Nutrient discharge to groundwater at the Kaharoa rainfall recharge site, Rotorua

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EXECUTIVE SUMMARY

Environment Bay of Plenty commissioned GNS Science to measure nitrogen and phosphorus concentrations in rainfall and rainfall recharge to groundwater at the Kaharoa rainfall recharge site. The aim of this work is to determine nutrient concentrations in rainfall recharge to groundwater and rainfall under pastoral land use.

The rainfall recharge site at Kaharoa has operated since June 2005 and measures rainfall in a ground-level gauge, rainfall in a standard rain gauge and rainfall recharge in two lysimeters under sheep, beef and deer land use.

Chemistry samples in lysimeters and in the ground-level recorder include:

- twelve measurements of nitrogen, phosphorus and chloride in lysimeter 1 in the period between 4th December 2006 and 8th January 2008;
- fourteen measurements of nitrogen, phosphorus and chloride in ground-level rainfall in the period between 4th December 2006 and 8th January 2008;
- seven measurements of oxygen and deuterium isotopes in ground-level rainfall in the period between 2nd April 2007 and 1st November 2007.

Two transformations in nitrogen reflect soil processes:

- typically most nitrogen in rainfall recharge measured in the lysimeters is in the form of nitrate-nitrogen whereas most nitrogen in ground-level rainfall is in forms other than nitrate-nitrogen;
- nitrate-nitrogen concentrations in rainfall recharge are typically higher than nitrate-nitrogen concentrations in ground-level rainfall.

Nitrate-nitrogen mass discharge in rainfall recharge is probably controlled by plant growth. Nitrate-nitrogen discharge in rainfall recharge measured in lysimeter 1 is greatest in the autumn, winter and spring months of March 2007 to August 2007. For example 99.7% of the annual nitrate-nitrogen discharge occurs in these months. This is because:

- rainfall recharge volumes are typically higher in these months;
- nitrate-nitrogen concentrations are typically higher in these months.

Plant growth probably controls nitrogen release and nitrogen leaching from pasture in the March to August months is a very important driver of nitrogen concentrations in Lake Rotorua groundwater. Therefore management of stock and soil, including best-practice land use, in the March to August period is a critical issue to management of nitrogen leaching to groundwater.

Annual nitrate-nitrogen mass discharge to groundwater is estimated as 8.7 kg N/ha/yr at the Kaharoa site for sheep, beef and deer land use. The average annual nitrate-nitrogen concentration in rainfall recharge measured in lysimeter 1 is calculated as 0.95 mg/L and maximum measured nitrate-nitrogen concentration in rainfall recharge in lysimeter 1 is 1.78 mg/L; concentrations in this range are commonly observed in groundwaters in the Lake Rotorua catchment.

1.0 INTRODUCTION

Groundwater quality in the Lake Rotorua catchment is impacted by land use (White et al. 2007) and elevated nitrogen concentrations in groundwater are finding their way into Lake Rotorua and impacting on lake water quality. Nitrogen travelling with groundwater recharge probably contributes to elevated nitrogen concentrations in groundwater. Groundwater recharge, as measured at a rainfall recharge site located on Penny Road near Kaharoa, north of Lake Rotorua, is typically high in winter and low in summer. However the pattern and rates of nitrogen discharge to groundwater over time in the Lake Rotorua catchment are generally unknown.

Therefore, Environment Bay of Plenty commissioned GNS Science to measure nitrogen and phosphorus concentrations in rainfall and rainfall recharge to groundwater at the Kaharoa rainfall recharge site (White et al. 2007) with the aim of assessing nutrient concentrations in rainfall recharge to groundwater under pastoral land use over time.

This report summarises nutrient chemistry measurements and observations of rainfall and rainfall recharge to groundwater at the Kaharoa rainfall recharge site in the period October 2006 to January 2008. Included are measurements at approximately monthly intervals of:

- nitrogen (including total nitrogen (TN), Total Kjeldahl Nitrogen (TKN) and nitrate-nitrogen);
- total phosphorus (TP);
- chloride;
- rainfall recharge in two lysimeters;
- rainfall in a ground-level rainfall recorder.

These results are interpreted as:

- nitrogen discharge with rainfall and rainfall recharge as mass and mass rates over time;
- phosphorus discharge with rainfall and rainfall recharge as mass and mass rates over time;
- relevance to the observed nitrogen and phosphorus concentrations in groundwater in the Lake Rotorua catchment.

2.0 SUMMARY OF NITROGEN AND PHOSPHORUS CHEMISTRY IN THE GROUNDWATER CATCHMENT OF LAKE ROTORUA

Total nitrogen concentrations in shallow groundwater samples in the Lake Rotorua catchment are broadly related to land use (Table 2.1). Commonly most of the nitrogen in groundwater is in the nitrate form (White et al. 2007). Nitrate-nitrogen concentrations in the groundwater catchment of Lake Rotorua are commonly greater than 1 mg/L. For example nitrate-nitrogen concentrations in the north-western catchment of Lake Rotorua (Figure 2.1) are commonly in the range 1 mg/L to 2 mg/L; the maximum nitrate-nitrogen concentration in the area is 17.7 mg/L.

Total phosphorus concentrations in shallow groundwater samples in the Lake Rotorua catchment are not particularly related to land use (Table 2.1). Total phosphorus concentrations in the groundwater catchment of Lake Rotorua are commonly less than 0.1 mg/L. For example total phosphorus concentrations in the north-western catchment of Lake Rotorua (Figure 2.1) are commonly in the range 0 mg/L to 0.1 mg/L; the maximum Total phosphorus concentration in the area is 4.73 mg/L.

Table 2.1 TN and TP in groundwater summary statistics (shallow sites only) and land use (White et al. 2007).

Land use	Number of sites	Number of samples	Statistic	TN (mg/L)	TP (mg/L)
Cropping	1	1	Median	3.620	0.099
Dairy	11	50	Median	5.965	0.038
Forest-forestry	22	172	Median	1.463	0.087
Pasture (beef, deer, sheep)	11	21	Median	1.430	0.058
Scrub-grassland	13	59	Median	1.470	0.054
Urban-road	9	37	Median	4.710	0.053
Total	67	340			

3.0 KAHAROA RAINFALL RECHARGE SITE

The rainfall recharge site at Kaharoa (Reeves et al., 2005), Figure 3.1 and Figure 3.2, has operated since June 2005 and measures rainfall in a ground-level gauge, rainfall in a standard rain gauge and rainfall recharge in two lysimeters. A summary of the monthly rainfall and rainfall recharge in the period August 2005 and July 2006 (White et al. 2007) indicates:

- ground-level rainfall is approximately 3% larger than rainfall in the primary rain gauge;
- rainfall recharge in lysimeter 1 is substantially larger than rainfall recharge in lysimeter 2;
- rainfall recharge in lysimeter 1 is 49% of rainfall in the ground-level rain gauge;
- rainfall recharge in lysimeter 2 is 17% of rainfall in the ground-level rain gauge.

Lysimeter 2 produced less rainfall recharge than lysimeter 1. Lysimeter 2 was removed (Cameron and White 2008) following various instrumental checks and field checks that indicated lysimeter was leaking. Lysimeter 2 was removed after collection of rainfall recharge chemistry samples.

3.1 Field installation to collect rainfall recharge chemistry samples

Sampling was completed by Martin Hawke (Bay of Plenty Farm and Pastoral Research) using the following procedure:

1. Rainfall contamination of the sample needs to be avoided so sampling was undertaken during dry conditions or the EBOP equipment shed was used for sample decants from the collection containers.

2. Samples were sent directly to R J Hill laboratory in Hamilton in appropriate bottles on ice in a chilly bin.
3. Each of the three collection containers had approximately 5mm layer of canola oil overlying the water to prevent sample evaporation. Sampling was undertaken directly from the collection containers by syringe with an appropriate length of plastic tubing with a new syringe and tubing for each container to avoid cross contamination. Syringes and tubing were discarded after use.
4. Used canola oil is discarded after use and replaced with approx 0.5 L of new canola oil per collection container.
5. Total monthly volume of water collected was recorded in each of the collection containers.

3.2 Land use at the site

Land use in the paddock at the site is mixed sheep, beef and deer (Steve Hewson, farm manager, pers. comm. November 2008). These livestock are rotated through the paddock during the year and stocking intensity is approximately 12 - 13 stock units per hectare.

4.0 OBSERVATIONS

Sampling equipment was installed on 27th September 2006. Chemistry samples were taken between 4th December 2006 and 8th January 2008.

4.1 Rainfall and groundwater recharge

Water volumes measured in collection containers are listed in Appendix 2, including:

- fourteen measurements of water volume in lysimeter 1 and lysimeter 2 measuring rainfall recharge to groundwater in the project period between 27th September 2006 and 8th January 2008;
- fourteen measurements of water volume of ground-level rainfall in the project period between 27th September 2006 and 8th January 2008.

Measured volumes are approximately:

- 195 L in lysimeter 1;
- 84 L in lysimeter 2;
- 87 L of ground-level rainfall.

Water volume collected from lysimeter 2 is considerably less than water volume collected from lysimeter 1 which is consistent with the observations of White et al. (2007) and (Cameron and White 2008), Section 3.0, that lysimeter 2 was leaking. Therefore water chemistry and volume data from lysimeter 1 only are used in the flowing analysis of nutrient discharge to groundwater.

4.2 Water chemistry

Water chemistry measurements and detection limits are listed in Appendix 2, including:

- twelve measurements of nitrogen, phosphorus and chloride in lysimeter 1 and lysimeter 2 in the period between 4th December 2006 and 8th January 2008;
- seven measurements of oxygen and deuterium isotopes in lysimeter 1 and lysimeter 2 in the period between 2nd April 2007 and 1st November 2007;
- fourteen measurements of nitrogen, phosphorus and chloride in ground-level rainfall in the period between 4th December 2006 and 8th January 2008;
- seven measurements of oxygen and deuterium isotopes in ground-level rainfall in the period between 2nd April 2007 and 1st November 2007.

Water chemistry is not measured in samples from lysimeter 1 and lysimeter 2 in the period 24h January 2007 and 28th February 2007 as no rainfall recharge occurred in the period.

Chemical processes and plant growth in the soil zone (Section 8) are a significant influence on nitrogen concentrations. For example (Table 4.1):

- total nitrogen concentrations in rainfall recharge are typically less than total nitrogen concentrations in rainfall;
- most nitrogen in rainfall recharge is in the nitrate-nitrogen form.

Table 4.1 Summary of chemistry in rainfall and rainfall recharge*

	Rainfall		**Rainfall recharge, lysimeter 1**	
	Mean (mg/L)	**Median (mg/L)**	**Mean (mg/L)**	**Median (mg/L)**
TN	0.34	0.26	1.15	0.71
NO_3-N	0.003	0.002	0.6	0.24
TP	0.263	0.209	0.126	0.006
Cl	2.4	2.2	2.3	1.5

* These statistics include values at the detection limit. Therefore they overestimate the real means and medians.

TKN in rainfall recharge is approximately 47% of total nitrogen and is much more constant than total nitrogen over the project period. Nitrogen as TKN is not significantly affected by either seasonality or rainfall and probably represents the refractory organic N that exists in most lakes, soil and groundwater and does not participate in significant biological reactions. Any reasonably biologically active organic N would be utilised as a bacterial substrate in the soil column. TKN concentrations in rainwater are similar to TKN concentrations in rainfall recharge.

Nitrate-nitrogen concentrations in rainfall recharge show seasonal variation with a rise in autumn and fall in early spring (Section 8).

4.2.1 Detection limits

Commonly, nutrient concentrations are below detection limits, for example:

- 4 of the 12 samples of rainfall recharge measured in lysimeter 1 are below the detection limit for nitrate-nitrogen;
- 4 of the 12 samples of rainfall recharge measured in lysimeter 2 are below the detection limit for nitrate-nitrogen;
- 11 of the 12 samples of ground-level rainfall are below the detection limit for nitrate-nitrogen.

Calculations of nitrogen and phosphorus mass (Section 5) use concentration at the detection limit, where the measured nutrient concentration is below the detection limit. Therefore estimates of nitrogen and phosphorus mass and yield in the following sections are estimates of the maximum mass and yield. Nitrate-nitrogen concentrations in rainfall recharge (e.g. lysimeter 1, Appendix 2) are commonly below the detection limit in summer and rainfall recharge in summer is a relatively small proportion of total recharge. Therefore the maximum mass and yield estimated in this report will not significantly over estimate the actual mass and yield.

