Contour grass filter strips: hydrology and water quality

NIWA Client Report: HAM2008-134
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Executive Summary

Grass filter strips (GFS) are a potential tool to improve runoff water quality on grazed pastures. Filter strips, located on contours at mid-slope locations (close to source) rather than in riparian zones, are used overseas to remove pollutants from surface runoff on cropped planar hillslopes. Riparian filter strips or paddock edge filter strips may be some distance from the source and as runoff moves downslope, surface runoff tends to converge into small channels which can bypass or locally inundate riparian filter strips. This report presents the final results for contour GFS trials on a dairy farm at Lake Rerewhakaaitu and a drystock farm at Kaharoa, near Lake Rotorua.

The trial compared adjacent 3 m wide GFS of retired ryegrass and *Phalaris aquatica* versus unfenced controls. The inputs and outputs of surface runoff and suspended sediment (SS), total phosphorus (TP), total nitrogen (TN) and *E. coli* were measured at each GFS after runoff events.

Surface runoff (>1L) was generated on 19 days at Rerewhakaaitu (Sep 06-Jun 08) and 10 days at Kaharoa (Jan 07-Jun 08). At Rerewhakaaitu about 10% of rainfall became surface runoff. However, most of the runoff occurred during the winter (mid July-mid August) when at least 35% of rainfall became surface runoff. At Kaharoa surface runoff was a smaller component (6%) of rainfall.

Pollutant concentrations in surface runoff were similar at both sites despite different land uses. Suspended sediment concentrations were between 10 and 4000 mg/L, median TN concentrations between 4 and 6 mg/L and median TP concentrations were less than 2 mg/L. *E. coli* concentrations ranged between 400 and 1.4×10^4 MPN/100 mL at Rerewhakaaitu, and between 10 and 5×10^6 MPN/100 mL at Kaharoa. High (10^4-10^6) *E. coli* concentrations were measured at Kaharoa for three events after recent sheep grazing.

The ryegrass GFS generally performed better than the planted phalaris GFS. Pollutant trapping efficiency generally declined for larger-sized runoff events for both ryegrass and phalaris. For the Rerewhakaaitu control the median concentration of pollutants increased particularly for *E. coli*. Suspended sediment, TN and TP loads were reduced by 35-87% compared with the control, and by a smaller amount compared with the inflow. The Kaharoa control reduced median concentrations, probably due to infiltration. Suspended sediment, TN and TP concentrations were reduced by 60-80% compared with the inflow and by <15-54% compared with the control.

These results suggest that hillslope GFS may be a useful best management practice (BMP) to remove pollutants from surface runoff close to the point of generation. However, GFS are only likely to be a practical and cost effective attenuation tool in those environments where surface runoff occurs, flow convergence is minimal and alternative attenuation tools are not available.

The trials have provided valuable data on the frequency, quantity and quality of surface runoff from two grazed pasture sites in the Rotorua lakes area. The key recommendations are:

1. Surface runoff attenuation tools are important for the Rerewhakaaitu area where soils are dominated by low permeability Rotomahana muds and surface runoff comprises >35% of the rainfall during winter, increasing the risk of pollutant mobilisation.
2. Surface runoff attenuation tools are not so important for Kaharoa Ash soils where soils are more permeable and surface runoff is a minor component of the total water balance.
3. Grass filter strips need to be actively maintained to retain a dense sward near the ground surface and maintain the desired species.
4. Prior to filter strips being adopted at a site the following issues should be considered:
    - the importance of surface runoff as a pollutant transporter;
    - the timing of surface runoff generation relative to the vigour of filter species;
    - landscape suitability for GFS (e.g., evidence of flow convergence); and
    - the practicality and performance of GFS *versus* other surface runoff attenuation tools (e.g., ponds, dams, wetlands, and sediment traps).

1. Introduction

1.1 Background

Several lakes within the Rotorua district have degraded water quality, mainly as a result of nutrient enrichment and faecal contamination. Environment Bay of Plenty requires information on the quality of surface runoff in the Rotorua district and the performance of BMPs. A wide range of BMPs are being explored to reduce the loading of nutrients and faecal microbes from farms so as to improve lake condition. As surface runoff moves over the soil surface it mobilises sediment, nutrients and faecal microbes. Contamination of runoff will depend on several key factors –fertiliser history, grazing history, amount of groundcover, slope, soils and climate. Grass filter strips (GFS) are a potential best management practice (BMP) designed to intercept surface runoff. This report contains the results from two trials, one established with NIWA Capability Funds and the other funded by Environment Bay of Plenty.

1.2 Filter strips

Filter strips can remove sediment and pollutants bound to the surface of the sediment from surface runoff. The key removal processes include deposition, physical filtering, and infiltration. In addition, some dissolved pollutants, colloids and clays may be removed from surface runoff by binding to the filter strip soil and vegetation surfaces (Dosskey 2001). Nutrient and sediment generation may also be reduced within retired filter strips due to the cessation of cropping or grazing (e.g., Moorby and Cook, 1992).

The majority of research on GFS comes from cropped land where they can be an effective water quality tool, significantly reducing sediment loads and concentrations in surface runoff (Dosskey 2001). Filter strips have been tested on land draining pasture, either with or without manure or effluent additions. Typically between 40 and 80% of the SS load is retained, but the variability in performance is large (e.g., (Magette et al. 1989; Schellinger & Clausen 1992; Smith 1989). Nutrients can also be removed from surface runoff, but the nutrient form will affect removal. Removal of particulate or sediment-associated nutrients from surface runoff is generally lower than that of sediment (e.g., Magette et al. 1989; Smith 1989). Significant amounts of particulate P can be removed from surface runoff if it is associated with large particles with short settling times, but if P is moving with clay particles or colloids then longer settling times are required. Dissolved pollutants transported by surface runoff (e.g., nitrate, FRP) are generally reduced the least. Filter strips may also be useful for reducing faecal microbe concentrations, although load and concentration reductions can vary between 0 and 99% and efficacy decreases with increasing flow (Collins et al. 2004; Tate et al. 2006; Tate et al. 2004).

Grass filter strips have been trialled on pasture in New Zealand. Smith (1989) established retired pasture filter strips on a Waikato drystock farm and monitored them for two years. Flow-weighted mean concentrations were reduced by between 40 and 50% for most parameters. Smith (1989) does not include data on infiltration of surface runoff, and suggests that the high trapping of dissolved nutrients (e.g., NO_3-N) was probably due to a reduced supply of nutrients within the retired strips. Collins et al. (2004) conducted a series of rainfall simulator experiments (40 minute duration) to evaluate the ability of filter strips to retain faecal microbes from effluent and concluded that trapping was a function of flow rate. Under high flow rates (13 l/min) trapping varied between 0-85%, while at low flow rates (4 l/min) trapping was much greater (>95%). The grass filter strips were a temporary store for some of the microbes trapped - they were mobilised and washed out of the filter strip in a subsequent event, 5 days later.

Maximum pollutant trapping by GFS can be expected when surface runoff is uniformly dispersed across the strip and the top edge of the filter strip should follow the elevation contour. GFS are typically located in riparian areas, however, surface runoff entering riparian areas is unlikely to be dispersed, sheet flow. As water moves downslope, surface runoff tends to converge into small channels which can bypass or locally inundate riparian filter strips (Dillaha et al. 1989).

Ideally, GFS should intercept contaminants before channelisation occurs. This study has trialled GFS at alternative, mid-slope, locations in the landscape. The potential advantages of this location are the close proximity of the GFS to pollutant sources and little or no opportunity for flow convergence, providing conditions suitable for high pollutant removal. In these positions there may be no need for GFS to be permanently fenced, so at times of low runoff risk the GFS could be grazed. Additionally, harvesting vegetation from filter strips could reduce the chances of nutrient saturation and weed invasion. However, on pasture susceptible to pugging and compaction, the soil structure under permanent contour GFS may improve and increase opportunities for runoff to infiltrate into the soil.

1.3 Objectives

This study investigates the potential of contour GFS to reduce yields of sediment, nutrients and faecal microbes in surface runoff generated by natural rainfall on intensively grazed pasture. Specific research questions are:

1. What volumes of surface runoff are generated on grazed pasture and under what conditions?

2. What is the water quality of surface runoff from grazed pasture?

3. How effective are contour GFS under field conditions?

4. Are stiff-stemmed phalaris GFS more effective at improving surface runoff water quality than retired pasture grass GFS?

2. Study sites

Contour GFS were established on a dairy farm in the Lake Rerewhakaaitu catchment, and a drystock farm near Kaharoa (Figure 1).

The Pacey property is a 110 ha dairy farm adjacent to Lake Rerewhakaaitu. The soils are Rotomahana Mud (Tephric Recent Soil), which typically has a high clay content, poor internal drainage, high nutrient status and is susceptible to cracking, drought, erosion, and pugging in winter (McIntosh et al. 2001). Reactive phosphate rock (RPR; Gafsa, 25 kg P/ha) and lime (Calcizest, 400 kg/ha) were applied to the farm in late Nov 2006. In May 2007 RPR was applied (26 kg P/ha) and in August 2007 25 kg N/ha was applied. Soil phosphorus as tested in September 2006 had an Olsen P of 43 mg/kg (target 20-30) and P retention of 36 mg/kg.

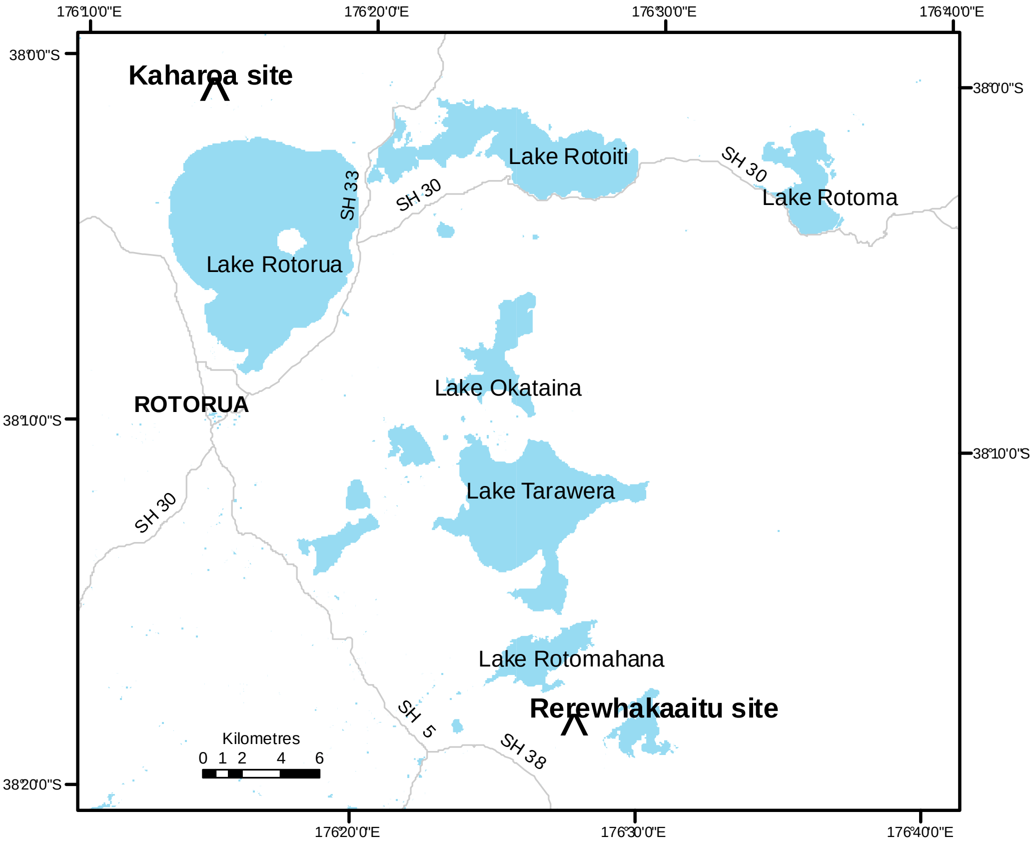


Figure 1: Field site locations.

