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A hydrological and nutrient load balance for the Lake Clearwater catchment, Canterbury, New Zealand

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Abstract

Nitrogen and phosphorus entering waterways from diffuse agricultural sources is a major problem in New Zealand and internationally. This problem is well documented for lowland areas but little is known about nutrient enrichment from farming in high country areas. The Lake Clearwater catchment, in the Canterbury high country of New Zealand, has a native ecosystem that has adapted to low-nutrient conditions. The Department of Conservation's Arawai Kākāriki Wetland Restoration Programme identifies wetlands in the catchment as one of three key endemic wetland types.

Uncertainty regarding diffuse nutrient load from agriculture into the lake and wetland is limiting effective management of this unique catchment. This study investigated the hydrological regimes and nitrogen and phosphorus concentrations and loads in five key surface waterways at ten surface water sites and three groundwater seeps for two years. It aims to improve knowledge of nutrient sources, characteristics and loads from agricultural land use in this 46 km^2 high country catchment. Additionally, nutrient load predictions from the Catchment Land Use for Environmental Sustainability (CLUES) model were compared to measured nutrient loads to assess the applicability of the model in high country catchments. The CLUES model was developed, primarily for lowland areas, to predict changes in water quality and nutrient loads from land-use change.

The total nitrogen concentrations downstream of farmland were typically above the Australia and New Zealand Environment and Conservation Council (ANZECC) water quality guideline and the median concentration for upland Canterbury waterways. Specifically, the nitrate concentration (0.19–0.29 g m^{-3}) in farmland subsurface runoff was elevated, compared to streams in the Lake Clearwater catchment with unfarmed catchments, and was estimated to contribute 52% of total nitrogen yield from farmland. The total nitrogen yield (1.96–2.94 kg ha^{-1} year^{-1}) for farmed land was comparable to minimum values for New Zealand pastoral land use reported in the literature. The total estimated nitrogen export from Lake Clearwater (2518 kg year^{-1}) was 83% greater than the estimated diffuse input from all land in the catchment (1375 kg year^{-1}). This indicated an additional source of nitrogen into the lake and seasonal nitrogen saturation. Total phosphorus yields (0.093–0.123 kg ha^{-1} year^{-1}) downstream of farmland were well below yields for New Zealand pastoral land

use reported in the literature. Total estimated phosphorus export from the lake (58 kg year^{-1}) was 24% less than total estimated diffuse loads into the lake (76 kg year^{-1}). The ratio of total nitrogen to total phosphorus in Lake Clearwater (49:1) indicated that phosphorus is the limiting nutrient and that nitrogen loads into the lake are above natural levels. Total nitrogen loads predicted by the CLUES model in the Lake Clearwater catchment were reasonable, providing land-use area inputs are accurate and nutrient loads exit catchments in surface water. However, CLUES greatly overestimated phosphorus loads from farmed and unfarmed land.

Keywords

Nitrogen, phosphorus, nutrient, load, yield, high country, Lake Clearwater, CLUES model, agricultural runoff, nitrate.

Introduction

Nitrogen and phosphorus entering waterways from diffuse agriculture sources is a major problem in New Zealand and worldwide and is well documented for lowland farming (Burt *et al.*, 1993; Harding *et al.*, 2004; Myers *et al.*, 2013). Fewer studies focus on upland areas and little is known about nutrient enrichment in New Zealand high country tussock grasslands or wetlands (Robertson and Suggate, 2011). The Lake Clearwater catchment in the Canterbury high country of New Zealand has a native wetland ecosystem and lake that are adapted to low nutrient concentrations. Wetlands in this catchment are recognised as excellent examples of native intermontane wetlands (Robertson and Suggate, 2011), consisting primarily of Red Tussock (*Chionochloa rubra)* and Purei (*Carex secta)*, and are a threatened ecosystem (Myers *et al.*, 2013). Wetlands such as these are vulnerable to eutrophication resulting from increased nutrient loads. Uncertainty regarding diffuse nitrogen and phosphorus loads from agriculture into the lake and wetland in this catchment limits conservation efforts.

Total nutrient yield values are available in literature for common land uses in New Zealand (Elliott and Sorrell, 2002). However, there is less information available for nutrient loss from agricultural land use in the high country, and the magnitude of nitrogen and phosphorus loads into the wetland and Lake Clearwater were previously unknown. The CLUES model (Semadeni-Davis *et al.*, 2011) was developed to estimate total nitrogen and total phosphorus loads for all New Zealand streams and rivers, and can be used to predict loads within the Lake Clearwater catchment. However, no published work that assesses the reliability of CLUES model predictions in high country catchments could be found.

To improve knowledge of nutrient fluxes in the Lake Clearwater catchment, this study attempted to answer the following questions. For farmed and unfarmed land in the Lake Clearwater catchment, what are the nitrogen and phosphorus transport pathways and yields? For Lake Clearwater, what are the annual nitrogen and phosphorus inputs and exports? Lastly, how well does the CLUES model predict nitrogen and phosphorus loads in this catchment?

The Lake Clearwater catchment

The 46 km^2 Lake Clearwater catchment (Fig. 1) is located in the Hakatere area of central Canterbury. The catchment is an intermontane basin on the eastern side of the Southern Alps inland from the township of Mt Somers at 171.048 E, 43.60 S. In summer, the temperature can rise as high as 30°C, and in winter is typically –15°C to 10°C (Burrows 2002). Snowfall is common in winter.

