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Regional river flow, water quality, aquatic ecological impacts and recovery from drought

BRIAN S. CARUSO
Otago Regional Council, 70 Stafford Street, Private Bag 1954, Dunedin, New Zealand
e-mail: carusobs@cdm.com

Abstract During severe drought and low flows in the Otago Region of the South Island of New Zealand, increased bacterial contamination of rivers occurred in agricultural/ pastoral catchments due to greater stock use of waterways and the lack of dilution and flushing flows. Concentrations and loadings of nitrogen and phosphorus generally decreased due to the lack of rainfall, runoff and transport from diffuse sources. Other analytes, including dissolved solids and pH, did not change to any considerable degree and were quite spatially variable. Although the health of benthic macroinvertebrate communities can decrease with a lower diversity and fewer sensitive taxa, effects were not significant in most rivers. Algal blooms occurred in some locations, particularly in lowland agricultural catchments with low water velocities and little shade. The prolonged lack of flushing flows can be a significant problem. Fish kills occurred where they became stranded and isolated from the main flow and where there was a lack of deeper pool refuges. Temperatures in excess of 25°C can also result in isolated fish kills, but the duration of these high temperatures appears to be the most critical factor. Adverse effects from drought can be widespread and severe in some locations, but appear to be relatively short-lived with recovery occurring rapidly with increasing flows at most locations. This indicates a degree of resilience of rivers to drought and low flows with long-term impacts that are not severe.

Key words rivers; low flows; drought; water quality; aquatic ecology; New Zealand

Impacts de la sécheresse, puis restauration, sur les écoulements régionaux, la qualité de l'eau et l'écologie aquatique

Résumé Lors d'une sécheresse et d'étiages sévères dans la région d'Otago de l'île Sud de Nouvelle-Zélande, une contamination bactérienne accrue a été observée dans des bassins versants agricoles et pastoraux, en raison du parcours plus important des cours d'eau par les troupeaux d'une part et du manque de dilution et de débits de chasse d'autre part. Les concentrations et les charges en azote et phosphore ont généralement décru suite à l'absence de pluie, d'écoulement et de transport à partir des sources diffuses. D'autres éléments d'analyse, dont les concentrations de certains solutés et le pH, n'ont pas été sensiblement modifiés et ont présenté une variabilité spatiale importante. