Land Use and Water Resources Research

Land-water interactions in five contrasting dairying catchments: issues and solutions

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Abstract

Monitoring of five dairy farming catchment streams in New Zealand shows they have high concentrations of N and P forms and faecal indicator bacteria. Suspended solids (SS) concentrations are sometimes high because of poor riparian management. Trend analysis and specific yields of N, P and SS for two streams that have been monitored for five years indicates that little change has occurred in water quality. However, improved water quality has been detected in the trends for two streams that have been monitored for 10 years, as a result of reductions in point sources and improved stock management (less intensive grazing and better stream bank fencing) that have taken place over the longer period. Surveys of farm management practices have been conducted at two-yearly intervals and best management practices are recommended for farming in each catchment, based on identified linkages between land use and water quality.

Introduction

The New Zealand dairy industry is challenged with achieving growth targets for production whilst reducing the size of its environmental footprint (Dairy InSight, 2004). In recent years dairying has expanded into areas that traditionally were less intensively farmed (i.e. sheep and beef cattle grazing), with concomitant increases in stocking rate and fertiliser use. Land used for dairy farming in New Zealand increased by >50% between 1990 and 2000 (from 1 050 800 ha to 1 640 400 ha) and is projected to increase by a further 16% by 2010 (Ward, 2002; Livestock Improvement, 2004). Leaching and runoff losses from dairying catchments typically have elevated concentrations of N, P and faecal microbes in run-off (Ledgard *et al*., 1999; Wilcock *et al*., 1999; McDowell *et al*., 2003; Monaghan *et al*., 2005). In addition, rural stream habitats in general are commonly degraded by having wide diel changes in pH, temperature and dissolved oxygen (DO), and poor visual clarity (Wilcock *et al*., 1999, 2004; Davies-Colley and Nagels, 2002; Duggan *et al*., 2002).

Concern about increasing degradation of soil and water quality and about the long-term sustainability of dairy farming led to the New Zealand dairy industry initiating a study in which four regionally representative dairying catchments were chosen for long-term monitoring, with the goal of improved environmental outcomes resulting from adoption of best management practices (BMPs). The catchments are located in two traditional dairy farming areas of the North Island and in two areas of the South Island that have only recently undergone conversion to dairy farming (Fig. 1). Monitoring of a fifth catchment located at Inchbonnie (in the South Island) began in June 2004. The main purpose of the programme is to (i) establish

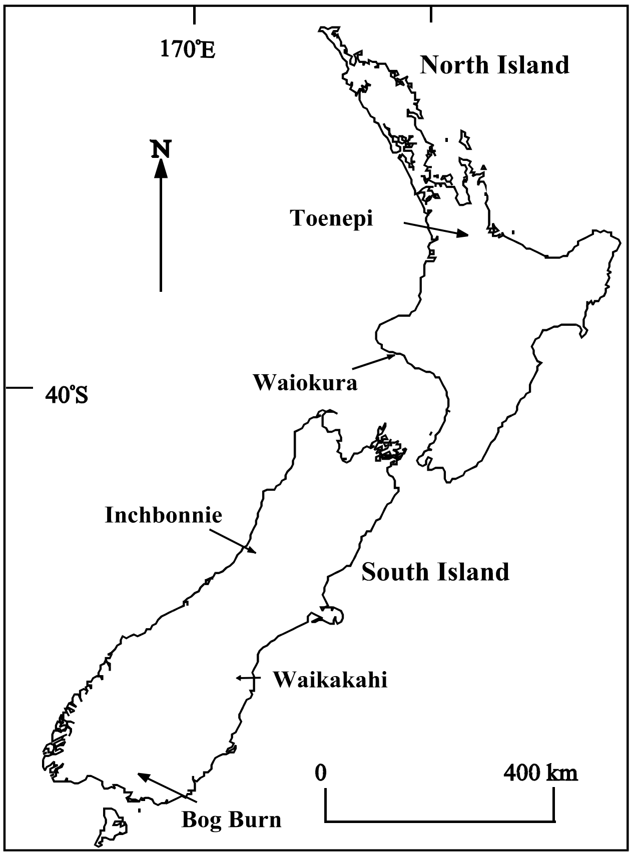

Figure 1. Map of New Zealand showing the approximate location of the five monitored dairy catchments. Pigeon Creek is in the Inchbonnie catchment.

baseline water quality in each stream, (ii) define linkages between land use and water quality and use these to derive best management practices (BMPs) that are appropriate for the sensitivities of receiving waters in each of the regions, and (iii) monitor water quality change as BMPs are implemented by farmers. Whole catchment studies integrate a range of farm management styles and provide a degree of 'realism' that is not possible for farm and reach scale studies (e.g. Allan and Johnson, 1997). The New Zealand dairy industry has promoted environmental sustainability for pastoral dairy farming through the 'Market Focused' and 'Dairying and Clean Streams Accord' initiatives (MfE, 2003). In this paper, we examine water quality in the five catchments against a background of increasing awareness by dairy farmers of environmental issues and the adoption of some of the recommended BMPs.

Methods

Site characteristics

Catchments were chosen because they were representative of their respective regions in terms of soils, rainfall, topography, farming methods and environmental challenges (Table 1). Streams had mean flows of 186–555 L s^{-1} and were selected because they either had recognisable amenity and ecological values, or were particularly good examples of highly impacted streams, so that improvements arising from adoption of BMPs might be most evident.

Toenepi Stream is a spring-fed headwater stream and has been previously shown to have high N, P and faecal bacteria concentrations associated with diffuse runoff from intensive dairy farming, and numerous discharges from oxidation ponds (Wilcock *et al*., 1999). An expert panel approach has been adopted to define water quality targets aimed at maintaining in-stream habitat quality, and downstream water quality suitable for contact recreation

Table 1. Catchment and stream characteristics. Fertiliser use, area in dairying, stocking rates and irrigation statistics are from farm surveys in 2003.