Lake Clearwater is a shallow lake, 19 m deep at it deepest point. The lake covers an area of approximately 2 km^2 and is

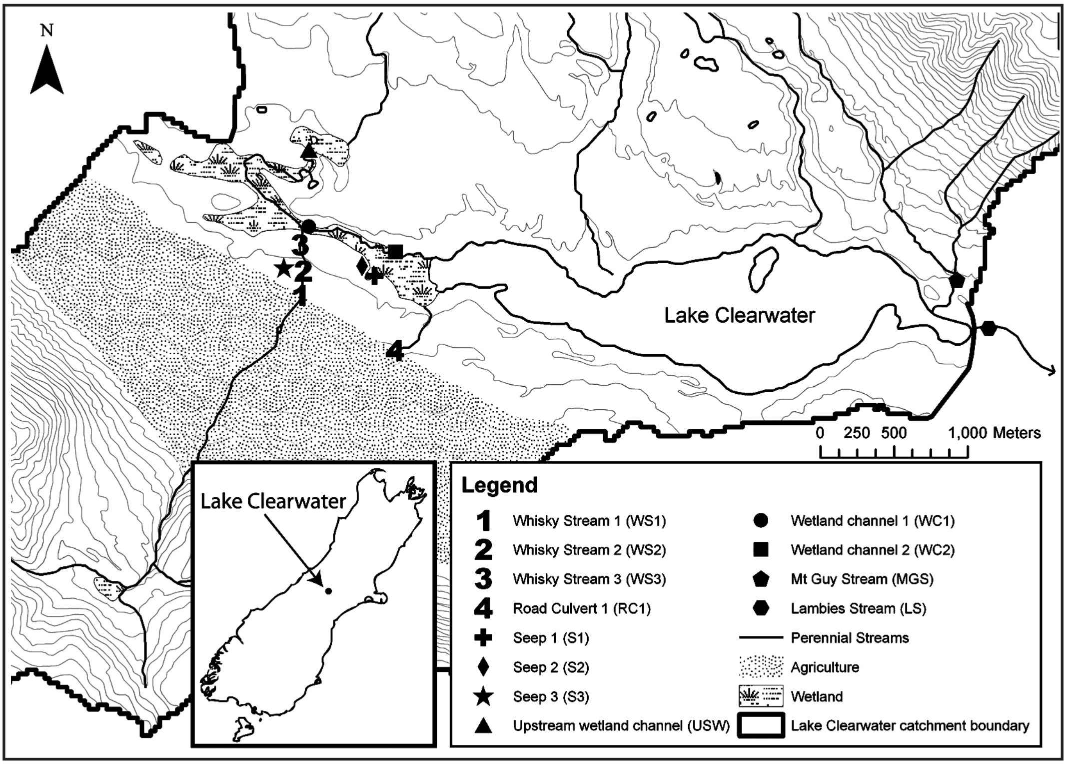

Figure 1 – The Lake Clearwater catchment showing monitoring sites and agricultural land area. The monitoring sites are described in the methods section.

667 m above sea level. Wetlands in the Lake Clearwater catchment are largely pristine examples of native intermontane wetland systems, consisting of ephemeral turfs, streams, swamps and bogs. The wetland vegetation is predominately Red Tussock (*Chionochloa rubra)* and Purei (*Carex secta)* (Bev Clarkson, Landcare Research, personal communication 2011) growing in a peat organic-rich soil.

Complex glaciated terrain, made up of fluvial sediments and moraines, dominates the catchment. Evans (2008) describes a two-metre thick fluvial gravel layer below a loess silt and organic soil surface layer. This gravel layer may provide a subsurface lateral flow pathway with high hydraulic conductivity.

The Lake Clearwater Catchment is 90% unfarmed tussock grassland typical of the Hakatere area, while 9% of the catchment is farmed. The remaining ~1% of the catchment consists of a small residential holiday home community located in a short 300 m gully that runs from Lake Camp down to Lake Clearwater. Land use within the catchments of key monitoring sites is shown in Table 1. Land to the north of Lake Clearwater is currently managed by the Department of Conservation (DOC) and is largely natural. Prior to DOC ownership (pre 2007), the majority of the catchment was lightly grazed as leasehold farmland.

The primary concern for water quality is the potential for increased diffuse nitrogen and phosphorus loads in waterways as agricultural land use intensifies on the south side of the wetland. Farming activities are predominantly sheep and beef grazing.

Table 1 – Land use summary for monitoring sites (Fig. 1). A description of these monitoring sites can be found in the method section.

	WS3	RC1	USW	WC2	LS	MGS
Total area (km^2)	4.51	0.47	6.56	19.12	46.00	3.65
Farmed (km^2)	0.72	0.36	0.00	2.92	4.18	0.00
Percent farmed (%)	16%	77%	0%	15%	9%	0%

Since 2009, roughly 60% of the farmland in the Lake Clearwater catchment has been ploughed and over-sown with rough pasture or brassica.

Ephemeral streams are common in the catchment and typically flow only during wet periods in winter and spring or in response to heavy rainfall. Whisky Stream (Fig. 1) is the only perennial stream that flows though farmland and only 20% of the farmed land area is within the Whisky Stream catchment. Three perennial streams drain natural tussock grassland catchments on the north side of the lake and wetland.

Methods

Hydrology

Measured rainfall from the Hakatere Remote Automated Weather Station (RAWS) (DOC, 2011) was used to estimate rainfall in the Lake Clearwater catchment. The station is 8 km east of Lake Clearwater and records hourly rainfall (2003 - present). Stream flow was monitored at eight surface water sites: WS1-3, WC1-2, RC1, MGS and LS1 (Fig. 1) for two full years, from June 2010 to July 2012, to estimate annual flow. Odyssey water-level logging probes were used at monitoring sites to record water level continuously throughout the study. Stream flow rate was gauged using the velocity-area method (seven gauging events at each site) over the course of the study to derive stage-discharge relationships. Six sites used stage-discharge curves to relate stage measurements to flow. Two sites (WS2 and MGS) used 90° v-notch weirs. Runoff yield for each flow-gauging site was calculated by dividing annual stream flow by catchment area.

The stream channels at flow gauging sites were stable. However, flow gauging at all sites was challenging due to the irregular shape of channels and small flow rates. More flow gauging measurements during storm flow events would have helped to improve stage-discharge relationships at high flows.

