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Scale-dependence of land use effects on water quality of streams in agricultural catchments

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"Capsule": *Land use influences water quality of streams at various spatial scales.*

Abstract

The influence of land use on water quality in streams is scale-dependent and varies in time and space. In this study, land cover patterns and stocking rates were used as measures of agricultural development in two pasture and one native grassland catchment in New Zealand and were related to water quality in streams of various orders. The amount of pasture per subcatchment correlated well to total nitrogen and nitrate in one catchment and turbidity and total phosphorous in the other catchment. Stocking rates were only correlated to total phosphorous in one pasture catchment but showed stronger correlations to ammonium, total phosphorous and total nitrogen in the other pasture catchment. Winter and spring floods were significant sources of nutrients and faecal coliforms from one of the pasture catchments into a wetland complex. Nutrient and faecal coliform concentrations were better predicted by pastural land cover in fourth-order than in second-order streams. This suggests that upstream land use is more influential in larger streams, while local land use and other factors may be more important in smaller streams. These temporal and spatial scale effects indicate that water-monitoring schemes need to be scale-sensitive.

Keywords: Catchment development; Pasture streams; Land cover patterns; Nutrients; Faecal coliforms

1. Introduction

Agricultural activities have been identified as major sources of sediments, nutrients and faecal bacteria to rivers and streams in New Zealand (Wilcock, 1986; Rutherford et al., 1987; Cooper and Thomsen, 1988; Quinn et al., 1997; Wilcock et al., 1999; Niyogi et al., 2003) and elsewhere (e.g., Carpenter et al., 1998; Hunter et al., 2000). Strong relationships have been found between declining water quality of streams and increasing extent of agricultural development in catchments in rural New Zealand (Smith et al., 1993). While pollution from point sources has declined noticeably over recent decades, non-point pollution from agricultural land is still the main factor causing water pollution in New Zealand (MfE, 2000).

The influence of land use on stream integrity is scale-dependent and varies in time and space (Allan et al., 1997; Townsend and Riley, 1999; Townsend et al., 2003). Rivers are hierarchical systems embedded in spatially heterogeneous landscapes whose ecosystem structures and functions are themselves scale-dependent (Frissell et al., 1986; Hunsaker and Levine, 1995). The increasing availability of geographic information systems and remote sensing techniques has allowed researchers to quantify landscape structures and assess influences of terrestrial ecosystems on river water quality at different scales. For example, some studies have found that catchment-wide land use is a better predictor of nutrient levels and in-stream habitat conditions (e.g. Omernik et al., 1981; Roth et al., 1996; Johnson et al., 1997) while others have related stream conditions better to land use within riparian zones adjacent to streams (e.g. Basnyat et al., 1999; Lammert and Allan, 1999; Sponseller et al., 2001).

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These spatial-scale patterns may also be confounded by seasonal trends. Johnson et al. (1997) demonstrated that total nitrogen and nitrate concentrations were better explained by riparian land cover in autumn but equally well explained by riparian and catchment-wide land cover in summer. Thus, different processes may occur at multiple scales within a catchment. Hierarchical sampling designs have been suggested as a means of addressing sources of variation in catchments and should help to clarify the scale-dependency of land-use effects on water quality (Richards et al., 1996; Townsend, 1996; Townsend et al., 1997).

Understanding of the cumulative contributions of different land uses as they change downstream may be a vital ingredient for successful water management (Sidle and Hornbek, 1991; Bolstad and Swank, 1997). Most comparative water quality studies have focussed on differences between agriculturally-impacted and pristine catchments (e.g. Cooper and Thomson, 1988; Quinn and Stroud, 2002), but have not related their findings to the changing intensity of agricultural development along the river network. Longitudinal water quality changes along the Pomahaka River in southern New Zealand were attributed to increasing agricultural intensity in the mid and lower reaches as compared to a pristine river system (Harding et al., 1999). Drastic increases in dissolved inorganic nitrogen and turbidity were attributed to stocking intensities exceeding a critical threshold. The same authors also suggested that stocking rates may be a better measure of agricultural development than widely used indicators such as land use cover.

The main objective of this study was to address the effects of scale and land use on water quality and their implications for catchment management. We examined streams in two pastoral catchments and one tussock grassland catchment on the South Island of New Zealand, and included a range of stream sizes and sampling seasons in our study design. We investigated the relationships between water quality, land cover and stocking rates at different scales.

2. Materials and methods

2.1. Study area

Samples were collected from streams in three catchments in the eastern part of the province of Otago in the South Island of New Zealand (Fig. 1, Table 1). The headwaters in the Lee Stream catchment typically originate in hill country with tussock grassland vegetation and flow through deeply incised gullies. Samples were taken along Lee Stream, Broad Stream and their

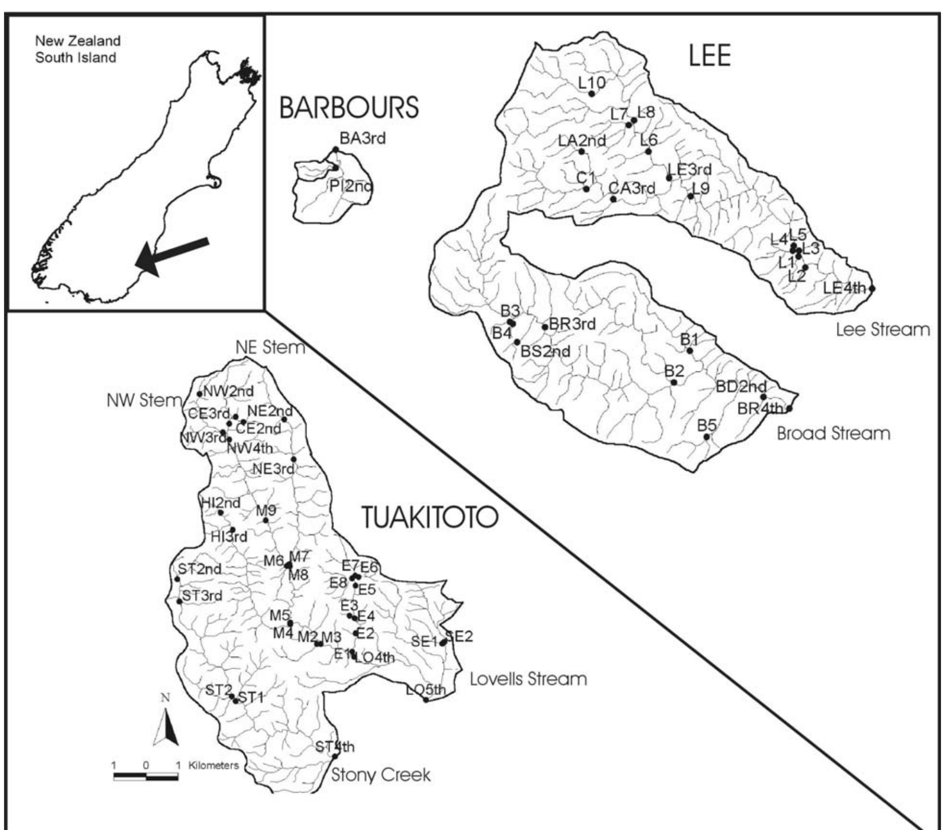

Fig. 1. Study catchments and sampling sites location.

