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EFFECTS OF CLIMATE VARIABILITY ON RIVERS: CONSEQUENCES FOR LONG TERM WATER QUALITY ANALYSIS[1]

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ABSTRACT: Associations between the El Niño Southern Oscillation (ENSO) climate pattern and temporal variability in flow and 12 water quality variables were assessed at 77 river sites throughout New Zealand over a 13-year period (1989 through 2001). Trends in water quality were determined for the same period. All 13 variables showed statistically significant linear regression relationships with values of the Southern Oscillation Index (SOI). The strongest relationships were for water temperature (mean R^2 = 0.20), dissolved reactive phosphorus (0.18), and oxidized nitrogen (0.17). The association with SOI varied by climate region. The observed patterns were generally consistent with known ENSO effects on New Zealand rainfall and air temperature. Trends in water quality variables for the periods 1989 through 1993, 1994 through 1998, and 1989 through 1998 were reasonably consistent with trends in SOI, even when the influence of river flow was removed from the data. This suggests that SOI effects on water quality are not necessarily a direct consequence of changes in flow associated with rainfall variation. In addition, both Baseline (32 upstream) and Impact (45 downstream) sites showed similar trends, indicating that changes in management were not directly responsible. We conclude that interpretation of long term water quality datasets in rivers requires that climate variability be fully acknowledged and dealt with explicitly in trend analyses.

(KEY TERMS: aquatic ecosystems; water quality; climate variability; trend analysis; El Niño-Southern Oscillation; New Zealand.)

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INTRODUCTION

Research on global climate variability and its effects on physical, chemical, and biological processes have burgeoned over the past 20 years (Allan *et al.,* 1996). This reflects both growing concerns over the state of the global environment and an increase in the availability of datasets to undertake such analyses. Much of this research has focused on the effects of the ENSO climate pattern, which constitutes the single largest source of natural variability in the global climate system (Diaz and Markgraf, 1992). While this pattern is best known for the extremes of the oscillation (i.e., El Niño and La Niña) the phenomenon is in fact part of a continuum reflecting changes in sea-level atmospheric pressure in the tropical Pacific Ocean (Allan *et al.,* 1996).

ENSO has been found to have strong influences on many aspects of marine (Allan *et al.,* 1996) and terrestrial ecology (Holmgren *et al.,* 2001), and recently freshwater ecosystems have also been shown to be influenced by this pattern (e.g., Lipp *et al.,* 2001). However, much of the work has focused on addressing issues of primary concern to humans (e.g., effects on fisheries, agriculture, and frequency and predictability of floods and droughts), and there is limited literature on climate variability effects on natural ecosystem attributes.

The string of mountainous, oceanic islands that make up New Zealand is considered to be outside the core areas of ENSO influence (Mullan, 1995). However, significant effects of ENSO have been recorded for a number of environmental attributes, including the occurrence of coastal algal blooms (Rhodes *et al.,* 1993), air temperature anomalies (Salinger and Mullan, 1999), rainfall patterns (Mullan, 1995), and river flows (McKerchar *et al.,* 1998; Mosely, 2000). New Zealand's orography plays a major role in determining the spatial distribution of ENSO influences on

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rainfall and air temperature (Salinger and Mullan, 1999). It is important therefore to provide a spatial context for assessing ENSO effects. In this paper we assess the influence of the ENSO climate pattern on physical and chemical characteristics of surface waters at 77 river sites throughout New Zealand over a 13-year period (1989 through 2001).

In addition to a description of the influence of climate variability on surface waters, we assess the implications of these climate influences for the interpretation of trend analysis results. Various international agreements and organizations (e.g., Organization for Economic Co-operation and Development, OECD) have dictated a responsibility of individual countries to monitor the state of their environments and assess long term trends in state variables (e.g., Ministry for the Environment, 1997; United Nations Environment Programme, 2002). A significant issue with respect to reporting on variations in state through space and time is that statements require a point of reference or a context within which to interpret results. This point of reference can be spatial (e.g., is this site degraded compared with control or reference sites?) and/or temporal (e.g., are changes at a site through time the result of changes in anthropogenic influences, or are they just natural climate variability?). As a consequence of this context dependency, the analysis of temporal trends in environmental data is heavily dependent on determination of the natural variability associated with all environmental data. In the past, analyses of water quality trends (e.g., Lettenmaier *et al.,* 1991; Smith *et al.,* 1996; Bauch and Spahr, 1998; Clow and Mast, 1999; Stalnacke *et al.,* 1999; Zipper *et al.,* 2002) have not explicitly considered the influence of climate variability, although Smith *et al.,* (1996) noted that temperature trends may have been associated with ENSO. We show that observed water quality trends may be driven to a significant extent by antecedent climate conditions.

METHODS

Study Sites

In 1989 New Zealand's National Rivers Water Quality Network (NRWQN) was initiated to provide a national context for information on the state of lotic environments (Smith and McBride, 1990; Ward *et al.,* 1990), both through time (e.g., Smith *et al.,* 1996; Scarsbrook *et al.,* 2000) and space (e.g., Smith and Maasdam, 1994). All operations are conducted by the National Institute of Water and Atmospheric Research (NIWA) Ltd. The Network includes 77 sites (Figure 1) in 35 catchments covering 45 percent of the total land area of New Zealand. Sites are distributed throughout the North Island (44 sites) and South Island (33 sites). At each site, river flow and 12 water quality variables are measured either monthly or every four weeks. According to criteria given by Smith and McBride (1990), sites were selected to reflect both "baseline" conditions (32 upstream sites) and "impact" conditions (45 downstream sites). Sites were selected to have median flow greater than 1 m^3/s. Fieldwork is carried out by NIWA's 14 regional hydrometric field teams. All laboratory analyses were performed at a single water quality laboratory.

Water Quality Sampling and Analysis

At an individual site, sampling on each occasion was generally at the same time of day to remove the variance inflation attributable to diurnal variability. Flow was measured or estimated on each sampling occasion. Other field measurements included dissolved oxygen (measured as percentage of saturation, %DO), temperature, and visual clarity (measured by horizontal black disc visibility; Davies-Colley, 1988). In the laboratory, pH, conductivity, turbidity, biochemical oxygen demand (five-day test; hereafter BOD_5), absorption coefficient at 440 nm (g_{440}), oxidized-N (i.e., NO_x-N = NO_2-N + NO_3-N), ammoniacal-N (i.e., NH_4-N = NH_4^+-N + NH_3-N), dissolved reactive P (DRP), and total P (TP) are measured. Analytical methods remained the same over the study period (January 1989 through December 2001) so as not to produce artificial step trends. Further details on sampling techniques and field and laboratory measurement are given elsewhere (Smith and McBride, 1990; Smith *et al.,* 1996).