Nutrient concentration measurement

Grab samples were taken at all twelve sites in Figure 1. Sampling events were spread evenly over different seasons from May 2010 until July 2012 in order to capture seasonal variability. Sampling events were also timed to cover as much flow variability as possible. Samples were taken at all sites for each sampling event where possible to evaluate instantaneous spatial variability. The samples were collected as per American Public Health Association 4500 sampling methods (APHA, 1992). Hill Laboratories in Christchurch carried out the nutrient analysis, and the analysis methods are summarised in Table 2. Samples were analysed for total nitrogen, nitrate + nitrite nitrogen, total Kjeldahl nitrogen, ammoniacal nitrogen, total phosphorus and dissolved reactive phosphorus. The total suspended solids concentration in samples was also analysed.

In-situ measurements were made using calibrated YSI field instruments, before taking grab samples. Parameters measured in the field were dissolved oxygen (YSI 550),

Table 2 – Nutrient analysis methods (Source: Hill Laboratories, 2013)

Test	Method Description	Detection Limit
Filtration, Unpreserved	Sample filtration through 0.45µm membrane filter.	–
Total Kjeldahl Digestion	Sulphuric acid digestion with copper sulphate catalyst.	–
Total Phosphorus Digestion	Acid persulphate digestion.	–
Total Suspended Solids	Filtration using Whatman 934 AH, Advantec GC-50 or 1-2 equivalent filters (nominal pore size 1.2-1.5µm), gravimetric determination. APHA 2540 D 21st ed. 2005.	3 g/m³
Total Nitrogen	Calculation: TKN + Nitrate-N + Nitrite-N.	0.05 g/m³
Total Ammoniacal-N	Filtered sample. Phenol/hypochlorite colorimetry. Discrete 1-2 Analyser. (NH4-N = NH4+-N + NH3-N). APHA 4500-NH3 F (modified from manual analysis) 21st ed. 2005.	0.010 g/m³
Nitrate-N + Nitrite-N	Total oxidised nitrogen. Automated cadmium reduction, flow 1-2 injection analyser. APHA 4500-NO3- I (Modified) 21st ed. 2005.	0.002 g/m³
Total Kjeldahl Nitrogen (TKN)	Total Kjeldahl digestion, phenol/hypochlorite colorimetry. 1-2 Discrete Analyser. APHA 4500-Norg C. (modified) 4500 NH3 F (modified) 21st ed. 2005.	0.10 g/m³
Dissolved Reactive Phosphorus	Filtered sample. Molybdenum blue colorimetry. Discrete 1-2 Analyser. APHA 4500-P E (modified from manual analysis) 21st ed. 2005.	0.004 g/m³
Total Phosphorus	Total phosphorus digestion, ascorbic acid colorimetry. Discrete 1-2 Analyser. APHA 4500-P E (modified from manual analysis) 21st ed. 2005.	0.004 g/m³

pH (YSI 60), temperature (YSI 30) and specific conductivity (YSI 30).

Monitoring sites

Two perennial streams were chosen (MGS and USW, Fig. 1) as un-impacted reference sites, from which a comparison to impacted streams could be made. USW was located in the main wetland channel upstream of farmland and MGS was located at the downstream end of Mt Guy Stream. Both of these catchments are natural tussock grassland. Three sites (WS1-3) formed a transect along the portion of Whisky Stream (WS) between farmland and the wetland channel. Road culvert (RC) sites one (RC1) and two (RC2) were located in ephemeral streams draining the farmed land; their catchments are both 80% farmed. The RC1 channel enters the main wetland just before the inlet to Lake Clearwater. The RC2 catchment is just outside the western boundary of the Lake Clearwater catchment but is part of the farmed hill slope. The RC2 catchment was assumed representative of ephemeral farmland runoff in the Lake Clearwater catchment. Median nutrient concentrations from RC1 and RC2 were used to estimate median concentrations in ephemeral farmland runoff. To estimate nutrient concentrations in subsurface flow downhill of farmland, samples were taken directly from small seeps (S1-3, Fig. 1) where subsurface return flow emerged from a gravel layer underlying the organic soils and flowed into the wetland. The sampling point coincided with subsurface flow emerging from subsurface gravels. Therefore, nutrient attenuation from contact with wetland riparian soils was assumed to be negligible. The nutrient concentrations from these sites were assumed to be representative of nutrient concentrations in subsurface flow.

Two sites (WC1 and WC2) were located in the main wetland channel (WC) running parallel to the farmed hill slope in the valley floor. This channel is the only perennial inlet to Lake Clearwater that drains farmland. Finally, a site was located at the only surface water outlet of Lake Clearwater in Lambies Stream (LS).

Nutrient load and yield calculation

Annual total nitrogen and phosphorus loads in waterways were calculated using estimated annual runoff and median nutrient concentration for samples from each waterway. The median concentration was used for the calculation of loads because nutrient concentration and flow rate did not show a strong correlation. This was likely due to a relatively small number of samples for each site. Use of a median concentration is a source of uncertainty for load estimates and may have led to underestimates of loads during high flow events.

The nutrient load from farmland carried in ephemeral streams was calculated as the product of the median concentration measured in monitored ephemeral streams and the estimated annual surface runoff from the total farmed catchment area of ephemeral streams.

An annual nutrient balance was calculated for the wetland channel to estimate subsurface nutrient loads. Total estimated nutrient loads from perennial and ephemeral surface water inputs to the wetland channel were subtracted from the measured in-stream load in the wetland channel. The remaining load was taken as an estimate of nutrient load in subsurface runoff from the farmed area inside the wetland channel catchment.