Table 1
Descriptive data for the three investigated catchments

	Lee	Tuakitoto	Barbours
Elevation range (m)	300–600	20–400	720–900
Catchment area (ha)	6830	6450	320
Annual Rainfall (mm)	492	631	492
Bedrock type (s)	Schist rock	Schist, Semi-Schist, Colluviums, Conglomerate	Schist rock
Dominant land use types	Sheep and beef cattle farming with some deer farming	Sheep, cattle and dairy farming with some forestry	Ungrazed tussock. Drinking water reserve
Mean stocking rates (range) (Stock units/ha)	6.9 (4.7–10.6)	11.3 (6.8–24.5)	No stock

tributaries. Land cover has been extensively modified to improved pasture in the middle and lower reaches of the catchment. Pockets of native and exotic scrub and tussock grassland exist in the middle and lower reaches as moderately to heavily grazed riparian slopes, which are too steep to be ploughed. Agricultural land use is predominately sheep farming with some deer farming.

A second set of study sites was located in the Lake Tuakitoto catchment along Lovells Stream, Stony Creek and their tributaries. In comparison to the Lee catchment, the Tuakitoto catchment has a higher degree of agricultural development, expressed as higher average stocking intensities. Land use is dominated by sheep and cattle farming with several dairy farms located in the upper catchment (Table 1). Patches of regenerating native forest can be found in the middle reaches of the catchment, forming a forested riparian buffer zone.

A final set of sites was in the Barbours Stream catchment just northwest of the Lee catchment (Fig. 1). This catchment is situated within a drinking water reserve and farming is not permitted. Land cover is characterised by tussock grassland. Water quality in this catchment was expected to be high and allowed a comparison between agricultural and relatively pristine streams.

2.2. Sampling methodology

During January and early February 2001, 60 first-to-fourth order sites were sampled during baseflow conditions in the Tuakitoto and Lee and Barbours catchments. Samples were taken from all major tributaries to assess water quality and land-use relationships (Fig. 1). Baseflow discharge in the Tuakitoto catchment was very low during summer conditions because of drought, and initial sampling along stream reaches in the lower catchment showed that most first-order tributaries entering the main stream channel had dried up. Sampling frequency was therefore reduced in the upper catchment.

Field measurements of dissolved oxygen (DO), specific conductivity (COND) and temperature (TEMP) were made using a portable meter (YSI Model 85). Stream discharge (FLOW) was calculated by measuring depth and velocity at 60% depth (with a Marsh-McBirney Flowmate Model 2000) at several points along a transect at each site. Turbidity (TURB) was recorded in the laboratory using a meter (Hach 2100A Model). Total suspended solids (TSS) were calculated by filtering the sample onto a tared filter, drying the filter to constant mass and weighing the dried filter (Method 2540 D, APHA, 1998). Dissolved nutrients were sampled mid-stream and filtered in the field through glass fibre filters (Whatman GF/F type, nominal pore size = 0.7 μm) into acid-washed polyethylene bottles and stored on ice during transport to the laboratory. Nutrient samples were then frozen prior to analysis. Within 30 days, samples were thawed to room temperatures and analysed for nitrite–nitrate nitrogen ($NO_3^- + NO_2^-$; colorimetry of diazonium salt after sulphanilamide reaction and reduction of NO_3 to NO_2 through cadmium column, 4500-NO_3-F-Method, APHA, 1998), ammonium-nitrogen (NH_4^+; colorimetry of indophenol blue after phenol/hypochlorite reaction, 4500 NH_3-G-Method, APHA, 1998) and dissolved reactive phosphorous (DRP; automated ascorbic acid reduction method, APHA, 1998). Preliminary sampling showed that nitrite concentrations were minimal (<5% of NO_3^-) and nitrite–nitrate nitrogen concentrations can thus be treated as equivalent to nitrate concentrations and will be referred to as NO_3 for the remainder of this paper. An unfiltered fraction was analysed for total nitrogen (TN) and total phosphorous (TP) (acid digestion followed by peroxidisulphate oxidation and addition of ammonium chloride, Ebina et al., 1983).

Out of the sixty sampled sites, 24 sites were selected from different stream orders in the Lee, Barbours and Tuakitoto catchment (Fig. 1, Table 2) and also analysed for faecal coliforms (FC). The FC samples were collected in sterilised plastic bottles and stored on ice until analysis by the Otago Regional Council facilities within 24 h (using membrane filtration methods 9222 D, APHA, 1998). The sites were chosen to reflect different stream orders and the main land uses in the catchments.

To allow a useful cross-comparison of spatial and temporal scales, the selected 24 sites were sampled again on two other baseflow occasions in May and October. Baseflow conditions were assumed if there had been at

Table 2
Sampling sites by stream order and land use type

Stream order	Land use type					
	Sheep	Dairy	Deer	Mixed	Tussock	Total
Second	5	2	1	–	1	9
Third	5	2	–	1	1	9
Fourth	3	–	–	2	–	5
Fifth	–	–	–	1	–	1
Total	13	4	1	4	2	24

least 5 days of no significant rain (<10 mm over 48 h) in the catchments, recorded at three nearby Otago Regional Council rainfall stations. Additionally, we collected stream samples following two heavy rainfall events in the Tuakitoto catchment in July (38.5 mm rain over 48 h) and November (26 mm rain over 48 h).

