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State and potential management to improve water quality in an agricultural catchment relative to a natural baseline

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ABSTRACT

Land use change and the expansion of dairying are perceived as the cause of poor water quality in the 1881 km^2 Pomahaka catchment in Otago, New Zealand. A study was conducted to determine the long-term trend at four sites, and current state in 13 sub-catchments, of water quality. Drains in 2 dairy-farmed sub-catchments were also sampled to determine their potential as a point source of stream contamination. Data highlighted an overall increase in the concentration of phosphorus (P) fractions at long-term sites. Loads of contaminants (nitrogen (N) and P fractions, sediment and *Escherichia coli*) were greatest in those sub-catchments with the most dairying. Baseline (without human influence) contaminant concentrations suggested that there was considerable scope for decreasing losses. At most sites, baseline concentrations were <20% of current median concentrations. Contaminant losses via drainage were recorded despite there being no rainfall that day and attributed to applying too much effluent onto wet soil. Modelling of P concentrations in one dairy-farmed sub-catchment suggested that up to 58% of P losses came from point sources, like bad effluent practice and stock access to streams. A statistical test to detect "contaminated" drainage was developed from historical data. If this test had been applied to remove contaminated drainage from samples of the two dairy-farmed sub-catchments, median contaminant concentrations and loads would have decreased by up to 58% (greater decreases were found for *E. coli*, ammoniacal-N and total P than other contaminants). This suggests that better uptake of strategies to mitigate contamination, such as deferred effluent irrigation (and low rate application), could decrease drainage losses from dairy-farmed land and thereby improve water quality in the Pomahaka catchment.

1. Introduction

The Pomahaka is a large catchment (1881 km^2) in Otago, New Zealand that contains a nationally significant recreational fishery. However, water quality as measured by the concentration of nutrients, sediment and faecal indicator bacteria in parts of the Pomahaka River and its tributaries is currently considered poor (Otago Regional Council, 2007). The state of the river has been attributed to a combination of factors such as: land use change from sheep to dairy farming and the use of artificial drainage (Harding et al., 1999). However, there is a perception that natural background contaminant concentrations may be naturally high (Otago Regional Council, 2010).

During land use change to dairying, paddocks may be modified either by resizing and adjusting fencing, or ploughed and new grasses sown together with a large application of fertiliser (especially phosphorus, P). This can result in a sudden increase in sediment and nutrient loss that decreases with time (Withers et al., 2007), but when aggregated can cause significant contamination on a catchment scale. Others have also highlighted areas like loafing pads and barnyards that can be a significant source of contaminant loss (Edwards et al., 2008; Withers et al., 2009).

Grazed pastoral farming in the Pomahaka catchment is characterised by the widespread use of artificial drainage. These drains respond quickly via macropores or artificial mole channels and preferential flow to remove excess water, but also act as a direct conduit for contaminants to enter streams. Common practice on dairy farms in the catchment is to land apply dairy shed effluent, often on a daily basis during the lactation season. The application of effluent on artificially drained land can, via macropores or ancillary drains connected to main drains, result in effluent reaching the stream (Monaghan and Smith, 2004; Houlbrooke et al., 2008). This loss can occur when drains would not typically be flowing in summer or autumn when ecosystem effects and recreational use are greatest (Jarvie et al., 2006). While past work has indicated that

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effluent application combined with artificial drainage can act as a source of contaminant loss, isolating this on a farm-by-farm or catchment scale is problematic, especially if natural background losses of contaminants are high.

Setting a natural background contaminant loss allows, by difference from current losses, the manageable proportion to be estimated and the value of mitigation strategies to be judged. If a natural loss is already similar to current losses, there may be limited opportunity for mitigation strategies. Techniques to define a natural loss include the measurements of contaminant concentrations or loads in reference catchments without development, but with a similar topographic and edaphic classification (e.g. ecoregion) to the impacted catchments, or the use of a metric like the 25th percentile of contaminant fluxes registered in that ecoregion (Lewis, 2002; Smith et al., 2003). Dodds and Oakes (2004) point out that these approaches are limited by either the availability of reference streams in an area, or may lead, as in the case of a 25th percentile, to overestimation of background losses. As an alternative, Dodds and Oakes (2004) developed a regression technique for estimating reference conditions based on the relationship between contaminant concentrations and the degree of anthropogenic land use within streams of a similar type as defined by a classification.

As part of a catchment management programme to improve water quality in the Pomahaka River and its tributaries, we set out to establish if there has been a significant trend over time in contaminant concentrations, and then rank contaminant contributions from sub-catchments of the Pomahaka River. These two datasets are then compared to background losses using the method of Dodds and Oakes (2004) to define the manageable contaminant loss rate. Although past work has established that contaminant losses from artificial drainage can be substantial, especially when effluent is being applied when soil is wet (e.g. Houlbrooke et al., 2008; McDowell et al., 2005), there is uncertainty over the definition of when drainage is contaminated via bad practice, and therefore acting as a point source of contaminants, and not background losses. Hence, a combination of historical data and a survey of drains in the catchment was used to: (a) establish a statistical test for contamination caused by bad practice associated with effluent application; and (b) using the test as an indicator, determine what influence mitigation may have, if any, on the manageable proportion estimated from measurements of drainage in two dairy-farmed sub-catchments of the Pomahaka River.

2. Materials and methods

2.1. Site description and sampling

The Pomahaka River drains a catchment of 1881 km^2 and supports a wide variety of land use typified by either red tussock, native forest, plantation forestry (largely *Pinus radiata*) or extensive rangeland farmed with drystock (red deer, sheep and beef) in uplands, while lowlands are dominated by a mixture of drystock and increasingly, dairying. Some tributaries, such as the upper Waipahi River, have also seen the conversion and drainage of large wetland areas in the last 10 years.

Rainfall varies from ca. 1250 mm in the headwaters draining altitudes of up to 1440 metres above sea level (msl) to ca. 650 mm near the catchment outlet at about 60 msl. Slopes tend to be steep (>20°) in the headwaters and often < 2° in the lowlands. Soils within the catchment are dominated by Pallic soils (NZ soil classification (Hewitt, 1998); encompassing Fragiudalfs and Haplustalfs in USDA taxonomy) of moderate natural fertility, but characterised by summer dry and winter wet soil moisture conditions, a high soil bulk density (>1.3 g cm^{-3}) and imperfectly to poorly drained. In low lying areas, profile drainage is facilitated by a network of mole channels (about 40–50 cm deep) that feed into tile or pipe drains at about 70–100 cm below the soil surface (collectively termed artificial drainage).

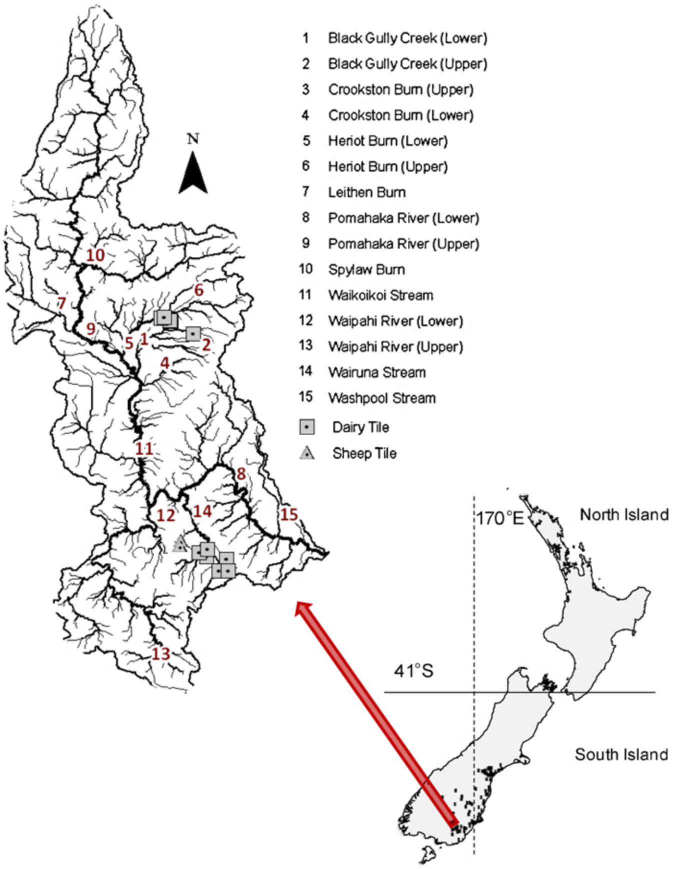

Fig. 1. Map of New Zealand showing the location of state of the environment reporting sites used to determine background median concentrations (rectangles) and the long-term, short-term and artificially (tile) drained sites in the Pomahaka River catchment.

