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Water quality and thermal regime of the Motueka River: influences of land cover, geology and position in the catchment

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Abstract We examined the effects of land use, geology, and longitudinal position within the river network on water quality and thermal regime at 23 sites within the Motueka River catchment. The concentrations of suspended solids, nitrate nitrogen, total nitrogen, *Escherichia coli*, and *Campylobacter* were higher at sites draining pastoral and horticultural land than in similar-sized native or plantation forest streams. Average daily mean temperature and minimum temperature in summer and maximum winter temperature were higher in unshaded pastoral and horticultural streams than at native forest sites. Differences in water quality and thermal regime were also observed among sites with contrasting geology. Conductivity, pH, and minimum winter temperatures were highest at sites draining marble terrain. In contrast, longitudinal patterns in water quality and temperature regime along the 120-km length of the river were relatively weak, although longitudinal patterns in amplitude of daily temperature fluctuation matched theoretical predictions. In this study, differences in land use appeared to have the strongest influence on most water quality and thermal variables examined. However, geology was an important factor explaining variation in certain variables (e.g., pH and conductivity). Longitudinal patterns in water quality and temperature were relatively weak and in many instances were linked with longitudinal patterns in land use and geology rather than catchment location alone.

Keywords water quality; temperature; thermal regime; land use; agriculture; horticulture; forestry; geology; nutrients; sediment; *Escherichia coli*; *Campylobacter*; conductivity

INTRODUCTION

Water quality and temperature are key variables affecting the health, biodiversity, and productivity of freshwater ecosystems (Karr & Schlosser 1978; Vannote & Sweeney 1980; Elliott 1994; Hawkins et al. 1997). Numerous studies have described the changes in water quality associated with some changes in land use. For example, agricultural streams in New Zealand and elsewhere have been associated with increased nutrient and sediment runoff (McColl et al. 1975; Wilcock 1986; Cooper & Thomson 1988; Close & Davies-Colley 1990; Maasdam & Smith 1994; Quinn & Stroud 2002) and increased levels of faecal bacteria (Hunter et al. 2000; Crowther et al. 2002; Davies-Colley et al. 2004; Larned et al. 2004) compared with similar streams draining undisturbed catchments. Agricultural streams in New Zealand also have warmer annual mean temperatures than neighbouring native

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forest streams (Quinn & Hickey 1990; Quinn et al. 1997). In contrast, plantation forests in New Zealand and elsewhere are considered to have relatively minor effects on water quality and temperature during the growing phase of the harvest cycle (Dons 1987; Quinn & Stroud 2002; Larned et al. 2004), with more marked effects after logging (Beschta & Taylor 1988; Holtby 1988; Hicks et al. 1991; Fahey & Jackson 1997; Johnson & Jones 2000). The effects of other land uses, such as horticulture, on water quality or thermal regime are less well known.

Although the effects of geology on water quality have not been so commonly studied in New Zealand as the effects of land use, the importance of geology in controlling broad-scale patterns of water quality is generally well recognised (Dillon & Kirchner 1975; Hill 1978; Close & Davies-Colley 1990; Biggs & Gerbeaux 1993; Biggs 1995; Kim et al. 1999). Export of dissolved ions is limited in catchments dominated by parent rock that is resistant to weathering, but relatively high in catchments with soft sedimentary rock, such as limestone or marble. There are also strong links between geology and water temperature regimes via geological differences in run-off mechanisms and surface-subsurface water interactions (Jones & Holmes 1996; Poole & Berman 2001).

Longitudinal changes in temperature and water quality are also expected within large river catchments. Vannote & Sweeney (1980) predicted that the amplitude of daily temperature fluctuation will peak in 4th–5th order rivers where the downstream increase in solar radiation, as the channel widens, begins to be offset by the thermal inertia associated with an increasing volume of water. Arscott et al. (2001) tested this prediction in a 7th order river system in Italy and found that longitudinal changes in geology and channel morphology altered longitudinal thermal patterns. Concentrations of suspended sediment can increase downstream because the average size of riverbed materials tends to decrease (Leopold 1994). Concentrations of suspended sediment, nutrients, and faecal bacteria also tend to increase downstream owing to increasing amounts of modified land at low elevations in most river catchments (Meybeck 1982; Allan 1995; Bolstad & Swank 1997; Harding et al. 1999).

Despite the abundance of information on the influence of land use, geology, and longitudinal position on water quality and temperature, the relative importance of each of these factors is unclear. Some studies have identified land use as the predominant factor controlling water quality (Maasdam & Smith 1994; Leland & Porter 2000), whereas other studies found geology to be more important (Close & Davies-Colley 1990; Biggs 1990). Catchment-wide land use may be important for controlling some water quality and thermal variables. However, land use within the narrow riparian zone may have a disproportionately large influence on other variables (e.g., faecal pollution, thermal regime; Rutherford et al. 1997). Management of river systems requires knowledge of how different combinations of land use, geology, and longitudinal position interact to influence different aspects of water quality and temperature. The purpose of this study was to compare sites with contrasting land cover, geology, and longitudinal position within a single catchment.

MATERIALS AND METHODS

Study sites

The study was conducted in the Motueka River catchment in the north of the South Island, New Zealand (Fig. 1). The Motueka River drains a catchment of 2180 km^2 and flows for c. 110 km from the headwaters before reaching Tasman Bay. The Motueka catchment is geologically complex, with old ultramafic and sedimentary rock (primarily argillite) in the southeastern headwaters, a complex array of sedimentary rocks (marble, greywacke, argillite, limestone, mudstone, and schist) underlying the western tributaries, a band of granitic rocks (Separation Point Granite) down the western centre of the catchment, and a large band of thick (up to 0.7 km) alluvial gravel and clay (Moutere Gravel) down the eastern centre of the catchment (Basher 2003).

Current land cover in the catchment is dominated by native forest (35%), plantation forest (25%), pastoral grassland (19%), scrub (12%), and tussock grassland (7%). The largest areas of native forest (dominated by *Nothofagus* spp.) are found in the western and southern headwaters, whereas plantation forest (primarily *Pinus radiata*) occupies part of the Separation Point Granite and Moutere Gravel terrains. Pastoral grassland generally occupies the valley floors and is mainly used for sheep and beef cattle grazing, although there are small areas of dairying. Intensive horticulture (0.6% of catchment area) is also found on some of the river flats, particularly near the coast, and includes pipfruit, kiwifruit, berries, hops, vegetables, and grapes.

Mean annual rainfall is c. 1600 mm. However, there are strong rainfall gradients across the

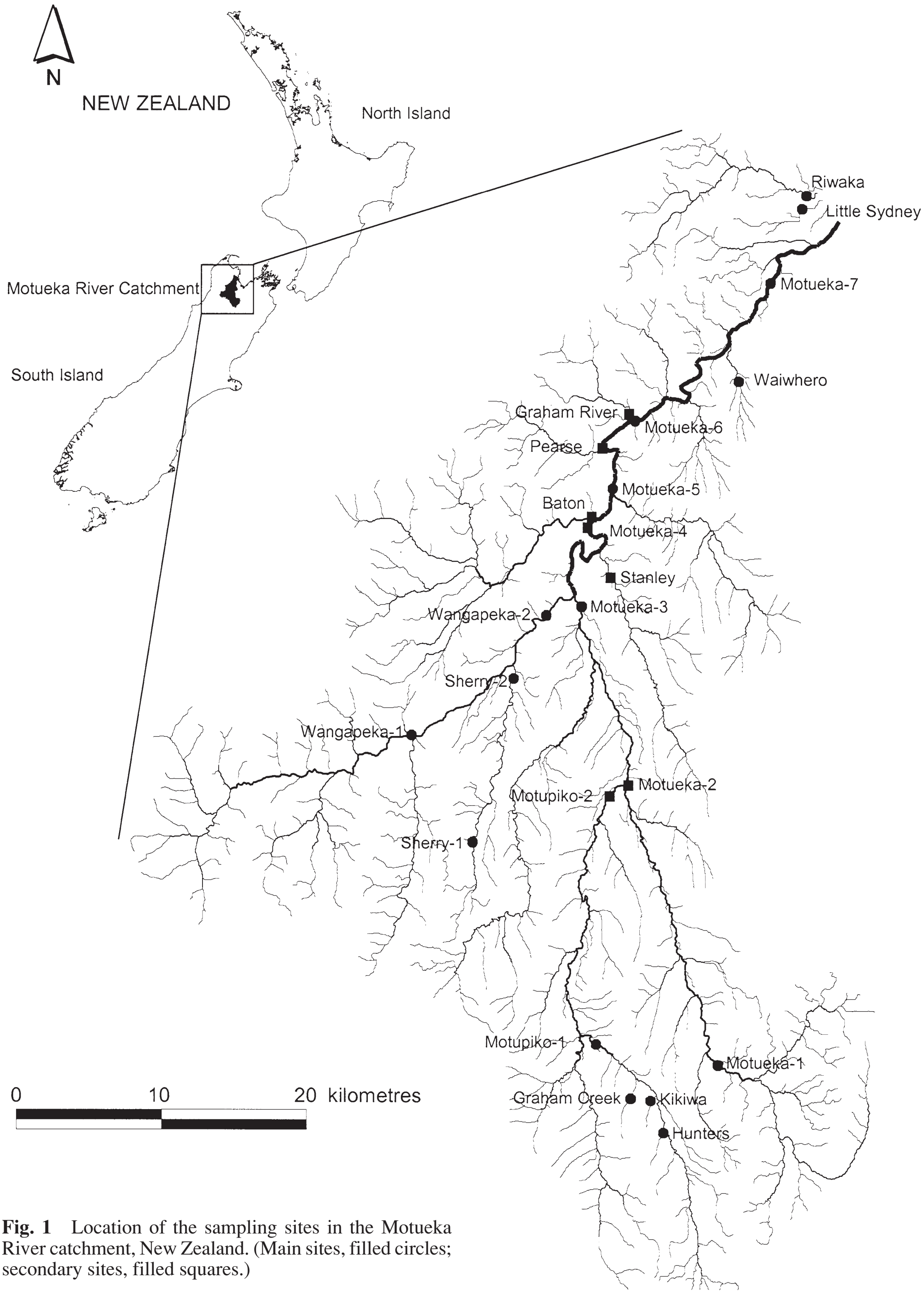

Fig. 1 Location of the sampling sites in the Motueka River catchment, New Zealand. (Main sites, filled circles; secondary sites, filled squares.)

catchment with the highest rainfall (3500 mm year^{-1}) occurring in the western headwaters (Basher 2003). In contrast, the low-elevation eastern parts of the catchment receive <1000 mm year^{-1} of rainfall (Basher 2003). The mean and median flows of the river at the main hydrological recording site (site Motueka-5 near Woodstock) are 58.6 $m^3 s^{-1}$ and 34.0 $m^3 s^{-1}$, respectively (Basher 2003).

Measurements

Water quality and temperature were measured at 23 sites in total, of which 16 were main sites, where all variables were measured, and 7 were secondary sites where a subset of field variables were measured (Fig. 1). The effect of land use on water quality and temperature regime was examined using 10 of these sites (Table 1) that represented the full range of land use types found in the catchment. The effect of geology was assessed at the catchment scale among 16 of the sites that were grouped into predominant geological types (Table 1). Finally, longitudinal changes in water quality and temperature along the mainstem of the Motueka and its two major tributaries (Wangapeka and Motupiko) were also determined.

Water quality

All sites were visited monthly from October 2000 to October 2001 (13 times) and then quarterly from January 2002 to April 2003 (6 times). All sites were sampled over a consecutive 2-day period on each sampling occasion so that preceding flow conditions were approximately equivalent among sites. The order in which sites were visited on each sampling occasion was varied to limit the likelihood of any differences in pH, dissolved oxygen (DO), and spot temperature among sites being a result of consistent differences in when they were sampled.

At each main site, water samples were collected for analysis of nitrate nitrogen (NO_3-N, g m^{-3}), ammoniacal nitrogen (NH_4-N, g m^{-3}), total nitrogen (TN, g m^{-3}), dissolved reactive phosphorus (DRP, g m^{-3}), total phosphorus (TP, g m^{-3}), total suspended solids (TSS, g m^{-3}), inorganic (fixed) suspended solids (FSS, g m^{-3}), organic (volatile) suspended solids (VSS, g m^{-3}), and indicator bacteria (*Escherichia coli*, cfu 100 ml^{-1}). Spot measurements of water temperature (°C, YSI 85), specific conductivity at 25°C (µS cm^{-1}, YSI 85), DO (g m^{-3}, YSI 85), turbidity (NTU, Hach 2100P), visual water clarity (m, black disc, Davies-Colley 1988), and pH (Orion 210A) were made in the field at each site. Sampling for the pathogen *Campylobacter* (MPN 100 ml^{-1}) was also carried out at the main sites on a monthly basis from October 2000 to September 2001, but not in January and August 2001. Discharge was determined at each site on each sampling occasion using either velocity and depth measurements across the river cross-section, or from permanent stage-height recorders at the sites. At the secondary sites, only the field-based measurements (temperature, specific conductivity, DO, turbidity, pH, and water clarity) were collected.

Samples for nutrient analysis were collected in 500 ml acid-washed polyethylene bottles containing mercuric chloride preservative, whereas samples for suspended solids and bacteria were collected in 2 litre polyethylene bottles and 110 ml sterile vials, respectively. Samples for *Campylobacter* analysis were collected using 1 litre sterile polypropylene bottles. Samples were kept on ice during transport to the laboratory.

Water samples for *E. coli* and *Campylobacter* analyses were processed within 24 h of collection using standard culture methods (APHA 1998 9222D) and the standard multiple tube MPN method (Donnison 1998), respectively. Sub-samples for dissolved nutrient analysis were filtered (0.45 µm membrane) within 48 h of sample collection and refrigerated (4°C) before analysis. Concentrations of NO_3-N, NH_4-N, and DRP were determined using cadmium reduction (APHA 1998; 4500-NO_3 I), phenol hypochlorite (APHA 1998; 4500-NH_3 H), and ammonium molybdate-ascorbic acid (APHA 1998 4500-P G) flow injection methods, respectively. TN and TP were determined, in the same way as NO_3-N and DRP, after persulphate oxidation (APHA 1998; 4500-N C and 4500-P A, B mod, G). TSS, FSS, and VSS were determined gravimetrically (APHA 1998 2540 D, E). Laboratory reporting limits for the chemical analyses were: NO_3-N 0.002 g m^{-3}; NH_4-N 0.005 g m^{-3}; TN 0.1 g m^{-3}; DRP 0.005 g m^{-3}; TP 0.005 g m^{-3}, TSS 0.3 g m^{-3}, FSS 0.3 g m^{-3}, VSS 0.3 g m^{-3}, and *E. coli* 5 cfu 100 ml^{-1}.

The sampling regime was designed to characterise patterns in water quality among sites, not to provide accurate information on yields of sediments or diffuse pollutants. We recognised that targeted sampling of floods would be required to calculate accurate yields since they are typically dominated by flood flows. Nevertheless, we wanted to know whether the length of record and frequency of sampling used in this study provided representative water quality values for each site. To help assess how representative our water quality data were, we used

Table 1 Position and characteristics of the sampling sites. Sites with mean discharge estimated using a relationship between spot gaugings and mean discharge at neighbouring sites are indicated using an asterisk.

Site	Site no.	Easting	Northing	Land-use group (%)	Geology group (%)	Catchment area (km^2)	Mean discharge ($m^3 s^{-1}$)	Altitude (m a.s.l.)
Waiwhero	1	2504155	6002085	Pasture (82)	Moutere Gravel (93)	8.9	0.06	45
Sherry-2	2	2487900	5980625	Pasture (30)	Sep. Point Granite (37)	79.0	1.95	150
Kikiwa	3	2497890	5950260	Pasture (100)	Moutere Gravel (97)	2.71	0.05	430
Motueka-1	4	2502705	5952765	Native (98)	Ultramafic (45)	163.3	7.07	375
Hunters	5	2498785	5947855	Native (97)	Moutere Gravel (100)	4.77	0.08	450
Wangapeka-1	6	2480520	5976475	Native (97)	Argillite/Greywacke (53)	243.7	5^*	220
Graham Creek	7	2496435	5953025	Plantation (84)	Moutere Gravel (100)	5.73	0.08	420
Sherry-1	8	2484985	5968790	Plantation (56)	Sep. Point Granite (48)	23.3	0.5^*	230
Little Sydney	9	2508685	6014545	Horticulture	Sep. Point Granite (84)	7.26	0.1^*	5
Riwaka	10	2509010	6015495	Horticulture	Marble (43)	92.9	4.2^*	5
Motupiko-1	11	2493920	5954230	Mixed	Moutere Gravel (49)	100.1	2.17	340
Motupiko-2	12	2494885	5972095	Mixed	Moutere Gravel (75)	327.6	5.15	195
Stanley	13	2494925	5987890	Mixed	Moutere Gravel (81)	81.0	1.19	110
Baton	14	2493535	5992280	Mixed	Argillite/Greywacke (67)	210.4	9.03	95
Pearse	15	2494310	5997205	Mixed	Marble (28)	50.5	3.46	70
Graham River	16	2496065	5999370	Mixed	Marble (28)	40.0	2.10	60
Wangapeka-2	17	2490280	5985160	Mixed	Mixed	468.4	23.4	130
Motueka-2	18	2496205	5972895	Mixed	Mixed	321.1	11.0	185
Motueka-3	19	2492810	5985805	Mixed	Mixed	834.6	12.0	120
Motueka-4	20	2493225	5991500	Mixed	Mixed	1427	35^*	90
Motueka-5	21	2495060	5994315	Mixed	Mixed	1748	58.6	75
Motueka-6	22	2496645	5999210	Mixed	Mixed	1856	68^*	55
Motueka-7	23	2506420	6009190	Mixed	Mixed	1997	82.2	10

data collected monthly since 1989 at Motueka-1 and Motueka-5 as part of the New Zealand National River Water Quality Network (Maasdam & Smith 1994). Mean and median values for each water quality parameter from the full record were compared with mean and median values calculated from a subset of the record that was equivalent to the frequency of sampling undertaken at the other sites.

Water temperature

Temperature loggers (Onset StowAway® TidbiT® or TruTrack TH-R) were deployed at each site and programmed to record water temperature every hour from at least March 2001 to February 2002. Before deployment, all loggers were run simultaneously for 3 days to check for consistency of readings. Differences between temperature loggers were <0.3°C, which corresponded with the manufacturer's accuracy specifications. Therefore, no correction factors were applied to data from the loggers. Each data logger was placed in an area of flowing water and housed in a protective metal casing, which was chained to a secure object (e.g., warratah, tree, bridge). Unfortunately, loggers from Sherry-2, Motueka-3, Baton, and Motupiko-2 were lost before any information could be downloaded. The logger at Hunters also disappeared after being downloaded several times, so we have an incomplete record for that site. During periods of extreme low flow, the loggers at Graham Creek and Little Sydney were exposed to the air. Data collected during these periods were identified by extreme daily changes in recorded temperature and were not included in the analysis. Similarly, the logger at Stanley was buried by gravel during a flood and subsequently exhibited much lower daily fluctuations in temperature than it recorded before burial. Data affected by this burial were not included in the analyses.

Factors affecting water quality and temperature

The percentage of land cover types in the subcatchments above each sampling site were determined from the New Zealand Land Cover database (Terralink International Limited, Wellington, New Zealand), which has a minimum mapping unit of 1 ha and was derived from SPOT satellite images taken in 1997. The geological composition of the subcatchments was determined similarly from the New Zealand Land Resource Inventory, which has a minimum mapping unit of 20 ha (Newsome 1995).

Distance from the headwaters was calculated by digitising the channel from the sampling site to the most distant point in the channel network upstream (as shown on 1:50 000 scale NZMS 260 series maps). Azimuth was measured as the clockwise angle (in degrees) that the valley differed from due north, where due north = 0°, due east = 90°, and due west = –90°. Following Hawkins et al. (1997), the absolute value of the azimuth was used in all analyses because streams with orientations of equal magnitude but different sign are expected to receive the same amount of solar radiation. The ratio of bank and/or riparian vegetation height to average wetted river width was used as an index of shading. Stream channel slope was estimated from contour lines on 1:50 000 (NZMS 260 series) maps.

Statistical analysis

Water quality

In instances where water quality data were below the reporting limit for a particular chemical analysis, we substituted a value of half the reporting limit for the calculation of statistics. The amount of censored data was <5% of the total for most variables, except for NH_4-N (10%), TN (10%), DRP (19%), FSS (31%), VSS (20%), and *E. coli* (13%). Before analysis, probability plots and histograms were inspected and most variables were $\log_e$-transformed to improve normality and homogeneity of variances, with the exception of specific conductivity (square-root transformed), pH and DO saturation (not transformed). The percentages of land cover and geology in each subcatchment were arcsine square-root transformed before being included in analyses. The normality of *Campylobacter* data was not improved by transformations, therefore subsequent analyses involving *Campylobacter* used non-parametric statistics (Spearman Rank correlation, Kruskal-Wallis test).

The strength of intercorrelations among the individual variables was quantified using Pearson correlation coefficients. Significance of the coefficients was assessed after Bonferroni correction. Comparisons of the effects of land cover were conducted using nested ANOVA with "land cover" and "site nested within land cover" as the terms within the model. Site was considered as a random factor; therefore, the *F* statistic for land cover was calculated using the mean square of the site nested within land cover term as the denominator (Quinn & Keough 2002). Comparisons of the effects of geology were also conducted using nested ANOVA in the same way as described above for land cover. Longitudinal patterns in site medians were determined using simple linear regression using distance from the headwaters as the independent variable. A significance level of $\alpha = 0.05$ was used for all tests. Statistical analysis was carried out using the STATISTICA software package.

An assessment of the likely factors influencing median site water quality was carried out using multiple regression analyses. To address the detrimental effects of collinearity, only single variables from any autocorrelated groups ($r > 0.70$) were selected for the multiple regression analyses (Quinn & Keough 2002). Because % native forest and % tussock were strongly correlated with % pasture and % ultramafic rock, respectively, they were not included in the analysis. Similarly, mean flow and mean width were strongly correlated with distance from the headwaters and were not included in the analysis. The factors included in the multiple regression were: % pasture, % horticulture, % plantation, % argillite, % Moutere Gravel, % Separation Point Granite, % marble, % mudstone, % ultramafic, distance from the headwaters, and slope. The best regression models were identified using Mallow's C_p, a statistic which compares specific regression models containing a subset of predictors with the full model containing all the predictors (Quinn & Keough 2002).

Water temperature

Data from a 2-month period in winter (1 June – 31 July) and a 2-month period in summer (15 December – 15 February) were extracted from the temperature records for further analysis. These periods cover the coolest and warmest parts of the year and thus were expected to cover the extremes in annual and diel temperature fluctuation. Information extracted from the 2-month temperature records at each site included average daily mean temperature, maximum temperature, minimum temperature, maximum diel temperature change, average diel temperature change, and maximum rate of heating and cooling. Following Arscott et al. (2001), average values (or maxima and minima) were calculated for the entire 2-month period giving one value for each thermal variable representing either winter or summer conditions. The effect of land use and geology on these thermal variables was assessed using one-way ANOVA ($\alpha = 0.05$). Longitudinal patterns in daily water temperature variation were explored using simple linear and polynomial regression models. Multiple regression was used to assess likely factors controlling the temperature regime throughout the catchment in the same way as described above for the water quality variables. However, shade ratio (canopy height:stream width) and azimuth were included as potential controlling factors, since they were expected to have a strong influence on stream lighting and thus thermal regimes.

RESULTS

Representativeness of the water quality record

A comparison of water quality statistics calculated from the full National River Water Quality Network record at Motueka-1 and Motueka-5 (monthly sampling since January 1989, 170 samples) and a subset of the record equivalent to that collected at the sites in this study (19 samples) is shown in Table 2. For some variables, such as DO, pH, and conductivity, the difference in mean and median values between the full and partial records were very small (<5%). Mean water clarity calculated from the partial record was within 1.1 m of the mean calculated from the full record. Mean concentrations of NH_4-N, DRP, and TP calculated from the partial record were within 0.004 g m^{-3} of the means calculated from the full record, whereas mean concentrations of NO_3-N and TN were within 0.024 g m^{-3} of the means calculated from the full record (Table 2). Mean turbidity varied by up to 2.3 NTU between the full and partial records. Concentrations of *E. coli*, TSS, FSS, and VSS are not measured in the National River Water Quality Network so no comparisons could be made for these variables.

Correlations among water quality variables

The correlations among water quality variables measured on all sampling occasions are shown in Table 3. There were strong correlations among turbidity, clarity, TSS, FSS, and VSS. *E. coli* and nutrient concentrations were also significantly correlated with these optical/sediment variables. Turbidity and water clarity were correlated with specific conductivity, which, in turn, was correlated with pH and DO % saturation (Table 3). *E. coli* concentrations were also weakly correlated with spot temperature recordings, whereas *Campylobacter* concentrations were correlated with water clarity and the concentrations of *E. coli*, NO_3-N, TN, and DRP.

On an individual site basis, flow was often strongly ($|r|>0.75$) negatively correlated with specific conductivity and water clarity, and positively correlated with turbidity. However, these strong correlations were not observed at all sites. There were also strong correlations between flow and

Table 2 Comparison of water quality statistics calculated from the full National River Water Quality Network record (170 samples) and partial record (19 samples) from Motueka-1 and Motueka-5 sites, New Zealand. The partial record is equivalent to the length and frequency of the sampling carried out in this study. Data supplied by NIWA. (DO, dissolved oxygen; TN, total nitrogen; DRP, dissolved reactive phosphorus; TP, total phosphorus.)

Site	Statistic	Flow ($m^3 s^{-1}$)	DO (% Sat.)	DO (mg $litre^{-1}$)	Clarity (m)	Turb. (NTU)	pH	Cond. (µS cm^{-1})	NH_4-N (g m^{-3})	NO_3-N (g m^{-3})	TN (g m^{-3})	DRP (g m^{-3})	TP (g m^{-3})
Motueka-1	Mean full record	7.9	100.3	11.3	8.4	2.5	8.0	96.6	0.004	0.025	0.062	0.003	0.006
	Mean partial record	8.9	100.4	11.2	9.5	1.6	8.0	98.3	0.003	0.023	0.069	0.003	0.006
	Mean % diff.	12.3	0.2	–1.0	13.1	–35.3	0.0	1.8	–25.8	–6.6	11.2	10.4	–10.4
	Median full record	4.1	100.4	11.4	8.7	0.5	8.0	98.3	0.003	0.022	0.054	0.003	0.004
	Median partial record	3.5	100.5	11.0	10.6	0.4	8.0	96.4	0.002	0.019	0.070	0.003	0.005
	Median % diff.	–14.6	0.1	–3.3	22.0	–19.1	–0.5	–1.9	–33.3	–14.0	30.2	6.6	15.6
Motueka-5	Mean full record	58.8	104.0	11.1	3.3	5.8	8.0	109.3	0.005	0.141	0.224	0.004	0.017
	Mean partial record	48.1	104.8	11.1	3.8	3.5	8.0	115.4	0.004	0.164	0.248	0.004	0.013
	Mean % diff.	–18.2	0.7	–0.3	12.6	–39.6	0.0	5.5	–22.1	16.6	10.9	0.4	–24.9
	Median full record	34.9	102.7	11.1	3.4	1.0	8.0	111.8	0.005	0.105	0.189	0.003	0.007
	Median partial record	28.6	104.5	11.1	3.9	0.8	8.0	116.2	0.004	0.115	0.216	0.003	0.006
	Median % diff.	–18.0	1.8	–0.4	16.8	–24.2	–0.4	4.0	–14.9	9.9	14.1	1.7	–20.2

Table 3 Correlations among the water quality variables. Pearson correlation coefficients are shown for all variables, except *Campylobacter*, which used Spearman Rank correlation. Correlations coefficients significant at $P < 0.001$ are shown in bold; correlation coefficients significant at $P < 0.05$ are italicised. (DO, dissolved oxygen; TSS, total suspended solids; FSS, fixed suspended solids; VSS, volatile suspended solids; TN, total nitrogen; DRP, dissolved reactive phosphorus; TP, total phosphorus.)

	n	Cond.	pH	DO%	Turb.	Clarity	*E. coli*	TSS	FSS	VSS	NH_4-N	NO_3-N	TN	DRP	TP	*Campy.*
Conductivity	291	1.00														
pH	291	**0.59**	1.00													
DO%	291	**0.25**	**0.44**	1.00												
Turbidity	291	**–0.27**	*–0.22*	–0.14	1.00											
Clarity	278	**0.26**	*0.23*	0.12	**–0.85**	1.00										
Escherichia coli	195	0.07	–0.12	0.06	**0.52**	**–0.59**	1.00									
TSS	195	0.04	–0.08	–0.14	**0.74**	**–0.74**	**0.51**	1.00								
FSS	195	0.05	–0.04	–0.20	**0.65**	**–0.63**	**0.41**	**0.87**	1.00							
VSS	195	0.01	–0.04	–0.01	**0.34**	**–0.42**	*0.28*	**0.52**	0.13	1.00						
NH_4-N	195	0.05	–0.02	–0.09	0.11	*–0.27*	*0.27*	0.23	0.18	0.20	1.00					
NO_3-N	195	0.20	–0.07	–0.06	*0.31*	*–0.31*	0.16	**0.34**	*0.28*	0.21	–0.00	1.00				
TN	195	0.09	–0.15	–0.12	**0.45**	**–0.49**	**0.33**	**0.47**	**0.36**	**0.36**	0.22	**0.75**	1.00			
DRP	195	–0.21	*–0.27*	**–0.34**	**0.45**	**–0.54**	**0.34**	**0.43**	**0.42**	*0.26*	**0.44**	0.22	**0.36**	1.00		
TP	195	–0.10	–0.17	*–0.30*	**0.48**	**–0.57**	**0.46**	**0.53**	**0.47**	*0.32*	**0.50**	0.10	**0.38**	**0.71**	1.00	
Campylobacter	95	–0.08	–0.17	–0.31	0.32	**–0.40**	**0.54**	0.28	0.22	0.24	0.09	**0.41**	**0.45**	**0.35**	0.31	1.00

nitrate concentrations at Little Sydney and Riwaka and between flow and TN concentration at Waiwhero. Flow and TSS concentration were strongly correlated only at Motueka-5.

