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Groundwater flow and quality in the Whakarewarewa Forest

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EXECUTIVE SUMMARY

Rotorua District Council (RDC)'s scheme to treat sewage and apply treated wastewater in Whakarewarewa Forest has reduced the discharge of nitrogen and phosphorus to Lake Rotorua. This scheme has contributed to the reduction of nutrient loads to the lake, which supports the aim of Bay of Plenty Regional Council (BOPRC) and the local community. However, water quality has recently declined in Lake Rotokakahi (Bruere, 2011), possibly due to nutrient discharge from the Whakarewarewa Forest spray irrigation field. Therefore, BOPRC requested that GNS Science review the geology, surface water data, and hydrogeologic data in the study area to assess the potential of treated wastewater to flow through the groundwater system from the Whakarewarewa Forest spray irrigation field into Lake Rotokakahi.

The groundwater catchment boundary between Whakarewarewa Forest and Lakes Rotokakahi and Tikitapu is probably similar to the surface catchment boundary as indicated by catchment water budgets, measured groundwater elevations and a groundwater flow model. Therefore, a groundwater divide consistent with topography probably prevents groundwater flow between Whakarewarewa Forest and Lakes Rotokakahi and Tikitapu. In addition, the vast majority of spray irrigation in the Whakarewarewa Forest occurs in spray blocks below the 394 m topographic contour, which is the surface water elevation of Lake Rotokakahi. Groundwater elevation at the 394 m topographic contour in Whakarewarewa Forest will be below the elevation of Lake Rotokakahi because the water table in wells is always below the ground surface. As a result it is highly unlikely that the treated wastewater flows through the groundwater system from the Whakarewarewa Forest spray irrigation field into Lake Rotokakahi.

1.0 INTRODUCTION

Rotorua District Council (RDC)'s scheme to treat sewage and apply treated wastewater in Whakarewarewa Forest has reduced the discharge of nitrogen and phosphorus to Lake Rotorua, thereby contributing to the aims of Bay of Plenty Regional Council (BOPRC) and the local community to reduce nutrient loads to the lake. For example, recent nitrogen discharge from the Whakarewarewa Forest spray irrigation field through Waipa Stream (Figure 1) was approximately 30 – 40 tonnes N/yr in the period 2006 – 2009 (Environment Bay of Plenty, 2009) and nitrogen discharge to Lake Rotorua may have been 100 tonnes N/yr before the current system was installed (McIntosh, 2011).

However, water quality has recently declined in Lake Rotokakahi (Bruere, 2011), Figure 1, and nutrient discharge from the Whakarewarewa Forest spray irrigation field is a possible cause of this decline. Therefore, BOPRC contracted GNS Science to assess the potential for treated wastewater to flow from the Whakarewarewa Forest spray irrigation field into Lake Rotokakahi through the groundwater system.

In this report, the geology, surface water and hydrogeological data in the study area are initially reviewed (Figure 1). This information includes: catchment hydrology, surface water quality, groundwater levels and groundwater quality. Secondly, the potential of treated wastewater to flow through the groundwater system to Lake Rotokakahi is assessed in this report.

2.0 STUDY AREA

The study area is located south and southeast of Rotorua City within the Puarenga Stream catchment (White et al., 2007), Figure 1. The area is bounded to the southeast by Lakes Rotokakahi and Tikitapu, by the Kauaka Stream to the west, the Rotorua Caldera rim to the north, and Tarawera Road to the northeast (Figure 2). The catchment covers a land area of approximately 34.8 km^2 including Whakarewarewa Forest and the Waipa Mill. Part of the Whakarewarewa Forest has been used for irrigation disposal of treated wastewater by RDC since 1991 (Environment Bay of Plenty, 2009). Treated wastewater is sprayed onto blocks, numbered 1 to 16 (Figure 2), in the Waipa Stream catchment. These blocks range in elevation between 320 m and 418 m above mean sea level (MSL). In comparison, the elevations of Lake Rotokakahi and Lake Tikitapu (Figure 1) are 394 m MSL and 415 m MSL, respectively (Bay of Plenty Regional Council, 2012).

3.0 GEOLOGY

Late Quaternary Tauranga Group sediments (alluvial and colluvial sand and gravels) occur over much of the Whakarewarewa Forest area (Figure 3). The Tauranga Group is subdivided into alluvium and lake sediments (silty, pumice dominated rhyolite fragments and felsic crystals). Fine grained sediments were deposited by large lakes that occupied the area south of the Rotorua Caldera (Nairn, 1987). The Hinuera Formation, also part of the Tauranga Group sediments, comprises cross-bedded sand and gravel, pumice, ash and some primary ignimbrite from the Oruanui eruption (Leonard et al., 2010).

The most recent major volcanism in the study area was approximately 65 thousand years ago (Nairn, 2002) and yielded the Rotoiti Formation, a non-welded ignimbrite, on the eastern side of the study area. Undifferentiated Quaternary Rhyolites, including Moerangi dome, occur in the east of the study area (Leonard et al., 2010).

4.0 SURFACE WATER

4.1 Catchment hydrology

Surface water streams are common in the Puarenga Stream catchment (Figure 4). Baseflow in Puarenga Stream is 1,700 l/s near Lake Rotorua with an estimated 580 l/s flowing from Waipa Stream. Stream beds in the upper reaches of the study area are typically dry. For example, The Wash stream bed is usually dry throughout the channel reach.

Catchment inflows and outflows have been assessed with water budgets. Thorpe (1987) estimated runoff and groundwater flow in the Waipa Stream catchment to be equivalent to 700 mm/yr. In comparison, results from gauging measurements have been reported to show equivalent runoff of 645 mm/yr (March 1987) and 805 mm/yr (May 1987); annual outflows were slightly higher than predicted with a simple water balance but within the margin of error for such estimates (Thorpe, 1987).

Specific mean flow for the Waipa Stream catchment was an estimated 21 $l/s/km^2$ which was similar to that of the entire Puarenga catchment (25 $l/s/km^2$) and therefore, 'no substantial inflows from outside the surface catchment are likely' (Nairn, 1987). In addition, a water balance calculation for the Puarenga catchment resulted in 'no suggestion … that water was lost from the accepted catchment boundaries' (McIntosh, 2011).

4.2 Stream water quality

Surface water samples were collected at a monthly interval from July 1996 to April 2010 at the M11 stream monitoring site (Figure 5; Lowe, 2012). This site is located in a pristine forest sub-catchment (ID 13, Figure 5). The hydrochemical dataset at both sites includes: pH, conductivity, Total Phosphorus (TP), ammonia (NH_3), Total Oxidised Nitrogen (TOXN, representing the sum of nitrate and nitrite) and Total Kjeldahl Nitrogen (TKN). Zero values were recorded in the chemical dataset. These values were substituted with a "less than" sign using the lowest measurement for the corresponding parameter to represent the detection limit.

Statistical trend analyses performed on stream quality data and on rainwater quality measured at the Kaharoa rainfall recharge site (White et al., 2008) using an automated calculator (Daughney 2007; Daughney, 2010). These tests included seasonality (Kruskal-Wallis, season starting on 1st March) and Mann-Kendall trend tests at the 95% confidence interval. Where seasonality was detected (Kruskal-Wallis test p value <0.05), the Mann-Kendall test was seasonality adjusted. Trend magnitudes were estimated using Sen's slope estimator (Daughney 2007, 2010).

Median flow at the M11 site was 4.0 l/s. Stream conductivity is indicative of dilute waters and does not vary significantly over time (Table 1).

Median stream TOXN and TP concentrations were 0.063 mg/l and 0.020 mg/l respectively (Table 1). The low values observed for TOXN at the M11 site are consistent with TOXN measured in rainwater at Kaharoa (<0.002 mg/l, except once, when measured as 0.008 mg/l, in nitrate form). However, TP concentrations (median 0.02 mg/l) are significantly lower compared to the 0.2 mg/l TP observed in Kaharoa rainwater (Figure 6). Lower phosphorous may arise from high allophane content in the soil, as allophane has the potential to bind phosphorous tightly. Where detected, TKN and NH_3 rainwater median concentrations (0.26 mg/l and 0.024 mg/l respectively) were significantly higher than the Whakarewarewa Forest sites (median concentrations of 0.099 mg/l and 0.004 mg/l respectively, Figure 6). In the M11 sub-catchment, nitrogen was found mostly in non-nitrate forms (TKN, NH_3). All chemical indicator concentrations at M11 are very low and in most contexts the water would be regarded as non-impacted by land use or natural background quality. The TOXN time series at the M11 site is characterised by low concentrations, with frequent, sporadic highs. The TP time series at M11 remains relatively stable around 0.02 mg/l with a detected trend magnitude less than 0.5% (Table 1).

Estimated Total Nitrogen (TN) concentration in the Waipa Stream at upstream site M10 (Figure 6) was an average of approximately 0.4 mg/l after 2000 (Park and Holst, 2009). In contrast, estimated average TN at downstream site M5 (Figure 6) was approximately 2.1 mg/l after 2000 (Park and Holst, 2009).

Table 1: Summary statistics of stream water quality data at site M11 (monthly measurements from July 1996 to April 2010). Zero values were substituted to a "less than" sign using the lowest measurements for a given parameter as a threshold for detection.

Analyte	Flow (l/s)	pH	Conductivity (µS/cm)	Cl (mg/l)	NH_3 (mg/l)	TKN (mg/l)	TOXN (mg/l)	TP (mg/l)
# Results Used	164	164	164	164	164	162	164	163
Minimum	2.00	6.50	46.5	<1	<0.001	0.031	<0.001	0.008
Median	4.00	7.03	66.2	4.05	0.004	0.100	0.006	0.020
Average	3.78	7.02	66.5	4.29	0.005	0.111	0.021	0.024
Maximum	12.00	7.62	79.9	41.00	0.099	0.419	0.573	0.170
Median Absolute Deviation (MAD)	1.68	0.08	3.3	0.55	0.001	0.021	0.004	0.004
Standard Deviation (SD)	1.85	0.14	5.1	3.25	0.008	0.055	0.055	0.017
TREND? (INCR, DECR, N or ND)	INCR	INCR	N	N	N	INCR	INCR	INCR
Trend magnitude (units/year)	0.19	0.01	-	-	-	0.003	0.0002	0.001
Mann-Kendall test p-value	0.00	0.04	0.47	0.42	0.08	0.00	0.02	0.00
SEASONALITY? (Y, N, ND)	N	N	Y	N	Y	Y	Y	Y
Kruskal-Wallis test p-value	0.18	0.39	<0.05	0.31	<0.05	<0.05	<0.05	<0.05

5.0 GROUNDWATER

5.1 Groundwater flow directions

A groundwater flow model of the Lake Rotorua catchment (White et al., 2007) incorporated estimates of baseflow, rainfall and geology to demonstrate that groundwater flow in the Puarenga Stream catchment is sufficient to support stream baseflow. This groundwater flow model was used to estimate groundwater catchment boundaries (Figure 8). The groundwater flow model calculated that groundwater flows from the upper reaches of The Wash catchment towards Rotorua (Figure 8). This flow direction is in agreement with Thorpe (1987), as. baseflow in The Wash is low (Thorpe, 1987) and baseflow in the Waitawa catchment (Figure 8) is comparatively high (White et al., 2007). However, in this report, the Puarenga Stream groundwater catchment boundary is tentatively drawn at the Rotorua caldera boundary because of the uncertainty in the estimates of baseflow (White et al., 2007).

