ISSN 2463-6029 (Print)
ISSN 2350-3432 (Online)

Final report: Inflow monitoring of Lake Mangakaware and the Rotopiko lakes

2014

ERI Report Number 49

Client report prepared for Waikato Regional Council

By Grant Tempero and David Hamilton

Environmental Research Institute

Faculty of Science and Engineering

University of Waikato, Private Bag 3105

Hamilton 3240, New Zealand

Cite report as:

Tempero G, Hamilton DP, 2014. Final report: Inflow monitoring of the Rotopiko lakes and Lake Mangakaware. Client report prepared for Waikato Regional Council. *Environmental Research Institute Report No. 49*, The University of Waikato, Hamilton. 63 pp.

Cover: Rotopiko North (Photo: G Tempero).

Reviewed by:

Aroon Parshotam

Research Fellow

Environmental Research Institute

University of Waikato

Approved for release by

John Tyrrell

Research Manager

Environmental Research Institute

University of Waikato

Executive Summary

Farm drains flowing into the Rotopiko (Serpentine) North, Rotopiko South and Lake Mangakaware were monitored from April 2012 to April 2014. These drains included two tributaries to Rotopiko North (designated Rotopiko North 01 and 02), one tributary to Rotopiko South (designated Rotopiko South 02) and three tributaries to Lake Mangakaware (designated Mangakaware 01, 05 and 06). Surface-water grab samples were taken from each tributary at two-month intervals. Discharge was also measured on 13 separate occasions in each tributary. In June 2012, water-level loggers were installed in the Rotopiko South site and two of the Mangakaware sites. These readings were used together with direct-discharge measurements to provide continuous, instantaneous discharge. High-frequency sampling was also undertaken over 48 h on four separate occasions. Single point-discharge measurements and water quality samples were taken at the four sites up to 48 h following the start of rainfall. In addition, one of the four inflows was sampled automatically at 2-h intervals for up to 48 h. Both grab and automated water samples were analysed for total suspended solids (partitioned by volatile and non-volatile fractions), total nutrients (total nitrogen and total phosphorus) and dissolved inorganic nutrients (nitrate-N, ammonium-N and dissolved reactive phosphorus).

All inflows showed high variability in water discharge and composition, driven primarily by weather and partly by drain maintenance. Droughts in the summers of 2012–13 and 2013–14 resulted in standing water with no measureable discharge in most of the inflows. In some cases, the inflow channel dried completely and no water samples were collected. Discharge to Lake Mangakaware captured with the high-frequency sampling responded to intense rainfall events with a 4–-6 h lag. Changes in drains due to plant growth and maintenance activities made it difficult to interpret some of the temporal responses of drains to rainfall. Drains became increasingly clogged with aquatic weeds and filamentous algae over summer.

Periods of elevated discharge were characterised by increases in particulate phosphorus and suspended solids concentrations in all drains. It is surmised that much of the phosphorus transported into drains (and subsequently to the lake ecosystems) is derived from sediment erosion from the agricultural landscape. Management of losses of sediment from these agricultural landscapes may have an important influence on the rate of growth of aquatic plants and also the trophic state and rates of sedimentation in the receiving lake environment. We observed different responses of Mangakaware 05 and 06 sites in high-frequency measurements of storm events. Concentrations of suspended solids increased rapidly in Mangakaware 05 at the onset of increased discharge; suggesting a nearby source of sediment. The Mangakaware 06 storm event was much smaller (29.6 mm) than the event monitored at Mangakaware 05 (58.5 mm) and increases in suspended solids concentrations tended to more closely align with increases in discharge in this tributary inflow, suggesting a more diffuse source of sediment input.

In contrast to the tributary inflows to Lake Mangakaware, many of the tributary inflows to the Rotopiko lakes were ephemeral, and measureable inflow ceased (or the drain dried up) for up to six months of the year. Without quantifying the contribution of groundwater, there may be a high degree of uncertainty in nutrient budgets or models constructed for these lakes on the basis of measured surface water inflows.

Over the short-term (1–2 days), however, high-intensity rainfall events contribute strongly to variations in suspended sediment and nutrient loads to the peat lakes in this study. Catchments with primarily peat soils (e.g. Rotopiko Lakes) appear to be particularly susceptible to high-intensity rainfall events; suspended solids concentrations of 120 g m^{-3} occurred in tributary inflows following rainfall of c. 10 mm h^{-1}, compared to typical baseflow suspended solids concentration <3 g m^{-3}.

Our results suggest that farm drains are highly dynamic and strongly influenced by: (i) the time scale of rainfall events, ranging from seasonal to hourly, (ii) growth and decay of aquatic plants and filamentous algae within the drains at seasonal time scales, and (iii) drain maintenance programmes that may have beneficial effects of removing fine, nutrient-rich sediments in the bed of the drains while at the same time resulting in rapid mobilisation of a fraction of these sediments and providing an easier conduit for sediment and nutrient inputs to enter the lakes.

The findings in this report indicate that storm events contribute to substantial variations in surface-water sediment and nutrient loads to the Rotopiko Lakes and Lake Mangakaware. Management efforts to reduce these loads are required as both systems, particularly the Rotopiko Lakes, support significant ecological communities and represent important remnant biodiversity. Within the agricultural landscapes of these lakes an important consideration should be identifying critical source areas of sediment and phosphorus and improving management of these areas to effect improvements in water quality and biodiversity. For agricultural drains it will be important to achieve some balance between drain access for maintenance, riparian planting of sufficient width and aspect to reduce sediment and nutrient loss, and in-drain plant establishment (to optimise opportunities for sediment and nutrient removal). Our results indicate a need for further research and consultation with the aim of developing consistent guidelines for drain maintenance and riparian planting, as well as supporting management of key areas where sediment and nutrient runoff is disproportionately large. Inflow monitoring programmes for farm drains should also be targeted towards storm events which are likely to make a disproportionately large contribution to surface-water sediment and nutrient loads compared with larger stream inflows which have a proportionately larger baseflow component. The monitoring could also be tailored specifically to support modelling required to construct lake water balances, identify groundwater contributions of water, sediment and nutrients to the lakes, and to calculate whole-lake nutrient and sediment budgets.

Table of Contents

List of Tables

List of Figures

Introduction

Nutrient runoff from intensive agriculture has been identified as a substantial contributor to the degradation of New Zealand's freshwater ecosystems (PCE 2012, 2013). Excessive nutrient loss from agricultural land often leads to eutrophication of lakes and rivers, which in turn leads to a reduction in their biodiversity, amenities and aesthetic values (PCE 2012). New Zealand's regional regulatory authorities have a strong interest in minimising sediment and nutrient losses to aquatic systems. Development of farm nutrient budgets has been identified as an important first step to addressing freshwater degradation (Oenema et al. 2003). Farm nutrient budgets provide information on minimising losses of plant nutrients, particularly nitrogen and phosphorus, and avoiding indiscriminate application of fertilisers, whilst maximising productivity and profitability of the farm system (McDowell et al. 2005; Monaghan et al. 2007). Nutrient budgets are typically developed in conjunction with farmers, consultants, and regional and district councils, using farm-scale models such as Overseer®. These farm-scale models have modest requirements for input data and provide relatively simple outputs that can easily be incorporated into farm management plans (Cichota and Snow 2009).

Many shallow lakes in the Waikato Region have mostly pastoral catchments. As pastoral land use has intensified over the past three decades there has been a significant increase in nutrient leaching and sediment runoff (Barnes 2002; Cichota and Snow 2009). An initial scoping investigation by Jenkins and Vant (2007) found that for shallow lakes in the Waikato region, implementation of 'best practice' farm management regimes proposed under the Overseer® model could mitigate nitrogen loading by 7% and phosphorus loading by 18%. These results appear somewhat conservative compared with what has been achieved for a number of farms in the upper Waikato River region (Dewes 2014).

In this context the Waikato Regional Council has identified several lake catchments in the Waikato region where water quality improvements may be possible with the development of farm nutrient budgets. These lake catchments currently include the Rotopiko (Serpentine) lakes and Lake Mangakaware.

Following the development and implementation of nutrient budgets for properties within the Rotopiko and Mangakaware catchments (Dean-Speirs pers. comm.), the University of Waikato was contracted to monitor representative inflows to these lakes, with the objectives of tracking changes in nutrient runoff following the implementation of farm nutrient budgets; providing an indication of seasonal variation in discharge, sediment and nutrient concentrations; and obtaining data on the magnitude of changes in discharge, sediment and nutrient concentrations occurring during heavy rainfall events. This report provides details on the selection of representative inflows into the Rotopiko lakes and Lake Mangakaware, and includes the results from two years of base-flow monitoring as well as from high-frequency monitoring of four major rainfall events during this period. This information is used to provide recommendations for future data collection, monitoring and modelling to underpin management actions to reduce sediment and nutrient inputs to the lakes.

Methods

Site descriptions

The Rotopiko lakes and Lake Mangakaware are located in the Waikato region south of Hamilton City and west of Cambridge (Figure 1). An initial survey of potential monitoring sites for Rotopiko North, Rotopiko South, Rotopiko East and Lake Mangakaware was conducted on 19 and 20 January 2012. Selection of monitoring sites was based on assessments of representative catchment soil characteristics, potential for consistent flow, likely flow volume and ease of access for sampling.

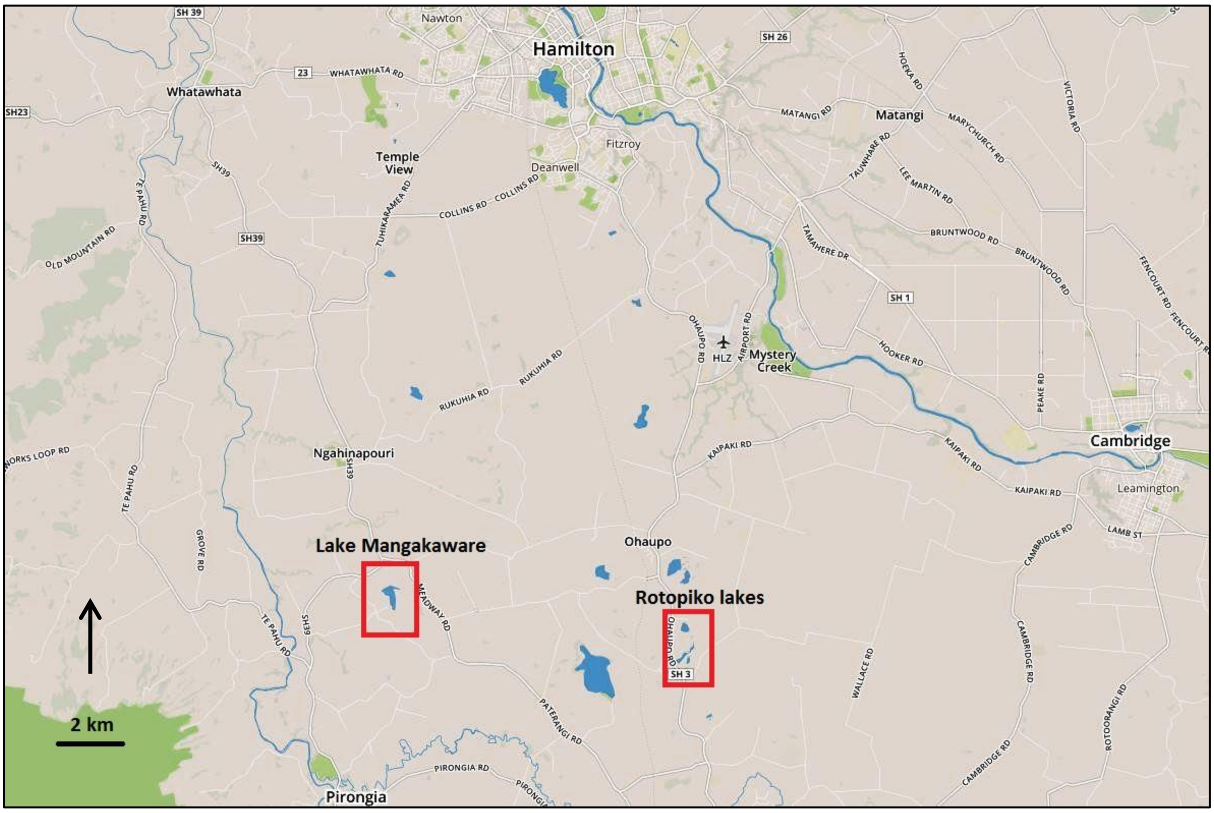

Figure 1. Location of Rotopiko lakes and Lake Mangakaware.

The Rotopiko Lakes are part of a lake complex, with Rotopiko North and Rotopiko East flowing into Rotopiko South which has an outflow on its eastern shore. However, flow between the lakes only occurs during high water levels, following sustained periods of rain. For the Rotopiko North catchment, two representative inflows (designated Rotopiko North 01 and Rotopiko North 02) were selected for sampling (Figure 2A). Both inflows had been fenced from stock access and the margins planted with a mixture of native flaxes (*Phormium* spp.), carex grasses (*Carex* spp.), manuka (*Leptospermum scoparium*) and other native species (Figure 2B). At the time of site selection (January 2012) there was very little water present in these inflows, however all other inflows into Rotopiko North were similar in nature and it was accepted that there would be periods of little or no surface flow to the lake. Subcatchment soils for these inflows were a mixture of clay on the hills and peat soils on the flat areas near the lake. It was also noted that Rotopiko North 01 drain was likely to receive overland flow from nearby sealed roads during periods of heavy rainfall.

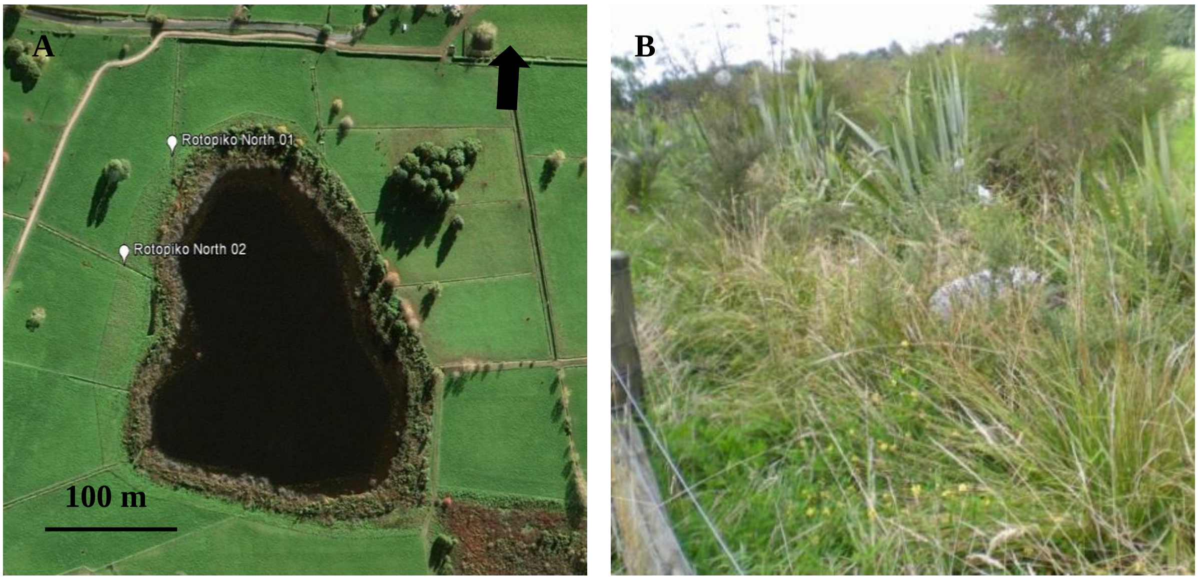

Figure 2. A) Inflow sampling locations for Rotopiko North (marked Rotopiko North 01 and 02). B) Thick planted vegetation bordering Rotopiko North 01. Photo from January 2012. Map source: Google Earth.

A single inflow was selected as a monitoring site for Rotopiko South (designated Rotopiko South 02) (Figure 3A). Other than the inflows from Rotopiko North and Rotopiko East, this was the only significant inflow to the lake. The Rotopiko South 02 site was fenced but the banks of the inflow were not planted beyond the lake riparian zone. Initially (April 2012 – June 2012), the sampling site was located closer to the lake to incorporate inflow from a smaller drain that connected to the inflow from the north. However, the sampling site was shifted approximately 15 m upstream following the realignment of the lake perimeter fence to incorporate a new settling pond. Following excavation of the drain in autumn 2012, the Rotopiko South 02 inflow was wider, deeper and free of vegetation (Figure 3B) compared with both the earlier state of this inflow and the Rotopiko North monitoring sites. In comparison to the Rotopiko North inflows, the Rotopiko South inflow appeared to be strongly influenced by the surrounding peat soils. The bottom sediment was soft, appeared to have a high organic material content and the water appeared to have high levels of dissolved colour. Rotopiko East is a comparatively small catchment (14.4 ha cf. Rotopiko South 87.3 ha) and none of the inflows were suitable for monitoring. It was therefore excluded from the monitoring programme.

Figure 3 A) Inflow sampling location for Rotopiko South (Google Earth) marked as Rotopiko South 02. B) Rotopiko South 02 sampling location following successful installation of a water level logger (photo in June 2012).

Three sites were selected for monitoring in the Lake Mangakaware catchment (Figure 4A). The first was designated Mangakaware 01 (Figure 4B) and was located on the western side of the lake. The soil on this side of the lake is primarily clay and the water flow was relatively consistent throughout the year as the water appears to originate from a spring. The site was fenced by a single wire on one side and bordered by a barberry (*Berberis glaucocarpa*) hedge on the other. Much of the inflow was overgrown with wild blackberry (*Rubus fruticosus*) and other vegetation. The water in the drain was shallow (<15 cm) but the bottom sediment is comprised of very fine, loose organic material approximately 20 cm in depth. These features, together with the abundance of in-stream vegetation and small subcatchment size, suggest it was unlikely that the discharge from this inflow would vary substantially, even during periods of heavy rainfall.

Figure 4. A) Inflow monitoring sites for the Lake Mangakaware catchment (source: Google Earth). B) Mangakaware 01 inflow monitoring site. Photo from June 2012. C) Mangakaware 05 inflow monitoring site with water level data logger. Photo from September 2012. D) Mangakaware 06 inflow monitoring site with water level data logger. Photos from June 2012.

The Mangakaware 05 site was located on the northern side of Lake Mangakaware (Figure 4A) and discharge was generally greater than for any of the other monitored sites. As with Rotopiko South 02 this site was excavated in autumn 2012, resulting in removal of all vegetation along the banks of the inflow for 50 m upstream and downstream of the sampling location. The site is now fenced on both sides. Following excavation it was largely devoid of vegetation, i.e., for most of the first year of sampling (Figure 4C). The soil at Mangakaware

05 was a mixture of silt and sand with little organic matter compared with the other Mangakaware monitoring sites.

The third Lake Mangakaware sampling site was designated Mangakaware 06 (Figure 4A) and was selected for its consistent water flow and representation of catchment soil characteristics. The site is located on the eastern side of the lake and has both clay and peat soils within the subcatchment. However, unlike Mangakaware 01, Mangakaware 06 appeared to have a greater peat soil influence as the water appeared to have the highest levels of dissolved colour of the three Mangakaware sites. The site was fenced by single wires and the riparian vegetation was a mixture of pasture and rushes (*Juncus* sp.) (Figure 4D). A summary of the characteristics for each monitoring site is provided in Table 1.

Table 1. Summary of inflow monitoring sites. Soil type refers to the soil composition type adjacent to the monitoring site. Inflow bottom sediment indicates the composition of the sediment layer at the monitoring site. Fencing refers to either a single or multi-wire electric fence restricting stock from the inflow. Riparian vegetation indicates the predominant type of vegetation in the riparian zone of the inflow. Inflow width and depth indicate the mean width and depth of water at the monitoring site.

Sampling Site	Soil type	Inflow bottom sediment	Fencing	Riparian vegetation	Inflow width (m)	Inflow depth (m)
Rotopiko North 01	Peat	Shallow organic mud	Multi-wire	Native	0.9	0.45
Rotopiko North 02	Peat	Shallow organic mud	Multi-wire	Native	1.1	0.63
Rotopiko South 02	Peat	Deep organic mud	Multi-wire	Pasture	1.4	1.45
Mangakaware 01	Clay-loam	Shallow mineral mud	Single wire	Pasture/barberry	1.0	0.74
Mangakaware 05	Sandy-loam	Hard bottom	Multi-wire	Pasture	1.2	1.83
Mangakaware 06	Peat	Deep organic mud	Single wire	Pasture	1.4	1.14

Inflow monitoring

Tributary inflows at each site were monitored at two-month intervals from April 2012 to April 2014. To determine discharges, the width of the water surface was measured using a fibreglass measuring tape. The inflow width was then divided into approximately five equal sections. The depth of each section was recorded and velocity at 0.6 of the depth was recorded using a Marsh-McBirney flow meter (Marsh McBirney, Frederick, USA). The width, depth and mean flow of each cell were then multiplied and summed to give total discharge ($l\ s^{-1}$).

Total and dissolved nutrient samples were also collected from each site according to Hill Laboratories requirements. A 1-l unfiltered sample was taken from below the water surface and a filtered sample was taken by filtering 250 ml through a 25-ml glass fibre GC50 filter (MicroScience, UK) held in an acid-washed Swinnex filter holder attached to a 50-ml syringe. Samples were then placed on ice and delivered to Hill Laboratories for analysis. Water samples were subsequently analysed for total oxidised nitrogen (nitrate and nitrite), ammonium, dissolved reactive phosphorus (DRP), total nitrogen, total phosphorus, and total suspended solids differentiated as volatile (organic) and non-volatile (inorganic) suspended solids.

Storm event sampling

An objective of this study was to monitor two rainfall ('storm') events each year. Single samples of discharge and water quality were taken at each location approximately 48 h following the commencement of rainfall using the same methodology as described for routine baseflow sampling. In addition, a single site was selected for intensive 2-hourly water quality sampling using an automated water sampling device (Manning Portable Vacuum Autosampler, Model VST, Manning Environmental Inc., Texas, USA) (Figure 5). The selected locations included Rotopiko South 02 (sampled once), Mangakaware 05 (sampled twice) and Mangakaware 06 (sampled once). These sites were selected as they represented the largest inflows and had sufficient water depth to allow water intake to the autosampler without the risk of air-locking. The autosampler was deployed for 48 h and was programmed to take a 500 ml sample at 2 h intervals. Concurrent sampling of other sites could not be undertaken due to constraints of equipment availability and sample analysis costs.