The Russell property off Te Waerenga Rd is a mixed deer, sheep and beef farm which drains via an ephemeral flowpath (or floodway) directly to Lake Rotorua (Figure 1). The soils are Kaharoa Ash (Typic Orthic Podzol), which has a poor water holding capacity, low nutrient status and is droughty in summer. The Kaharoa site was fertilised in October 2007 with Pasturezeal G2, Sulphur gain and Muriate of potash (26 kg N/ha, 36 kg P/ha)

3. Experimental design and methods

3.1 Contour GFS

The experimental design incorporates three metre wide (perpendicular to the slope) retired pasture and phalaris *(Phalaris aquatica* cv. Maru*)* filter strips and adjacent controls on planar hillslopes (Figure 2). The controls were open to normal farm grazing practice and consequently had variable pasture cover throughout the trial.

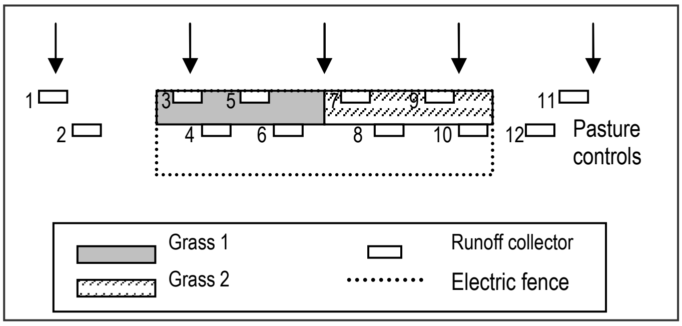


Figure 2: Schematic of the contour GFS experimental design (not to scale) with collectors numbered 1-12.

Phalaris (Harding grass or bulbous canary grass) was chosen for the trial as it is tall and stiff-stemmed with a dense sward suitable for trapping sediment. It is a perennial grass that has vigorous growth during autumn, winter and spring and is semi-dormant during summer. The phalaris was grown in a nursery until it had reached a height of 15 cm. It was planted as plugs and over-sown with ryegrass. At Rerewhakaaitu the retired pasture strip was a mixture of perennial ryegrass (*Lolium perenne*), white clover (*Trifolium repens*) and browntop (*Agrostis capillaris*). At Kaharoa the retired pasture GFS is a mixture of predominantly ryegrass and white clover, with yorkshire fog (*Holcus lanatus*), cocksfoot (*Dactylis glomerata*), browntop (*Agrostis capillaris*) and sweet vernal (*Anthoxanthum odoratum*).

At Rerewhakaaitu, runoff collectors were installed in the retired pasture GFS in May 2006 and monitoring of the GFS performance commenced in September 2006 when the grass had grown. Some water quality samples and runoff volumes were collected at the inflow of the rye grass filter at Rerewhakaaitu during July and August 2006, before the filter strips were established. These results are not included in the analysis. The site was closed in June 2008, 22 months later. At Kaharoa, monitoring started in December 2006 and ceased in June 2008 (19 months). The data logger was damaged by lightening in March 2008 and rainfall and runoff time series data are missing between 5 March 2008 and 16 April 2008.

The sites were surveyed in detail using a total station (Geodimeter 464). Digital elevation models were constructed in ArcGIS and the catchment areas estimated using the Spatial Analyst tools ‘Flow Direction’ and ‘Watershed’. The catchment areas draining to the inflow collectors are 160 m² and 170 m² for Kaharoa and Rerewhakaaitu, respectively (Figure 3, Figure 4). At Kaharoa the contributing area has slopes between 1 and 20%, with a flatter area at the top of the catchment grading into a zone of 5-10% slopes and then an area with 10-20% slopes near the runoff collectors (Figure 3). At Rerewhakaaitu the slope is mostly 10-20%, with the steepest zone being the 20 m upslope of the runoff collectors (Figure 4).

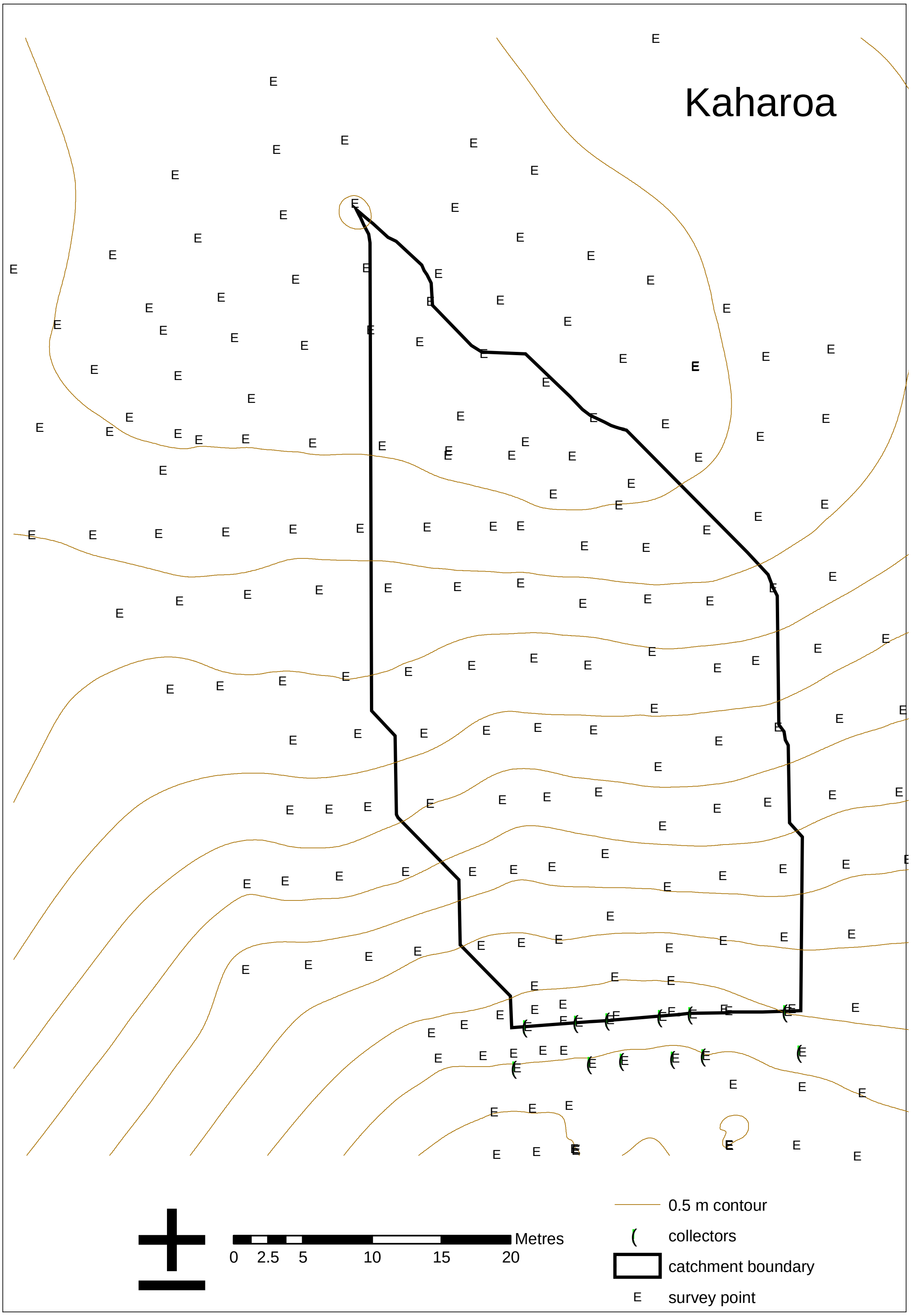


Figure 3: Catchment boundaries and 0.5 m contours at Kaharoa.

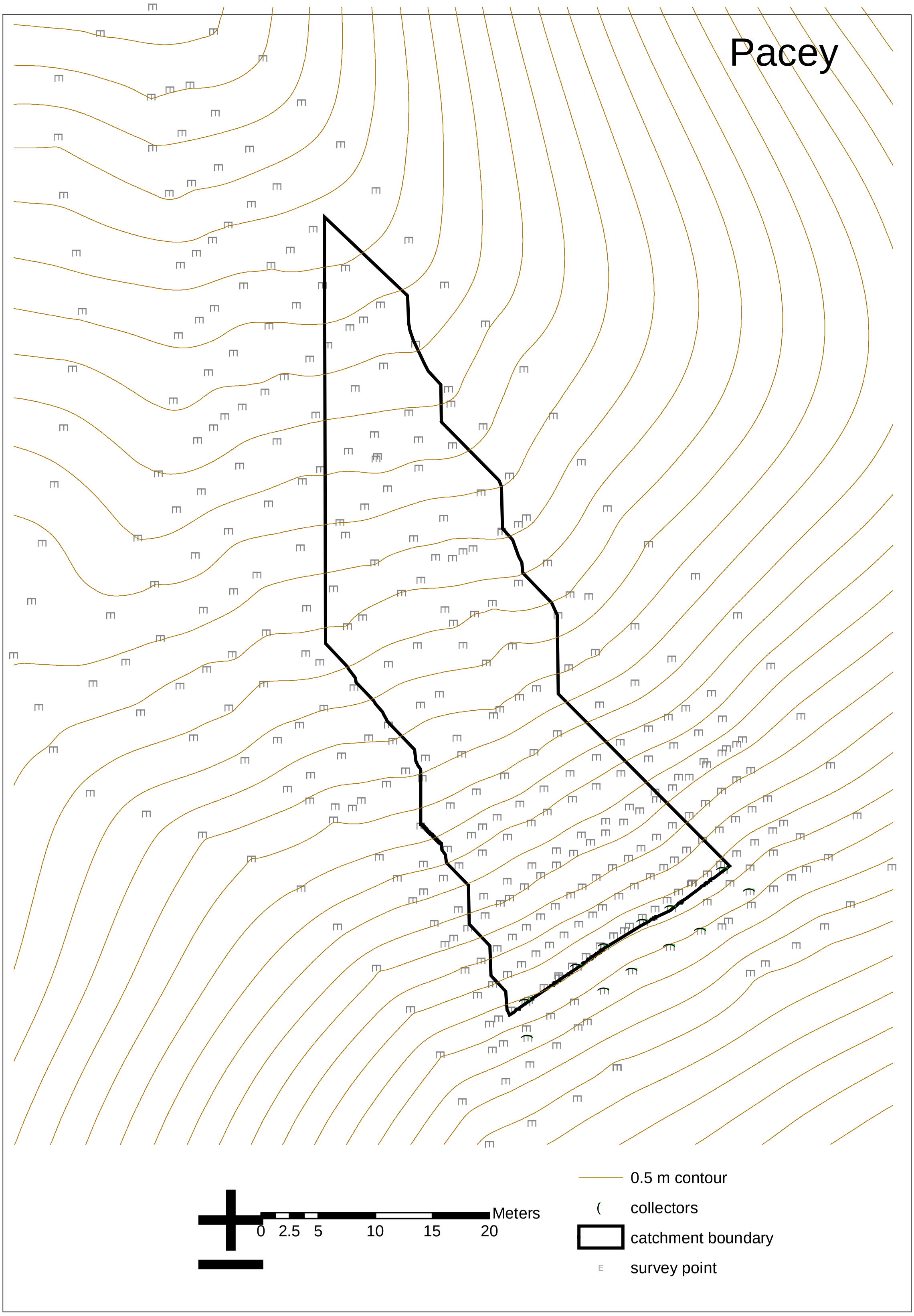


Figure 4: Catchment boundaries and 0.5 m contours at the Rerewhakaaitu site.

3.2 Water quality sampling and analysis

Twelve 30 cm wide surface runoff collectors were installed to capture runoff which is diverted to a 64 L storage trough (Figure 5). The surface runoff volumes in each trough were measured after a runoff event and a sample collected for analysis. During several of the larger events at Rerewhakaaitu the storage container capacities were exceeded. The runoff volumes, concentration data and load estimates for these events contain some uncertainty, particularly the nutrient data. We can reasonably assume that a large proportion of the SS remained in the sample containers. So while the SS concentrations and volume values contain uncertainty, the load estimates are probably reasonable. The nutrient loads for these events are likely to be underestimated.

Figure 5: Inflow (foreground) and outflow collectors on the Phalaris plot at Rerewhakaaitu (Lucy McKergow, 21 July 2007).

Surface runoff hydrographs were also measured by tipping bucket flow gauges (Unidata, 6506H) on two retired pasture collectors at each site (Figure 6).

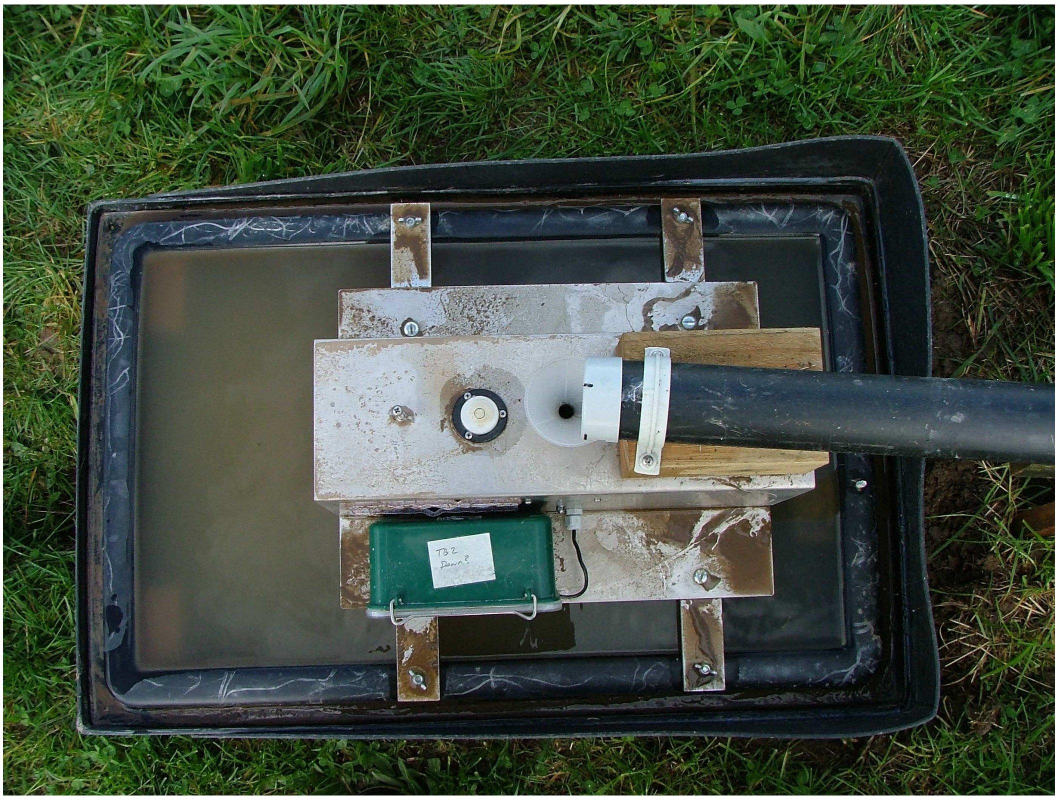


Figure 6: Tipping bucket flow gauge over runoff trough at Rerewhakaaitu (Graham Timpany, 30 July 2007).

Rainfall was measured on site by tipping bucket rain gauges (Ota 0.2 mm tip at Rerewhakaaitu and Unidata 6212 0.2 mm tip at Kaharoa) and daily rainfall records were also available from the farmers.

All samples were stored on ice and sent to NIWA's Chemistry Lab in Hamilton for analysis. Samples were analysed for, suspended sediment (SS), total nitrogen (TN), total phosphorus (TP) and a samples collected within 36 hours were analysed for *E. coli* and filterable reactive phosphorus (FRP). Table 1 summarises the analysis methods and detection limits.

Table 1: Water quality analysis methods.

Analyte	Method description	Units and detection limit	Method code
Suspended sediment (SS)	Gravimetric determination after filtration & drying at 104℃	0.5 mg/L	APHA 2540D
E. coli	IDEXX Laboratories Inc Colilert Test Kit	1 MPN/100mL	APHA 9223B
Total nitrogen (TN)	Persulphate digest, auto cadmium reduction, FIA	10 µg/L	Lachat
Total phosphorus (TP)	Acid persulphate digestion, molybdenum blue colorimetry	1 µg/L	NWASCO 38
Filterable reactive phosphorus (FRP)	filtered through 0.45 µm filter, FIA	1 µg/L	Lachat

Soil samples were collected at both sites from the retired pasture GFS and the pasture contributing areas on 20 June 2008. Soil samples were taken between a depth of 20 and 40 mm using rings 20 mm high and 50 mm diameter. Three sample rings were taped together and the bottom and top rings were cut away in the lab and the middle ring (20-40 mm below the surface) analysed. In the retired pasture the sampling locations were pre-selected by randomly generated coordinates on a grid pattern, while in the paddock samples were taken at pre-selected random points along a line. All cores were carefully carved into the soil following trimming of the grass to the ground surface. Cores were used for total porosity, macroporosity and bulk density determinations and analysis was conducted by NZ Labs in Hamilton. Pore-size distribution was measured using pressure plates (pores >60 and >30 µm at 10 kPa). All cores were saturated before measurement.

3.3 Data analysis

Various graphical and statistical methods are used to summarize data and facilitate comparisons between the sites and GFS treatments. Boxplots are used to show the distribution of the concentration or soil structure data in a format that allows for easy comparison. Non-parametric statistics are used because of small outflow sample sizes and non-normal distributions. The statistical analyses used include basic descriptive statistics and Kruskal-Wallis and Kolmogorov-Smirnov tests. All statistical analysis was conducted using SYSTAT version 11. Exploratory data analysis included inspections for normality. For each parameter a Kruskal Wallis One Way ANOVA on Ranks was used to detect differing distributions between inflow and outflow samples.

If the distributions were significantly different a Kolmogorov-Smirnov Two Sample Test (K-S) was used to identify differing pairs.

To assess the overall importance of surface runoff as a pollutant source and transport pathway the exports entering the trial (all inflow collectors, kg/ha) and the surface runoff (mm) were calculated. There are six inflow collectors with a total sampling width of 1.8 m. At Rerewhakaaitu the total trial width is 23.4 m, so the measured loads were scaled by a factor of 13 and then converted to kg/ha. At Kaharoa the total trial width is 21 m, so the measured loads were scaled by a factor of 11.7.

Filter strip effectiveness can be evaluated using either pollutant concentrations or loads and trapping efficiencies can be reported for either individual events or entire monitoring periods. Filters can be sinks for pollutants when the data shows a: (i) decrease in the average signal, (ii) decrease in the range, or (iii) decrease in the maximum (Viaud et al. 2004). Effectiveness analysis compares the combined inflow dataset with combined outflow samples from the pairs of control and GFS collectors. In this paper, load reductions on individual events are not examined; however, the variability in trapping between events can be large, with larger proportions of the incoming load trapped in smaller events. Load reductions were calculated and then assessed relative to the controls. During many smaller events no outflow samples were collected, presumably due to infiltration between collector pairs. The total loads analysis includes the inflowing data for these events.

4. Results

4.1 Soil structure

At Rerewhakaaitu all three soil structure indices show an improvement in soil structure with 2 years of pasture retirement. The macroporosity of the paddock samples ranged between 3 and 22 % (Figure 7), with a median of 12 %, just above the critical threshold for pasture growth (10%). In contrast, in the retired GFS macroporosity values were all above 10%, with a median of 19%. The median total porosities were 64 and 60% for the retired GFS and paddock, respectively. The soil bulk densities were higher in the paddock, with a median of 0.94 g/m³ compared to 0.84 g/m³ in the retired pasture GFS (Figure 7).

At Kaharoa there were no statistical differences between the structure indices between the paddock and retired GFS. The paddock macroporosity range was smaller than the retired pasture GFS range (Figure 7). The median total porosities were 73 and 72% for the retired GFS and paddock, respectively. The soil bulk densities were low, reflecting the porous nature of the soil, with medians of 0.66 g/m³ in the paddock and 0.62 g/m³ in the retired pasture GFS.

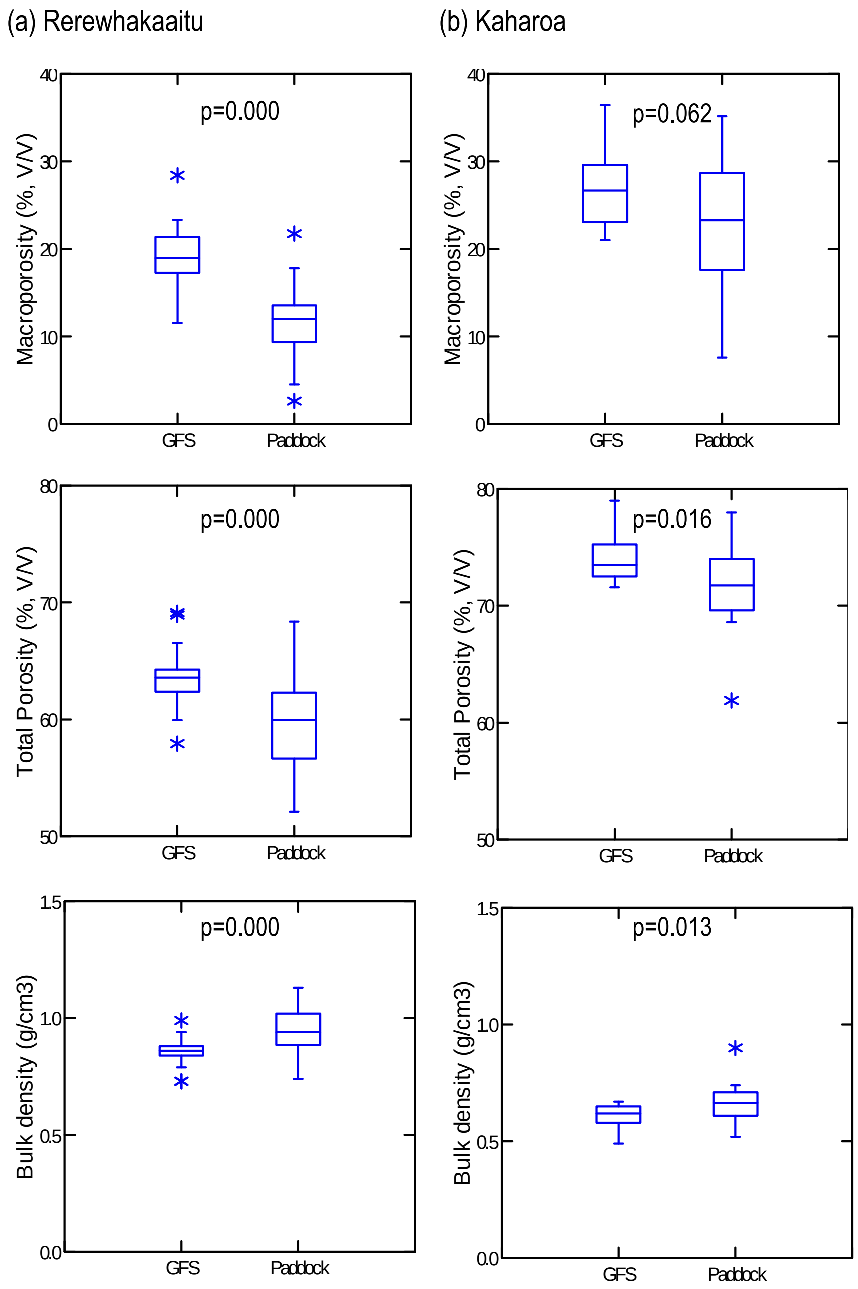


Figure 7: Boxplots of soil structure results for (a) Rerewhakaaitu and (b) Kaharoa. Box represents the median with 25th and 75th percentiles, whiskers are the appropriate quartile ± 1.5 x IQR and outliers are shown as stars. p-values ≤ 0.05 indicate a statistically significant difference between the distributions (Mann Whitney test).

4.2 Hydrology

The mean annual rainfall at Rerewhakaaitu (station B86242, 1977-2002) is 1345 mm, with average winter (June-August) rainfalls over 130 mm/month. The annual totals during the monitoring period were below average; in 2006 the farm rain gauge recorded 1250 mm and in 2007 the total was 1045 mm. Daily totals were generally less than 25 mm, with the exception of 8 events between the end of March and mid August 07 (Figure 8). The maximum rainfall intensities recorded (to the end of 2007) were: 5 mm/5 min, 8 mm/10 min, 11 mm/30 min and 15 mm/1 hr.

At Kaharoa the annual rainfall is around 1900 mm (station B86033, 1975-2007 1920 mm/y, station B86011, 1966-2005, 1826 mm/y). The 2007 annual total was 1947 mm. Fourteen daily totals were ≥50 mm (Figure 9) and the maximum rainfall intensities recorded during 2007 were: 5.4 mm/5 min, 10 mm/10 min, 21.8 mm/ 30 min and 30.4 mm/1 hr.

Surface runoff was generated on 37 days at Rerewhakaaitu (as recorded by tipping bucket on trough 7), but 19 of these days had only traces of runoff (<1L; Figure 8). Runoff was recorded on 15 days at Kaharoa, with volumes >1 L on 10 days (Figure 9). At Rerewhakaaitu more than 100 mm of runoff entered the trial over the monitoring period (Sep 06- June 08) and so at least 10% of rainfall becomes surface runoff. The runoff:rainfall ratio calculation is a minimum value because of the collectors overflowing. However, during 2007 most of the surface runoff occurred during the winter (mid July-mid August) and during this period at least 35% of rainfall became surface runoff (94 mm runoff, 266 mm rainfall).

Surface runoff was a smaller component of the water balance at Kaharoa. During 2007 the total runoff depth entering the trial was estimated as 94 mm and so the 2007 annual runoff:rainfall ratio was 0.06.

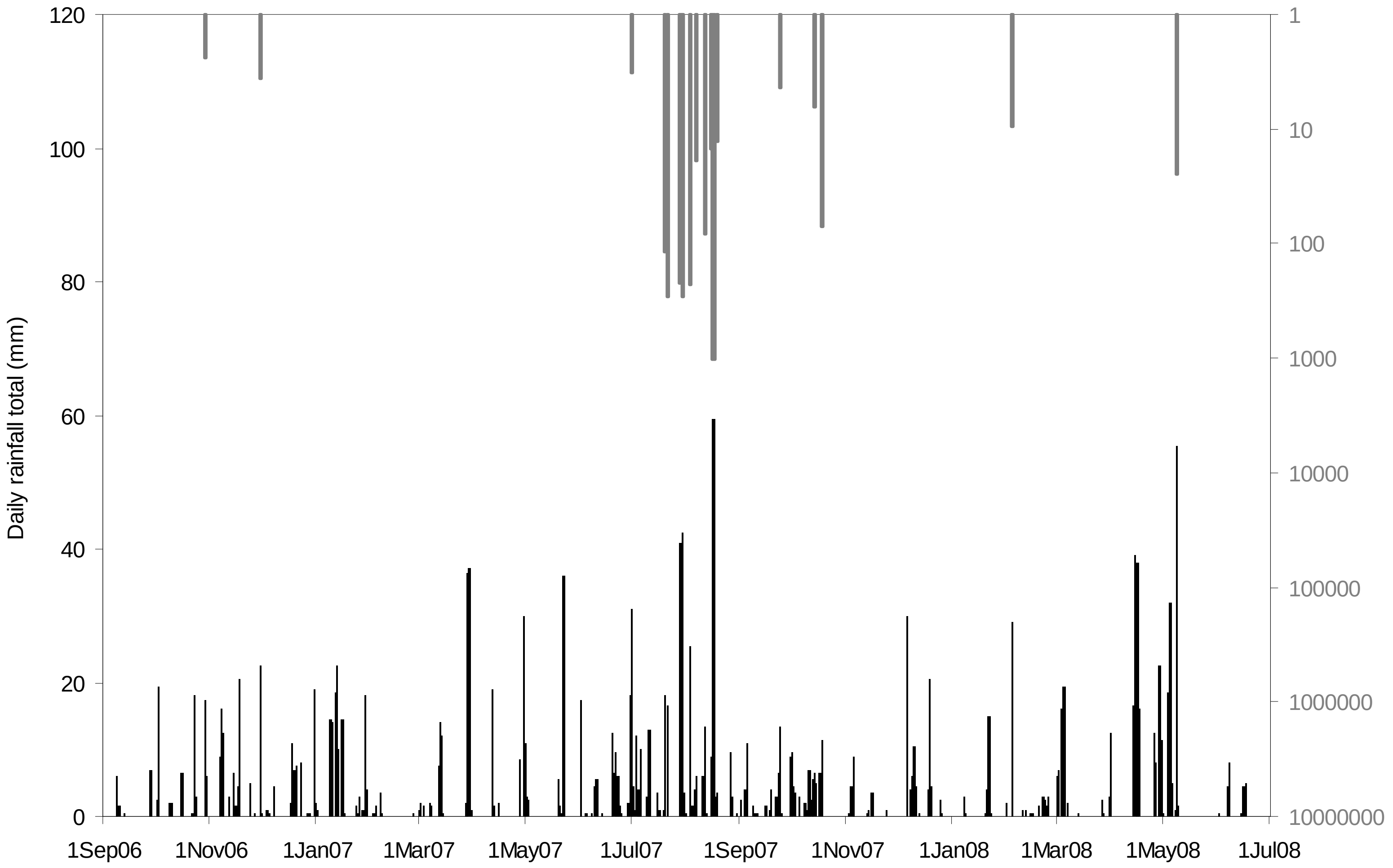


Figure 8: Daily rainfall totals and runoff totals (note reversed axis numbering and log scale) for the inflow ryegrass collector at Rerewhakaaitu (1 Sep 2006-19 June 2008).

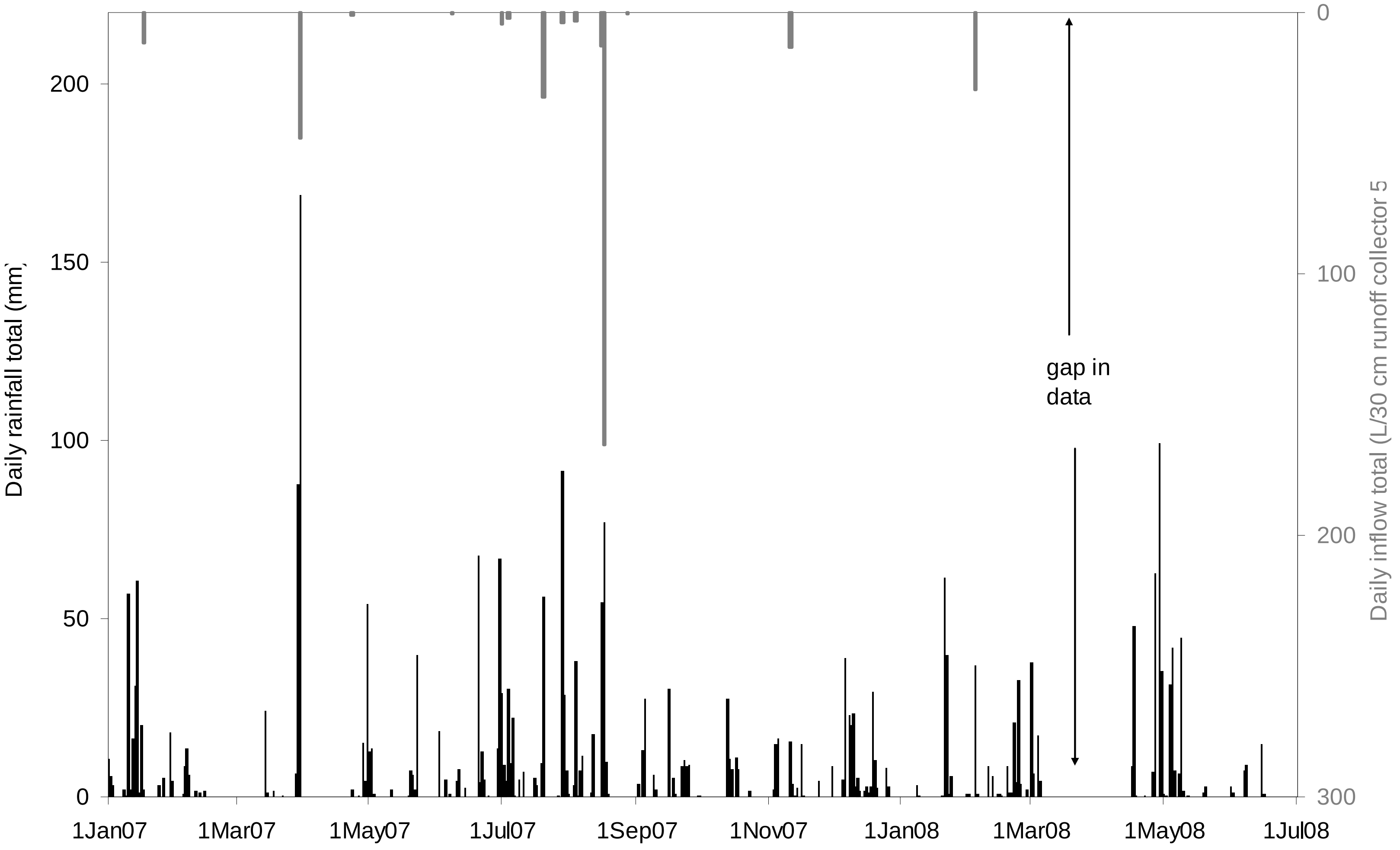


Figure 9: Daily rainfall totals and runoff totals (note reversed axis numbering) for the inflow ryegrass collector at Kaharoa (1 Jan 2007-19 June 2008).

One event at Rerewhakaaitu (17 Aug 07) resulted in 1030 L passing through the inflow tipping bucket in a 24 hour period. Other events generated less surface runoff, with seven events over 70 L/d and the remainder less than 20 L/d. At Kaharoa three events generated more than 30 L/d, with the largest generating 165 L/d. The remaining eight events resulted in a small amount of surface runoff (< 15 L/d) at the tipping bucket.

At Rerewhakaaitu almost all of the inflowing surface runoff recorded at trough 7 (96%) was generated between 20 July and 19 August 2007 (Figure 8). The paddock was grazed between 13 and 17 July and on July 30 the pasture was 50 mm high. Daily rainfall totals in excess of 6 mm all generated surface runoff. Rainfall intensities generating surface runoff were variable, for example, during the first event on 4 August (14 mm) the max 5 min rainfall intensity was 0.5 mm/5 min and 63 L of runoff was measured at trough 7 (Figure 10). The second event (11.5 mm) had marginally higher intensities (1.5 mm/5 min) and 160 L of runoff was measured.

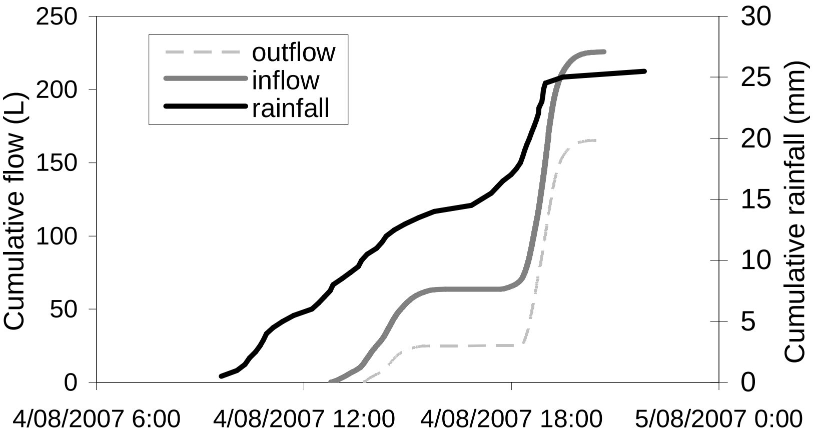


Figure 10: Cumulative rainfall and runoff for trough 7 at Rerewhakaaitu on 4 August 2007.

4.3 Hillslope runoff quality and loads

Suspended sediment concentrations were higher at Rerewhakaaitu (median 430 mg/L) than Kaharoa (median 129 mg/L). Median TN concentrations were the same at both sites and the TN concentration ranges were similar. Total P concentrations were higher at Kaharoa, between 835 and 62400 μg/L (Table 2). Phosphorus transport is dominated by particulate P (particles > 0.45 μm, 90%) at Rerewhakaaitu, while at Kaharoa the particulate fraction ranges from 7-92% (Table 2).

E. coli concentrations were high at Kaharoa than Rerewhakaaitu, with a median concentration of 2.2×10^4 MPN/100 mL at Kaharoa (Table 2). High (10^4-10^6) *E. coli* concentrations were measured in surface runoff at Kaharoa on 31 March 07 and 5 and 17 August 07, during or after sheep had grazed the paddock.

Table 2 also contains summary statistics for the troughs at Rerewhakaaitu that did not overflow. The median concentrations are lower than for the entire dataset, but in the same ball park. Lower concentrations could be expected for these events as the runoff events were smaller (and did not cause the troughs to overflow).

The majority of the inflowing sediment and nutrient loads were measured during 2007 (Table 2) at both sites. The incoming loads for Rerewhakaaitu contain considerable uncertainty due to the underestimated runoff volumes and the actual loads are likely to be considerably higher.

Table 2: Summary statistics for all inflowing sample (control, rye and phalaris combined) concentrations and loads for the entire monitoring period and 2007.

		SS (mg/L)	***E. coli* (MPN/100 mL)**	**TN (µg/L)**	**TP (µg/L)**	**FRP (µg/L)**	**FRP:TP**
Rerewhakaaitu (All troughs)	N	40	22	40	40	20	20
	min	34.4	413	2350	69	73	0.018
	max	4090	1.4×10^{4}	29500	5950	577	0.515
	median	350	2654	5065	953	277	0.11
	load (kg/ha/22 months)	1414		10.5	2.3		
	2007 load (kg/ha/y)	1409		10.4	2.3		
Rerewhakaaitu (Troughs that did not overflow)	N	24	6	24	24	9	9
	min	34.4	413	2350	69	73	0.085
	max	2350	1.1×10^{4}	12200	4030	577	0.515
	median	271	1246	4315	830	325	0.150
	load (kg/ha/22 months)	279		2.3	0.5		
	2007 load (kg/ha/y)	274		2.3	0.5		
Kaharoa	N	53	34	52	52	45	45
	min	4.2	10	1500	798	119	0.07
	max	875	5.5×10^{6}	22400	62400	4900	0.92
	median	129	2.2×10^{4}	6330	1940	586	0.61
	load (kg/ha/19 months)	283		7.5	1.07		
	2007 load (kg/ha/y)	272		5.8	0.95		

4.4 GFS performance

The ryegrass GFS generally performed better than the planted phalaris GFS, reducing the concentrations by a greater amount (Figure 11, Figure 12). In addition, over time observations show that the phalaris was outcompeted by weeds and clover.

At Kaharoa no significant statistical differences were detected between the combined inflows and control outflow concentrations (Figure 11b, Figure 12b). Both GFS reduced the median SS concentration by >80% compared to the combined inflow median. In addition the SS range was reduced and most of the outflow samples had concentrations less than 40 mg/L. There is no evidence that the GFS successfully reduced *E. coli* concentrations, although 50% of the ryegrass samples had concentrations less than 10000 MPN/100 mL. Rabbit diggings were observed in the phalaris GFS and may explain the increase in *E. coli* concentration. TN and TP median concentrations were reduced by 70% in the ryegrass GFS and 60% in the phalaris GFS, compared to the combined inflow median.

At Rerewhakaaitu median concentrations increased between the combined inflow and outflow for all pollutants, particularly *E. coli* (Figure 11a, Figure 12a). The median *E. coli* concentration increased 350% between the combined inflows and control outflow. This increase for the control is probably due to dung deposition on the unfenced control. While there is no statistical evidence of decreases in SS, TN or TP for the ryegrass GFS, the concentrations were typically lower (Figure 11a, Figure 12a).

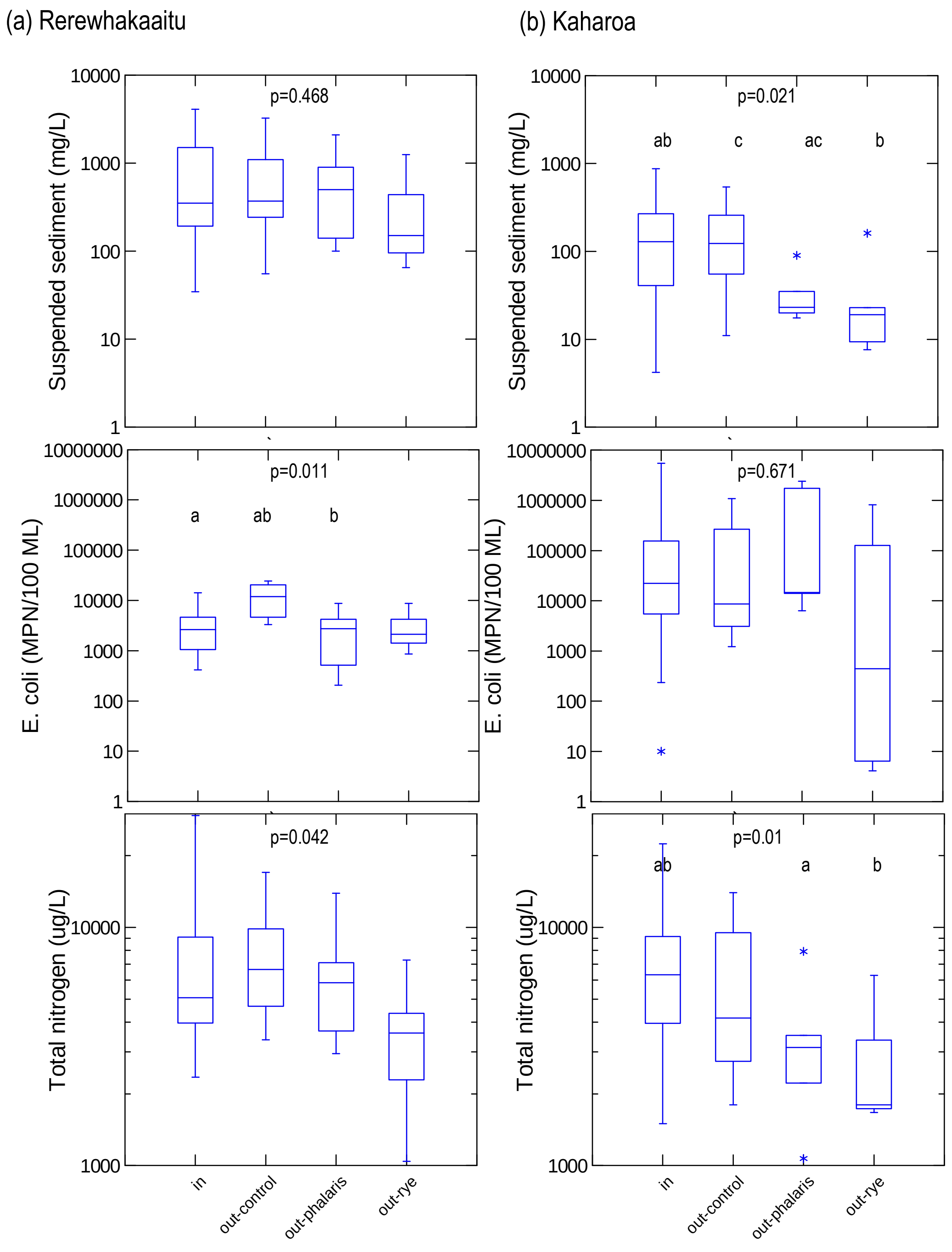


Figure 11: Boxplots of inflow and outflow surface runoff concentrations at (a) Rerewhakaaitu and (b) Kaharoa. Box represents the median with 25th and 75th percentiles, whiskers are the appropriate quartile ± 1.5 x IQR and outliers are shown as stars. p-values ≤ 0.05 indicate a statistically significant shift in the median of at least one group (Kruskal-Wallis) and where this occurred letters identify pairs of sites with significantly different distributions (Kolmogorov-Smirnov, $p \leq 0.05$).