	Toenepi	*Waiokura*	*Waikakahi*	*Pigeon*	*Bog Burn*
CATCHMENT					
Area (km^2)	15.8	20.9	41.0†	6.0	24.8
Rainfall (mm yr^{-1})	1160	1250	520	4830	900
Topography	Flat-rolling	Flat	Flat	Flat	Flat
Area in dairying (%)	83	99	62	100	37
Average stocking rate‡ (cow ha^{-1})	3.0	3.4	2.8	2.0	2.9
Fertiliser input (kg ha^{-1} yr^{-1})					
N	73	88	172	178	68
P	61	65	60	50	68
Irrigation (mm yr^{-1})	0	0	810	0	0
STREAM					
Flow (L s^{-1})					
range	0–5530	69–6070	28–3180	28–18600	8–12600
mean	210	448	537	396	324
median	73	397	482	104	161

†Approximation of the flat area that is extensively modified by drainage channels connecting with the Waitaki River. Inclusion of the non-irrigated hill slopes increases the catchment area to 63.2 km^2.
‡ Statistics are from surveys of dairy farms within the catchment in 2003.

(Wilcock *et al*., 2006). Waiokura Stream is typical of many lowland third-order spring-fed streams in the Taranaki region (Fig. 1) with mean flows <500 L s^{-1} (River Ecosystem Classification; Snelder and Biggs, 2002). The Waiokura catchment has a high stream density (32 m ha^{-1}), and a total stream length of 68 km. The stream receives numerous discharges from oxidation ponds and the upper catchment is characterised by several small tributaries that are directly accessible to stock.

Waikakahi Stream is a small, lowland, spring-fed stream similar to many found on agricultural plains alongside major alpine rivers in Canterbury. The flow regime is augmented by Waitaki River water that is sourced for extensive border-dyke (flood) irrigation and generates large volumes of runoff (Meredith *et al*., 2003; Carey *et al*., 2004). As a result, Waikakahi summer flows are 4–9 times those measured in winter (Canterbury Regional Council, unpublished data). Monitoring of Waikakahi Stream commenced in 1995 because of concerns about the effects of agricultural intensification (notably, excessive inputs of sediment) (Meredith *et al*., 2003).

Bog Burn is a headwater of the Oreti River. The upper catchment (1300 ha) is mostly used for sheep farming and plantation forestry but the lower catchment (1200 ha) is predominantly in dairy farming. Pukemutu (Argillic-mottled Fragic Pallic soil) silt loam occupies most of the lower catchment. This soil grades to a silty clay texture at greater than 35 cm depth and is naturally poorly drained due to the presence of a dense fragipan between 60 and 90 cm depth. Accordingly, this soil is typically mole and tile drained before being put to intensive agricultural use, although is still vulnerable to short-term waterlogging after heavy rainfall (Monaghan *et al*., 2007). Inputs of N, P and faecal matter to Bog Burn from the extensive drainage network effectively by-pass riparian areas that might otherwise mitigate them and have a marked effect on water quality (McDowell and Wilcock, 2004; Monaghan *et al*., 2007).

Pigeon Creek, Inchbonnie, drains alluvial soils adjacent to the Taramakau River valley and discharges via Bruce Creek to Lake Brunner. Average rainfall is 5 m yr^{-1} (Chater, 2005) making it by far the wettest of the five catchments. The catchment was chosen because Inchbonnie is one of two main dairy farming areas within the Lake Brunner catchment, and because of the desire by the community to maintain good lake water quality through the adoption of sustainable farming practices (Derks, 2005).

Monitoring and analysis

Water level recording stations were established to give continuous flow records at catchment outlets in: 1995 for Toenepi Stream; 2001 for Waiokura Stream, Waikakahi Stream and Bog Burn; and 2004 for Pigeon Creek. Spot flow measurements were made during water quality sampling events. Water quality monitoring at two-weekly intervals was carried out on Waiokura Stream, Pigeon Creek and Bog Burn, at three sites, including the recorder site, over 18–24 months. Thereafter, sampling was monthly at the recorder sites. Waikakahi and Toenepi have been monitored monthly at their catchment outlets since 2001 because of previous intensive monitoring at multiple sites (Meredith *et al*., 2003, Wilcock *et al*., 1999).

Stream water was analysed for pH, conductivity (µS cm^{-1}), *in situ* temperature (°C) and water clarity by black disc (m), turbidity (NTU), dissolved oxygen (g m^{-3} and % saturation), suspended solids (SS) and volatile SS, *Escherichia coli* (*E. coli*, MPN/100 ml), nitrate plus nitrite N (NO_X-N), ammonia N (NH_4-N), total N (TN), total organic nitrogen (TON = TN – (NO_X-N + NH_4-N)), filterable reactive P (FRP) and total P (TP) concentrations. Results are expressed as g m^{-3} except where shown otherwise. Standard protocols for sampling, sample stabilisation and analysis were adopted for all water quality variables (APHA, 1998; Wilcock *et al*., 1999, 2006). *E. coli* were determined by the Colilert most probable number (MPN) method (IDEXX Laboratories, USA). Multiprobe data loggers (DataSonde, Hydrolab Corp., Austin, Texas) were used to monitor DO, temperature and pH continuously for 2–5 day periods with accuracies of ± 0.2 g m^{-3}, ± 0.1°C and ± 0.2 units, respectively. Sondes were calibrated before each deployment in accordance with the manufacturer's recommendations. Seasonal deployments were carried out in Toenepi, Waiokura, Waikakahi and Bog Burn streams to obtain continuous diel data sets.

Turbidity, DO, pH, NO_X-N, TN, FRP and TP data were compared with guidelines for slightly disturbed lowland rivers, derived from percentile values for reference rivers (ANZECC, 2000). NH_4-N concentrations were compared with the toxicant guideline level for protection of 95% of freshwater species, viz. 0.90 g m^{-3} and, where relevant, contact recreation and stock water supply guidelines were referred to for faecal indicator bacteria and water clarity (ANZECC, 2000). Monitoring data were also compared with a more recent guideline for contact recreation that groups waters for contact recreation in terms of a 95%-ile classification scheme with a minimum requirement of 20 data points. Freshwaters with a single *E. coli* value exceeding 550 *E. coli*/100 ml are given 'red alert' status and are deemed to be probably unsuitable for contact recreation until further monitoring shows otherwise (MfE/MoH, 2003). Differences between sites were deduced from the fixed interval monitoring data and from longitudinal surveys conducted at least twice (winter and spring) in each catchment. These surveys involved measuring flow and water quality variable concentrations at several points down the length of each stream, as well as for all measurable inflows (tributaries, surface and subsurface drains, seeps and wetlands). Fluxes from longitudinal surveys were calculated from the instantaneous products of concentration and flow.