5.2 Groundwater levels and springs

Groundwater depths in boreholes (Figure 9) drilled in Tauranga Group sediments were measured before irrigation began (Thorpe, 1987). Typically, groundwater elevations were below the ground surface (Table 2), and were greater at higher elevations in the Whakarewarewa Forest area (Figure 10). Groundwater elevation in the Undifferentiated Quaternary Rhyolite in the Whakarewarewa Forest is also likely to increase with ground elevation as suggested by Nairn (1987), Figure 11.

The two major springs in the study area are the Waipa Spring, at the foot of Moerangi dome and the Hemo Spring (Figure 3). These two springs are assumed to be the 'old Rotorua water supply spring' and 'small spring' as described by Nairn (1987). Both springs have similar oxygen-18 isotope composition to that of local rainfall (Nairn, 1987). Waipa Spring water is relatively old: 'of the order of 100 years' (Nairn, 1987), indicating that the groundwater feeding the spring has a relatively long travel path (i.e., through undifferentiated rhyolite lava, Figure 11). In comparison, the groundwater age of Hemo Spring is much younger, with 'a significant component of water on the order 10 years old', which indicates rapid drainage through the Tauranga Group sediments (Nairn, 1987).

Table 2: Summary statistics of groundwater depths and groundwater elevation* (Thorpe, 1987).

Bore no	NZMG Northing	MZMG Easting	Ground Elevation (m)	Casing length (m)	Top of casing to ground (m)	Groundwater elevation 14/04/1987 (m MSL)	Groundwater elevation 27/04/1987 (m MSL)
1	6331500	2794900	330	2.55	0.43	328.1	328.2
2	6331300	2794900	310	2.8	0.82	308.5	308.6
3	6331700	2796300	343	10.17	0.42	333.7	333.7
4	6331100	2796800	333	4.2	0.5	330.3	330.4
5	6330900	2797100	348	7.62	0.78	dry	dry
6	6331300	2797700	363	7.12	0.38	356.3	356.3
7	6330900	2795800	322	6.13	0.32	317.2	320.9
8	6330500	2796900	334	4.79	0.64	dry	329.8
9	6330600	2797300	341	1.83	0.23	339.9	336.3
10	6330800	2798000	353	11.13	0.68	dry	342.1
11	6330300	2796800	336	2	0.4	335.0	335.0
12	6330200	2797600	334	4.44	0.67	dry	330.2
13	6330400	2798100	346	6.16	0.44	dry	340.5
14	6330600	2798800	362	10.58	0.39	dry	dry
15	6329300	2796200	370	11.7	0.75	dry	dry
16	6329400	2796800	343	1.96	0.08	dry	dry
17	6329700	2797400	334	3.39	1.67	dry	332.9
18	6328500	2797800	388	11.18	0.3	dry	dry

Footnote to Table 2:

* ground elevation is estimated with a digital terrain model (DTM) of the Whakarewarewa Forest area provided by RDC (Watts, 2012), except for bore 1 and 2 which are located outside the DTM and were derived from the NZ 50:000 scale Land and Information New Zealand topographic contours (20 m interval).

5.3 Groundwater quality

The dataset of piezometer and lysimeter chemical measurements consists of monthly analysis of composite samples for conductivity, pH, chloride (Cl), Dissolved Reactive Phosphorus (DRP), ammonia (NH_3), TOXN and TKN (Appendix 1).

The samples were obtained from three separate areas of the Whakarewarewa Forest (Lowe, 2012): the L15 – 16 area within spray blocks; L12 – 13 area located up-gradient of the spray areas; and the Trial area (Figure 9), located immediately above the artificial ponds (Moreau-Fournier and White, 2012).

The "LP15" samples are composite samples from ten sites, each site consisting of two lysimeters: one set at a depth of 40 cm and a second set at a depth of 70 cm below ground level. These sites are labelled from 15A to 15J on Figure 9. The "LP16" samples are composite samples from ten piezometers labelled 16A to 16J (Geddes, 2012). The "LP12" samples are composite groundwater samples collected from ten piezometers labelled from 12A to 12J. The "LP13" samples are composite lysimeter samples from ten sites, in a similar arrangement to that of "LP15", these sites are labelled 13A to 13J (Moreau-Fournier and White, 2012). The "TB1" to "TB6" samples are also composites samples from lysimeters located in the trial area. TB1 comprises 15 lysimeters; however for the others sites the actual number of lysimeters is unknown. Up to 55 lysimeters were identified with the markings of TB2 during a field visit, and the other sites could not be confirmed or numbered due to overgrowth or damage along the spray lines. However, all lysimeters may not have been routinely sampled.

Sites LP12, LP13 and TB1 are outside spray blocks. The groundwater chemical signature at these sites is consistent with non-impacted or natural background quality areas. Median conductivity was less than 62 μS/cm, and median Cl concentration was below 8.4 mg/l (Figure 12, Appendix 1). Nutrient concentrations were generally low, with median values less than the following: NH_3 (0.012 mg/l) TOXN (0.021 mg/l) and DRP (0.045 mg/l, Figure 13, Appendix 1).

Sites LP15, LP16 and sites in the trial block (TB2, TB3, TB4, TB5 and TB6) were located within spray blocks (Figure 12). The groundwater chemical signature at these sites was: median conductivity up to 310 μS/cm in the trial area (Appendix 1); Cl concentration up to 35.8 mg/l at TB4; and median TOXN concentrations up to 8.2 mg/l at TB2 (Figure 13) (Appendix 1). These concentrations are all significantly higher than at sites outside the spray blocks. This demonstrates the negative impact of irrigation on groundwater quality. For example, groundwater conductivity within spray blocks is up to five times greater than outside spray blocks. The impact of irrigation is also demonstrated by elevated NH_3 concentrations in the trial area (median NH_3 concentration of 1.4 to 2.1 mg/l for TB5 and TB6) whereas elsewhere concentrations were at or below 0.01 mg/l (Figure 13). The highest DRP concentrations were also observed in the trial area (median concentrations 0.269 and 0.245 mg/l for TB5 and TB6, respectively), whereas elsewhere median concentrations were at or below 0.05 mg/l. It is important to note that high DRP and NH_3 concentrations associated with low TOXN concentrations, may indicate locally reducing conditions at TB5 and TB6.

Although significant trends were detected at several sites, there was no consistent pattern between each site (Appendix 1). For instance, pH increased by about 0.1 pH unit per year at LP16, but decreased by the same magnitude at LP15. In addition, Cl concentration increased at LP13 and decreased at LP12. The most consistent trend was an increase in conductivity, which occurred in three of the six trial area sites at rate up to 5 μS/cm per year. Over the whole time period, some trends were not monotonic. Therefore, trend analysis results should be viewed with caution. An example of a trend that was not monotonic is the increase in Cl concentrations at LP15 and LP16 until year 2000, followed by a decrease down to levels similar to those of the beginning of monitoring in 1994 until 2006 (Figure 14).

Three groundwater samples were collected over two days in May 2012. The samples were collected at half day intervals from monitoring wells 3, 4, 9, 11 and 14, and were analysed for DRP, NH_3, TKN, TOXN, and TP. Wells 4, 9, 11 and 14 were located down-gradient from spray blocks, whereas well 3 was sited away from the spray blocks (Figure 9). Median concentrations are listed in Table 3. Wells 9 and 14 exhibit significantly higher TOXN concentrations (4.1 and 1.9 mg/l, respectively) than the other wells which are all below 0.1 mg/l. Although the median TOXN concentration at well 14 was not as high as that observed for well 9, it was also associated with the highest NH_3 concentration (0.66 mg/l). TN and TOXN levels in groundwater samples from wells 9 and 14 were markedly different from that for well 3. This difference may be explained by the location of wells 9 and 14 in proximity to, and down gradient of spray blocks, whereas well 3 is not located down gradient of spray blocks. The higher concentrations of TN and TOXN in well 9 is likely to be a result of the well location in a central position among a cluster of spray blocks.

TP concentrations reflect the sum of suspended phosphorus and organic and inorganic-bound dissolved phosphorus. The difference between TP and DRP indicates either a large amount of suspended phosphorus rich materials (possibly bound to muds or clays), or that most of the phosphorous in the composite samples is organic at all wells. As noted previously, soils in the study area are allophanic and phosphorus is expected to bind tightly to clays.

Table 3: Median concentrations from May 2012 groundwater samples.

Well ID	DRP (mg/l)	NH_3 (mg/l)	TKN (mg/l)	TN (mg/l)	TOXN (mg/l)	TP (mg/l)
Well 3	0.01	0.05	0.78	0.89	0.1	0.43
Well 4	<0.01	0.01	0.19	0.245	0.06	0.02
Well 9	0.01	0.01	0.22	4.32	4.1	0.01
Well 11	0.08	0.03	1.10	1.17	0.08	0.14
Well 14	0.02	0.66	1.12	3.18	1.89	0.15

6.0 POTENTIAL FOR GROUNDWATER FLOW TO LAKE ROTOKAKAHI

Catchment water budgets developed before the irrigation of treated wastewater typically estimate groundwater inflows to the Waipa Stream catchment that are similar to outflows measured in stream gaugings (Thorpe, 1987; Nairn, 1987). After the commencement of irrigation, surface water flows gave 'a strong indication that all the water from the irrigated effluent flows back down the Waipa Stream' (McIntosh, 2011). The various physical water resource measurements summarised in this report indicate that groundwater flow from the Whakarewarewa Forest to Lake Rotokakahi and Lake Tikitapu, is very unlikely.

Rainfall recharge in the Puarenga Stream catchment is sufficient to support baseflow in the catchment (White et al., 2007). The Wash, on the northern side of Whakarewarewa Forest, is one area where groundwater recharge from rainfall is possibly in excess of surface water flow. In this area, groundwater has the potential to flow into the Waitawa catchment (Figure 8).