Detection limits vary in each test. This is because the laboratory may have used differing sample dilutions. For example:

- the detection limit for TKN in ground-level rainfall was 2 mg/L for the sample collected on the 4/01/2007 (Appendix 2);
- the detection limit for TKN in ground-level rainfall was 0.1 mg/L for the sample collected on the 24/01/2007 (Appendix 2).

5.0 NUTRIENT DISCHARGE TO GROUNDWATER

Water chemistry and volume data from lysimeter 1 only are used in the flowing analysis of nutrient discharge to groundwater because lysimeter 2 leaked in the project period (White et al. 2007 and Cameron and White 2008), Section 3.0 and Section 4.1.

5.1 Rate of rainfall recharge and ground-level rainfall

Rainfall recharge and ground-level rainfall are calculated as millimetres in sample periods, factoring the area of the rainfall recorder and the area of the lysimeter (White et al. 2007), with:

- rainfall recharge (mm in sample period) = rainfall recharge volume (mL in sample period) / 196 mL/mm, Table 5.1;
- ground-level rainfall (mm in sample period) = rainfall volume (mL in sample period) / 31.4 mL/mm, Table 5.2.

Rates of rainfall recharge and ground-level rainfall in sample periods are calculated by dividing the rainfall and rainfall recharge by the number of days in the sample period (Table 5.1 and Table 5.2).

Rainfall recharge in lysimeter 1 totals 994.1 mm (Table 5.1) in the project period, which is the equivalent of approximately 2.1 mm/day over the 468 day project period. The range in average rainfall recharge in the sample periods is:

- greatest at 6.53 mm/day between 2/07/2007 and 30/07/2007;
- least at 0 mm/day between 24/01/2007 and 28/02/2007.

Annual rainfall recharge is estimated as approximately 920 mm/year for an approximate annual monitoring period with:

- the period of samples 24/1/2007 to 8/1/2008;
- 369 days in period;
- rainfall recharge in the period is 994.1 - 64.1 (Table 5.1) = 930 mm;
- annual rainfall recharge = 930 / 369 * 365 = approximately 920 mm.

Table 5.1 Rainfall recharge as millimetres and millimetres per day, lysimeter 1, in sample period and project period.

Lysimeter 1, site 2597						
Sample Date	**Time**	**Days in sample period**	**Rainfall recharge volume in period (mL)**	**Rainfall recharge in period (mm)**	**Rainfall recharge cumulative sum (mm)**	**Rainfall recharge average in period (mm/day)**
27/09/2006	16:30					
25/10/2006	14:00	28	5625	28.7	28.7	1.03
4/12/2006	11:15	40	6612.5	33.7	62.4	0.84
4/01/2007	11:00	31	330	1.7	64.1	0.05
24/01/2007	11:00	20	23800	121.4	185.5	6.07
28/02/2007	14:00	35	0	0	185.5	0
2/04/2007	11:00	33	37120	189.4	374.9	5.74
1/05/2007	11:00	29	9520	48.6	423.5	1.68
2/07/2007	11:00	62	25700	131.1	554.6	2.11
30/07/2007	09:15	28	35820	182.8	737.4	6.53
29/08/2007	11:00	30	19220	98.1	835.5	3.27
1/10/2007		33	9900	50.5	886	1.53
1/11/2007	11:00	31	12720	64.9	950.9	2.09
3/12/2007	11:00	32	2597	13.3	964.2	0.42
8/01/2008	11:00	36	5870	29.9	994.1	0.83
Total (project period)		468	194834.5		994.1	2.1 (average project period)

Rainfall in the ground-level recorder totals 2765.4 mm (Table 5.2) in the whole monitoring period, which is the equivalent of approximately 5.9 mm/day over the 468 day period, or approximately 2154 mm/year. The range in average rainfall in the sample periods is:

- greatest at 15.45 mm/day between 4/01/2007 and 24/01/2007;
- least at 1.6 mm/day in between 25/10/2006 and 4/12/2006.

Annual rainfall recharge is estimated as approximately 2505 mm/year for an approximate annual monitoring period with:

- the period of samples 24/1/2007 to 8/1/2008;
- 369 days in period;
- rainfall recharge in the period is 2765.4 – 233.4 (Table 5.2) = 2532 mm;
- annual rainfall recharge = 2532 / 369 * 365 = approximately 2505 mm.

Table 5.2 Ground-level rainfall as millimetres in period and millimetres per day.

Ground-level rainfall, site 2599						
Sample date	**Time**	**Days in sample period**	**Rainfall volume in period (mL)**	**Rainfall in period (mm)**	**Rainfall cumulative sum (mm)**	**Rainfall average in period (mm/day)**
27/09/2006	16:30					
25/10/2006	14:00	28	2625	83.6	83.6	2.99
4/12/2006	11:15	40	2012.5	64.1	147.7	1.6
4/01/2007	11:00	31	2690	85.7	233.4	2.76
24/01/2007	11:00	20	9700	308.9	542.3	15.45
28/02/2007	14:00	35	4300	136.9	679.2	3.91
2/04/2007	11:00	33	13520	430.6	1109.8	13.05
1/05/2007	11:00	29	6220	198.1	1307.9	6.83
2/07/2007	11:00	62	10050	320.1	1628	5.16
30/07/2007	09:15	28	11370	362.1	1990.1	12.93
29/08/2007	11:00	30	5570	177.4	2167.5	5.91
1/10/2007		33	4800	152.9	2320.4	4.63
1/11/2007	11:00	31	4870	155.1	2475.5	5
3/12/2007	11:00	32	2900	92.4	2567.9	2.89
8/01/2008	11:00	36	6200	197.5	2765.4	5.49
Total (project period)		468	86827.5		2765.4	5.9 (average whole period)

Rainfall recharge in lysimeter 1 is approximately:

- 36% of rainfall in the project period, i.e. 994.1 mm / 2765.4 mm as a percentage;
- 37% of rainfall in an approximate annual period including samples collected between 24/1/2007 and 8/1/2008 i.e. 920 mm / 2505 mm as a percentage.

These percentages are lower than the 49% rainfall recharge of ground-level rainfall measured the period August 2005 and July 2006 (White et al. 2007) in lysimeter 1, Section 3.0. Rainfall recharge, as a proportion of ground-level rainfall, in the different measurement periods will be investigated in a future report.

Rainfall recharge is greater when ground-level rainfall is greater (Figure 5.1).

5.2 Whole monitoring period

Mass discharge (Table 5.3) and median (Table 5.4) discharge in lysimeter 1 and ground-level rainfall are calculated for the whole monitoring period including samples collected between the 4th December 2007 and 8th January 2008.

Mass discharge in lysimeter 1 is calculated from concentrations measured in lysimeter 1 and rainfall recharge volumes measured in lysimeter 1 as follows:

- mass in period (mg) = concentration (mg/L) * rainfall recharge volume (mL) / 1000 in each collection period;
- mass discharge in period (mg/day) = mass in period (mg) / number of days in period;
- mass discharge in month (kg/ha/month) = mass discharge in month (mg/day/lysimeter) * 30.4 (average number of days per month) / 1000000 (mg/kg) * 51020 (10000 / 0.196 lysimeter/ha i.e. scaling-up the lysimeter area to 1 ha);
- mass discharge (Table 5.3) in the whole period for lysimeter 1 (kg/ha/yr) = sum of mass discharge in period (mg/period) / days in period (days per lysimeter) * 365 (days per year) / 1000000 (mg/kg) * 51020 (10000 / 0.196 lysimeter/ha i.e. scaling-up the lysimeter area to 1 ha);
- rounding.

Mass discharge (Table 5.3) in ground-level rainfall is calculated from concentrations measured in ground-level rainfall and ground-level collection volumes as follows:

- mass in whole period (mg) = concentration (mg/L) * collection volume (mL) / 1000;
- mass discharge in period (mg/day) = mass in period (mg) / number of days in period;
- mass discharge in month (kg/ha/month) = mass discharge in month (mg/day/lysimeter) * 30.4 (average number of days per month) / 1000000 (mg/kg) * 318471 (10000 / 0.0314 recorder/ha i.e. scaling-up the ground-level recorder area to 1 ha);
- mass discharge in whole period for the ground-level rainfall (kg/ha/yr) = sum of mass discharge in period (mg/period) / days in period (days per lysimeter) * 365 (days per year) / 1000000 (mg/kg) * 318471 (10000 / 0.0314 recorder/ha i.e. scaling-up the ground-level recorder area to 1 ha);
- rounding.

Nitrate-nitrogen concentrations are not measured for the sample collected on 3/12/2007 because the sample volume was not sufficient for dilution (R.J Hill laboratory, pers. comm.).

Mass discharge estimates in the whole monitoring period (Table 5.3) indicate:

- nitrate-nitrogen mass discharge (7.3 kg N/ha/yr) in rainfall recharge is much greater than nitrate-nitrogen mass discharge in ground-level rainfall (0.05 kg N/ha/yr). To demonstrate, nitrate-nitrogen mass discharge in ground-level rainfall in Figure 5.3 is plotted at the same scale as nitrate-nitrogen mass discharge in rainfall recharge in Figure 5.2;

- total phosphorus mass discharge in ground-level rainfall (5.6 kg/ha/yr) is much greater than total phosphorus mass discharge in rainfall recharge (0.3 kg/ha/yr) reflecting low phosphorus concentrations in rainfall recharge as is normal for these types of soils.

Median mass discharge, weighted by water mass, (Table 5.4) is calculated as follows:

- calculate median mass discharge (as mg/day) in period from Table 5.5, Table 5.6, Table 5.7, Table 5.8 and Table 5.9;
- weighted median mass discharge in the whole period lysimeter 1 (kg/ha/yr) = median mass discharge (mg/day) * 365 (days per year) / 1000000 (mg/kg) * 51020 (10000 / 0.196 lysimeter/ha);
- weighted median mass discharge in the whole period for ground-level rainfall (kg/ha/yr) = median mass discharge (mg/day) * 365 (days per year) / 1000000 (mg/kg) * 318471 (10000 / 0.0314 recorder/ha);
- rounding.

Relative median mass discharge are summarised as follows:

- nitrate-nitrogen in rainfall recharge is much greater than nitrate-nitrogen in ground-level rainfall;
- total phosphorus in rainfall recharge is much less than total phosphorus in ground-level rainfall.

Table 5.3 Mass discharge in whole monitoring period*.

	Rainfall recharge Lysimeter 1		**Ground-level rainfall**		
	Nitrate-nitrogen	**Total phosphorus**	**Nitrate-nitrogen**	**Total nitrogen**	**Total phosphorus**
Mass discharge in period (mg)	172.974	7.315	0.19	25.076	19.748
Mass discharge (kg/ha/yr), rounded	7.3	0.31	0.05	7.1	5.6
Weighted average concentration[1] (mg/L)	0.9	0.04	0.002	0.31	0.2
Reference table	Table 5.5	Table 5.8	Table 5.6	Table 5.7	Table 5.9

* Rainfall recharge volume lysimeter 1 189209.5 mL in whole period.

Ground-level rainfall volume 81302.5 mL in whole period. This volume excludes the volume of the sample taken on 3/12/2007 as nitrogen measurements were not made on this sample.

Duration of whole period 440 days for lysimeter 1.

Duration of whole period 408 days for ground-level recorder which excludes the 32-day period of sample taken on 3/12/2007 as nitrogen measurements were not made on this sample.

Scale collection area to hectare for lysimeter 1 = 51020 (i.e. 10000 / 0.196).

Scale collection area to hectare for ground-level rainfall = 318471 (i.e. 10000 / 0.0314).

[1] Mass discharge in period divided by rainfall recharge volume (lysimeter 1) or ground-level rainfall volume.

Table 5.4 Median mass discharge in whole monitoring period*

	Rainfall recharge lysimeter 1		Ground-level rainfall		
	Nitrate-nitrogen	Total phosphorus	Nitrate-nitrogen	Total nitrogen	Total phosphorus
Median mass discharge in period (mg/day)	0.07	0.0048	0.0002	0.04	0.04
Median mass discharge (kg/ha/yr), rounded	1.3	0.1	0.02	5.0	4.1
Reference table	Table 5.5	Table 5.8	Table 5.6	Table 5.7	Table 5.9

* Calculation parameters as in footnote to Table 5.3.