Since April 1997, water quality and continuous flow have been measured bi-monthly at four long-term "State of the Environment" sites on the Pomahaka and Waipahi Rivers as part of regular assessments made by regional government. For 14 months, beginning in October 2008 this was supplemented by fortnightly sampling ($n = 30$) and continuous flow measurements (gauged fortnightly) of the long-term sites and 11 other "short-term" sites on the Pomahaka and its tributaries. On the same day as sampling short-term sites, an additional 20 drains (7 draining dairy- and 6 draining sheep-farmed land in the Wairuna Stream, and 7 draining dairy-farmed land in the Heriot Burn) were also sampled and flow gauged (Fig. 1). All long- and short-term sites were classified as belonging to either Low-elevation (L) or Hill topography (H) according to the River Environment Classification (REC) (Snelder and Biggs, 2002). The REC is often used to explain broad patterns in water quality data as part of analysis and reporting (e.g., Larned et al., 2004).

2.2. Sample analysis

In the laboratory, samples (2 L) were immediately filtered (<0.45 μm) and analysed for dissolved reactive phosphorus (DRP) within 24 h, and an unfiltered sample digested with persulphate and total P (TP) measured within 7 days. The P analyses were made using the colorimetric method of Watanabe and Olsen (1965). Suspended sediment (SS) was determined by weighing the oven dry (105 °C) residue left after filtration through a

GF/A glass fibre filter paper. Filtered samples were also analysed for NH_4^+–N (this includes NH_3 and NH_4^+, but referred to here as NH_4–N), $(NO_2^- + NO_3^-)$–N = NNN, and total N (TN, after persulphate digestion) concentrations using standard auto-analyser procedures (APHA, 1998). *Escherichia coli* (*E. coli*) was measured as the preferred faecal indicator bacteria for freshwater in New Zealand (MfE, 2003) using the Colilert® media and the Quanti-Tray® system (IDEXX Laboratories, Maine, USA).

Annual loads on a kg ha^{-1} basis of N and P fractions and SS were calculated via interpolation of fortnightly samples (see method 5; Johnes, 2007). While it should be noted that this method may underestimate loads for contaminants such as SS which are dominated by stormflow (Johnes, 2007), the recommended weekly sampling could not be achieved due to cost. However, as stormflow was not specifically targeted, but is known to carry >90% of annual *E. coli* loads (Davies-Colley et al., 2008), loads for this contaminant are not presented. Summary statistics (mean, median, standard deviation and range) for each site and trend analysis for the long-term sites was conducted with Time Trends v3.0 (Jowett, 2010). For trend analysis individual parameters were subject to Seasonal Kendall tests on raw and flow-adjusted data. The Sen Slope Estimator (SSE) was used to represent the magnitude and direction of trends (median concentrations) in data. Flow adjustment was carried out using LOWESS smoothing (30% span; Hirsch and Slack, 1984).

2.3. Baseline water quality

We used the method of Dodds and Oakes (2004) to estimate the baseline water quality of the study streams (i.e. the expected water quality for the streams if they were in a reference, or minimally disturbed, state). The method assumes that water quality monitoring sites represent a gradient of human impacts on water quality, but that minimally disturbed sites are rare or absent. The expected baseline water quality is inferred from the data by fitting a regression relationship to a water quality contaminant (e.g. median concentration) against a gradient representing human impacts as the independent variable. The *Y*-intercept of the regression is therefore the estimated baseline median concentration of the water quality contaminant. The method also allows for a factor, such as a region, to explain some of the variation in water quality that is attributable to natural characteristics of the sites (e.g. climate, topography and geology) (Dodds and Oakes, 2004).

We obtained water quality data collected over a 10-year period (1998–2007) as part of long term regional state of environment (SoE) monitoring at 100 sites in the Otago and South Canterbury regions (Fig. 1). All regional SoE sites were classified as either Low-elevation (L) or Hill (H) topography according to the River Environment Classification (REC) (Snelder and Biggs, 2002). The data consisted of a time series of monthly or quarterly measurements of water variables. We obtained the median concentration of the water quality contaminants for each site for which there were at least 40 sampling occasions. The percentage of the catchment occupied by High Producing Exotic Grassland land cover (*%Pasture*), as defined by the New Zealand Land Cover Database (MfE, 2004), was extracted for each site using a GIS. The *%Pasture* varied between 2 and 76% for sites classified as Hill and between 25 and 98% for sites classified as Low-elevation.

We used analysis of covariance (ANCOVA) to fit linear models of the median concentration of the water quality contaminants for each site to *%Pasture* as the continuous variable and the REC Topography category as the factorial explanatory variable. Prior to analysis, median concentrations were log (base 10) transformed to improve the normality of the distributions. Standard forwards and backwards stepwise linear regression was applied to the saturated ANCOVA models for each water quality contaminant to identify the minimal adequate. In this procedure the Akaike information criterion (Akaike, 1973) was used to apply a penalised log-likelihood method to evaluate the trade-off between the degrees of freedom and fit of the model as explanatory parameters are added or removed (Crawley, 2002). As selecting terms on the basis of AIC alone has been shown to be somewhat liberal in its choice of terms (Venables and Ripley, 2002), the value used for the multiple of the number of degrees of freedom used for the penalty in the stepwise procedure was adjusted such that all terms included in each model were statistically significant ($P < 0.05$). When slope terms of the minimal adequate models were significant, we used the intercept as the estimated baseline concentration of the water quality variable. Finally, we assumed that water quality at the study sites was significantly degraded when the median concentration was more than one standard error in excess of the estimated baseline concentration.

2.4. Modelling and management of contaminants

The concentration and load of contaminants that exhibited the most consistent trend among the long-term sites, DRP and TP, were further investigated in the Wairuna stream, which contributed a disproportionately high P load to the Pomahaka River. Although a member of the short-term group of sites, an additional 5 years of grab samples plus instantaneous, but not continuous, flow data were available. The Wairuna stream also contained a high proportion of dairying and was therefore a good candidate site for examining the role of potential point sources via effluent. The P load apportionment model of Bowes et al. (2008) was used to define a point and diffuse P load. Within this model, point sources were defined as those that enriched stream P concentration independent of flow (Q; L s^{-1}), i.e. were contributing to stream loads when, for example, dairy effluent was being applied, but caused little increase in stream flow. In contrast, diffuse sources were defined as those which enriched the stream as flow increased. However, because the model assumes a constant point source input, data analysis was restricted to data the lactation season (August to May) when effluent was being applied daily and a portion may be discharged to water depending on the soil moisture deficit. Jarvie et al. (2010) also note that the load apportionment model gives best results when samples cover the range of flow rates likely in the stream. Insufficient sampling may miss high flows and bias the output towards low flows. Over the course of the sampling period, stream flow recorded at the time of sampling covered 60% of the range in daily mean flows. Hence, the output of this model should be interpreted with caution.