Groundwater catchment boundaries of spring-fed streams in the Waipa Stream catchment calculated with a groundwater flow model (White et al., 2007), do not include land outside the surface catchment boundary. Therefore, no groundwater flow from outside the surface catchment boundary is required to support surface flow within the catchment. Groundwater flow directions calculated with this model indicate that groundwater flow directions within the catchment are strongly related to topographic gradients (White et al., 2007).

Shallow water table elevations are also generally assumed to be consistent with, and indicated by topography (Figures 10 and 11). Groundwater level measurements taken before irrigation showed that the water table was always below ground level (Table 2). Therefore, a groundwater divide probably exists below or near to the topographic divide, and is likely to prevent groundwater flow from Whakarewarewa Forest to Lakes Rotokakahi and Tikitapu. The vast majority of irrigation spray blocks in the Whakarewarewa Forest (94%) are below the 394 m topographic elevation of Lake Rotokakahi (Figure 9). The maximum spray block elevation is 418 m. Groundwater level below the 394 m topographic contour in Whakarewarewa Forest will therefore always be below the level of Lake Rotokakahi, Much of the water table underlying land between 394 m and 415 m will also be below Rotokakahi lake level because the level in the wells is always below ground level (Table 2). At higher land elevations in this catchment the depth below ground level to the water table tends to be greater than further down slope (Figure 11). This provides further assurance that spray irrigation in the Whakarewarewa Forest remains in the Puarenga Stream catchment.

Lastly, the increase in nitrogen concentration in the Waipa Stream is further supports that groundwater travels from the spray irrigation field to the stream. For example, at upstream site M10 (Figure 9), the estimated TN average concentration was approximately 0.4 mg/l; whereas at downstream site M5 (Figure 9), the estimated TN average concentration was approximately 2.1 mg/l, after 2000 (Park and Holst, 2009).

7.0 CONCLUSIONS

Catchment water budgets developed before the irrigation of treated wastewater typically estimate groundwater inflows to the Waipa Stream catchment that are similar to outflows measured in stream gaugings (Thorpe, 1987; Nairn, 1987). In addition, rainfall recharge in the Puarenga Stream catchment is generally sufficient to support baseflow in catchment streams (White et al., 2007). Moreover, the water table elevation generally increases with topographic elevation (Figures 10 and 11) but more gradually, so the difference between the two levels increases (i.e. depth to water table increases) towards the topographic divide. Groundwater depths measured before irrigation showed that the groundwater table in wells was always below ground level (Table 2). Therefore, a groundwater divide probably exists in the vicinity of the topographic divide, which prevents groundwater flow between Whakarewarewa Forest and Lakes Rotokakahi and Tikitapu.

The vast majority of irrigation spray blocks in the Whakarewarewa Forest are below the 394 m topographic contour which is the elevation of Lake Rotokakahi (Figure 2). Groundwater elevation at the 394 m topographic elevation in Whakarewarewa Forest will be below the elevation of Lake Rotokakahi because the water table (measured in wells) is below the ground surface.

8.0 ACKNOWLEDGEMENTS

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FIGURES

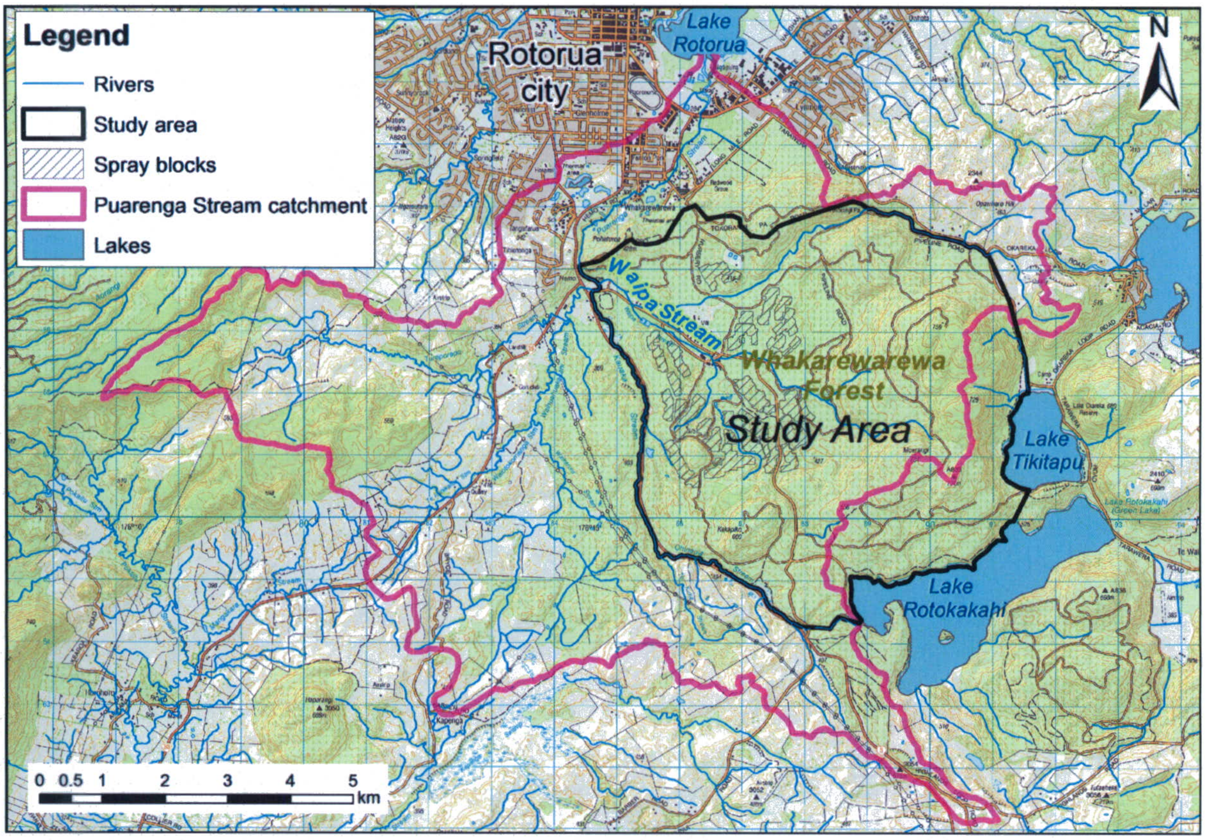

Figure 1: Map of the Whakarewarewa Forest study area.

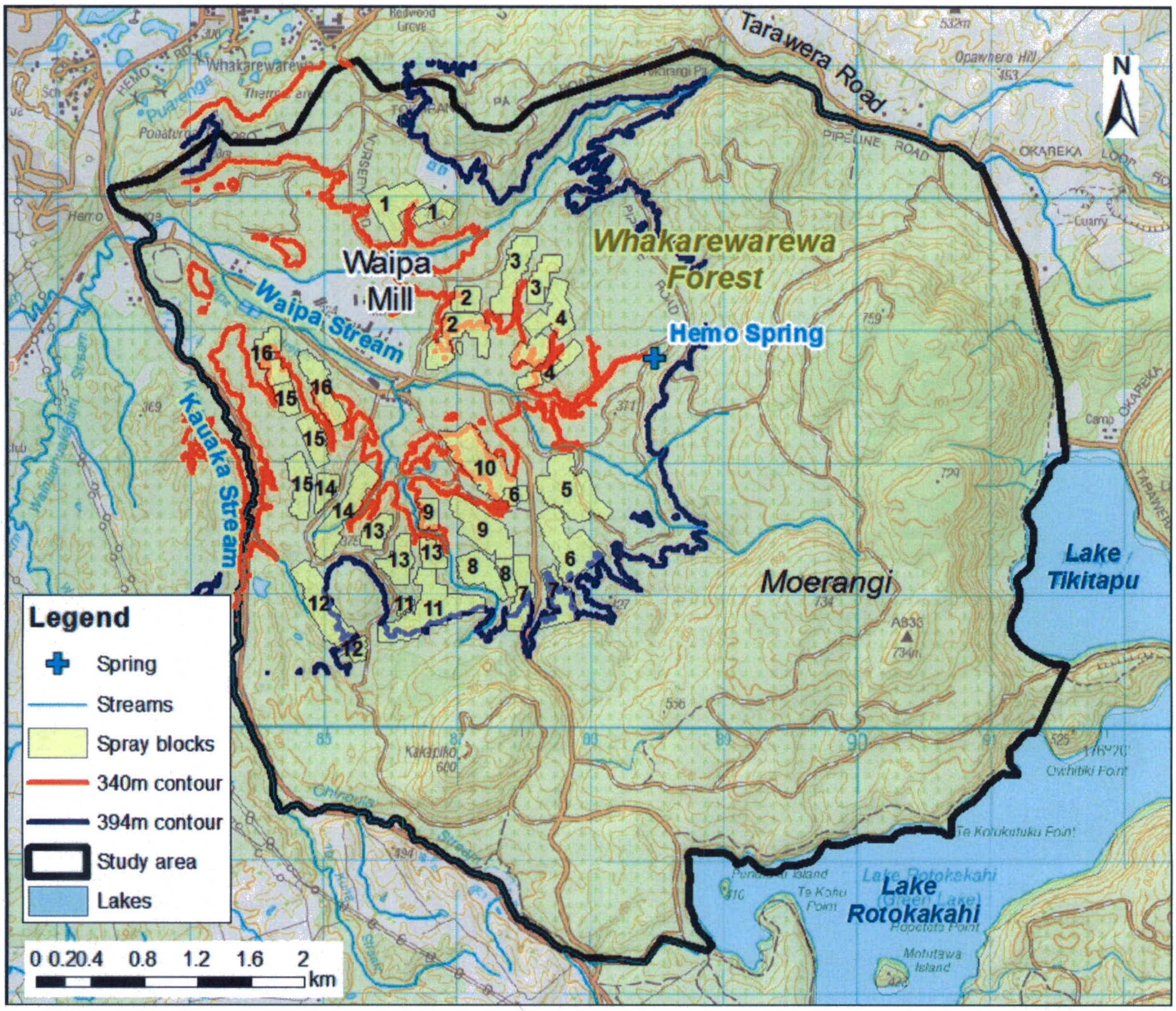

Figure 2: Location of Rotorua District Council spray blocks in the Whakarewarewa Forest study area.