Nitrate-nitrogen mass discharge (kg/ha/month) in lysimeter 1 is greatest in the months of March 2007 to August 2007 (Figure 5.2) as:

- rainfall recharge volumes are typically higher in these months;
- nitrate-nitrogen concentrations are typically higher in these months.

Nitrate-nitrogen mass discharge in lysimeter 1 (Figure 5.2) is much greater than nitrate-nitrogen mass discharge in ground-level rainfall (Figure 5.3).

Table 5.5 Nitrate-nitrogen concentrations in rainfall recharge (lysimeter 1), rainfall recharge volume and nitrate-nitrogen discharge rate.

Sample date	Days in sample period	Days (cumulative sum)	NO_3-N mg/L	Rainfall recharge volume period (mL)	NO_3-N mass in period (mg)	NO_3-N mass discharge in period (mg/day)	NO_3-N mass discharge in period (kg/ha/month)
27/09/2006							
25/10/2006							
4/12/2006	40	40	0.002	6612.5	0.013	0.0003	0.0005
4/01/2007	31	71	0.002	330	0.001	0	0
24/01/2007	20	91	0.002	23800	0.048	0.0024	0.0037
28/02/2007	35	126	na	0	0	0	0
2/04/2007	33	159	1.27	37120	47.142	1.4285	2.2156
1/05/2007	29	188	1.78	9520	16.946	0.5843	0.9063
2/07/2007	62	250	1.42	25700	36.494	0.5886	0.9129
30/07/2007	28	278	1.46	35820	52.297	1.8678	2.897
29/08/2007	30	308	0.731	19220	14.05	0.4683	0.7263
1/10/2007	33	341	0.231	9900	2.287	0.0693	0.1075
1/11/2007	31	372	0.25	12720	3.18	0.1026	0.1591
3/12/2007	32	404	0.002	2597	0.005	0.0002	0.0003
8/01/2008	36	440	0.087	5870	0.511	0.0142	0.022
Total (project period)		440		189209.5	172.974		

Table 5.6 Nitrate-nitrogen concentrations in ground-level rainfall, rainfall volume and nitrate-nitrogen discharge rate. Measured nitrate-nitrogen concentrations are commonly below the detection limit. Mass calculations in this table are a maximum as the calculations use the detection limit where measured concentrations are below the detection limit.

Sample date	Days in sample period	Days (cumulative sum)	NO_3-N (mg/L)	Rainfall volume period (mL)	NO_3-N mass in period (mg)	NO_3-N mass in period (mg/day)	NO_3-N (kg/ha/month)
27/09/2006							
25/10/2006							
4/12/2006	40	40	0.002	2013	0.004	0.0001	0.001
4/01/2007	31	71	0.002	2690	0.005	0.00016	0.0016
24/01/2007	20	91	0.002	9700	0.019	0.00095	0.0092
28/02/2007	35	126	0.002	4300	0.009	0.00026	0.0025
2/04/2007	33	159	0.002	13520	0.027	0.00082	0.0079
1/05/2007	29	188	0.002	6220	0.012	0.00041	0.004
2/07/2007	62	250	0.002	10050	0.02	0.00032	0.0031
30/07/2007	28	278	0.002	11370	0.023	0.00082	0.008
29/08/2007	30	308	0.002	5570	0.011	0.00037	0.0035
1/10/2007	33	341	0.008	4800	0.038	0.00115	0.0111
1/11/2007	31	372	0.002	4870	0.01	0.00032	0.0031
3/12/2007	32	na	Na	na	na	na	na
8/01/2008	36	408	0.0020	6200	0.012	0.00033	0.0032
Total (project period)		408		81302.5	0.19		

Table 5.7 Total nitrogen concentrations in ground-level rainfall, rainfall volume and nitrate-nitrogen discharge rate. Measured total nitrogen concentrations are commonly below the detection limit. Mass calculations in this table are a maximum as the calculations use the detection limit where measured concentrations are below the detection limit.

Sample date	Days in sample period	Days (cumulative sum)	TN (mg/L)	Rainfall volume period (mL)	TN mass in period (mg)	TN mass discharge in period (mg/day)	TN (kg/ha/month)
27/09/2006							
25/10/2006							
4/12/2006	40	40	0.3	2012.5	0.604	0.0151	0.1462
4/01/2007	31	71	0.1	2690	0.269	0.0087	0.0842
24/01/2007	20	91	0.1	9700	0.97	0.0485	0.4696
28/02/2007	35	126	0.3	4300	1.29	0.0369	0.3572
2/04/2007	33	159	0.2	13520	2.704	0.0819	0.7929
1/05/2007	29	188	1.4	6220	8.708	0.3003	2.9074
2/07/2007	62	250	0.3	10050	3.015	0.0486	0.4705
30/07/2007	28	278	0.1	11370	1.137	0.0406	0.3931
29/08/2007	30	308	0.2	5570	1.114	0.0371	0.3592
1/10/2007	33	341	0.5	4800	2.4	0.0727	0.7038
1/11/2007	31	372	0.27	4870	1.315	0.0424	0.4105
3/12/2007	32	na	Na	na	na	na	na
8/01/2008	36	408	0.25	6200	1.55	0.0431	0.4173
Total (project period)		408		81302.5	25.076		

Total phosphorus mass discharge (kg/ha/month) is greatest in the samples measured on 4/12/2006 and 24/01/2007 (Table 5.8) i.e. in summer months. However total phosphorus data in the sample period is not useful for identifying any seasonal trends because total phosphorus concentrations are below the detection limit in below detection in 6 of the 12 samples (Appendix 2).

Table 5.8 Total phosphorus concentrations in rainfall recharge (lysimeter 1), rainfall recharge volume and phosphorus discharge rate.

Sample date	Days in sample period	Days (cumulative sum)	TP (mg/L)	Rainfall recharge volume period	TP mass in period (mg)	TP mass in period (mg/day)	TP (kg/ha/month)
27/09/2006							
25/10/2006							
4/12/2006	40	40	0.58	6612.5	3.835	0.0959	0.1487
4/01/2007	31	71	0.55	330	0.182	0.0059	0.0092
24/01/2007	20	91	0.077	23800	1.833	0.0917	0.1422
28/02/2007	35	126		0	0	0	0
2/04/2007	33	159	0.004	37120	0.148	0.0045	0.007
1/05/2007	29	188	0.007	9520	0.067	0.0023	0.0036
2/07/2007	62	250	0.004	25700	0.103	0.0017	0.0026
30/07/2007	28	278	0.004	35820	0.143	0.0051	0.0079
29/08/2007	30	308	0.004	19220	0.077	0.0026	0.004
1/10/2007	33	341	0.004	9900	0.04	0.0012	0.0019
1/11/2007	31	372	0.014	12720	0.178	0.0057	0.0088
3/12/2007	32	404	0.26	2597	0.675	0.0211	0.0327
8/01/2008	36	440	0.0058	5870	0.034	0.0009	0.0014
Total		440		189209.5	7.281	7.315	

Total phosphorus concentrations in ground-level rainfall show no particular seasonal trend (Table 5.9).

Table 5.9 Total phosphorus concentrations in ground-level rainfall, rainfall volume and phosphorus discharge rate.

Sampling date	Days in period	Days (cumulative sum)	TP	Vol mL period	TP mass in period (mg)	TP mass discharge in period (mg/day)	TP (kg/ha/month)
27/09/2006							
25/10/2006							
4/12/2006	40	40	0.247	2012.5	0.497	0.0124	0.1201
4/01/2007	31	71	0.258	2690	0.694	0.0224	0.2169
24/01/2007	20	91	0.177	9700	1.717	0.0859	0.8316
28/02/2007	35	126	0.131	4300	0.563	0.0161	0.1559
2/04/2007	33	159	0.086	13520	1.163	0.0352	0.3408
1/05/2007	29	188	0.164	6220	1.02	0.0352	0.3408
2/07/2007	62	250	0.528	10050	5.306	0.0856	0.8287
30/07/2007	28	278	0.382	11370	4.343	0.1551	1.5016
29/08/2007	30	308	0.209	5570	1.164	0.0388	0.3756
1/10/2007	33	341	0.307	4800	1.474	0.0447	0.4328
1/11/2007	31	372	0.18	4870	0.877	0.0283	0.274
3/12/2007	32	na	Na	Na	na	na	na
8/01/2008	36	408	0.15	6200	0.93	0.0258	0.2498
Total (project period)		48		81302.5	19.748		

5.3 Approximate annual monitoring period

The whole monitoring period (Section 5.2) includes two summers and one winter which will bias the estimates of annual mass discharge. This section calculates average and median mass discharge over an approximate annual monitoring period which includes samples collected in the 369 day period including samples collected between 24/1/2007 and 8/1/2008 with the aim of reducing the bias in mass discharge estimates.

Characteristics of mass discharge (Table 5.10) include:

- nitrate-nitrogen discharge, and concentration, in rainfall recharge is much greater than in ground-level rainfall;
- average nitrate-nitrogen concentration in ground-level rainfall is the detection limit of 0.002 reflecting the concentrations majority of samples being below the detection limit and use of the detection limit in these calculations;
- total phosphorus discharge and concentration in ground-level rainfall is much greater than in rainfall recharge.

Table 5.10 Mass discharge in approximate annual period including samples collected between 24/1/2007 and 8/1/2008*.

	Rainfall recharge Lysimeter 1		Ground-level rainfall		
	Nitrate-nitrogen	Total phosphorus	Nitrate-nitrogen	Total nitrogen	Total phosphorus
Mass discharge in period (mg)	172.96	3.26	0.18	24.20	18.56
Mass discharge (kg/ha/yr), rounded	8.7	0.17	0.06	7.6	5.8
Weighted average concentration[1] (mg/L)	0.95	0.02	0.002	0.3	0.2
Reference table	Table 5.5	Table 5.8	Table 5.6	Table 5.7	Table 5.9

* Rainfall recharge volume lysimeter 1 182267 mL in approximate annual period.

Ground-level rainfall volume 76600 mL in approximate annual period. This volume excludes the volume of the sample taken on 3/12/2007 as nitrogen measurements were not made on this sample.

Duration of approximate annual period 369 days.

Scale collection area to hectare for lysimeter 1 = 51020 (i.e. 10000 / 0.196).

Scale collection area to hectare for ground-level rainfall = 318471 (i.e. 10000 / 0.0314).

[1] Mass discharge in period divided by rainfall recharge volume (lysimeter 1) or ground-level rainfall volume.

Characteristics of median mass discharge (Table 5.11) include:

- nitrate-nitrogen discharge in rainfall recharge is much greater than in rainfall recharge;
- total phosphorus discharge in ground-level rainfall is much greater than in rainfall recharge.

Mass discharge estimates (Table 5.10) are greater than comparable median calculations (Table 5.11) as most of the mass discharge occurs at higher nutrient concentrations. The annual mass discharge estimates in Table 5.10 are preferred over median mass discharge estimates in Table 5.11 because median estimates of mass discharge only partially reflect the bias of mass discharge to the autumn-winter-spring period.

Table 5.11 Median mass discharge in approximate annual period including samples collected between 24/1/2007 and 8/1/2008*.

	Rainfall recharge Lysimeter 1		Ground-level rainfall		
	Nitrate-nitrogen	**Total phosphorus**	**Nitrate-nitrogen**	**Total nitrogen**	**Total phosphorus**
Median mass discharge (mg/day)	0.10	0.003	0.004	0.05	0.04
Mass discharge (kg/ha/yr), rounded	1.9	0.05	0.007	0.85	0.69
Reference table	Table 5.5	Table 5.8	Table 5.6	Table 5.7	Table 5.9

* Calculation parameters as in footnote to Table 5.10.

6.0 CHLORIDE BALANCE MODEL

A chloride balance model can be used to estimate rainfall recharge and evaporation using:

chloride mass input to soil = chloride mass output from soil, or

chloride mass in rainfall = chloride mass in evaporation + chloride mass in rainfall recharge, or

$C_R * M_R$ $= C_E * M_E + C_{RR} * M_{RR}$ i.e.