Non-parametric statistics were used to show central tendency (median) and dispersion (interquartile range, IQR) for selected variables' datasets that were non-normally distributed. Loads leaving the catchment in stream water were calculated using the product of discharge-weighted mean concentration and true mean flow, for selected variables (Fergusson, 1987). Specific yields (kg ha^{-1} yr^{-1}) were calculated for the 24-month periods of Mar 2002 to Feb 2004 and Mar 2004 to Feb 2006 from average annual loads divided by catchment area, with uncertainties estimated to be ±25% for TN, NO_X-N, FRP and TP and ±60% for SS (Fergusson, 1987). Older data sets were used to derive average annual yields for 1995–97 (Toenepi) and 1996–98 (Waikakahi). The whole available data set (June 2004 to March 2006) was used to calculate an average annual yield for Pigeon Creek. Trend analysis was carried out using the Seasonal Kendall test (Hirsch and Slack, 1984) for SS, NH_4-N, NO_X-N, FRP and *E. coli* May 2001–February 2006 data for Toenepi Stream, Waiokura Stream, Waikakahi

Stream and Bog Burn. The monitoring period for Pigeon Creek (2004–2006) was insufficient for trend analysis to be meaningful.

Results

Routine monitoring data

Water quality monitoring data summary statistics are summarised for the period May 2001–February 2006, for the Toenepi, Waiokura, Waikakahi and Bog Burn datasets; and June 2004–February 2006 for Pigeon Creek data (Table 2, overleaf). Median conductivity ranged from 71 (Pigeon Creek) to 271 (Waiokura) µS cm^{-1}, reflecting differences in catchment lithology and source water composition. Streams were mostly well-oxygenated (above 80% saturation) but Toenepi occasionally had daytime DO values below 40% saturation in summer (Wilcock *et al*., 2006). All streams were quite turbid for much of the time, but Toenepi water clarity has improved markedly since the first study was carried out in 1995–97 (Wilcock *et al*., 2006). Median turbidities were 2.6–11 NTU (Table 2), compared with a median of about 1 NTU for 96 rivers measured under base-flow conditions (Close and Davies-Colley, 1990). About 20–40% of suspensoids was organic matter, with the balance being suspended sediment. Mean and median concentrations of SS recorded in the Waiokura Stream are notably higher than those observed for the other streams, presumably reflecting higher levels of soil erosion in this catchment and/or greater disturbance of stream channels and riparian areas.

Median faecal indicator (*E. coli*) concentrations range from 290–1250 MPN/100 ml. The ANZECC (2000) guideline for contact recreation states that the median bacterial content in freshwater samples taken over the bathing season should not exceed 150 faecal coliform organisms/100 ml and approximates the (DoH, 1992) guideline of 126 *E. coli*/100 ml, given that *E. coli* comprises about 80% of faecal coliforms in natural waters (Alonso *et al*., 1999). Median *E. coli* levels in the five dairy streams are 2–10 times the ANZECC guideline for contact recreation. The five dairy catchment streams have 95%-ile *E. coli* concentrations that are 5–17 times the 'Red Alert' value (Fig. 2) and thus regularly exceed both guidelines for contact recreation.

Nutrient concentrations of N and P forms were broadly similar for Toenepi, Waiokura, Waikakahi and Bog Burn (Table 2) with mean concentrations well above typical low elevation streams in New Zealand (Larned *et al*., 2004). Pigeon Creek had lower median concentrations of NO_x-N and TN than the other four streams, and a higher proportion of NH_4-N in TN. TON was a major part of TN in Pigeon Creek with a median proportion of 45%, compared with 6–30% for the other streams, for which NO_x-N was the dominant N form. Linear regressions of NO_x-N on TN yielded slopes of 0.82–0.94 (r^2 0.86–0.94) for Toenepi, Waiokura and Bog Burn, and a slope of 0.52 ($r^2 = 0.45$) for Waikakahi. By contrast, the Pigeon Creek regression slope was 0.07 ($r^2 = 0.07$). Concentrations of TP (median 0.050–0.174 g m^{-3}) and FRP (0.023–0.089 g m^{-3}) were higher than are commonly found in New Zealand streams (Larned *et al*., 2004). Median FRP:TP ratios were 0.28 (Waiokura) and 0.48–0.69 for the other streams, indicating that FRP is a major component of TP in dairy catchment streams. By

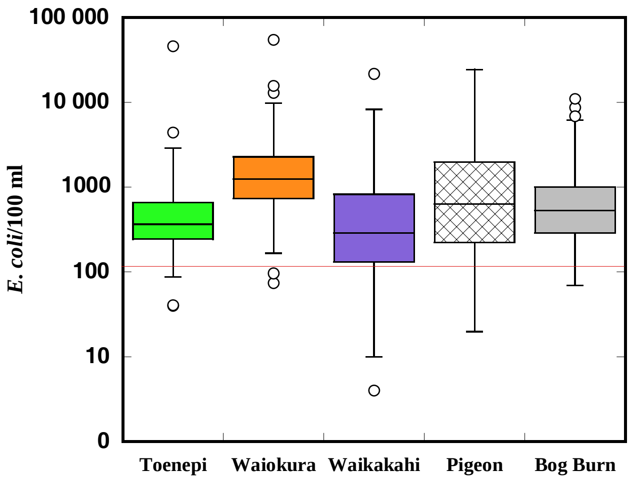

Figure 2. Box plots showing the *E. coli* concentration data in the five dairy catchment streams. Boxes contain the upper and lower quartiles (the interquartile range) and medians are shown by horizontal bars in each box. The lines extending above and below each box mark the minimum and maximum values within an acceptable range. Values outside this (O) are desi-gnated as outliers. The red line is the median contact recreation standard guideline (126/100 ml) (DoH, 1992).

contrast, median FRP and TP values in the 'Hundred Rivers' project were about 0.005 and 0.020 g m^{-3}, respectively, with an overall FRP:TP ratio of *c*. 0.3 (Close and Davies-Colley, 1990). All median concentrations of TN, FRP and TP, and all median concentrations of NO_x-N except for Pigeon Creek, were well above the respective ANZECC (2000) guideline values (Table 2).