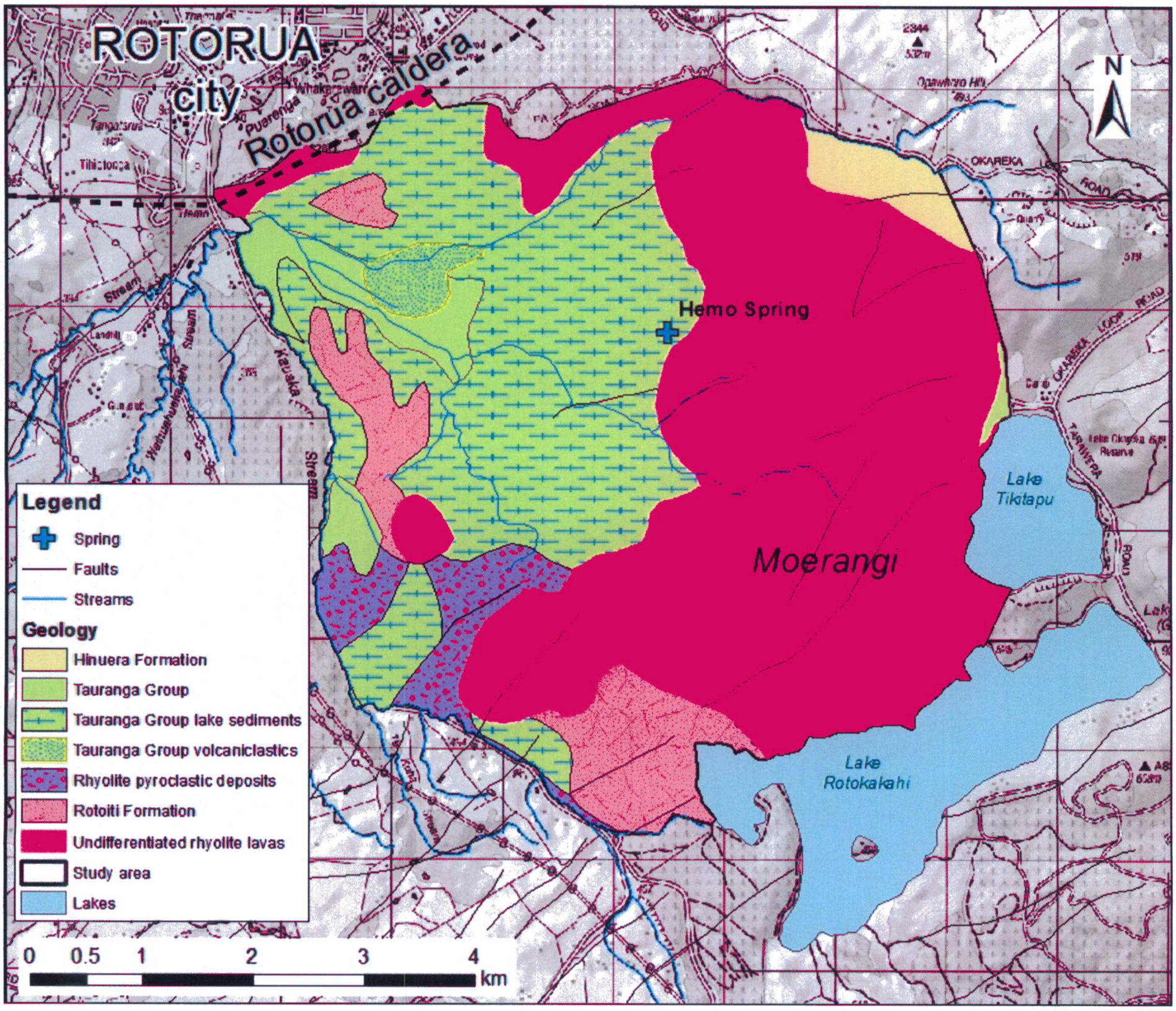

Figure 3: Geological map of the study area (after Leonard et al., 2010).

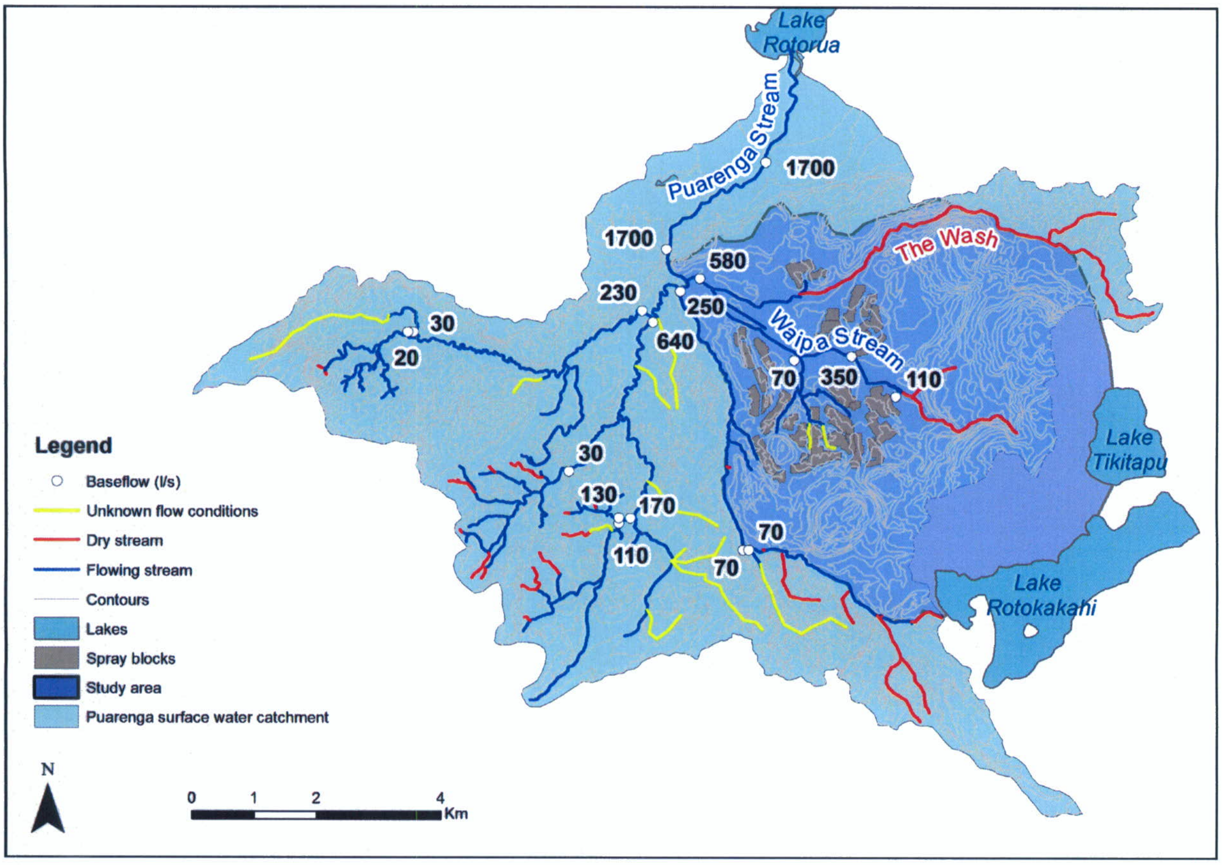

Figure 4: Model of baseflow, location of gauging measurements and location of dry stream beds in the Puarenga Stream catchment. Yellow lines in stream beds show where the stream bed type (either flowing or dry) is unknown (White et al., 2007).

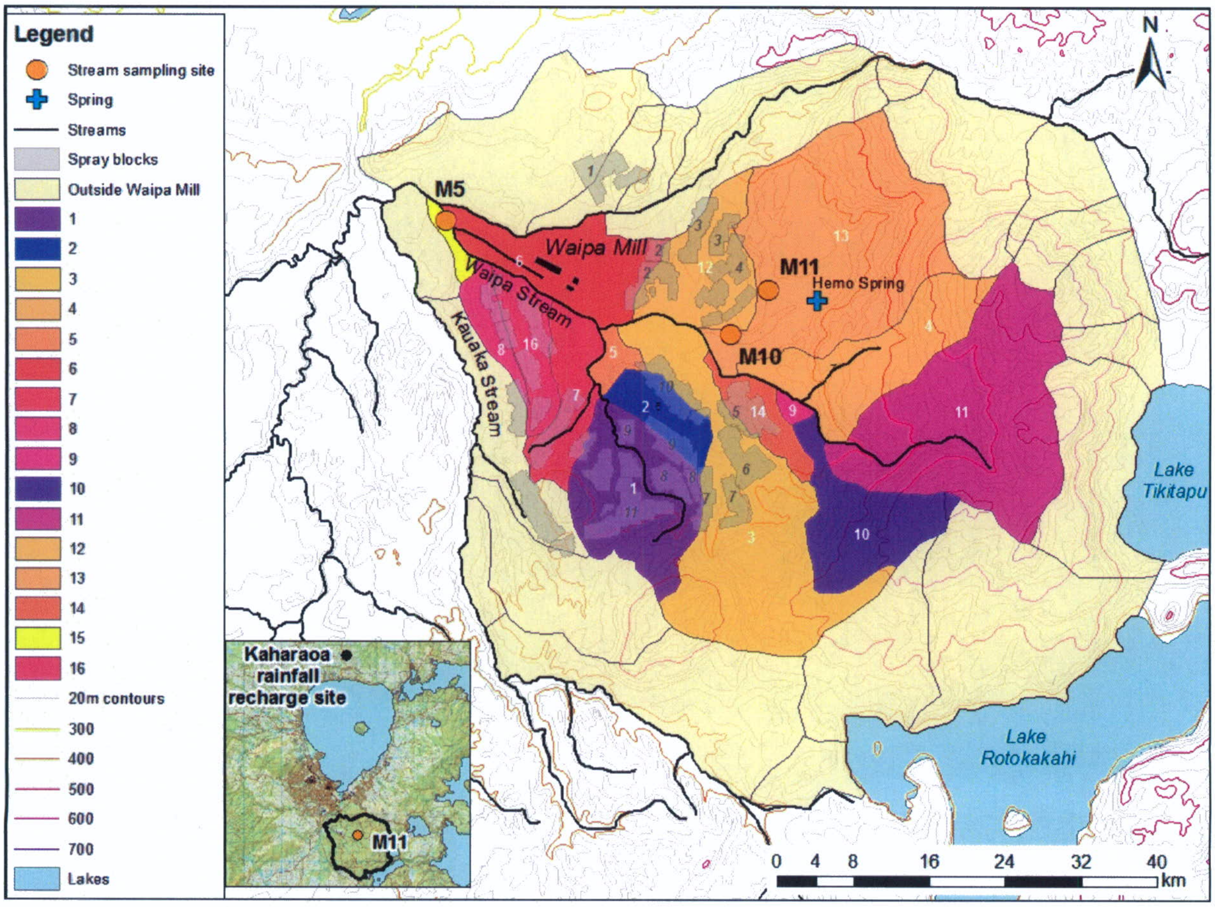

Figure 5: Stream sampling sites and sub-catchments up-gradient of the Waipa Mill highlighted in colour. The inset shows the location of the Kaharoa rainfall recharge site (White et al., 2008).