Following retrieval of the vacuum sampler, 50-ml filtered (GC 50 glass fibre filter) and unfiltered subsamples were taken and frozen for dissolved and total nutrient analysis. The remaining water was vacuum-filtered through pre-weighed, ashed MSGC50 glass fibre filters (MicroScience, UK). The samples were then dried at 105 °C for 6 h and weighed again to determine total suspended solids. Filters were then ashed at 550 °C for 1 h and weighed again to determine concentrations of inorganic suspended solids and volatile suspended solids. In addition to the water samples collected for nutrient analysis, discharges were measured from all autosampler sites and used to calculate discharge by regression against water level data. Rainfall data from the NIWA National Climate Database was retrieved for the first storm event (Hamilton Airport station, max.12 km from monitoring sites). Rainfall for subsequent storm events was measured using Odyssey rain gauge loggers coupled with a Davis tipping bucket (Dataflow Systems Ltd, Christchurch, New Zealand) deployed at the high frequency monitoring site.

Water level loggers

Water level loggers (Odyssey, Dataflow Systems Ltd, Christchurch, New Zealand) were installed at the Rotopiko South 02, Mangakaware 05 and Mangakaware 06 monitoring sites in June 2012. These sites were selected as they produced the highest discharges of the six monitored sites and had water levels with sufficient depth for variations to be measured by the data loggers. Water level loggers were checked for fouling during routine baseflow sampling and were downloaded every four months.

Discharge was calculated from water level logger data using linear regression relationships that were derived from measured discharge plotted against water level for the same time period. Relationships between measured discharge and water level for the Rotopiko South 02, Mangakaware 05 and Mangakaware 06 sites are presented in Appendix 1.

Figure 5. Manning automatic sampling equipment deployed at Rotopiko South 02.

Results

Discharge

Discharge was calculated from water level loggers installed at three sites from 20 June 2012 to 24 April 2014. Discharges for Mangakaware 05, Mangakaware 06 and Rotopiko South 02 are presented in Figures 6, 8 and 9, respectively. There are missing data for the Rotopiko South 02 site from 3 November 2012 to 12 December 2012 due to a fault in the water level logger. Also of note was a period of variable discharge recorded at the Mangakaware 05 monitoring site from mid-January to early March 2014 (Figure 6 and 7). During this time no significant rainfall was recorded at the nearest meteorological station, Hamilton airport, however discharge increased rapidly and then decreased over a 5–6 h period commencing at approximately 05:00 h and returning to near zero by 10:00 h. This cyclical discharge was evident on most days, with discharge peaking at just over 20 l s^{-1} for short periods of time. An example of this event is given in Figure 7.

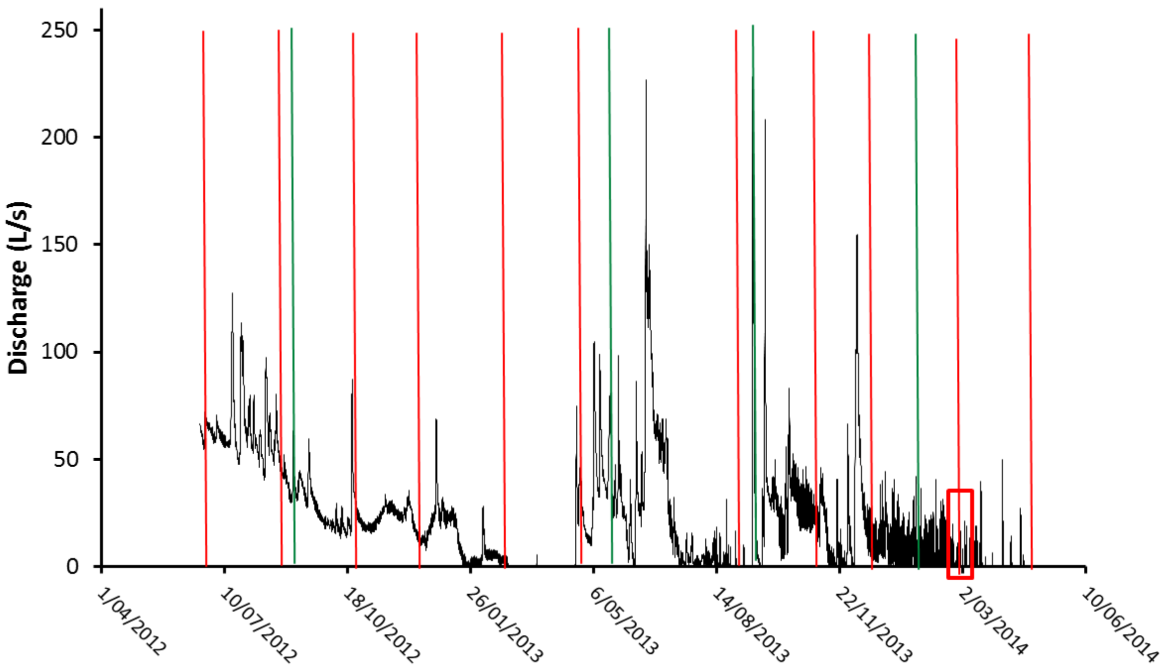

Figure 6. Discharge at Mangakaware 05 monitoring site from 20 June 2012 to 24 April 2014. Red lines indicate monitoring events; green lines indicate sampled storm events. Red rectangle indicates discharge data reproduced in detail in Figure 7.

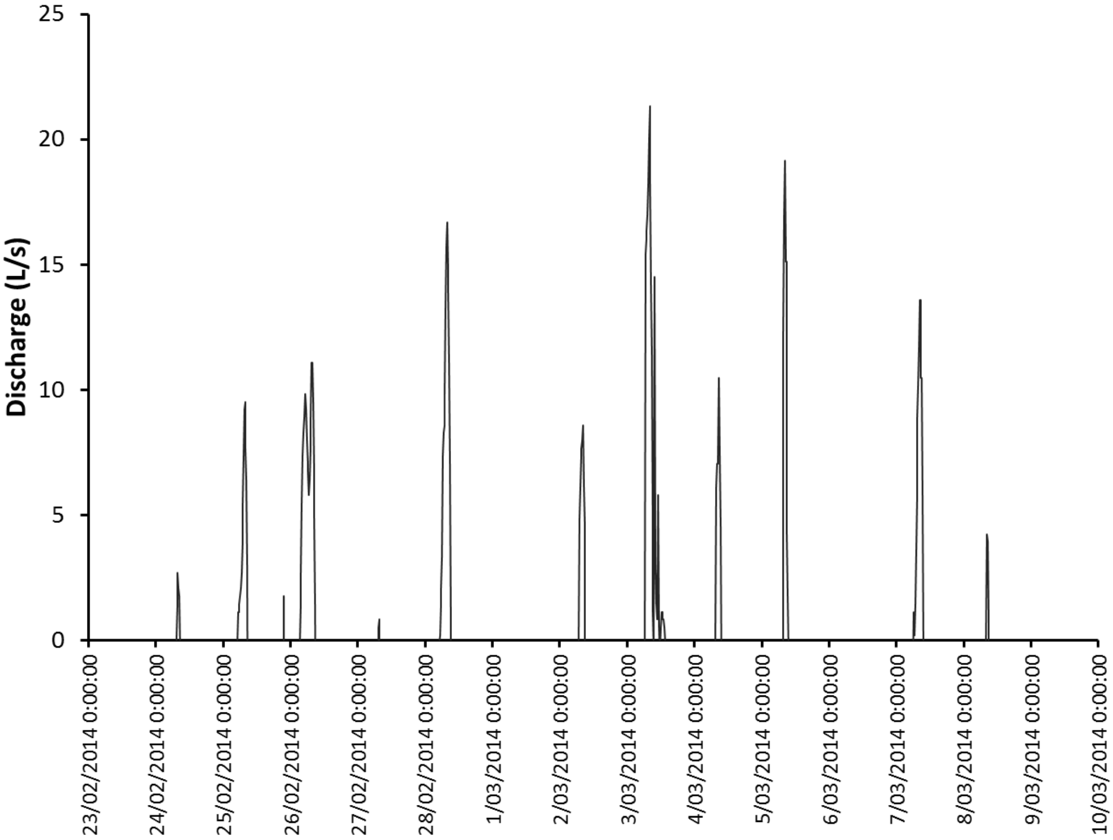

Figure 7. Example of the periodic discharge observed at the Mangakaware 05 monitoring site during late summer and early autumn of 2014. Discharge typically commenced at 05:00 h and ended by 10:00 h.

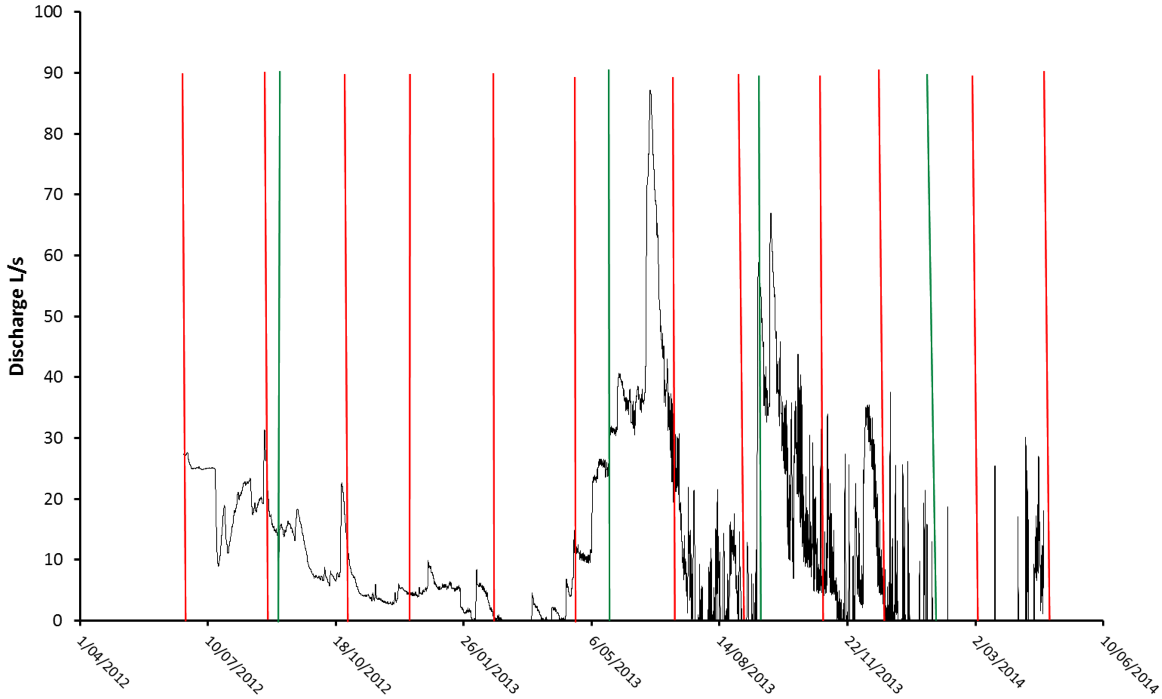

Figure 8. **Calculated discharge at Mangakaware 06 monitoring site from 20 June 2012 to 24 April 2014. Red lines indicate monitoring events; green lines indicate sampled storm events.**

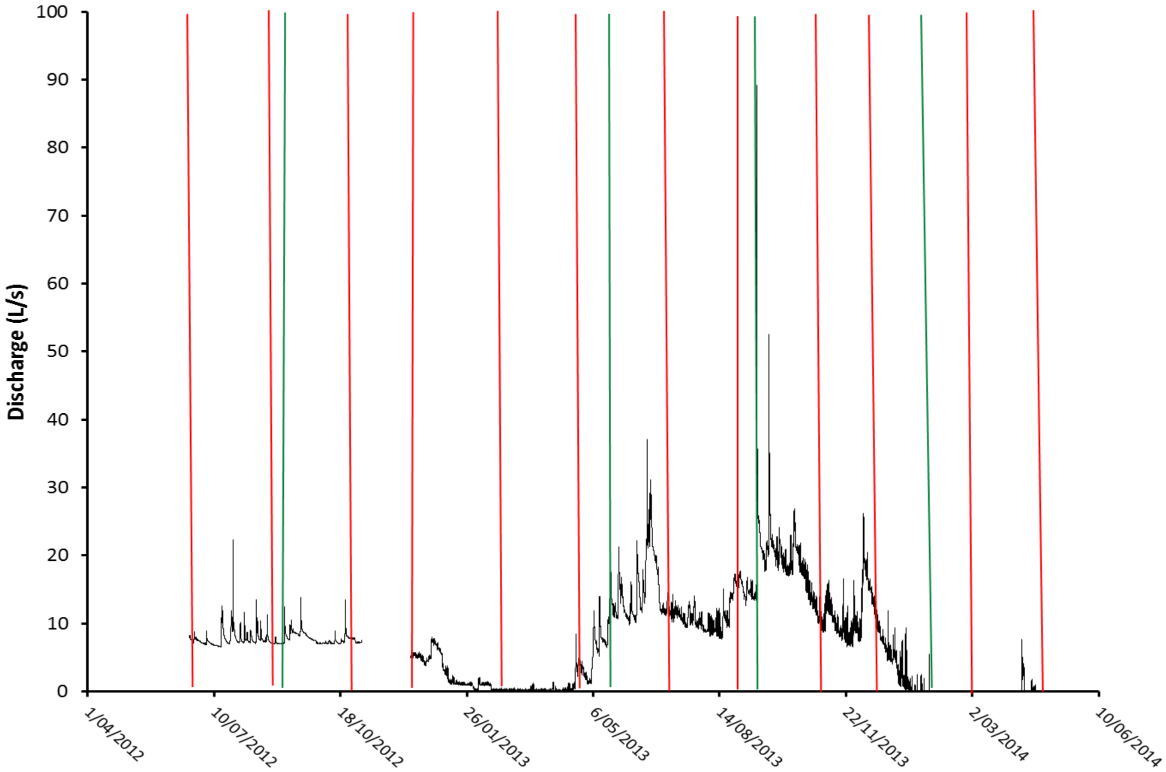

Figure 9. **Calculated discharge at Rotopiko South 02 monitoring site from 20 June 2012 to 24 April 2014. Red lines indicate monitoring events; green lines indicate sampled storm events. Due to a fault with the water level logger no data was recorded from 3 November 2012 to 12 December 2012.**

Base-flow monitoring

Water quality variables and discharge measurements from baseflow monitoring are presented in Appendices 2.1–2.6. Consistent discharges in the Rotopiko North 01 and Rotopiko North 02 inflows only occurred during winter months (Appendix 2, Tables A2.1 and A2.2). The ephemeral nature and highly variable results of the Rotopiko North inflows made determining patterns or trends in water quality difficult to ascertain. In April and December 2012 there was only shallow (<3 cm depth) standing water in the two inflows and in February 2013 the drain was completely dry. As a consequence it was not possible to retrieve samples without disturbing sediments, and no samples were taken for sediment or nutrient analysis. Samples taken in April 2013 followed the first significant rainfall in more than three months. At this time there was a large amount of decaying vegetative matter in the drains. This material may have contributed to elevated concentrations of total suspended solids (TSS), volatile suspended solids (VSS) and total phosphorus, particularly in Rotopiko North 01. Soil conditions and discharges in the Rotopiko North catchment were very different between the months of August 2012 and August 2013. Soils in these subcatchments were close to saturation in August 2012 and discharges were correspondingly high, while soil moisture content and discharges were much lower in August 2013. Low discharges continued through the spring of 2013 and into the summer of 2014, with the Rotopiko North inflows becoming completely dry from January-April 2014, precluding water samples from being taken for nutrient analysis.

Rotopiko South 02 had no measurable flow in April 2012 and December 2012 and was completely dry in February 2013 (Appendix 2, Table A2.3). Unlike the Rotopiko North inflows, Rotopiko South 02 still retained sufficient standing water in April 2012 and December 2012 to obtain uncontaminated samples (i.e. free of resuspended sediment) for analysis. However, large amounts of filamentous algae and suspended detrital matter were present in the inflow during the December 2012 and April 2013 sampling periods and were associated with increased VSS concentrations. Flows were generally lower during the spring of 2013 compared to 2012, and the inflow was completely dry from January–April 2014. During the summer months of 2012 measureable discharge was prolonged (cf. summer 2013), and it was possible to obtain water quality measurements. During this time it was observed that TN was comparatively elevated (>4 g m^{-3}) compared with typical winter baseflow concentrations (<2 g m^{-3}) although increases were evident following storm events. Nitrate concentrations were highly variable with no discernible pattern; nitrite concentrations were more consistent although there was an unusual peak in nitrite (0.036 g m^{-3} cf. mean 0.005 g m^{-3}) in April 2013.

Mangakaware 01 also had large amounts of filamentous algae and plant detrital matter present during the April 2012 and April 2013 sampling periods, resulting in increased VSS concentrations. Additional organic material likely arose from barberry vegetation falling into the drain following routine maintenance of the hedge beside the drain. Otherwise TSS concentrations were usually very low (~5 g m^{-3}) in comparison to the other monitored sites. Mangakaware 01 TN concentrations (mean 2.38 g m^{-3}) were more consistent than any of the other monitored sites and did not display a strong seasonal pattern. Nitrate levels were variable (range 0.72 – 3.2 g N m^{-3}) and tended to increase during the spring. Concentrations of nitrite were low (<0.002 – 0.007 g N m^{-3}). As with the Rotopiko inflows, measured discharges were lower in the spring of 2013 compared with 2012 and the inflow was either dry or too shallow to sample from January to April 2014.

Mangakaware 05 consistently had the highest flow velocities (Appendix 2, Table A2.6). In February 2013 it was one of only two inflows that still had surface water. There was no flow at this time and the drain contained large amounts of vegetation and filamentous algae, likely giving rise to elevated TSS and VSS concentrations. The corresponding water sample also had comparatively high levels of total Kjeldahl nitrogen (TKN) and total phosphorus (TP). Total nitrogen concentrations (range 0.59 – 4.1 g m^{-3}) peaked during the winter or early spring months but values were in the same range as other monitored sites. Concentrations of dissolved reactive phosphorus (DRP) and TP were generally lower at the Mangakaware 05 site (mean DRP = 0.010 g m^{-3}; mean TP = 0.044 g m^{-3}) compared to other monitored sites (mean DRP = 0.024 g m^{-3}; mean TP = 0.082 g m^{-3}) and is likely a reflection of the silt/sand soil type at this site compared to the peat soils in the other subcatchments. Measured discharges from Mangakaware 05 and Mangakaware 06 were typically substantially larger compared to other monitored inflows and this is reflected in the fact that they were the only inflows to retain water during the February 2013 sampling period. However, the extended drought period in the summer of 2014 coupled with the low rainfall in the spring of 2013 resulted in both drains having insufficient water to sample in February 2014. As with Mangakaware 05, the Mangakaware 06 inflow was extensively covered in submerged vegetation and filamentous algae during the summer dry periods. The February 2013 sampling period was also associated high levels of TKN and TP, with suspended organic material (e.g., algae and suspended decaying plant material) likely contributing to the elevated phosphorus and nitrogen levels. As with the Rotopiko Lake inflows, there was a large difference in discharges for the Mangakaware inflows between August 2012 and August 2013. Farm soils in the Mangakaware catchment were observed to be considerably drier in 2013 and 2014 compared to 2012.

Routine base-flow monitoring revealed peak TP concentrations that were higher in catchments with peat soils, and there was an inverse relationship between TP concentration and discharge across all inflows. Generally, storm event TP concentrations 48 h after the onset of heavy rainfall were only slightly elevated compared with seasonal base-flow levels. Dissolved reactive phosphorus (DRP) concentrations followed the same trends as TP concentrations. Due to the reduced number of samples, trends in base-flow total nitrogen (TN) concentrations were less apparent in the Rotopiko inflows. However, the Mangakaware inflows exhibited a trend of increasing TN concentrations with increasing discharges. As with TP, TN concentrations were elevated 48 h following the onset of heavy rainfall compared with seasonal baseflow levels. Variations in total oxidised nitrogen (NO_x) concentrations in base-flow were closely associated with variations in TN concentrations and discharge. However, ammonium concentrations were more variable and increases were often concurrent with decreases in NO_x in periods of no discharge. Unlike TN concentrations, NO_x and ammonium concentrations were not consistently elevated 48 h after heavy rainfall events compared with seasonal base-flow conditions.

Storm flow monitoring

High-resolution, 48-h storm flow monitoring was conducted on four occasions during the 2-year sampling period. Monitoring was conducted at the Rotopiko South 02 site on 11–13 September 2013, the Mangakaware 06 site on 3–5 September 2012 and twice at the Mangakaware 05 site, on 17–19 May 2013 and 20-22 January 2014.

The first high-resolution storm flow monitoring was conducted at Mangakaware 06 over 3–5 September 2012. A total of 55 mm of rain was recorded over the sampling period and discharge peaked at 16.4 l s^{-1}. Total phosphorus, DRP, TSS and discharge data are presented in Figure 10. Changes in TSS, VSS and discharge are presented in Appendix 3, Figure A3.1. Despite the relatively small increase in discharge (1–2 l s^{-1}), a large increase in TSS was observed 4–6 h following the onset of rainfall, suggesting that the majority of TSS was being mobilised higher in the catchment. Total phosphorus concentrations increased in association with increasing TSS, but there was a time lag of 4–5 h before DRP concentrations increased (Figure 10). Calculations of instantaneous TP, DRP and TSS loads (in units mg s^{-1}) are presented in Appendix 3, Figure A3.2 and display a similar pattern of change to the concentration data. Total nitrogen, ammonium (NH_4), nitrite (NO_2) and nitrate (NO_3) concentrations are presented in Figure 11. In contrast to phosphorus and sediment concentrations, nitrogen species concentrations remained relatively stable, although TN did increase with increasing discharge. Calculations of instantaneous TN, NH_4, NO_2 and NO_3 loads are presented in Appendix 3, Figure A3.3. Ammonium instantaneous loads initially decreased in response to increasing discharge (likely due to a dilution effect), but then increased in line with other nitrogen species as discharge increased, indicating leaching from other sources in the subcatchment.

Single-point water samples were also taken at the other monitored locations on 3 September 2012. Discharge, suspended sediment and nutrient concentrations for these point samples are presented in Table 2. Discharge and most water quality measures were only slightly elevated in comparison to the baseflow monitoring levels for each site, illustrating the flashy nature of surface runoff in farm drains. It also suggests that important temporal variation in water quality variables was missed at sites where autosampling could not be undertaken. Interestingly, there was significant variation in NH_4 concentrations between sites (Table 2), with higher NH_4 concentrations present in subcatchments strongly influenced by peat soils. There appeared to be no relationship between water quality variables such as TN and TP and discharge (i.e. subcatchment size).

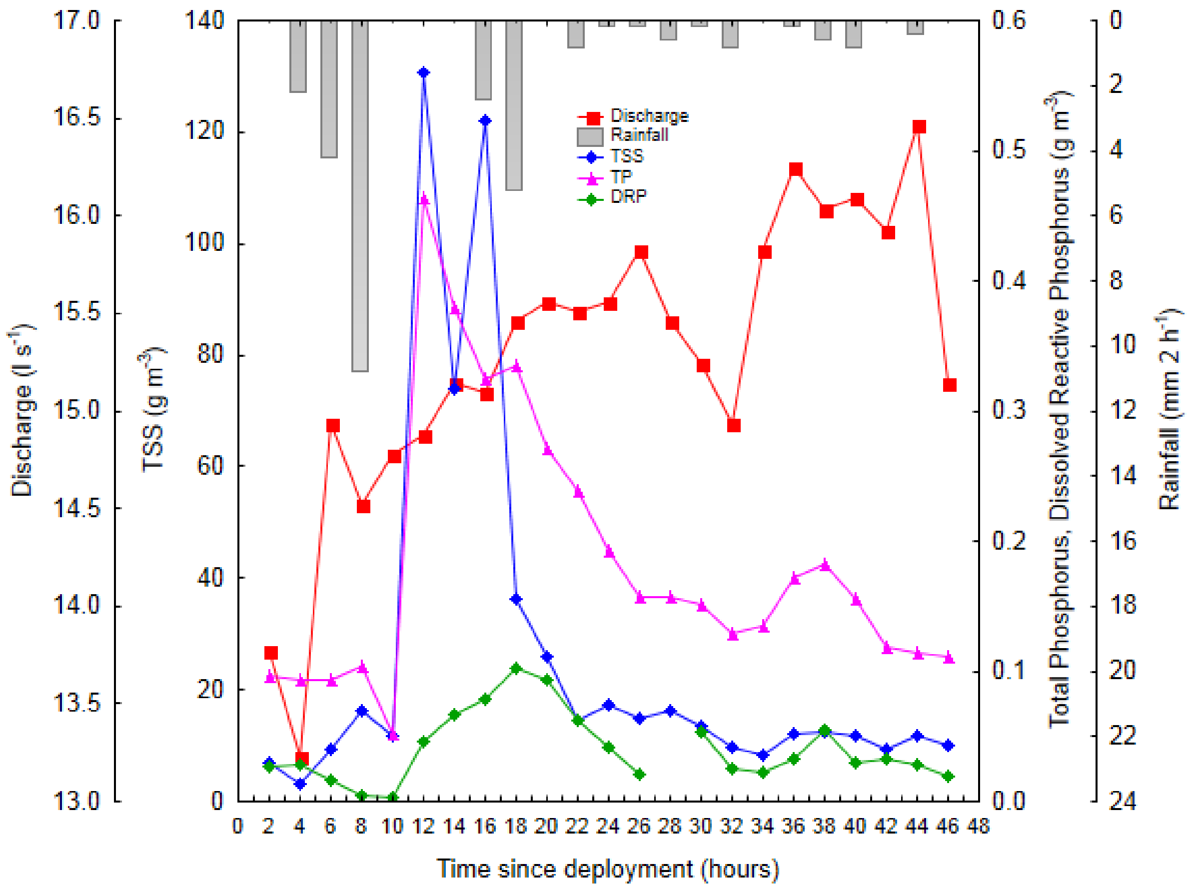

Figure 10. Changes in total phosphorus (TP), dissolved reactive phosphorus (DRP), discharge, total suspended solids (TSS) and rainfall at the Mangakaware 06 monitoring site during the September 2012 storm event. Sampling is at 2-h intervals beginning at 10:00 h. Note: dissolved reactive phosphorus sample not available for 28-h due to sample container leakage.

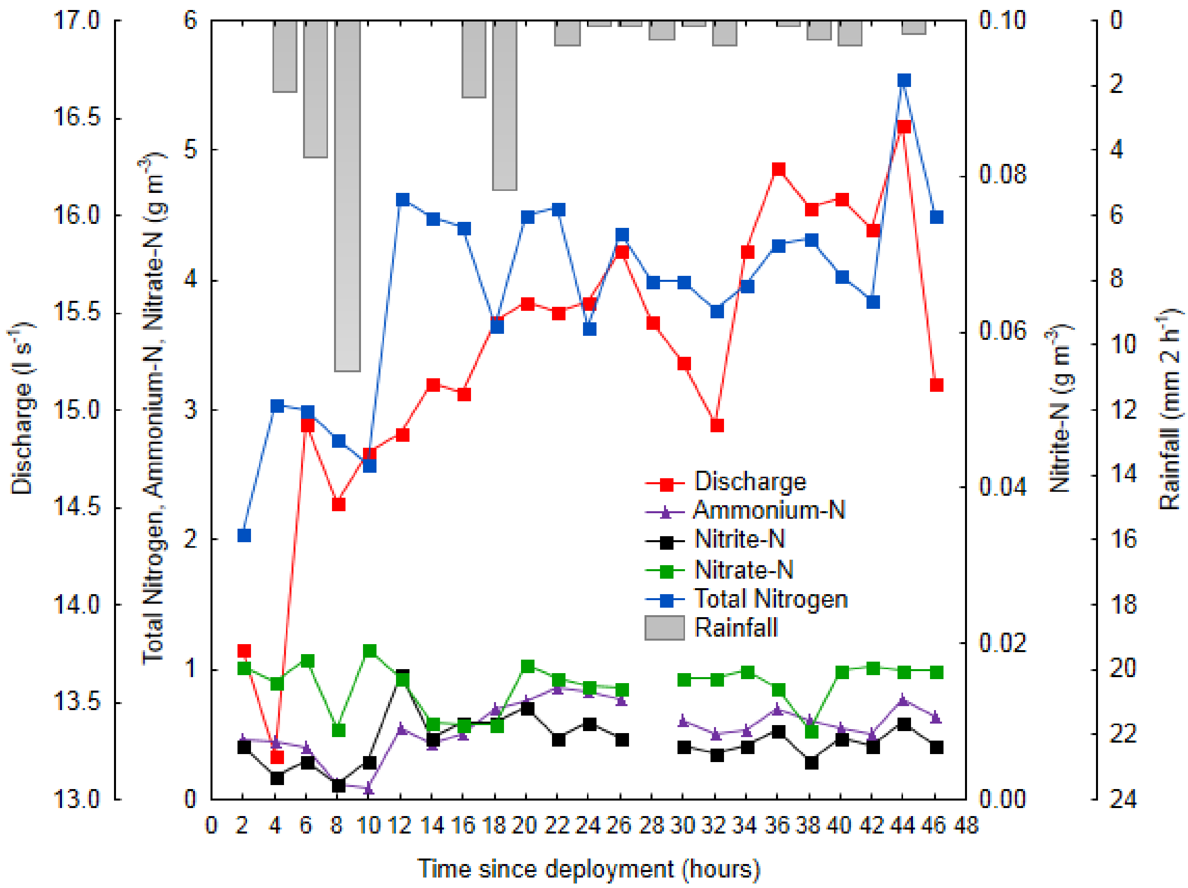

Figure 11. Changes in total nitrogen, ammonium-N, nitrate-N, nitrite-N, discharge and rainfall at the Mangakaware 06 monitoring site during the September 2012 storm event. Sampling is at 2-h intervals beginning at 10:00 h. Note: ammonium-N, nitrate-N and nitrite-N concentrations not available for 28-h sample.

Table 2. Results of storm inflow and grab sample monitoring conducted on 3 September 2012.

Water Quality Variables	Rotopiko North 01	Rotopiko North 02	Rotopiko South 02	Mangakaware 01	Mangakaware 05	Mangakaware 06
Volatile Suspended Solids (g m^{-3})	<8	10	4	<3	2	2
Total Suspended Solids (g m^{-3})	18	12	6	<3	7	7
Inorganic Suspended Solids (g m^{-3})	3	<5	<5	<5	5	5
Total Nitrogen (g m^{-3})	3.100	3.700	5.200	3.500	2.270	2.044
Total Ammoniacal-N (g m^{-3})	0.018	0.149	0.900	0.018	0.045	0.465
Nitrite-N (g m^{-3})	<0.002	0.006	0.007	<0.002	0.001	0.007
Nitrate-N (g m^{-3})	3.300	2.500	2.100	3.300	2.223	1.028
Nitrate-N + Nitrite-N (g m^{-3})	3.300	2.506	2.107	3.300	2.224	1.035
Total Kjeldahl Nitrogen (g m^{-3})	0.170	1.194	3.093	0.200	0.046	1.009
Dissolved Reactive Phosphorus (g m^{-3})	0.026	0.015	0.014	0.026	0.020	0.027
Total Phosphorus (g m^{-3})	0.036	0.025	0.04	0.036	0.095	0.097
Stream Flow (l s^{-1})	1.56	2.96	7.60	4.62	44.48	11.60

The second high-frequency storm flow monitoring took place over 17–19 May 2013 at the Mangakaware 05 site. Rainfall was less intense but more sustained compared with the September 2012 storm event. A total of 58.5 mm of rainfall was recorded over the sampling period. Inflows were again sampled every 2 h for 48 h commencing at 13:30 h on 17 May 2013. Changes in TSS, TP, DRP, rainfall and discharge at 2-h intervals are presented in Figure 12. Changes in TSS, VSS concentrations in relation to discharge are presented in Appendix 3, Figure A3.4. Consistent rainfall over the monitoring period resulted in steadily increasing discharges. Total suspended solids concentrations were considerably lower than the September 2012 storm event, but did show a general increase with increasing discharge. However, TP and DRP did not display the same close covariance with discharge as observed in the previous storm event. This attribute was more evident in the calculated instantaneous TP, DRP and TSS loads presented in Appendix 3, Figure A3.5. As would be expected, TN and NO_3 did co-vary, and both displayed an increasing trend with discharge (Figure 13). This resulted in a different pattern in the instantaneous loads compared to that observed in the September 2012 storm event with, TN, NH_4, and NO_3 all displaying an increasing trend with increasing discharge rather than a static or decreasing trend as may be expected with potential dilution (Appendix 3, Figure A3.6). Single grab samples were taken at the other sampling locations on 19 May, up to 48 h following the start of the storm event. Results from these samples are presented in Table 3. Water quality values were similar to those observed in the September 2012 storm event. Total nitrogen and NH_4 were elevated at the Rotopiko South 02 site relative to the other monitoring sites; while DRP was unusually elevated at the Mangakaware 01 site. However, none of these values was outside the range observed under baseflow conditions.

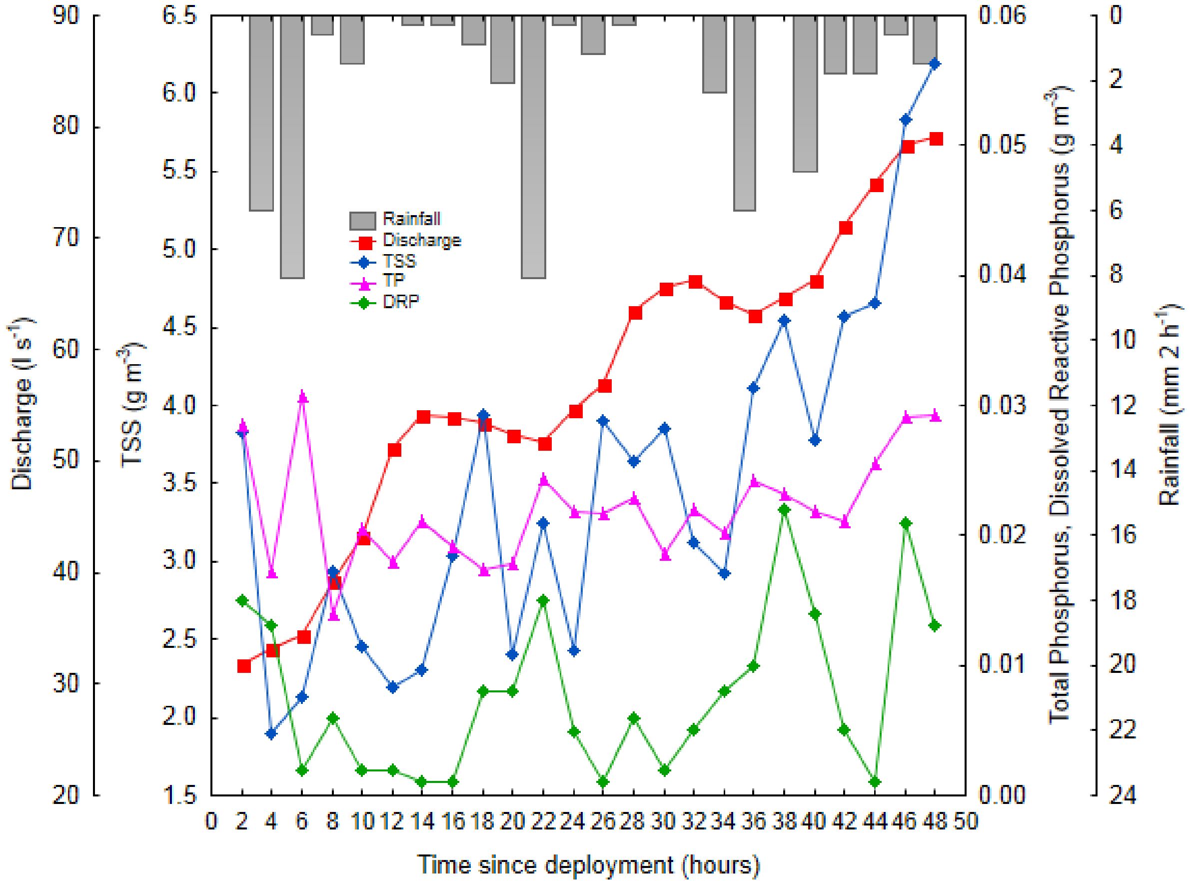

Figure 12. Changes in total phosphorus (TP), dissolved reactive phosphorus (DRP), discharge, total suspended solids (TSS) and rainfall at the Mangakaware 05 monitoring site during the 17-19 May 2013 storm event. Sampling is at 2 h intervals commencing at 13:30 h, 17 May 2013.

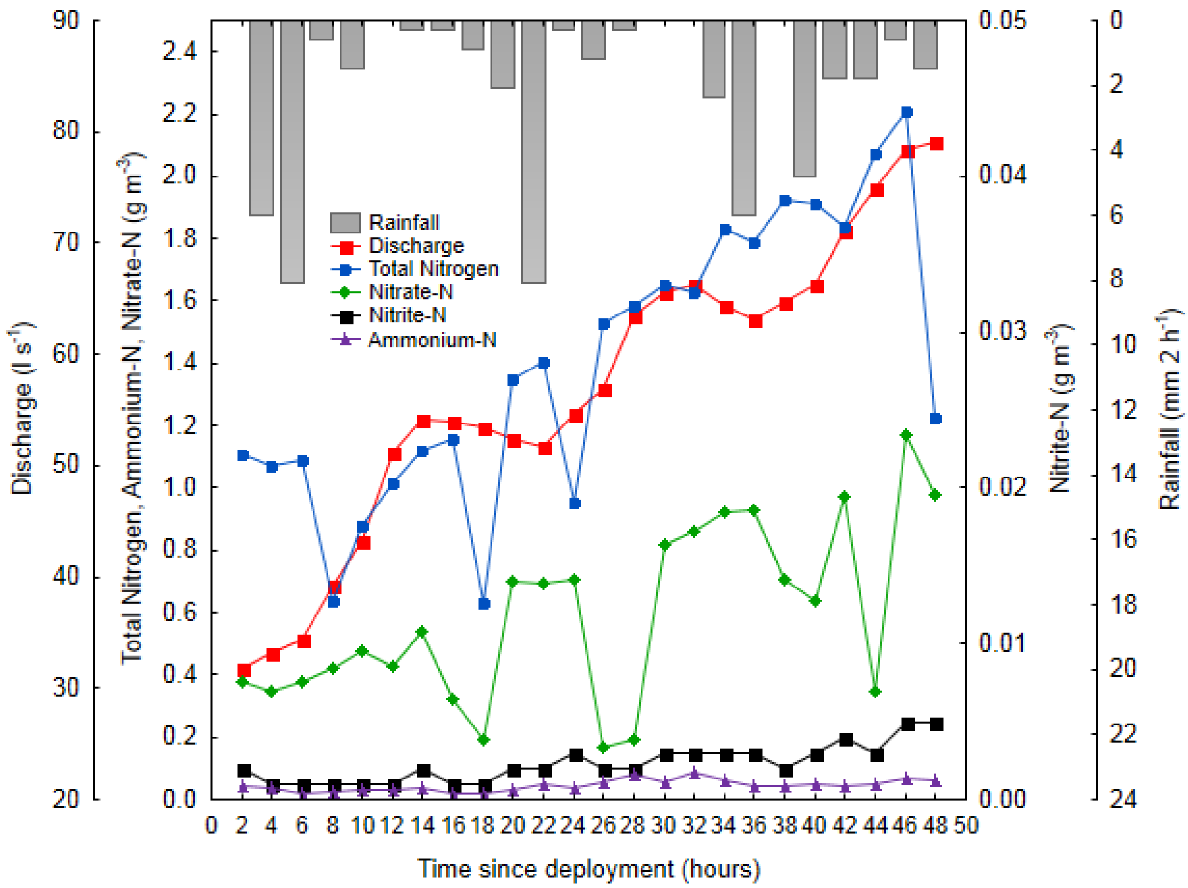

Figure 13. Changes in total nitrogen, ammonium-N, nitrate-N, nitrite-N, discharge and rainfall at the Mangakaware 05 monitoring site during the 17-19 May 2013 storm event. Sampling is at 2 h intervals commencing at 13:30 h, 17 May 2013.

Table 3. Results of storm inflow point monitoring conducted on 19 May 2013.

Water Quality Variables	Rotopiko North 01	Rotopiko North 02	Rotopiko South 02	Mangakaware 01	Mangakaware 05	Mangakaware 06
Volatile Suspended Solids (g m^{-3})	6	10	4	<3	<3	4
Total Suspended Solids (g m^{-3})	13	12	6	<3	3	6
Inorganic Suspended Solids (g m^{-3})	6	<5	<5	<5	<5	<5
Total Nitrogen (g m^{-3})	1.230	3.700	5.200	2.200	2.000	2.300
Total Ammoniacal-N (g m^{-3})	0.024	0.149	0.900	0.097	0.026	0.066
Nitrite-N (g m^{-3})	<0.002	0.006	0.007	0.029	0.009	0.007
Nitrate-N (g m^{-3})	0.103	2.500	2.100	1.860	1.310	1.380
Nitrate-N + Nitrite-N (g m^{-3})	0.105	2.500	2.100	1.890	1.320	1.380
Total Kjeldahl Nitrogen (g m^{-3})	1.130	1.240	3.100	0.360	0.710	0.930
Dissolved Reactive Phosphorus (g m^{-3})	0.015	0.015	0.014	0.047	0.009	0.014
Total Phosphorus (g m^{-3})	0.036	0.025	0.040	0.052	0.029	0.039
Stream Flow (l s^{-1})	1.60	0.90	2.40	1.38	52.30	28.14

The rainfall event on 11–13 September 2013 at the Rotopiko South 02 site was the most intense of the four storm events. Rainfall peaked at 17.6 mm h^{-1} with a total of 106.7 mm recorded over the 48-h sampling period and discharge peaked at 55.2 l s^{-1}. The variation in the timing of peaks in discharge, TSS, TN and TP during this storm event increases the complexity of interpretation, and suggests that mobilised material from a variety of sources contributed to the observed variations. The response to this intense rainfall was a major increase in TSS (~8 to >400 g m^{-3}), though concentrations rapidly returned to near baseflow levels following the cessation of rainfall (Figure 14). Total phosphorus and DRP both increased in response to increasing discharge; however there was a small off-set (2–4 h) in the peaks between TSS and TP (Figure 14). Instantaneous TP, DRP and TSS loads are presented together with discharge in Appendix 3, Figure A3.8. Both TSS and TP loads exceeded 140 g s^{-1}, although not concurrently, giving an unexpected disparity between suspended sediment and bound phosphorus delivery in the inflow. Total nitrogen and NO_3 peaked approximately 20 h following the onset of heavy rain, which aligned more closely with increases in TSS rather than discharge. However, there was comparatively little variation in NH_4 and NO_2 concentrations under heavy rainfall, and values were not dissimilar to seasonal base-flow conditions (Figure 15). Calculated instantaneous TN, NH_4, NO_2 and NO_3 loads presented in Appendix 3, Figure A3.9 show a closer alignment with discharge. Loads initially increase as discharge increases, reflecting mobilisation of dissolved and particulate material in the catchment and from stream stores (particulate material only), before decreasing as discharge declines. Single water samples were taken at the other monitored locations on 13 September 2013, approximately 48 h following the start of the storm event. Results corresponding to this time are presented in Table 4. There was considerable variation in the concentrations of water quality variables, in particular NH_4, NO_3 and DRP, between monitored locations. The difference between Rotopiko North 01 and Rotopiko North 02 is particularly striking as these locations are only separated by approximately 100 m.

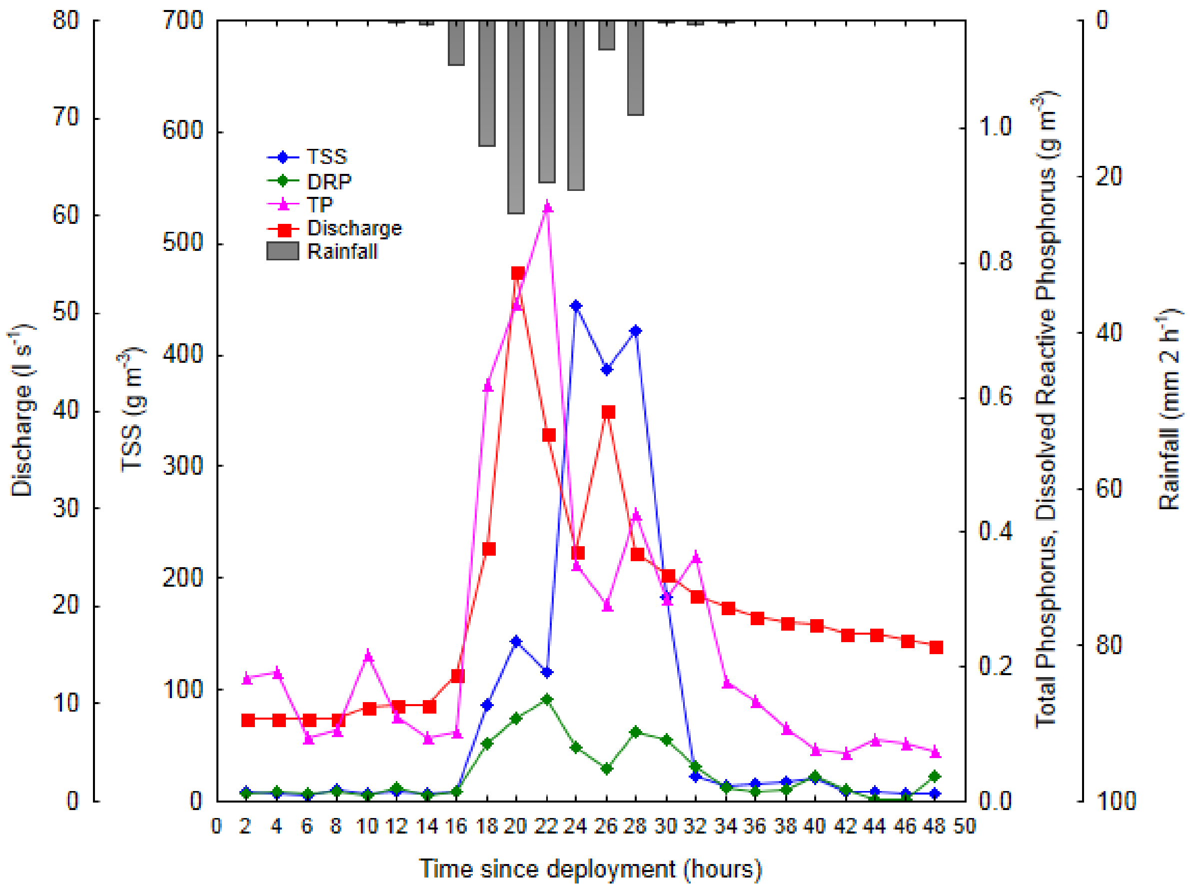

Figure 14. Changes in total phosphorus (TP), dissolved reactive phosphorus (DRP), total suspended solids (TSS), discharge and rainfall at the Rotopiko South 02 monitoring site during the September 2013 storm event. Sampling is at 2 h intervals commencing at 14:20 h on 11 September 2013.

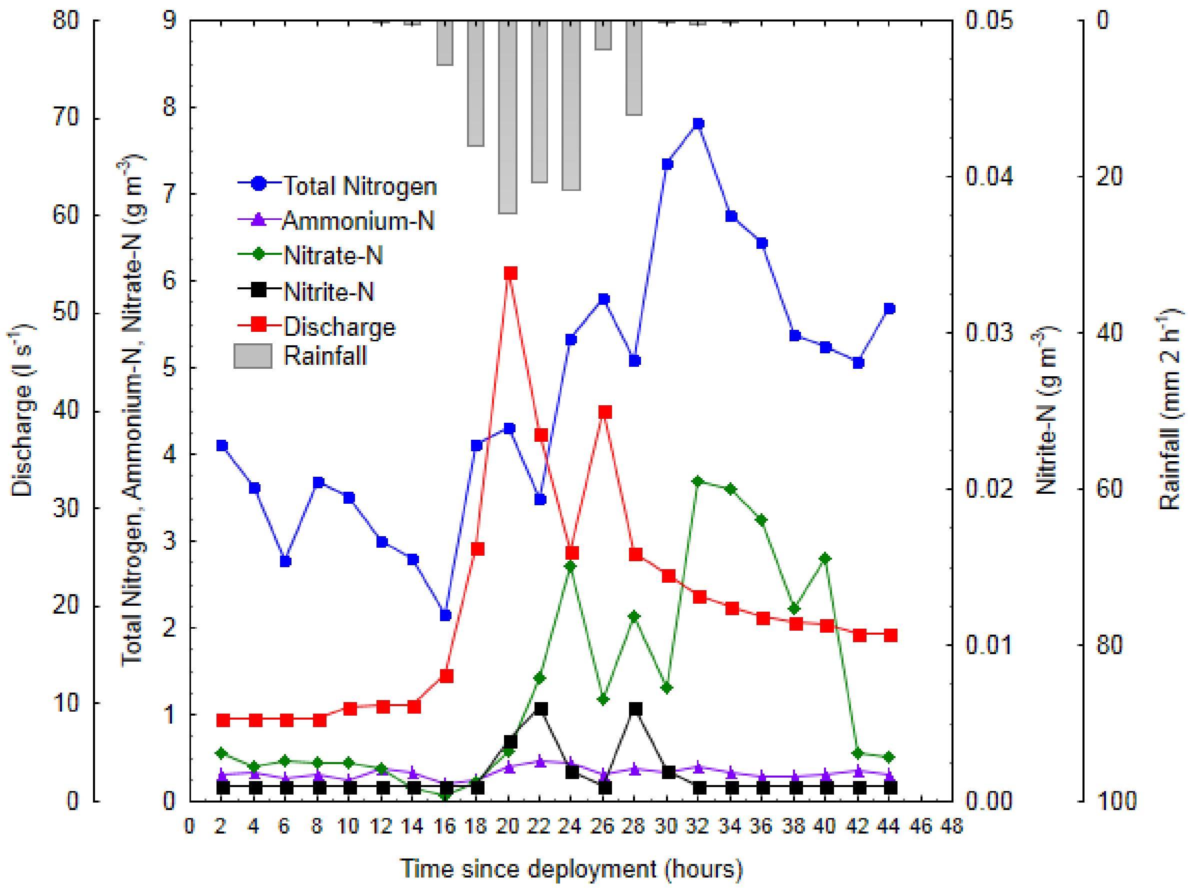

Figure 15. Changes in total nitrogen, ammonium-N, nitrate-N, nitrite-N, discharge and rainfall at the Rotopiko South 02 monitoring site during the September 2013 storm event. Sampling is at 2 h intervals commencing at 14:20 h on 11 September 2013.

Table 4. Results of storm inflow point monitoring conducted on 13 September 2013.

Water Quality Variables	Rotopiko North 01	Rotopiko North 02	Rotopiko South 02	Mangakaware 01	Mangakaware 05	Mangakaware 06
Volatile Suspended Solids (g m^{-3})	3	<3	<3	<3	<3	3
Total Suspended Solids (g m^{-3})	8	3	3	<3	7	7
Inorganic Suspended Solids (g m^{-3})	5	<5	<5	<5	4	<5
Total Nitrogen (g m^{-3})	2.100	3.900	4.100	3.000	2.900	2.800
Total Ammoniacal-N (g m^{-3})	0.030	0.100	0.260	0.044	0.060	0.360
Nitrite-N (g m^{-3})	0.003	0.008	0.008	0.004	0.006	0.030
Nitrate-N (g m^{-3})	1.390	3.100	2.300	2.700	1.950	1.400
Nitrate-N + Nitrite-N (g m^{-3})	1.393	3.108	2.308	2.704	1.956	1.430
Total Kjeldahl Nitrogen (g m^{-3})	0.700	0.820	1.760	0.300	0.950	1.350
Dissolved Reactive Phosphorus (g m^{-3})	0.014	0.035	0.009	0.018	0.035	0.020
Total Phosphorus (g m^{-3})	0.038	0.058	0.038	0.022	0.081	0.106
Stream Flow (l s^{-1})	1.44	7.04	40.82	3.72	116.34	65.94

The passage of ex-tropical cyclone 'June' over the North Island from 20–22 January 2014 was forecast to bring heavy rainfall. However, only 8.5 mm rainfall was recorded at the Mangakaware 05 site during the period of autosampler deployment. No further heavy rainfall events were able to be monitored due to the extended period without significant rainfall over the summer and autumn of 2014. The storm event for 20–22 January 2014 was the only rainfall to produce significant discharge over these two seasons (Figures 16–17; Table 5). As expected with the low rainfall, discharge was considerably reduced compared to the previous storm event monitored at this site in May 2013 (Figure 12). In contrast, mean TSS and VSS concentrations were significantly higher (*t*-test; $p < 0.05$) in the January 2014 event compared with the May 2013 event. The rainfall and discharge from 20–22 January storm event resulted in a large increase in TP and DRP compared with the May 2013 event, with phosphorus peaks occurring soon after the initial peak in discharge, but well before the peak in TSS (Figure 16) suggesting that first organic nutrient sources were mobilised in the drain and then inorganic sediment sources washed into the drain from higher in the catchment. Instantaneous TP, DRP and TSS loads (Appendix 3, Figure A3.11) and TN peak concentrations (Figure 17) also support this hypothesis. Also of note were the low concentrations of NO_3, while NH_4 and NO_2 concentrations were comparatively low and consistent with those observed in the May 2013 storm event (instantaneous TN, NH_4, NO_2 and NO_3 loads are presented in Appendix 3, Figure A3.12). Attempts to retrieve samples from other monitored sites on 22 September 2014 (approximately 48 h following the start of the storm event) were not possible as there had been insufficient rainfall and discharge was negligible. Mangakaware 06 was the only other inflow to have water of sufficient depth to allow samples to be retrieved (Table 5).

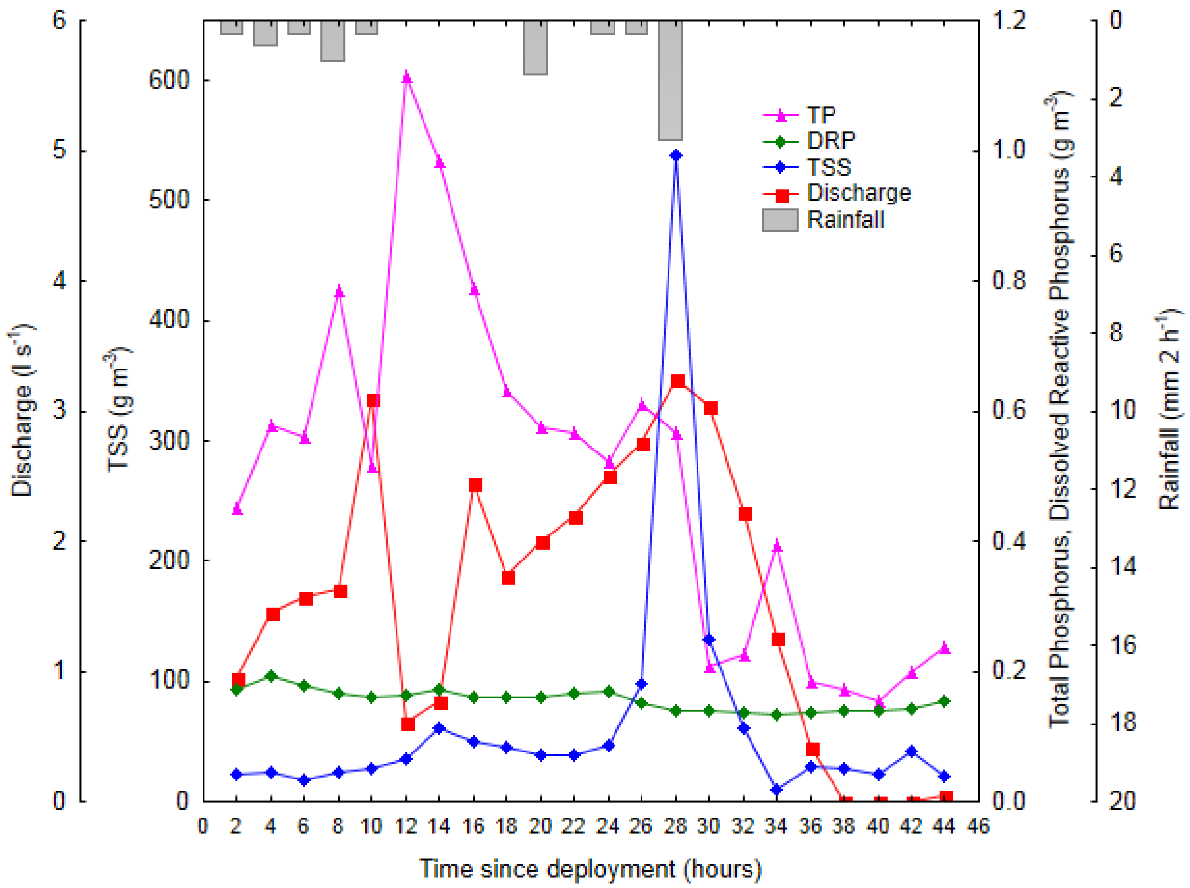

Figure 16. Changes in total phosphorus (TP), dissolved reactive phosphorus (DRP), total suspended solids (TSS), discharge and rainfall at the Mangakaware 05 monitoring site during the January 2014 storm event. Sampling is at 2 h intervals commencing at 11:45 h on 20 January 2014.

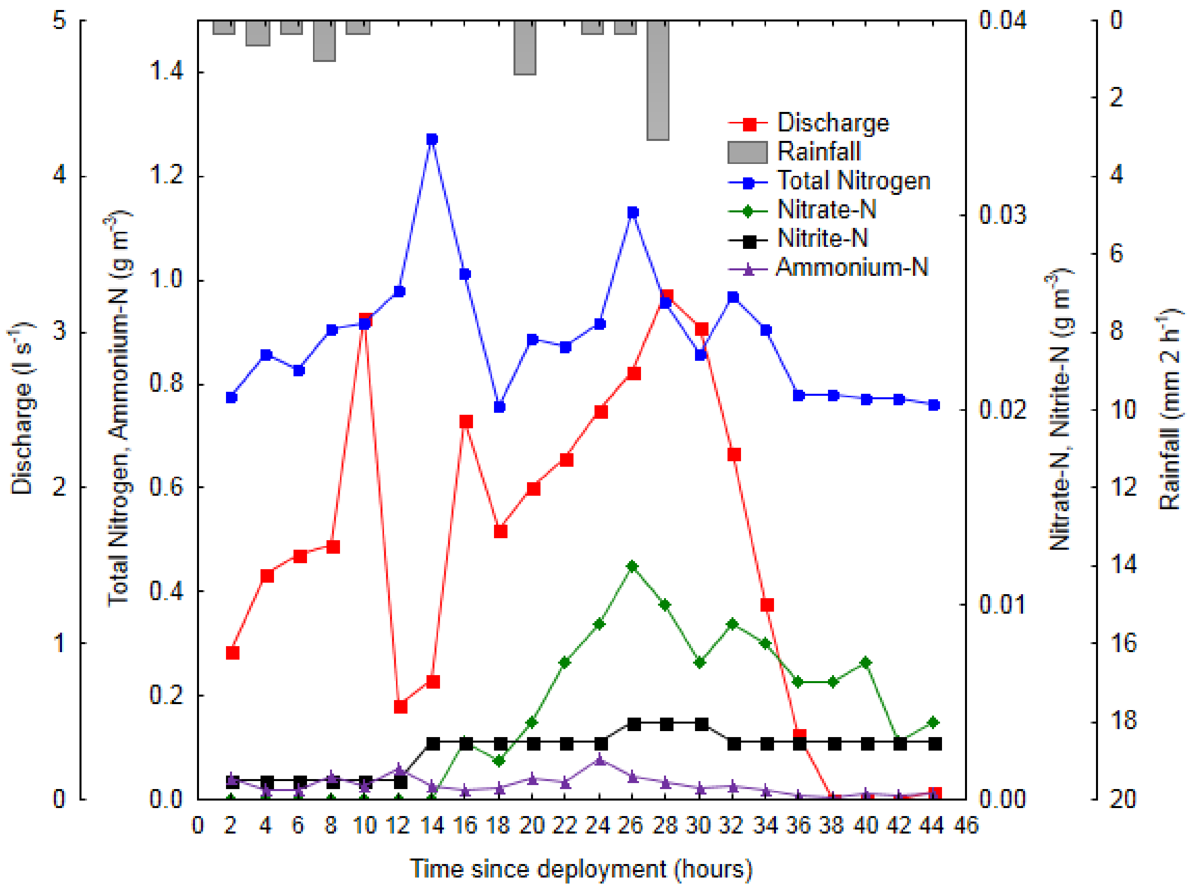

Figure 17. Changes in total nitrogen, ammonium-N, nitrate-N, nitrite-N, discharge and rainfall at the Mangakaware 05 monitoring site during the January 2014 storm event. Sampling is at 2 h intervals commencing at 11:45 h on 20 January 2014.

Table 5. Results of storm inflow point monitoring conducted on 22 January 2014. A discharge of 0.00 l s^{-1} indicates standing water but no flow, "Dry" indicates no water present. N/A indicates no result available as the water was too shallow to retrieve an uncontaminated sample for analysis.

Water Quality Variables	Rotopiko North 01	Rotopiko North 02	Rotopiko South 02	Mangakaware 01	Mangakaware 05	Mangakaware 06
Volatile Suspended Solids (g m^{-3})	N/A	N/A	N/A	N/A	6	12
Total Suspended Solids (g m^{-3})	N/A	N/A	N/A	N/A	11	12
Inorganic Suspended Solids (g m^{-3})	N/A	N/A	N/A	N/A	5	<11
Total Nitrogen (g m^{-3})	N/A	N/A	N/A	N/A	0.400	1.000
Total Ammoniacal-N (g m^{-3})	N/A	N/A	N/A	N/A	0.015	0.035
Nitrite-N (g m^{-3})	N/A	N/A	N/A	N/A	0.004	<0.020
Nitrate-N (g m^{-3})	N/A	N/A	N/A	N/A	0.010	<0.020
Nitrate-N + Nitrite-N (g m^{-3})	N/A	N/A	N/A	N/A	0.010	<0.020
Total Kjeldahl Nitrogen (g m^{-3})	N/A	N/A	N/A	N/A	0.420	0.950
Dissolved Reactive Phosphorus (g m^{-3})	N/A	N/A	N/A	N/A	0.026	0.064
Total Phosphorus (g m^{-3})	N/A	N/A	N/A	N/A	0.114	0.123
Stream Flow (l s^{-1})	Dry	Dry	Dry	Dry	1.28	0.00

The proportional changes in TSS, TN and TP in relation to base flow concentrations prior to commencement of rainfall were calculated for Mangakaware 06 (September 2012), Mangakaware 05 (May 2013) and Rotopiko South 02 (September 2013) storm events (Figure 18). Data for the Mangakaware 05 (January 2014) are omitted as there was no measureable discharge prior to the commencement of rainfall. This analysis illustrates the variety and magnitude of water quality responses to storm events. Significant changes in TN, TP and TSS concentrations occurred relatively quickly (1–2 h), and concentrations then returned to baseflow flow levels over similar duration to the increases. It also demonstrates different responses between TN, TP and TSS between major discharge events.

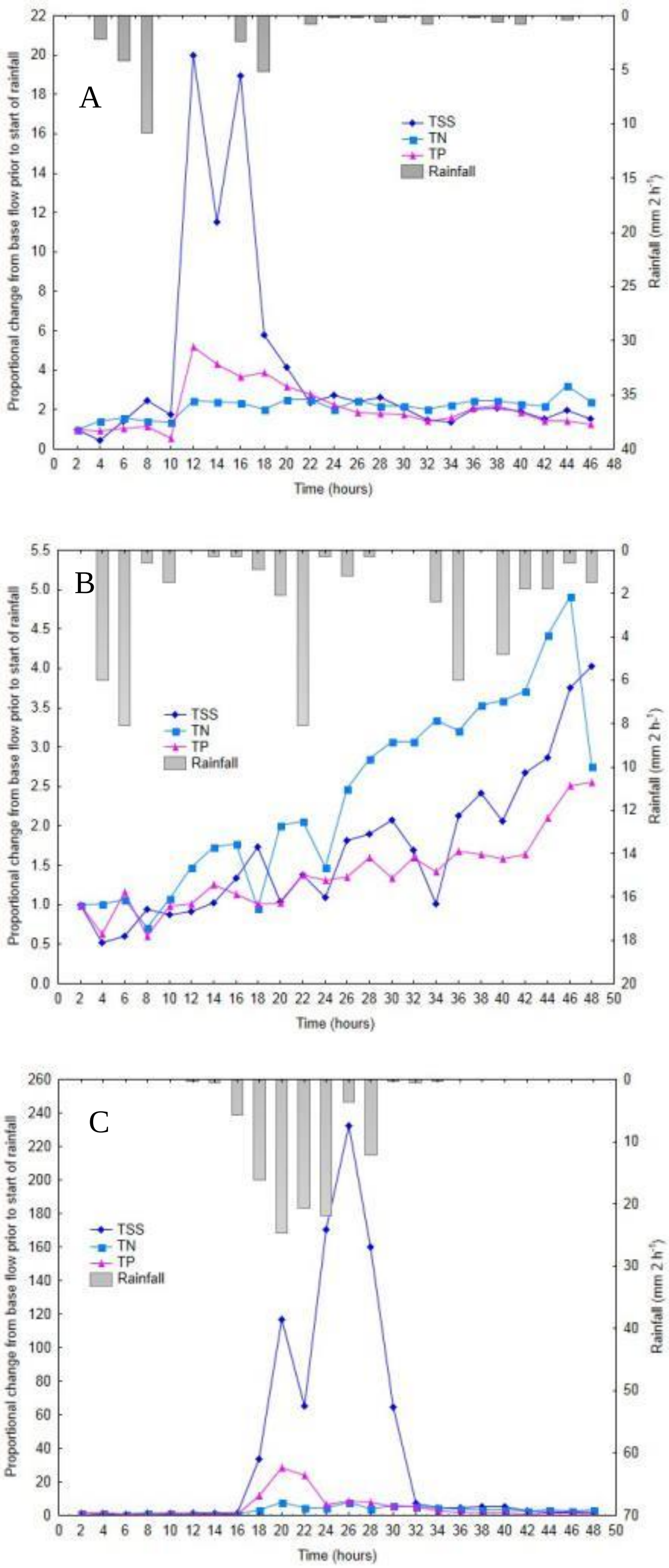

Figure 18. Proportional changes in TSS, TN and TP in relation to base flow concentrations for A) Mangakaware 06 (September 2012), B) Mangakaware 05 (May 2013) and C) Rotopiko South 02 (September 2013). Data for the Mangakaware 05 inflow (January 2014) are omitted as there was no measureable discharge prior to the commencement of rainfall.

Discussion

Rates of delivery of sediment and nutrients to lakes can vary widely between baseflow and stormflow conditions (e.g. Abell et al. 2013). In New Zealand, research has focused on discharges of natural stream and river systems. These systems may be subject to less variation in composition between stormflow and baseflow than artificially constructed drainage systems that receive runoff from intensively farmed agricultural catchments and are designed specifically to provide a rapid conduit for this surface water runoff. Not only is the composition of the inflows highly variable, but also the discharge, i.e., these systems are highly flashy. In our study, variability in discharge was likely to have been accentuated by the very low summer rainfall in 2012–12 and 2013–14, which resulted in complete drying of some drains.

Total suspended solids concentrations were generally within a low to moderate range (<3 to 15 g m^{-3}) for most grab samples but there were occasional large peaks. These peaks relate to the following samples: Rotopiko North 01 in April 2013 (187 g m^{-3}), Rotopiko South 02 in October 2013 (60 g m^{-3}), Rotopiko South 02 in December 2012 (53 g m^{-3}) and April 2013 (25 g m^{-3}), Mangakaware 01 in April 2012 (28 g m^{-3}) and April 2014 (42 g m^{-3}), Mangakaware 06 in February 2013 (106 g m^{-3}), and Mangakaware 05 in February 2013 (106 g m^{-3}) and April 2013 (25 g m^{-3}). The peaks commonly occurred during summer-autumn, when there was minimal or no discharge (e.g., Rotopiko North 01 had TSS of 187 g m^{-3} in April 2013 when the discharge was only 0.52 l s^{-1}). During this time there was a proliferation of filamentous algae and suspended material in the inflow. The dominant component of TSS was volatile material, i.e. of organic origin. The high levels of suspended solids observed in this sample were likely to be due to suspended fine organic particulates derived from decaying plant material that had previously grown within the drain. Concentrations of inorganic suspended solids were also elevated in these samples. We attribute the high levels of inorganic material at this time to a large mass of fine inorganic sediment that had settled onto the dense in-stream vegetation over summer (e.g., onto the plant leaves). The lack of strong flushing flows likely prevented this material from being washed off the plants. Whilst due care was taken to try to avoid any disturbance when samples were taken, it is possible that some of the fine sediments in the inflow channel, and particularly material associated with filamentous algae, may have been liberated and could therefore have artificially elevated suspended solids concentrations in these samples.

By contrast, the high-frequency samples associated with storm events had less organic suspended sediment and were more clearly associated with mobilisation of inorganic sediments from the catchment. Given the semi-continuous nature of the high frequency samples, we were able to capture some extreme changes in sediment and nutrient fluxes due to stormflows. For example, at the peak of the Rotopiko South 02 storm event in September 2013 there was more than a 200-fold increase in the rate of delivery of suspended sediments through the drain. Over a 24-h duration suspended sediments, total phosphorus and total nitrogen mass fluxes were elevated by c. 70-, 8- and 4-fold respectively during this event, compared with baseflow conditions. In other words, this one stormflow event produced the equivalent of 70 days of baseflow suspended sediment.

The increased levels of inorganic suspended solids associated with some of the TSS peaks (e.g. Mangakaware 05 in February 2013, ISS = 31 g m^{-3}) were associated with moderate to strongly elevated total phosphorus concentrations (up to 0.37 g m^{-3}). This suggests that much of the phosphorus in stormflows was associated with particulate material, as the dissolved organic phosphorus component was likely to be small and concentrations of dissolved reactive phosphorus also appeared to be affected little by changes in discharge. Suspended sediments can potentially adsorb phosphorus as well as liberate it, depending on the phosphorus equilibrium concentration of the sediments (Peryer-Fursdon 2014) and prevailing water conditions (e.g., redox, pH, temperature). Suspended sediments represent the primary mechanism for transport of phosphorus through drains and into lake ecosystems. The ultimate fate of this phosphorus is not known but it could be re-worked within the lake and made biologically available through a range of processes (e.g., desorption from sediments when lake phosphorus concentrations are low, high or low pH, and anoxia either in the water column, within bottom sediments or in microzones within suspended organic particles (Paerl and Pinckney 1996).

Nitrate was usually the dominant form of inorganic nitrogen (over ammonium and nitrite), suggesting that water in the drains was reasonably well oxidised (i.e. not anoxic) and that soils in the drain catchments may be becoming increasingly mineralised, gradually losing their natal peat character in which ammonium may be the dominant form of inorganic ntirogen. Exceptions occurred in summer, for example at Rotopiko South 02 in April 2013, when the ammonium concentration exceeded 0.5 mg N l^{-1}, possibly when decaying vegetation produced a lot of ammonium and there was little nitrification in the poorly oxidised drain water. By contrast, at this time there were very low dissolved inorganic nitrogen concentrations in Rotopiko North 01 and 02, most likely as a result of uptake by the large plant biomass present in the drains at this time.

During both summers we observed inflows in which there was no obvious flow and some that dried up completely. This progression is clearly demonstrated by the continuous discharge calculated from Mangakaware 05 and 06 water level recorders. The two stations showed highly synchronous discharge but station 05 had approximately 4–5 times higher discharge than station 06. The intermittent discharge (c. 5 am to 10 am) at the Mangakaware 05 monitoring site during late summer and early autumn of 2014 is intriguing. The intermittent nature of this discharge suggests that it is unlikely to be natural, with flows peaking at c. 20 l s^{-1}. The continuous level recorder at Rotopiko South 02 indicated a similar pattern to Mangakaware of low discharge or none at all during summer, but with a more abrupt transition from reasonably continuous discharge to no discharge. We hypothesise that this rapid transition was related to artificial control of water levels, either in the drain or the lake.

A caveat should be added to evaluation of the discharges for the Rotopiko South 02 site. A critical period of reduced water level between November and early December 2012 was not recorded because of a data logger malfunction. Other points to note in relation to the variability of the inflows are that there was prolific plant growth – both filamentous algae and macrophytes – in most drains during summer, and that the morphology of some drains appeared to change quite substantially between sampling periods. For example, Rotopiko South 02 inflow was deep and appeared to have been excavated prior to summer 2012–13. It dried up over the 2012–13 summer, but in the April 2013 sampling it had substantially reduced channel volume due to a deep (c. 30 cm), soft layer of sediment that may have been related to bank instability from prior deep excavation of the drain. The only other drain excavated was Mangakaware 05. This excavation appeared to have been undertaken around the same time. This drain did not show the same degree of sedimentation possibly due to greater stability, gradient and higher mineral content of the drain channel compared with the peat drain of Rotopiko South 02.

The above observations illustrate some of the inherent difficulties of periodic inflow samplings over extended time intervals. Channel morphology can change rapidly depending on recent history of loads and stream gauging, (as undertaken in our sampling routine) may be required each time if water samples are being used for the purpose of developing estimates of nutrient delivery to lake ecosystems. Most drain maintenance and excavation is carried out to aid water flow and deliver water as rapidly as possible into the receiving environment (i.e., lakes). Plants grow rapidly over summer under low discharges and then decay or are scoured by increasing discharge in winter. Samples can potentially be taken without knowledge of hydrological stage if there is no water level monitoring with which to provide a semi-continuous measurement of discharge and without knowledge of maintenance schedules in drains which will alter connectivity and transport of water into the lake receiving environment. We therefore consider that meaningful spot sampling of inflows cannot be carried out without prior knowledge of drain maintenance, plant growth and decay, and sediment mass in the drain. A log of these details would be valuable, including some attempt to determine sediment mass within drains and what might be removed during maintenance.

Our approach of monitoring inflow water levels continuously, conducting periodic stream gauging, and identifying discrete periods of stormflow for automated high-frequency water sample collection for nutrients and suspended solids has provided valuable insights into the highly dynamic nature of drains. Further work could be done to include a complete storm-event sequence; starting with base flow, capturing the storm-flow peak and then a return to baseflow; this would provide more detailed information on comparative changes in nutrient and sediment loads and the time-frame on which these changes occur. At present, no record exists for a single storm event with variations in discharge and water quality between farm drains which have sub-catchments of different soil types. Nor is there a clear understanding of the seasonal differences in nutrient loads to farm drains during storm events. Another target could be monitoring downstream of an area where drain maintenance was being carried out to determine the relative impact of drain disturbance to lake systems. Our work has demonstrated the important role that drain maintenance may have on the integrity of the drain itself, as well as its function, and maintenance schedules appear to be targeted almost solely to maintaining the drain as a water transport conduit rather for specific environmental purposes such as protection of downstream lakes.

Capture of a substantial rainfall event at Mangakaware 06 on 3–5 September 2012 yielded some interesting and perhaps unexpected results for suspended sediments. The major peak of suspended solids (both inorganic and organic) was more closely aligned with very intense rainfall early on during the 48-h high-frequency monitoring period, rather than with the overall trend of increasing discharge over the entire sampling period. This result (suspended solids concentrations up to c. 120 mg L^{-1}) suggests dominance of localised sources of sediment input to the drain rather than more diffuse inputs from a more extensive area of the catchment. We hypothesise that localised sources of this nature could be from exposed riparian areas adjacent to the drain or from concentrated sediment pools associated with stock crossings (which may explain increases in volatile suspended solids concurrently with inorganic suspended solids in this particular case). These localised areas of concentrated input are often referred to as 'critical souce areas' (McDowell and Houlbrooke 2009) and represent an opportunity to achieve signficant environmental gains more easily than more broadly dispersed areas of the agricultural landscape which have lower sediment and nutrient yields.

The second high-frequency monitoring event, at Mangakaware 05 from 17–19 May 2013, was during a period of progressively increasing discharge, from c. 30 to 70 l s^{-1} over 48 h. It was associated with an approximate doubling of suspended solids, though concentrations in all samples remained moderate at less than 10 mg l^{-1}. This event demonstrates what may be considered a more typical sequence of increasing discharge and increasing suspended sediment (cf. Abell et al. 2013). A comparison with the Rotopiko samples suggests that sediments are more likely to be mobilised in a peat catchment than a clay mineral catchment.

The current monitoring programme has identified some major challenges due to variability in drain inflows, as well as due to the drain maintenance schedules discussed above. This variability is driven primarily by climate, drain maintenance regimes, soil composition and drain capacity in relation to catchment area. At a seasonal time scale, single drains can vary from continuous moderate flow in winter to standing water and even completely dry during late summer. At higher frequency, intense rainfall events may bring about large changes in discharge and composition, and the mulitplicative effect of these variables in terms of downstream loads of suspended sediment and nutrients (i.e. load = discharge x concentration) suggests that these events should be a focus for future work. This would include the development of rating curves and other robust methodologies for estimating discharge that have a large influence on calculating annual loads. Climate also plays a role in growth of vegetation in drains, with increased water temperature and solar radiation in summer contributing to rapid growth of aquatic plants and filamentous algae. This vegetation appears to play an important role in trapping fine inorganic sediments but its influence will be temporary as sediments will be resuspended when plants decay or with elevated discharge velocities during storm events.

The drain maintenance schedule may also be critical in relation to these plants. Removing plants from drains prior to their decay, and before larger winter flows resuspend sediment, provides an opportunity for reducing lake inputs of both inorganic sediments and decaying plant material. Drain maintenance is important for preventing flooding of surrounding farmland but it will inevitably lead to temporarily elevated concentrations of suspended sediments and nutrients to the downstream receiving environment. Drain maintance becomes less of an issue when drains are part of the peat lake riparian area that is retired. Drains will eventually fill in and discharges will then be distributed over a broader riparian area which will become increasingly boggy and periodically inundated with water. These areas are likely to provide an increased capacity to attenuate sediment and nutrients (e.g. through sedimentation for phosphorus in particular and denitrification for nitrogen).

We consider that the complexities around climate, drain maintenance, critical source areas for generation of sediment and phosphorus, and nutrient transformation cycles, necessitate very careful considerations related to monitoring of drains and recommendations on drain maintenance. Scientists, planners and farmers may be able to offer reasoning and insights into how best to tackle a significant environmental issue relating to the health and welbeing of downstream peat lakes that are sensitive to inputs of nutients and sediment. The current situation needs to be addressed as the ecological state of many riverine and peat lakes in the Waikato region is compromised (McDowell et al. 2009; Abell et al. 2010; McDowell et al. 2013; PCE 2013). In this context it is concerning that stormflows induce large variations in sediment and nutrients, transported in surface flows to the Rotopiko lake system. This system is one of the few in the Waikato region where there are native macrophytes beds persist. The need to address the issue of ongoing deterioration of water quality and ecological health of lowland lakes in the Waikato region will be reinforced through the National Objectives Framework of the National Policy Statement for Freshwater Management, which will set a minimum regulatory standard for lake water quality. Many lowland lakes in the region will not meet the ‘bottom line’ for water quality. Actions to address this situation must transcend boundaries that have traditionally hindered improvements in lake water quality such as perceived lack of knowledge and certainty of outcomes, setting of catchment load lmits and targets, and delineation of responsibilities for actions. This study has contributed information which indicates that mitigation of sediments and nutrients in stormflows should be a major focus of future restoration work and that quantifying these inputs is likely to be important in improving the accruacy of nutrients load calculations and model simulations.

Recommendations

We consider that it is important to continue to monitor the drains used in this study so that a better quantitative understanding can be developed between nutrient and sediment loads in farm drains and associated factors such as land use, drainage maintenance activities and climate variability. On the basis of relatively high rates of transport of sediment and nutrients and the fugacious nature of storm flows, high-frequency data should be considered an essential part of the monitoring. High-frequency monitoring will also be important in providing data for modelling purposes; development of catchment models will be necessary to interpolate information from measurements and to extrapolate results more widely, including to other lake catchments. The relative contribution to the lakes of flow, sediment and nutrients derived from groundwater is largely unknown, and while this situation persists it will be difficult to develop accurate water, nutrient and sediment budgets for the lakes. Investigations of groundwater contributions and dynamics would provide valuable additional data in the development of catchment modells and management decisions.

Key areas specific to the Rotopiko and Mangakaware catchments are management of peat soils, drain maintenance and mitigation of impacts from high intensity rainfall events. Peat soils appear to be susceptible to mobilisation of material during rainfall events. Therefore, careful management is needed during cropping or re-grassing to prevent increased sediment loads entering the lake inflows. This may involve the planting of riparian strips or leaving a wide margin of undistubed ground next to inflows during cropping, to help intercept overland flows. As discussed above, planting of riparian margins will also help reduce sediment loss from drain maintanance; alternatively diversion of inflows into sedimentation areas during drain maintenace will also help reduce sediment loads. Specifically, sedimentation basins may have a key role in drain maintenance, to act as repositories for sediments mobilised during drain maintenance, with the sedimentation basins themselves also carefully maintained. This can be facilitated by further research to identify areas that are susceptible to sediment loss and examining the dynamics of sediment loss in varying rainfall events, to help with modelling of catchment processes.

We recommend a workshop be convened amongst technical experts to better quantify research needs and ensure that clear and consistent recommendations are made by regulatory agencies to farmers. A workshop will also provide an opportunity to develop guidelines for monitoring stratiges and techniques to ensure adequate, high resolution data is gathered, suitable for modelling purposes. It is recommended that specific consideration be given to hydrological methodologies for measuring and calculating discharge and loads. This approach will lead to the development of clear guidelines on farm practices to reduce sediment transportation in lake catchments.

Acknowledgements

Additional support for this project was provided through the Lake Biodiversity Restoration program funded by the Ministry of Business, Innovation and Employment (Contract UOWX0505). Support with fieldwork was provided by Lee Laboyrie, Warrick Powrie, Claire Heiwy, Jeremy Garrett-Walker and Jasmine Whanga. We also thank Tracie Dean-Spears, Bill Vant, Bruno David and Aroon Parshotam for reviewing this document.

References

Abell JM, Özkundakci, D, Hamilton DP 2010. Nitrogen and phosphorus limitation of phytoplankton growth in New Zealand lakes: implications for eutrophication control. *Ecosystems* 13. 966-977.

Abell J, Hamilton DP, Rutherford JC, 2013. Temporal and spatial variations in sediment, nitrogen and phosphorus transport in stream inflows to a large eutrophic lake. *Environmental Science Processes and Impacts* 15: 1137-1152.

Barnes G, 2002. *Water Quality Trends in Selected Shallow Lakes in the Waikato Region, 1995-2001*. Environment Waikato Technical Report 2002/11. Environment Waikato. Hamilton. 31 pp.

Cichota R, Snow VO, 2009. Estimating nutrient loss to waterways-an overview of models of relevance to New Zealand pastoral farms. *New Zealand Journal of Agricultural Research* 52: 239-260.

Dewes A, 2014. Economic resilience and environmental performance of dairy farms in the upper Waikato region. MSc thesis, University of Waikato, Hamilton.

Jenkins B, Vant B, 2007. *Potential for Reducing the Nutrient Loads from the Catchments of Shallow Lakes in the Waikato Region*. Environment Waikato Technical Report 2006/54. Environment Waikato. Hamilton. 29 pp.

McDowell RW, Monaghan RM, Wheeler D, 2005. Modelling phosphorus losses from pastoral farming systems in New Zealand. *New Zealand Journal of Agricultural Research* 48: 131-141.

McDowell, RW, Houlbrooke DJ, 2009. Management options to decrease phosphorus and sediment losses from irrigated cropland grazed by cattle and sheep. *Soil Use and Management* 25: 224-233.

McDowell RW, Larned ST, Houlbrooke DJ 2009. Nitrogen and phosphorus in New Zealand streams and rivers: control and impact of eutrophication and the influence of land management. *New Zealand Journal of Marine and Freshwater Research* 43: 985-995.

McDowell RW, Snelder TH, Cox N, Booker DJ, Wilcock RJ 2013. Establishment of reference or baseline conditions of chemical indicators in New Zealand streams and rivers relative to present conditions. *Marine and Freshwater Research* 64: 387-400.

Monaghan RM, Hedley MJ, Di HJ, McDowell RW, Cameron KC, Ledgard SF, 2007. Nutrient management in New Zealand pastures— recent developments and future issues. *New Zealand Journal of Agricultural Research* 50: 181-201.

Oenema O, Kros H, de Vries W, 2003. Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental policies. *European Journal of Agronomy* 20: 3–16.

Paerl HW, Pinckney JL, 1996. A mini-review of microbial consortia: their roles in aquatic production and biogeochemical cycling. *Microbial Ecology* 31: 225-247.

Parliamentary Commissioner for the Environment, 2012. *Water Quality in New Zealand: Understanding the Science*. Office of the Parliamentary Commissioner for the Environment, Wellington, 93 pp.

Parliamentary Commissioner for the Environment. 2013. *Water Quality in New Zealand: Land Use and Nutrient Pollution.* Office of the Parliamentary Commissioner for the Environment, Wellington, 82 pp.

Appendices

Appendix 1

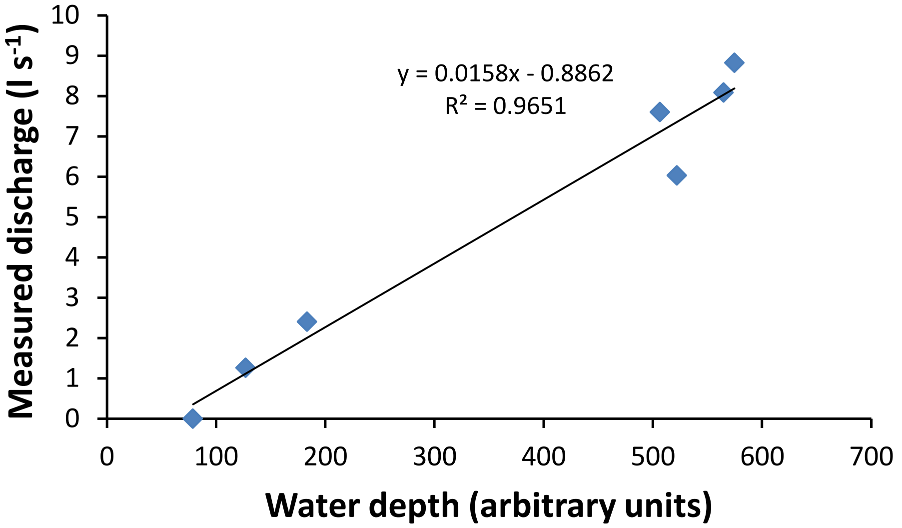

Figure A1.1. Relationship between measured discharge (y) and water depth (x) for the Rotopiko South 02 sampling site. The linear regression equation (y = 0.0158x – 0.8862) derived from this plot was used to calculate discharge from measured water levels.

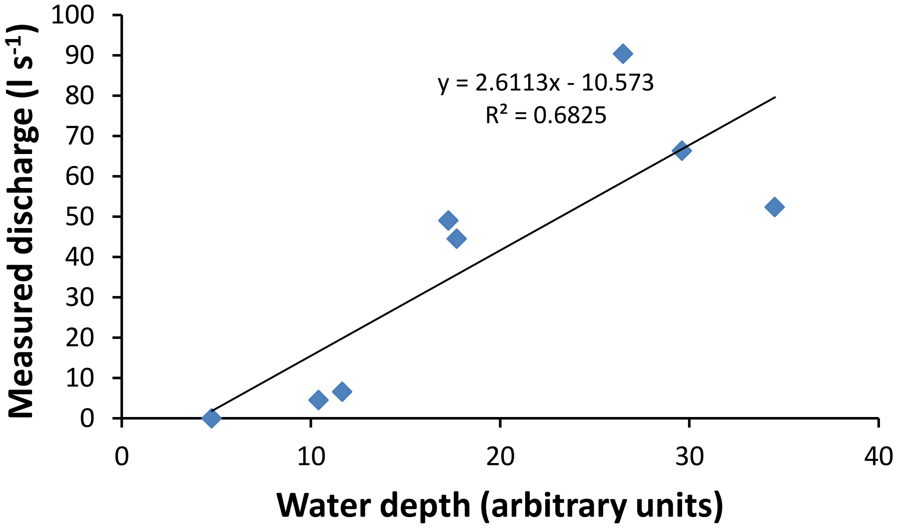

Figure A1.2. Relationship between measured discharge (y) and water depth (x) for the Mangakaware 05 sampling site. The linear regression equation (y = 2.6113x – 10.573) derived from this plot was used to calculate discharge from measured water levels.

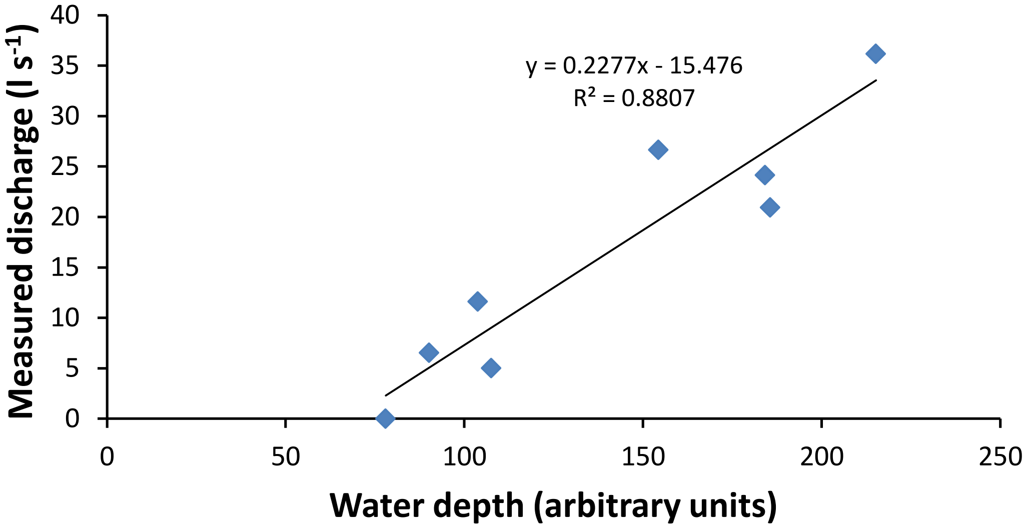

Figure A1.3. Relationship between measured discharge (y) and water depth (x) for the Mangakaware 06 sampling site. The linear regression equation (y = 0.2277x – 15.476) derived from this plot was used to calculate discharge from measured water levels.

Appendix 2

Table A2.1. Water quality variables and discharge for Rotopiko North 01, monitored from April 2012 - April 2014. A discharge of 0.00 ls^{-1} indicates standing water but no flow, "Dry" indicates no water present, N/A indicates no result available as the water was too shallow to retrieve an uncontaminated sample for analysis. Results from storm event point sampling are presented in bold.

Water Quality Variables	20 Apr. 2012	20 Jun. 2012	22 Aug. 2012	3 Sep. 2012	23 Oct. 2012	12 Dec. 2012	20 Feb. 2013	23 Apr. 2013	19 May 2013	5 Jul. 2013	28 Aug. 2013	13 Sep. 2013	31 Oct. 2013	13 Dec. 2013	22 Jan. 2014	25 Feb. 2014	24 Apr. 2014
Volatile Suspended Solids (g m^{-3})	N/A	7	<3	**<8**	<3	N/A	N/A	96	**6**	15	34	**3**	N/A	7	**N/A**	N/A	N/A
Total Suspended Solids (g m^{-3})	N/A	15	3	**18**	3	N/A	N/A	187	**13**	16	73	**8**	N/A	12	**N/A**	N/A	N/A
Inorganic Suspended Solids (g m^{-3})	N/A	8	<5	**13**	<5	N/A	N/A	90	**6**	<5	38	**5**	N/A	5	**N/A**	N/A	N/A
Total Nitrogen (g m^{-3})	N/A	1.620	1.350	**3.100**	1.210	N/A	N/A	2.700	**1.230**	1.790	0.910	**2.100**	N/A	1.540	**N/A**	N/A	N/A
Total Ammoniacal-N (g m^{-3})	N/A	0.125	0.057	**0.790**	0.062	N/A	N/A	<0.010	**0.024**	0.017	<0.010	**0.030**	N/A	0.033	**N/A**	N/A	N/A
Nitrite-N (g m^{-3})	N/A	0.010	<0.002	**0.026**	0.004	N/A	N/A	0.006	**<0.002**	0.002	<0.002	**0.003**	N/A	0.003	**N/A**	N/A	N/A
Nitrate-N (g m^{-3})	N/A	0.830	0.980	**0.620**	0.460	N/A	N/A	0.005	**0.103**	0.980	0.280	**1.390**	N/A	0.009	**N/A**	N/A	N/A
Nitrate-N + Nitrite-N (g m^{-3})	N/A	0.840	0.980	**0.640**	0.470	N/A	N/A	0.012	**0.105**	0.980	0.280	**1.390**	N/A	0.012	**N/A**	N/A	N/A
Total Kjeldahl Nitrogen (g m^{-3})	N/A	0.780	0.360	**2.500**	0.740	N/A	N/A	2.600	**1.130**	0.810	0.630	**0.700**	N/A	1.520	**N/A**	N/A	N/A
Dissolved Reactive Phosphorus (g m^{-3})	N/A	0.015	0.008	**0.036**	0.022	N/A	N/A	0.030	**0.015**	0.010	0.007	**0.014**	N/A	0.053	**N/A**	N/A	N/A
Total Phosphorus (g m^{-3})	N/A	0.065	0.023	**0.195**	0.059	N/A	N/A	0.290	**0.036**	0.044	0.092	**0.038**	N/A	0.210	**N/A**	N/A	N/A
Stream Flow (l s^{-1})	0.00	1.30	3.77	**1.56**	2.70	0.00	Dry	0.52	**1.60**	0.48	0.36	**1.44**	0.00	0.25	**Dry**	Dry	Dry

Table A2.2. Water quality variables and discharge for Rotopiko North 02, monitored from April 2012 - April 2014. A discharge of 0.00 l s^{-1} indicates standing water but no flow, "Dry" indicates no water present, N/A indicates no result available as the water was too shallow to retrieve an uncontaminated sample for analysis. Results from storm event point sampling are presented in bold.

Water Quality Variables	20 Apr. 2012	20 Jun. 2012	22 Aug. 2012	3 Sep. 2012	23 Oct. 2012	12 Dec. 2012	20 Feb. 2013	23 Apr. 2013	19 May 2013	5 Jul. 2013	28 Aug. 2013	13 Sep. 2013	31 Oct. 2013	13 Dec. 2013	22 Jan. 2014	25 Feb. 2014	24 Apr. 2014
Volatile Suspended Solids (g m^{-3})	N/A	10	<3	**10**	8	N/A	N/A	4	**10**	<3	<3	**<3**	23	21	**N/A**	N/A	N/A
Total Suspended Solids (g m^{-3})	N/A	23	<3	**12**	12	N/A	N/A	5	**12**	<3	<3	**3**	60	38	**N/A**	N/A	N/A
Inorganic Suspended Solids (g m^{-3})	N/A	13	<5	**<5**	5	N/A	N/A	<5	**<5**	<5	<5	**<5**	36	17	**N/A**	N/A	N/A
Total Nitrogen (g m^{-3})	N/A	2.600	2.500	**3.700**	2.100	N/A	N/A	2.900	**3.700**	1.710	1.300	**3.900**	1.420	2.100	**N/A**	N/A	N/A
Total Ammoniacal-N (g m^{-3})	N/A	0.067	0.014	**0.149**	0.042	N/A	N/A	0.023	**0.149**	0.061	0.050	**0.100**	0.055	0.220	**N/A**	N/A	N/A
Nitrite-N (g m^{-3})	N/A	0.014	<0.002	**0.006**	0.006	N/A	N/A	0.010	**0.006**	0.003	<0.002	**0.008**	<0.002	0.010	**N/A**	N/A	N/A
Nitrate-N (g m^{-3})	N/A	1.660	2.000	**2.500**	1.420	N/A	N/A	1.710	**2.500**	0.850	0.640	**3.100**	0.162	0.028	**N/A**	N/A	N/A
Nitrate-N + Nitrite-N (g m^{-3})	N/A	1.670	2.000	**2.506**	1.426	N/A	N/A	1.720	**2.500**	0.850	0.640	**3.100**	0.164	0.039	**N/A**	N/A	N/A
Total Kjeldahl Nitrogen (g m^{-3})	N/A	0.960	0.510	**1.194**	0.710	N/A	N/A	1.180	**1.240**	0.850	0.670	**0.820**	1.260	2.000	**N/A**	N/A	N/A
Dissolved Reactive Phosphorus (g m^{-3})	N/A	0.030	0.024	**0.015**	0.021	N/A	N/A	0.030	**0.015**	0.013	0.007	**0.035**	0.023	0.053	**N/A**	N/A	N/A
Total Phosphorus (g m^{-3})	N/A	0.133	0.036	**0.025**	0.081	N/A	N/A	0.041	**0.025**	0.016	0.021	**0.058**	0.230	0.210	**N/A**	N/A	N/A
Stream Flow (l s^{-1})	0.00	0.81	4.80	**2.96**	5.08	0.00	Dry	0.98	**0.90**	0.48	0.76	**7.04**	0.00	0.41	**Dry**	Dry	Dry

Table A2.3. Water quality variables and discharge for Rotopiko South 02, monitored from April 2012 - April 2014. A discharge of 0.00 l s^{-1} indicates standing water but no flow, “Dry” indicates no water present, N/A indicates no result available as the water was too shallow to retrieve an uncontaminated sample for analysis. Results from storm event point sampling are presented in bold.

Water Quality Variables	20 Apr. 2012	20 Jun. 2012	22 Aug. 2012	3 Sep. 2012	23 Oct. 2012	12 Dec. 2012	20 Feb. 2013	23 Apr. 2013	19 May 2013	5 Jul. 2013	28 Aug. 2013	13 Sep. 2013	31 Oct. 2013	13 Dec. 2013	22 Jan. 2014	25 Feb. 2014	24 Apr. 2014
Volatile Suspended Solids (g m^{-3})	4	4	<3	**<5**	6	43	N/A	15	**4**	3	<3	**<3**	4	10	**N/A**	N/A	N/A
Total Suspended Solids (g m^{-3})	6	7	<3	**7**	11	54	N/A	25	**6**	4	<3	**3**	9	14	**N/A**	N/A	N/A
Inorganic Suspended Solids (g m^{-3})	<5	<5	<5	**<8**	6	11	N/A	10	**<5**	<5	<5	**<5**	<6	<9	**N/A**	N/A	N/A
Total Nitrogen (g m^{-3})	1.940	2.900	1.580	**1.640**	1.630	5.700	N/A	5.100	**5.200**	2.200	1.700	**4.100**	2.000	2.100	**N/A**	N/A	N/A
Total Ammoniacal-N g m^{-3})	0.380	0.580	0.240	**0.440**	0.220	0.760	N/A	0.520	**0.900**	0.047	0.260	**0.260**	0.290	0.220	**N/A**	N/A	N/A
Nitrite-N (g m^{-3})	0.007	0.013	0.005	**0.006**	0.004	0.003	N/A	0.036	**0.007**	0.008	<0.002	**0.008**	0.002	<0.020	**N/A**	N/A	N/A
Nitrate-N (g m^{-3})	0.050	0.700	0.470	**0.066**	0.068	0.024	N/A	1.990	**2.100**	0.210	0.057	**2.300**	0.014	<0.020	**N/A**	N/A	N/A
Nitrate-N + Nitrite-N (g m^{-3})	0.057	0.713	0.475	**0.072**	0.072	0.027	N/A	2.026	**2.100**	0.220	0.058	**2.300**	0.017	<0.020	**N/A**	N/A	N/A
Total Kjeldahl Nitrogen (g m^{-3})	1.880	2.200	1.100	**1.570**	1.550	5.600	N/A	3.100	**3.100**	2.000	1.600	**1.760**	2.000	2.100	**N/A**	N/A	N/A
Dissolved Reactive Phosphorus (g m^{-3})	0.009	0.031	0.007	**0.015**	0.022	0.021	N/A	0.028	**0.014**	0.008	0.004	**0.009**	0.016	0.017	**N/A**	N/A	N/A
Total Phosphorus (g m^{-3})	0.044	0.093	0.028	**0.050**	0.065	0.370	N/A	0.156	**0.04**	0.020	0.018	**0.038**	0.064	0.089	**N/A**	N/A	N/A
Stream Flow (l s^{-1})	0.00	8.08	6.73	**7.60**	8.82	0.00	Dry	1.26	**2.40**	0.92	1.08	**40.82**	0.00	0.00	**Dry**	Dry	0.00

Table A2.4. Water quality variables and discharge for Mangakaware 01, monitored from April 2012 – April 2014. "A discharge of 0.00 l s^{-1} indicates standing water but no flow, "Dry" indicates no water present, N/A indicates no result available as the water was too shallow to retrieve an uncontaminated sample for analysis. Results from storm event point sampling are presented in bold.

Water Quality Variables	20 Apr. 2012	20 Jun. 2012	22 Aug. 2012	3 Sep. 2012	23 Oct. 2012	12 Dec. 2012	20 Feb. 2013	23 Apr. 2013	19 May 2013	5 Jul. 2013	28 Aug. 2013	13 Sep. 2013	31 Oct. 2013	13 Dec. 2013	22 Jan. 2014	25 Feb. 2014	24 Apr. 2014
Volatile Suspended Solids (g m^{-3})	17	<3	<3	**<3**	<3	<3	N/A	5	**<3**	<3	4	**<3**	<3	<3	**N/A**	N/A	N/A
Total Suspended Solids (g m^{-3})	28	<3	<3	**<3**	<3	5	N/A	12	**<3**	3	9	**<3**	10	5	**N/A**	N/A	N/A
Inorganic Suspended Solids (g m^{-3})	12	<5	<5	**<5**	<5	<5	N/A	7	**<5**	<5	6	**<5**	7	<5	**N/A**	N/A	N/A
Total Nitrogen (g m^{-3})	2.300	2.800	3.400	**3.500**	3.100	1.920	N/A	1.120	**2.200**	1.580	2.800	**3.000**	2.700	2.100	**N/A**	N/A	N/A
Total Ammoniacal-N (g m^{-3})	0.016	0.028	<0.010	**0.018**	<0.010	0.018	N/A	0.082	**0.097**	0.064	0.029	**0.044**	0.014	0.029	**N/A**	N/A	N/A
Nitrite-N (g m^{-3})	0.003	0.006	<0.002	**<0.002**	<0.002	0.002	N/A	0.007	**0.029**	0.005	<0.002	**0.004**	<0.002	<0.002	**N/A**	N/A	N/A
Nitrate-N (g m^{-3})	1.920	2.500	3.200	**3.300**	2.900	1.680	N/A	0.720	**1.860**	0.900	2.200	**2.700**	2.600	1.880	**N/A**	N/A	N/A
Nitrate-N + Nitrite-N (g m^{-3})	1.923	2.506	3.300	**3.300**	2.900	1.682	N/A	0.727	**1.890**	0.900	2.200	**2.700**	2.600	1.880	**N/A**	N/A	N/A
Total Kjeldahl Nitrogen (g m^{-3})	0.420	0.290	0.150	**0.200**	0.220	0.230	N/A	0.390	**0.360**	0.680	0.570	**0.300**	0.100	0.200	**N/A**	N/A	N/A
Dissolved Reactive Phosphorus (g m^{-3})	0.064	0.052	0.021	**0.026**	0.026	0.01	N/A	0.056	**0.047**	0.009	0.017	**0.018**	0.014	0.027	**N/A**	N/A	N/A
Total Phosphorus (g m^{-3})	0.104	0.062	0.025	**0.036**	0.041	0.026	N/A	0.076	**0.052**	0.020	0.043	**0.022**	0.051	0.039	**N/A**	N/A	N/A
Stream Flow (l s^{-1})	0.08	2.55	5.81	**4.62**	1.96	1.50	Dry	0.50	**1.38**	6.24	0.20	**3.72**	1.03	1.05	**Dry**	Dry	0.00

Table A2.5. Water quality variables and discharge for Mangakaware 05, monitored from April 2012 – April 2014. A discharge of 0.00 l s^{-1} indicates standing water but no flow, "Dry" indicates no water present, N/A indicates no result available as the water was too shallow to retrieve an uncontaminated sample for analysis. Results from storm event point sampling are presented in bold.

Water Quality Variables	20 Apr. 2012	20 Jun. 2012	22 Aug. 2012	3 Sep. 2012	23 Oct. 2012	12 Dec. 2012	20 Feb. 2013	23 Apr. 2013	19 May 2013	5 Jul. 2013	28 Aug. 2013	13 Sep. 2013	31 Oct. 2013	13 Dec. 2013	22 Jan. 2014	25 Feb. 2014	24 Apr. 2014
Volatile Suspended Solids (g m^{-3})	<3	< 3	<3	**2**	<3	<3	28	3	**<3**	<3	<3	**<3**	<3	<3	**6**	N/A	36
Total Suspended Solids (g m^{-3})	5	11	<3	**7**	<3	<3	59	4	**3**	5	<3	**7**	<3	<3	**11**	N/A	42
Inorganic Suspended Solids (g m^{-3})	<5	11	<5	**5**	<5	<5	31	<5	**<5**	<5	<5	**4**	<5	<5	**5**	N/A	6
Total Nitrogen (g m^{-3})	0.890	2.600	3.500	**2.270**	2.400	0.590	1.190	2.100	**2.000**	4.100	2.200	**2.900**	2.300	1.010	**0.400**	N/A	1.460
Total Ammoniacal-N (g m^{-3})	<0.010	0.093	0.043	**0.045**	0.025	0.016	0.040	0.066	**0.026**	0.033	0.024	**0.060**	0.024	0.016	**0.015**	N/A	0.290
Nitrite-N (g m^{-3})	0.002	0.023	0.008	**0.001**	0.012	<0.002	0.005	0.013	**0.009**	0.008	0.003	**0.006**	0.004	0.005	**0.004**	N/A	0.015
Nitrate-N (g m^{-3})	0.440	1.670	3.000	**2.223**	1.780	0.220	0.018	1.400	**1.310**	3.600	1.750	**1.950**	1.930	0.520	**0.010**	N/A	0.280
Nitrate-N + Nitrite-N (g m^{-3})	0.442	1.693	3.008	**2.224**	1.792	0.220	0.023	1.413	**1.320**	3.600	1.750	**1.960**	1.940	0.530	**0.010**	N/A	0.290
Total Kjeldahl Nitrogen (g m^{-3})	0.450	0.940	0.430	**0.046**	0.600	0.360	1.160	0.064	**0.710**	0.510	0.480	**0.950**	0.390	0.480	**0.420**	N/A	1.160
Dissolved Reactive Phosphorus (g m^{-3})	0.013	0.025	0.008	**0.020**	0.013	0.010	0.005	0.012	**0.009**	0.005	0.005	**0.035**	0.006	0.008	**0.026**	N/A	0.010
Total Phosphorus (g m^{-3})	0.048	0.094	0.024	**0.095**	0.029	0.021	0.161	0.037	**0.029**	0.010	0.016	**0.081**	0.015	0.018	**0.114**	N/A	0.050
Stream Flow (l s^{-1})	2.22	66.27	90.30	**44.48**	49.04	4.52	0.00	6.56	**52.30**	44.20	14.72	**116.34**	12.99	2.16	**1.28**	Dry	0.20

Table A2.6. Water quality variables and discharge for Mangakaware 06, monitored from April 2012 – April 2014. A discharge of 0.00 l s^{-1} indicates standing water but no flow, "Dry" indicates no water present, N/A indicates no result available as the water was too shallow to retrieve an uncontaminated sample for analysis. Results from storm event point sampling are presented in bold.

Water Quality Variables	20 Apr. 2012	20 Jun. 2012	22 Aug. 2012	3 Sep. 2012	23 Oct. 2012	12 Dec. 2012	20 Feb. 2013	23 Apr. 2013	19 May 2013	5 Jul. 2013	28 Aug. 2013	13 Sep. 2013	31 Oct. 2013	13 Dec. 2013	22 Jan. 2014	25 Feb. 2014	24 Apr. 2014
Volatile Suspended Solids (g m^{-3})	4	4	<3	**2**	<3	<3	71	5	**4**	<3	<3	**3**	<3	8	**12**	N/A	<3
Total Suspended Solids (g m^{-3})	6	8	4	**7**	4	4	106	5	**6**	3	<3	**7**	<3	13	**12**	N/A	<3
Inorganic Suspended Solids (g m^{-3})	<5	<5	<5	**5**	<5	<5	34	<5	**<5**	< 5	<5	**<5**	<5	<9	**<11**	N/A	<5
Total Nitrogen (g m^{-3})	1.090	2.600	2.100	**2.044**	1.930	0.800	1.750	1.250	**2.300**	1.580	1.110	**2.800**	0.730	0.930	**1.000**	N/A	0.570
Total Ammoniacal-N (g m^{-3})	0.270	0.143	0.197	**0.465**	0.115	0.045	<0.010	0.150	**0.066**	0.064	0.045	**0.360**	0.034	0.057	**0.035**	N/A	0.048
Nitrite-N (g m^{-3})	0.005	0.015	0.017	**0.007**	0.008	0.004	<0.010	0.011	**0.007**	0.005	0.004	**0.030**	0.005	0.007	**<0.020**	N/A	0.003
Nitrate-N (g m^{-3})	0.133	1.530	0.147	**1.028**	1.010	0.164	0.019	0.510	**1.380**	0.900	0.560	**1.400**	0.080	<0.002	**<0.020**	N/A	0.009
Nitrate-N + Nitrite-N (g m^{-3})	0.138	1.545	0.164	**1.035**	1.018	0.168	0.020	0.521	**1.380**	0.900	0.560	**1.430**	0.090	0.007	**<0.020**	N/A	0.012
Total Kjeldahl Nitrogen (g m^{-3})	0.950	1.010	0.620	**1.009**	0.910	0.630	1.730	0.730	**0.930**	0.680	0.550	**1.350**	0.640	0.920	**0.950**	N/A	0.550
Dissolved Reactive Phosphorus (g m^{-3})	0.053	0.024	0.028	**0.027**	0.026	0.061	0.038	0.010	**0.014**	0.009	0.009	**0.020**	0.023	0.053	**0.064**	N/A	0.010
Total Phosphorus (g m^{-3})	0.136	0.069	0.066	**0.097**	0.057	0.076	0.200	0.037	**0.039**	0.020	0.024	**0.106**	0.042	0.105	**0.123**	N/A	0.020
Stream Flow (l s^{-1})	0.00	20.92	36.16	**11.60**	26.64	6.54	0.00	5.00	**28.14**	6.24	4.92	**65.94**	4.74	0.00	**0.00**	0.00	1.20

Appendix 3

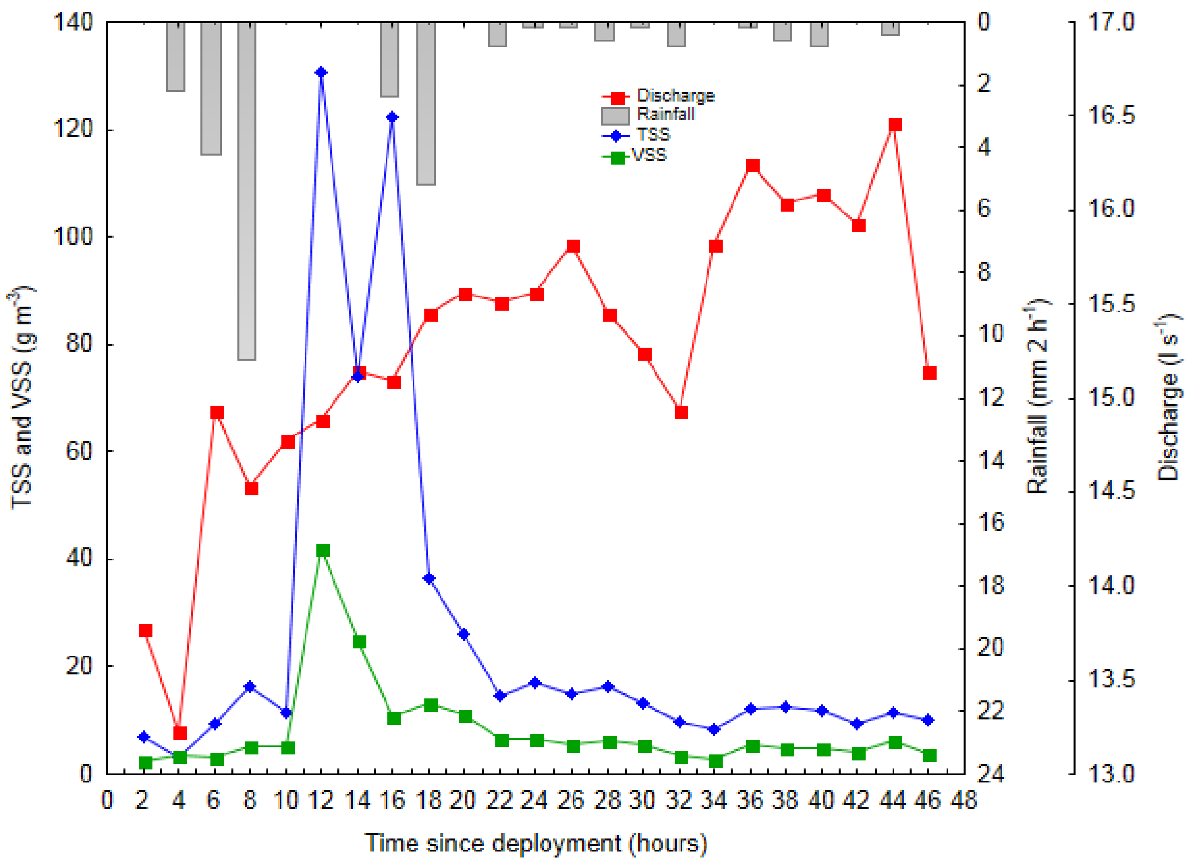

Figure A3.1. Total suspended solids (TSS) and volatile suspended solids (VSS) from the Mangakaware 06 monitoring site for the period 3–5 September 2012. Two-hour rainfall data sourced from NIWA National Climate Database, Hamilton Airport station (12 km). Discharge calculated from water level height is also presented. Hour 0 is the time of sampler deployment at 10:00 h on 3 September 2012.

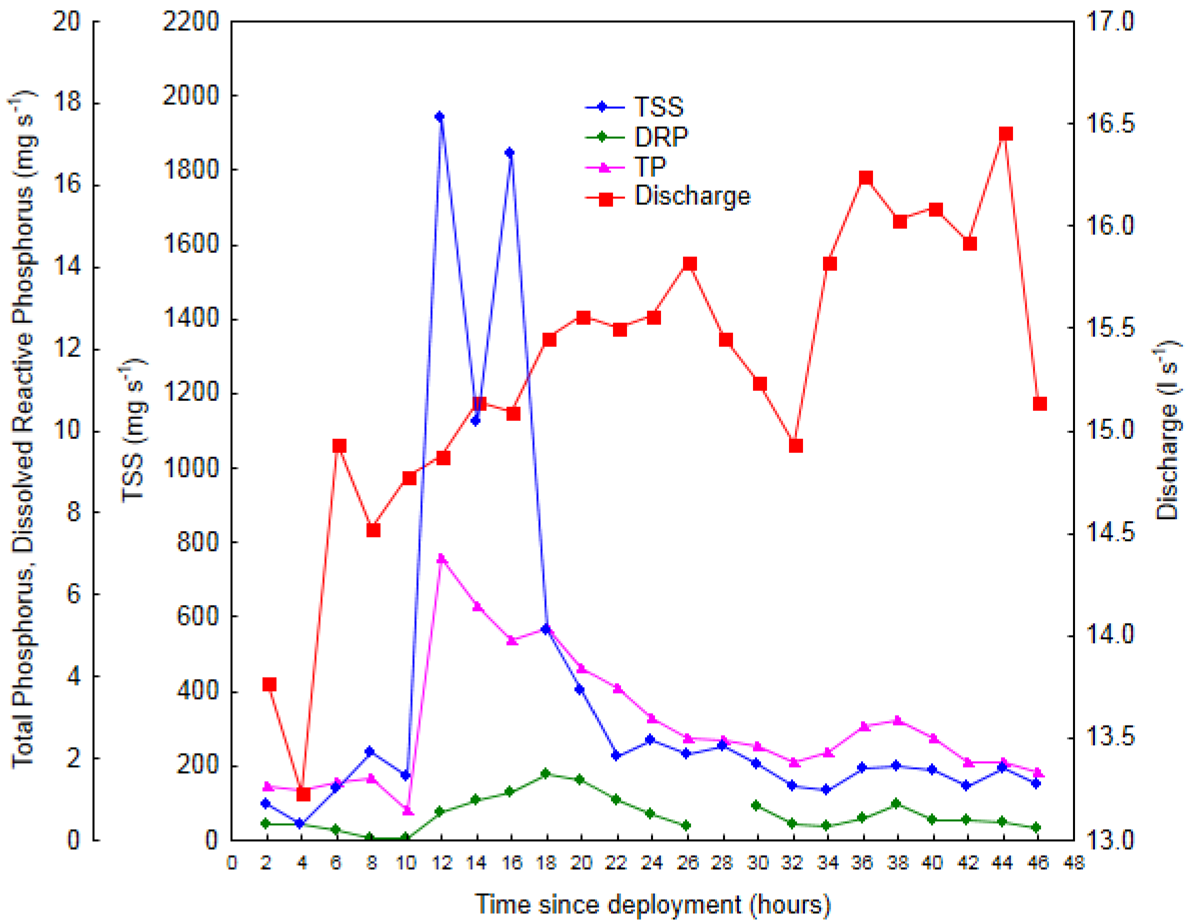

Figure A3.2. Instantaneous total phosphorus (TP), dissolved reactive phosphorus (DRP) and total suspended solids (TSS) loads in relation to discharge for the Mangakaware 06 monitoring site during the September 2012 storm event. Sampling is 2-hourly beginning at 10:00 h. Note: no dissolved reactive phosphorus data available for 28-h sample.

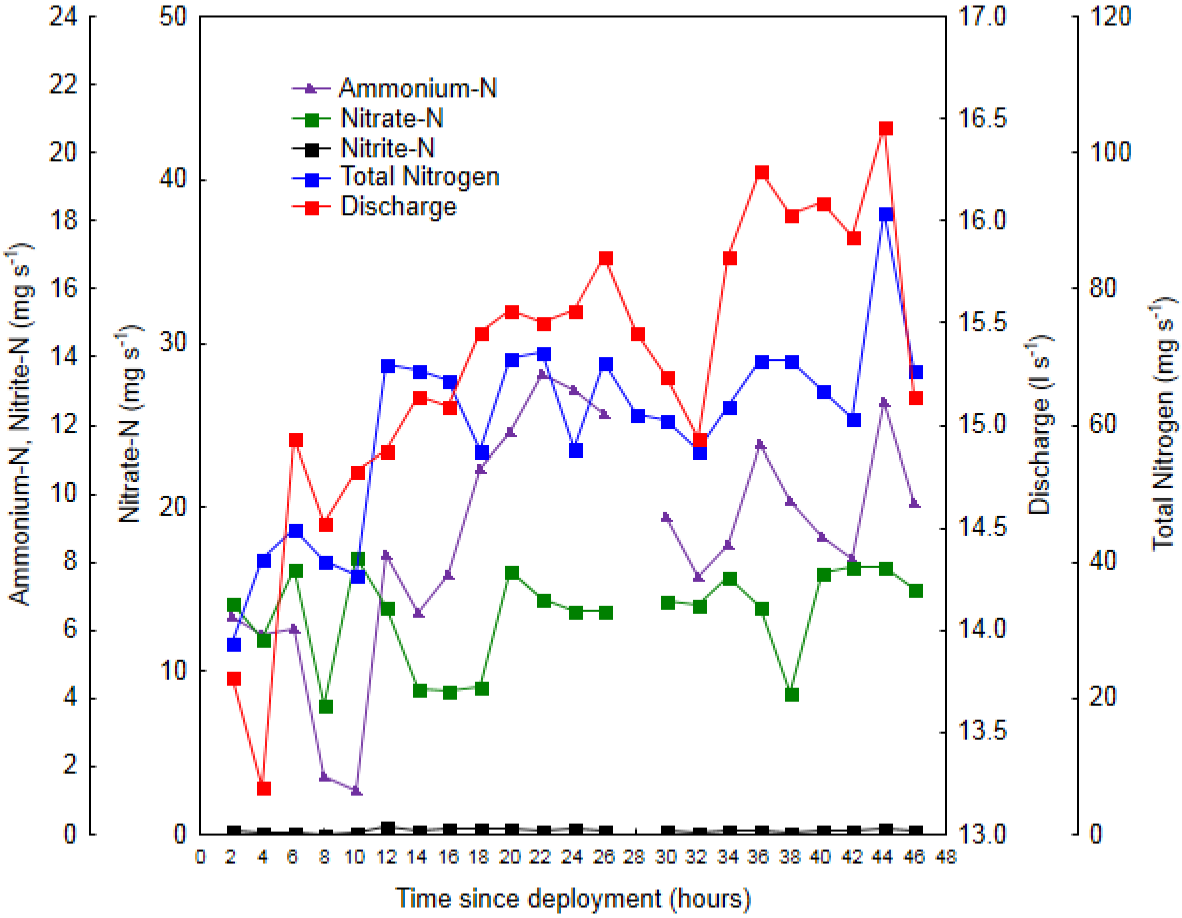

Figure A3.3. Instantaneous total nitrogen, ammonium, nitrate and nitrite loads in relation to discharge for the Mangakaware 06 monitoring site during the September 2012 storm event. Sampling is 2-hourly beginning at 10:00 h. Note: no ammonium-N, nitrate-N and nitrite-N data available for 28-h sample.

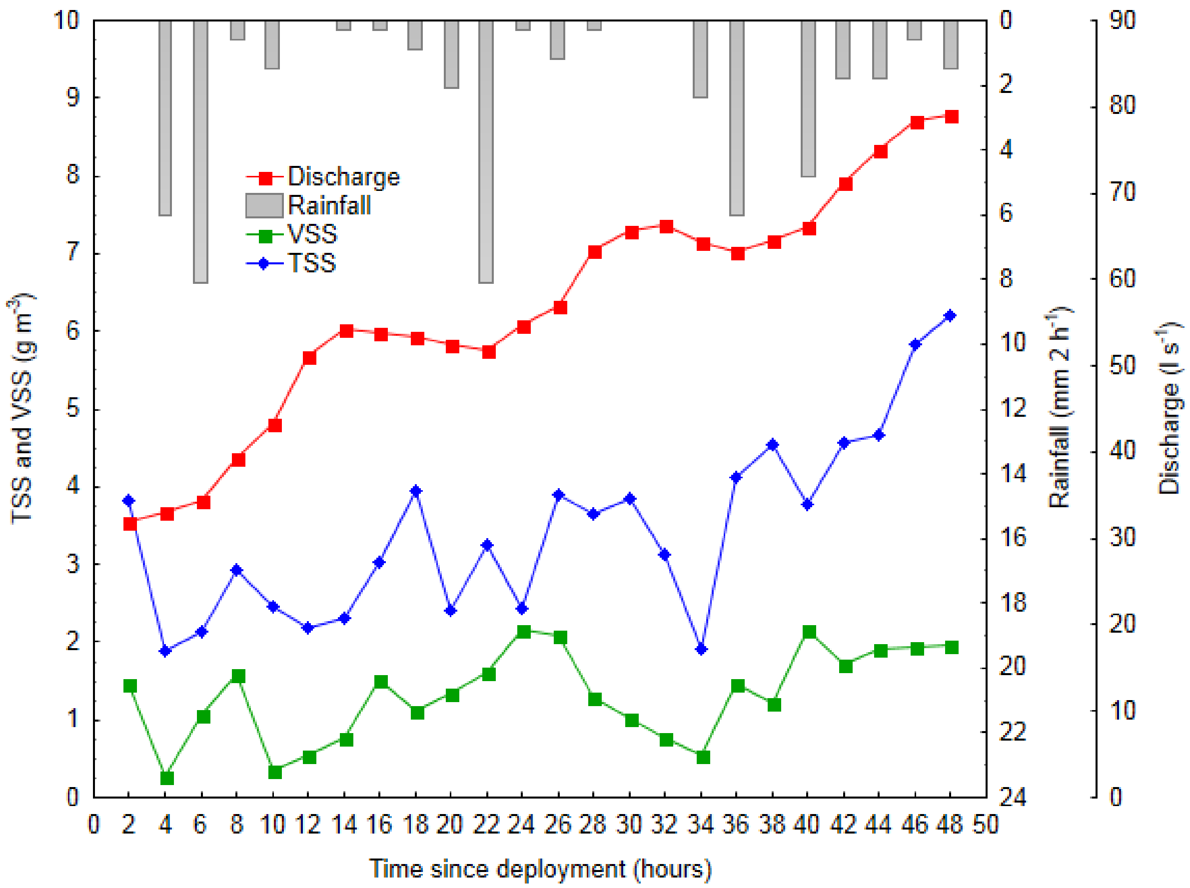

Figure A3.4. Total suspended solids (TSS), volatile suspended solids (VSS), rainfall and discharge from the Mangakaware 05 monitoring site for the period 17–19 May 2013. Hour 0 is the time of deployment at 13:30 h on 17 May 2013.

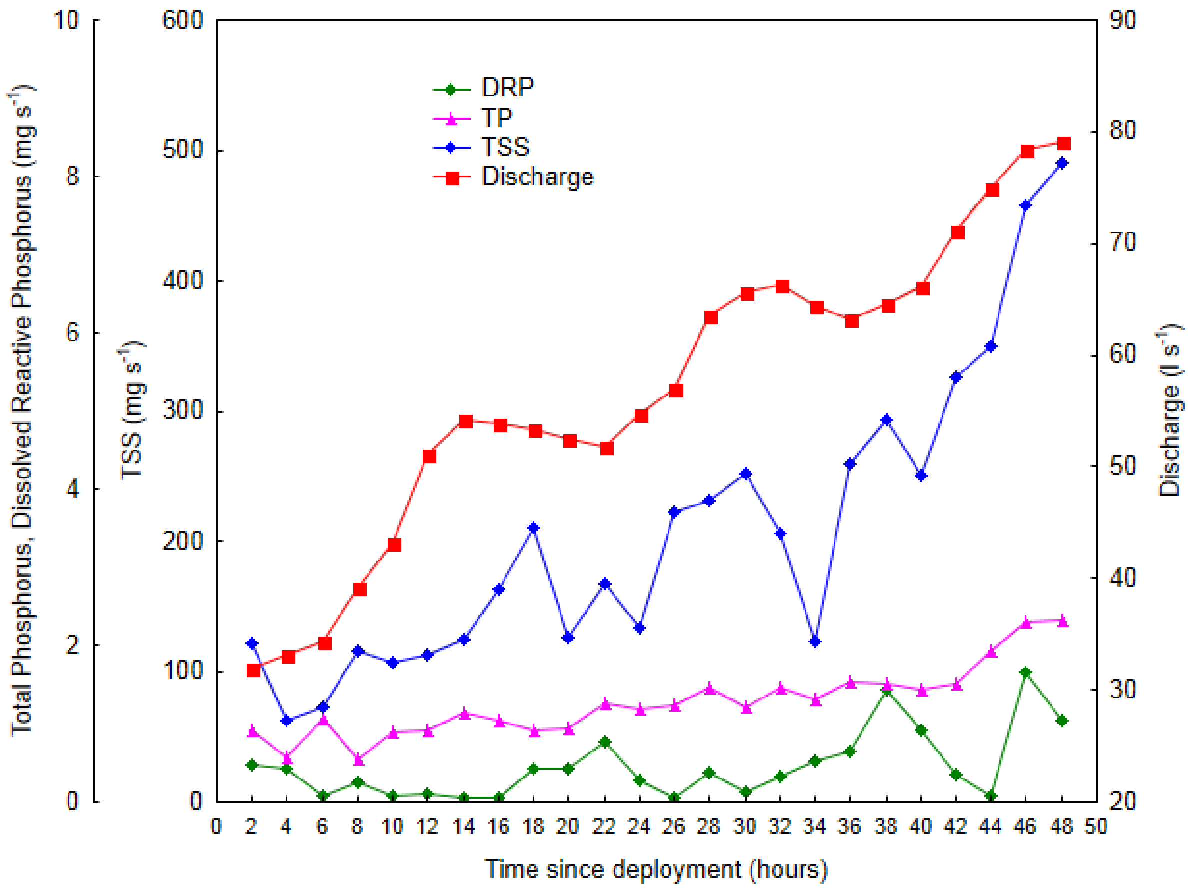

Figure A3.5. Instantaneous total phosphorus (TP), dissolved reactive phosphorus (DRP) and total suspended solids (TSS) loads in relation to discharge for the Mangakaware 05 monitoring site during the 17–19 May 2012 storm event. Sampling is at 2 h intervals commencing at 13:30 h, 17 May 2013.

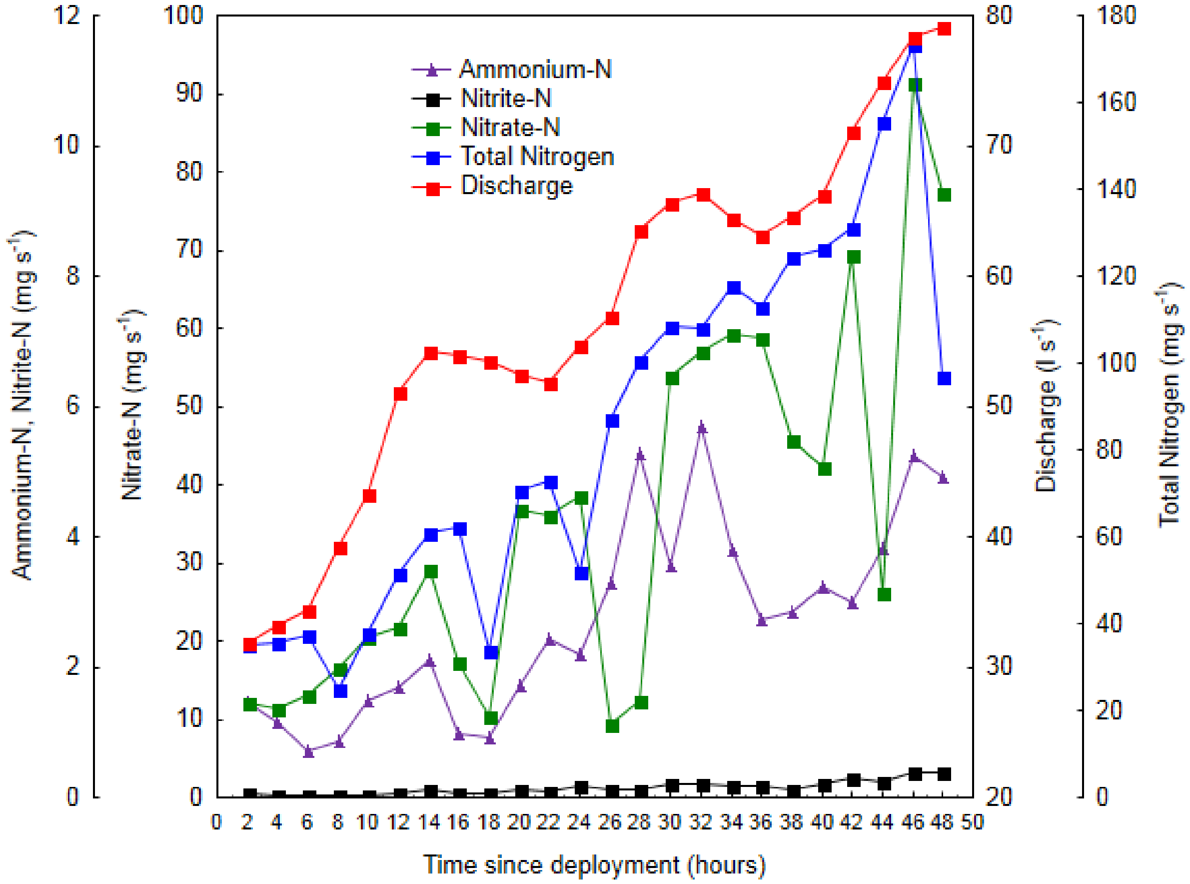

Figure A3.6. Instantaneous total nitrogen, ammonium-N, nitrate-N and nitrite-N loads in relation to discharge for the Mangakaware 06 monitoring site during the 17–19 May 2013 storm event. Sampling is at 2-h intervals commencing at 13:30 h, 17 May 2013.