Diel variations

Continuous data records for pH, temperature and DO revealed extreme values not normally observed in routine monitoring programmes (Fig. 3). Minimum diel DO values

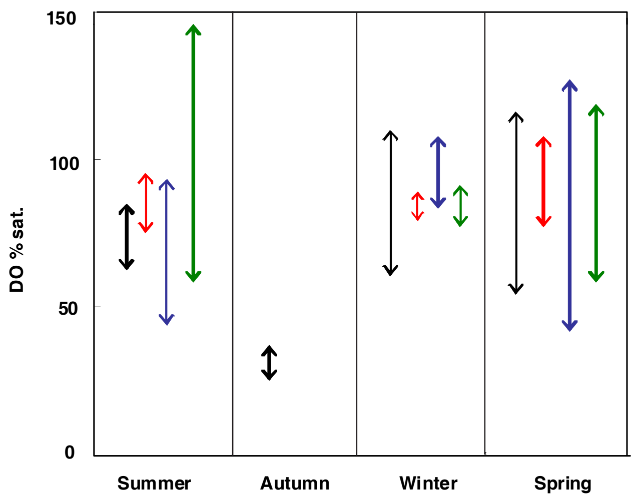

Figure 3. Diel dissolved oxygen (DO% saturation) ranges from seasonal sonde deployments in Toenepi (black), Waiokura (red), Waikakahi (blue) and Bog Burn (green) streams.

Table 2. Range, mean, **median** and interquartile range (IQR), respectively, for May 2001- Feb 2006 (except Pigeon Creek, Jun 2004-Feb 2006) fixed interval monitoring data in the five dairy catchment streams at their catchment outlet sites. Concentrations are g m^{-3} except where shown otherwise.

	pH	Conductivity (µS cm^{-1})	Temperature (ºC)	DO (% sat.)	Turbidity (NTU)	Black disc (m)	SS	VSS	VSS/SS	*E.coli* (MPN/100ml)
Toenepi	–	119-387	8.5-22.5	25.5-166	1.1-48	0.17-2.42	0.3-120	0.05-22.0	0.04-1.00	40-46000
	–	200	15.2	75.8	4.8	1.43	7.7	1.9	0.31	1550
	–	**188**	**16.0**	**80.7**	**2.6**	**1.40**	**3.0**	**0.8**	**0.26**	**367**
	–	47	4.4	37.7	2.2	0.74	3.5	1.0	0.19	442
Waiokura	7.27-7.85	233-311	5.6-17.8	83.9-109	4.5-35	0.15-0.78*	6.0-98.0	3.4-35.0	0.24-0.62	70-54800
	7.67	273	12.7	96.7	12.4	0.40	24.4	9.5	0.40	2670
	7.68	**271**	**12.6**	**96.5**	**11.0**	**0.38**	**20.5**	**8.2**	**0.40**	**1250**
	0.09	13	5.0	8.9	4.9	0.14	12.0	4.9	0.05	1600
Waikakahi	7.10-8.90	132-338	4.1-18.5	49.7-121	1.2-3	0.16-2.27	1.4-175	0.3-157	0.05-0.90	4-21800
	7.93	201	10.8	87.6	26.2	0.85	12.5	5.2	0.27	980
	7.91	**190**	**10.9**	**87.4**	**4.6**	**0.77**	**7.2**	**2.0**	**0.23**	**290**
	0.60	80	5.0	24.4	4.1	0.54	6.8	1.5	0.15	700
Pigeon	–	37-81	2.4-22.2	73.5-110	1.5-101	0.06-1.90*	0.3-110	–	–	20-24300
	–	69	10.9	89.6	7.7	0.84	8.5	–	–	2500
	–	**71**	**10.9**	**90.6**	**4.0**	**0.86**	**4.6**	–	–	**640**
	–	9	5.9	10.7	3.2	0.42	3.7	–	–	1720
Bog Burn	6.60-9.00	103-215	3.3-19.2	70.7-127	2.6-34	0.22-1.90	1.50-36.0	0.25-8.5	0.05-0.7	270-11000
	7.34	157	10.3	94.3	8.1	1.03	6.4	2.1	0.36	1140
	7.30	**161**	**9.8**	**92.5**	**6.2**	**1.05**	**4.2**	**1.5**	**0.34**	**530**
	0.40	47	6.9	15.2	3.0	0.33	3.4	1.0	0.08	700
Guideline**	7.2–8.0	–	–	98–105	5.6	1.6	–	–	–	126†

Table 2. (continued)