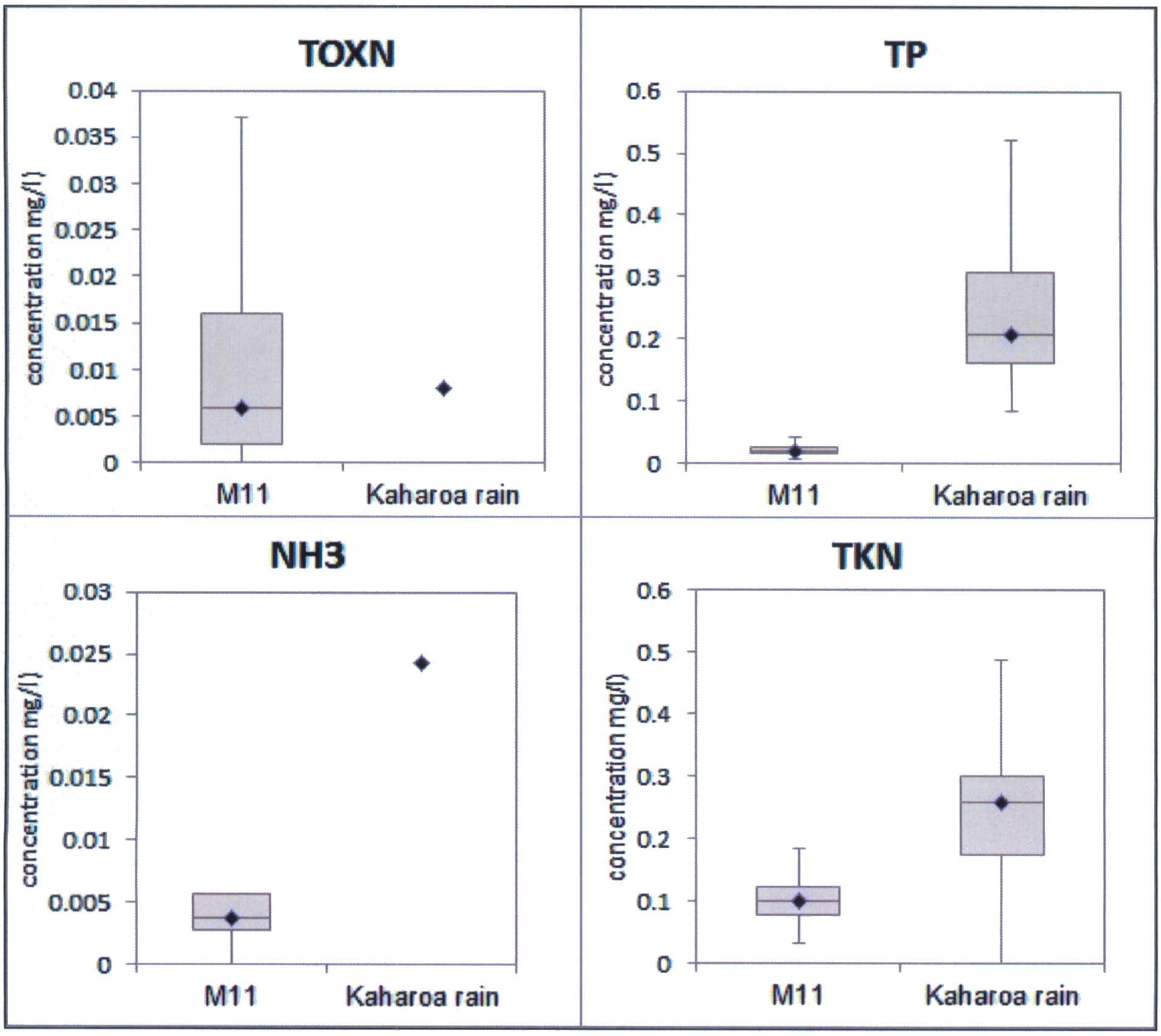

Figure 6: Box plots of nitrogen species and phosphorous concentrations in stream site M11 and rainwater.

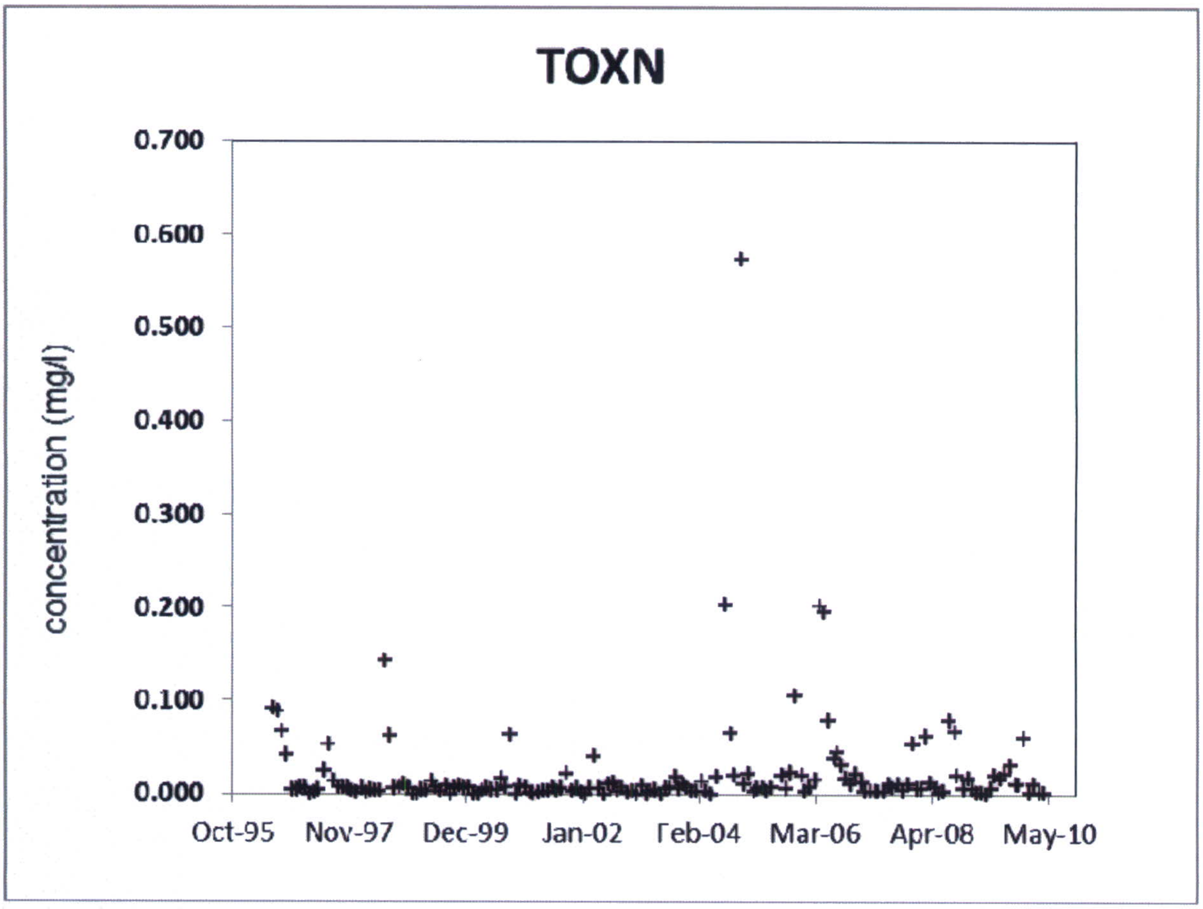

Figure 7: TOXN time series for stream water at site M11.

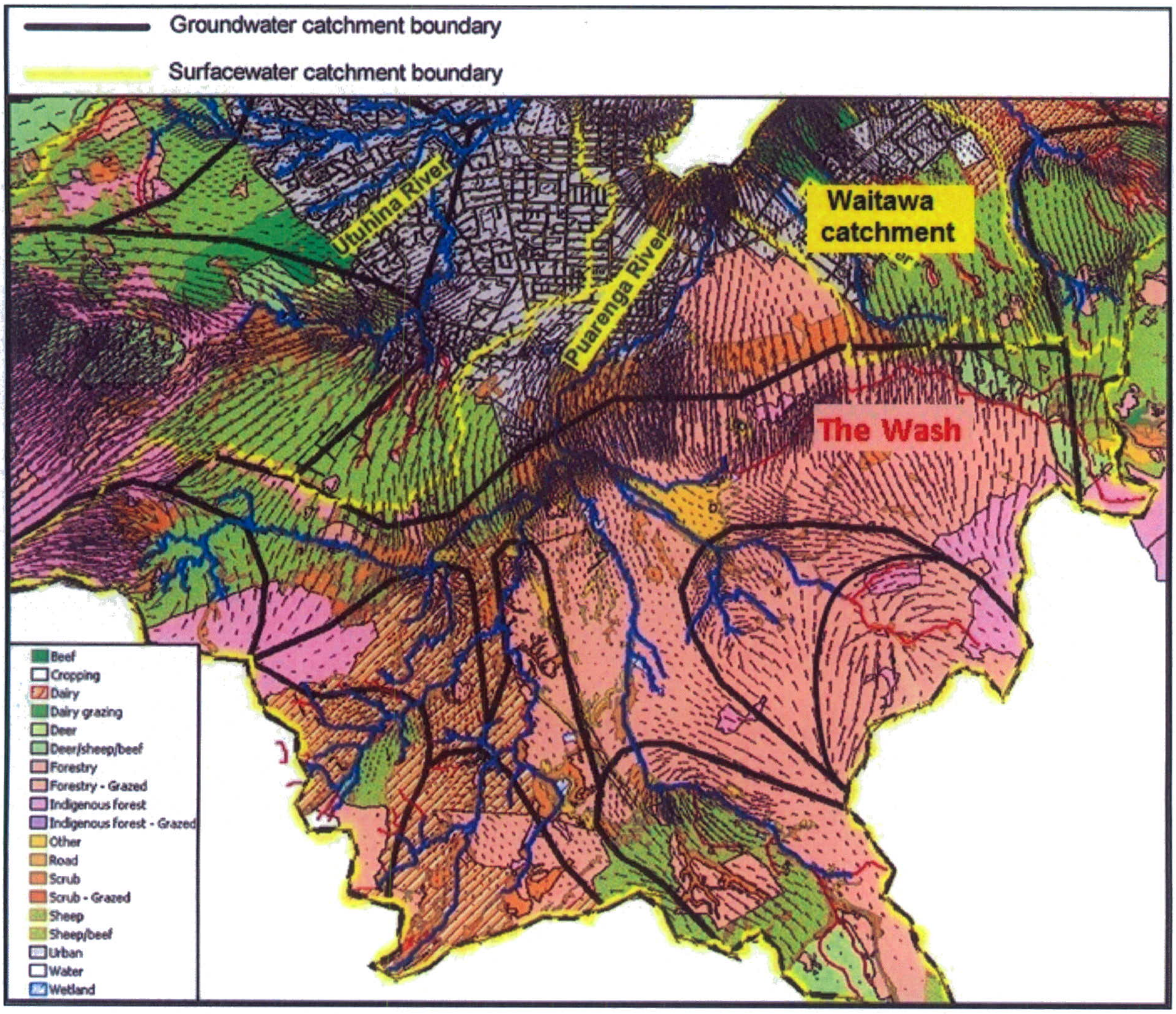

Figure 8: Groundwater catchment boundaries and land use in the Puarenga, Waitawa and Utuhina catchments. The black arrows represent groundwater flow directions. The black lines represent the groundwater catchment boundaries. The yellow lines are surface water catchment boundaries (White et al., 2007).

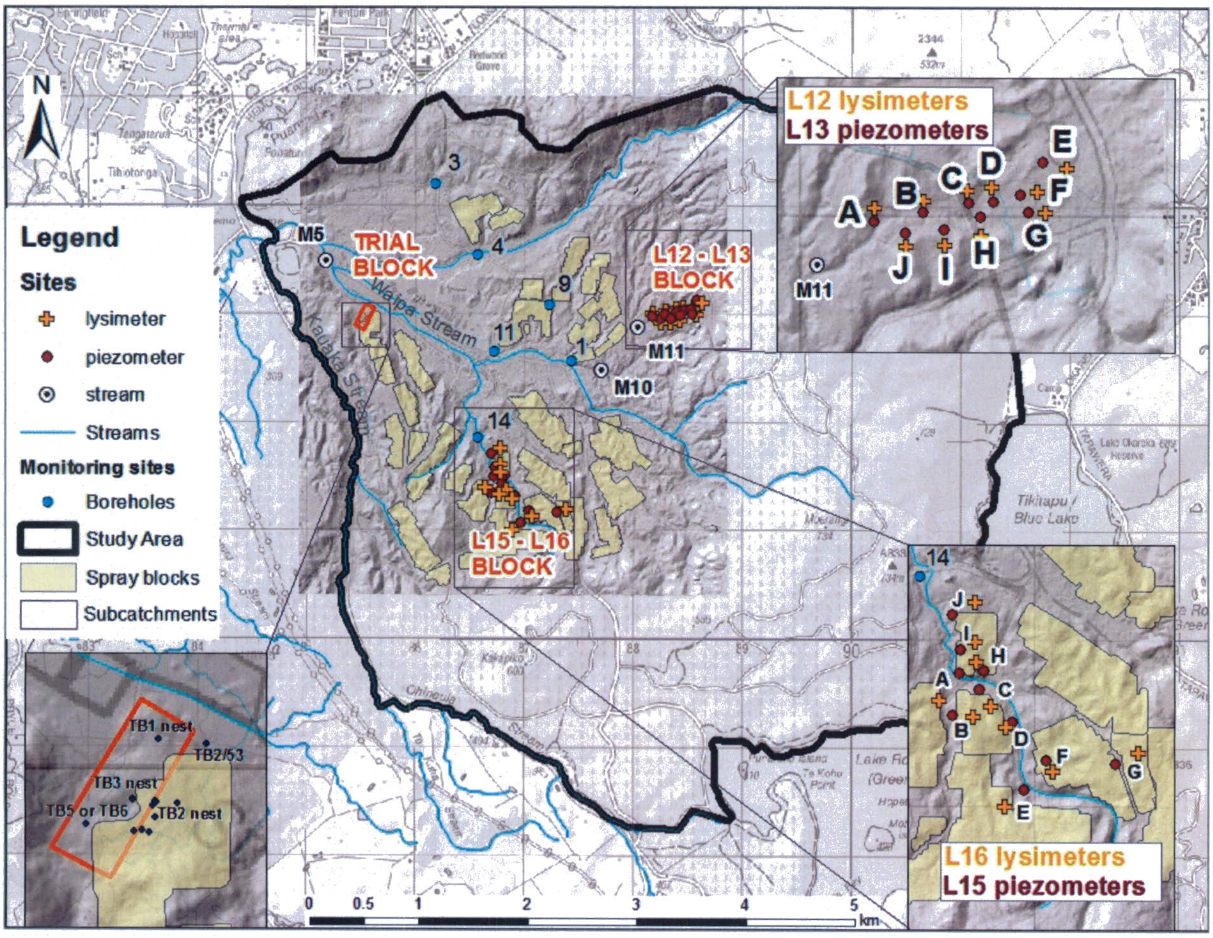

Figure 9: Location of bore holes, stream and groundwater monitoring sites.

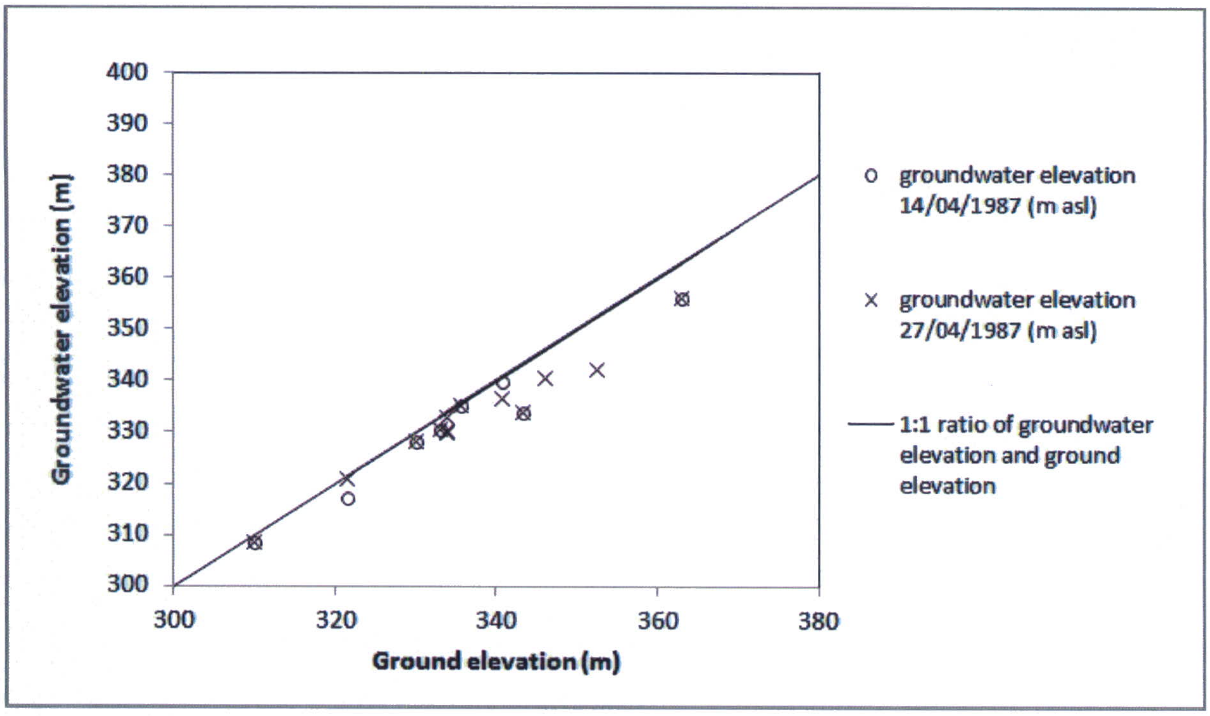

Figure 10: Ground elevation and groundwater elevation in the Waipa catchment.

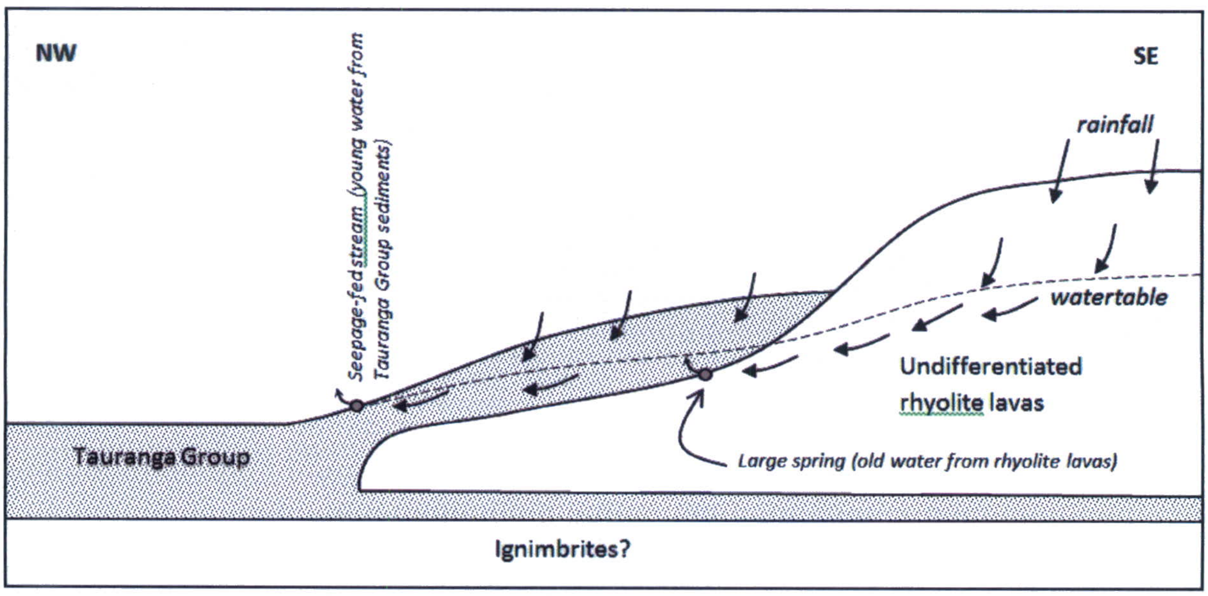

Figure 11: Conceptual cross section of geology and groundwater level in the Waipa Stream catchment (after Nairn, 1987). Not to scale.

