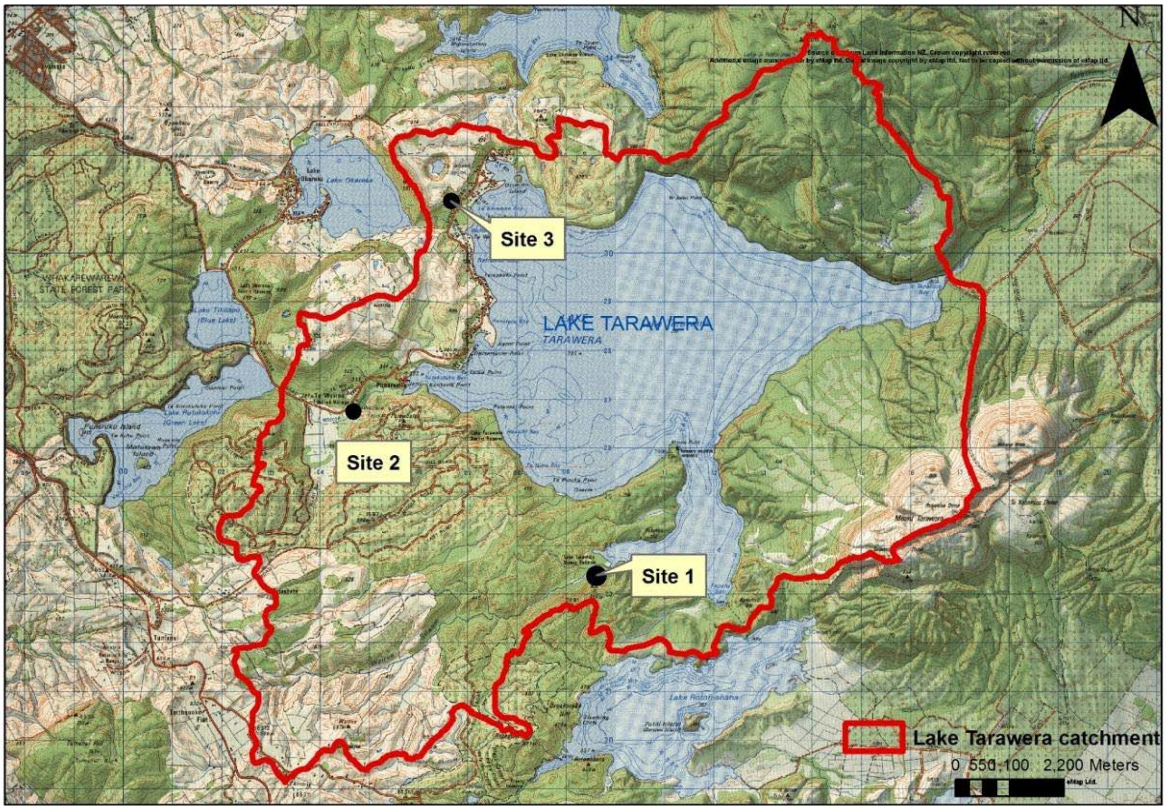

Figure 38 - Proposed drill holes sites for the Lake Tarawera catchment.

Table 15 - Objectives for proposed drill sites.

Proposed site number	Site Description	Bore hole use	Objective
1	Lake Tarawera - Lake Rotomahana link. Geothermal area	Pump test Piezometric level Water quality Temperature	• Assess the pumice and alluvium hydraulic conductivity. • Check and monitor the nitrogen concentration from the pastoral land use. • Look at a possible connection with geothermal activity
2	Lake Tarawera - Lake Rotokakahi link	Pump test Piezometric level Water quality	• Assess the pumice and alluvium hydraulic conductivity • Monitor the nitrogen concentration in groundwater inflowing to Lake Tarawera
3	Lake Tarawera – Lake Okareka link	Pump test Piezometric level Water quality	• Assess the Pokopoko and Onuku ignimbrites hydraulic conductivities. • Check and monitor the nitrogen concentration from the pastoral land use

- The current Lake Tarawera catchment groundwater model was defined by only one layer. Model calibration revealed that heterogeneity of geology in the Lake Tarawera catchment modifies the hydraulic conductivity. The Lake Tarawera catchment groundwater model should integrate at least two layers.
- In the current groundwater model, interactions between groundwater and rivers haven't been considered. The future model should take into consideration these interactions.

11. Summary

Formed 5000 years ago, Lake Tarawera is in the centre of the Okataina caldera complex. A water budget for lakes and catchments in the Okataina caldera indicates that Lake Tarawera receives a groundwater inflow of 3.8 $m^3 s^{-1}$ from the surrounding catchments including those of Lake Rotomahana, Lake Rotokakahi, Lake Okareka and Lake Okataina. Groundwater outflow from the Lake Tarawera catchment was estimated as 0.9 $m^3 s^{-1}$ to the Tarawera River valley. A water budget for the Lake Tarawera, and its catchment, indicates that 58 % of the inflowing water comes from underground flow.

Lake Tarawera catchment land use is dominated by forests but for the last 30 years, conversion of forest to pasture has occurred, causing an increase in nitrogen inputs to the lake. To assess nitrogen inflow to the lake, a hydrogeologic model was created with the FEFLOW software. The Lake Tarawera catchment groundwater model considers one layer generally representing rhyolite.

The FEFLOW model was used to assess possible future nitrogen loads to Lake Tarawera for current land use and five scenarios of future land use within the Lake Tarawera catchment. Table 16 summarises the maximum expected nitrogen load with groundwater flow to Lake Tarawera for current land use and five scenarios of future land use.

Table 16 - Maximum expected nitrogen load by groundwater flow into Lake Tarawera for scenarios of land use within the Lake Tarawera catchment.

Sub-catchment	***Pre-historic land use***	***Current Land use***	***Cattle farming extension on existing pasture***	***Dairy extension on existing pasture***	***Tourist development***	***On-site effluent treatment***	***Wastewater treatment plant***
Maximum expected nitrogen load by groundwater flow to Lake Tarawera (tonne N yr^{-1})	66	95	108	136	103	89	89

Future maximum nitrogen load by groundwater flow to Lake Tarawera from current land use in the Lake Tarawera catchment was estimated as 95 tonnes N yr^{-1}. Land use outside the Lake Tarawera catchment may impact on water quality in Lake Tarawera because groundwater travels into the lake from other catchments.

The worst case scenario assessed in this project for Lake Tarawera water quality was a conversion of all existing pasture in the Lake Tarawera catchments into dairy land use. In this case future nitrogen load to Lake Tarawera may increase to 136 tonnes N yr^{-1}.

A wastewater treatment plant would allow some reduction of the nitrogen load to Lake Tarawera. However, the best way to improve lake water quality, i.e. reduce the Lake Tarawera TLI to Environment Bay of Plenty’s target of 2.6, is to address pastoral land use because most of the nitrogen that currently enters the lake comes from pastoral land. Options for pastoral use may include reducing the area of farm land or reducing nitrogen discharge from the existing farm area.

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