2.3. Land use and cover data

To calculate land cover percentages, subcatchment boundaries were delineated for each sampling site using 1:50,000 topographical maps (NZSLI, 1998) and overlain on land cover data within a GIS system (ArcView, ESRI Ltd.). Pre-defined land cover data based on SPOT4 satellite images taken in January 1999 were used in the Lake Tuakitoto catchment and combined to four functional vegetation cover types: Pasture, Pasture/Scrub, Scrub, and Exotic Forest. Land cover in the Lee catchment was newly classified using equally dated georeferenced SPOT4 satellite data. A supervised classification was performed using the maximum likelihood algorithm within the imaging software package ERDAS IMAGINE 8.5. Reference sites for the classification were identified on the images based on field knowledge and 1:27,500 aerial photographs from May 1997 and grouped into four functional vegetation cover types: Pasture, Tussock, Scrub/Grazed tussock, Exotic Forest. Land cover in the Barbours catchment was almost entirely tussock grassland. An explicit land cover classification was thus not performed in these catchments and land use interrelationships were not performed.

Stocking rates (livestock numbers per unit area) were also incorporated into the GIS system as a separate data layer. The Otago Regional Council surveyed livestock numbers and farm boundaries in the Tuakitoto catchment in 1999. Animal numbers and property boundaries in the Lee catchment were recorded during a telephone survey and farm visits in July 2001; the data were then digitised and entered into the GIS. Animal numbers were converted into stock units and divided by subcatchment area. The stock unit is a standardized, weighted index to estimate the pasture's capacity to support different types of livestock (1 cow = 6 stock units, 1 sheep = 1 stock unit, 1 deer = 2 stock units). Because catchment boundaries are not necessarily the same as farm boundaries, stocking rates were averaged using the area proportion occupied by each farm as weighting factors.

2.4. Data analysis

Descriptive statistics were calculated to describe the baseflow water chemistry using a standard statistical software package (SPSS Version 9.0). Linear relationships among water quality variables were determined using Pearson's correlation coefficients (r). Positively skewed data were log-transformed prior to analysis. Kendall's Tau correlation coefficient is less influenced by the effects of outliers and small sample numbers and was used if small data sets were strongly influenced by unusual values (Hesel and Hirsch, 1995). Kendall's Tau value is generally lower than values of the Pearson's r coefficient, because a different scale of correlation is used and strong r correlations of 0.9 or above correspond to tau values of about 0.7 or above (Hesel and Hirsch, 1995). Because hydrological and geological conditions are different in the Tuakitoto and Lee catchments, separate statistical analyses were made for the two catchments. Nutrient, sediment and faecal coliform yields (expressed as g d^{-1} km^{-2} and cfu d^{-1} km^{-2}) were calculated using spot discharge measurements, upstream catchment areas and concentration values to evaluate the amount of contaminants leaving a subcatchment per unit area. Yield values allow comparison among different sized catchments with variable discharges.

Land cover was calculated at two different spatial scales within the GIS. The percentage of each land cover type upstream of the sampling location was calculated for the whole subcatchment area and a 120 m riparian corridor, extending laterally 60 m each side of the stream. A minimum riparian buffer width of 60 m was chosen due to the spatial resolution of the SPOT4 satellite data, which requires a minimal cluster size of 3×3 pixels (i.e. 60×60 m) to identify land cover patches (Lillesand and Kiefer, 2000). Pearson's correlation coefficients (r) were calculated among land cover data, stocking rates and water quality variables at both scales. Scatterplots were used to investigate if there were non-linear relationships between the data sets, which could have been overlooked by calculating Pearson's and Kendall's correlation coefficients.

3. Results

3.1. Relationships among water quality variables during summer baseflow

Correlation coefficients for relationships among physico-chemical variables during summer baseflow are shown in Table 3. TURB was positively correlated

Table 3
Relationships among water quality variables during January sampling in the Lee (lower table triangle) and Tuakitoto subcatchments (upper table triangle) expressed as Pearson correlation coefficient

	Tuakitoto												
	Order	DO	COND	TEMP	TURB	FLOW	NO_3	DRP	NH_4	TP	TN	FC*	TSS
Lee													
Order		**0.50**	0.19	0.19	**−0.41**	**0.83**	0.07	0.04	0.06	−0.28	0.02	−0.10	***−0.47***
DO	**0.46**		−0.30	−0.23	**−0.57**	**0.74**	0.30	0.01	−0.06	***−0.48***	0.07	−0.30	−0.29
COND	−0.40	−0.33		0.28	0.12	−0.10	***−0.40***	0.06	0.01	−0.23	0.20	−0.26	0.01
TEMP	**−0.48**	**−0.59**	0.33		0.16	−0.01	−0.31	−0.06	−0.04	−0.12	−0.23	0.11	−0.02
TURB	−0.22	−0.22	**0.61**	0.10		***−0.42***	0.07	0.10	0.21	**0.68**	***0.46***	0.27	**0.67**
FLOW	**0.90**	**0.41**	**−0.52**	***−0.45***	−0.38		0.33	−0.06	−0.04	−0.36	0.12	−0.14	***−0.46***
NO_3	0.06	0.16	**0.56**	−0.21	***0.49***	−0.14		−0.06	**0.44**	0.23	**0.79**	−0.16	−0.07
DRP	0.08	−0.06	0.33	−0.03	0.22	−0.03	***0.40***		***0.36***	***0.44***	0.29	−0.16	0.25
NH_4	−0.22	−0.11	**0.53**	0.26	**0.60**	***−0.45***	***0.49***	**0.51**		***0.45***	***0.44***	−0.31	0.28
TP	−0.33	**−0.41**	***0.48***	0.25	**0.72**	−0.38	***0.43***	**0.54**	**0.63**		0.35	−0.11	***0.43****
TN	−0.23	−0.18	**0.71**	0.15	**0.66**	***−0.48***	**0.80**	0.30	**0.78**	**0.58**		***−0.40***	0.14*
FC*	0.29	0.11	0.04	−0.11	0.35	0.15	**−0.84**	0.18	0.55	0.18	−0.18		0.38*
TSS*	−0.21	**−0.39**	0.44	0.17	**0.77**	−0.25	0.00	0.39	***0.56***	0.39	0.33	0.26	

Kendall's Tau correlation coefficients were calculated for sample numbers <20 and marked with an asterisk. All data are log-transformed, except Temp and Order. Bold values are statistically significant at $P<0.01$, italics at $P<0.05$. $n=24-35$, expect for FC and TSS, where $n=8-15$.

to NO_3, NH_4, TP and TN in the Lee catchment and TP and TN in the Tuakitoto catchment. The strong relationships between TP and TURB reflect the particle-bound transport of P. Surprisingly, TP and TSS were only weakly related in the Tuakitoto catchment and showed no relationships in the Lee catchment. However, the data for the Tuakitoto catchment were highly correlated (Kendall's Tau = 0.61, $P<0.01$) after two outliers were excluded from the analysis. Both outliers were sites in an active dairy farm and instream plant growth under very low flow conditions at these sites could have accounted for differences in nutrients and suspended sediments. Surprisingly TSS and TURB showed no correlation with FC in either catchment (Table 3).