M_{RR} $= (C_R * M_R - C_E * M_E)/C_{RR}$ and assuming

C_E $= 0$ i.e. evaporated water has a zero chloride concentration,

then M_{RR} $= C_R * M_R/C_{RR}$ i.e. rainfall recharge is in proportion to chloride concentration in rainfall chloride concentration in rainfall recharge and rainfall.

Average chloride concentrations in the project period are:

- 2.3 mg/L in rainfall recharge, lysimeter 1, (C_{RR});
- 2.4 mg/L in ground-level rainfall (C_R).

and M_{RR} $= 2.4 * M_R/2.3$

Therefore the rainfall recharge rate estimated with chloride data is approximately the same as observed rainfall rate and the estimate of rainfall recharge with chloride data is significantly larger than observed rainfall recharge.

Therefore losses of chloride with evaporation are suspected and the following text aims to estimate the chloride balance considering chloride yields, i.e.

Chloride yield with rainfall = chloride yield (rainfall recharge) + chloride yield (evaporation)

Average total chloride mass discharge (kg Cl/ha/year) in rainfall recharge (lysimeter 1) in the project period is calculated as approximately 20 kg Cl/ha/year with:

- total chloride mass discharge 481.8 mg Cl in the project period;
- ground-level rainfall volume 189209.5 mL in the project period;
- project period 440 days;

- chloride mass discharge in project period (kg Cl/ha/year) = 481.8 (mg Cl) / 440 day/lysimeter) * 365 (days per year) / 1000000 (mg/kg) * 51020 (10000 / 0.0314 recorder/ha - i.e. scaling-up the rainfall recorder area to 1 ha) and rounded to one decimal place.

Average total chloride mass discharge (kg Cl/ha/year) in ground-level rainfall in the project period is calculated as approximately 51 kg Cl/ha/year with:

- total chloride mass discharge 192.7 mg Cl in the project period;
- ground-level rainfall volume 84202.5 mL in the project period;
- project period 440 days;
- chloride mass discharge in project period (kg Cl/ha/year) = 192.7 (mg Cl) / 440 day/lysimeter) * 365 (days per year) / 1000000 (mg/kg) * 318,471 (10000 / 0.0314 recorder/ha - i.e. scaling-up the rainfall recorder area to 1 ha) and rounded to one decimal place.

Therefore chloride yield with evaporation = 51 kg Cl/ha/year - 20 kg Cl/ha/year

= 31 kg Cl/ha/year

This calculation does not provide an independent check of observed rainfall recharge rates as this calculation depends on observed rainfall recharge.

7.0 STABLE ISOTOPES IN RAINFALL AND RAINFALL RECHARGE

Stable isotopes of rainfall sampled at the Kaharoa rainfall recharge site show a strong seasonal pattern with more negative values during winter and less negative values towards summer due to the effect of temperature. Stable isotope compositions of rainfall and rainfall recharge plot along the local meteoric water line for the west coast of the north island ($\delta^2H = 8*\delta^{18}O + 13$; Michael Stewart, pers. comm.) (Figure 7.1) with very little deviation, indicating rapid infiltration of rainwater with little evaporation during recharge.

The variation of stable isotope composition is smaller for rainfall recharge than for rain water, suggesting that there is an attenuation of the isotopic signals due to mixing and homogenisation of water in the soil during recharge. A comparison of δ^2H and $\delta^{18}O$ compositions in rainfall and rainfall recharge in lysimeter 1 over time (Figure 7.2 and 7.3) shows that there is a time lag between changes in the rainfall stable isotope composition and the rainfall recharge stable isotope composition of approximately three months. Therefore water residence time in the lysimeter column’s soil may be three months.

However it is not possible to determine water residence times using a quantitative approach because of the relatively short measurement period (six months) of the stable isotopes.

8.0 PLANT GROWTH AS A CONTROL ON NITROGEN LEACHING

Rainfall, rainfall recharge and nitrogen data give weight to the notion that plant growth controls nitrogen release. Nitrogen in recharge is related directly to the annual cycle of grass growth and therefore to nitrogen uptake by grass.

Groundwater recharge responds almost immediately to current rainfall (Figure 5.1) so that there is little storage in the soil within the frequency of sampling (approximately monthly) that is used here. This analysis is important because it indicates that what happens to the rainfall between its arrival at the surface and its delivery to groundwater is a product of the contemporary soil environment. Therefore both the volume of water and its chemistry on arrival at the bottom of the lysimeters are a result of the biology and chemistry of the soil during the analysis period.

Nitrate-nitrogen concentration will be a product of the combined biological processes of ammonia mineralization to nitrate and nitrate uptake by plant roots. When uptake exceeds production, as normally occurs in pastures in summer, there will be vanishing levels of nitrate detectable. As autumn arrives and temperature and day length decline the balance changes dramatically and nitrate levels will rise. No nitrate-nitrogen levels are recorded for March because no rainfall recharge occurred in this period. However the April figures show a dramatic rise in nitrate-nitrogen concentration and this rise continues through the winter. The fall in nitrate-nitrogen concentration is equally dramatic in spring which again mirrors the normally strong spring increase in pasture productivity.

Little storage on nitrate-nitrogen in the soil column is observed with a comparison of recharge, nitrate-nitrogen concentrations and nitrate-nitrogen recharge mass (Figure 8.1). Nitrate-nitrogen mass calculated here is an upper limit as nitrate-nitrogen concentrations are taken as the detection limit for samples where measured concentrations are below the detection limit.

Nitrate-nitrogen mass delivered to groundwater increases dramatically in the sixth sampling, on the 2nd April, which represents the first of the autumn samplings. The amount of nitrate-nitrogen in groundwater is the product of nitrate-nitrogen concentration and recharge volume. Therefore both nitrate-nitrogen and recharge volume contribute to nitrate-nitrogen mass movement in groundwater. The rise in nitrate-nitrogen concentration at the end of summer coincides with a drop in temperature at the end of March. It is most significant that over 99% of the nitrate-nitrogen generated in the lysimeters arises in the autumn/winter and spring months and is partitioned between the autumn and spring flushes in grass growth. As grass growth is constrained by falling temperatures in the autumn mineralised nitrogen uptake is reduced and excess nitrate-nitrogen appears in the groundwater. This is flushed out by higher rainfall recharge during the winter; in the spring, increasing temperatures and lengthening days bring about a flush of grass growth and all available mineral nitrogen is absorbed. The 1 October 2007 sampling represents the September spring grass flush in which ryegrass reaches its maximum growth.

Nitrate-nitrogen recharge mass in the March – August (i.e. autumn, winter and spring) period dominates annual total nitrate-nitrogen recharge mass. For example in lysimeter 1:

- observed nitrate-nitrogen recharge mass between March 2007 and August 2007 totals approximately 172 mg, or 99.7% of the annual total;
- observed annual nitrate-nitrogen recharge mass between January 2007 and December 2007 totals approximately 173 mg (Table 5.10).

8.1 Note on land management and nitrogen concentrations in groundwater

Nitrogen leaching from pasture in the March to August months is a very important driver of nitrogen concentrations in Lake Rotorua groundwater as the vast majority of nitrate-nitrogen generation occurs in these months. Therefore management of stock and soil in the March to August period is a critical issue to management of nitrogen leaching to groundwater.

Protection of Lake Rotorua water quality should include best-practice land use to reduce nitrate-nitrogen discharge through the soil, particularly in the March to August months. Best-practice land use is therefore very important and this requires understanding and integrating the hydrology (surface and groundwater), the soil biology and the management of stock and soil.

9.0 RELEVANCE TO THE OBSERVED NITROGEN AND PHOSPHORUS CONCENTRATIONS IN GROUNDWATER IN THE LAKE ROTORUA CATCHMENT

Nitrate-nitrogen concentrations in rainfall recharge measured in this project are up to 1.78 mg/L (Appendix 2, lysimeter 1) observed in the lysimeter under a mixed sheep/beef/deer farm and concentrations in this range are commonly observed in the Lake Rotorua catchment (Figure 2.1). Other land uses (e.g. dairy and cropping, Section 2) may be associated with higher nitrate-nitrogen concentrations in groundwater.

Nitrate-nitrogen concentrations in groundwater in the Lake Rotorua catchment are commonly greater than 1 mg/L (Figure 2.1). This may be explained by:

- land uses that are more intensive than sheep, beef and deer. For example other land uses (e.g. dairy and cropping, Section 2) may be associated with higher nitrate-nitrogen concentrations in groundwater;
- point sources of nitrate-nitrogen, for example septic tanks.

Phosphorus concentrations in rainfall recharge are mostly below detection as is normal for these types of soils. Therefore phosphorus concentrations in groundwater are probably relatively independent of land use.

10.0 SUMMARY

The rainfall recharge site at Kaharoa (Reeves et al., 2005) has operated since June 2005 and measures rainfall in a ground-level gauge, rainfall in a standard rain gauge and rainfall recharge in two lysimeters under sheep, beef and deer land use.

Chemistry samples in lysimeters and in the ground-level recorder between 4th December 2006 and 8th January 2008 include:

- twelve measurements of nitrogen, phosphorus and chloride in lysimeter 1 and lysimeter 2 in the period between 4th December 2006 and 8th January 2008;

- seven measurements of oxygen and deuterium isotopes in lysimeter 1 and lysimeter 2 in the period between 2nd April 2007 and 1st November 2007;
- fourteen measurements of nitrogen, phosphorus and chloride in ground-level rainfall in the period between 4th December 2006 and 8th January 2008;
- seven measurements of oxygen and deuterium isotopes in ground-level rainfall in the period between 2nd April 2007 and 1st November 2007.

Typically most nitrogen in rainfall recharge measured in the lysimeters is in the form of nitrate-nitrogen due to chemical processes in the soil zone. For example mean nitrate-nitrogen concentration in lysimeter 1 is 0.6 mg/L and mean total nitrogen concentration is 1.15 mg/L (Table 4.1).

Typically most nitrogen in ground-level rainfall is in forms other than nitrate-nitrogen, for example mean total nitrogen concentration in ground-level rainfall is 0.34 mg/L and mean nitrate-nitrogen concentration in ground-level rainfall is 0.003 mg/L (Table 4.1).

Nitrate-nitrogen concentrations in ground-level rainfall are typically less than nitrate-nitrogen concentrations rainfall recharge. For example mean nitrate-nitrogen concentration in ground-level rainfall is 0.003 mg/L and mean nitrate-nitrogen concentration in rainfall recharge from lysimeter 1 is 0.6 mg/L (Table 4.1).

Phosphorus concentrations in ground-level rainfall are typically greater than phosphorus concentrations in rainfall recharge, for example mean total phosphorus concentration in ground-level rainfall is 0.263 mg/L and mean total phosphorus concentration in rainfall recharge from lysimeter 1 is 0.126 mg/L (Table 4.1), including measured concentrations below the detection limit. Phosphorus concentrations in rainfall recharge are mostly below detection as is normal for these types of soils. Therefore phosphorus concentrations in groundwater are probably relatively independent of land use.

Nitrate-nitrogen mass discharge (as kg/ha/month and as mass) in rainfall recharge measured in lysimeter 1 is greatest in the autumn, winter and spring months of March 2007 to August 2007 (Figure 8.1). For example 99.7% of the annual nitrogen-nitrogen discharge occurs in these months because:

- rainfall recharge volumes are typically higher in the winter months;
- nitrate-nitrogen concentrations are typically higher in the winter months;
- nitrogen release is most probably controlled by plant growth in these months.

Annual nitrate-nitrogen mass discharge to groundwater is estimated as 8.7 kg N/ha/yr (Table 5.10) at the Kaharoa site for sheep, beef and deer land use.

The average annual nitrate-nitrogen concentration in rainfall recharge measured in lysimeter 1 is calculated as 0.95 mg/L (Table 5.10) and maximum measured nitrate-nitrogen concentration in lysimeter 1 is 1.78 mg/L (Appendix 2); concentrations in this range are commonly observed in groundwaters in the Lake Rotorua catchment.

Nitrate-nitrogen concentrations in groundwater are commonly greater than 1 mg/L in the Lake Rotorua catchment. This may be explained by:

- land uses that are more intensive than sheep, beef and deer. For example other land uses (e.g. dairy and cropping) may be associated with higher nitrate-nitrogen concentrations in groundwater;
- point sources of nitrate-nitrogen.