To support the detection of point sources within tile drainage a statistical test was devised using tile drainage data from two long-term trials on dairy farms, one at Kelso within the Pomahaka River catchment, which ran from 2001 to 2008, and another at Tussock Creek, 20 km northeast of Invercargill, Southland, which ran from 2000 to 2003, and exhibited a similar climate (e.g. rainfall of 850–1000 mm yr^{-1}) and soil (Mottled Fragic Pallic Pukemutu silt loam) to that found in most of the lowland Pomahaka River catchment. Both trials generated flow weighted concentrations of DRP, TP, NO_3–N, NH_4–N, SS and *E. coli* in mole-pipe drainage from hydrologically isolated plots. The plots at Kelso were 27 m wide by 35 m long and 12 m wide by 13 m long rotationally grazed, on average every 26–28 days, except in June and July. At Kelso, data was also available for drainage that coincided during or within 24 h after the application of effluent. No rainfall occurred during this time and the resulting drainage was therefore due to bad effluent practice and not natural drainage. This data was used to define a contaminated and uncontaminated population. From this data, a statistical test was then developed to detect, bad effluent practice via water quality contaminant concentrations in samples of tile drainage taken as

Table 1
Summary statistics and seasonal Kendall test for constituents (all mg L^{-1} except for *E. coli* which is measured as coliform forming units 100 mL^{-1}) measured from 1997 to 2010 at long-term sites in the Pomahaka catchment.

Site/constituent	Mean	Standard deviation	Range	Median	Sen slope trend (change in median)	Significance
Waipahi upper						
DRP	0.017	0.009	0.003–0.050	0.018	0.003	***
TP	0.072	0.064	0.012–0.394	0.057	0.006	***
NH_4^+–N	0.019	0.013	0.005–0.070	0.020	<0.001	ns
NNN	0.719	0.402	0.020–1.870	0.616	−0.004	ns
TN	1.121	0.493	0.440–3.700	0.980	0.036	*
E. coli	1343	4657	10–37,000	250	−7	ns
SS	16.8	28.8	7.0–206.0	7.0	0.2	ns
Waipahi lower						
DRP	0.013	0.008	0.001–0.044	0.013	0.001	***
TP	0.049	0.027	0.001–0.155	0.040	0.002	**
NH_4^+–N	0.019	0.015	0.003–0.070	0.020	0.006	***
NNN	0.964	0.706	0.002–2.920	0.939	0.020[a]	**
TN	1.334	0.731	0.170–3.460	1.340	0.022[a]	**
E. coli	555	1447	1–10,800	130	−6	ns
SS	9.1	13.0	0.5–72.0	4.0	<0.1	ns
Pomahaka upper						
DRP	0.008	0.005	0.001–0.027	0.008	<0.001	***
TP	0.025	0.020	0.002–0.113	0.019	<0.001	*
NH_4^+–N	0.010	0.008	0.005–0.040	0.005	< −0.001	*
NNN	0.090	0.152	0.001–1.090	0.036	−0.001	ns
TN	0.268	0.197	0.025–1.050	0.210	< −0.001	ns
E. coli	442	874	18–4800	140	−5	ns
SS	5.7	9.4	0.5–53.0	2.0	<0.1	ns
Pomahaka lower						
DRP	0.012	0.007	0.001–0.039	0.011	0.006	***
TP	0.048	0.053	0.005–0.500	0.035	0.008[b]	*
NH_4^+–N	0.020	0.024	0.005–0.220	0.020	−0.001	***
NNN	0.594	0.483	0.003–2.870	0.471	0.003	ns
TN	0.953	0.053	0.090–4.000	0.740	−0.007	ns
E. coli	700	1911	1–12,000	99	−5	ns
SS	11.8	27.6	0.5–260.0	5.0	−0.1	ns

*, **, and *** represent significance for the annual change in median concentration (seasonal Kendall test) with time at the $P < 0.05$, 0.01 and 0.001 level, respectively. ns = not significant.

[a] Sen slope estimator presented for flow adjusted data where model accounts for >50% of the variance.

part of the short-term sampling of drains in the Wairuna Stream and Heriot Burn. Further details of the Kelso site can be found in McDowell et al. (2005).

3. Results and discussion

3.1. Current state and trend analysis of water quality contaminants at long-term sites

Summary statistics, including mean, median, standard deviation and range, for each of the 4 long-term sites within the Pomahaka River catchment are given in Table 1. Guidelines for good surface water quality in lowland streams in New Zealand are set at 0.009, 0.033, 0.444, 0.9, 0.614, and 8.2 mg L^{-1} for DRP, TP, NNN, NH_4–N, TN and SS, respectively (ANZECC, 2000), and 126 cfu 100 mL^{-1} (*E. coli*) for contact recreation (MfE, 2003). The median concentrations of DRP, TP, NNN and TN exceeded their guideline at all but the upper Pomahaka River site, while the median concentration of *E. coli* was exceeded at all but the lower Pomahaka River site. Ammoniacal-N and SS met guideline concentrations at all sites.

Trend analysis of contaminant concentrations for the 4 long-term sites within the Pomahaka River catchment from 1997 to 2010 indicated a significant increase in DRP and TP at all sites, whereas ammoniacal-N increased at the lower Waipahi River site, but decreased at both Pomahaka River sites (Table 1). Total N and NNN also increased at the lower Waipahi River site, while an increase in TN was noted for the upper Waipahi River site. Visual inspection of DRP and TP data showed that concentrations tended to be least in 2003 (Fig. 2). Focusing on those contaminants that exhibited a trend from 1997 to 2010, and splitting the data either side of June 30, 2003, showed that there was often a decreasing trend in DRP or TP concentration before June 30, 2003 and a much stronger increasing trend after June 30, 2003 (Table 2). Median concentrations of DRP, in particular, doubled after this date. Anecdotal evidence suggested that the improvement up to 2003 was due to the uptake of better management of existing dairy farms (especially regarding effluent) in the catchment, which was supported by relatively constant rates of compliance with regional government rules (Otago Regional Council, 2010). However, the increase after 2003 coincided with a period of rapid expansion and conversions to dairying, such that the number of dairy farms had almost tripled to 106 by 2010 (M. Hickey, Otago Regional Council, personal communication).

3.2. Contribution of contaminants by tributaries (short-term sites)

More intensive sampling of all sites occurred for 14 months from October 2008. Sites were chosen to reflect and capture most land use and potential contaminant sources within the wider Pomahaka River catchment. Using an interpolation procedure, area specific loads were also calculated for each contaminant, and listed alongside land use, for each site in Table 3. A stepwise multiple linear regression was then used to determine those land use, hydrologic, topographic and geological factors that most influenced median contaminant concentrations or loads (Table 4). Although the percentage of land use not in forest or pasture and acid soluble P (other land use) were often significant variables affecting contaminant loads or median concentrations, this was largely due to the influence of the Upper Waipahi River site. This site, which contains