Influence of Climate Variability on River Water Quality

The index used to characterize ENSO was the SOI, which is calculated as the normalized anomalies of the monthly mean sea level pressure difference between Tahiti and Darwin. Several other indices have been developed, but the SOI is most frequently used (Allan *et al.,* 1996; Mosely, 2000). Monthly values of the SOI were obtained from the Australian Bureau of Meteorology (Commonwealth of Australia, 2002) and we use the Troup convention, whereby normalized index values are multiplied by 10.

To examine the effect of climate variability on flow and water quality variables we performed simple

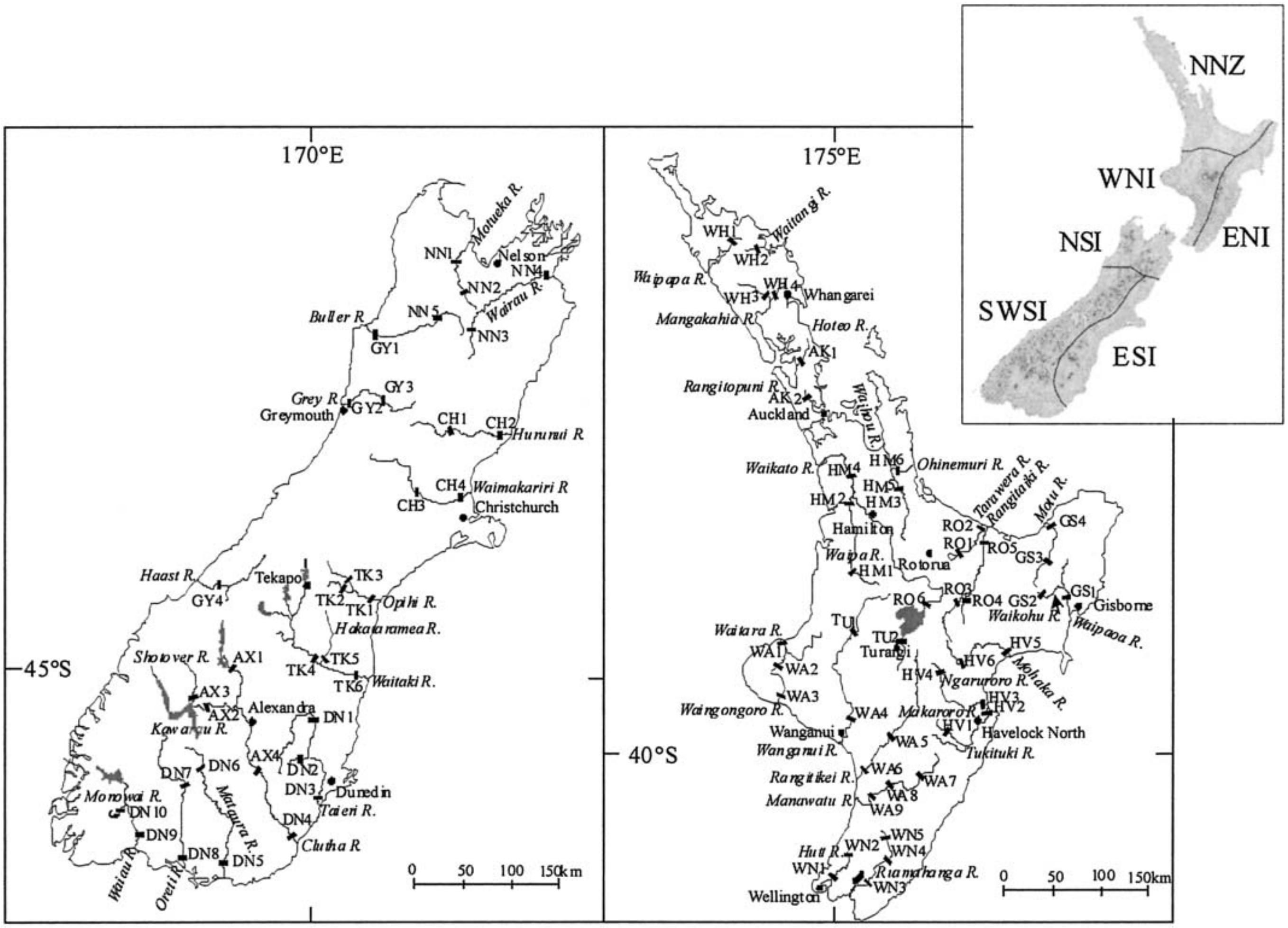


Figure 1. Sampling Sites in New Zealand's National River Water Quality Network. Inset figure shows New Zealand separated into six broad climate regions: NNZ = northern New Zealand; ENI = eastern North Island; WNI = western North Island; NSI = northern South Island; ESI = eastern South Island; and SWSI = southwestern South Island.

linear regression of each variable on the SOI. This was done for each site. To minimize the variability associated with regular seasonal changes, all dependent variables were deseasonalized by employing 12-month moving averages (strong seasonality is often exhibited by water quality variables, such as water temperature). The SOI was treated similarly (Figure 2a). The coefficient of determination (R^2) was used to indicate the strength of linear relationships between deseasonalized SOI and individual water quality variables at each site (Figure 2b), and the slope of the line was used to indicate the direction of that relationship. Inspection of our results indicates that a linear approximation is appropriate for New Zealand. We note that Mullan (1995) found that a linear relationship between air temperature and SOI held for a majority of New Zealand subregions.

We assessed the spatial distribution of SOI effects on water quality variables by climate region (see Figure 1 inset). These six climate regions are a simplification of the eight rainfall and three temperature regions of New Zealand determined by Salinger and Mullan (1999). For this spatial analysis we defined the "SOI association variable" (I_{SOI}) as the sign added R^2 values of the SOI regressions with the sign determined by the direction of the regression slope. A one-way ANOVA was used to examine differences in this variable among regions. Tukey's HSD post-hoc tests were employed to test the significance of pairwise comparisons. All tests were performed at the five percent significance level.

(a)

(b)