3.2. Land cover distribution

Catchment-wide analysis showed that pasture was the dominant land cover in all the Tuakitoto and Lee subcatchments (Fig. 2). The upper Tuakitoto catchment was dominated by intensive pastoral land use. Extensively grazed tussock grasslands still remained in the upper Lee catchment. Moving further downstream, land cover became more diverse in the Tuakitoto catchment because of remaining patches of indigenous and exotic scrub along the mid-reaches of Lovells Stream. In the Lee catchment, scrub-tussock vegetation was present in all subcatchments on steep riparian slopes, which were not ploughed. Exotic forestry was minimal in both catchments and occupied generally less than 5% of the land. The minimal amount of forestry was not expected to have any significant effect on water quality and was not included in further analysis.

Land cover patterns within the 60 m riparian corridor zone were very similar to subcatchment-wide land cover in both catchments (Fig. 2). Overall, riparian vegetation contained more scrub in the Tuakitoto catchment and scrub-tussock vegetation in the Lee catchment. Both these land cover classes are commonly located along the steep riparian slopes in the two catchments, explaining their slightly higher contribution to riparian buffer land cover. Because of similar land cover distributions, further correlation analysis produced almost identical results at the corridor and subcatchment scale and results are only presented for the latter.

3.3. Relationships among land use and water quality

PASTURE was the dominant land cover in both catchments and was closely related to TP and TURB levels in the Tuakitoto catchment (Table 4). In the Lee catchment, pastoral land use was significantly related to TN and TP. PASTURE/SCRUB in the Tuakitoto subcatchments had a weak negative correlation with DRP concentrations. SCRUB had a strong negative relationship with the sediment-related variables TURB and TP. In the Lee catchment, TUSSOCK was negatively related to COND, NO_3, DRP, TP and TN.

Stocking rates corresponded poorly to water quality variables in the Tuakitoto catchment and were only correlated with TP (Table 4). Conversely, stocking rates were more strongly related to water quality variables in the Lee catchment. Increasing stocking rates were correlated with COND, NH_4, TP and TN. Surprisingly, stocking rates did not have a significant relationship with FC contamination in either catchment, but were related to TURB in the Lee catchment.

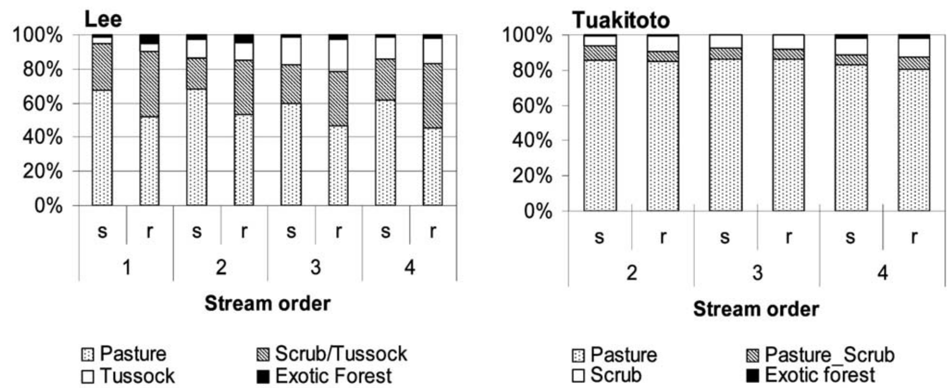

Fig. 2. Mean land cover distribution by stream order in the Lee and Tuakitoto subcatchments (s) and along 120 m-wide riparian corridors (r).

3.4. Spatial scale effects

Some correlations in the Lee catchment were strongly influenced by sampling sites on first-order streams (Fig. 3). Two of these sites (B3 and B4, Fig. 3) were on streams draining two small gullies next to each other. They both had a similar size, vegetation, stocking rates, and topography with very low stream flows and considerable stream channel vegetation, but considerable differences in water quality. Turbidity was about 10 times higher, NO_3 more than 20 times higher, NH_4 three times higher and TP and TN more than twice as high in one compared to the other subcatchment. These differences could be related to local stock numbers. During sampling about 500 sheep were visible upstream in one subcatchment, while only about 100 sheep were upstream in the other subcatchment. This might have increased nutrient and turbidity levels through stock access prior to sampling.

Excluding the four first-order streams from the correlation analysis, relationships between water quality and land cover changed considerably in the Lee catchment (Table 4). Stronger relationships were then found between PASTURE and COND, NO_3 and TN, while TP was no longer significantly correlated. Relationships were also stronger between SCRUB/TUSSOCK and TN, and between TUSSOCK and COND, NO_3, TP and TN.

More spatial scale effects became evident by plotting pastoral land use versus nutrient concentrations for different stream orders in both study catchments (Fig. 4). The amount of pasture was a good predictor of TN and to a lesser extent of TP and FC in fourth order sites, but not in second and third order sites. Similar scale-dependent relationships were found for TURB and NO_3 (graphs not shown), while no differences were observed for the other measured variables. Several of the fourth order sites in the Tuakitoto catchment were located downstream of each other along the main Lovells Stream, so they are not entirely independent of each other. However, independent fourth order sites on Stony Creek and in the Lee catchment supported the observed relationships, albeit more strongly for TN than for TP and FC.

Table 4
Land use influence on water quality at the subcatchment (S) and riparian corridor scale (R) expressed as Pearson correlation coefficient