Land-use effects

Water quality

The concentrations of TSS ($F_{3,6} = 5.2$, $P = 0.040$), NO_3-N ($F_{3,6} = 27.8$, $P = 0.001$), TN ($F_{3,6} = 18.0$, $P = 0.002$), *E. coli* ($F_{3,6} = 7.7$, $P = 0.020$), and *Campylobacter* ($F_{3,6} = 14.0$, $P = 0.004$) were significantly different among land-use groups with higher concentrations at the horticultural and pastoral sites than at the native forest sites (Fig. 2). Plantation forest sites were either statistically similar to all the other sites (TSS, *E. coli*), or had significantly lower concentrations than the horticultural and pastoral sites (NO_3-N, TN, *Campylobacter*). Although there were significant differences among sites in many of the other water quality variables, the effects of land cover across sites were not significant ($P > 0.05$) for these variables (e.g., conductivity, turbidity, DRP, TP; Fig. 2).

Temperature

Average daily mean temperatures in summer were significantly higher at the pastoral sites than at the native forest sites (Fig. 3, $F = 6.0$, $P = 0.041$). In contrast, thermal variables related to diel changes in temperature (i.e., maximum and average amplitude and maximum rates of warming and cooling) showed no significant differences ($P > 0.05$) across land cover types.

Effects of geology

Water quality

Geology had a clear influence on some water quality variables (Fig. 4). Sites with a predominance of marble in their catchments had significantly higher conductivity than sites dominated by Moutere Gravel or Separation Point Granite ($F_{4,12} = 14.4$, $P < 0.001$). Conductivity at sites dominated by basement rocks such as argillite and greywacke was also significantly higher than at sites dominated by Moutere Gravels. Similarly, sites dominated by marble or argillite/greywacke had a significantly higher pH than sites dominated by Moutere Gravel or Separation Point Granite ($F_{4,12} = 18.1$, $P < 0.001$). In addition, sites dominated by Separation Point Granite had significantly higher turbidity ($F_{4,12} = 4.2$, $P = 0.024$) and lower clarity ($F_{4,12} = 3.5$, $P = 0.040$) than sites dominated by argillite/greywacke or ultramafic rocks.

Temperature

Geology also had an influence on the thermal regime of the sites (Fig. 5). Minimum winter temperatures were significantly warmer at sites dominated by marble than at sites with Separation Point Granite ($F = 5.3$, $P = 0.018$). Average daily mean winter temperatures also tended to be warmest at sites dominated by marble ($F = 3.4$, $P = 0.058$), although this difference was not quite significant at the $\alpha = 5\%$ level.

Longitudinal patterns

Water quality

Along the mainstem of the Motueka River and including the two major tributaries (Wangapeka and Motupiko) there were significant longitudinal patterns in several water quality variables (Fig. 6). Median site turbidity ($r^2 = 0.60$, $F = 11.98$, $P = 0.009$) and the median site concentrations of TSS ($r^2 = 0.60$, $F = 7.4$, $P = 0.042$), FSS ($r^2 = 0.61$, $F = 7.9$, $P = 0.038$), NO_3-N ($r^2 = 0.58$, $F = 6.8$, $P = 0.048$), TN ($r^2 = 0.58$, $F = 6.9$, $P = 0.047$) and DRP ($r^2 = 0.57$, $F = 6.6$, $P = 0.050$) increased downstream, whereas median site water clarity decreased downstream ($r^2 = 0.68$, $F = 16.8$, $P = 0.003$).

Temperature

Some aspects of the thermal regime also varied longitudinally (Fig. 7). Average daily mean winter temperature increased downstream ($r^2 = 0.64$, $F = 10.8$, $P = 0.017$), as did the winter maximum ($r^2 = 0.44$, $F = 4.6$, $P = 0.075$) and winter minimum ($r^2 = 0.41$, $F = 4.2$, $P = 0.085$) temperatures. There were also summer trends for warmer average daily mean temperatures ($r^2 = 0.45$, $F = 4.8$, $P = 0.070$) and higher minimum temperatures ($r^2 = 0.42$, $F = 4.4$, $P = 0.081$) downstream. Thermal variables related to diel temperature variability showed no significant linear longitudinal patterns. The average daily amplitude in temperature peaked in the middle reaches of the river during summer and winter (Fig. 7), as predicted by Vannote & Sweeney (1980). However, quadratic regression of distance from the headwaters versus average amplitude were not significant (winter, $r^2 = 0.12$, $P = 0.730$; summer, $r^2 = 0.22$, $P = 0.540$, Fig. 7). The sharp decline in average amplitude of daily temperature change between 85 and 90 km downstream from the headwaters during summer may also be related to inputs from two cool tributaries draining marble geology (Graham River and Pearse River), which join the Motueka in that section (Fig. 7).

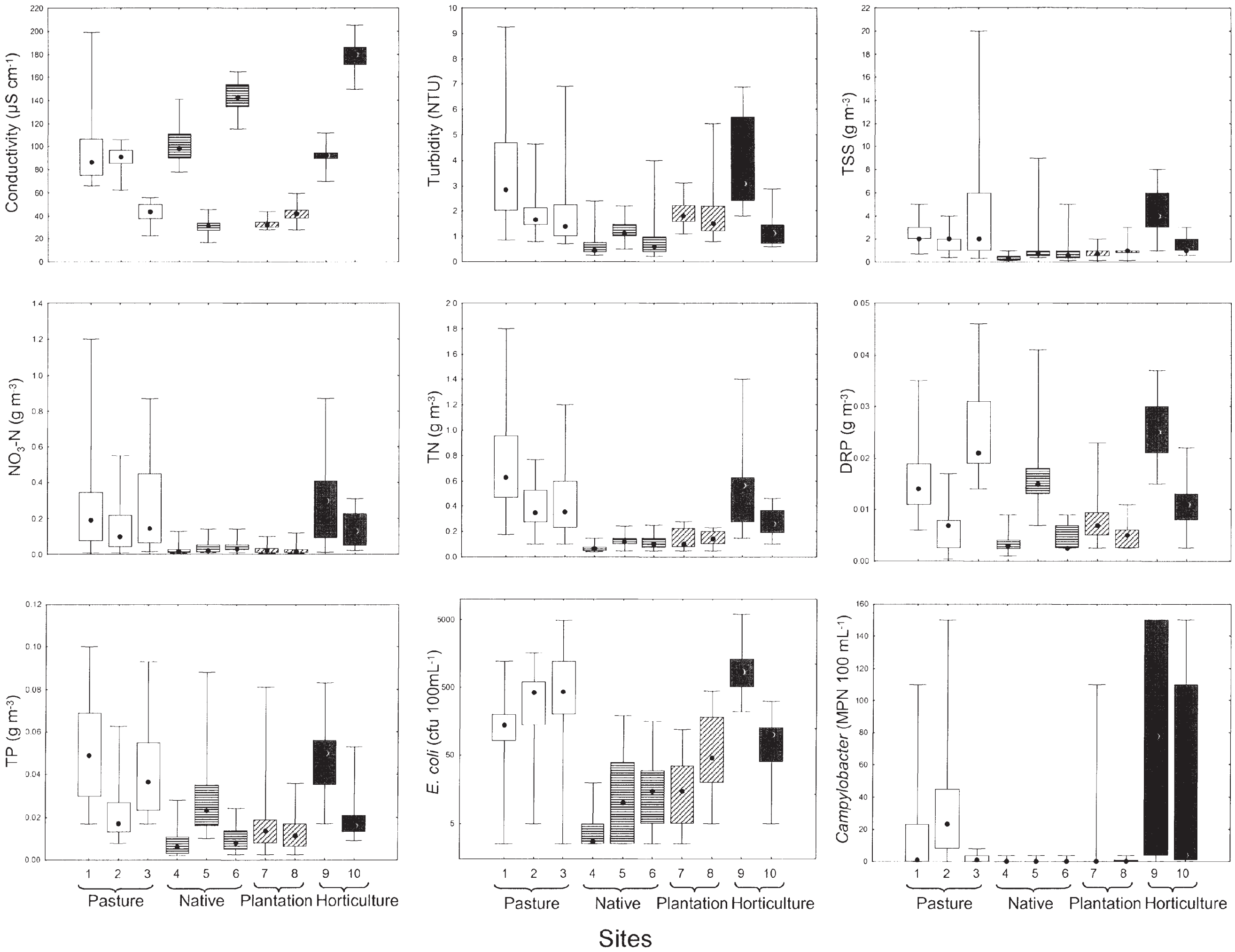

Fig. 2 Comparison of water quality variables among groups of sites with contrasting land use. (TP, total phosphorus; TN, total nitrogen; TSS, total suspended solids; DRP, dissolved reactive phosphorus). Site numbers are shown along the *x* axis and correspond with those presented in Table 1. (Median values, dots; boxes, upper (75th) and lower (25th) quartiles; whiskers, 5th and 95th percentiles.)