A comparison of δ^2H and δ^{18}O compositions in rainfall and rainfall recharge in lysimeter 1 over time shows that there is a time lag between changes in the rainfall stable isotope composition and the rainfall recharge stable isotope composition of approximately three months. Therefore water residence time in the lysimeter column's soil may be three months. However it is not possible to determine water residence times using a quantitative approach because of the relatively short measurement period (six months) of the stable isotopes.

Plant growth probably controls nitrogen release and nitrogen leaching from pasture in the March to August months is a very important driver of nitrogen concentrations in Lake Rotorua groundwater. Therefore management of stock and soil, including best-practice land use, in the March to August period is a critical issue to management of nitrogen leaching to groundwater.

11.0 ACKNOWLEDGEMENTS

Our thanks to Martin Hawke, Bay of Plenty Farm and Pastoral Research, for completing sampling at the Kaharoa rainfall recharge site.

Our thanks also to University of Waikato's lakes research programme for part-funding this project.

Thanks also to Caroline Meilhac (GNS Science), Matthias Raiber (GNS Science) and Christopher Daughney (GNS Science) for reviewing the draft of this report.

12.0 REFERENCES

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Reeves, R., White, P.A., Cameron, S.G., Kilgour, G., Morgenstern, U., Daughney, C., Esler, W., Grant, S. 2005. Lake Rotorua groundwater study: results of the 2004-2005 field programme. *GNS Client report 2005/66.* 67 p. + App.

White, P.A., Zemansky, G., Hong, T., Kilgour, G., Wall, M., 2007. Lake Rotorua groundwater and Lake Rotorua nutrients – phase 3 science programme technical report. GNS Client report 2007/220 to Environment Bay of Plenty. 402p.

FIGURES

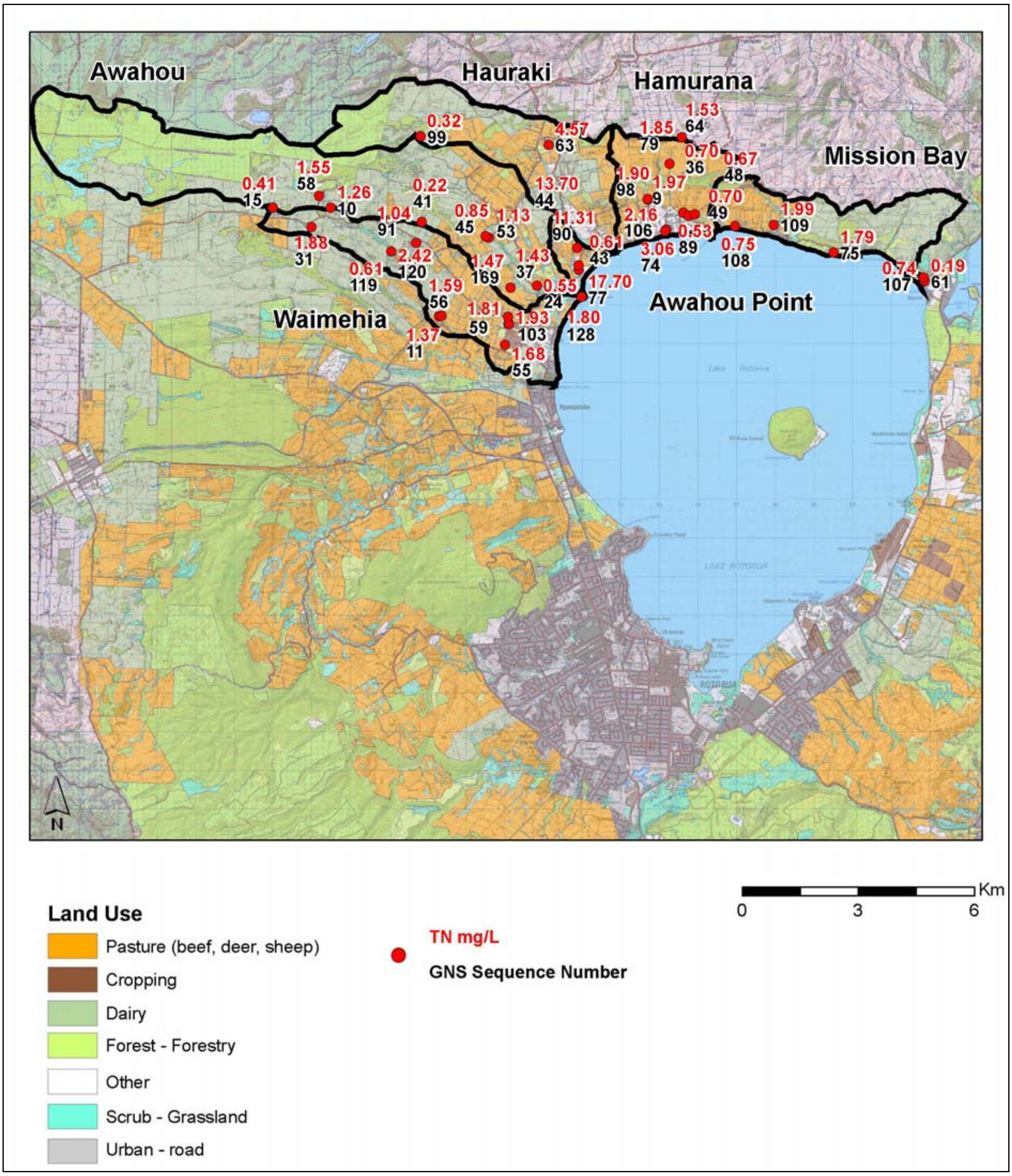

Figure 2.1 North-western surface catchments of Lake Rotorua, land use and TN median values (White et al. 2007).

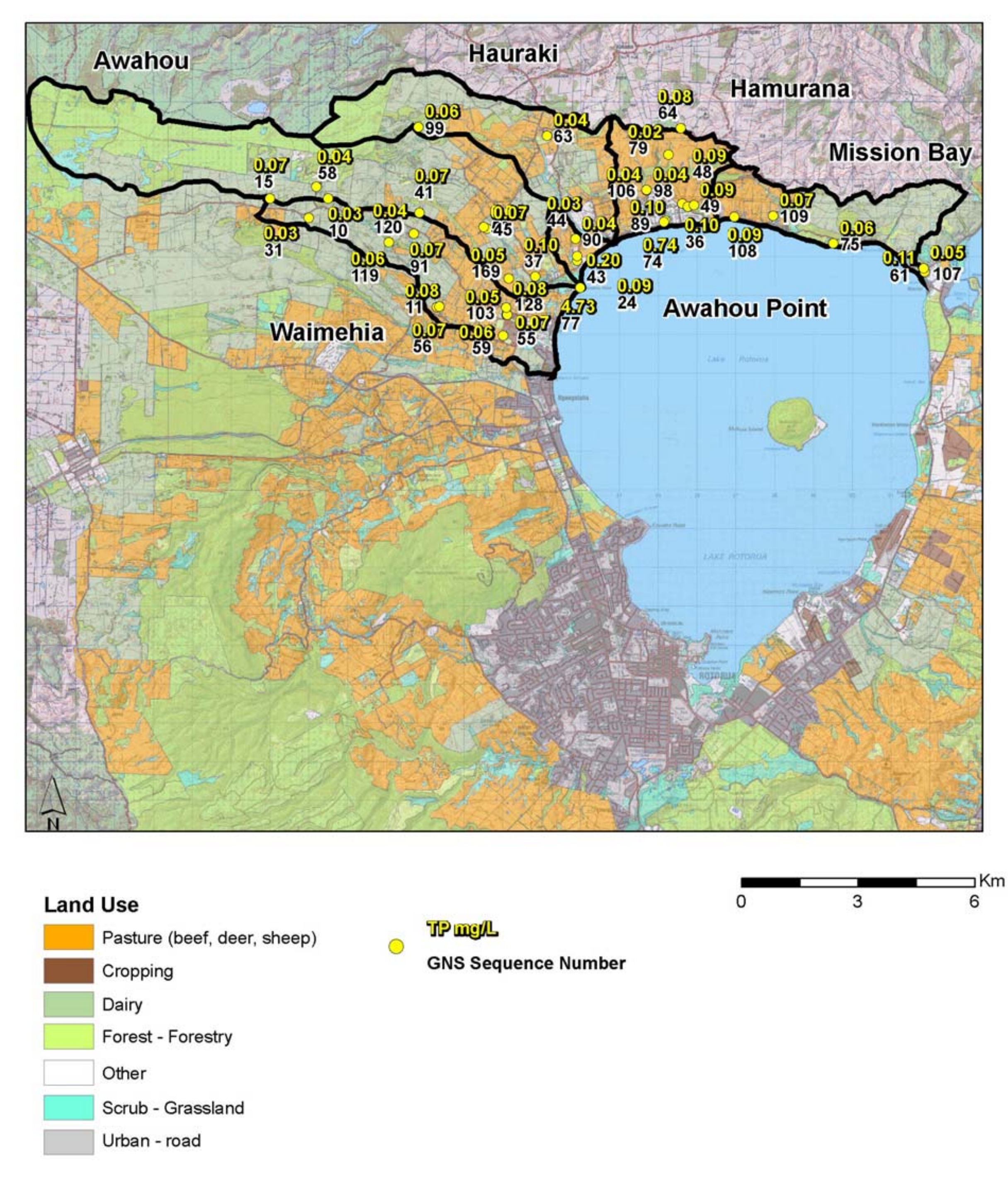

Figure 2.2 North-western surface catchments of Lake Rotorua, land use and TP median values (White et al. 2007).

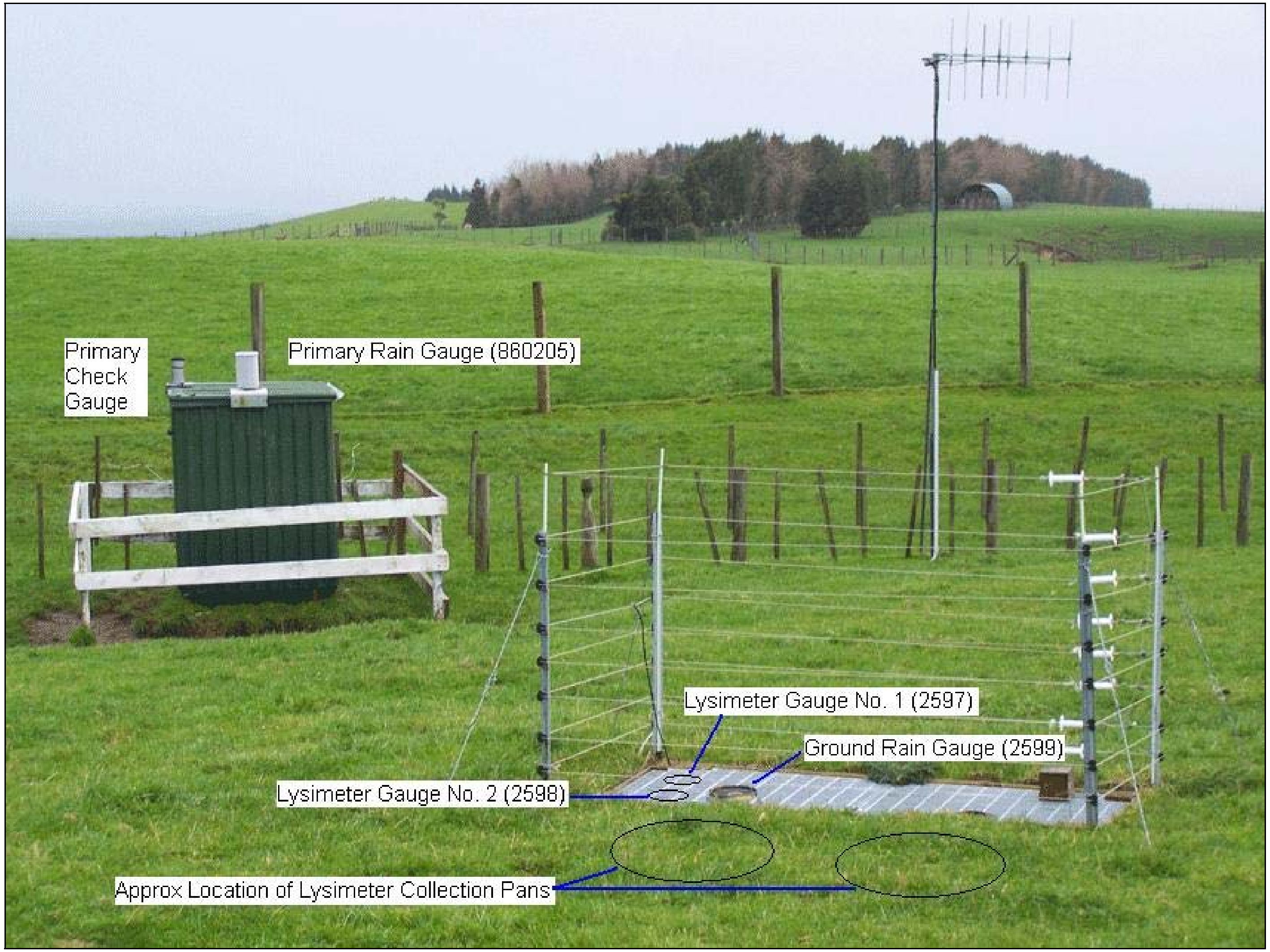

Figure 3.1 Kaharoa rainfall recharge site (White et al. 2007).