	NO_x-N	NH_4-N	TON	TN	FRP	TP	DOC	FRP/TP	NO_x-N/TN
Toenepi	0.032-4.19	0.009-2.8	0.227-1.86	0.405-5.86	0.010-0.177	0.068-0.251	2.2-10.2	0.09-0.82	0.06-0.89
	1.51	0.119	0.604	2.13	0.091	0.159	4.9	0.56	0.55
	1.19	**0.022**	**0.527**	**1.76**	**0.089**	**0.174**	**4.8**	**0.55**	**0.65**
	1.71	0.043	0.268	1.76	0.049	0.080	2.5	0.11	0.48
Waiokura	1.62-4.26	0.001-0.159	0.025-1.42	2.05-4.50	0.016-0.107	0.064-0.392	–	0.13-0.64	0.56-0.98
	2.91	0.032	0.406	3.35	0.036	0.126	–	0.30	0.87
	2.82	**0.026**	**0.389**	**3.29**	**0.032**	**0.111**	**–**	**0.28**	**0.88**
	1.02	0.016	0.174	0.96	0.017	0.042	–	0.15	0.07
Waikakahi	0.79-3.50	0.001-0.315	0.008-2.94	1.16-5.20	0.001-0.560	0.031-0.699	1.7-14.5	0.13-1.0	0.35-0.99
	1.87	0.051	0.462	2.34	0.113	0.162	3.5	0.67	0.80
	1.76	**0.022**	**0.349**	**2.30**	**0.075**	**0.120**	**2.7**	**0.69**	**0.83**
	0.94	0.049	0.278	0.97	0.117	0.131	1.4	0.23	0.16
Pigeon	0.049-0.671	0.015-0.498	0.080-1.83	0.296-2.71	0.016-0.362	0.033-0.483	0.4-4.9	0.39-0.83	0.05-0.81
	0.297	0.161	0.440	0.898	0.082	0.137	1.7	0.61	0.39
	0.284	**0.104**	**0.323**	**0.713**	**0.059**	**0.102**	**1.5**	**0.62**	**0.39**
	0.194	0.235	0.340	0.647	0.058	0.105	1.6	0.13	0.25
Bog Burn	0.036-3.60	0.001-0.130	0.000-1.99	0.26-4.30	0.010-0.130	0.024-0.220	–	0.15-0.98	0.10-0.99
	0.925	0.025	0.444	1.40	0.027	0.056	–	0.51	0.59
	0.755	**0.020**	**0.356**	**1.10**	**0.023**	**0.050**	**–**	**0.48**	**0.62**
	1.00	0.012	0.206	0.95	0.011	0.017	–	0.20	0.34
Guideline**	0.444	0.900	–	0.614	0.010	0.033	–	–	–

*Calculated from turbidity (Smith et al., 1997)

**ANZECC (2000); pH and DO guidelines are for daytime measurements; the black disc water clarity guideline is for contact recreation; the NH_4-N guideline is the toxicants trigger value for the 95% level of protection.

†DoH (1992)

were almost all below the new Zealand statutory guideline of >80% saturation, recommended for managing water for the protection of aquatic ecosystems, fisheries and fish spawning (Brooker's 1991). Maximum temperatures did not exceed 22ºC. The autumn diel DO survey for Toenepi Stream yielded data that were all below 50% saturation. Other studies have reported Toenepi Stream DO values <10% saturation (Wilcock and Croker, 2004; Wilcock *et al*., 2006), notably during late summer–early autumn when stream velocities are very low and plant respiration is vigorous (Wilcock and Nagels, 2001; Wilcock *et al*., 2002).

Diel ranges of DO were quite wide in winter (59–107%) and spring (54–118%). Toenepi temperatures were mostly well below 20ºC. Toenepi stream commonly had night-time pH minima <7, possibly as a result of the production of organic acids from decomposing plant matter (Webster and Benfield, 1986; Wilcock and Nagels, 2001).

Waiokura DO was generally close to saturation and diel excursions were on average ±10%. There was little diel variation in pH (typically, 7.6±0.2) and stream temperatures were always below 20ºC. These results indicate that Waiokura Stream is generally well aerated and is sufficiently shaded to not be adversely affected by photosynthetic production and respiration. These results contrast with Waikakahi Stream, which is variously supplied by water with different composition, coming from headwater springs, the Waitaki River via irrigation canals, and border-dyke surface and sub-surface irrigation run-off (Carey *et al*., 2004). Thus, DO excursions during spring and summer were on average 65±33% and were frequently supersaturated during daytime as a result of extensive photosynthetic production by submerged macrophytes (Meredith *et al*., 2003). Diel pH data weres highly variable, probably as a result of different combinations of source water and the influence of primary production and respiration by macrophytes. The overall range was 6.30–9.34; greater than the routine, daytime monitoring range (Table 2).

Bog Burn diel DO ranges in summer (±41%) and spring (±30%) were the widest of the four streams recorded. The maximum diel DO concentration was 148% during the summer sonde deployment; consistent with the influence of plant photosynthetic production and respiration. Diel variations in pH ranged from a low of 6.02 in November to 9.0 in late summer, with an average diel pH of 7.3±1.0 for summer and spring.

Longitudinal differences

Regular monitoring at three sites on each stream showed a pattern of increasing concentration with distance downstream for NO_x-N and decreasing concentration downstream for SS. Suspended sediment and biomass generated in the upper reaches of each stream were diluted or redeposited downstream. Water quality variables in longitudinal surveys in Toenepi and Waiokura Streams behaved either as quasi-conservative solutes (viz. NO_x-N, FRP and DOC) that were more-or-less additive, or were strictly non-conservative (viz. SS, NH_4-N, TP and *E. coli*) (Wilcock and Singleton, 2006). The first group comprised anions (NO_3^-, HPO_4^{2-} and organic anions) that are freely soluble (Thurman, 1985), whereas the second group comprised cations (NH_4^+) and particulates (SS, organic-P in plant biomass, and bacteria) that are subject to re-suspension and trapping by macrophytes within the stream channel (Russell *et al*., 2001, Pluntke and Kozerski, 2003).

Fluxes in Waikakahi Stream were affected by border-dyke runoff but behaved similarly to the Toenepi and Waiokura survey results. The Bog Burn results indicated additional inputs that were not quantified in the surveys. A longitudinal survey of Pigeon Creek and its two main tributaries revealed 18 places where cattle regularly ford stream channels, presenting a significant potential source of faecal pollution (Davies-Colley *et al*., 2004). Concentrations of FRP and TP increased down the length of each tributary, from source water springs having very low concentrations (1–4 mg m^{-3}) to the downstream recorder site (107 and 163 mg m^{-3}, respectively). On the other hand, the *E. coli* concentration in one spring was 197 MPN/100 ml compared with 216 MPN/100 ml at the recorder site, possibly as a result of stock grazing nearby.