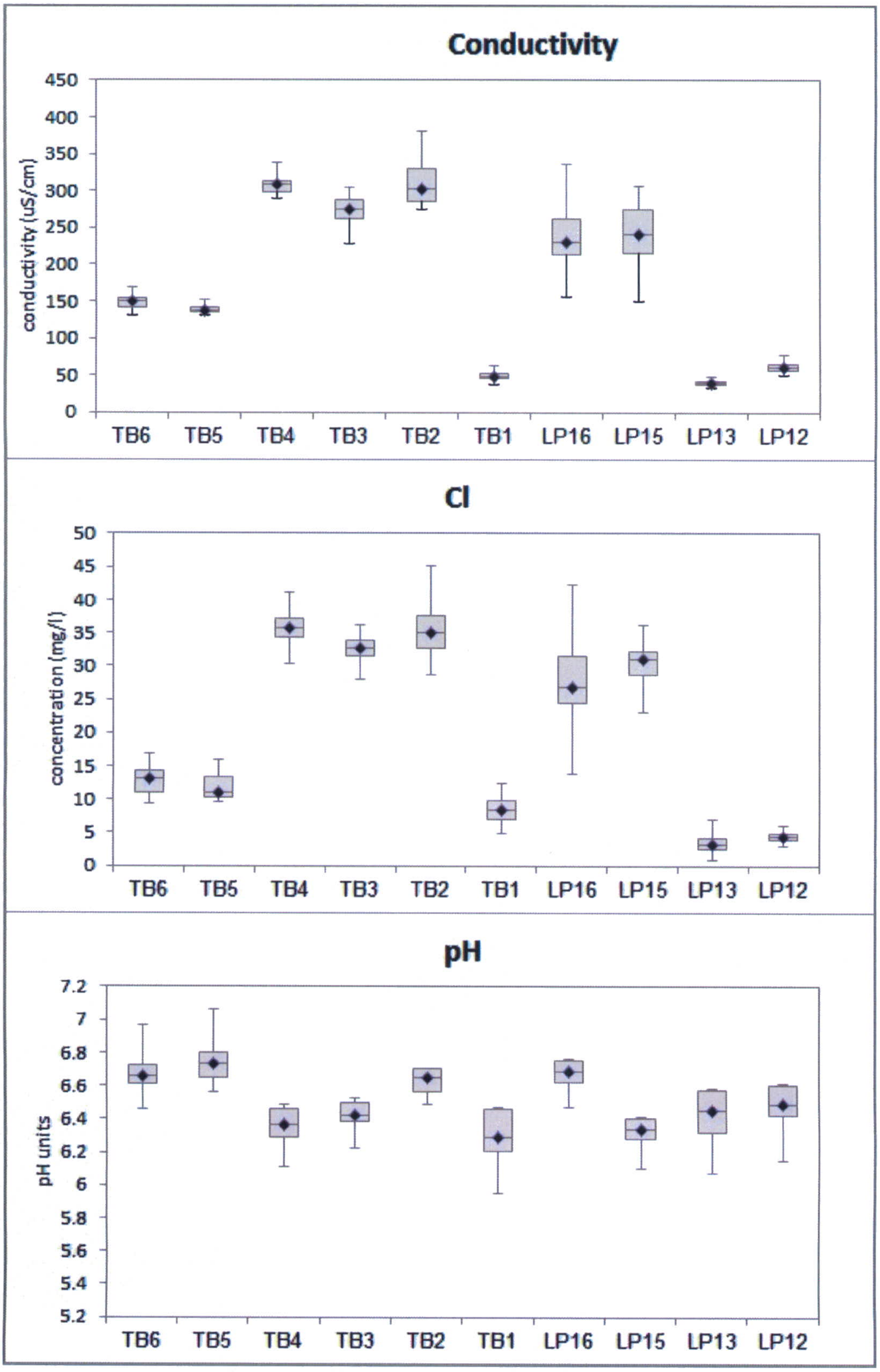

Figure 12: Box plots of conductivity, chloride concentration and pH in groundwater.

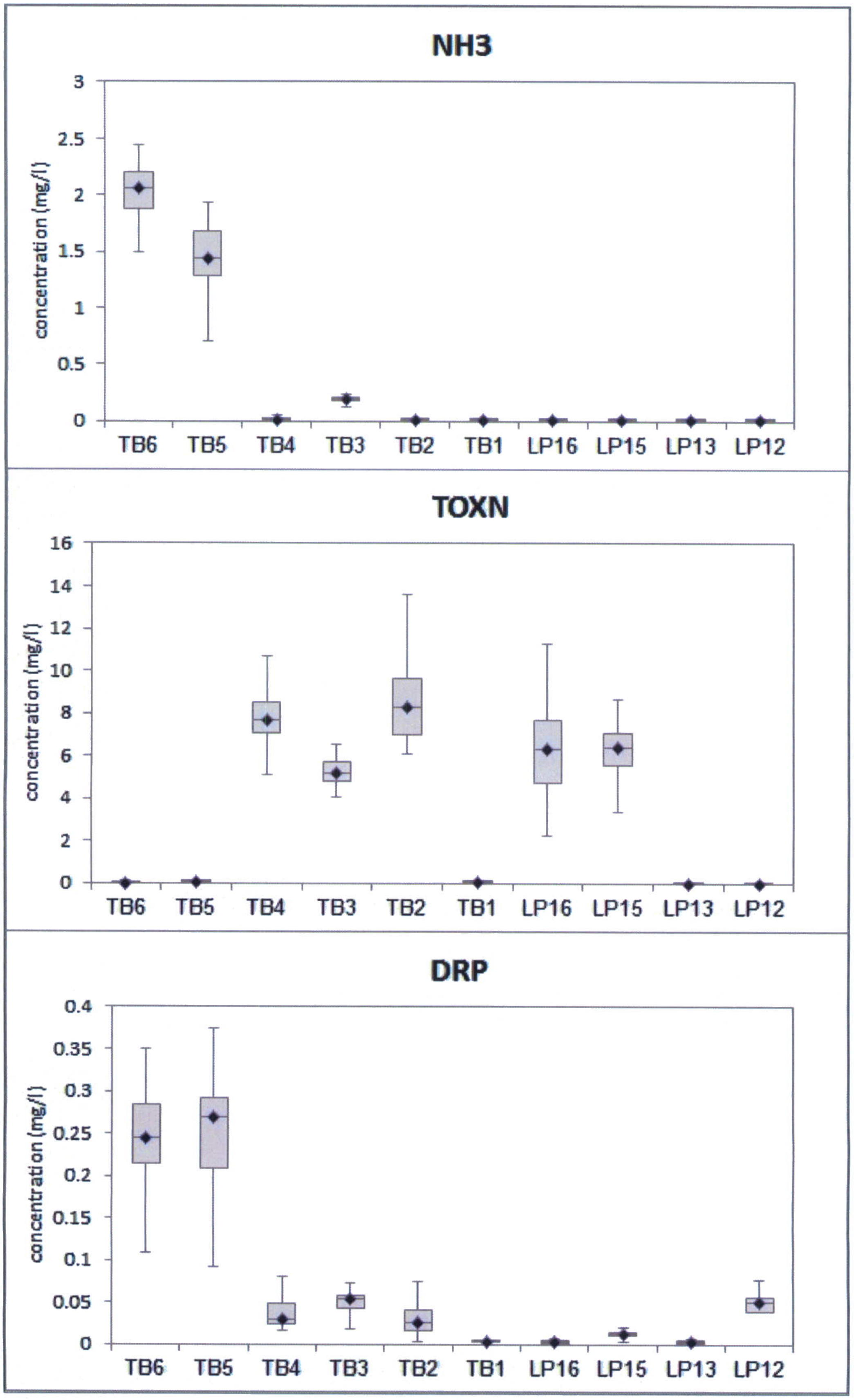

Figure 13: Box plots of nitrogen species and phosphorous concentrations in groundwater.

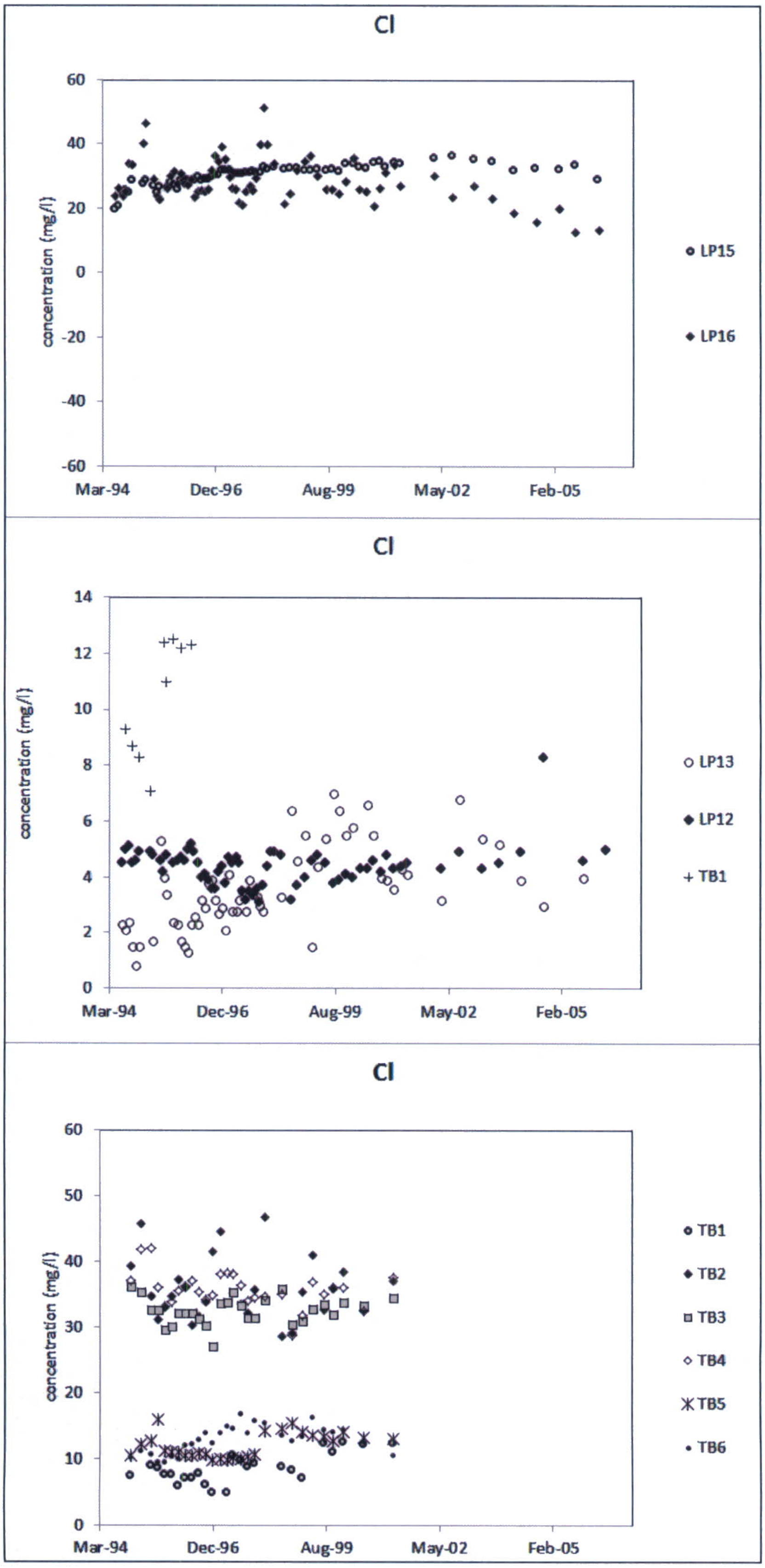

Figure 14: Time series of chloride in groundwater between 1994 and 2006.