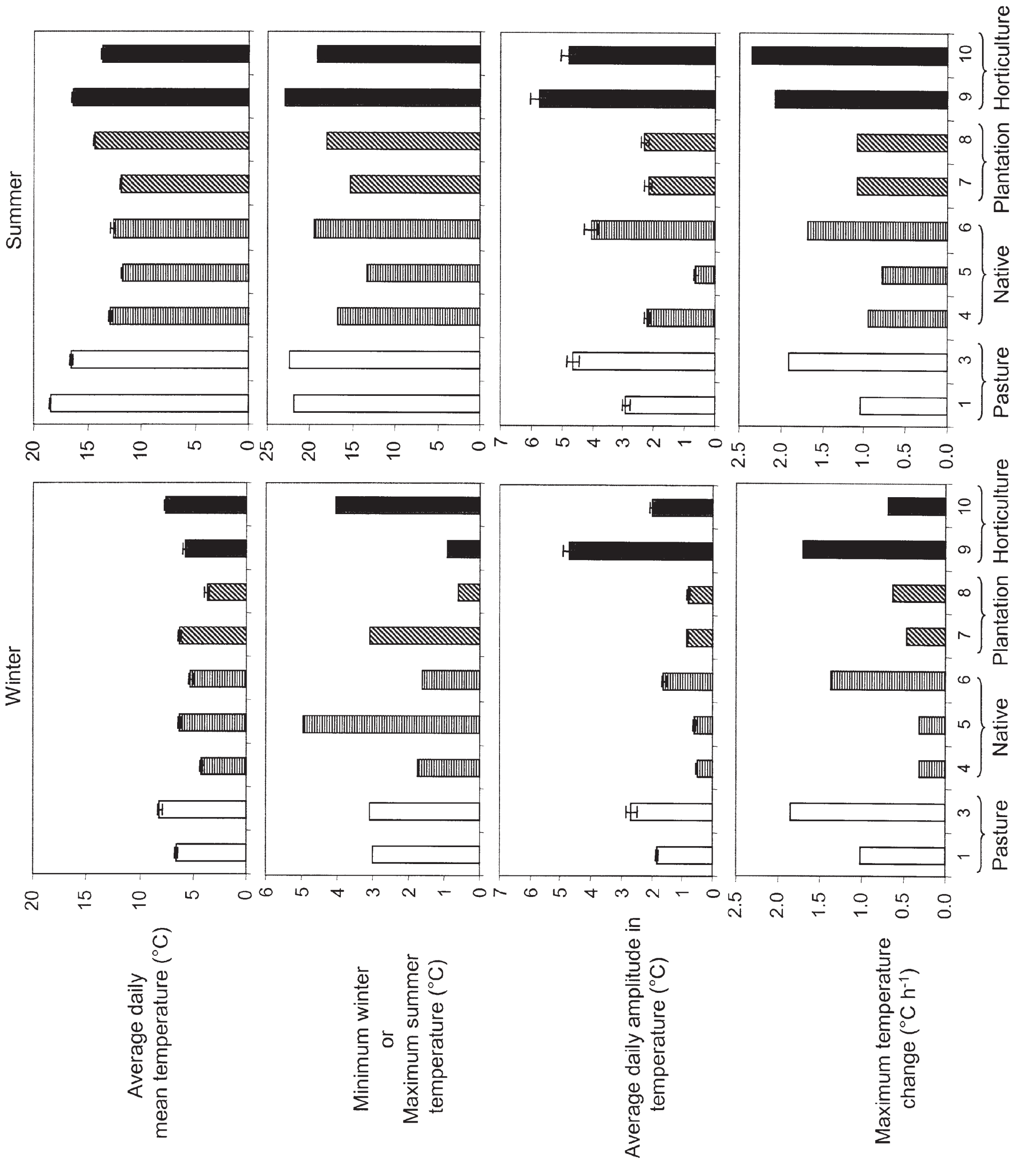

Fig. 3 Comparison of thermal parameters among groups of sites with contrasting land use. Site numbers are shown along the *x* axis and correspond with those presented in Table 1. Standard errors (±1SE) are shown where appropriate.

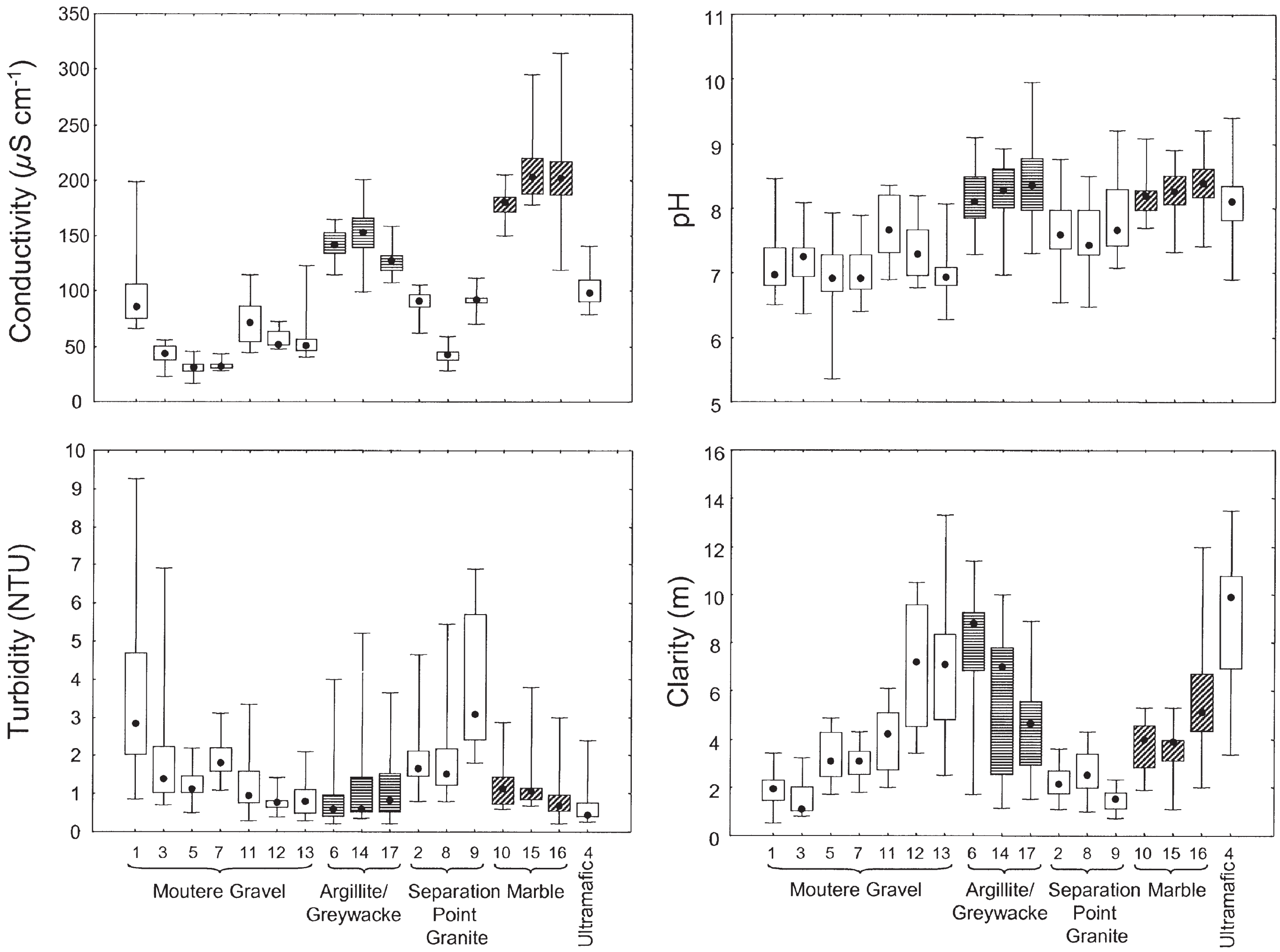

Fig. 4 Comparison of water quality variables among groups of sites with contrasting geology. Site numbers are shown along the *x* axis and correspond with those presented in Table 1. (Median values, dots; boxes, upper (75th) and lower (25th) quartiles; whiskers, 5th and 95th percentiles.)