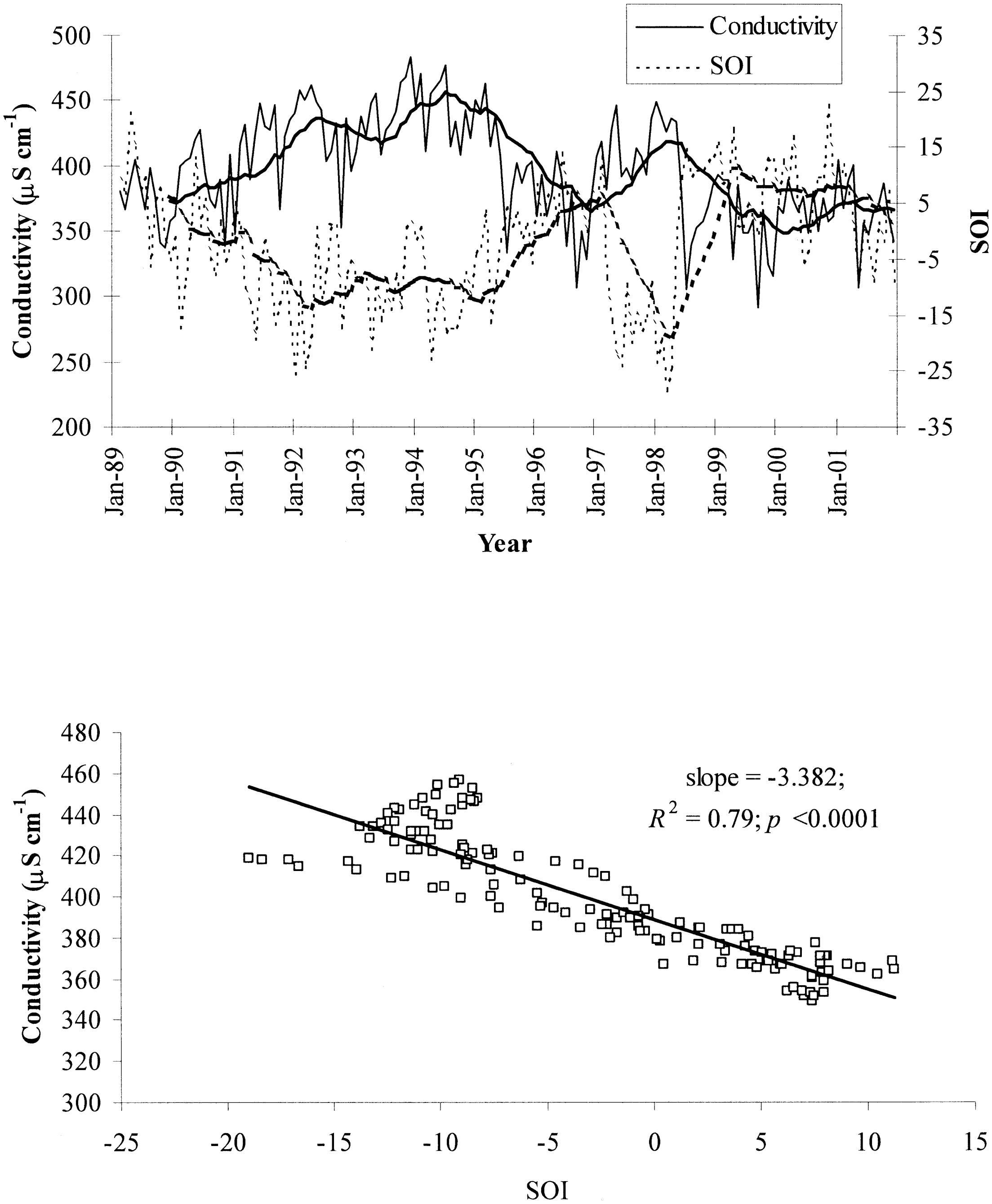


Figure 2. (a) Plot of Monthly SOI and Conductivity Values Through Time for a Single Site in Northern New Zealand (RO2; Tarawera River at Awakaponga). Moving averages with a 12-month period are shown. (b) Relationship Between Moving Average Values of SOI and Those of Conductivity.

Trend Analysis

Trend analysis for raw (i.e., not flow adjusted) data over the first five calendar years of this dataset (1989 through 1993) was carried out by Smith *et al.* (1996). We carried out additional trend analyses for the periods 1994 through 1998 and 1989 through 1998. The trend analysis has been broken into five-year blocks due to an analysis of the power required to detect statistically significant trends, where this trend was defined to be a change in its mean value of at least the standard deviation of the record after removal of any seasonal pattern (Smith and McBride, 1990).

Water quality data typically have strong seasonal patterns, and often the data are not normally distributed (Lettenmaier *et al.,* 1991; Smith and Maasdam, 1994). Because of this, the nonparametric method seasonal Kendall slope estimator (SKSE) is widely used to assess the magnitude of temporal trend, accompanied by the seasonal Kendall trend test to assess its statistical significance (Gilbert, 1987; Harcum *et al.,* 1992; Helsel and Hirsch, 1992; Griffith *et al.,* 2001). Analyses were carried out using the WQStat Plus package (IDT, 1998). We ignore the effects of serial correlation, which is justified if the scale of interest is confined to the period of record (Loftis *et al.,* 1991).

The values of many water quality variables are influenced by river flow through a range of mechanisms, including dilution and washoff (e.g., McDiffert, 1993; Smith *et al.,* 1996). A simplistic example would be of a variable that is delivered to a river at a more or less constant rate. In this case concentrations of the variable would decrease as flow increases (i.e., dilution). For many variables the mechanisms through which flow may influence concentrations are neither simple nor predictable – hysteresis may be present whereby concentrations on the rising and falling limbs of a flood hydrograph can differ (e.g., McDiffert, 1993; Sokolov and Black, 1996). Nevertheless, by removing the variation in values associated with flow, variability in water quality values can be reduced and the power of trend detection increased. Accordingly, we have analyzed both raw and flow-adjusted data using the log-log regression procedure available in WQStat Plus (IDT, 1998). Note that Smith *et al.* (1996) used LOWESS smoothing in making flow adjustments for 1989 through 1993, whereas we have employed log-log regression procedures – because LOWESS procedures are not in WQSTAT Plus. Accordingly we have reanalyzed the 1989 through1993 data using the log-log procedure, so that a common flow adjustment procedure was used for all three periods (i.e., 1989 through 1993, 1994 through 1998, and 1989 through 1998).

To summarize the trend analysis results – 13 variables by 77 sites by 2 (raw and flow adjusted) – we report median values of the SKSE at the national scale (n = 77) for each variable over three time periods (1989 through 1993; 1994 through 1998; 1989 through 1998). In addition, we present separate median SKSE values for flow adjusted data from Baseline (n = 32) and Impact (n = 45). A comparison of Baseline and Impact sites allows assessment of the potential effects of natural variability versus effects associated with human management practices. The statistical significance of trends at both national and Baseline/Impact levels was determined from a binomial test of the hypothesis that the true proportion of upward (or downward) slopes is one half. If this hypothesis was rejected, a trend for the period of interest was inferred. We use all slope estimates rather than just the "significant" ones (as did Smith *et al.,* 1996) because the power of the binomial test is highly dependent on sample size. In particular, as one increases the number of sites, the proportion of positive (or negative) slopes required to reject this hypothesis becomes ever closer to one half. For example, with n =10, we would require nine (i.e., 90 percent) of the slopes to be positive to conclude a statistically significant upward trend. When n = 77 we require 47 (61 percent) of the slopes to be positive to make the same inference. By taking all slope estimates at face value we provide equivalent sample sizes for all comparisons at the national scale, allowing for a fair comparison between time periods. However, because samples sizes differ slightly for assessments of Baseline (n = 32) and Impact sites (n = 45), comparisons of trends at Baseline and Impact sites must be viewed with caution.