Figure 3.2 Kaharoa rainfall recharge site – instruments (White et al. 2007).

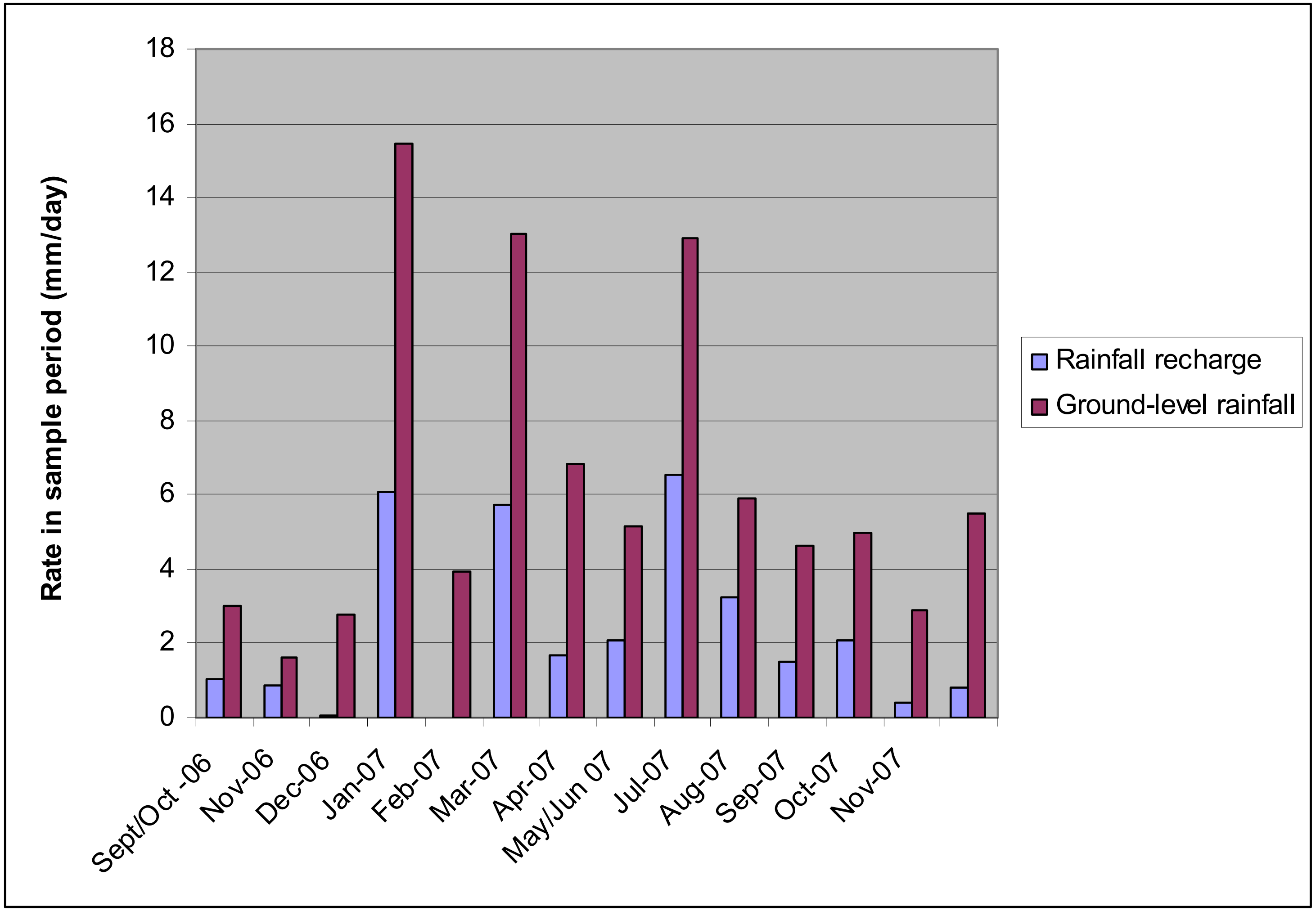

Figure 5.1 Rainfall recharge and ground-level rainfall in the sample period.

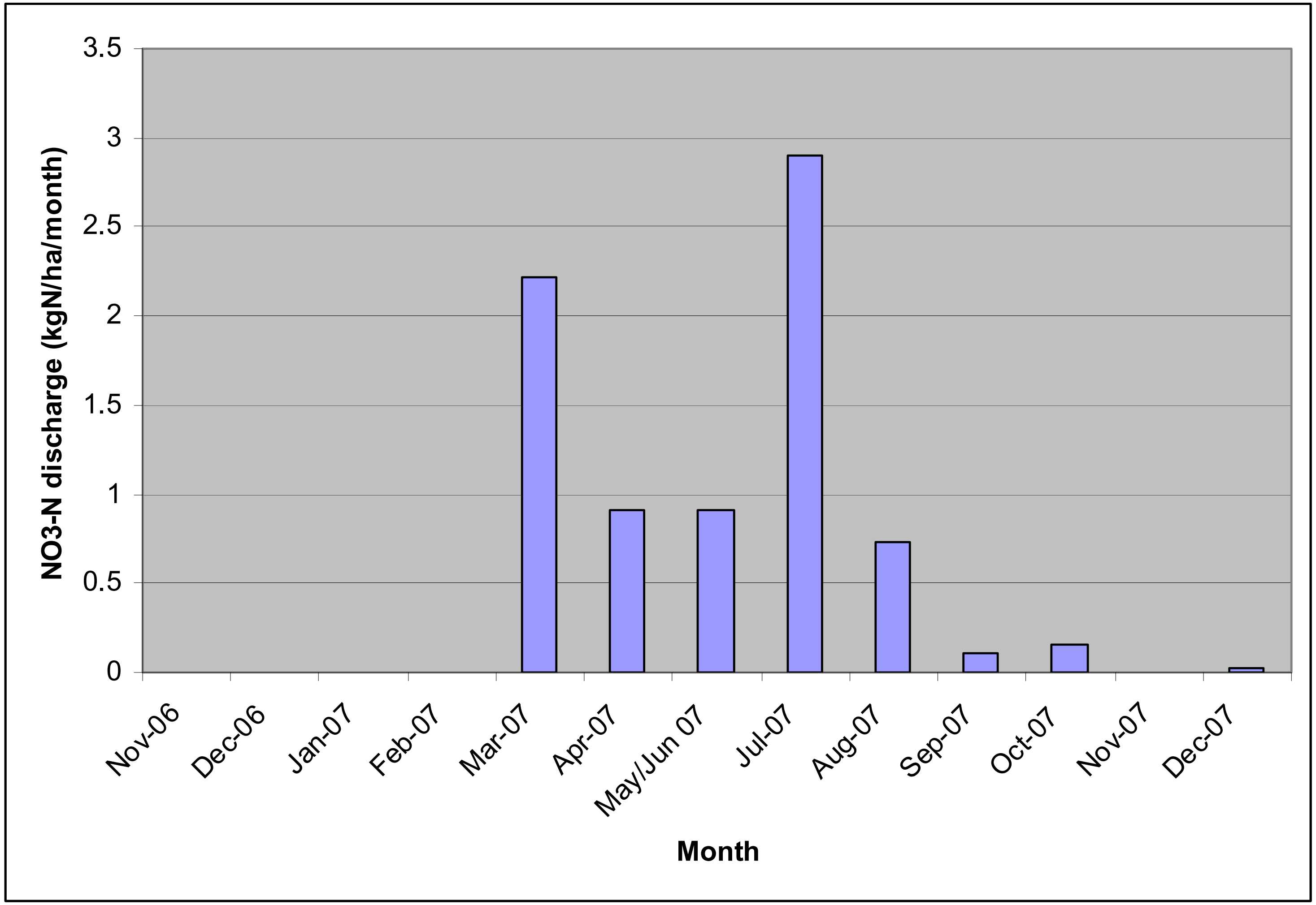

Figure 5.2 Nitrate-nitrogen discharge in rainfall recharge, lysimeter 1 (kgN/ha/month) by month in the sampling period.

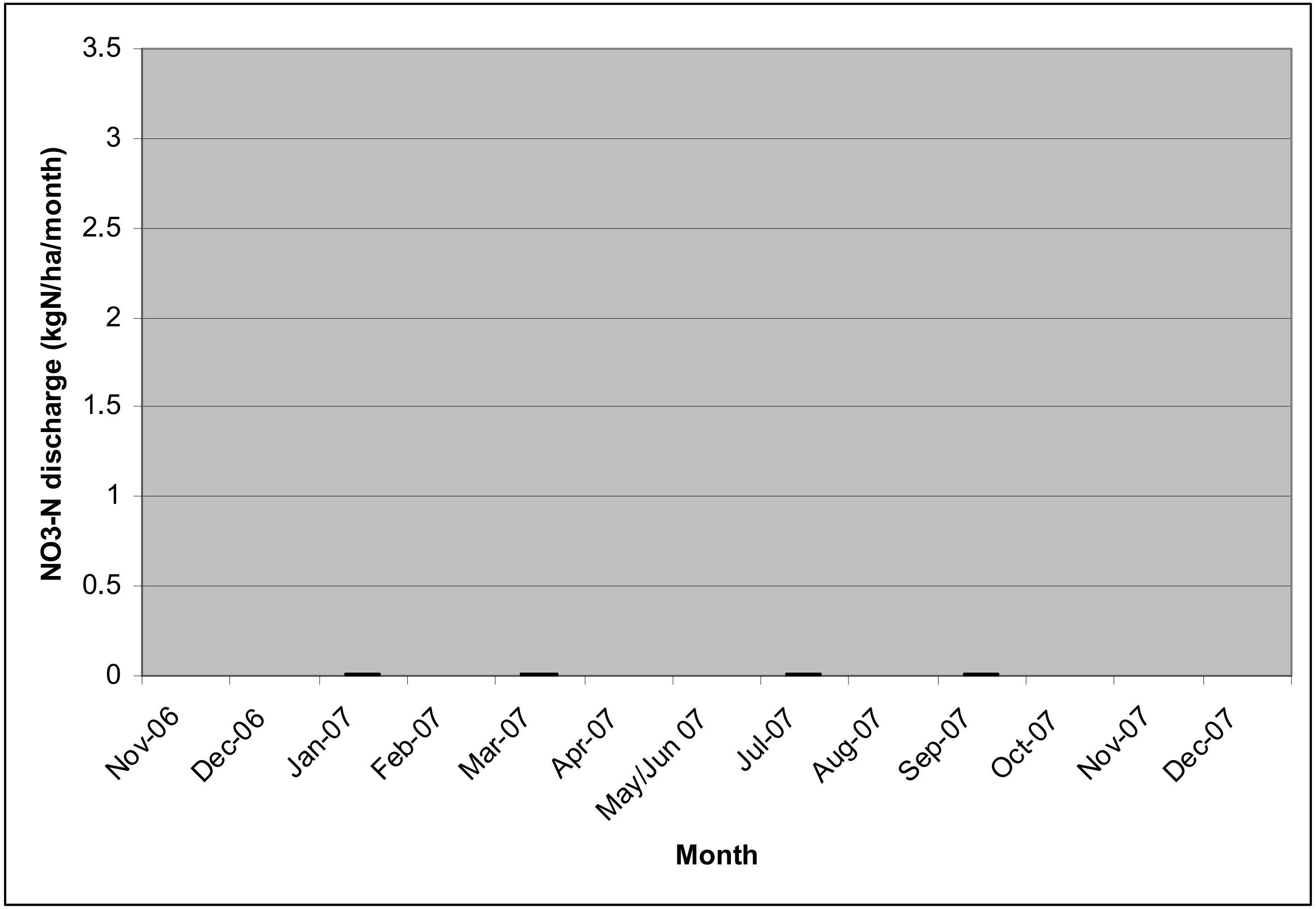

Figure 5.3 Nitrate-nitrogen discharge in ground-level rainfall (kgN/ha/month) by month in the sampling period, plotted at the same vertical scale as rainfall recharge in Figure 5.2 to indicate that nitrate-nitrogen discharge in ground-level rainfall is much less than Nitrate-nitrogen discharge in rainfall recharge.