	Lee											Tuakitoto						
	Pasture			Tussock			Scrub/Tussock			SR		Pasture		Pasture/Scrub		Scrub		SR
	S	R	E	S	R	E	S	R	E	S	E	S	R	S	R	S	R	S
DO	−0.40	−0.25	−0.21	0.37	0.30	0.38	0.32	0.24	0.07	−0.21	−0.11	−0.01	0.10	***−0.38***	***−0.35***	***0.35***	0.33	−0.23
COND	0.35	0.32	***0.57***	**−0.67**	**−0.65**	**−0.76**	0.07	0.10	−0.13	***0.66***	**0.60**	−0.29	−0.23	0.22	0.14	0.11	0.11	−0.13
TEMP	0.34	0.21	0.18	−0.39	−0.37	−0.35	−0.24	−0.21	−0.10	0.35	0.21	0.02	0.14	0.17	0.11	−0.20	−0.25	−0.16
TURB	0.20	0.18	0.40	−0.26	−0.26	−0.41	−0.07	−0.10	−0.28	**0.62**	**0.76**	**0.50**	**0.57**	−0.04	−0.13	**−0.58**	**−0.53**	−0.16
NO_3	0.28	0.33	**0.67**	**−0.55**	**−0.55**	**−0.77**	0.07	0.65	−0.26	0.34	0.44	−0.02	0.06	0.09	−0.15	0.04	0.08	0.01
DRP	0.34	0.31	0.27	***−0.45***	***−0.45***	−0.43	−0.10	−0.93	0.04	0.29	0.34	0.32	0.21	***−0.39***	−0.22	0.03	0.00	0.14
NH_4	0.27	0.27	0.34	−0.26	−0.24	−0.26	−0.19	−0.22	−0.39	***0.50***	***0.47***	0.15	0.24	−0.04	−0.15	−0.18	0.20	0.30
TP	***0.44***	0.37	0.44	***−0.44***	−0.41	***−0.47***	−0.31	−0.27	−0.35	***0.48***	***0.52***	**0.60**	**0.62**	−0.22	−0.26	**−0.57**	**−0.51**	***0.41***
TN	***0.43***	***0.44***	**0.66**	***−0.49***	***−0.47***	**−0.63**	−0.23	−0.22	***−0.50***	***0.49***	***0.56***	0.18	0.24	−0.14	−0.24	−0.07	0.10	0.01
FC	−0.49	−0.18	−0.49	0.47	0.33	0.47	0.38	−0.04	0.38	0.00	0.00	0.05	0.03	0.24	0.24	−0.14	−0.08	−0.37
TSS	0.42	0.16	0.42	−0.64	0.42	−0.64	−0.36	0.28	−0.36	0.42	0.42	0.22	0.11	−0.16	0.01	−0.12	−0.13	0.11

Kendall's Tau coefficient was calculated for FC in the Lee and Tuakitoto and TSS in the Lee subcatchments. Data were log−transformed, except Temp. Bold values are statistically significant at $P<0.01$, italics at $P<0.05$. $n=23-35$, except FC and TSS, where $n=8-24$. SR = Stocking rates. E = 1st order sites excluded.

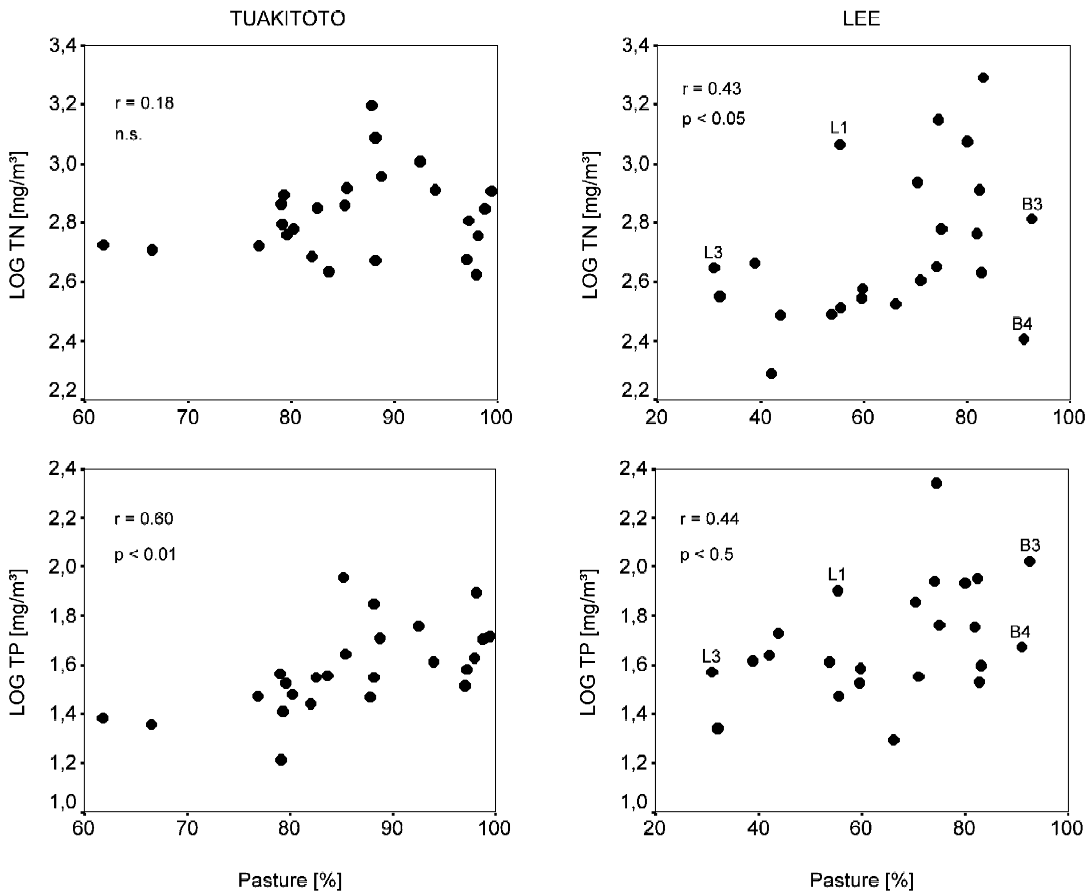

Fig. 3. Total nitrogen and total phosphorous vs. pastoral land cover in the Lee and Tuakitoto subcatchments. The first order sites in Lee are labelled with their site identification. Pearson's (*r*) correlation coefficient, n.s. = not statistically significant at $P<0.05$.

In the Barbours catchment there was no evidence that stream order had an influence on water quality, given that nutrient and FC concentrations were very low in both tussock streams. Additional sampling on nearby 4th and 5th order tussock streams also showed extremely low concentrations of nutrients (D.K. Niyogi, unpublished data).

3.5. Temporal changes in water quality

Additional baseflow sampling during May and October revealed that median NO_3 and NH_4 concentrations were highest during May in both agricultural catchments and that these differences were most pronounced in the Tuakitoto catchment (Fig. 5). While highest TN values were also recorded in the Tuakitoto area during May, highest values in the Lee catchment were measured during October. Seasonal changes in DRP concentrations were less pronounced with highest values recorded in both catchments during January. FC contamination during baseflow was also highest during January. TSS showed higher variation in the Tuakitoto catchment with median concentrations being doubled during January compared to May and October. Nutrient, TSS, and FC concentrations in streams of the Barbours tussock catchment were low during all samplings.