RESULTS

SOI and River Water Quality Characteristics (deseasonalized)

The strength of the relationship between SOI and the 13 individual river water variables varied considerably across the 77 sites (Figure 3). The maximum R^2 value (0.79) was for conductivity at RO2 (Tarawera River at Awakaponga; see Figure 2b). This site also showed maximum R^2 values for flow, %DO, and ammoniacal-N. Average R^2 values were highest for temperature (mean = 0.20), DRP (0.18), oxidized-N (0.17), and conductivity (0.14). Turbidity, TP, BOD5, flow, pH, and ammoniacal-N all had average R^2 values less than 0.10. A one-way ANOVA on log (x + 1) transformed data (raw data were right skewed) showed significant differences between variables ($F_{12,988}$ = 6.94; p < 0.001; n = 77). Tukey's HSD posthoc tests showed significant differences between temperature and %DO, pH, flow, clarity, ammoniacal-N, turbidity, BOD_5, and TP. DRP and oxidized-N were significantly different from ammoniacal-N, flow, turbidity, BOD_5, and TP. In none of the other pairwise comparisons was the null hypothesis rejected.

All sites exhibited significant relationships with SOI for at least some of the variables, although no sites showed significant relationships with all 13 variables (minimum = 4; median = 9; maximum = 12). Known interactions between flow and surface water properties (e.g., dilution effects on conductivity) would suggest that the patterns observed between SOI and individual water quality variables may simply be reflecting the influence of SOI driven variation in rainfall on flow. If this were the case, we would expect to see strong correlations between (1) patterns of SOI relationships with water quality variables and (2) patterns of SOI relationship with river flow. To assess this we carried out a (Pearson) correlation analysis of I_{SOI} values for the flow SOI regression versus the I_{SOI} values for regressions of individual water quality variables with SOI. Statistically significant correlations were observed for clarity, turbidity, %DO, pH, conductivity, and TP (Table 1), with the pattern for conductivity most strongly matching that for flow. However, patterns for temperature, nitrogen species, DRP, BOD_5, and g_{440} all showed lower degrees of matching with flow patterns. The sign of the correlation coefficient provides an indication of the mechanism by which SOI relationships with river flow affect relationships with water quality variables. For example, the negative correlation for conductivity suggests that relationships between SOI and conductivity are strongly negative at sites where SOI effects on flow are strongly positive, implying a dilution effect. In contrast, the positive correlation for turbidity implies a washoff effect, with turbidity increasing most strongly with SOI at sites where SOI is also strongly associated with increased flow.

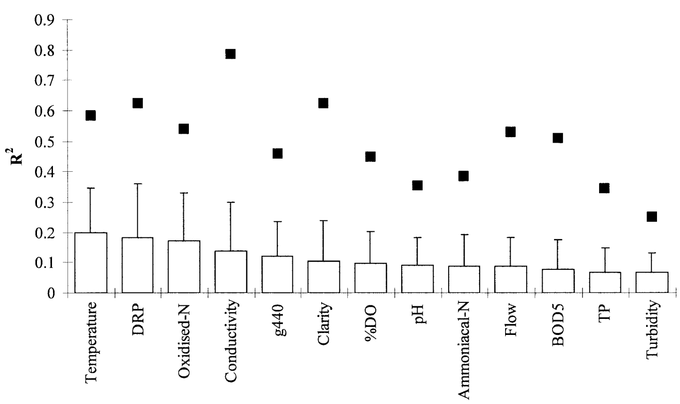


Figure 3. Mean (bars) and Maximum (black squares) R^2 Values for Relationships Between SOI and 13 Physicochemical Variables at 77 Sites Around New Zealand. Error bars extend one standard deviation above the mean.

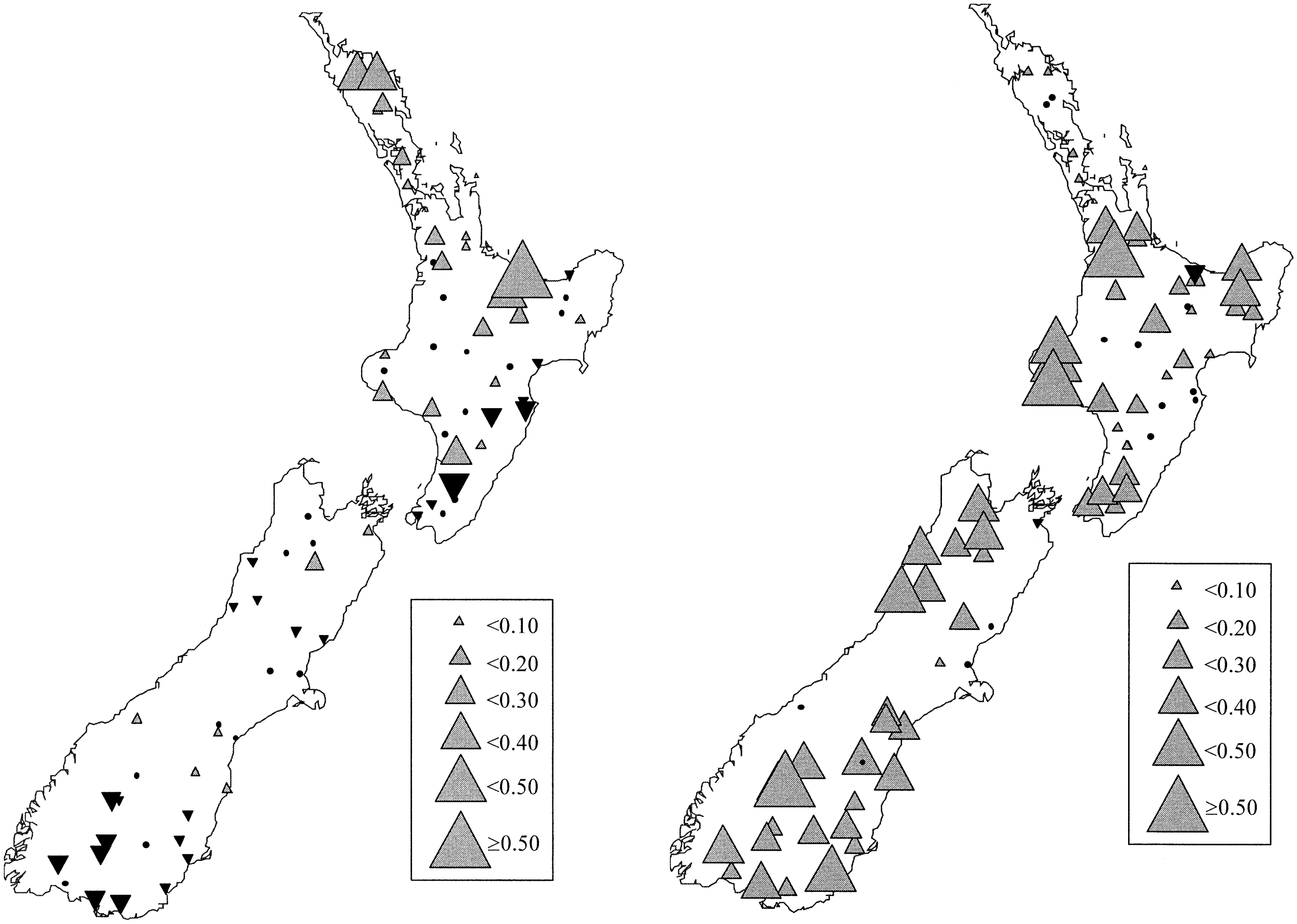
The spatial patterns of SOI relationships with flow and water quality are presented in two ways. First, the regression results for flow and the three most strongly affected water quality variables (temperature, DRP, and oxidized-N) are plotted by geographical location to provide a summary of national patterns of relationships with SOI (Figures 4a-4d). In addition, we separate the 77 sites into six climate regions (Figure 1 inset) and address the question of whether different regions vary in how surface water characteristics are associated with the SOI (Table 2).