Two estimates of total nitrogen and phosphorus yield from unfarmed natural land were calculated using in-stream loads measured at MGS and USW. In-stream loads where divided by catchment area for each site to give an estimate of nutrient yield. The partially farmed hillside, within the wetland channel catchment, to the south of the wetland channel was used to calculate the loads and yields for farmed land. Load and yield estimates for farmed land in this catchment were obtained by subtracting an estimate of the natural load from unfarmed land from the total measured load into the wetland channel.

Total diffuse nutrient loads from all farmed land into the lake where estimated by multiplying the nutrient yields estimated for farmed land by the total area of farmed land in the Lake Clearwater catchment. Total nutrient load for unfarmed land was estimated in the same way.

Loads from farmed land outside the wetland channel catchment enter the lake directly (not via the wetland channel). These loads were estimated by multiplying the nutrient yield found for farmed land by the area of farmed land in the Lake Clearwater catchment that is outside the wetland channel catchment. Nutrient loads for unfarmed land outside the wetland channel catchment were estimated in the same way. The range in nutrient load estimates is due to the difference in yields calculated for unfarmed land from the USW and the MGS catchments. The estimate of yield from MGS was used to calculate the lower estimate of load, and the estimate from USW was used to calculate the higher load estimate.

Another potential nitrogen load is leachate from holiday home on-site wastewater systems into the lake. Subsurface outflow from Lake Camp was found to flow under the community into Lake Clearwater. Nitrogen leached from wastewater systems could be an additional source of nitrogen into Lake Clearwater. The potential total nitrogen load from the holiday home community to the lake was estimated from literature values. A value of 11 kg of total nitrogen per dwelling per year was used as the nitrogen load into on-site wastewater systems (Loe, 2012; Andrew Dakers, EcoEng Limited, personnel communication, 2013). The load per dwelling was multiplied by the number of dwellings (225) and the estimated occupancy rate (10%). Attenuation of nitrogen in on-site wastewater treatment systems was assumed to be negligible for the purpose of calculating a potential nitrogen load.

Estimates of subsurface runoff volume

Three methods were used to estimate subsurface runoff. Firstly, the subsurface runoff volume was estimated by dividing the estimated subsurface load by the median nutrient concentration found at seep locations.

Estimations of potential subsurface flow through a fluvial gravel layer were made using Darcy's equation to provide an additional estimate of subsurface flow. Estimates were calculated using high (4250 mm hour^{-1}), low (0.42 mm hour^{-1}) and mid point (42.5 mm hour^{-1}) literature values (Stephenson *et al.*, 1998) for saturated hydraulic conductivity in glacial fluvial gravels. The slope followed by subsurface flow was assumed to be parallel to topography (a slope of 1:13) and the gravel layer with high saturated conductivity was assumed to be 2 metres thick based on observations in Evans (2008).

The difference between total runoff yield estimated for the Hakatere Basin and measured surface runoff yield from the farmed hill slope also provided an estimate of subsurface runoff.

CLUES model

The CLUES model calculates nutrient loads by estimating the point source and diffuse load from each catchment (Elliot *et al.*, 2005). Estimated loads from each catchment are carried through the surface water drainage network, allowing cumulative loads to be estimated at any point in surface waterways.

The default CLUES model requires no user-defined input parameters to run. However, for this catchment the land-use input layer was modified to reflect current land use. Farmland area in the catchment was overestimated in the model's default land-use input layer. For the default land-use input layer, the valley floor of the catchment was predominantly hill country sheep and beef farming. However, actual farmed land area (4.18 km^2) was only 28% of default farmed land area in the CLUES land-use input layer. Land use is a key input to the CLUES model, as each land use has associated source coefficients that are used to calculate total nitrogen and phosphorus loads from diffuse sources in each catchment. The proportion of each land use was modified manually for each sub-catchment. Default values were used for all other input parameters. Total nitrogen and phosphorus in-stream load predictions from the CLUES model were compared with measured in-stream loads for Whisky Stream (WS), Road culvert 1 (RC1), the upstream and downstream wetland channel (USW and WC), Lambies Stream (LS) and Mt Guy Stream (MGS).

Results and discussion

Hydrology

Total annual rainfall at the Hakatere RAWS weather station for July 2010 to June 2011 was 606 mm year^{-1} and in 2011 to 2012 was 605 mm year^{-1}. Average annual rainfall from 2003 to 2012 was 538 mm year^{-1}. For July 2011 to June 2012, the highest surface runoff yield was at Whisky Stream (WS3), 223 mm year^{-1} (Table 3). Runoff yield in the wetland channel (WC1) was comparable (188 mm year^{-1}). Annual ephemeral runoff yield at RC1 (146 mm year^{-1}) was estimated using the flow record at WS3 and is more uncertain than directly measured annual flow. Moreover, catchment boundary delineation for RC1 was challenging due to complex terrain and potential subsurface lateral flow sources from surrounding catchments. Lambies Stream is the only surface outlet to Lake Clearwater and annual runoff yield was lower than expected (88 mm year^{-1}). Low surface outflow from the lake could be due to high evaporation and/or subsurface outflow.

Table 3 – Estimated annual runoff yield.

Site	2010–2011 (mm year^{-1})	2011–2012 (mm year^{-1})
WS2	122	242
WS3	200	223
RC1	158	146
WC1	161	188
LS1		88
MGS		106

Table 4 shows estimates of subsurface runoff from the farmed hill slope. Although methods used to estimate subsurface flow had considerable uncertainty, each estimation method indicated that subsurface flow contributes a significant proportion of the total runoff from farmed land.