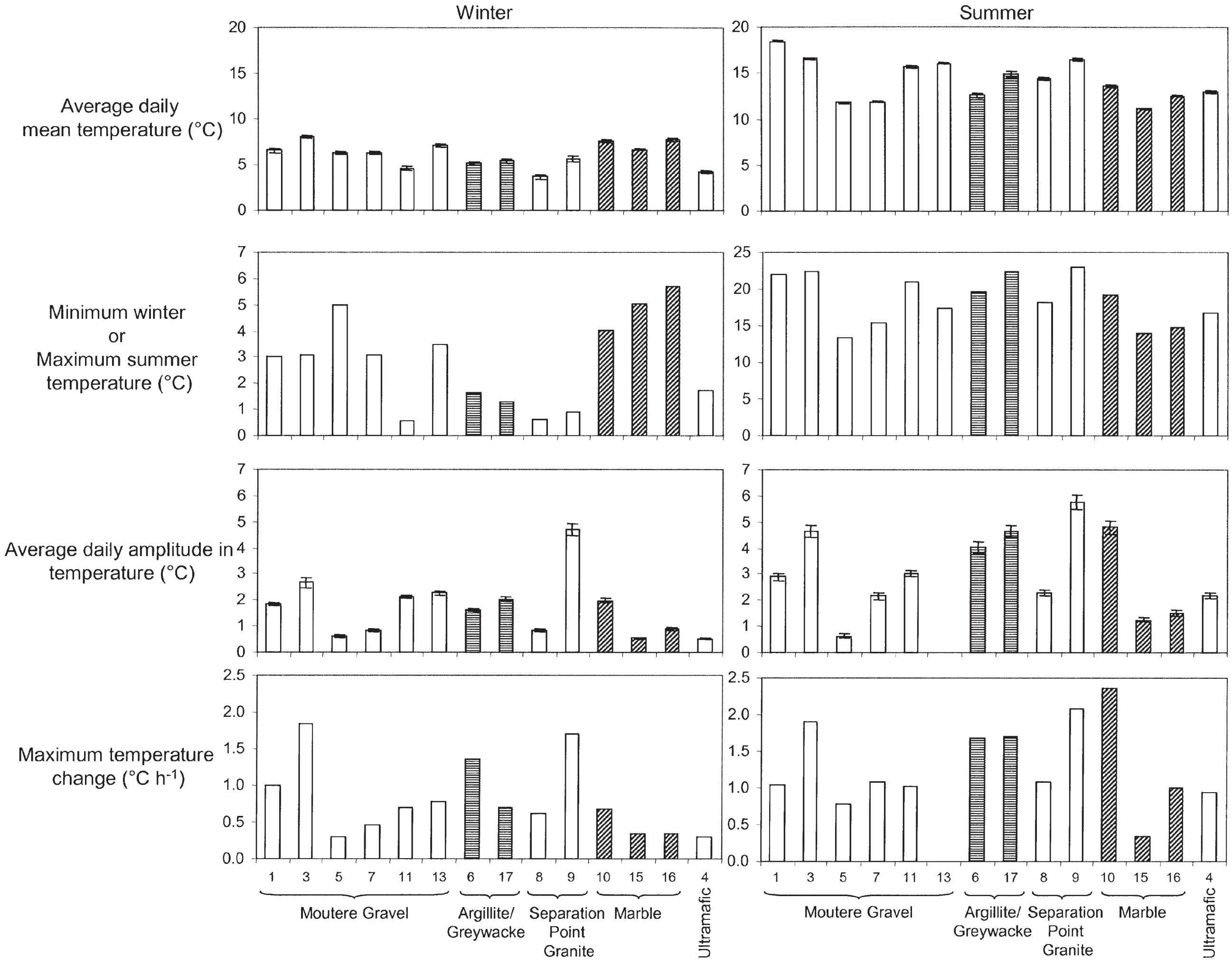

Fig. 5 Comparison of thermal parameters in winter and summer at sites grouped according to differences in geology. Site numbers are shown along the *x* axis and correspond with those presented in Table 1. Standard errors (±1SE) are shown where appropriate.

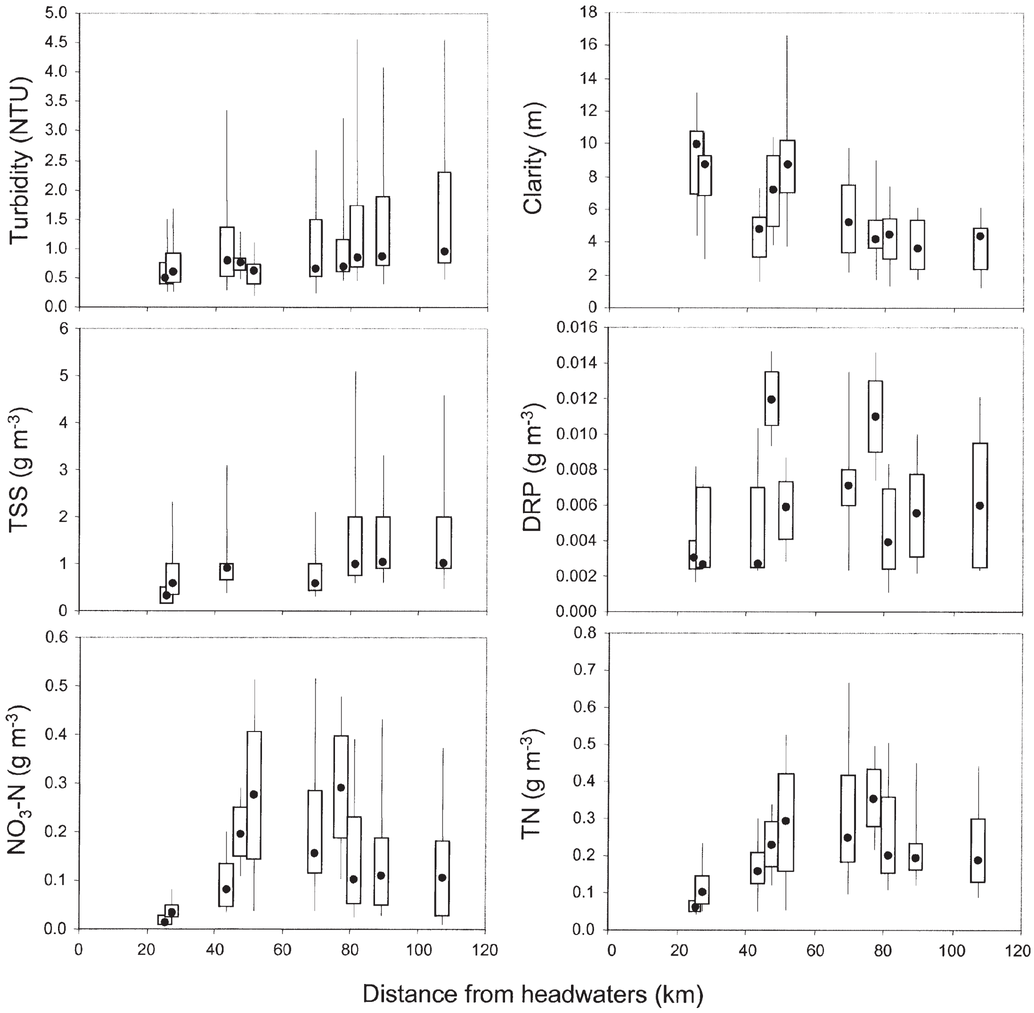

Fig. 6 Longitudinal patterns in water quality variables at sites distributed along the mainstem and major tributaries of the Motueka River, New Zealand. (TSS, total suspended solids; DRP, dissolved reactive phosphorus; TN, total nitrogen). (Median values, dots; boxes, upper (75th) and lower (25th) quartiles; whiskers, 5th and 95th percentiles.)

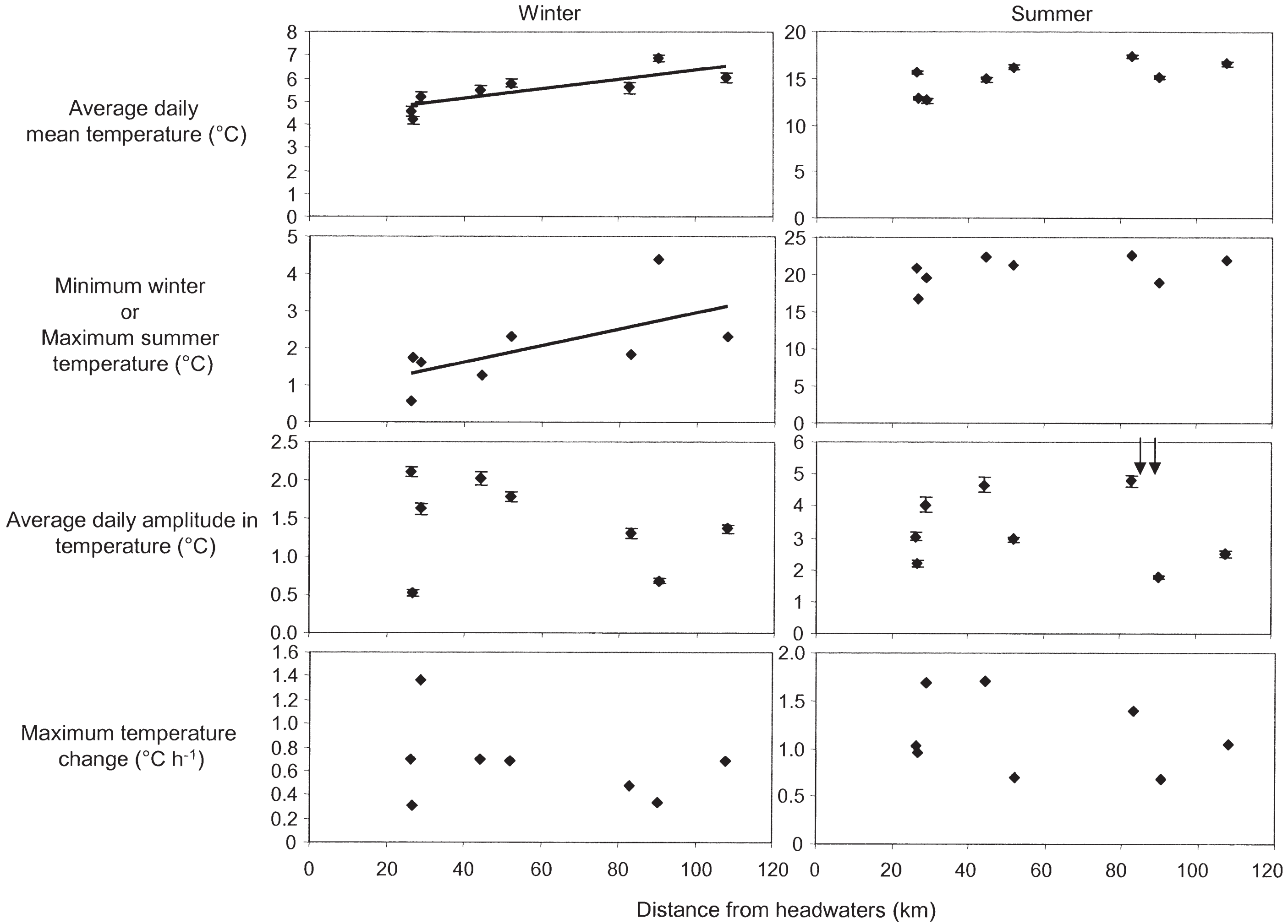

Fig. 7 Comparison of thermal parameters in winter and summer at sites distributed along the mainstem and major tributaries of the Motueka River, New Zealand. Standard errors (±1SE) are shown where appropriate. The positions where two cool karst tributaries discharge into the Motueka River are shown with arrows.