Specific yields

Specific yields for all variables in Toenepi Stream declined during 1995–2006 (Table 3) as a result of decreasing water yields (NO_x-N, TN, FRP, TP and SS) and a reduction in point source discharges during this period (NH_4-N) (Wilcock *et al*., 2006). Monitoring in Waikakahi has been undertaken for a similar period, but without a continuous flow record until 2001. Yields in Waikakahi Stream for all variables except SS increased over 1996–2006, but the differences were within calculated uncertainties. In the early 1990s large amounts of sediment entered the stream as a result of frequent stock crossings and unrestricted herd access to the stream, and very high grazing intensity in parts of the upper catchment (Meredith *et al*., 2003). Water clarity has

Table 3. Specific yields (kg ha^{-1} yr^{-1}) for TN, NO_x-N, FRP, TP and SS averaged over two-year periods.

	Toenepi			*Waiokura*		*Waikakahi**			*Pigeon*	*Bog Burn*	
	1995-97**	2002-04	2004-06	2002-04	2005-06	1996-98	2002-04	2004-05	2004-06†	2002-04	2004-06
TN	35.0	13.2	14.8	25.5	25.6	7.48	7.87	8.90	23.2	9.75	7.33
NO_x-N	29.3	10.0	11.8	22.1	22.4	4.93	5.77	6.98	3.39	6.68	4.99
FRP	0.54	0.36	0.33	0.23	0.17	0.50	0.46	0.68	2.27	0.29	0.15
TP	1.16	0.67	1.18	1.00	0.72	0.74	0.79	0.89	5.02	0.53	0.30
SS	142	67	38	231	149	135	34	72	883	82	32

*Assuming a contributing catchment area of 41 km^2
**1995-97 yields from Wilcock *et al.* (1999)
†June 2004-March 2006 data

improved (lower SS concentrations) with better riparian management but intermittent inputs of sediment caused by cattle grazing near stream banks are still occurring, albeit less frequently (Meredith *et al*., 2003).

Specific yields of TN and NO_X-N for Pigeon Creek were surprisingly low, given the high rainfall in the catchment (Table 1). The low NO_X-N yield is offset by relatively high yields of TON (15±5) and NH_4-N (5±2) kg N ha^{-1} yr^{-1}, indicating that a larger than usual proportion of N enters the stream before mineralisation and oxidation occurs. The FRP, TP and SS yields for Pigeon Creek were substantially greater than for the other streams and are undoubtedly a result of the high rainfall intensity in the catchment (Table 1).

Discussion

All five dairying catchment streams can be characterised as being more turbid (except for Toenepi Stream) and having generally higher N, P and *E. coli* concentrations than most low gradient streams in New Zealand, with medians generally well above guideline values for slightly disturbed lowland ecosystems (ANZECC, 2000; Larned *et al*., 2004). With the exception of Toenepi Stream, levels of NH_4-N were always less than the ANZECC (2000) guideline for acute toxicity. Toenepi NH_4-N values have declined markedly since 1995 as more dairy shed effluent is diverted from being discharged to the stream and is irrigated onto land (Wilcock *et al*., 2006). All streams other than Waiokura are open and unshaded for much of their lengths so that diel variations in DO, pH and temperature are greater than for shaded streams (Wilcock and Nagels, 2001). Maximum pH values were not sufficiently high to influence ammonia toxicity at any time (USEPA 1999).

Trends

A recent review of Toenepi Stream monitoring data showed significant reductions in concentrations and yields of nutrients, and improved water clarity, had occurred over a period of nine years. These changes were thought to be at least partly a result of better effluent management through greater use of land application and thus reduced direct discharges from ponds to the stream (Wilcock *et al*., 2006). Trend analysis carried out on 1995–2002 Waikakahi Stream data (Meredith *et al*., 2003) showed a downward trend in DO and increasing trends in NH_4-N (95% confidence level), NO_X-N, TN and FRP (90% confidence level).

Trend analysis conducted on May 2001–February 2006 water quality data for Toenepi, Waiokura Waikakahi and Bog Burn streams showed no significant changes (95% confidence level) other than for: SS in Toenepi Stream (+0.57 g m^{-3} yr^{-1}), NO_X-N and FRP in Waiokura Stream (+0.089 g m^{-3} yr^{-1} and –0.0037 g m^{-3} yr^{-1}, respectively), and NH_4-N and FRP in Bog Burn (+0.0033 g m^{-3} yr^{-1} and –0.0032 g m^{-3} yr^{-1}, respectively). The trend of increasing SS in Toenepi Stream is at variance with observed improved water clarity and turbidity over 1995–2005 (Wilcock *et al*., 2006) and is likely influenced by the occurrence of the two highest SS concentrations in August 2002 (120 g m^{-3}) and May 2005 (81 g m^{-3}) occurring during base-flow (280 and 180 L s^{-1}, respectively). *E. coli* levels at those times exceeded 95%-ile values, being 4410 and 4605 MPN/100 ml respectively, suggesting that cattle in the stream channel may have been the cause of the elevated SS values and the positive trend value (Davies-Colley *et al*., 2004).

Best management practices – Toenepi catchment

A suite of BMPs have been derived for implementation on dairy farms in the catchments (Table 4), depending on the particular water quality issues in each of the streams and the specific interactions between land use and surface waters. High concentrations of faecal bacteria (*E. coli*) are the main target for mitigation of dairy farming impacts in the Toenepi catchment (Wilcock *et al*., 2006). N and P forms, although high by comparison with other lowland streams, were deemed to be of lesser importance in Toenepi Stream because of light limitation for growth of aquatic plants caused by riparian shading and low light penetration in downstream waters (Larned *et al*., 2004; Wilcock *et al*., 2006).

Riparian fencing and has been identified as a key BMP in Waiokura catchment to reduce stock access to the stream but costs may limit the extent to which this is practicable (Betteridge *et al*., 2005). Runoff from the 107 culverts and bridge crossings on Waiokura Stream are likely to be significant sources of farm pollutants (viz. P and faecal matter) and minor earthworks that divert runoff from the stream to small dams have been suggested as an appropriate BMP (Betteridge *et al*., 2005).

Table 4. BMPs relevant to dairy farms in the dairy catchments.