Nutrient concentrations and transport

Figure 2 summarises the total nitrogen concentrations found in monitored waterways in the Lake Clearwater catchment. Median total nitrogen concentration in un-impacted perennial streams (MGS and USW) was close to the median for Canterbury alpine-fed upland rivers (0.093 g m^{-3}) (Stevenson *et al.*, 2010) and the median reference concentration (0.11 g/m^3) estimated in McDowell (2013) for New Zealand waterways in cool dry mountain catchments. Whisky Stream total nitrogen concentrations were consistently above natural baseline concentrations but below the Australia and New Zealand Environment and Conservation Council (ANZECC) guideline (0.295 g m^{-3}) for un-impacted upland rivers (ANZECC, 2000) and the 95th percentile for Canterbury alpine-fed upland rivers (0.32 g m^{-3}) (Stevenson *et al.*, 2010). Total nitrogen concentrations sometimes increased in Whisky Stream (WS) during high flow, but this was not consistent. The relationship between total nitrogen concentration and flow for all sampling events is shown in Figure 3.

Table 4 – Estimations of subsurface runoff yield from the farmed land south of the wetland channel (Fig 1).

Estimation Method	Subsurface runoff (mm year^{-1})
Comparison of runoff yields	136
Nitrogen mass balance	79 - 149
Phosphorus mass balance	81 - 136
Darcy's equation (low-mid-high)	1.25 - 127 - 12692

Total nitrogen concentration in the main wetland channel was consistently elevated above the natural baseline concentrations measured in this study and was higher than in Whisky Stream and the upstream wetland channel. The total nitrogen concentrations appeared to increase along the wetland channel from WC1 to WC3, although this trend was not statistically significant (p-value=1). Increases in total nitrogen concentration along

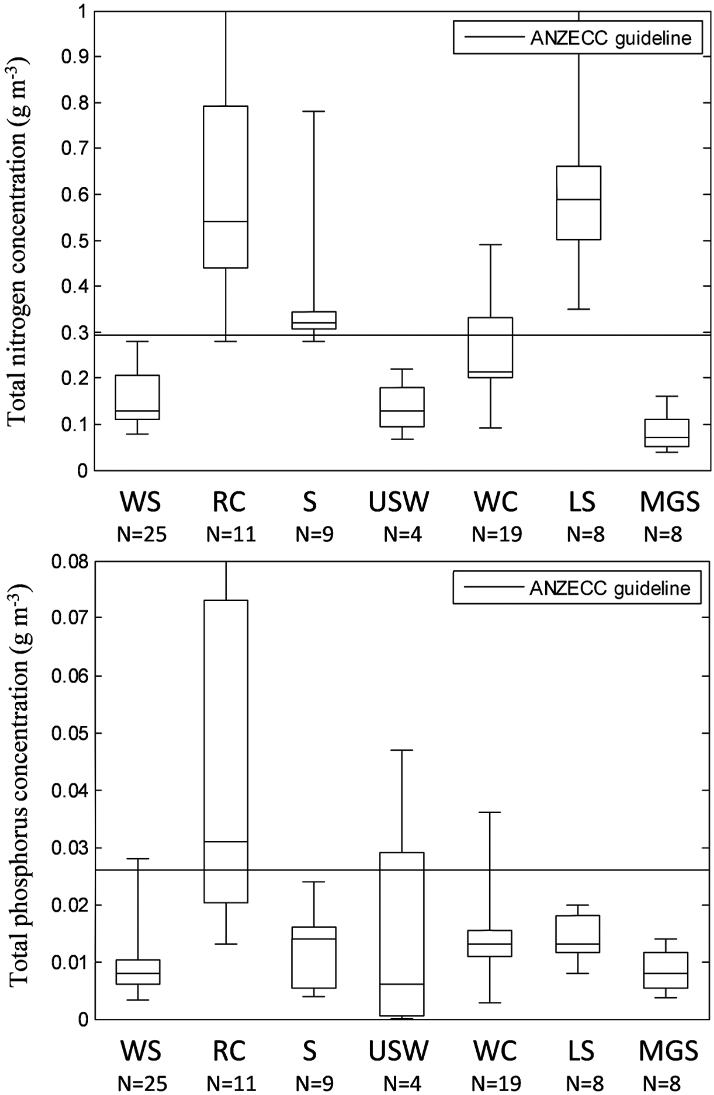

Figure 2 – Boxplots showing total nitrogen and total phosphorus concentrations in monitored waterways. WS, RC, S and WC represent all samples in a waterway, not a single monitoring station. WS is Whisky Stream (WS1-3); RC is the road culvert sites (RC1-2); S is the subsurface seeps (S1-3); WC is the wetland channel (WC1 and 2). Further description of the monitored waterways and their abbreviations is included in the methods section. On each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles and the whiskers extend to the most extreme data points not considered outliers.

the length of the wetland channel may be due to high nitrogen concentration (0.28-0.78 g m^{-3}) in subsurface lateral runoff entering the wetland channel as it flows along the base of the farmed hill slope. No seasonal or inter-annual trends were evident in total nitrogen or phosphorus concentrations in the wetland channel. However, a longer monitoring period may show temporal trends.

On average, 94% of the total nitrogen measured in all surface water samples was measured as total Kjeldahl nitrogen. Ammoniacal nitrogen concentrations were very low. Therefore, the majority of nitrogen measured as total Kjeldahl nitrogen was in the organic form. This indicated that nitrogen sources into surface water on farmland were predominantly in the organic form or that nitrate and ammoniacal nitrogen was rapidly transformed into organic forms of nitrogen in surface waterways. Ammoniacal nitrogen concentrations were low in all waterways. Only 20% of all samples had ammoniacal