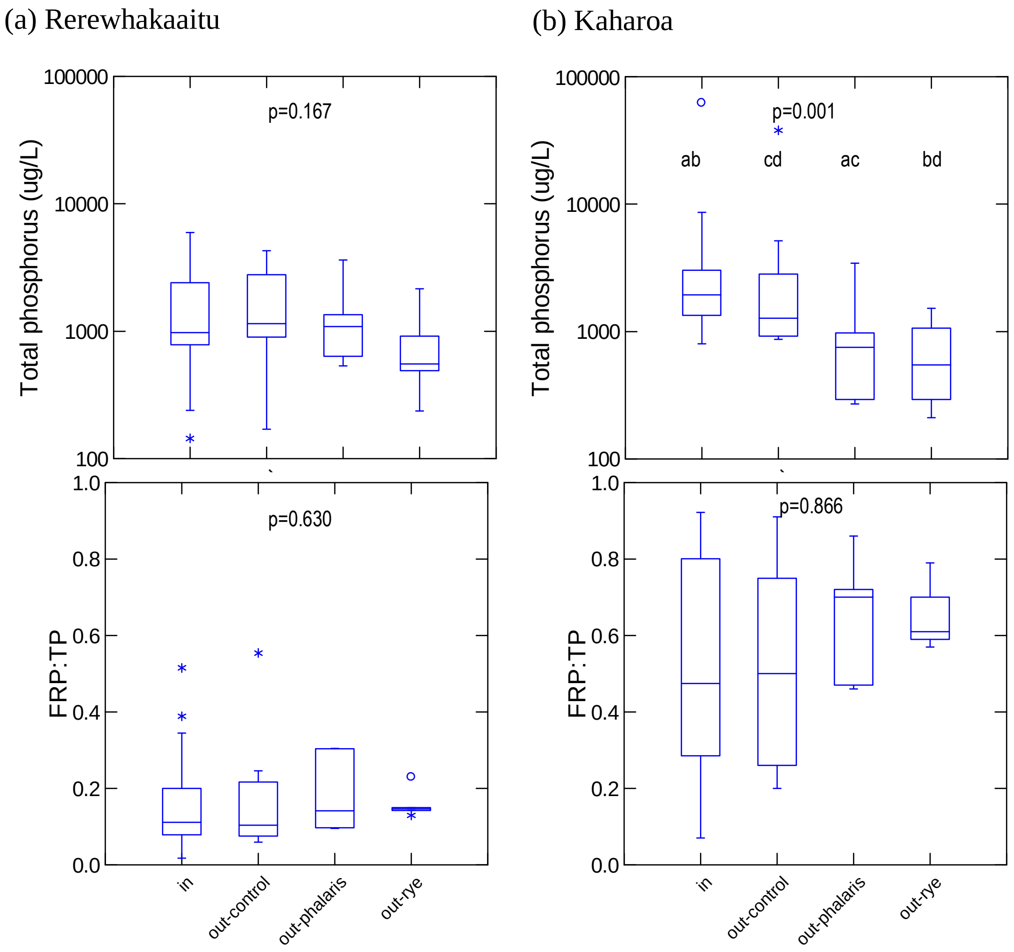


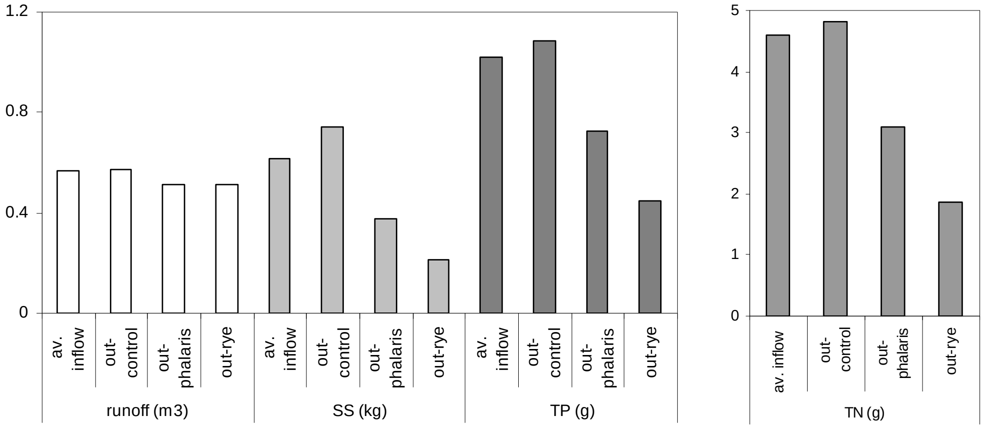
Figure 12: Boxplots of inflow and outflow phosphorus concentrations at (a) Rerewhakaaitu and (b) Kaharoa. Box represents the median with 25th and 75th percentiles, whiskers are the appropriate quartile ± 1.5 x IQR and outliers are shown as stars. p-values ≤ 0.05 indicate a statistically significant shift in the median of at least one group (Kruskal-Wallis) and where this occurred letters identify pairs of sites with significantly different distributions (Kolmogorov-Smirnov, $p \leq 0.05$).

Load reductions between the inflow and outflow collectors were highly variable between events so only total loads are presented (Figure 13). The general trend for SS, TN and TP at both sites are load reductions (from the average inflow load) by the GFS.

At Kaharoa total load reductions were less than 55% (relative to control), with larger reductions for SS (40% relative to control) and TN (54% relative to control) than TP (15% relative to control). Runoff volumes were reduced by around 70-80% in the GFS and 50% for the control. The 20-30% greater reduction in the GFS could be the result of improved soil structure without grazing.

At Rerewhakaaitu the control loads all increased from the average inflow load by between -5 and -20 %. Load reductions between the median average inflow collectors and GFS outflow collectors of SS, TN and TP at Rerewhakaaitu were in the order of 30 and 65%, although there is uncertainty in these figures due to the overflowing troughs. Given the fact that the control loads increased (negative trapping), the reductions relative to control were 35-87%. Given the small reductions in runoff volume (around 10% in both GFS), the trapping is likely to be dominated by concentration reductions.

(a) Rerewhakaaitu



(b) Kaharoa

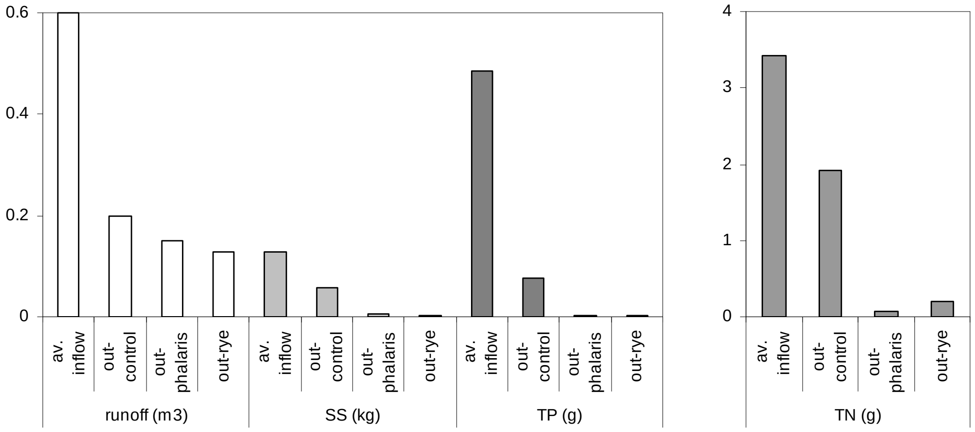


Figure 13: Total measured runoff (m^3), SS (kg), TP (g), and TN (g) average inflow (6 collectors / 3) and outflow loads for the control and GFS during the monitoring periods at (a) Rerewhakaaitu (22 months) and (b) Kaharoa (19 months).

5. Discussion

5.1 Hillslope runoff quality and loads

The concentration data collected in this study has similar nutrient concentrations to other New Zealand studies on surface runoff water quality from grazed systems. Previously measured TP concentrations in surface runoff range between 0.2 to 18 mg/L (Table 3), while total Kjeldahl N concentrations range between 0.03 to 1100 mg/L. The maximum concentrations measured in this study are well within this range (Table 2). Grazing, accompanied by treading damage can increase total nitrogen (TN) and total phosphorus (TP) losses in surface runoff. For example, Nguyen et al. (1998) measured 89% increases in TN losses and >94 % increase in TP losses from heavily grazed steep land at Whatawhata, Waikato, compared with undamaged areas, largely due to increased suspended sediment mobility.

Table 3: Measured surface runoff SS, N and P concentrations for a range of NZ farming types and climates.

Reference	Location/stock/terrain/soil	Parameter	Concentration range (mg/L)	Load (kg/ha/y)
Smith & Monaghan 2003	Southland, dairy, flat, silt loam	NO_3-N	0-12	
		NH_4-N	0-12	
		TP	0.5-6	max 0.23
		FRP	0.5-3	
Monaghan (unpublished data cited in Monaghan et al. 2007)	Dairy, pallic soil	FRP:TP ratio	0.45	0.42
Cooke 1988; Cooke & Cooper 1988	Waikato, drystock, rolling-moderately steep, silt loam over gleyed silt clay loam	NO_3-N	0.01-9.2	
		TKN	0.83-151	
		TP	0.35-18	
		TFP[a]	0.13-16.7	
		FRP	0.05-15.7	
Sharpley & Syers 1979	Palmerston North, dairy, flat-rolling, 40-50 m^2 plots	TP		0.31
		SS		1220
McColl & Gibson 1979	Hutt Valley, sheep, steep, silt loam, approx 40 m^2 unbounded plots	TP	0.2-30[b]	0.11
		TKN	0.2-1100 [b]	0.59
		TSS	35-6000 [b]	

[a] TFP = total filterable phosphorus or total dissolved P (TDP)
[b] Estimated from Figure 1 McColl & Gibson, 1979b

Estimated nutrient loads in this study are higher than those measured in previous New Zealand surface runoff studies, where nutrient losses from undrained grazed pastures without effluent irrigation have been estimated to be in the range of 0.1 to 0.3 kg P/ha/y and up to 0.6 kg TKN/ha/y. The 2007 loads entering both trials are an order of magnitude higher than those reported in Table 3. Sediment loads entering the Rerewhakaaitu site are similar (although they may be underestimates) to the 1200 kg TSS/ha/yr (Table 3) measured by Sharpley and Syers (1979) on grazed dairy pasture. The 2007 total SS loads entering the trial at Kaharoa are significantly lower (270 kg/ha/y), probably due to the lower runoff volumes and coarser textured soils. Loads estimated in this study must be used with caution, because (i) there is uncertainty in some of the runoff volumes and concentrations due to overflowing troughs and consequently the inflowing loads at Rerewhakaaitu are likely to be underestimates and (ii) they are dependent on the measurement scale and location (Beven et al. 2005). At smaller scales exports can be significantly higher than those actually delivered to channels, due to intermediate storages and transformations along the delivery pathway.