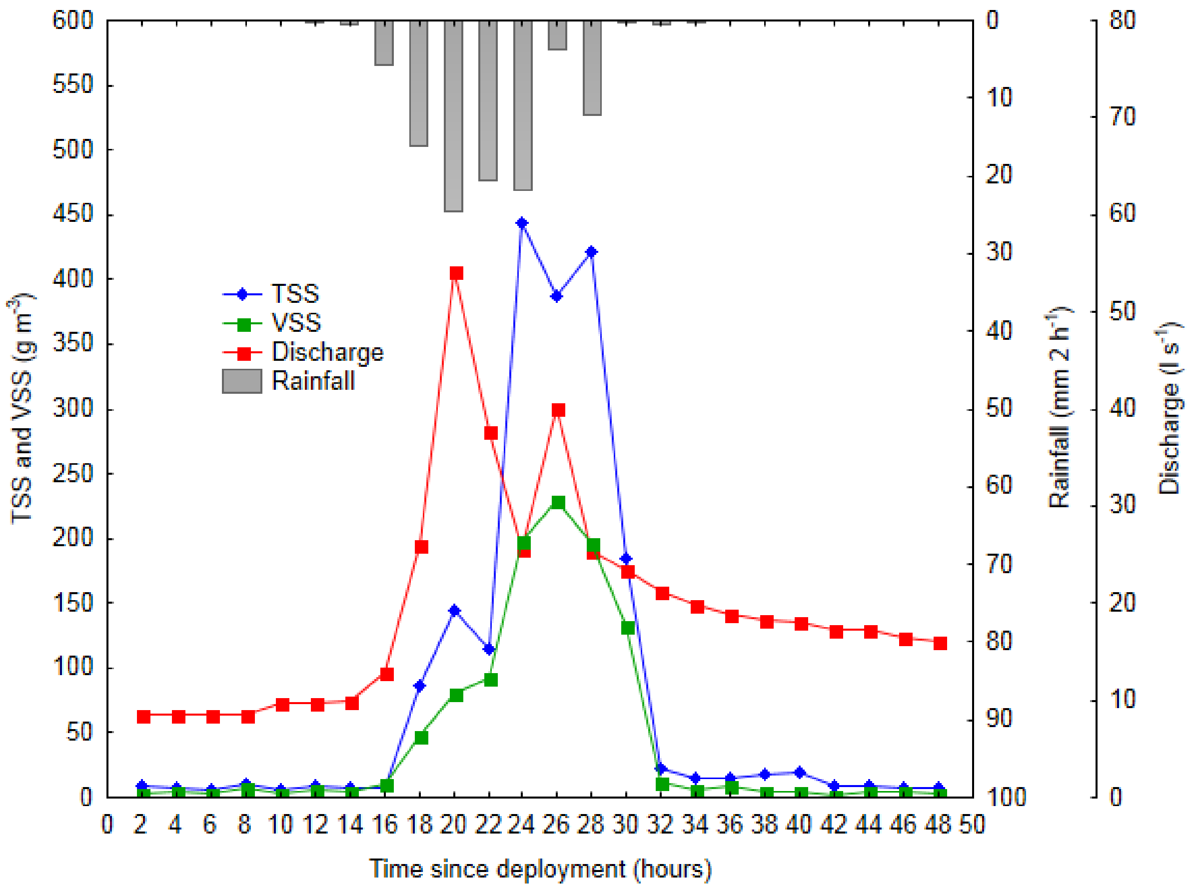

Figure A3.7. Total suspended solids (TSS) and volatile suspended solids (VSS), rainfall and discharge from the Rotopiko South 02 monitoring site for the period 11–13 September 2013. Hour 0 is the time of deployment at 14:20 h on 11 September 2013.

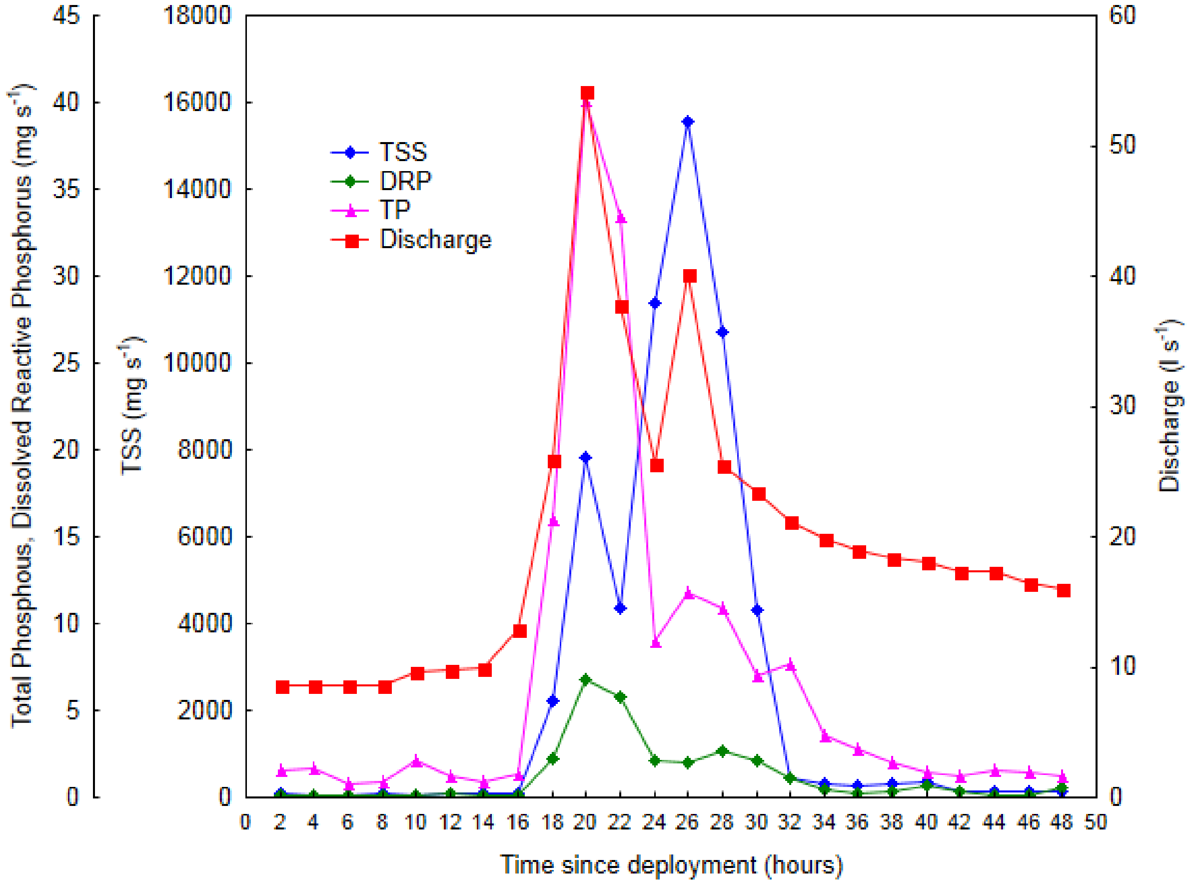

Figure A3.8. Instantaneous total phosphorus (TSS), dissolved reactive phosphorus (DRP) and total suspended solids (TSS) loads in relation to discharge for the Rotopiko South 02 monitoring site during the September 2013 storm event. Sampling is at 2 h intervals commencing at 14:20 h on 11 September 2013.

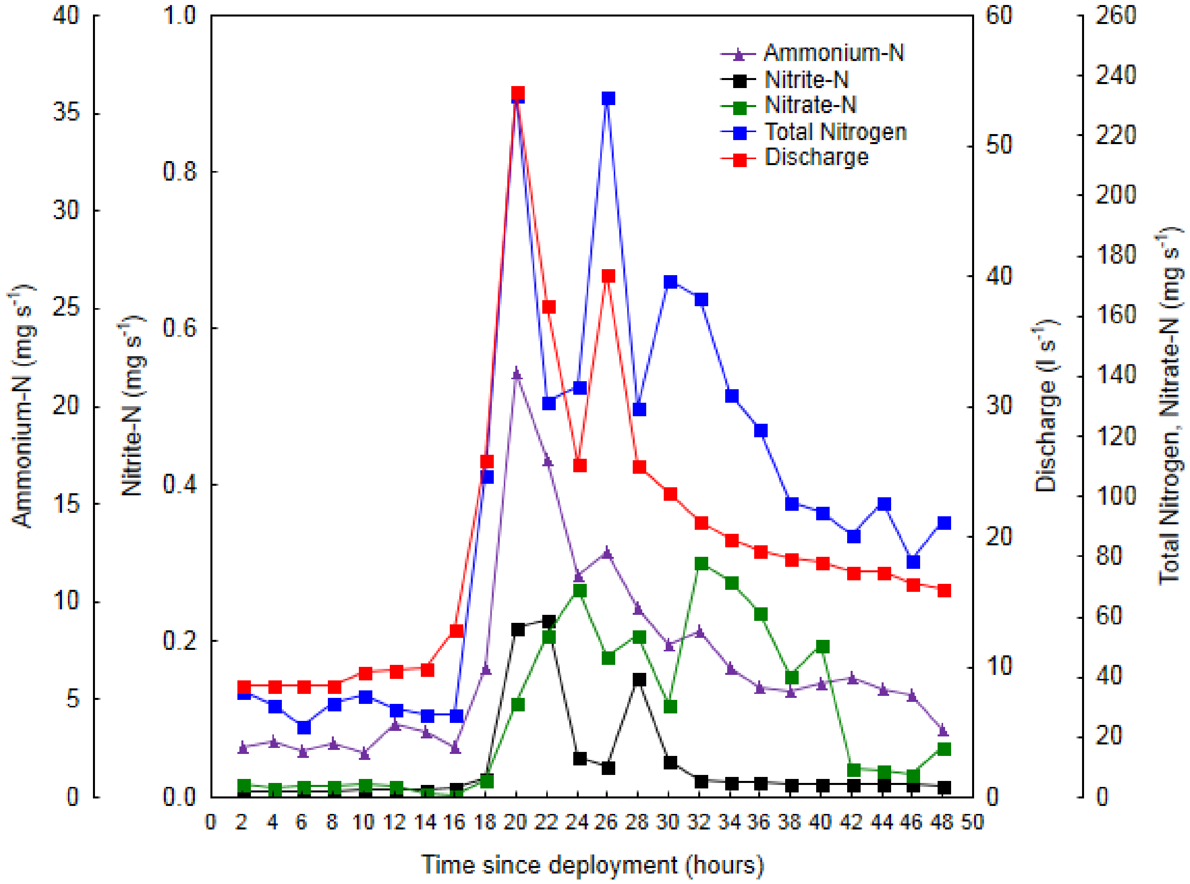

Figure A3.9. Instantaneous total nitrogen, ammonium-N, nitrate-N and nitrite-N loads in relation to discharge for the Rotopiko South 02 monitoring site during the September 2013 storm event. Sampling is at 2 h intervals commencing at 14:20 h on 11 September 2013.

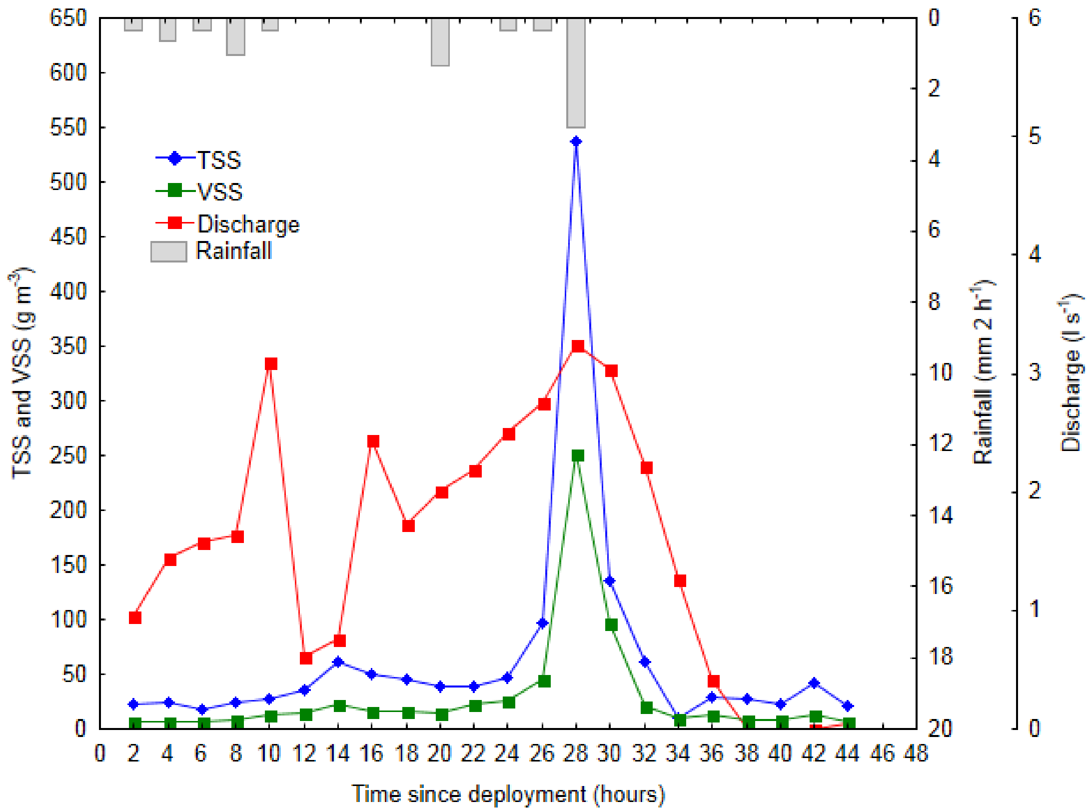

Figure A3.10. Total suspended solids (TSS) and volatile suspended solids (VSS), rainfall and discharge from the Mangakaware 05 monitoring site for the period 20–21 January 2014. Hour 0 is the time of deployment at 11:45 h on 20 January 2014.

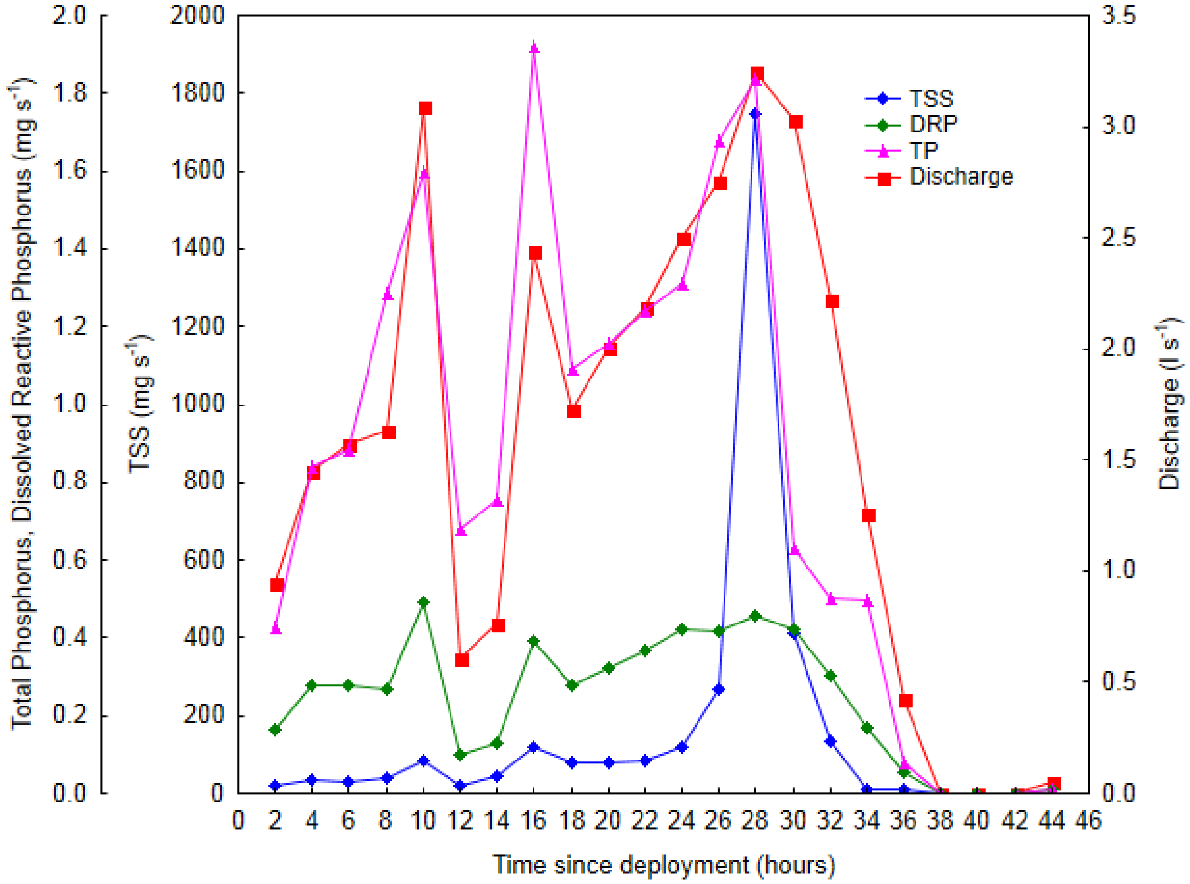

Figure A3.11. Instantaneous total phosphorus (TP), dissolved reactive phosphorus (DRP) and total suspended solids (TSS) loads in relation to discharge for the Mangakaware 05 monitoring site during the January 2014 storm event. Sampling is at 2 h intervals commencing at 11:45 h on 20 January 2014.

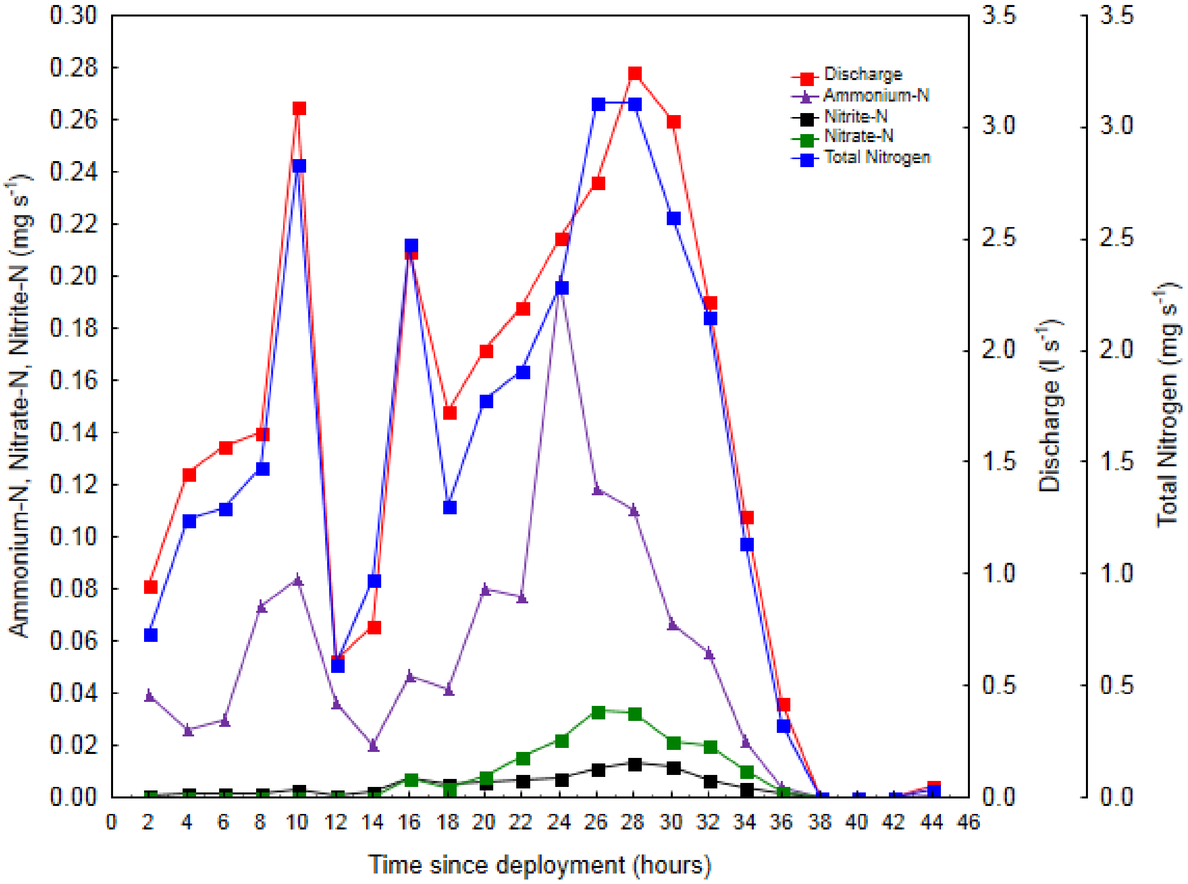

Figure A3.12. Instantaneous total nitrogen, ammonium-N, nitrate-N and nitrite-N loads in relation to discharge for the Mangakaware 05 monitoring site during the January 2014 storm event. Sampling is at 2 h intervals commencing at 11:45 h on 20 January 2014.