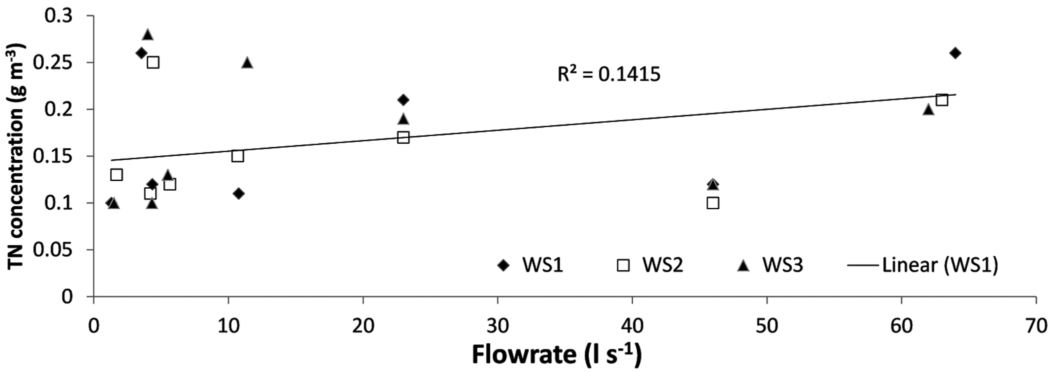

Figure 3 – Scatter plot of total nitrogen concentration versus flow rate in Whisky Stream

nitrogen concentrations above the detection limit and ANZECC guideline, both 0.01 g m^{-3}. All samples exceeding 0.01 g m^{-3} were below 0.04 g m^{-3} apart from one sample taken from RC1 during a high flow event (0.11 g m^{-3}).

The median nitrate concentrations (Table 5) in perennial surface waterways were below the median concentrations found in Canterbury rivers and streams (Stevenson *et al.*, 2010) but within the range (0.002–0.07 g/m^3) estimated in McDowell (2013), for natural reference concentrations in New Zealand waterways with cool dry mountain catchments. However, the median nitrate concentrations (Table 5) in subsurface runoff from farmland (S1, 4 and 5) were above baseline natural concentrations (this study). The high concentration of nitrate in subsurface flow in conjunction with the large subsurface flow component meant nitrate transported in subsurface runoff was likely a major pathway for nitrogen loss from farmland into the wetland. Nitrate concentrations (0.19–0.29 g m^{-3}) in seeps down gradient of farmland were 15–125 times higher than in surface waterways (0.004–0.034 g m^{-3}).

The median total nitrogen concentration was lower in the wetland channel (0.26 g m^{-3}) than in the lake (0.57 g m^{-3}), despite the wetland channel being the only perennial surface water inlet to the lake downstream of farmland. This is discussed in further detail later in this paper. The total nitrogen concentration in the lake outlet (LS) consistently exceeded the ANZECC guideline (0.295 g m^{-3}) over the entire study period. An increase in nitrogen concentration

Table 5 – Summary statistics for nitrate concentrations at each site (mg m^{-3}) (see Fig. 1). N is the number of samples taken.

	WS1	WS2	WS3	RC1	RC2	S1	S4	S5	USW	WC1	WC2	LS1	MGS
Min	1	1	1	1	2	250	187	230	1	1	3	1	1
Max	19	24	18	520	23	290	191	250	8	21	22	9	34
Mean	8	6	6	118	10	268	189	240	4	6	8	4	10
Median	5	2	4	17	4	270	189	240	4	3	4	3.5	7
N	8	9	8	5	3	5	2	2	4	8	5	8	8

over time was seen for Lake Clearwater from 0.2 g m^{-3} in 2005 to 0.6 g m^{-3} in 2012 (Meredith and Wilks, 2007, Adrian Meredith personal communication 2012). Nitrogen concentration in Lake Clearwater increased above the eutrophic threshold of 0.337 g m^{-3} (Burns *et al.*, 2000) in 2005.

Figure 2 also summarises the total phosphorus concentrations found in monitored waterways. Concentrations in perennial waterways were generally below the ANZECC guideline for upland unimpacted rivers (0.026 g m^{-3}) and within the normal range for natural upland streams in Canterbury (0.004-0.051 g m^{-3}) (Stevenson *et al.*, 2010). Total phosphorus concentrations were also within the range (0.005–0.022 g/m^3) estimated in McDowell (2013), for reference concentrations in New Zealand waterways with cool dry mountain catchments. The median total phosphorus concentration in Whisky Stream (WS) (0.008 g m^{-3}) was the same as the median concentration in un-impacted streams (MGS and USW). As with total nitrogen, higher concentrations of total phosphorus were observed in some, but not all, high flow events in Whisky Stream. As an example, the relationship between total phosphorus concentration and flow for all sampling events in Whisky Stream is shown in Figure 4.

Ephemeral and subsurface flows were the primary phosphorus transport pathways from farmland, each contributing approximately half of the total load into the wetland. Phosphorus concentrations were highest in the ephemeral streams draining agricultural land (RC1 and RC2), with a median concentration of 0.03 g m^{-3}. The dissolved reactive phosphorus concentration was below the detection limit for 83% of all samples. Dissolved reactive phosphorus concentrations (0.025, 0.026 and 1.00 g m^{-3}) above baseline natural concentrations were only seen in three samples from ephemeral streams draining farmland during high flow events. The primary source of phosphorus in these streams was expected to be via direct input of animal excrement, as well as erosion due to treading damage within the channels. Animals have direct access to the channels on farmed land and gather in these areas.

The median total phosphorus concentration in subsurface runoff (0.012 g m^{-3}) was above baseline natural concentrations in perennial streams but not to the same extent as in ephemeral flow. The median total phosphorus concentration was above baseline natural concentrations in the wetland channel (WC) and the outlet of the lake (LS) (both 0.013 g m^{-3}).