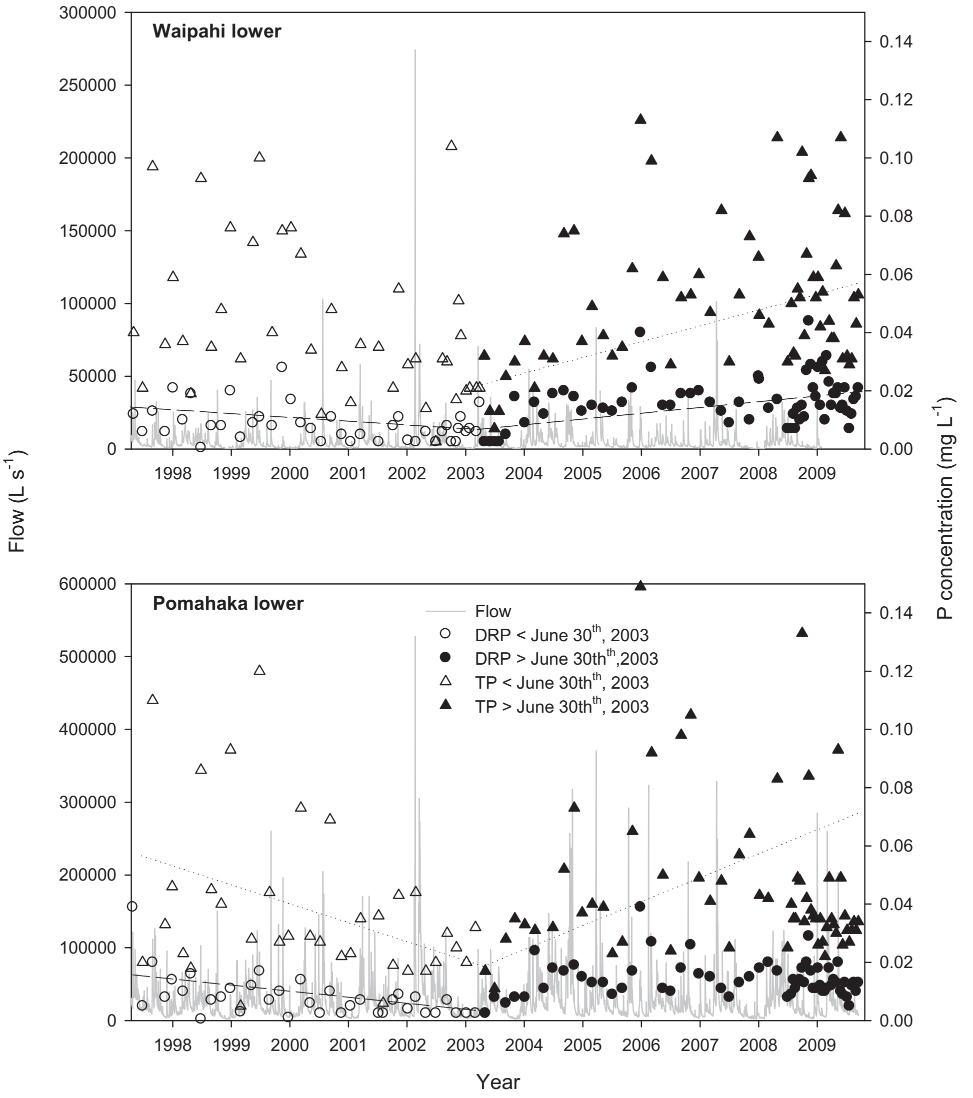

Fig. 2. Variation in flow and the concentration of dissolved reactive P (DRP) and total P (TP) in the Pomahaka and Waipahi Rivers downstream sites < and > June 30, 2003. Lines represent a significant fit ($P < 0.05$ or better) of the data as assessed by the seasonal Kendall test pre and post June 30, 2003.

Table 2
Pre and post June 30, 2003 median concentration and seasonal Kendall test results for constituents exhibiting significant trend with time (1997–2010) at long-term sites in the Pomahaka catchment.

Site/constituent	<June 30, 2003			>June 30, 2003		
	Median	Sen slope trend (change in median)	Significance	Median	Sen slope trend (change in median)	Significance
Waipahi upper						
DRP	0.004	<0.001	ns	0.018	0.002	***
TP	0.027	<0.001	ns	0.057	0.007	*
Waipahi lower						
DRP	0.008	−0.001	*	0.016	0.001	*
TP	0.036	−0.002	*	0.050	0.004	*
NH_4^+–N	0.020	−0.002	ns	0.019	< −0.001	ns
NNN	1.050	−0.027	ns	1.005	0.055	ns
TN	1.400	−0.046	ns	1.315	0.077	*
Pomahaka upper						
DRP	0.004	−0.001	ns	0.009	<0.001	ns
TP	0.017	−0.001	ns	0.020	0.002	*
NH_4^+–N	0.013	−0.001	ns	0.010	< −0.001	*
Pomahaka lower						
DRP	0.007	−0.002	**	0.013	<0.001	ns
TP	0.029	−0.004	*	0.040	0.001	*
NH_4^+–N	0.020	<0.001	ns	0.018	<0.001	ns

*, **, and *** represent significance for the annual change in median concentration (seasonal Kendall test) with time at the $P < 0.05$, 0.01 and 0.001 level, respectively. ns = not significant.

Table 3
Land use (km^2) and loads of contaminants (all $\text{kg ha}^{-1}\ \text{yr}^{-1}$) estimated for each site for 2009.

Site	Land use				Loads					
	Total	Dairy	Sheep & beef	Forest	$\text{NH}_4^+\text{–N}$	NNN	TN	DRP	TP	SS
Black Gully Creek lower	25	9	6	10	0.09	5.1	6.0	0.08	0.15	26
Black Gully Creek upper	6	0	6	0	0.03	0.6	1.0	0.15	0.17	11
Crookston Burn	32	14	8	10	0.31	11.2	13.5	0.17	0.35	32
Flodden Creek	43	11	19	13	0.05	7.6	8.6	0.07	0.16	29
Heriot Burn lower	142	22	17	103	0.05	3.4	4.2	0.04	0.13	25
Heriot Burn upper	25	3	6	16	0.05	2.9	4.0	0.05	0.31	252
Leithen Burn	72	0	29	43	0.03	0.7	1.4	0.06	0.15	30
Pomahaka River lower	1881	141	245	1495	0.07	4.8	6.9	0.05	0.34	60
Pomahaka River upper	714	0	40	674	0.02	0.8	1.6	0.04	0.15	38
Spylaw Burn	167	2	0	165	0.01	0.7	1.3	0.02	0.07	6
Waikoikoi Stream	116	23	0	93	0.06	1.7	2.6	0.04	0.14	11
Waipahi River lower	299	4	8	287	0.11	8.0	10.2	0.09	0.33	104
Waipahi River upper	15	0	0	15	0.09	25.4	38.2	0.12	2.61	528
Wairuna Stream	39	20	0	19	0.57	12.4	17.7	0.24	1.01	292
Washpool Stream	35	28	0	8	0.11	3.6	5.2	0.10	0.32	51

forest, has recently seen a wetland within the catchment drained for grazing and, as a result, enriched losses of contaminants (Otago Regional Council, 2011a). Excluding this site, placed greater weight on the other dominant factor identified by the analysis – percentage of land in dairy farming. Enriched contaminant concentrations and loads were particularly evident in the Washpool and Wairuna streams, both of which drain a much larger proportion of dairy-farmed land than other sites.

Loads of contaminants on a per ha basis ranged from a low in the upper Black Gully creek to a high in either the upper Waipahi River or Wairuna stream (Table 4). As a comparison, McDowell and Wilcock (2008) established mean loads ($\text{kg ha}^{-1-}\text{yr}^{-1}$) in New Zealand pastoral catchments of TN, TP and SS at 11, 1.3 and 1156, respectively for sheep and beef farmed land; 27, 1.9 and 299, respectively for dairy farmed land; and 2, 0.2 and 174, respectively for forest or native bush. Among sites, those that had at least 25% dairying in the catchment (lower Black Gully creek, Crookston Burn, Flodden Creek, and the Wairuna and Washpool streams) had similar loads to means loads for dairy-farmed catchments in New Zealand. The exception was the large TN and TP load from the forested upper Waipahi river site, ascribed as mentioned before, to the drainage of a large wetland.