Target	*Best Management Practice (BMP)*
Faecal pollution	• Fencing of all major waterways (i.e. stock exclusion) • Minor earthworks that divert runoff from farm tracks entering streams, to sediment traps or to fields • Deferred irrigation of dairy shed effluent to land (i.e. fewer pond discharges) • Grass filtration strips in riparian zones • Avoiding grazing saturated soils in order to minimise runoff losses • Maximise soil infiltration by the use of stand-off pads in wet conditions – reduced overland flow
P	• Deferred irrigation of dairy shed effluent • Reducing soil P fertility to their economic optimum (NB this also reduces effluent losses of P) • Avoiding soil compaction caused by over-stocking • Open-drain vegetation (grasses) for trapping particulate P
N	• Nutrient budgeting to optimise farm nutrient inputs via fertiliser and imported feed • Nitrification inhibitors (Di and Cameron, 2002) • Feedpad systems for wintering animals – avoiding the deposition of excreta N during times when drainage is likely • Natural and constructed wetlands for enhancing denitrification losses

The influence of border-dyke irrigation is the dominant feature of the Waikakahi Stream and catchment (Carey *et al*., 2004). Excess irrigation water affects stream hydrology and water quality (Meredith *et al*., 2003) and hence, stream habitat quality. Waikakahi Stream has a history of high sediment loads that are attributable to poor riparian management and overstocked 'sacrifice' paddocks (Meredith *et al*., 2003). Current sedimentation may be the cause of observed low survival rates for trout eggs in Waikakahi Stream (J. Hayes, Cawthron Institute, *pers. comm.*).

The dairying part of the Bog Burn catchment has extensive mole-tile drainage systems that sometimes deliver high-strength effluent directly to the stream following land application. These drainage systems thus act as conduits between land and water, effectively by-passing the riparian zone. BMPs have accordingly focused on minimising pollutant loads at source. High stocking rates in forage paddocks used for animal wintering are thought to contribute much N and sediment to surface waters (Monaghan *et al*., 2007).

Best management practices are still being developed for the Pigeon Creek catchment. Phosphorus is the limiting nutrient for eutrophication in Lake Brunner (authors' unpublished data) and recreation in the lake may be compromised by faecal pollution from farm runoff. Thus, BMPs will be aimed at reducing inputs of surface runoff containing P and faecal matter and will have to take into account the extremely high annual rainfall (*c.* 5 m yr^{-1}) in this catchment. Fertiliser management (timing, amount and type) may be an important focus for future BMPs, as well as minimising stock contact with natural waterways.

Summary and conclusions

The five dairy catchments streams all have degraded water quality. Monitoring has established that they all have high concentrations of N and P forms and faecal indicator bacteria. In addition, SS concentrations are sometimes high as a result of poor riparian management. Stream diel excursions of DO and pH are consistent with high photosynthetic production in unshaded streams with high plant biomass. Trends for the more recently monitored streams (Waiokura, Bog Burn and Pigeon) show little change over five years but Toenepi Stream, which has been monitored for 10 years, has undergone significant improvement in water quality. Waikakahi Stream has shown some improvement in SS as a result of better riparian management but has changed little in other ways over the past 10 years. Best management practices have been derived to either reduce loadings to land, or to intercept runoff along critical pathways. Most of the BMPs are generally applicable but some are limited to land–water interactions characteristic of dairy farming within particular regions.

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References

ANZECC, 2000. National water quality management strategy: Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand, Canberra, Australia.

APHA, 1998. Standard methods for the examination of water and wastewater. 20th edn. American Public Health Association, American Water Works Association and Water Environment Federation. Washington, D.C., U.S.A.

Allan, J.D. and Johnson, L.B., 1997. Catchment-scale analysis of aquatic ecosystems. *Freshwater Biol.*, **37**, 107–111.

Alonso, J.L., Soriano A., Carbajo, O., Amoros, I. and Garelick, H., 1999. Comparison and Recovery of *Escherichia coli* and thermotolerant coliforms in water with a chromogenic medium incubated at 41 and 44.5°C. *Applied and Environ. Microbiol.*, **65**, 3746–3749.

Betteridge, K., Wilcock, R.J., Costall, D., Shearman, D. and Roach C., 2005. Impacts of dairy intensification on stream-water quality in a south Taranaki catchment. In *Developments in fertilizer application technologies and nutrient management,* L. D. Currie and J.A. Hanly (Eds.). Occasional report no. 18. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 141–149.

Brooker's, 1991. Resource Management, Brookers Ltd., Wellington, New Zealand.

Carey, P.L., Drewry, J.J., Muirhead, R.W. and Monaghan, R.M., 2004. Potential for nutrient and faecal bacteria losses from a dairy pasture under border dyke irrigation: a case study. *Proc. N. Z. Grassland Assn. 66*: 141–149.

Chater, M., 2005. *West Coast climate and surface water quality*. State of the environment technical report 05003. West Coast Regional Council, Greymouth.

Close, M.E. and Davies-Colley, R.J., 1990. Baseflow water chemistry in New Zealand rivers. 1. Characterisation. *N. Z. J. Mar. Freshwater Res.,* **24**, 319–341.

Dairy InSight 2004. *Strategic framework for dairy farming's future*. Dairy InSight, Wellington.

Davies-Colley, R.J. and Nagels, J.W., 2002. Effects of dairying on water quality of lowland streams in Westland and Waikato. *Proc. N.Z. Grasslands Ass. Conf.*, Greymouth. 107–114.

Davies-Colley, R.J., Nagels, J.W., Smith, R.A., Young, R.G. and Phillips, C.J., 2004. Water quality impact of a dairy cow herd crossing a stream. *N. Z. J. Mar. Freshwater Res.*, **38**, 569–576.

DoH, 1992. *Provisional microbiological water quality guidelines for recreational and shellfish-gathering waters in New Zealand*. January, 1992. Public Health Services, Department of Health, Wellington.

Derks, D.J., 2005. *Sustainable farming in the Lake Brunner catchment*. Final report for Ministry of the Environment Sustainable Management Fund. Wellington.

Di, H.J. and Cameron, K.C., 2002. Mitigation of nitrous oxide emissions in spray-irrigated grazed grassland by treating the soil with dicyandiamide, a nitrification inhibitor. *Soil Use Manage.*, **19**, 284–290.