Lake Clearwater has a nitrogen to phosphorus ratio of 49:1 by mass, indicating

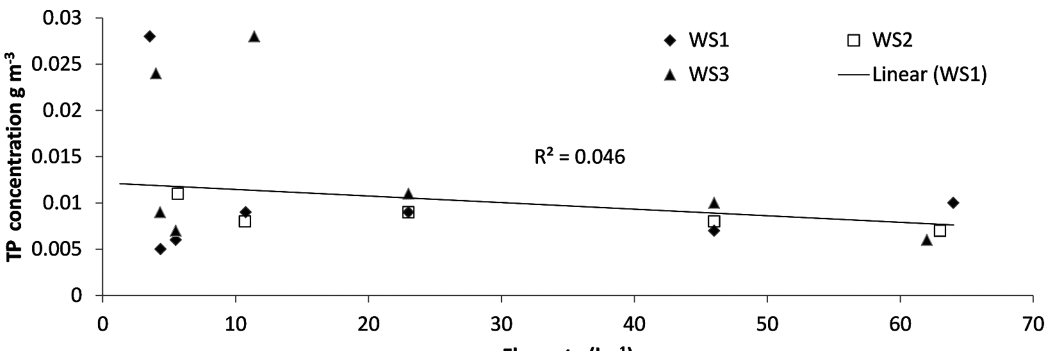

Figure 4 – Scatter plot of total phosphorus (TP) concentration versus flow rate in Whisky Stream.

that phosphorus may be the limiting nutrient for phytoplankton growth (Abell *et al.*, 2010). The excess of nitrogen in the lake suggested that nitrogen input into the lake was elevated above natural levels. The median concentration in the lake in 2012 (0.015 g m^{-3}) was approaching the phosphorus concentration threshold (0.02 gm^{-3}) for a eutrophic lake, given in Burns *et al.* (2000). An increase in phosphorus concentration in Lake Clearwater would likely increase the trophic state of the lake.

Nutrient loads

A schematic of estimated total nitrogen and total phosphorus loads in the Lake Clearwater catchment is shown in Figure 5. Subsurface runoff from farmland was estimated to deliver 38–54% of the total estimated total nitrogen load from farmland into the wetland (656 kg $year^{-1}$). The total phosphorus load from farmland was 29 kg $year^{-1}$. Annual measured surface water nitrogen export from Lake Clearwater (2518 kg $year^{-1}$) was 83% greater than the total estimated load into the lake (1375 kg $year^{-1}$). This indicates that diffuse nutrient loads shown in Figure 5 may not include all significant sources of nitrogen into Lake Clearwater and further study would be useful to produce a more complete nutrient balance for the lake. One potential unmeasured nutrient load from farmland is subsurface load from beneath the main wetland channel into the lake. Investigation of groundwater nutrient concentrations and flow beneath the wetland channel would be useful to address uncertainty regarding the total nutrient load from the wetland.

Potential nitrogen load from the holiday home community on-site wastewater systems was estimated to be up to 250 kg of total nitrogen per year. Although this is only an approximate estimation, this indicates that the total load from domestic wastewater is unlikely to completely explain the residual load (1143 kg $year^{-1}$) in the nitrogen mass balance for Lake Clearwater. Investigation of nutrient concentrations in springs downstream of the community would be useful to further investigate nitrogen load from domestic wastewater.

Annual phosphorus export from Lake Clearwater (58 kg $year^{-1}$) was 24% less than total estimated loads into the lake (76 kg $year^{-1}$). This indicated phosphorus attenuation. Phosphorus may become bound to sediment in Lake Clearwater or taken up during organic matter production.

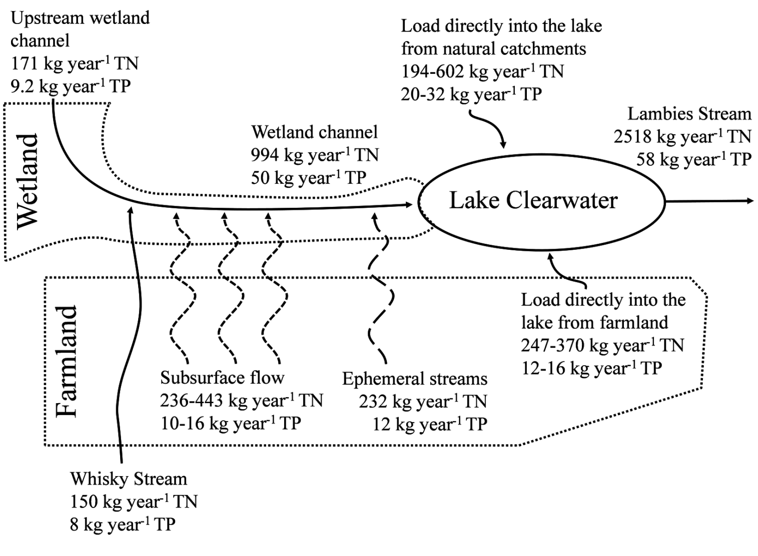

Figure 5 – Schematic of estimated loads in the Lake Clearwater catchment. Loads directly into the lake are loads from land in the Lake Clearwater catchment that is outside the wetland catchment.

Nutrient yields

Nitrogen yield from unfarmed natural land was found to be 0.084 kg ha^{-1} $year^{-1}$ for the Mt Guy Stream catchment and 0.26 kg ha^{-1} $year^{-1}$ for the upstream wetland catchment. Phosphorus yield was 0.0085 kg ha^{-1} $year^{-1}$ from the Mt Guy Stream (MGS) catchment and 0.014 kg ha^{-1} $year^{-1}$ from the upstream wetland channel (USW) catchment.

The total nitrogen yield for farmed land was estimated to be 1.96–2.94 kg ha^{-1} $year^{-1}$. This includes surface and subsurface runoff. The total nitrogen yield from subsurface runoff was estimated to be 0.81–1.52 kg ha^{-1} $year^{-1}$. The total nitrogen yield (from both surface and subsurface runoff) was comparable to the lowest yield (2.8 kg ha^{-1} $year^{-1}$) published for catchments containing primarily low intensity pastoral agriculture in New Zealand (Elliott and Sorrell, 2002). Total phosphorus yield was estimated to be 0.093–0.123 kg ha^{-1} $year^{-1}$. This was similar to minimum values published for New Zealand native catchments 0.12 kg ha^{-1} $year^{-1}$, but approximately a third of the minimum value found for catchments containing primarily low intensity pastoral agriculture (0.3 kg ha^{-1} $year^{-1}$ (Elliott and Sorrell, 2002)). Nitrogen and phosphorus yields found in this study were below published yields for low-land agricultural pastoral land use in New Zealand and internationally (Cooper and Thomsen, 1988; Quinn and Stroud, 2002; Young *et al.*, 1996). Low nutrient yields are likely to reflect the low stocking intensity of this pastoral land.