TABLE 1. Pearson Correlation Coefficients (r) for the Relationship Between the SOI Influence Variable (ISOI) on Flow and on the Water Quality Variables. Values in bold are statistically significant (n = 77).

Variable	r
Temperature	-0.23
Clarity	**-0.40**
Turbidity	**0.44**
%DO	**0.29**
pH	**-0.49**
Conductivity	**-0.63**
Ammoniacal-N	0.05
Oxidized-N	-0.21
DRP	-0.01
TP	**0.40**
BOD_5	0.19
g_{440}	0.22

Increasing values of the SOI generally lead to increased river flows in the north of New Zealand and decreases in the south (Figure 4a). Results of a one-way ANOVA (Table 2) indicate that the association of flow with SOI (strength and direction of relationship) varies with region. The influence of SOI on flows in northern New Zealand differs significantly from that in the eastern North Island and eastern and south-western areas of the South Island. Significant differences are also apparent for variables closely correlated with flow. For clarity, turbidity, and conductivity SOI has different influences in northern New Zealand compared with the southern and western regions of the South Island (Table 2).

At almost all sites, water temperature tended to increase with values of the SOI (Figure 4b). The influence of SOI on temperature appears to be strongest in the west of both islands and weakest in the east of the South Island (Table 2). A significant linear relationship (R^2 = 0.19, slope = 0.009, p < 0.0001) exists between maximum catchment elevation (range = 136 to 2,728 m) and the strength of the SOI-temperature relationship, suggesting that SOI exerts more influence on water temperature in rivers draining mountainous areas. For example, R^2 values were particularly strong (0.44 to 0.52) at the three sites draining the isolated volcano Mt. Taranaki (elevation 2,518 m) on the west coast of the North Island.



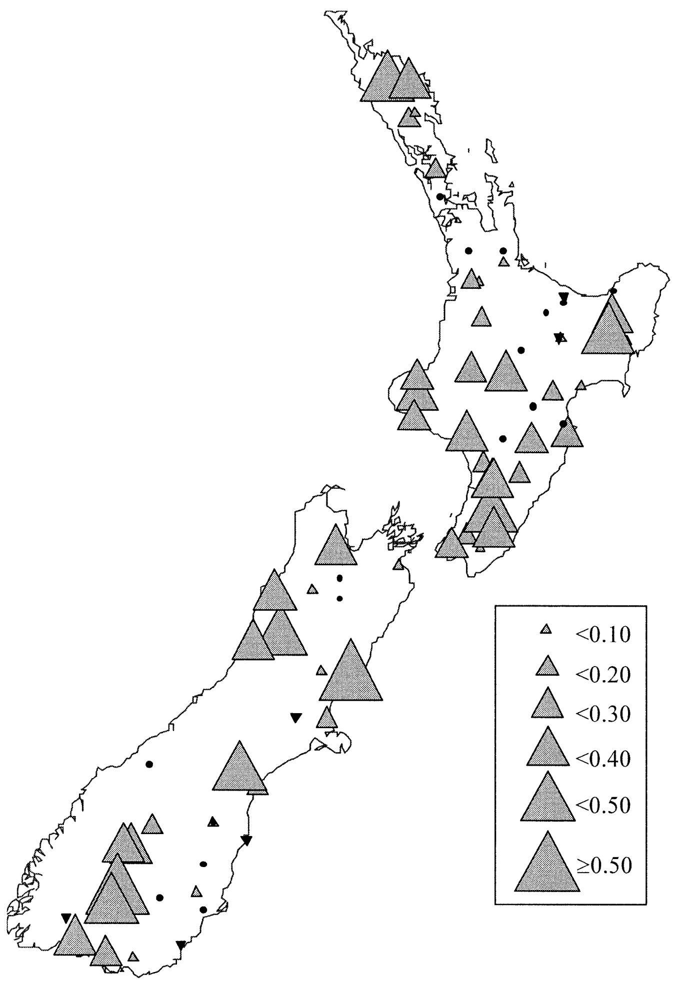
(a) Relationships With Flow

(b) Relationships With Water Temperature

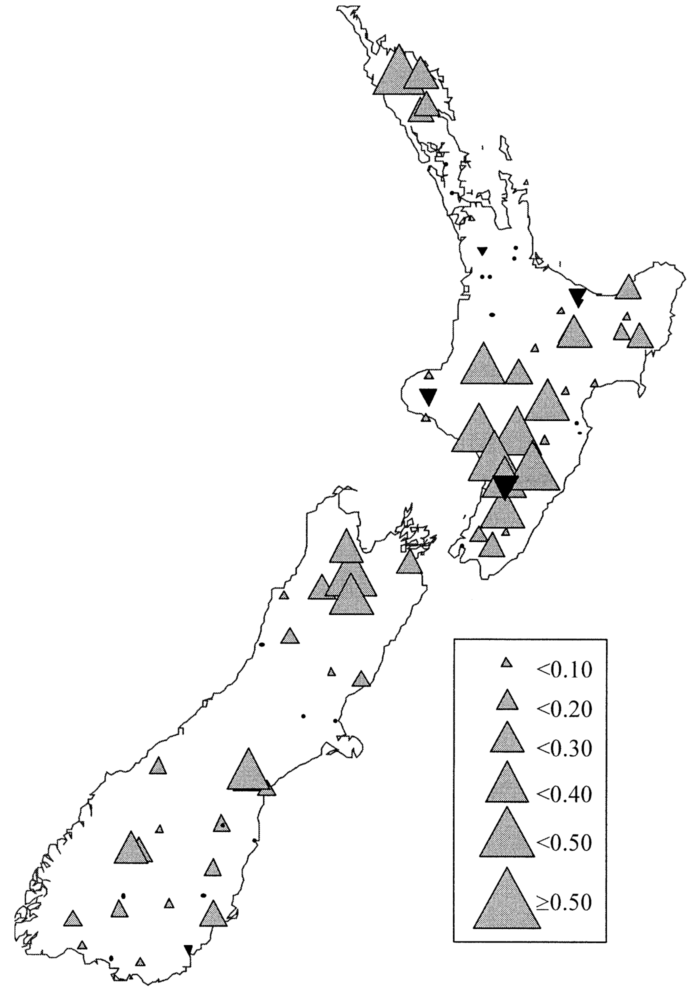
Figure 4. Spatial Summary of R^2 Values for SOI and Four Physicochemical Variables at 77 New Zealand River Sites. Significant negative relationships with SOI are shown as filled downward triangles, significant positive relationships as shaded upward triangles, and nonsignificant relationships as black dots. Triangle size varies according to R^2.