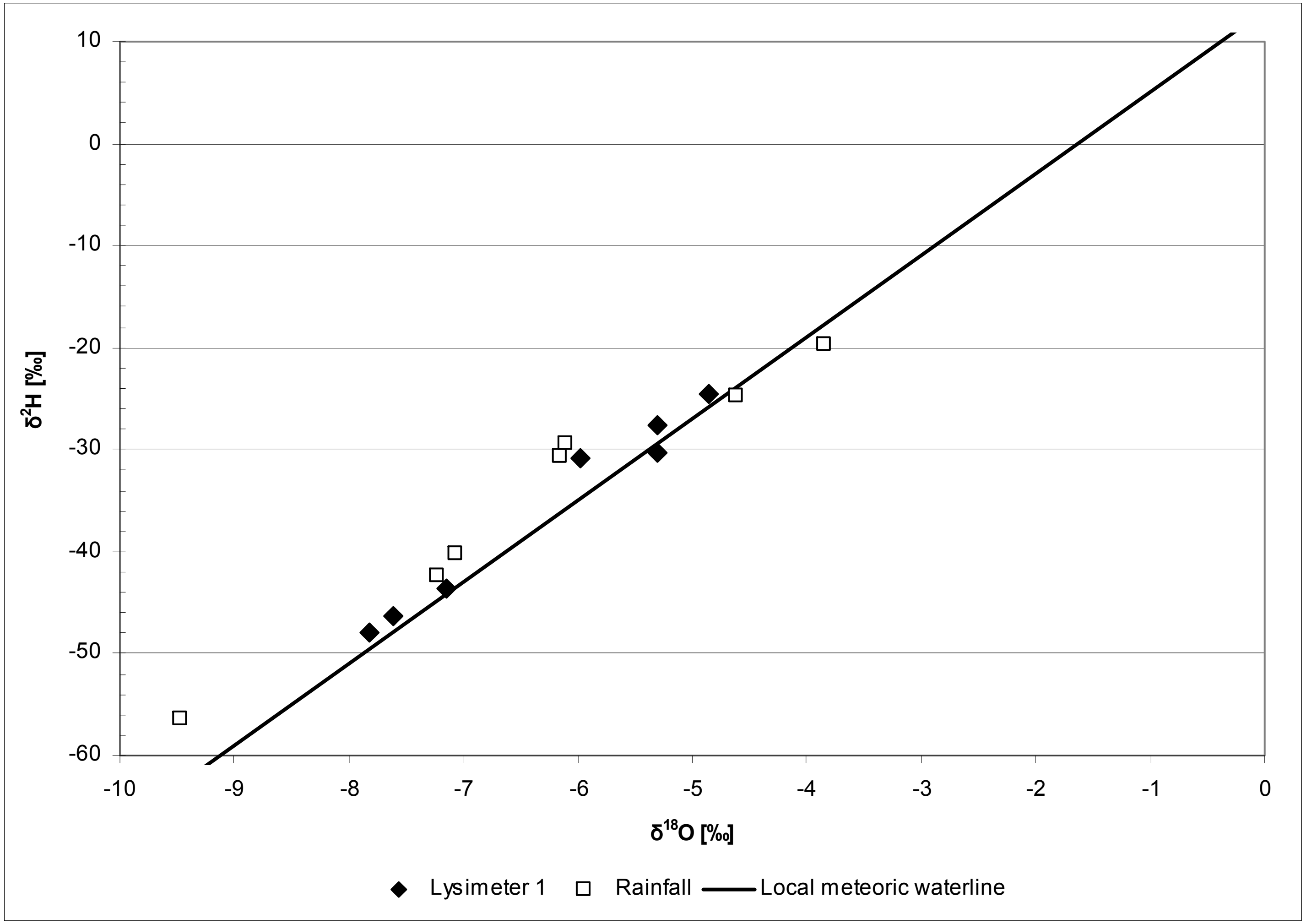

Figure 7.1 δ^{18}O and δ^{2}H of rainfall and rainfall recharge (lysimeter 1) in relation to the local meteoric water line.

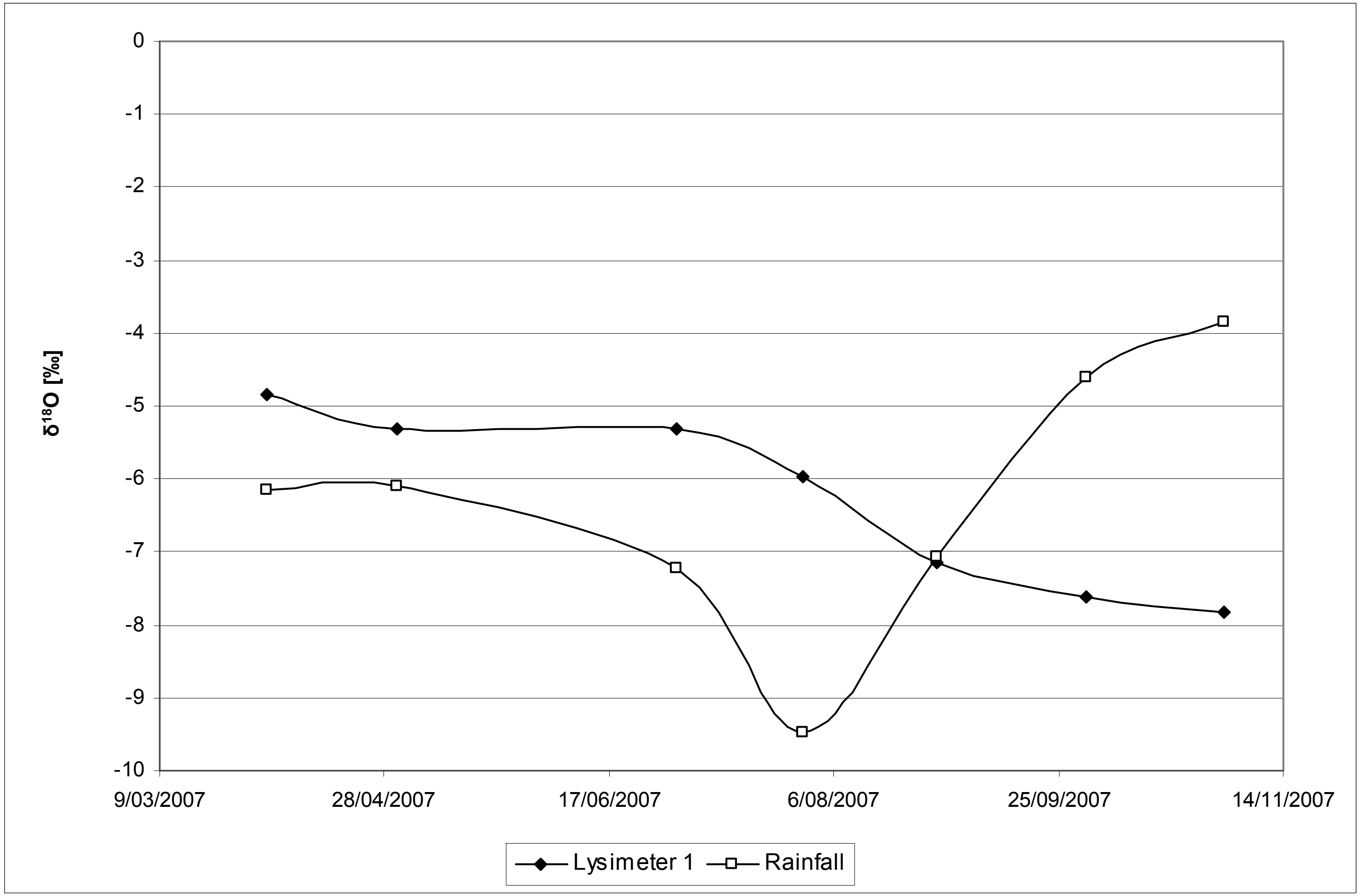

Figure 7.2 Evolution of $\delta^{18}O$ in rainfall and rainfall recharge (lysimeter 1) over time.

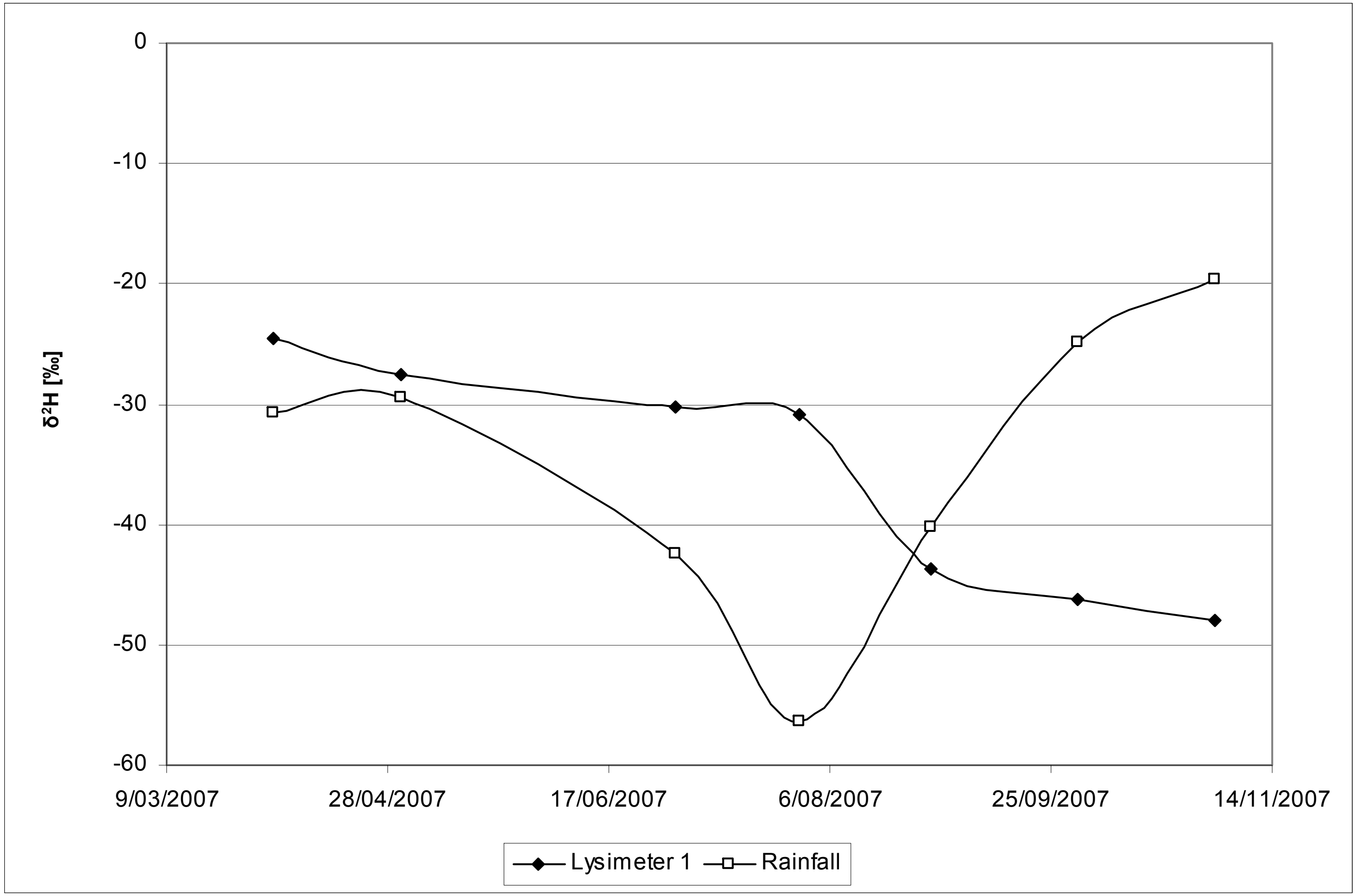

Figure 7.3 Evolution of δ^2H in rainfall and rainfall recharge (lysimeter 1) over time.