Stream *E. coli* concentrations dominate the New Zealand literature, with limited studies of faecal pathogens in surface runoff. This study shows that runoff from sheep and beef grazed pasture can have similar or higher *E. coli* concentrations than grazed dairy pasture (in the absence of effluent irrigation). The *E. coli* concentrations measured in this study are similar to those previously reported for surface runoff from grazed pasture. For example, Collins et al. (2005) used a rainfall simulator to generate surface runoff on steep sheep grazed pasture in the Waikato and measured peak concentrations between 10^3 and 10^7 MPN/100 mL, equating to 10^5 to 10^8 *E. coli* per m^2 of hillside. We measured the highest *E. coli* concentration at Kaharoa during or shortly after sheep grazing. This is consistent with the study of Collins et al. 9205) who found that *E. coli* concentrations in surface runoff from sheep grazed hill country pasture decreased with time since grazing. This suggests that the risk of *E. coli* transport by surface runoff is likely to vary widely, depending on the co-incidence of rainfall and grazing.

5.2 GFS performance and water quality mitigation

The ryegrass GFS generally performed better at retaining pollutants than the planted phalaris GFS at both sites. Possible explanations include the clumpy nature of the transplanted phalaris allowing channels to form, together with the soil disturbance cause by transplanting. At Rerewhakaaitu the phalaris GFS was cultivated prior to transplanting of the plants, but the similar inflow and outflow runoff volumes suggest that this did not increase the infiltration capacity of the soil significantly compared with the retired pasture GFS. Over the longer term the phalaris did not manage to retain its vigour and weeds and clover were able to out-compete the grass.

The porosity and bulk density results for Rerewhakaaitu suggest that the soil structure improved in the retired pasture GFS during the monitoring period. Over time, with further improvement in soil structure, infiltration of surface runoff might become an important GFS function.

Data from this study suggests that natural event durations may reduce the ability of GFS to retain and inactivate *E. coli*. Collins et al. (2004) demonstrated that grass filter strips could be useful for trapping *E. coli* at low flow rates (<4 L/min) on 10-15 degree slopes. Flow rates in this study were up to 3.25 L/min, but most events were long duration or events were closely spaced in time allowing limited intervals for natural inactivation of faecal microbes.

6. Recommendations

Recommendation 1: Surface runoff attenuation tools have potential for the Rerewhakaaitu area/ Rotomahana muds.

At Rerewhakaaitu >9% of the annual rainfall total becomes surface runoff, but during the winter >35% of rainfall can become surface runoff. During the winter months, particularly July and August, any BMP that treats surface runoff and can cope with large volumes would therefore be beneficial. The seasonal nature of runoff means that any contour GFS retired from grazing may be under-utilised for 10 months of the year. However, there are clearly soil structure benefits with retirement of pasture from grazing. While there is no evidence that the improved soil porosity increased infiltration during the trial, with continued retirement this may occur.

While the contour GFS have shown potential at Rerewhakaaitu, the limited or seasonal occurrence of surface runoff may undermine the return from permanently retiring pasture for this purpose. An alternative option is to temporarily retire GFS on a seasonal basis. This would be advised well before the soil moisture levels make the soil structure more susceptible to treading damage. For example, temporary contour GFS could be retired during April at Rerewhakaaitu and maintained until October.

Alternative attenuation tools, such as ponds, sediment filters and wetlands, could have greater potential to improve surface runoff water quality on these soils, and may prove to be a cheaper option or provide additional benefits such as biodiversity value and landscape aesthetics (see McKergow et al. 2008). These alternative attenuation tools may also be able to more permanently retain pollutants, particularly sediment. In contrast, pollutants trapped by GFS may be re-mobilised in successive events.

Recommendation 2: Surface water quality attenuation tools are NOT likely to be useful for Kaharoa Ash soils.

At Kaharoa only 6% of the rainfall becomes surface runoff and the soils are highly porous so surface runoff probably does not occur frequently enough to justify the retirement of pasture from grazing. Any surface runoff that is generated is likely to infiltrate downslope, particularly where the topography flattens out or very porous soils are present reducing the potential for surface runoff to reach waterways. Widespread surface runoff was evident on 7 August 2006, prior to the trial commencing. Flattened grass showed that the runoff entered ephemeral channels rather than remaining dispersed across the entire landscape.

Recommendation 3: Grass filter strips need to be actively maintained to retain a dense sward near the ground surface and maintain the desired species.

During the summer months the grass filter strips required active maintenance and the grass was cut back to less than 10 cm every 5-8 weeks to help maintain a dense sward close to the ground. The cut grass was removed from the filter strips by raking. During the 5-8 weeks between cutting the grass grew to heights of up to 45 cm. Clover growth was also noted at both sites, particularly during the summer.

Recommendation 4: Process for evaluating the potential of filter strips

In order to maximise the water quality benefits from grass filter strips at a specific site the following steps should be taken:

1. Evaluate the importance of surface runoff as a pollutant transporter. If surface runoff is not an important flowpath, then source control and attenuation tools that address the main flowpaths should be evaluated.

2. Consider the timing of surface runoff generation, for example, seasonality. If surface runoff is only generated during the winter, then permanent retirement of pasture from grazing may be unnecessary and temporary GFS might be more appropriate.

3. Examine the landscape and assess the likelihood of flow convergence occurring. Once runoff concentrates into channels a large amount of the surface runoff is able to bypass the GFS. For example, Dosskey et al. (2002) modelled sediment removal by GFS on four farms and estimated removals in the range of 41-90% from paddock runoff for uniformly distributed runoff. However, because of topographically driven non-uniform runoff leading to channelised flow, only 15 to 43% would actually be removed. Other attenuation options that target flow convergence zones or channel may be more appropriate in these areas.

4. Compare the likely performance, fate of trapped pollutants, ease of application, maintenance requirements and cost of GFS with other surface runoff attenuation tools, such as wetlands, sediment traps, dams and ponds.

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8. Acknowledgements

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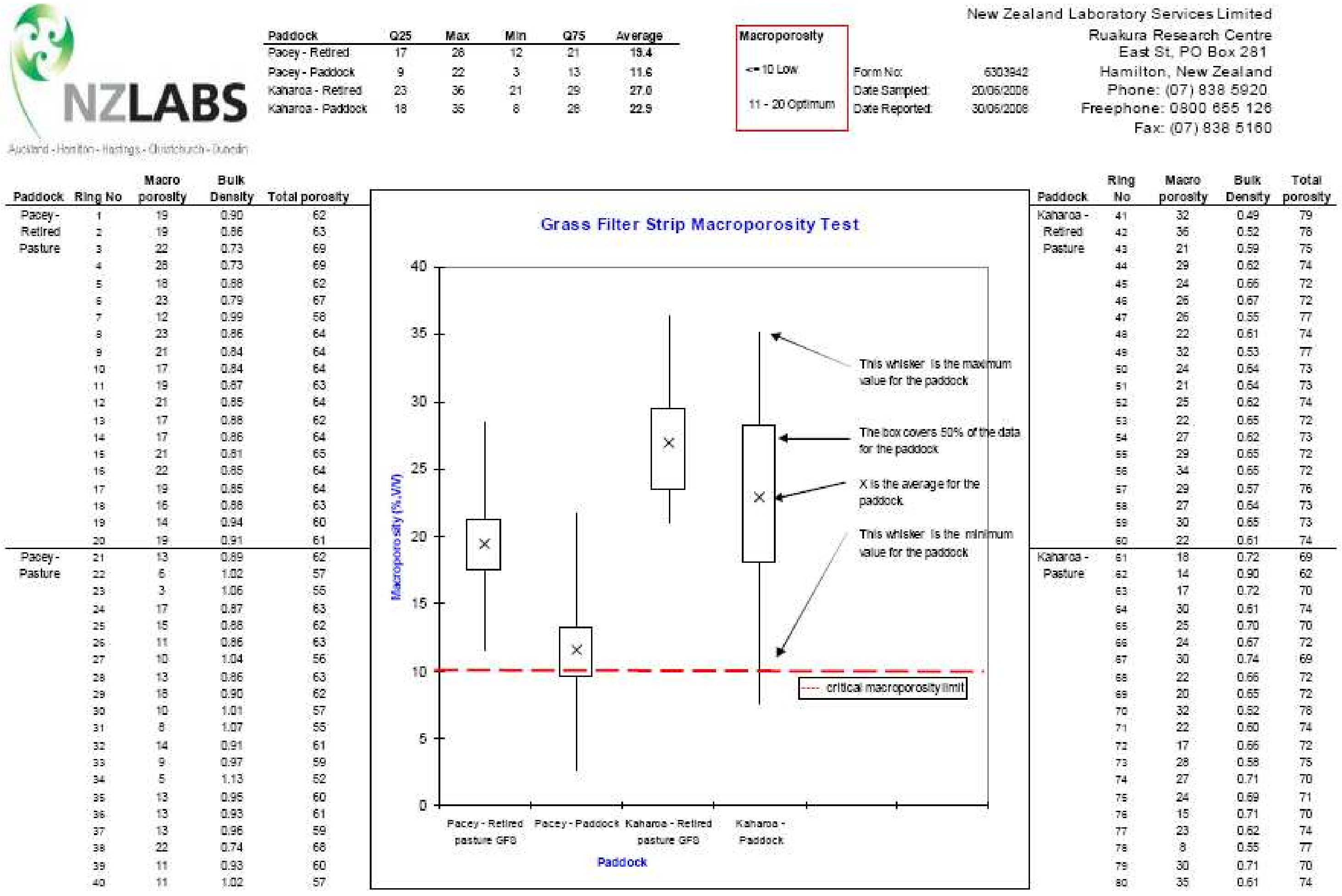
9. Appendix 1 – Kaharoa event water quality data (BOP07207)