Levels of oxidized-N generally increased with increasing values of SOI (Figure 4c). The relationship between SOI and concentrations of oxidized-N varied significantly with climate region and was more strongly positive for sites in the western North Island than in northern New Zealand (Table 2). Seven sites in the NRWQN are downstream of large natural and/or hydroelectricity storage lakes (AX1, AX4, DN4, DN10, RO1, RO6, and TK4). The association of SOI and levels of oxidized-N was lower at these sites (mean R^2 = 0.06) than for the average for all 77 sites (mean R^2 = 0.17).

The general pattern for SOI-DRP relationships was for increasing DRP concentrations with positive values of SOI (Figure 4d). Sites in central New Zealand –- particularly in the Whanganui (TU1, WA4), Rangitikei (WA5, WA6), and upper Manawatu (WA7, WA8) Rivers – had DRP levels strongly associated with SOI (range of R^2 was 0.47 to 0.62). The association of SOI with DRP varied significantly with climate region (Table 2), with sites in the northern South Island more strongly associated than sites in the southwest of the South Island. There appears to be a general pattern whereby the relationship between SOI and DRP changes with distance along a river system. Most of the NRWQN sites are located as upstream (Baseline) and downstream (Impact) paired sites (i.e., there are 28 pairs of sites), and the R^2 values for SOI and DRP differs significantly (paired t-test: mean difference = -9.74, p = 0.016, n = 28) between these upstream and downstream paired sites.



(c) Relationships With Concentrations of Oxidized-N



(d) Relationships With Concentrations of Dissolved Reactive Phosphorus

Figure 4 (cont'd.). Spatial Summary of R^2 Values for SOI and Four Physicochemical Variables at 77 New Zealand River Sites. Significant negative relationships with SOI are shown as filled downward triangles, significant positive relationships as shaded upward triangles, and nonsignificant relationships as black dots. Triangle size varies according to R^2.

Trends in SOI and Water Quality

Sampling in the NRWQN has been undertaken within a context of changing climatic conditions. Over the first five years of sampling, monthly SOI values showed a consistent decreasing trend (Figure 5), as an El Niño event persisted and intensified. The following five years were characterized by highly variable conditions, with an initial increasing phase followed by the 1997 and 1998 El Niño, the strongest such event in the past 100 years (Changnon, 2000). Over the period 1994 through 1998 period the line of best fit through monthly SOI values showed a positive slope, although this slope was not significantly different from zero (Figure 5). The full 10-year period (1989 through 1998) was characterized by a negative slope (-0.019), but this slope was also not significantly different from zero.

Given the evidence of strong associations between SOI and surface water characteristics, we would expect that trends in water quality variables observed over the three time periods would reflect the trends in SOI (Figure 5). However, if the patterns reflect the influence of SOI working through river flows, we would also expect patterns to weaken following flow adjustment of the data. Furthermore, significant trends for flow adjusted data at Baseline sites will provide evidence for the association of patterns observed with aspects of natural climate variability (e.g., temperature regimes) rather than with the influence of changing management practices.

TABLE 2. Mean Values of an Index of SOI Influence (I_{SOI}) by Climate Region (see Figure 1 for climate regions).

Variable	*p*-value	NNZ	ENI	WNI	NSI	ESI	SWSI
n		19	11	8	6	19	14
Flow	<0.001	0.15[a]	0.01[b]	0.03[ab]	0.04[ab]	-0.02[b]	-0.07[b]
Temperature	0.008	0.15[b]	0.15[ab]	0.26[ab]	0.25[ab]	0.13[b]	0.30[a]
Clarity	0.001	-0.12[b]	0.06[a]	0.11[a]	-0.02[ab]	-0.05[ab]	0.09[a]
Turbidity	<0.001	0.04[a]	0.05[a]	0.03[a]	0.05[a]	-0.02[ab]	-0.08[b]
%DO	0.028	0.03[a]	-0.06[ab]	-0.16[b]	-0.04[ab]	-0.06[ab]	-0.02[ab]
pH	0.005	-0.11[b]	-0.08[ab]	-0.10[b]	-0.05[ab]	-0.08[b]	0.04[a]
Conductivity	0.001	-0.19[b]	-0.16[ab]	-0.01[ab]	-0.06[ab]	0.04[a]	0.02[a]
Ammoniacal-N	0.204	0.01	0.04	-0.03	-0.02	-0.08	0.01
Oxidized-N	0.014	0.08[b]	0.25[ab]	0.27[a]	0.15[ab]	0.12[ab]	0.22[ab]
DRP	0.019	0.11[ab]	0.30[ab]	0.19[ab]	0.32[a]	0.12[ab]	0.09[b]
Total P	0.005	0.05[a]	0.04[a]	0.03[ab]	0.03[ab]	-0.01[ab]	-0.08[b]
BOD_5	0.67	-0.05	-0.04	-0.10	-0.05	-0.07	-0.02
g_{440}	0.106	-0.07	-0.03	-0.08	-0.05	-0.04	-0.18

Note: The numbers of individual sites within each group are given. The *p*-value summarizes a one-way ANOVA assessing the differences in SOI influence across these regions. Tukey's HSD post-hoc test was used to assess significance of pair wise comparisons among regions. Mean values of I_{SOI} for climate regions with the same letter given in superscript are not significantly different.