Seasonal changes in contaminant loads are demonstrated by plots of mean monthly *E. coli* concentration at each site in Fig. 3. Changes in *E. coli* concentration over time were consistent with flow rates (i.e. diluting concentrations in winter months of June to August when no enriched source like effluent was being applied). However, evident at many of the sites was a sudden increase in

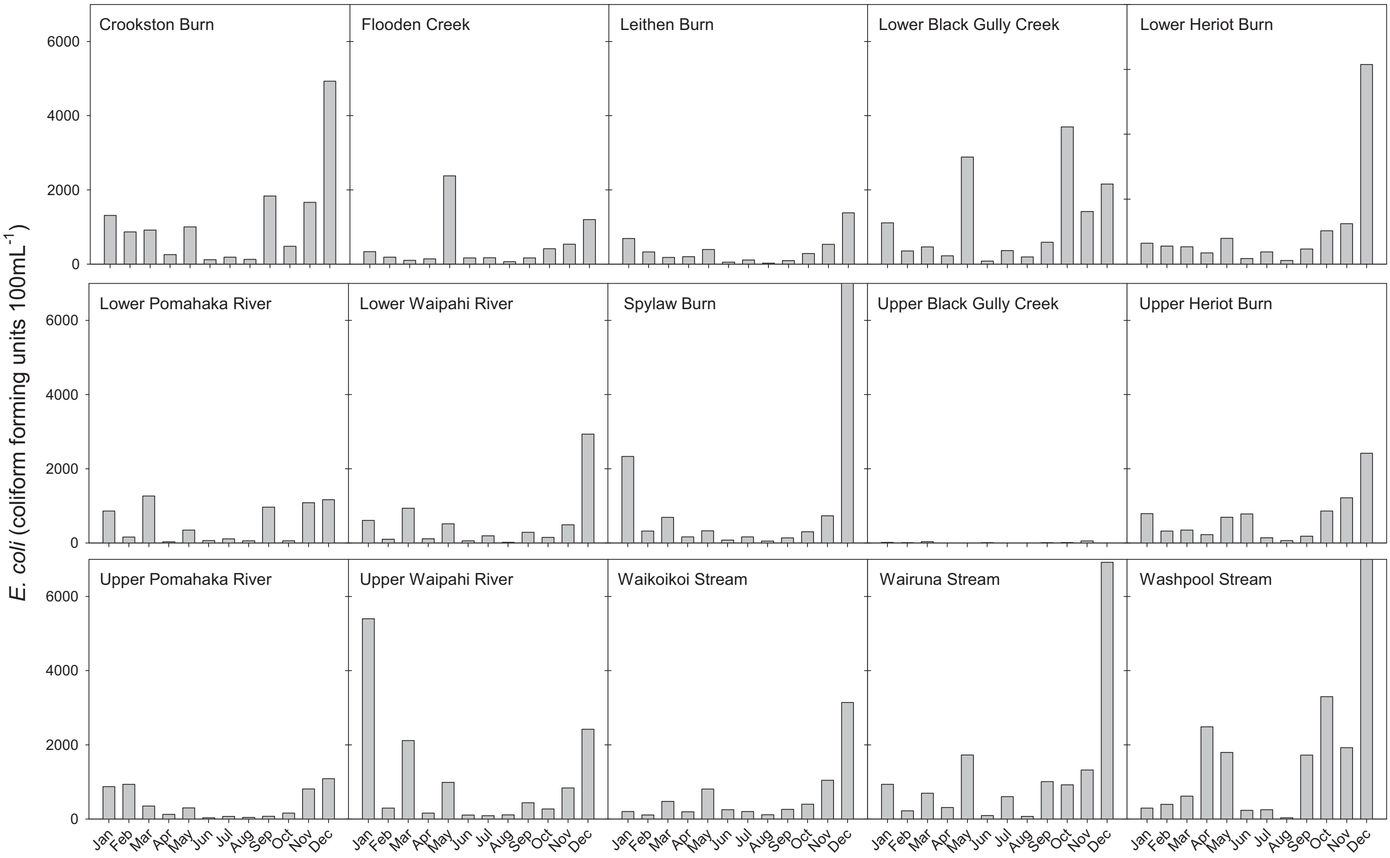

Fig. 3. Mean monthly concentration of *E. coli* ($\log_{10}$) at long- and short-term sites.

Table 4

Results from stepwise linear regression analysis for contaminant loads (log-transformed) and median concentrations against land use, hydrologic, topographic and geological classifications from the River Environment Classification for all sites measured 2008–2009 in the Pomahaka River catchment.

Loads	NH_4^+–N		NNN		TN		DRP		TP		SS		*E. coli*	
	Coef.	*P*-value	Coef.	*P*-value	Coef.	*P*-value	Coef.	*P*-value	Coef.	*P*-value	Coef.	*P*-value	Coef.	*P*-value
Dairy (%)	0.015	0.002	–	–	0.014	0.002	–	–	0.010	0.017	–	–	–	–
Sheep and beef (%)	–	–	−0.008	0.040	–	–	−0.008	0.003	–	–	–	–	–	–
Forestry/native (%)	–	–	–	–	–	–	–	–	–	–	–	–	−0.013	0.010
Other land use (%)[a]	3.800	0.148	9.300	0.013	9.200	0.002	4.300	0.042	9.400	0.002	6.300	0.131	–	–
Total area (ha)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Mean annual flow ($m^3 s^{-1}$)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Soil strength[b]	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Acid soluble phosphorus	1.440	0.031	2.050	0.014	2.060	0.003	0.870	0.071	0.960	0.107	–	–	–	–
Particle size	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Slope (degrees)	–	–	−0.067	0.006	–	–	–	–	–	–	–	–	–	–
Area >30° slope (%)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Constant	−6.034	−4.983	−6.231	−3.443	−4.004	1.496	4.418							
r^2	0.65	0.70	0.73	0.59	0.62	0.17	0.42							
Median concentrations														
Dairy (%)	–	–	0.009	0.060	0.010	0.079	0.001	<0.001	0.002	0.001	0.052	0.027	–	–
Sheep and beef (%)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Forestry/native (%)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Other land use (%)	–	–	–	–	–	–	–	–	–	–	25.000	0.100	–	–
Total area (ha)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Mean annual flow ($m^3 s^{-1}$)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Soil strength	–	–	–	–	–	–	–	–	–	–	–	–	−175	0.001
Acid soluble phosphorus	–	–	2.030	0.025	1.420	0.050	–	–	–	–	–	–	−284	0.125
Particle size	–	–	–	–	−0.320	0.061	–	–	–	–	–	–	–	–
Slope (degrees)	−0.002	0.008	–	–	–	–	–	–	–	–	–	–	–	–
Area > 30° slope (%)	–	–	–	–	–	–	–	–	–	–	14.300	0.173	–	–
Constant	0.033	−5.865	−2.847	0.012	0.027	−11.100	1605							
r^2	0.43	0.45	0.76	0.67	0.61	0.56	0.61							

[a] Includes wetlands, urban areas and bare ground.

[b] The variables – soil strength, acid soluble phosphorus and particle size are based on ordinal values derived from the Land, Environments of New Zealand (Leathwick et al., 2002).

Table 5
Baseline statistics (median, standard error and significance as *P*-value) for contaminant concentrations classified as low elevation or hill topography sites (if separation is applicable, otherwise indicated as suitable to both) determined via the intercept of a regression between median concentrations and percentage pasture at 100 state of the environment monitoring sites. Non-significant baselines are not given.

Contaminant	Classification	Baseline (median mg L^{-1})	Standard error	Significance
DRP	Both	0.003	0.001	<0.001
NH_4^+–N	Hill	0.006	0.001	<0.001
NH_4^+–N	Low	0.009	0.002	0.031
NNN	Hill	0.024	0.009	<0.001
NNN	Low	0.058	0.027	0.022
SS	Both	1.432	0.275	0.044
TN	Both	0.140	0.025	<0.001

concentrations in May, and enriched concentrations in spring for those sites with at least 25% dairying (e.g. Wairuna and Washpool). The increase in May could be due to a flushing effect as sediment, and entrained NH_4–N, P fractions and *E. coli*, are re-suspended in the water column as flow rates increase (Muirhead et al., 2004). However, the May samplings occurred before any significant rainfall. Furthermore, *E. coli*, TP and NH_4–N concentrations in tile drainage (see Section 3.5), sampled before rainfall, were also enriched suggesting the source as effluent-derived. The seasonal pattern for NH_4–N, SS, DRP and TP at the short-term sites was similar to *E. coli*, whereas NNN and TN (NNN generally comprised >60% of TN) were greatest in May to July as NNN was flushed from the soil upon the onset of autumn/winter drainage.