Duggan, I.C., Collier, K.J., Champion, P.D., Davies-Colley, R.J., Nagels, J.W. and Wilcock, R.J., 2002. Ecoregional differences in macrophyte and macroinvertebrate communities between Westland and Waikato: are all lowland streams the same? *N. Z. J. Mar. Freshwater Res.*, **36**, 831–845.
Fergusson, R.I., 1987. Accuracy and precision of methods for estimating river loads. *Earth Surf. Process. Landf*, **12**, 95–104.
Hirsch, R.M. and Slack, J.R 1984. A nonparametric trend test for seasonal data with serial dependence. *Water Resour. Res.*, **20**, 727–732.
Larned, S.T., Scarsbrook, M.R., Snelder, T.H., Norton, N.J. and Biggs, B.J.F., 2004. Water quality in low-elevation streams and rivers of Nw Zealand: recent state and trends in contrasting land-cover classes. *N. Z. J. Mar. Freshwater Res.*, **38**, 347–366.
Ledgard, S.F., Penno, J.W. and Sprosen, M.S., 1999. Nitrogen inputs and losses from grass/clover pastures grazed by dairy cows, as affected by nitrogen fertiliser application. *J. Agric. Sci.*, **132**, 215–225.
Livestock Improvement, 2004. *Dairy statistics 2003-2004*. Hamilton, Livestock Improvement Corporation Ltd.
McDowell, R.W., Monaghan, R.M. and Morton, J., 2003. Soil phosphorus concentrations to minimise potential P loss to surface waters in Southland. *N.Z. J. Agric. Res.*, **46**, 239–253.
McDowell, R.W. and Wilcock, R.J., 2004. Particulate phosphorus transport within stream flow of an agricultural catchment. *J. Environ. Qual.*, **33**, 2111–2121.
Meredith, A., Smith, Z. and Lavender, R., 2003. *Waikakahi stream: assessment of water quality and ecosystem monitoring, 1995–2002.* Environment Canterbury, R03/14, p. 67, Christchurch.
MfE, 2003. *Dairying and clean streams accord*. Fonterra, Local Government New Zealand, Ministry for the Environment, Ministry of Agriculture and Forestry, Wellington.
MfE/MoH, 2003. *Microbiological water quality guidelines for marine and freshwater recreational areas*. Ministry for the Environment and Ministry of Health. Wellington.
Monaghan, R.M., Paton, R.J., Smith, L.C., Drewry, J.J. and Littlejohn, R.P., 2005. The impacts of nitrogen fertilisation and increased stocking rate on pasture yield, soil physical condition and nutrient losses in drainage from a cattle-grazed pasture. *N. Z. J. Agric. Res.*, **48**, 227–240.
Monaghan, R.M., Wilcock, R.J., Smith, L.C., Tikkisetty, B., Thorrold, B.S. and Costall, D., 2007. Linkages between land management activities and water quality in the Bog Burn stream, Southland. *Agric. Ecosyst. Environ.*, **118**, 211–222.
Pluntke, T. and Kozerski, H-P., 2003. Particle trapping on leaves and on the bottom in simulated submerged plant stands. *Hydrobiologia*, 506–509, 575–581.
Russell, M.A., Walling, D.E. and Hodgkinson, R.A., 2001. Suspended Sediment Sources in Two Small Lowland Agricultural Catchments in the UK. *J. Hydrol.*, **252**, 1–24.
Smith, D.G., Davies-Colley, R.J., Knoeff, J. and Slot, G.W.J., 1997. Optical characteristics of New Zealand rivers in relation to flow. *J. Amer. Water Resour. Ass.*, **33**, 301–312.
Snelder, T.H. and Biggs, B.J.F., 2002. Multi-scale river environment classification for water resources management. *J. Amer. Water Resour. Ass.*, **38**, 1225–1240.
Thurman, E.M., 1985. *Organic Geochemistry of Natural Waters.* Martinus Nijhoff/Dr W. Junk publishers, Dordrecht. 497pp.
USEPA, 1999. *1999 Update of ambient water quality criteria for ammonia*. EPA-822-R-99-014, US Environmental Protection Agency, Office of Water, Washington DC. 147pp.
Ward, C., 2002. T*he effect of change in land use on irrigation demand.* MAF resource management update. Wellington, New Zealand, Ministry of Agriculture and Forestry.
Webster, J.R. and Benfield, E.F., 1986. Vascular plant breakdown in freshwater ecosystems. *Ann. Rev. Ecol. Systematics*, **17**, 567–594.
Wilcock, R.J. and Croker, G.F., 2004. Distribution of carbon between sediment and water in macrophyte dominated lowland streams. *Hydrobiologia*, **520**, 143–152.
Wilcock, R.J. and Nagels, J.W., 2001. Effects of aquatic macrophytes on physico-chemical conditions of three contrasting lowland streams: a consequence of diffuse pollution from agriculture? *Water Sci. Technol.*, **43**, 163–168.
Wilcock, R.J. and Singleton, P.L. 2006. Longitudinal surveys identifying key contaminant sources in a dairying watershed. *Proc. 2nd Int. Conf. Environ. Science and Technology*, American Academy of Sciences, Houston, TX, 19-22 August 2006 (in press).
Wilcock, R.J., Nagels, J.W., Rodda, H.J.E., O'Connor, M.B., Thorrold, B.S. and Barnett, J.W., 1999. Water quality of a lowland stream in a New Zealand dairy farming catchment. *N. Z. J. Mar. Freshwater Res.*, **33**, 683–696.
Wilcock, R.J., Scarsbrook, M.R., Costley, K.J. and Nagels, J.W., 2002. Controlled addition experiments to determine the effects of plants and shading on nutrient retention in a lowland stream. *Hydrobiologia*, **485**, 153–162.
Wilcock, R.J., Monaghan, R.M., Quinn, J.M., Campbell, A.M., Duncan, M.J., McGowan, A.W. and Betteridge, K.. 2006. Land use impacts and water quality targets in the intensive dairying catchment of the Toenepi Stream, New Zealand. *N. Z. J. Mar. Freshwater Res.*, **40**, 123–140.