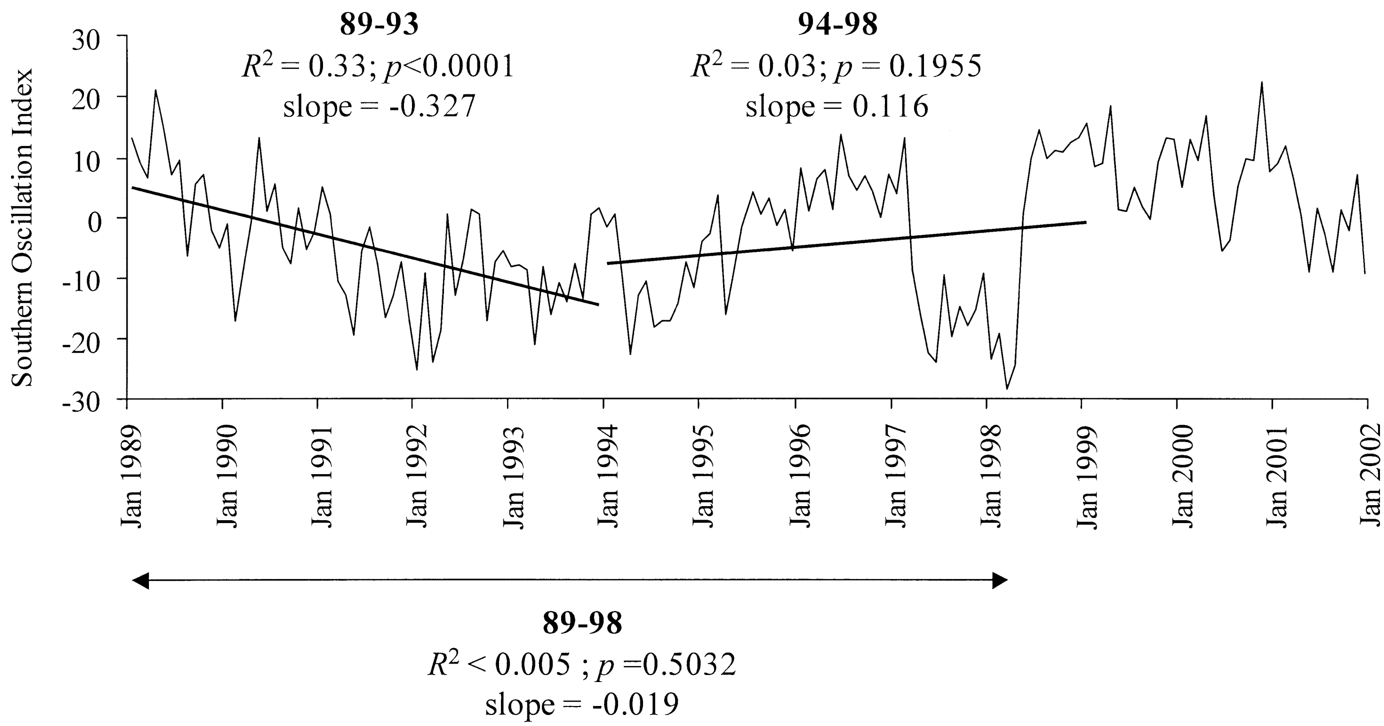


Figure 5. Values of the Southern Oscillation Index Over the 13-year Period Covered in this Study. Details of linear regressions for the first and second five-year periods and full 10-year period are shown.

Table 3 summarizes national-scale trend information for the water quality variables analyzed. The period 1989 through 1993 was characterized by evidence of national trends for raw data of decreasing water temperature, BOD_5, ammoniacal-N, and oxidized-N, along with increasing trends for %DO, clarity, conductivity, DRP, and g_{440}. Flow adjusted values over the same period showed similar trends, although the trend for DRP was no longer statistically significant, whereas significant negative trends in TP and turbidity appeared.

Several water quality variables exhibited trends that are consistent with trends in SOI given the relationship of variables with SOI. For example, water temperatures showed a significant negative trend for the period 1989 through 1993. Values of SOI also went down over this period, and we have shown that temperature is strongly influenced by SOI (Figure 4b). Flow adjustment of the temperature data strengthened this apparent match, and the effect was equally strong in Baseline and Impact sites (Table 4). Flow adjusted data trends for other variables were also consistent with direction of SOI trends, except for BOD_5, which showed a consistent downward trend irrespective of trends in SOI.

When flow adjusted data were separated according to Baseline and Impact site classifications, the patterns for both site types were generally consistent. Although statistical significance was not always consistent, the median SKSE was of a similar slope and magnitude in most cases, possibly as a result of differences in sample size. However, it is worth noting that oxidized-N and DRP both showed significant decreasing trends at Baseline sites (n = 32) during the 1989 through 1993 period, whereas Impact sites did not show significant trends despite their increased power of trend detection (i.e., n = 45).

Overall, the period 1989 through 1993 had the strongest trend in SOI, and 10 of the 13 physicochemical variables (excluding flow) showed significant flow adjusted national trends during that period. There were significant trends in only six variables at the national scale for 1984 through 1998 and the 10-year period (1989 through 1998), coinciding with weak trends in SOI. Full trend results are available on request.

DISCUSSION

Climate variability, characterized by the SOI, is associated with substantial variability in flow and water quality characteristics of New Zealand rivers. However, the strength and slope of the relationship between SOI and individual variables is highly variable in space. There are national patterns in some variables despite this variability, and these patterns generally agree with what would be expected, given known ENSO effects on New Zealand. For example, Salinger and Mullan (1999) indicate a general pattern of decreased rainfall over northern New Zealand during El Niño periods and increased rainfall during La Niña. The opposite pattern is observed in southern New Zealand. Our results for flow support this pattern, with increasing flows in the north with positive

TABLE 3. Median Seasonal Kendall Slope Estimator (SKSE) (n = 77 sites) across Three Time Periods. Values in bold italics are cases where the binomial test's hypothesis is rejected (P < 0.05).

	Raw Data			Flow Adjusted Data		
	1989 to 1993	1994 to 1998	1989 to 1998	1989 to 1993	1994 to 1998	1989 to 1998
SOI	***-0.327***	0.116	-0.019			
Flow (m^3/s/yr)	-0.094	***-0.255***	***0.134***			
Temperature (°C/yr)	***-0.200***	***0.152***	0.000	***-0.234***	0.071	-0.001
%DO	***0.200***	-0.025	-0.020	***0.119***	-0.082	-0.008
Clarity (m/yr)	***0.050***	***0.040***	***-0.018***	***0.029***	0.016	0.005
Turbidity (NTU/yr)	-0.062	0.032	***0.065***	***-0.051***	***0.117***	***0.036***
pH (pH units/yr)	0.005	0.000	***-0.008***	0.000	***-0.005***	***-0.004***
Conductivity (µS/cm/yr)	***1.075***	-0.050	0.093	***0.536***	***-0.287***	***0.192***
BOD5 (µg O_2/L/yr)	***-0.025***	***-0.017***	***-0.017***	***-0.025***	***-0.014***	***-0.017***
Ammoniacal-N (µg/L/yr)	***-0.333***	-0.042	***-0.334***	***-0.300***	0.000	***-0.355***
Oxidized-N (µg/L/yr)	***-4.000***	-0.202	0.000	***-2.462***	0.010	-0.001
DRP (µg/L/yr)	***0.001***	***0.210***	***0.052***	-0.003	***0.316***	***0.049***
Total P (µg/L/yr)	0.000	-0.090	***0.065***	***-0.200***	0.151	-0.001
g440 (m/yr)	***0.030***	***-0.016***	0.002	***0.025***	***-0.016***	-0.004

Note: Slope values for Southern Oscillation Index (SOI) are from simple linear regression (see Figure 5).