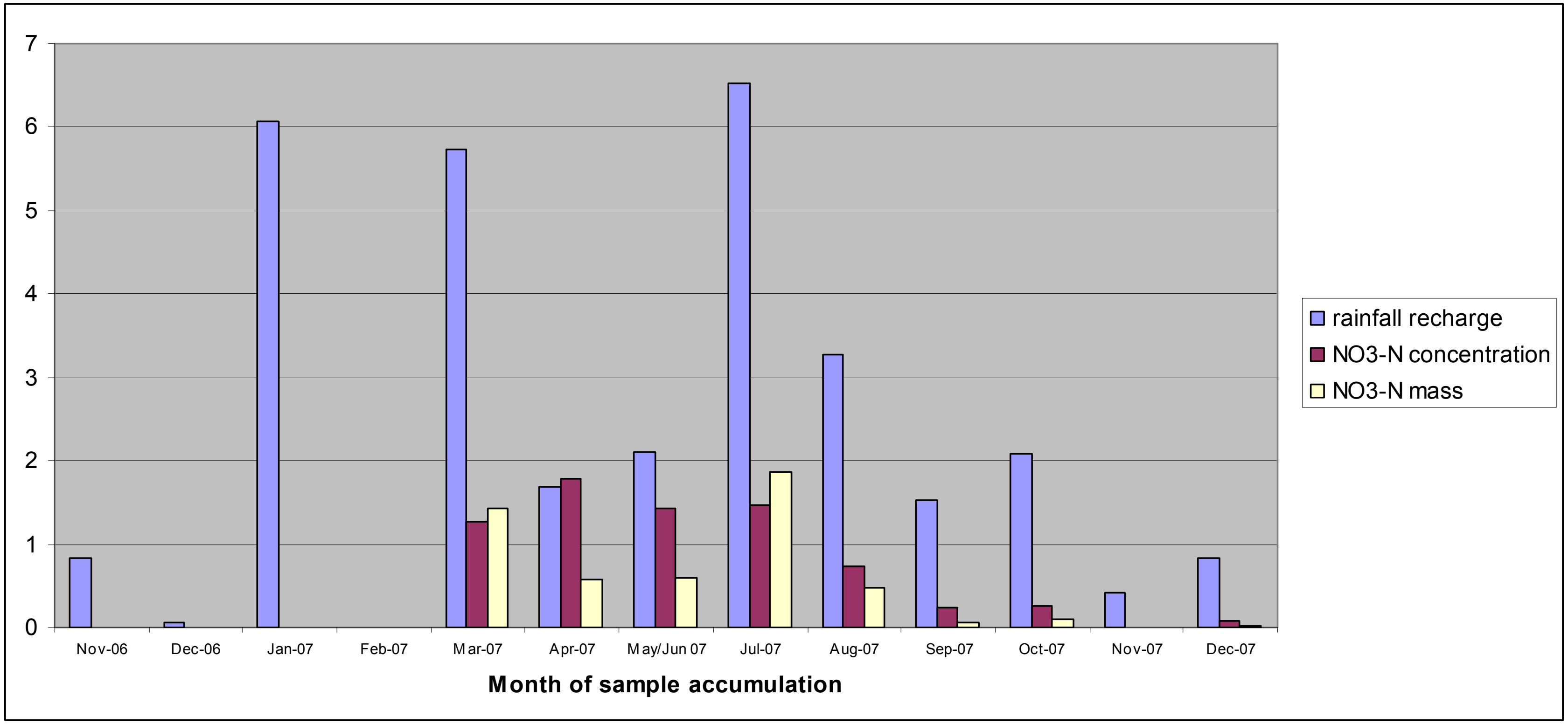

Figure 8.1 Rainfall recharge (mm/day), nitrate concentration (mg/L) and nitrate-nitrogen mass in recharge (mg/day) at lysimeter 1.

APPENDICES

APPENDIX 1 CONTRACT FROM ENVIRONMENT BAY OF PLENTY

The following work was agreed with Environment Bay of Plenty for assessments water chemistry in rainfall and rainfall recharge at the Kaharoa rainfall recharge site:

- design and install water collection systems for rainfall and rainfall recharge where the tipping-bucket rain gauges discharge to allow collection of composite samples;
- collect composite water samples each month for one year of rainfall and each month for one year of rainfall recharge from each of the two lysimeters (special sample collection and handling methods are necessary in the case of O-18);
- send samples to R.J. Hill Laboratories Ltd. (Hill Lab) for chloride, all three nitrogen species, and phosphorus analysis each month for one year;
- send samples to GNS for deuterium and O-18 analysis for the initial sampling event and for O-18 for each month for the remainder of one year;
- estimate recharge using the chloride mass balance approach;
- estimate recharge using rainfall and lysimeter water volume data;
- estimate nutrient fluxes (nitrogen and phosphorus) from rainfall and in rainfall recharge with one year of data;
- estimate water residence time from O-18 measurements with one year of data;
- using deuterium and O-18 measurements, compare site results with the meteoric line;
- report to Environment Bay of Plenty.

APPENDIX 2 OBSERVED WATER CHEMISTRY AND RAINFALL RECHARGE DATA

Measurements of nitrogen, phosphorus, chloride, oxygen, deuterium and water volumes collected in the lysimeters and in ground-level rainfall are listed. Concentrations below laboratory detection limits are listed in red-coloured text.

Lysimeter 1

Date Unit	**Time**	**Lysimeter 1, site 2597**										
		T-AmN mg/L	**TN mg/L**	**TKN mg/L**	**TON mg/L**	**NO$_3$-N mg/L**	**NO2-N mg/L**	**TP mg/L**	**Cl mg/L**	**$\delta^{18}O$**	**δD**	**Volume mL**
27/09/2006	16:30	**Installation**										
25/10/2006	14:00											**5625**
4/12/2006	11:15	0.01	0.2	0.2	0.002	0.002	0.002	0.58	0.8			**6612.5**
4/01/2007	11:00	0.01	3	3	0.002	0.002	0.002	0.55	1.4			**330**
24/01/2007	11:00	0.01	0.1	0.1	0.002	0.002	0.002	0.077	0.5			**23800**
28/02/2007	14:00											**0**
2/04/2007	11:00	0.01	1.6	0.3	1.27	1.27	0.002	0.004	2.7	-4.85	-24.6	**37120**
1/05/2007	11:00	0.01	2.8	1	1.79	1.78	0.005	0.007	8.0	-5.31	-27.6	**9520**
2/07/2007	11:00	0.01	1.7	0.3	1.42	1.42	0.002	0.004	4.7	-5.31	-30.3	**25700**
30/07/2007	09:15	0.01	1.7	0.2	1.46	1.46	0.002	0.004	3.1	-5.97	-30.9	**35820**
29/08/2007	11:00	0.01	1.0	0.3	0.732	0.731	0.002	0.004	1.6	-7.15	-43.7	**19220**
1/10/2007		0.01	0.4	0.2	0.231	0.231	0.002	0.004	1.1	-7.62	-46.3	**9900**
1/11/2007	11:00	0.01	0.42	0.17	0.25	0.25	0.0028	0.014	0.59	-7.82	-47.9	**12720**
3/12/2007	11:00	0.01	0.4	0.4	0.002	0.002	0.002	0.26	2.6			**2597**
8/01/2008	11:00	0.016	0.42	0.33	0.087	0.087	0.0020	0.0058	0.5			**5870**
TOTALS												**194835**

Red text = detection limit (concentration less than detection)

Lysimeter 2

Date Unit	Time	Lysimeter 2, site 2598										
		T-AmN mg/L	TN mg/L	TKN mg/L	TON mg/L	NO_3-N mg/L	NO2-N mg/L	TP mg/L	Cl mg/L	$\delta^{18}O$	δD	Volume mL
27/09/2006	16:30	**Installation**										
25/10/2006	14:00											**5188**
4/12/2006	11:15	0.02	0.8	0.8	0.002	0.002	0.002	0.274	0.6			**950**
4/01/2007	11:00	0.01	0.1	2.0	0.002	0.002	0.002	0.59	1.5			**300**
24/01/2007	11:00	0.01	0.1	0.1	0.002	0.002	0.002	0.03	0.5			**10600**
28/02/2007	14:00											**0**
2/04/2007	11:00	0.01	0.2	0.1	0.039	0.039	0.002	0.004	0.5	-5.53	-26.0	**20920**
1/05/2007	11:00	0.04	0.3	0.2	0.103	0.102	0.002	0.008	0.5	-4.92	-23.0	**3720**
2/07/2007	11:00	0.01	0.4	0.2	0.207	0.206	0.002	0.01	0.9	-5.31	-30.1	**12500**
30/07/2007	09:15	0.01	1.0	0.2	0.869	0.864	0.005	0.004	1.7	-6.00	-30.6	**15770**
29/08/2007	11:00	0.01	1.8	0.2	1.60	1.59	0.008	0.004	1.6	-7.12	-43.3	**9470**
1/10/2007		1.48	7.3	6.4	0.920	0.892	0.028	0.596	2.4	-7.16	-42.7	**220**
1/11/2007	11:00	0.85	1.9	1.3	0.550	0.52	0.028	0.16	0.65	-7.94	-48.9	**3070**
3/12/2007	11:00	0.01	1.5	1.5	0.012	0.002	0.01	0.059	1.5			**16**
8/01/2008	11:00	0.044	1.7	1.4	0.26	0.26	0.0020	0.13	1.3			**970**
TOTALS												**83694**

Red text = detection limit (concentration less than detection)

Ground-level rainfall

Date Unit	Time	Rainfall (ground-level), site 2599										
		T-AmN mg/L	**TN mg/L**	**TKN mg/L**	**TON mg/L**	**NO$_3$-N mg/L**	**NO2-N mg/L**	**TP mg/L**	**Cl mg/L**	**$\delta^{18}O$**	**δD**	**Volume mL**
27/09/2006	16:30	**Installation**										
25/10/2006	14:00											**2625**
4/12/2006	11:15	0.01	0.3	0.3	0.002	0.002	0.002	0.247	2.8			**2013**
4/01/2007	11:00	0.01	0.1	2	0.002	0.002	0.002	0.258	2.2			**2690**
24/01/2007	11:00	0.01	0.1	0.1	0.002	0.002	0.002	0.177	1.8			**9700**
28/02/2007	14:00	0.02	0.3	0.3	0.003	0.002	0.002	0.131	1.9			**4300**
2/04/2007	11:00	0.02	0.2	0.2	0.002	0.002	0.002	0.086	2.5	-6.16	-30.7	**13520**
1/05/2007	11:00	0.02	1.4	1	0.002	0.002	0.002	0.164	1.7	-6.10	-29.4	**6220**
2/07/2007	11:00	0.01	0.3	0.3	0.002	0.002	0.002	0.528	2.2	-7.22	-42.4	**10050**
30/07/2007	09:15	0.01	0.1	0.1	0.002	0.002	0.002	0.382	1.9	-9.47	-56.4	**11370**
29/08/2007	11:00	0.01	0.2	0.2	0.002	0.002	0.002	0.209	2.5	-7.07	-40.2	**5570**
1/10/2007		0.01	0.5	0.4	0.009	0.008	0.002	0.307	2.1	-4.61	-24.8	**4800**
1/11/2007	11:00	0.01	0.27	0.27	0.002	0.002	0.002	0.18	2.5	-3.85	-19.7	**4870**
3/12/2007	11:00	0.01	**INSUFFICIENT SAMPLE**					0.60	3.9			**2900**
8/01/2008	11:00	0.010	0.25	0.25	0.0020	0.0020	0.0020	0.15	3.2			**6200**
TOTALS												**86828**

Red text = detection limit (concentration less than detection)

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