3.3. *Baselines of water quality*

There were significant relationships between the median concentration and *%Pasture* for all water quality contaminants measured at the 100 regional SoE sites except *E. coli* and TP. Intercepts derived from setting the *%Pasture* to zero were interpreted as baseline concentrations (Table 5). These baselines differed for the Hill and Low-elevation classes for two variables (NH_4^+–N and NNN). The slope of the regression was not significantly different between the classes for any variable (hence, data is not presented). The median concentrations of water quality contaminants were significantly greater than the estimated baselines at all sites except for six, two and one site for NH_4^+–N, NNN and SS, respectively (Table 6). Thus, the site concentrations are set against a natural or background median concentration (Smith et al., 2003; Unwin et al., 2010) that highlights the effect of development in the catchment. The background TN calculated for the sites in the Pomahaka catchment would appear to be much lower than for most regions in the US calculated by Dodds and Oakes (2004) or Smith et al. (2003), which ranged from 0.120 to 2.108 mg L^{-1} and had a mean of 0.569 mg L^{-1}. This could be due to a number of reasons, including edaphic and climatic differences and the absence of native N-fixing plants in the region's native cover (beech forest, *Nothofagus* sp.) (Fahey and Jackson, 1997).

3.4. *Artificial drainage*

Contaminant concentrations are presented as box and whisker plots in Fig. 5 draining from dairy and sheep farmed land and for the receiving waterways, the Heriot Burn and Wairuna stream.

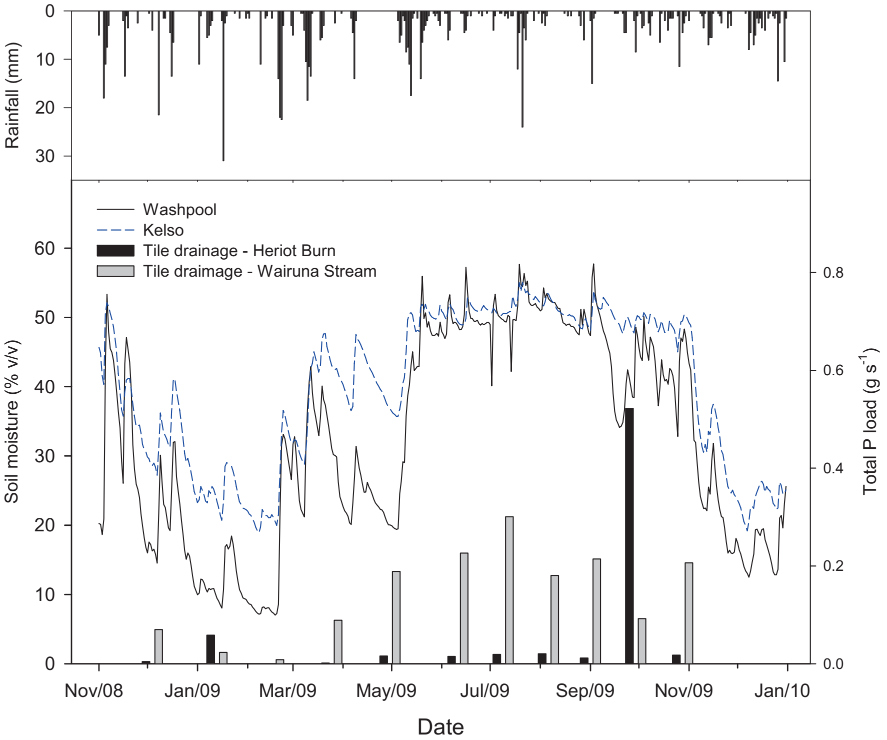

Fig. 4. Mean rainfall and soil moisture at two sites in the Pomahaka catchment (within the Washpool and adjacent to the Wairuna Stream catchment and at Kelso, adjacent to the Heriot Burn catchment; Otago Regional Council, 2011b) and the mean load of total P in drainage from dairy-farmed sites in the Heriot Burn and Wairuna Stream catchments.

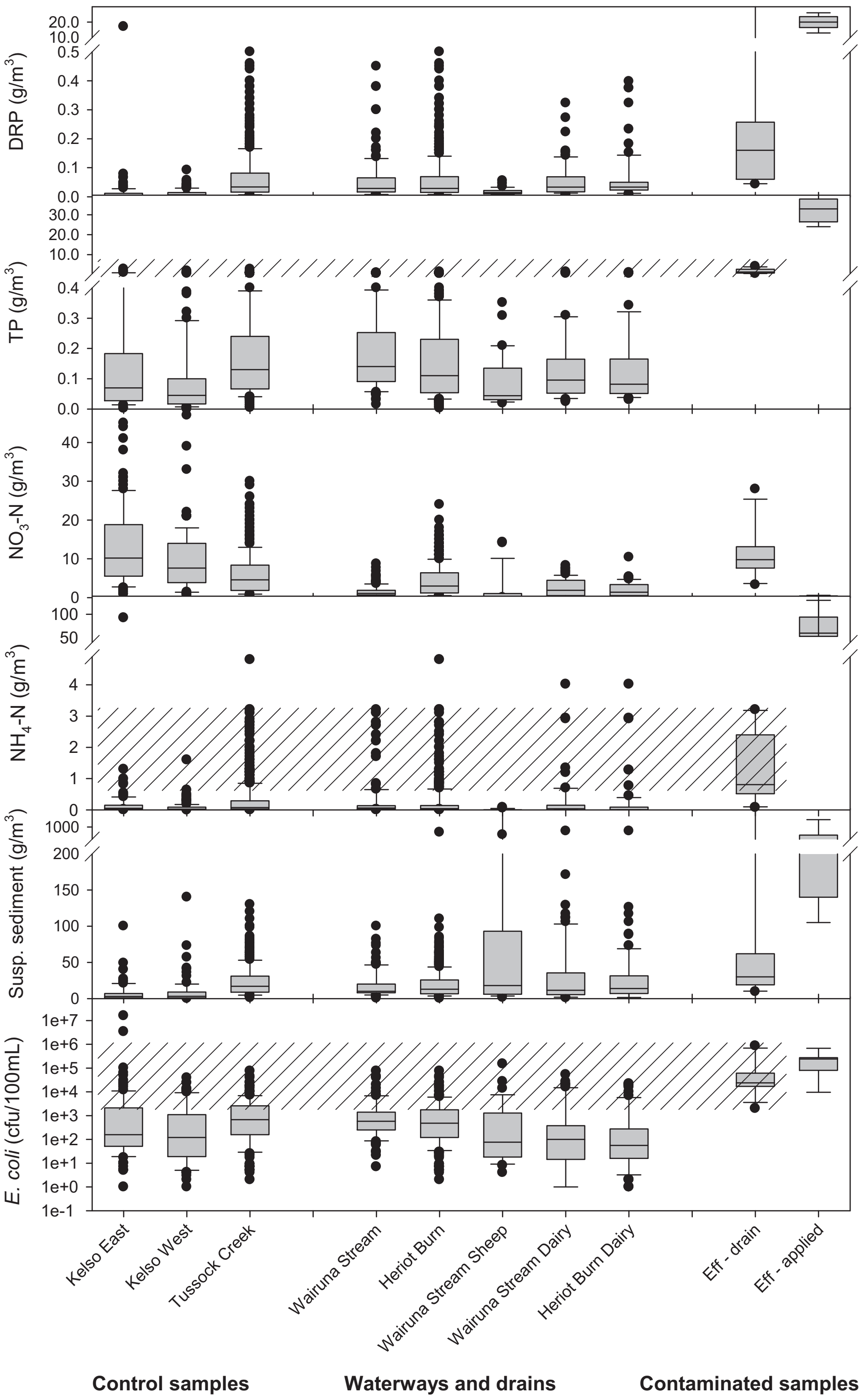

Fig. 5. Box (25th and 75th percentile and median) and whisker (5th and 95th percentile, outliers shown as filled circles) plots indicating the concentration of contaminants in control samples and samples of effluent and drainage within 24 h of effluent application (Eff. Drain) that denote contaminated samples from Kelso and Tussock Creek, and Heriot Burn and Wairuna Stream and dairy or sheep drainage samples. The cross-hatched boxes denote the range of samples from the Eff. drain dataset relative to all other samples.