Factors controlling water quality

Multiple regression analyses produced significant regression models for all the water quality variables (Table 4). The percentage of pasture in the catchment upstream was included as an independent variable in almost all of the water quality regression models (Table 4). The only exceptions to this were for pH, which was primarily associated with geological factors (argillite, Separation Point Granite, marble, ultramafic), and *Campylobacter* concentration, which was positively related to the percentage of horticulture in the catchment upstream. The percentage of horticulture in the catchment was also related to turbidity, clarity, FSS, and the concentrations of NO_3-N, TN, DRP, and TP (Table 4). In contrast, the percentage of plantation forest in the catchment was only significantly related to turbidity.

The percentage of argillite, marble, and ultramafic rock in the catchment upstream were included in models and positively related to conductivity and pH (Table 4). The percentage of mudstone was included only in models explaining variation in turbidity and clarity. The inclusion of the percentage of ultramafic rock in models explaining clarity, VSS, NH_4-N, *E. coli*, and *Campylobacter* concentration was probably owing to the high clarity and low concentrations of the aforementioned variables at the Motueka-1 site, which has a relatively high percentage of ultramafic rock, rather than a direct effect of ultramafic rock itself.

Distance from the headwaters was included as an independent variable in models related to turbidity, clarity, NO_3-N, and TP. However, the relationships were negative for turbidity and TP, and positive for clarity, which were the opposite of what we would have predicted given the increased level of catchment modification in the lower parts of the catchment. Slope was included in models explaining variation in clarity, VSS, pH, and TN (Table 4).

Factors controlling the thermal regime

Multiple regression produced significant models for average daily mean, maximum and minimum temperatures in both winter and summer (Table 5). Significant models were also produced for average amplitude of daily temperature change, maximum amplitude, warming rates and cooling rates in winter. However, no significant relationships between potential controlling variables and these temperature change parameters were found in summer (Table 5).

The percentage of pasture in the catchment upstream was often included in models explaining variation in thermal parameters. Sites with relatively high amounts of pasture tended to have higher mean temperatures in summer, higher maximum temperatures in winter and summer, higher minimum temperatures in summer, and larger and faster daily changes in temperature in winter (Table 5). The percentage of horticulture in the catchment upstream was included in the same models as the percentage of pasture, except for mean and minimum summer temperatures. However, the partial regression slopes in models for maximum amplitude and maximum rate of warming were not significant at $P < 0.05$.

The percentage of Moutere Gravel, Separation Point Granite, and marble in the subcatchment upstream were often included together in the models. These three geological types appear to have a buffering effect on water temperature, resulting in warmer average and minimum temperatures in winter, and smaller and slower daily changes in temperature in winter (Table 5). Sites with substantial amounts of marble also tended to have lower average daily mean temperatures in summer. Mudstone appeared to have the opposite effect with a negative relationship with daily mean and minimum temperature in winter and a positive relationship with maximum temperature in summer, perhaps reflecting the lack of interaction with groundwater in this geology. The negative relationship between the percentage of ultramafic rock in the catchment upstream and the size and rate of daily temperature changes was probably owing to the characteristics of the Motueka-1 site, which has a relatively high percentage of ultramafic rock, rather than a direct effect of ultramafic rock itself.

Distance from the headwaters was positively related to mean, maximum, and minimum temperature in summer and average daily amplitude in winter. The shade ratio (canopy height:stream width) was negatively related to average daily mean temperature in winter and maximum warming and cooling rates in winter (Table 5). However, it was also positively related to average daily mean temperature in summer. Azimuth was often included in models, and was negatively related to average daily mean temperature and minimum temperature in summer and the size and speed of daily temperature fluctuations in winter (Table 5). This was expected given the likely reduction in solar radiation reaching the water surface in channels rotating away from a north/south orientation towards an east/west alignment.

Table 4 Summary of results from the multiple regression analysis for the water quality variables. Standardised partial regression slopes (β-coefficients) for each factor included in the best models are shown and give an indication of the importance of each factor in the models (Quinn & Keough 2002). Partial regression slopes that were not significantly different ($P > 0.05$) from zero are marked with an asterisk. (Hort, horticulture; Plant, plantation.)

Water quality variable	F	P	R^2_{adj}	Pasture	Hort.	Plant.	Argillite	Moutere Gravel	Separation Point Granite	Marble	Mud-stone	Ultramafic	Distance from head-waters	Slope
Turbidity	18.2	<0.001	0.796	0.35	0.45	0.39					0.29		–0.61	
Clarity	31.0	<0.001	0.906	–0.49	–0.19*			–0.77	–0.64	–0.26	–0.36	–0.34	0.51	
TSS	32.9	<0.001	0.895	0.62				0.24*	0.77				–0.19*	
FSS	15.0	<0.001	0.737	0.44	0.59							–0.27*		
VSS	26.0	<0.001	0.870	0.46			–0.29					–0.60		–0.27
Conductivity	48.3	<0.001	0.928	0.22			0.25	–0.29		0.62		0.22		–0.15
pH	50.6	<0.001	0.931			–0.11*	0.33		0.28	0.47		0.45		–0.20
NO_3	29.2	<0.001	0.849	0.79	0.48								0.46	
TN	24.0	<0.001	0.821	0.74	0.32									–0.30
NH_4	18.8	<0.001	0.703	0.44								–0.62		
DRP	22.4	<0.001	0.851	0.33	0.59		–0.28	0.50						
TP	22.7	<0.001	0.813	0.49	0.33								–0.51	
Escherichia coli	30.5	<0.001	0.887	0.64			–0.19*		0.48			–0.27		
Campylobacter	45.2	<0.001	0.922		0.77			–0.34		–0.47		–0.25		

Table 5 Summary of results from the multiple regression analysis for the thermal parameters. Standardised partial regression slopes (β-coefficients) for each factor included in the best models are shown and give an indication of the importance of each factor in the models (Quinn & Keough 2002). Partial regression slopes that were not significantly different ($P > 0.05$) from zero are marked with an asterisk. (Hort, horticulture; Plant, plantation.)

Thermal parameter	Season	F	P	$R^2_{\text{adj.}}$	Pasture	Hort.	Plant.	Argillite	Moutere Gravel	Separation Point Granite	Marble	Mud-stone	Ultra-mafic	Distance from head-waters	Slope	Shade ratio	Azimuth
Average daily mean	Winter	17.4	<0.001	0.828					1.02	0.30*	0.93	–0.56				–0.40	
	Summer	49.1	<0.001	0.934	0.82						–0.21			0.76		0.19	–0.43
Maximum	Winter	16.7	<0.001	0.787	0.76	0.49	0.27				0.29						
	Summer	12.5	<0.001	0.772	0.72	0.61				–0.41		0.49		0.53			
Minimum	Winter	8.5	0.002	0.569					0.62		0.82	–0.41					
	Summer	16.0	<0.001	0.779	0.82		0.37							0.38			–0.30
Maximum amplitude	Winter	8.9	0.001	0.776	0.52	0.34*			–1.20	–0.90	–0.44*		–0.78				–0.37*
	Summer		NS														
Average amplitude	Winter	8.2	0.002	0.748	0.47	0.61			–0.65	–1.01			–0.77	0.44			–0.50
	Summer		NS														
Maximum warming	Winter	11.6	<0.001	0.833	0.38	0.23*			–1.04	–1.00	–0.41*		–0.95			–0.37	–0.36
	Summer		NS														
Maximum cooling	Winter	20.4	<0.001	0.888	0.56				–0.99	–0.77			–0.70		–0.21*	–0.28	–0.52
	Summer		NS														

DISCUSSION

Land-use effects

Water quality

The water quality of native forest streams examined in this study was high compared with pastoral streams. This finding is generally consistent with that reported in other studies of the effects of land use at local (Cooper et al. 1987; Dons 1987; Hall et al. 2001; Quinn & Stroud 2002), catchment-wide (Townsend et al. 1997; Harding et al. 1999), and national scales (Close & Davies-Colley 1990; Maasdam & Smith 1994; Larned et al. 2004). The effects on water quality of vegetation clearance and stock presence in and around stream channels appear to be very strong and regularly result in increased concentrations of land-derived contaminants such as sediment, nutrients, and faecal indicator bacteria in waterways. The elevated concentrations of nitrogen and phosphorus in the pastoral streams have the potential to increase the growth of nuisance periphyton (Biggs 2000), whereas concentrations of *E. coli* in the pastoral streams were often above guidelines for contact recreation (MfE 2002).

Water quality in the plantation forest streams was generally equivalent to that in native forest streams and often significantly better than at the horticultural or pastoral sites. In general, the percentage of plantation forest in the catchment upstream was a poor predictor of water quality and was only included in the regression model explaining variation in turbidity among sites. Other studies of water quality in streams draining mature plantation forest have also indicated relatively good water quality (Cooper et al. 1987; Dons 1987; Townsend et al. 1997; Larned et al. 2004), although high turbidity and suspended solids concentrations have been reported from streams where pine forest has replaced pasture and subsequently shaded out grasses along the stream banks, remobilising stored sediment held by the grasses (Davies-Colley 1997; Quinn et al. 1997; Quinn & Stroud 2002). Major problems with water quality in plantation forest streams usually only become evident after logging where increased light and increased run-off of sediment and nutrients may occur (Graynoth 1979; Harding et al. 2000), and/or associated with erosion from unsealed roads (Fahey & Coker 1989; Coker et al. 1993).