Spot sampling during two floods showed that nutrient and faecal coliform concentrations were dramatically increased in the Tuakitoto catchment (Tables 5 and 6). Extreme bacterial contamination was recorded during the July flood, when notable surface runoff as overland flow occurred. FC concentrations of more than 28,000 cfu/100 ml occurred at five of the 14 sample sites during this flood with highest values reaching 88,000 cfu/100 ml. Faecal coliform export during the July flood (estimated from instantaneous measurements) was more than 2000 times higher than during the May baseflow sampling (Table 5). Nutrient and sediment export rates were up to 300 and 1700 times higher than during May baseflow.

4. Discussion

4.1. Relationships among variables during summer baseflow

Sediment-driven processes were most likely responsible for significant relationships observed among

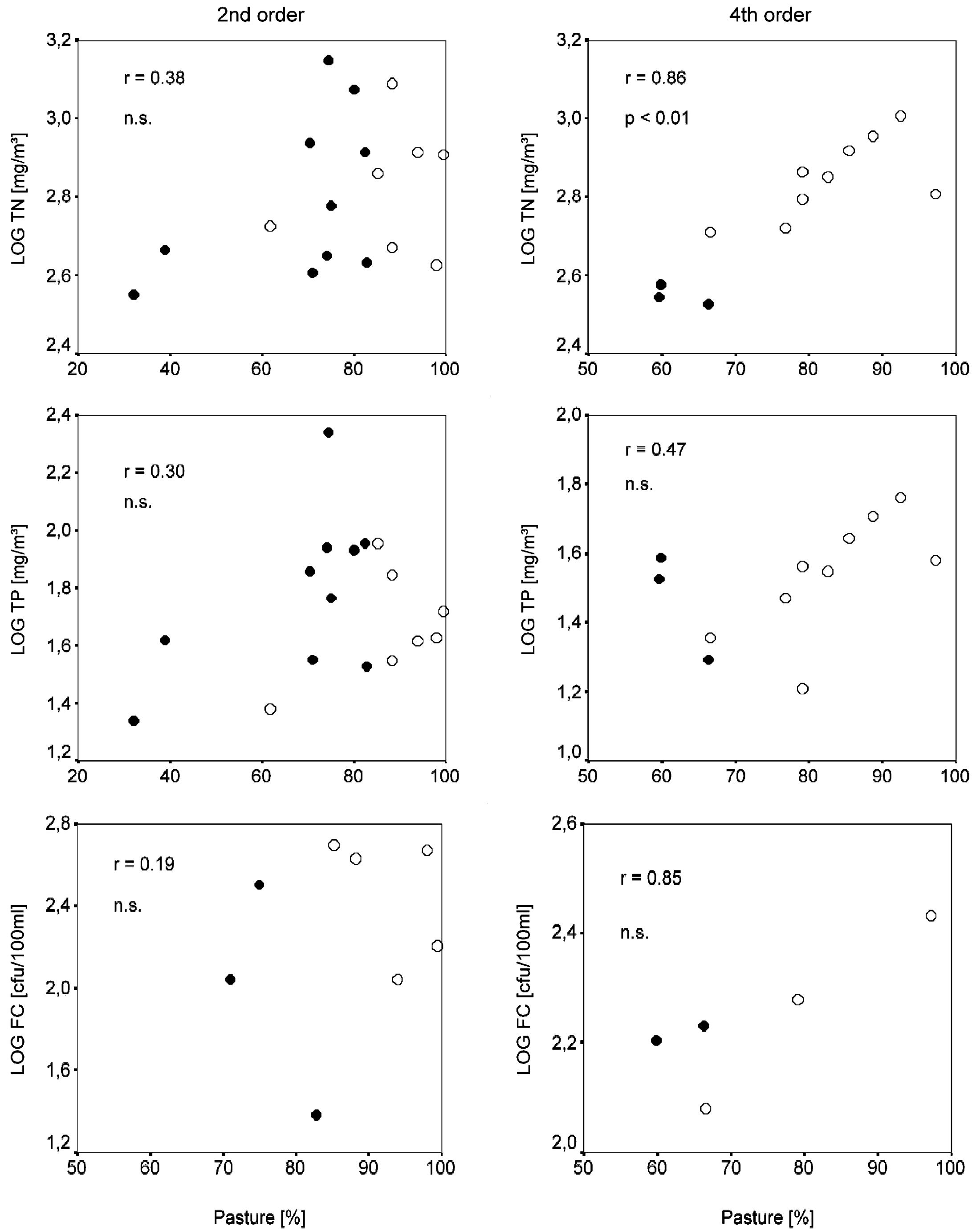

Fig. 4. TN, TP and FC vs. pastoral land cover for different stream orders in the Tuakitoto (open circles) and Lee subcatchments (full circles). Pearson's (r) correlation coefficient, n.s. = not statistically significant at $P < 0.05$.

physico-chemical variables during summer. The strong correlations among turbidity, TSS and TP emphasize the predominantly sediment-bound transport of phosphorous. This is in accordance with several studies in pasture catchments in New Zealand, which reported that the majority (62–91%) of P exported into waterways was particulate P (reviewed in Gillingham and Thorrold, 2000).

Sediment-driven processes could also be responsible for the relationship between TN and turbidity. Quinn and Stround (2002) found that surface runoff and erosion played an important role in N loss in steep New Zealand hill catchments. During summer in the Tuakitoto catchment, only about one third of TN was exported as NO_3 or NH_4 compared to 80% and almost 50% during the May and October baseflow sampling, respectively. In