Generally, a greater range of contaminant concentrations existed in drainage than the receiving waterways, while median concentrations also tended to be greater. As it was not possible to establish the area being drained by each drain (only the dominant land use), loads were not presented. However, there is much evidence within the catchment and on similar soil types and climates to show that the enrichment of dairy-farmed drains may partly be due to the application of effluent to artificially drained lands (e.g. Monaghan and Smith, 2004; McDowell et al., 2005). Losses are exacerbated when too much is applied and/or effluent is applied to wet soils. Such a scenario is common in spring, especially in the Pomahaka catchment, when soils are wet and what effluent ponds

Table 6
Median contaminant concentrations (all mg L^{-1} except for *E. coli* which is measured as coliform forming units 100 mL^{-1}) for each site, as classified by the River Environment Classification (REC) into Low elevation or Hill topography, and the percentage of the median concentration manageable (man.) relative to a natural baseline (i.e. ((Median − Baseline)/Median) × 100%).

Site	REC topography class	NH$_4^+$–N		DRP		NNN		SS		TN		TP	*E. coli*
		Median	% man.	Median	% man.	Median	% man.	Median	% man.	Median	% man.	Median	Median
Black Gully Creek upper	H	0.005	0	0.030^{a,b}	90	0.122^{b}	80	1.5	5	0.200^{b}	30	0.032	6
Heriot Burn upper	H	0.010^{b}	40	0.016^{a,b}	81	0.683^{a,b}	96	4.0^{b}	64	0.910^{a,b}	85	0.038^{a}	210^{a}
Leithen Burn	H	0.005	0	0.014^{a,b}	79	0.068^{b}	65	4.0^{b}	64	0.230^{b}	39	0.029	170^{a}
Pomahaka River upper	H	0.020^{b}	70	0.011^{a,b}	73	0.480^{a,b}	95	5.0^{b}	71	0.745^{a,b}	81	0.035^{a}	100
Black Gully Creek lower	L	0.020^{b}	55	0.025^{a,b}	88	0.754^{a,b}	92	4.0^{b}	64	1.000^{a,b}	86	0.044^{a}	340^{a}
Crookston Burn lower	L	0.010	10	0.018^{a,b}	83	1.550^{a,b}	96	3.0^{b}	52	1.680^{a,b}	92	0.031	180^{a}
Crookston Burn upper	L	0.010	10	0.027^{a,b}	89	1.535^{a,b}	96	2.3^{b}	36	1.770^{a,b}	92	0.0435^{a}	235^{a}
Heriot Burn lower	L	0.020^{b}	55	0.022^{a,b}	86	1.080^{a,b}	95	6.0^{b}	76	1.590^{a,b}	91	0.058^{a}	460^{a}
Pomahaka River lower	L	0.008	0	0.008^{b}	63	0.037	0	2.0^{b}	28	0.210^{b}	33	0.020	140^{a}
Spylaw Burn	L	0.010	10	0.018^{a,b}	83	0.056	0	2.5^{b}	43	0.730^{a,b}	81	0.077^{a}	200^{a}
Waikoikoi Stream	L	0.020^{b}	55	0.021^{a,b}	86	0.335^{b}	83	3.0^{b}	52	0.760^{a,b}	82	0.068^{a}	290^{a}
Waipahi River lower	L	0.020^{b}	55	0.013^{a,b}	77	0.939^{a,b}	94	4.0^{b}	64	1.340^{a,b}	90	0.040^{a}	130^{a}
Waipahi River upper	L	0.020^{b}	55	0.018^{a,b}	83	0.616^{a,b}	91	7.0^{b}	80	0.980^{a,b}	86	0.057^{a}	250^{a}
Wairuna Stream	L	0.055^{b}	84	0.030^{a,b}	90	1.000^{a,b}	94	8.0^{b}	82	1.660^{a,b}	92	0.119^{a}	440^{a}
Washpool Stream	L	0.030^{b}	70	0.080^{a,b}	96	0.406^{b}	86	7.5^{b}	81	1.635^{a,b}	91	0.245^{a}	380^{a}

[a] The median concentration exceeded the ANZECC guideline value for DRP, TP, NNN, NH$_4$–N, TN and SS, (ANZECC, 2000) or 126 cfu 100 mL^{-1} for *E. coli* (MfE, 2003).

[b] The median concentration exceeded the estimated baseline concentration.

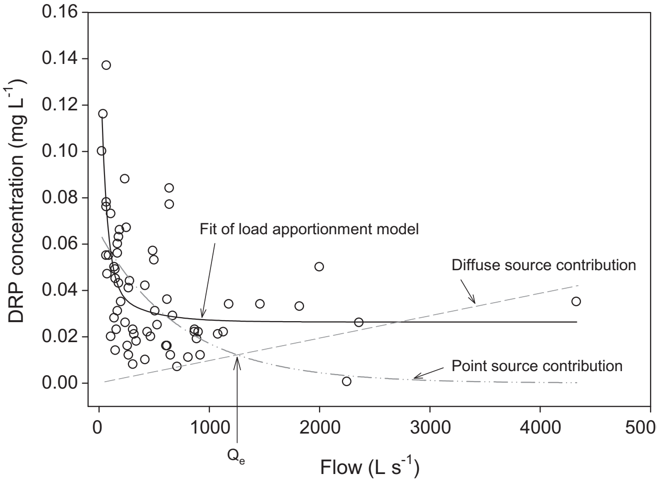

Fig. 6. Fit of the load apportionment model to a plot of DRP concentration and flow at the Wairuna site. The dashed and dotted grey lines indicate the models estimate of point and diffuse DRP sources with increasing flow. Q_e is the flow rate at which diffuse and point source contributions to stream load are equal.

exist tend to be small and full (Houlbrooke et al., 2008). In addition to the example highlighted for *E. coli* in Section 3.2, data for TP indicated that while enhanced loads were evident in drainage, when the soil was wet, loads were also enriched despite there being no rainfall (Fig. 4), indicative of contamination by effluent: P loss via spring flow (also independent of rainfall) is low.

Given the potential for enhanced TP loads, independent of rainfall, artificial drainage during these periods could be classified as a point source in the load apportionment model of Bowes et al. (2008). Fitting the model to DRP and TP concentration and instantaneous flow estimated that point sources within the Wairuna accounted for 58% and 53% of DRP and TP loss, respectively (Fig. 6). This is greater than the 35% of P load estimated as originating from farmyard discharge from a dairy farm in Scotland by Edwards and Hooda (2008). However, because data only covers 60% of the range in flows in the Wairuna stream, the estimated load is likely to be biased towards low flows and point sources. Furthermore, Neal et al. (2010) also point out that point sources may include spillage (e.g. leakage of silage stacks) and runoff of hard-standing areas and farmyards. However, in New Zealand the effluent from washing hard-standing areas on dairy farms is generally routed into the effluent pond system and hence subject to land application. What is not accounted for by the model is the potential for direct depositions. James et al. (2007) showed that P loads in a New York catchment could be decreased by a third if grazing dairy cows were fenced out of streams. In New Zealand, streams wider than 1-m and deeper 30-cm are required to be fenced off from dairy cattle (MAF, 2009). While these streams are common in the Pomahaka and dairy farmed land, they also occur in areas that are farmed by other grazing animals, which have no requirement to fence-off streams. This exposes streams to direct deposition and other ‘high risk’ agricultural practices such as the grazing of wet pastures or winter forage crops by deer, sheep and beef cattle in paddocks close to streams (McDowell, 2006).