In contrast to the other land uses studied, the effects of horticulture on water quality of adjacent streams has received little attention in the past. The majority of previous studies have focused on inputs of pesticides associated with spraying of crops (Liess & Schulz 1999) or groundwater contamination (Close & Rosen 2001). The water quality of horticultural streams in this study was generally similar to that of pastoral streams with elevated levels of suspended sediment, nutrients, and surprisingly, faecal bacteria. Concentrations of the pathogen *Campylobacter*, in particular, were very high in both horticultural streams studied, whereas concentrations of *E. coli* often exceeded guidelines for contact recreation (MfE 2002). We were initially puzzled by the high levels of bacterial contamination, considering that stock are not common in these catchments. Further investigations by the Tasman District Council have indicated that several leaky septic tanks upstream were probably responsible for these high bacterial levels. It is possible that this problem (and result) is specific to the streams examined in this study. However, horticultural regions in New Zealand, and presumably elsewhere, are generally characterised by a relatively high density of permanent inhabitants with a large influx of seasonal staff often living in low-quality accommodation on the property, or nearby. Septic tanks and other arrangements for sewage treatment and disposal may become overloaded during these periods of peak usage leading to bacterial contamination of surrounding waterways.

Water temperature

The lack of tall vegetation above and surrounding the pastoral streams, and associated lack of shade, was presumably responsible for the differences in daily mean temperature among sites with contrasting land use (Rutherford et al. 1997). However, more detailed measures of the thermal regime such as the daily amplitude of temperature change and rate of temperature change did not differ significantly among land-use groups. Differences among sites in other factors such as geology, altitude, stream width, distance from the headwaters, and azimuth appear to mask any differences among land-use groups. Nevertheless, when these other variables were taken into account, the percentage of pasture and horticulture in the catchment upstream were included in regression models explaining variation in maximum winter and summer temperatures and the amplitude and rate of temperature change in winter.

Maximum temperatures in summer in some unshaded streams reached levels that were likely to exclude sensitive macroinvertebrate species, such as some stoneflies (Quinn & Hickey 1990; Quinn et al. 1994; Cox & Rutherford 2000) and were beyond the temperatures considered appropriate for some fish species (e.g., brown trout *Salmo trutta*, Elliott 1994). The importance of tall riparian vegetation for reducing mean and maximum water temperatures has been demonstrated in earlier studies of sites with contrasting land use and riparian vegetation (Quinn et al. 1997; Rutherford et al. 1997) and of changes resulting from forest harvest (Holtby 1988; Johnson & Jones 2000).

Given that shading is a key factor controlling the thermal regime of streams (Rutherford et al. 1997), we expected that it would be irrelevant whether the shading was from native vegetation or introduced plantation forest. Plantation forest streams appeared to be thermally equivalent to native forest streams and the percentage of plantation forest in the catchment upstream was rarely included in regression models for thermal parameters. Quinn et al. (1997) also found that maximum and mean temperature in small plantation forest streams was equivalent to that in neighbouring native forest streams.

Effects of geology

Geology only influenced a minority of water quality variables such as conductivity, pH, turbidity, and water clarity. The high solubility of marble was the primary difference among geologies, and presumably related to carbonates dissolving into solution and increasing conductivity and pH. The cohesive strength of rocks also appeared to explain the higher turbidity and lower clarity at sites draining Separation Point Granite, which is deeply weathered and has a high natural sediment yield (Basher 2003). Some previous studies in New Zealand have shown broad-scale relationships between geology, conductivity, and nutrient enrichment in streams (Close & Davies-Colley 1990; Biggs 1995). In a previous study of some sites within the Motueka Catchment, Biggs & Gerbeaux (1993) postulated that increased concentrations of dissolved nitrogen (N), periphyton cellular N, and periphyton biomass in the lower reaches of the river were the result of nutrient inputs from tributaries draining marble geology. Marble is not a significant source of N, however, Biggs & Gerbeaux (1993) speculated that alkaline conditions within soils developed on marble, may lead to increased N turnover rates and consequently elevated concentrations of N. However, in the present study we found no significant difference in dissolved nutrient concentrations among geologies, despite the large difference in conductivity. It is possible that the differences in nutrient concentrations resulting from different land uses were much bigger and tended to mask any effect of geology.

Differences in thermal buffering among geologies were also observed, with warmer mean and minimum temperatures during winter, and cooler mean temperatures in summer, in sites draining marble geology. Significant caves and resurgences are common in karst topographies, and therefore water within streams draining marble is strongly connected to deep groundwater and thus isolated from temperature variations on the land surface. We were surprised that the daily amplitude of temperature change and maximum rate of temperature change in streams draining marble catchments were not significantly lower than in streams draining the other geologies. However, there was a large variation in thermal regime among the three streams draining marble. Two of these sites (Graham River and Pearse) had small daily amplitudes of daily temperature change and slow rates of temperature change, as expected, whereas the other marble site (Riwaka) had a relatively high daily amplitude of temperature change and the fastest observed maximum temperature change in summer (Fig. 5). The site on the Riwaka River is further from the spring source than the sites on the Graham and Pearse rivers and is surrounded by horticultural land use. Therefore, there was time and opportunity for solar radiation to increase temperature fluctuations at this site.

Multiple regression analyses also provided evidence that the Moutere Gravel and Separation Point Granite geologies act to buffer winter temperatures, with positive relationships between these factors and average daily mean temperature, and the size and rate of daily temperature change in winter. Both of these geologies have the potential for thermal buffering, as unconsolidated gravels underlying the terraces and floodplains within the Moutere Gravel terrain are highly permeable and contain large quantities of groundwater, whereas Separation Point Granite is deeply fractured allowing infiltration and storage of water (Basher 2003). Johnson (2004) has also demonstrated the importance of substrate type and associated changes in the degree of hyporheic exchange on thermal regimes.

Longitudinal patterns down the river continuum

The river continuum concept (Vannote et al. 1980) emphasises the importance of longitudinal linkages within river systems and has strongly influenced river ecologists' thinking. However, the strength of longitudinal trends may be masked by other factors. When only sites on the mainstem and major tributaries were considered, our results show that longitudinal patterns were evident in some water quality variables. For example, we found increases in turbidity, suspended sediment, and nutrient concentrations in a downstream direction (Fig. 6), as was also shown in earlier studies of sites along the mainstem of the Motueka River (Davies-Colley 1990; Biggs & Gerbeaux 1993). In contrast, the multiple regression analyses included all sites and showed a negative relationship between distance from the headwaters and turbidity, suspended sediment and TP, and a positive relationship with water clarity which was the opposite of what we had expected. The discrepancy between these two sets of analyses was presumably related to the fact that some sites, relatively close to their headwaters, are highly developed for pasture and horticulture and have high concentrations of sediment and nutrients. However, the effects of these "hot spots" of contamination are generally diluted downstream after mixing with water from undeveloped parts of the catchment. Maasdam & Smith (1994) included distance from the headwaters in their analyses of New Zealand's National River Water Quality Network and found that it differed significantly between their river clusters. However, distance from the headwaters was presumably strongly intercorrelated with other factors like the percentage of the catchment in developed pasture, which were strong predictors of water quality. Therefore it is difficult to determine if distance from the headwaters was an important factor in its own right.

Water temperatures generally warmed downstream during both winter and summer, presumably owing to the effect of altitude on water temperature. Vannote & Sweeney (1980) predicted that the amplitude of daily temperature variation should peak in 4th–5th order rivers where the downstream increase in exposure to solar radiation, as the channel widens, begins to be offset by the thermal "inertia" associated with increasing water depth. The longitudinal pattern in daily amplitude of temperature change that we observed in summer supported this prediction (Fig. 7), although it was not clear if the decline in daily amplitude in the downstream reaches was a result of increased thermal inertia or of contributions from two cool tributaries (Graham River, Pearse River) draining marble geology. Tributaries with contrasting temperature regimes have been shown to cause significant shifts in downstream temperature patterns elsewhere (Torgersen et al. 1999; Arscott et al. 2001; Gardner et al. 2003). There have been few published tests of the predictions of Vannote & Sweeney (1980) regarding longitudinal patterns in daily amplitude of temperature change along natural, unimpounded river systems. In the only study that we are aware of, Arscott et al. (2001) found that the daily amplitude of temperature change in main channel sections of a braided floodplain river in northeastern Italy peaked in 2nd order headwater streams, rather than 4th–5th order reaches. They concluded that interactions with subsurface waters in downstream reaches of their study catchment strongly buffered daily temperature changes (Arscott et al. 2001).

Factors affecting daily water temperature variation

Significant regression models explaining daily variation in water temperature in winter were obtained using the multiple regression analyses. However, daily temperature variations in summer were not able to be predicted using the suite of potential environmental variables that we chose, for reasons that are obscure. Arscott et al. (2001) obtained significant regression models for maximum amplitude of daily temperature change, and maximum rate of warming in both winter and summer, but only maximum rate of cooling in summer. Azimuth, slope, and an index of shading were included in all of the significant models reported by Arscott et al. (2001), but did not appear to be significant descriptors of the daily changes in water temperature in this study. Maximum depth, conductivity, current velocity, and elevation were also included in some of the models reported by Arscott et al. (2001). However, inclusion of these variables in additional regression analyses did not result in any significant models. Perhaps other variables reflecting the amount of potential groundwater interaction, substrate type or other forms of heat exchange would have enabled significant models to be developed (Johnson 2004).

Relative importance of land use, geology, and longitudinal position

Some studies have indicated that land use is the predominant variable controlling water quality (Maasdam & Smith 1994; Leland & Porter 2000), whereas other studies indicate that geology is more important than land use (Biggs 1990; Close & Davies-Colley 1990). In this study, differences in land use appeared to have the strongest influence on most water quality and thermal parameters examined. This was demonstrated by the inclusion of the percentage of pasture in the catchment upstream in almost all of the significant regression models identified during the regression analyses. However, geology also appeared to be an important factor, and probably more important than land use for explaining variation in pH and conductivity among sites. In contrast, longitudinal patterns in water quality and temperature were relatively weak and in many instances were linked with longitudinal patterns in land use and geology rather than location in the river network as such. Our results emphasise the importance of land use and geology for controlling water quality and thermal patterns in rivers. Decisions on catchment management need to recognise the dual importance of these factors and consider how the effects of land-use change may differ between contrasting geologies.

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