Date collected	Trough	Strip	Location	Event number	Turb (NTU)	SS (g/m3)	TN (mg/m3)	TP (mg/m3)	Coliforms (MPN/100mL)	E. coli (MPN/100mL)	FRP (mg/m3)	TDP (mg/m3)	Trough depth (mm)	Runoff volume (L)	Trough overflow
17Jan07	5	rye	in	1	2.0	9.2	4500	1570	>2419.2	235.9	1400		55	12	
17Jan07	6	rye	out	1	2.2	7.6	1800	210	>2419.2	4.1	119		143	32	
17Jan07	7	phalaris	in	1	14.6	110	11600	5740	>24192	350	4900		20	3.7	
17Jan07	9	phalaris	in	1	5.2	47	8140	2940	>24192	2613	2710		35	7	
30Mar07	1	control	in	2	37.8	37	2320	1330	6131000	5.48E+06	1060		204	46.6	
30Mar07	2	control	out	2	8.1	11	1800	1060	>241920	1.55E+05	966		17	2.3	
30Mar07	3	rye	in	2	25.9	44	1500	1100	>241920	1.99E+05	836		119	25.9	
30Mar07	5	rye	in	2	25.3	27	1770	1020	>241920	1.99E+05	822		275	63.4	
30Mar07	6	rye	out	2	17.5	23	1670	739	1081000	8.13E+05	586		218	49.2	
30Mar07	7	phalaris	in	2	41.2	49	2360	1250	4884000	3.65E+06	950		273	63.7	
30Mar07	8	phalaris	out	2	27.6	35	3520	777	>2419200	2.42E+06	561		273	62.9	
30Mar07	9	phalaris	in	2	39.2	41	4480	1880	>2419200	1.99E+06	1620		273	61.7	
30Mar07	10	phalaris	out	2	19.7	22	2220	726	>2419200	1.73E+06	508		97	21.5	
30Mar07	11	control	in	2	46.6	45	3050	1830	3654000	3.08E+06	1470		42	9	
30Mar07	12	control	out	2	19.2	55	2320	885	1467000	1.08E+06	662		143	31.1	
30Jun07	5	rye	in	3		14.8			2046	10			15	2.6	
30Jun07	6	rye	out	3		9.4			3873	<10			30	6	
30Jun07	11	control	in	3		26.0	8670	3130	>241920	31300			10	1.5	
30Jun07	12	control	out	3		16.2	6650	1730	>241920	4800			20	2.7	
06Jul07	1	control	in	4		875	10400	6400					267	61.4	
06Jul07	3	rye	in	4		595	9930	4590					28	4.6	
06Jul07	5	rye	in	4		313	7980	3650					90	20.2	
06Jul07	7	phalaris	in	4		580	9560	6120					210	48.8	
06Jul07	9	phalaris	in	4		507	9840	7040					110	24.3	
06Jul07	11	control	in	4		765	11400	8630					57	12.6	
06Jul07	12	control	out	4		540	9510	5150					61	12.2	
13Jul07	11	control	in	5		428	11800	8580						0.3	
13Jul07	12	control	out	5		258	13900	4340					5	1.125	
20Jul07	1	control	in	6	135	428	9780	2370					275	63.3	
20Jul07	2	control	out	6	38.1	135	4160	1270					16	2.1	

Date collected	Trough	Strip	Location	Event number	Turb (NTU)	SS (g/m3)	TN (mg/m3)	TP (mg/m3)	Coliforms (MPN/100mL)	E. coli (MPN/100mL)	FRP (mg/m3)	TDP (mg/m3)	Trough depth (mm)	Runoff volume (L)	Trough overflow
20Jul07	3	rye	in	6	144	486	8940	2310					72	14.9	
20Jul07	5	rye	in	6	91.0	219	5200	1430					251	57.8	
20Jul07	6	rye	out	6	83.6	161	6280	1520					27	5.3	
20Jul07	7	phalaris	in	6	230	558	9640	2850					275	64.2	
20Jul07	8	phalaris	out	6	36.7	90	3130	972					17	3	
20Jul07	9	phalaris	in	6	131	322	6920	2190					172	38.5	
20Jul07	11	control	in	6	146	360	7220	2550					82	18.5	
20Jul07	12	control	out	6	127	342	7300	1930					142	30.9	
30Jul07	1	control	in	7		214	3950	1350	>24192	6488	250	299	270	62.1	
30Jul07	5	rye	in	7		145	3180	1120	>24192	3448	264	266	105	23.7	
30Jul07	7	phalaris	in	7		256	4450	1540	>24192	5475	215	257	262	61.1	
30Jul07	9	phalaris	in	7		262	5100	2000	>24192	1500	354	422	105	23.1	
30Jul07	11	control	in	7		171	5300	1520	>24192	9804	402	474	60	13.3	
30Jul07	12	control	out	7		109	2740	867	>24192	1211	172	210	226	50.3	
05Aug07	1	control	in	8		85	6760	2560	166400	8.82E+04	864	931	205	46.9	
05Aug07	5	rye	in	8		127	5810	1760	120100	4.72E+04	835	925	15	2.6	
05Aug07	7	phalaris	in	8		153	5240	1800	96000	7.71E+04	634	706	40	8.5	
05Aug07	9	phalaris	in	8		153	8550	2530	218700	7.94E+04	1140	1260	20	3.6	
05Aug07	11	control	in	8		127	8140	2100	41600	1.71E+04	666	747	10	1.5	
17Aug07	1	control	in	9		858	16700	3360	24300	8.40E+03	237		270	62.1	
17Aug07	2	control	out	9		109	2410	886	21100	2.00E+03	231		29	5.1	
17Aug07	3	rye	in	9		145	2030	835	35900	1.45E+04	249		196	43.9	
17Aug07	5	rye	in	9		129	2970	1010	41900	2.59E+04	298		276	63.7	
17Aug07	6	rye	out	9		19.0	916	406	47200	1.99E+04	247		159	35.6	
17Aug07	7	phalaris	in	9		268	6010	1360	21300	5.20E+03	223		272	63.5	
17Aug07	8	phalaris	out	9		24.4	912	293	32700	6.30E+03	139		270	62.2	
17Aug07	9	phalaris	in	9		123	3810	1090	39900	2.49E+04	345		274	62	
17Aug07	10	phalaris	out	9		17.5	1070	269	38400	1.46E+04	124		12	1.7	
17Aug07	11	control	in	9		182	4820	1570	71200	6.24E+04	434		139	31.9	
17Aug07	12	control	out	9		123	3160	1080	35000	8.60E+03	316		275	61.7	
14Jan08	1	control	in	10									169	38.4	

Date collected	Trough	Strip	Location	Event number	Turb (NTU)	SS (g/m3)	TN (mg/m3)	TP (mg/m3)	Coliforms (MPN/100mL)	E. coli (MPN/100mL)	FRP (mg/m3)	TDP (mg/m3)	Trough depth (mm)	Runoff volume (L)	Trough overflow
14Jan08	3	rye	in	10									20	2.7	
14Jan08	5	rye	in	10									122	27.6	
14Jan08	7	phalaris	in	10									201	46.6	
14Jan08	9	phalaris	in	10									170	38.1	
14Jan08	12	control	out	10									40	7.3	
22Feb08	1	control	in	11		4.2	7650	2480					40	8.1	
22Feb08	2	control	out	11		370	14000	38000					251	55.5	
22Feb08	3	rye	in	11		13	10200	3170					53	10.4	
22Feb08	5	rye	in	11		8	8280	3200					205	47.1	
22Feb08	7	phalaris	in	11		15	8550	2680					255	59.4	
22Feb08	9	phalaris	in	11		12	9370	2590					256	57.8	
22Feb08	11	control	in	11		210	22400	62400					50	10.9	
22Feb08	12	control	out	11		17	9750	2830					120	25.8	
16Apr08	1	control	in	12		78	2030	1070	>24192	15530.7	796		208	47.6	
16Apr08	3	rye	in	12		47	1920	798	>241920	155307	586		55	10.9	
16Apr08	5	rye	in	12		76	5740	1770	24191.7	17328.7	1340		91	20.4	
16Apr08	6	rye	out	12									5	0.2	
16Apr08	7	phalaris	in	12		30	2390	1190	>241920	241917	981		158	36.4	
16Apr08	8	phalaris	out	12		20	7920	3430	>24192	14136	2950		69	15.1	
16Apr08	9	phalaris	in	12		190	3950	1060	>241920	198628	889		107	23.6	
16Apr08	11	control	in	12		31	5200	832	>24192	19862.8	551		50	10.9	
16Apr08	12	control	out	12		170	3100	921	>2419200	461100	656		118	25.3	

10. Appendix 2 – Soil structure report



NZLABS

Auckland - Hamilton - Hastings - Christchurch - Dunedin

Paddock	Q25	Max	Min	Q75	Average
Pacey - Retired	17	28	12	21	19.4
Pacey - Paddock	9	22	3	13	11.6
Kaharoa - Retired	23	36	21	29	27.0
Kaharoa - Paddock	18	35	8	28	22.9

Macroporosity

<= 10 Low

11 - 20 Optimum

Form No:	6303942
Date Sampled:	20/06/2008
Date Reported:	30/06/2008

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Paddock	Ring No	Macro porosity	Bulk Density	Total porosity
Pacey - Retired Pasture	1	19	0.90	62
	2	19	0.86	63
	3	22	0.73	69
	4	28	0.73	69
	5	18	0.88	62
	6	23	0.79	67
	7	12	0.99	58
	8	23	0.86	64
	9	21	0.84	64
	10	17	0.84	64
	11	19	0.87	63
	12	21	0.85	64
	13	17	0.88	62
	14	17	0.86	64
	15	21	0.81	65
	16	22	0.85	64
	17	19	0.85	64
	18	16	0.88	63
	19	14	0.94	60
	20	19	0.91	61
Pacey - Pasture	21	13	0.89	62
	22	6	1.02	57
	23	3	1.06	55
	24	17	0.87	63
	25	15	0.88	62
	26	11	0.86	63
	27	10	1.04	56
	28	13	0.86	63
	29	16	0.90	62
	30	10	1.01	57
	31	8	1.07	55
	32	14	0.91	61
	33	9	0.97	59
	34	5	1.13	52
	35	13	0.95	60
	36	13	0.93	61
	37	13	0.96	59
	38	22	0.74	68
	39	11	0.93	60
	40	11	1.02	57
Kaharoa - Retired Pasture	41	32	0.49	79
	42	36	0.52	78
	43	21	0.59	75
	44	29	0.62	74
	45	24	0.66	72
	46	26	0.67	72
	47	26	0.55	77
	48	22	0.61	74
	49	32	0.53	77
	50	24	0.64	73
	51	21	0.64	73
	52	25	0.62	74
	53	22	0.65	72
	54	27	0.62	73
	55	29	0.65	72
	56	34	0.65	72
	57	29	0.57	76
	58	27	0.64	73
	59	30	0.65	73
	60	22	0.61	74
Kaharoa - Pasture	61	18	0.72	69
	62	14	0.90	62
	63	17	0.72	70
	64	30	0.61	74
	65	25	0.70	70
	66	24	0.67	72
	67	30	0.74	69
	68	22	0.66	72
	69	20	0.65	72
	70	32	0.52	78
	71	22	0.60	74
	72	17	0.66	72
	73	28	0.58	75
	74	27	0.71	70
	75	24	0.69	71
	76	15	0.71	70
	77	23	0.62	74
	78	8	0.55	77
	79	30	0.71	70
	80	35	0.61	74

Grass Filter Strip Macroporosity Test

This whisker is the maximum value for the paddock

The box covers 50% of the data for the paddock

X is the average for the paddock

This whisker is the minimum value for the paddock