CLUES model

In-stream load prediction from the CLUES model using default and modified land use inputs are shown alongside measured loads in Table 6. The CLUES model over predicted in-stream nitrogen loads by 3 to 15 times with default inputs. An overestimate of farmed area in the model inputs was found to be the primary reason for this. Default CLUES land use may have better reflected past land use in the catchment. Before tenure review in 2007, more land area in the Lake Clearwater catchment was used for low-intensity sheep grazing. CLUES model predictions were improved when the land use was changed in the input layer to reflect actual land use. However, load estimates did increase in WS and RC1 catchments. This was because the proportion of farmed land increased in these catchments in the corrected land-use layer. Using the corrected land-use layer as an input, nitrogen load estimates for natural tussock grassland catchments at USW and MGS were reasonable.

Nitrogen loads predicted by CLUES at WS and RC1 were higher than measured in-stream loads. However, the measured in-stream loads did not include nitrogen load in subsurface runoff. Shallow subsurface runoff was estimated to carry a considerable proportion of total nutrient load out of these small catchments. In this case, nutrient load carried by shallow subsurface lateral flow only enters surface waterways downstream in the wetland channel. The load predicted by CLUES in the wetland channel downstream from the farmed land was only 17% greater than measured in-stream load.

Nitrogen export from Lake Clearwater was under-predicted by 37% by the CLUES model. However, as discussed earlier, the lake may receive nutrient loads from sources other than diffuse loads from farmed and unfarmed land. Results indicated that the total nitrogen loads predicted by the CLUES model are reasonable in catchments similar to the Lake Clearwater catchment, provided land-use area inputs are accurate, all important nitrogen sources are accounted for, and nitrogen load exits the catchment in surface water.

The CLUES model was less able to predict phosphorus loads. The model prediction of total phosphorus load was nine times higher than the measured load in the wetland channel. Overestimates of loads at all other sites were even greater (Table 6). This was primarily due to an over-estimate of phosphorus loads from unfarmed land (tussock grassland) by the CLUES model. With corrected land-use inputs, the area of unfarmed land increased. As a result, the model predicted higher phosphorus loads using the corrected land-use layer. The model has a phosphorus load associated with the sediment load. Overestimates of sediment loads from natural land, and the associated phosphorus loads, caused CLUES to overestimate phosphorus loads from natural catchments (Sandy Elliot, NIWA, personal communication, 2012). This conclusion was established by investigating the coefficients and calculations the model utilises to estimate phosphorus load from diffuse sources in tussock grassland catchments. High sediment loads are not realistic for the Lake Clearwater catchment, as total suspended solid concentrations were typically below the detection limit (3 g m^{-3}), even during high flows. The measured total phosphorus yields are particularly low in this catchment, both for farmed and non-farmed land, compared with measurements elsewhere in New Zealand. Since CLUES is calibrated to measured loads nationally (primarily lowland locations) and the measured loads from the study catchment load are low, CLUES over-predicts loads in the Lake Clearwater catchment. Measurements such as those from this study will help improve future calibration of CLUES.

Table 6 – Comparison of measured and CLUES model estimates of in-stream loads.

Site	Measured	CLUES (Default)	CLUES (Corrected land use)
Total nitrogen in-stream load (kg^{-1} year^{-1})			
WS	150	354	409
RC1	50	235	281
USW	171	539	97
WC	994	2164	1159
LS	2518	3920	1588
MGS	31	165	48
Total phosphorus in-stream load (kg^{-1} year^{-1})			
WS	8	83	101
RC1	3	41	41
USW	9	192	206
WC	50	449	505
LS	58	463	518
MGS	3	163	171

Conclusions

Surface runoff and subsurface runoff contributed approximately equal nutrient yields from farmland for both nitrogen and phosphorus. Further investigation of nutrient loads in ephemeral and subsurface runoff would be useful to reduce uncertainty in load estimates and improve understanding of the nutrient loss pathways from high country farmland into waterways.

From June 2011 to July 2012, the total nutrient yield for farmed land, from all sources, was estimated to be 1.96–2.94 kg ha^{-1} $year^{-1}$ for nitrogen and 0.093–0.123 kg ha^{-1} $year^{-1}$ for phosphorus. Nutrient concentrations, yields and loads were low when compared with typical values from lowland pastoral land use. Measured surface water nitrogen export from Lake Clearwater (2518 kg $year^{-1}$) was 83% greater than total estimated loads into the lake (1375 kg $year^{-1}$). This indicated an additional unmeasured source of nitrogen load into the lake. In contrast, annual phosphorus export from Lake Clearwater (58 kg year^{-1}) was 24% less than total estimated loads into the lake (76 kg year^{-1}). This indicated phosphorus attenuation. Phosphorus may be the limiting nutrient for phytoplankton growth in Lake Clearwater; an increase in phosphorus concentration would likely increase the trophic state of the lake.

Total nitrogen loads predicted by the CLUES model in the Lake Clearwater catchment were reasonable, providing the land-use area inputs are accurate and nutrient load exited the catchment in surface water. However, CLUES greatly overestimated phosphorus load in the Lake Clearwater catchment. The measured total phosphorus yields are particularly low in this catchment, both for farmed and non-farmed land, compared with measurements elsewhere in New Zealand. Since CLUES is calibrated to measured loads nationally (primarily lowland locations) and the measured loads from the study catchment load are low, CLUES over-predicts loads from the Lake Clearwater catchment. Measurements such as those from this study will help improve future calibration of CLUES.

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