3.5. Implications and management

An effect of enriched P loss to the Pomahaka River and its tributaries will be increased periphyton growth. If flows are stable during November to April, i.e. when day length is long and temperatures warm enough to promote growth (Young and Huryn, 1996), periphyton utilise dissolved N and P to grow until one of the nutrients limits growth. We calculated a dissolved N

Table 7
Log-transformed (and in parentheses the untransformed) mean concentrations all mg L^{-1} except for *E. coli* which is measured as coliform forming units 100 mL^{-1}) of contaminants in the contaminated (contam.) dataset minus one and two standard deviations (SD) and the respective percentile of the control dataset.

Statistic	Contaminant			
	E. coli	NH_4–N	Total P	Combination
Control mean	5.39 (220)	−2.64 (0.071)	−2.28 (0.102)	−1.10 (0.332)
Contam. mean	10.13 (25,010)	−0.22 (0.805)	0.27 (1.305)	1.41 (4.078)
% of control dataset	97.0	94.7	99.0	99.4
Contam. Mean – 1 SD	8.67 (5852)	−1.30 (0.271)	−0.44(0.646)	0.92 (2.517)
% of control dataset	90.4	81.4	95.4	97.8
Contam. Mean – 2 SD	7.22 (1369)	−2.39 (0.091)	−1.14 (0.319)	0.44 (1.554)
% of control dataset	76.6	56.6	85.0	93.7

(NH_4–N + NNN) to P (DRP) ratio for each site and used the ratios published by Guildford and Hecky (2000) of <7:1 and >15:1 N:P to indicate N- and P-limitation, respectively (mass basis). These ratios are analogous to those used by the MfE (2007) and White (1983). Ratios indicative of P-limitation, during November to April, were evident at Lower Black Gully Creek, Upper, the Crookston Burn, Flodden Creek, both Heriot Burn sites, the Lower Pomahaka, both Waipahi sites, and the Wairuna Stream, all others were N-limited. Apart from the upper Pomahaka site, all other sites had a significant proportion of dairying in the catchment. In addition, the mean N:P ratio for artificial drainage was >100. Withers et al. (2009) also found discharges from drainage of farmyards and hard-standing areas was P-limited, but noted that due to the greatly enriched concentrations of both N and P, P-limitation would only occur when biomass was already high. The prevalence of P-limitation in the streams, and P-rich discharge from tiles, suggests that tile drainage could have a large effect on periphyton growth.

Although contaminant inputs via drainage can be considerable, a test is required to determine whether or not this is due to bad practice or is simply a reflection of increased rainfall and flow. A total of 1100 drainage events from two sites (Kelso and Tussock Creek) were used to create a control (uncontaminated) population, and a contaminated population which derived from drainage either during or within 24 h of dairy shed effluent being applied to land. A non-parametric Krustall–Wallis test of median concentrations for each contaminant indicated that there was no significant difference between either Tussock Creek or Kelso sites, or between the analysis of annual data and those generated from October to April. Hence, data for all sites, irrespective of time of year, was pooled. From inspection of the data (Fig. 5), *E. coli*, NH_4–N and TP concentrations were used to generate the two populations (control and contaminated).

The mean TP concentration for the contaminated population was greater than 99.0% of the control population (Table 7). In addition, 95% of the control population P concentrations were less than 1 standard deviation below the contaminated mean (i.e. the lower 16% of contaminated samples), and 85% of the control population P concentrations were less than 2 standard deviations below the contaminated mean (i.e. the lower 2.5% of contaminated samples). Due to a greater overlap between control and contaminated data, the percentiles for NH_4–N and *E. coli* concentrations were less at 56.6% and 76.6% for the mean of contaminated data minus two standard deviations (Table 7). However, a discriminant analysis was able to show that a combination of the three variables separated the control and contaminated populations better than a single variable:

$$\text{Combination} = 0.13 \times \ln(E.\,coli + 1) + 0.14 \times \ln(\mathrm{NH}_4^{-}\mathrm{N} + 0.005) + 0.57 \times \ln(\mathrm{TP} + 0.0025)$$

Using this combination variable, 93.7% of the control concentrations was below a value of 1.554 (or 0.44 when using the above calculation that incorporates a log transformation), while only 2.5% of the contaminated population were below this value (Table 7). Using a combination value of 1.554 as a limit, 9% of dairy drainage samples taken in the Wairuna Stream and Heriot Burn catchments were found to be "contaminated". The effect on water quality from the drains is clear if the contribution of contaminated samples is removed from the dairy drainage dataset. The resulting median concentration and load decreases by an estimated 3–58% (Table 8). Unsurprisingly, the greater decreases were evident for those contaminants used to denote a "contaminated" drainage sample (e.g. NH_4–N, *E. coli* and TP), rather than for those, like NNN, that were not.

While this test may statistically identify a "contaminated" sample, strategies are still required to decrease the loss of contaminants associated with the application of dairy effluent to artificially drained land. Recent work has focused on recommendations on the appropriate design of dairy effluent storage facilities, maximum annual rates of dairy effluent-N applications to land (and thus the farm area required to receive effluent loadings), split applications, improved application methods, and exclusion times for grazing animals after application (McDowell et al., 2009). One strategy, deferred irrigation, which involves pond storage of effluent during periods when soil moisture is close to or at field capacity and the use of low application rate irrigation systems (movable irrigation sprinklers that apply effluent at rates <10 mm/h), has proven effective at decreasing or eliminating the direct contribution of effluent to waterways (Houlbrooke et al., 2004, 2006; Monaghan and Smith, 2004). For example, Houlbrooke et al. (2008) compared the loss of N and P from a 'one-off' application onto wet artificially drained land with measured annual losses of N and P when using a deferred irrigation strategy over a whole year. Nitrogen and P losses from the

Table 8
Median concentrations (all mg L^{-1}, except *E. coli* which is cfu 100 mL^{-1}) and loads (all mg s^{-1} except *E. coli* which is cfu s^{-1}) for existing dairy drainage samples from the Wairuna stream and Heriot Burn catchments in existing condition and with "contamination" due to bad effluent practice removed. The percentage decrease for median concentrations and loads is also given.

Parameter	Condition		Percent decrease
	Existing	Without contamination	
Median concentration			
NH_4–N	0.030	0.020	33
DRP	0.038	0.033	13
E. coli	56	39	30
NNN	1.97	1.97	0
SS	14	12	14
Total N	2.985	2.390	20
Total P	0.099	0.090	9
Loads			
NH_4–N	9	5	42
DRP	4	3	17
E. coli	1,150,376	487,994	58
NNN	354	344	3
SS	1890	1456	23
Total N	438	413	6
Total P	11	9	22

'badly-managed' irrigation (12 kg N/ha and 2 kg P/ha) were 6–10 times greater than losses associated with deferred irrigation (5 events). Such strategies are not yet common place in the catchment, and would have considerable scope, in addition to other simple measure like stream fencing, in improving water quality in the Pomahaka if correctly implemented.

4. Conclusions

Monitoring of water quality indicators has indicated a strong increase in the concentration of P fractions. Much of the increase in P concentrations, and other indicators, was attributed to an increase in dairying. An analysis of baseline contaminant concentrations suggested that for most sites, natural concentrations were commonly <20% of current concentrations. Of the 80% attributable to anthropogenic inputs, a portion comes from artificial drainage. During sampling, significant concentrations of contaminants were detected despite there being no rainfall, indicating the likely input of contaminants via poor practice such as applying effluent to wet (near saturated) soil. Using a statistical test to isolate effluent-contaminated samples from drainage samples entering the Heriot Burn and Wairuna Stream, showed that, if contaminated drainage was prevented, there was potential to decrease median concentrations and loads of contaminants by up to 58% (greater decreases were found for *E. coli*, NH_4–N and total P than other contaminants). The prevention, or mitigation, of contaminant loss via effluent can be achieved with strategies, such as deferred irrigation (and low rate application). Such strategies are not commonly practiced in the catchment. This indicates not only is there a large anthropogenic input of contaminants, but also that there is considerable opportunity, via mitigation strategies that, for example, focus on effluent, to improve water quality within the Pomahaka River.

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