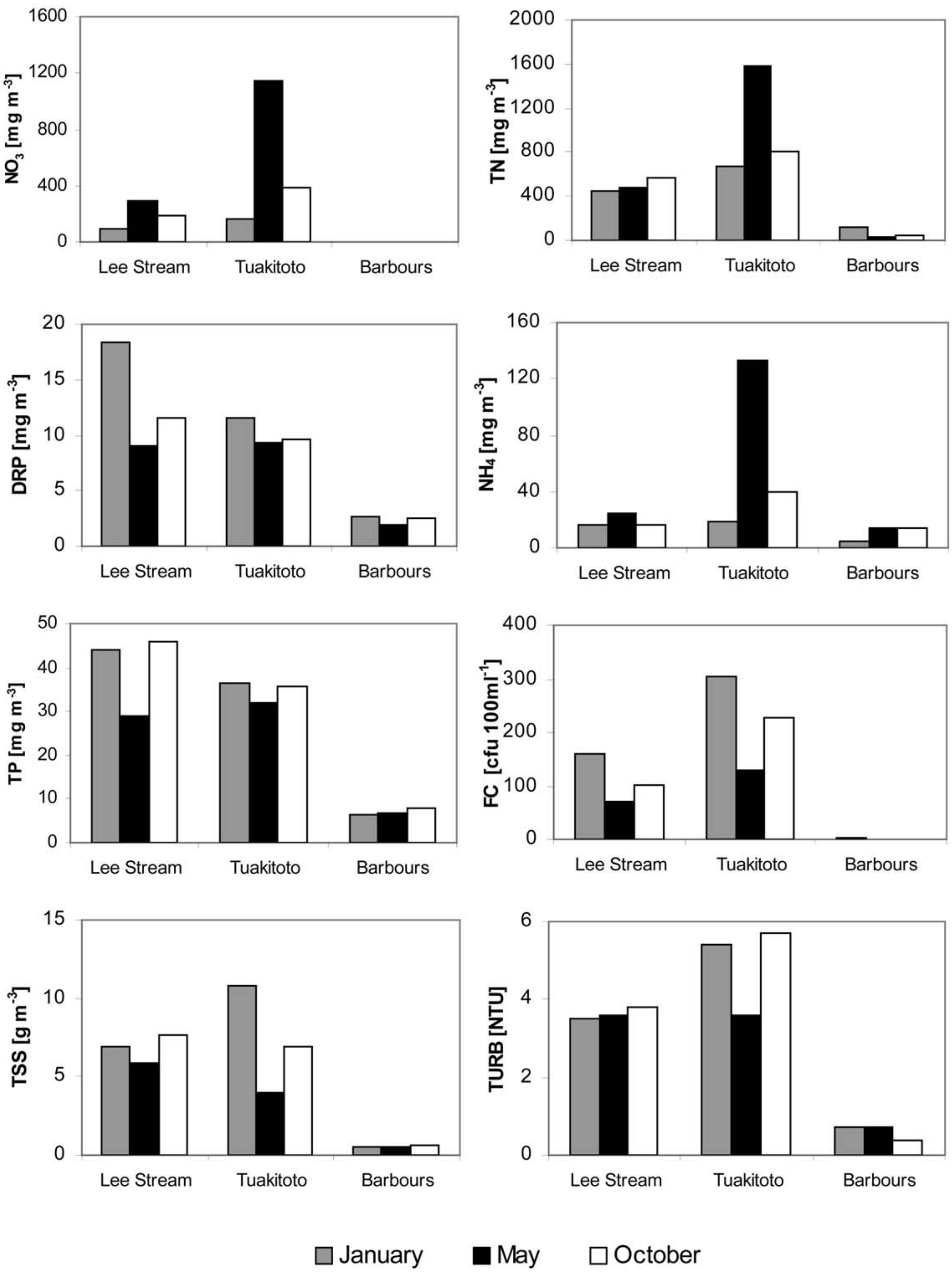

Fig. 5. Median concentrations of selected water quality variables during three baseflow samplings. Note that NO_3 and PC concentrations In the Barbours tussock catchment were consistently very low (<2 mg m^{-3} and <2 cfu 100 ml $^{-1}$, respectively) and are therefore not visible in the graphs.

the Lee catchment this proportion rose from slightly more than 20% in January to 57% in May and 30% in October. This means that the majority of N entering the waterways during summer was either transported as dissolved organic or particulate nitrogen. Effective land management strategies to control N and particularly P loss during summer in these steep catchments should focus on mitigating sediment transport. This could include limiting stock access points to reduce stream bank damage and riparian pasture retirement (Smith, 1989).

Table 5
Spot sampled export rates during selected baseflow and flood events in the Tuakitoto catchment

	May baseflow		July flood		October baseflow		November flood	
	Median	Range	Median	Range	Median	Range	Median	Range
NO_3	538.9	264.1–1406.5	1.3×10^5	1.3×10^4–3.3×10^5	120.0	6.8–602.3	1356	328–4432
DRP	5.8	1.7–21.0	1982	87–1.1×10^4	3.1	0.5–20.6	45	25–404
NH_4	71.1	34.7–132.8	1.4×10^4	2320–7.4×10^4	12.0	2.4–58.5	254	70–4296
TP	21.6	8.9–108.8	6956	1039–3.4×10^4	12.4	2.4–92.7	333	114–1583
TN	741.8	411.4–2.2×10^3	2.3×10^5	2.5×10^4–5.5×10^5	265.1	52.7–1399.7	5391	2007–1.8×10^4
FC	7.6×10^8	1.1×10^8–3.4×10^9	1.7×10^{12}	4.1×10^{11}–5.4×10^{13}	5.9×10^8	4.2×10^8–8.1×10^9	1.3×10^{11}	4.4×10^8–7.8×10^{11}
TSS	1776	530–1.3×10^4	9.8×10^6	5.9×10^5–5.0×10^7	2983	153–7.6×10^4	1.0×10^5	2.0×10^4–5.0×10^5

Nutrient and sediment yields in (g d^{-1} km^{-2}), FC yield in (cfu d^{-1} km^{-2}), Sample size = 11–14.

4.2. Land cover and stocking rates as development indicators

Most previous studies have related land cover to stream water quality on large geographical scales, ranging over multiple catchments, or have investigated only few catchments with strongly contrasting land-use patterns (e.g. forest, urban, row crops) (Quinn et al., 1997; Hunsaker and Levine, 1995; Sponseller et al., 2001). Our study extended these approaches by comparing relatively homogeneous and highly developed pasture catchments at the subcatchment scale.

On a national scale, Close and Davies-Colley (1990) showed that the amount of intensive pasture was one of the most important variables determining water quality in streams throughout New Zealand. In our study the amount of pasture per catchment also showed strong linear relationships with nutrient concentrations at the subcatchment scale. Pasture correlated well to TP in both catchments, but showed differences between catchments for other water quality variables. Pasture was well correlated with NO_3 and TN in the Lee catchment but not in the Tuakitoto catchment, where pasture was correlated to TURB in addition to TP. This suggests that pastoral land use affects water chemistry differently in the two catchments and that erosion and sediment delivery processes might be more important in the Tuakitoto catchment.