TABLE 4. Median Seasonal Kendall Slope Estimator (SKSE) Calculated From Flow Adjusted Data for Baseline (n = 32) and Impact Sites (n = 45) Over Three Time Periods. Values in bold italics are cases in which the binomial test's hypothesis is rejected ($P < 0.05$).

	1989 to 1993		1994 to 1998		1989 to 1998	
	Baseline	Impact	Baseline	Impact	Baseline	Impact
SOI	***-0.327***	***-0.327***	0.116	0.116	-0.019	-0.019
Flow (m^3/s/yr)	***-0.252***	***-0.222***	0.087	0.071	-0.010	-0.001
Temperature (˚C/yr)	0.173	***0.067***	-0.031	***-0.083***	0.003	-0.026
%DO	0.017	***0.030***	0.031	0.001	0.021	0.001
Clarity (m/yr)	-0.004	***-0.110***	***0.035***	***0.188***	***0.036***	0.027
Turbidity (NTU/yr)	0.000	-0.005	***-0.009***	-0.005	***-0.004***	***-0.006***
pH (pH units/yr)	***0.445***	***0.824***	-0.198	***-0.481***	***0.119***	***0.231***
Conductivity (µS/cm/yr)	***-0.017***	***-0.027***	***-0.013***	***-0.015***	***-0.016***	***-0.019***
BOD_5 (µg O_2/L/yr)	***-0.252***	***-0.314***	-0.001	0.000	***-0.348***	***-0.388***
Ammoniacal-N (µg/L/yr)	***-2.194***	-3.161	-0.060	1.438	-0.156	0.573
Oxidized-N (µg/L/yr)	***-0.031***	0.017	***0.206***	***0.527***	***0.019***	***0.144***
DRP (µg/L/yr)	-0.124	-0.565	-0.004	0.270	-0.008	0.075
Total P (µg/L/yr)	***0.030***	***0.017***	***-0.014***	***-0.018***	0.002	***-0.013***

Note: Slope values for Southern Oscillation Index (SOI) are from simple linear regression (see Figure 5).

values of SOI (La Niña) and decreasing flows in the south under the same conditions.

The pattern observed for river water temperature also matches known ENSO effects on air temperature and sea surface temperature around New Zealand. Allan *et al.* (1996) indicated that cooler air masses are found to the north of New Zealand during El Niño years, and warmer air masses are found during La Niña. In addition, it is known that sea surface temperatures are usually lower than normal during El Niño periods (Rhodes *et al.,* 1993). These air and sea surface temperature variations are matched by our finding of positive relationships between river water temperature and SOI at sites around New Zealand. Mullan (1995) found that at central and southern South Island sites, air temperatures in winter were cooler than average at both extremes of the Southern Oscillation. Our results do not indicate such strong nonlinear effects, as results of linear regression showed that water temperatures in the southwest South Island sites were more strongly influenced by SOI than some other regions. However, our use of 12-month running averages deliberately sought to minimize seasonal effects, so we probably lost detail of the smaller scale temporal patterns that Mullan (1995) indicated were important.

The different patterns observed for SOI effects on temperature and flow indicate that effects of global climate patterns on rivers may not simply be a function of variation in rainfall, as has been indicated by some studies in the Northern Hemisphere. For example, Lipp *et al.* (2001) found that levels of fecal coliform bacteria in rivers draining into Tampa Bay, Florida, varied with ENSO phases, and these patterns were related to known changes in discharge driven by ENSO (Schmidt *et al.,* 2001). Molles and Dahm (1990) showed strong correspondence between ENSO and streamflow in New Mexico, and subsequent work showed that this pattern resulted in increased carbon export during "wet" El Niño years in an Arizona desert stream (Jones *et al.,* 1996).

Our results indicate that temperature variation is also linked to SOI and appears to be relatively independent of rainfall flow variation. In a large scale study of SOI effects on rainfall and temperature patterns in the western United States, Redmond and Koch (1991) similarly found that SOI had opposite effects on precipitation and temperature.

The effects of climate variability on water temperature patterns have been assessed in several studies. For example, Monteith *et al.* (2000) found that variations in winter nitrate peaks from the River Gwy in Wales were positively correlated with the mean December to March values of the North Atlantic Oscillation index. In this case the mechanism driving the observed pattern was suggested to be a link with the length of time the soil profile remained frozen, affecting nitrate mobilization and processing. Nicholls (1998) also implicated temperature anomalies caused by ENSO as a factor explaining variation in phosphorus concentrations leaving the Laurentian Great Lakes.

The relationship with SOI was significantly correlated with the strength and direction of relationships between flow and SOI for several water quality variables. This suggests that variation in rainfall/flow associated with SOI is related to the patterns observed in variables such as conductivity, water clarity/turbidity, and total phosphorus levels. In contrast, the lack of correlation with nitrogen species, DRP, BOD_5, and river color (g_{440}) suggests alternative mechanisms. It is worth noting that these variables (particularly oxidized-N, DRP, and BOD_5) are strongly influenced by biological processes occurring both internally (instream processing) and externally to river ecosystems. The potential for both internal and external modifiers to influence these variables makes establishing causal links for our observed patterns extremely difficult. For example, Holmgren *et al.* (2001) suggest there is often a boost in terrestrial primary productivity associated with increased rainfall during El Niño. This increased productivity can be expected to increase nutrient retention in terrestrial systems, and as a result surface water concentrations may be reduced. Therefore, variation in terrestrial nutrient cycling associated with climate variation may well explain much of the variation in stream nutrient concentrations (e.g., Monteith *et al.,* 2000).

Consequences of Climate Driven Patterns for Interpretation of Long Term Trends

A principal goal of long term environmental monitoring is to determine the effects of human environmental management on the state or "health" of the environment. To achieve this goal, sources of natural variability in time and space must be accounted for before anthropogenic effects can be reliably determined. In this study we have shown a strong relationship between climate variability and surface water characteristics in New Zealand rivers over a 13-year period. We have also shown that these patterns are not necessarily a direct consequence of changes in flow associated with rainfall variation. The implication of these results is that trends in river water quality are somewhat dependent on climatic variability, making trends associated with human river management more difficult to detect. This is further supported by the finding that trends in water quality for sites with both minimal human modification and those impacted by human activity are generally consistent with trends in SOI. That is, many of the trends observed are equally apparent in Baseline and Impact sites and are, therefore, more likely to be associated with natural climate variability. These results suggest that the interpretation of long term datasets requires that climate variability be fully acknowledged and dealt with explicitly, particularly in trend analyses. It may be fruitful to use indices such as the SOI in future analyses to provide a climatic adjustment for water quality data prior to trend analyses. However, by removing or minimizing the effect of climate variability, there is a risk that trends associated with changing human management practices may actually be obscured, particularly where those management practices are themselves influenced by climatic conditions.

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