APPENDIX 1 Summary statistics of groundwater quality datasets (Lowe, 2012). The detection limit is indicated with a "less than" sign using the lowest measurements for a given parameter.

Analyte	**pH**									
Site	TB6	TB5	TB4	TB3	TB2	TB1	LP16	LP15	LP13	LP12
# Results Used	28	28	28	28	28	24	69	69	62	68
Minimum	6.46	6.56	6.11	6.11	6.49	5.95	6.47	6.01	6.07	6.10
Median	6.66	6.73	6.37	6.43	6.65	6.29	6.69	6.34	6.46	6.49
Average	6.67	6.72	6.37	6.44	6.65	6.33	6.69	6.35	6.48	6.51
Maximum	6.92	6.88	6.61	6.73	6.88	6.73	6.94	6.65	7.07	6.82
Median Absolute Deviation (MAD)	0.06	0.07	0.09	0.05	0.07	0.12	0.07	0.06	0.13	0.08
Standard Deviation (SD)	0.10	0.09	0.12	0.11	0.10	0.20	0.10	0.12	0.19	0.13
TREND? (INCR, DECR, N)	N	N	INCR	N	N	DECR	INCR	DECR	N	N
Trend Magnitude (units/year)	-	-	0.05	-	-	-0.04	0.01	-0.01	-	-
Mann-Kendall test p-value	0.88	0.23	0.01	0.24	0.14	0.02	0.02	0.02	0.66	0.06
SEASONALITY? (Y, N)	N	N	N	N	N	N	N	N	Y	N
Kruskal-Wallis test p-value	0.28	0.96	0.40	0.86	0.62	0.31	0.12	0.24	0.01	0.61
Analyte	**Conductivity**									
Site	TB6	TB5	TB4	TB3	TB2	TB1	LP16	LP15	LP13	LP12
# Results Used	28	28	28	28	28	23	69	69	61	68
Minimum	130	131	290	229	275	38.1	156	151	32.3	51.2
Median	150	138	309	275	304	48.8	230	242	39.5	61.4
Average	149	139	310	274	311	49.7	240	242	40.7	61.5
Maximum	169	151	345	304	382	62.0	383	307	60.7	78.2
Median Absolute Deviation (MAD)	7.0	3.7	10.5	13.5	21.5	3.7	23.0	29.0	2.3	4.7
Standard Deviation (SD)	9.9	5.6	15.8	17.1	30.7	6.4	42.9	36.7	5.6	5.8
TREND? (INCR, DECR, N)	INCR	INCR	N	INCR	N	INCR	DECR	INCR	INCR	N
Trend Magnitude (units/year)	4.9954	1.4668	-	7.0048	-	2.4042	-3.742	14.61	0.5282	-
Mann-Kendall test p-value	0.00	0.00	0.60	0.00	0.21	0.01	0.02	0.00	0.05	0.07
SEASONALITY? (Y, N)	N	Y	Y	Y	Y	N	Y	N	N	Y
Kruskal-Wallis test p-value	0.78	0.01	0.01	0.00	0.02	0.12	0.00	0.43	0.16	0.00

Analyte	Cl									
Site	TB6	TB5	TB4	TB3	TB2	TB1	LP16	LP15	LP13	LP12
# Results Used	28	28	28	28	28	24	69	69	62	68
Minimum	9.40	9.70	28.70	27.00	28.60	4.80	12.80	19.70	0.80	3.10
Median	13.15	11.05	35.80	32.60	34.95	8.45	26.80	31.10	3.30	4.50
Average	12.87	11.95	35.75	32.59	35.75	8.59	28.22	30.41	3.56	4.41
Maximum	16.80	15.90	42.00	36.20	46.70	12.50	51.10	36.30	7.00	8.30
Median Absolute Deviation (MAD)	1.30	1.20	1.30	1.20	2.35	1.40	3.30	2.00	0.90	0.30
Standard Deviation (SD)	2.09	1.86	2.71	2.06	4.71	2.30	6.81	3.23	1.50	0.70
TREND? (INCR, DECR, N)	INCR	N	N	N	N	INCR	DECR	INCR	INCR	DECR
Trend Magnitude (units/year)	0.83	-	-	-	-	0.84	-0.69	1.09	0.41	-0.06
Mann-Kendall test p-value	0.00	0.21	0.09	0.14	0.94	0.02	0.01	0.00	0.00	0.04
SEASONALITY? (Y, N)	N	N	Y	Y	Y	N	Y	N	Y	N
Kruskal-Wallis test p-value	0.59	0.64	0.01	0.00	0.00	0.31	0.00	0.32	0.00	0.23
Analyte	**DRP**									
Site	TB6	TB5	TB4	TB3	TB2	TB1	LP16	LP15	LP13	LP12
# Results Used	28	28	28	28	28	24	69	69	62	68
Minimum	0.108	0.092	0.017	0.006	0.004	<0.001	<0.001	0.004	0.001	0.003
Median	0.245	0.269	0.030	0.054	0.025	0.003	0.003	0.012	0.003	0.050
Average	0.244	0.251	0.036	0.050	0.039	0.003	0.004	0.012	0.003	0.045
Maximum	0.350	0.375	0.080	0.073	0.129	0.010	0.023	0.024	0.014	0.076
Median Absolute Deviation (MAD)	0.039	0.046	0.009	0.009	0.011	0.000	0.001	0.002	0.001	0.009
Standard Deviation (SD)	0.052	0.073	0.017	0.015	0.035	0.002	0.004	0.003	0.002	0.018
TREND? (INCR, DECR, N)	N	N	INCR	INCR	INCR	N	INCR	N	N	DECR
Trend Magnitude (units/year)	-	-	0.007	0.007	0.008	-	0.000	-	-	-0.003
Mann-Kendall test p-value	0.30	0.21	0.00	0.00	0.03	0.73	0.00	0.81	0.14	0.01
SEASONALITY? (Y, N)	N	Y	N	N	N	N	N	N	N	N
Kruskal-Wallis test p-value	0.47	0.03	0.77	0.36	0.57	0.67	0.44	0.07	0.10	0.36

Analyte	NH$_3$									
Site	TB6	TB5	TB4	TB3	TB2	TB1	LP16	LP15	LP13	LP12
# Results Used	28	28	28	28	28	24	69	69	62	68
Minimum	1.49	0.70	0.003	0.002	0.001	0.005	<0.001	<0.001	<0.001	<0.001
Median	2.05	1.44	0.008	0.197	0.009	0.012	0.007	0.006	0.005	0.008
Average	2.04	1.43	0.022	0.181	0.011	0.015	0.007	0.009	0.007	0.010
Maximum	2.44	1.94	0.144	0.241	0.059	0.064	0.024	0.035	0.054	0.029
Median Absolute Deviation (MAD)	0.16	0.20	0.004	0.019	0.002	0.004	0.003	0.002	0.002	0.004
Standard Deviation (SD)	0.25	0.29	0.031	0.055	0.010	0.013	0.004	0.007	0.007	0.007
TREND? (INCR, DECR, N)	DECR	N	N	INCR	N	N	N	N	N	INCR
Trend Magnitude (units/year)	-0.11	-	-	0.016	-	-	-	-	-	0.000
Mann-Kendall test p-value	0.01	0.05	0.06	0.00	0.77	0.44	0.21	0.83	0.20	0.04
SEASONALITY? (Y, N)	N	N	N	N	N	N	N	N	N	N
Kruskal-Wallis test p-value	0.87	0.44	0.15	0.22	0.48	0.99	0.89	0.33	0.29	0.17
Analyte	**TKN**									
Site	TB6	TB5	TB4	TB3	TB2	TB1	LP16	LP15	LP13	LP12
# Results Used	0	0	0	0	0	0	<0.38	<0.38	0	0
Minimum	ND	ND	ND	ND	ND	ND	0.38	0.80	ND	ND
Median	ND	ND	ND	ND	ND	ND	0.38	0.80	ND	ND
Average	ND	ND	ND	ND	ND	ND	0.38	0.80	ND	ND
Maximum	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Median Absolute Deviation (MAD)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Standard Deviation (SD)	ND	ND	ND	ND	ND	ND	N	N	ND	ND
TREND? (INCR, DECR, N)	ND	ND	ND	ND	ND	ND	-	-	ND	ND
Trend Magnitude (units/year)	ND	ND	ND	ND	ND	ND	0.90	0.90	ND	ND
Mann-Kendall test p-value	ND	ND	ND	ND	ND	ND	N	N	ND	ND
SEASONALITY? (Y, N)	ND	ND	ND	ND	ND	ND	0.44	0.34	ND	ND
Kruskal-Wallis test p-value	ND	ND	ND	ND	ND	ND	<0.38	<0.38	ND	ND

Analyte	TOXN									
Site	TB6	TB5	TB4	TB3	TB2	TB1	LP16	LP15	LP13	LP12
# Results Used	28	28	28	28	28	24	69	69	62	68
Minimum	0.002	0.005	5.13	4.06	6.05	0.003	2.26	3.04	<0.001	<0.001
Median	0.013	0.036	7.70	5.15	8.24	0.021	6.29	6.42	0.005	0.006
Average	0.042	0.071	7.96	5.25	8.70	0.040	6.30	6.33	0.007	0.032
Maximum	0.285	0.592	10.88	6.56	13.66	0.184	11.28	8.61	0.039	0.392
Median Absolute Deviation (MAD)	0.008	0.023	0.73	0.35	1.30	0.016	1.53	0.75	0.004	0.003
Standard Deviation (SD)	0.059	0.111	1.38	0.70	2.12	0.048	2.22	1.15	0.008	0.077
TREND? (INCR, DECR, N)	DECR	N	N	N	N	INCR	DECR	INCR	DECR	DECR
Trend Magnitude (units/year)	-0.005	-	-	-	-	0.01	-0.41	0.39	-0.001	-0.002
Mann-Kendall test p-value	0.02	0.60	0.24	0.66	0.88	0.00	0.00	0.00	0.00	0.00
SEASONALITY? (Y, N)	N	Y	N	N	N	Y	Y	N	Y	N
Kruskal-Wallis test p-value	0.06	0.02	0.62	0.57	0.25	0.03	0.00	0.46	0.03	0.59

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