Table 6
Comparison of stormflow nutrient and FC concentrations during the winter flood in the Tuakitoto catchment with other pasture catchments

	Tuakitoto		Purukohukoho[a]		Toenepi[b]
	Median	Range	Median	Range	Max
NO_3	3569	2096–7288	364	2–7453	5950
DRP	55	17–182	93	8–1557	362
NH_4	508	255–1208	205	3–6023	1370
TP	281	103–560	293	19–6838	1090
TN	7455	3702–9169	n.m.	n.m.	6940
FC	6600	1200–88,000	n.m.	n.m.	26,000

Nutrients in (mg m^{-3}), FC in (cfu 100 ml^{-1}).
[a] Cooper and Thomsen (1988).
[b] Wilcock et al. (1999) n.m. = not measured.

Scrub and pasture-scrub in the Tuakitoto catchment showed negative correlations to several nutrient and sediment variables. This might be explained by their relative distribution within the subcatchments. Most of these vegetation types are located within riparian zones and on steep slopes. Small riparian zones can have profound effects on water quality by filtering overland flow and removing nitrate from shallow groundwater (Smith, 1989; Quinn et al., 1993). Of greater importance, however, might be that dense scrub vegetation, as encountered in parts of the Tuakitoto catchment, could have limited stock access to the stream and thus reduced stream bank damage and the direct input of animal waste into the stream during baseflow. Scrub-tussock vegetation in the Lee catchment showed only a weak correlation to TN and no relationships to other sediment-related variables. However, the grazed scrub-tussock in the Lee catchment, where the vegetation is much less dense, does not restrict stock access to the stream as does the scrub in the Tuakitoto catchment.

Stocking rates as a measurement of agricultural intensity to assess the impact of agriculture have rarely been quantified in water quality studies (Harding et al., 1999). In our study stocking rates related better to water quality in the Lee catchment than in the Tuakitoto area. This could be attributed to variables not measured in this study, including stock management techniques. Intensive rotational grazing is a common management technique in many parts of the Tuakitoto catchment. This may be reflected in the greater amount of soil disturbance and erosion associated with more intensive grazing regimes (Lambert et al., 1985). Our findings also raise the question of whether averaged farm stocking rates are sufficient to reflect the consequence of smaller scaled spatial and temporal stock movements in the catchment. This could be seen in the high water quality variation at first order streams in the Lee catchment. Areas of concentrated stock near streams may have a large effect on water quality during sampling, regardless of the farm-wide stocking rate. A recent study in the Aorere catchment in Golden Bay, New Zealand, also failed to detect a relationship between farm-wide stocking rates and water quality and attributed this to the local importance of stream disturbances, such as local stock crossings, stream bank erosion and point source discharges (Nottage, 2001). Thus, the use of stocking rates as a measure of agricultural development has limitations without knowledge of stock distribution and access to the stream.

4.3. Spatial scale effects

The amount of pasture related better to water quality in fourth order than second order sites. Local land use and variation might be of greater importance in small second order streams, while water quality in larger streams is better predicted by the amount of pastoral land use in the whole catchment upstream, as other have found (Gburek and Folmar, 1999). This trend may also be related to the averaging out of the effects of local heterogeneity at broader scales, a phenomenon commonly encountered in ecological patterns (Wiens, 1989). This aspect has been often overlooked in water quality monitoring. Successful catchment management in upstream areas will need to focus on ‘‘small-scale’’ effects of local land management such as the location of stock crossings and water access points and damage to riparian buffer zones. These factors clearly influence water quality at the catchment outlet, but with increasing catchment size, management options will also have to address processes at larger scales, such as catchment-wide pastoral land cover, fertilizer use, or stock numbers.

4.4. Temporal changes in water quality

Knowledge about temporal changes in water quality is crucial for successful catchment management. The Lovells Stream drains into the Lake Tuakitoto complex, a wetland with significant ecosystem values (ORC, 1995, 1998). Traditionally, baseline nutrient concentrations in this catchment are monitored at bi-monthly intervals, regardless of season and river discharge. This might be insufficient to assess the impact of agricultural land use on the wetland complex. If, for example, nitrate export is of management concern, then land management strategies should focus on the wet autumn and winter seasons. However, reducing nitrate input into the wetland during autumn/winter might not necessarily mitigate the total nitrogen input. Nitrate taken up during the growing season by stream channel vegetation can still reach the catchment outlet as dissolved or particulate organic nitrogen. In storm events, sloughing of partially decayed plant material and release of sediment-trapped nutrients can occur and increase nitrogen in particulate form in the wetland, which may cause a potential eutrophication risk. This was evident in the sampled storm events, which delivered large amounts of nutrients and faecal coliforms to the Tuakitoto wetland.

Contaminant concentrations during storms are governed by several variables, including peak discharge (Hoare, 1982), season (McColl and Gibson, 1979; Dils and Heathwaite, 1996) and land use (Cooper and Thomsen, 1988; Cooke, 1988). This makes it difficult to compare our spot-sampled flood results with previously published data. However, nutrient and sediment concentrations during the July flood were in the upper range of stormflow concentrations reported by Cooper and Thomsen (1988) for a pasture catchment and similar to peak values observed in a winter flood reported by Wilcock et al. (1999) in a dairy catchment (Table 6). The most striking differences were observed in faecal contamination, which were higher than 28,000 cfu/100 ml at five of the 14 subcatchments during the winter flood, with maximum levels of 88,000 cfu/100 ml. These levels are considerably higher than previously reported levels such as Nottage (2001), who recorded peak FC levels of about 9000 cfu/100 ml during continuous monitoring of a spring flood in an agricultural catchment in the Golden Bay region of New Zealand.

TP, sediment and faecal coliform export during the July flood were up to 300, 1700 and more than 2000 times higher than during baseflow in May, respectively. These values are only estimates because contaminant concentrations vary considerably throughout the course of a flood. Nevertheless, our results indicate the importance of flood exports and their contribution to total annual exports. This observation is supported by Muirhead (2001), who found that a single flood exported more than 20% of the annual *E. coli* export calculated from routine baseflow monitoring data. Similarly, Hoare (1982) estimated that 42% of the annual TP load was carried on 3 days in the Ngongotaha Stream.

5. Conclusions

Scale-sensitive catchment analysis and management are needed to effectively care for land and water resources. Rigid water sampling at fixed time intervals, for example, cannot provide sufficient information to assess the influence of agricultural land use on water quality. Seasonal changes in nutrient export and extreme contamination during single flood events showed the importance of including flood events in standard monitoring protocols and adjusting these according to the season.

Catchment management also needs to address spatial scale effects. Depending on the scale, different data will be needed to address the effects of land use on water quality. Data on local land use such as stocking densities and movements are important in small upstream headwaters, whereas the total influence of a certain land use in the whole catchment provides a better indication of water quality in larger streams.

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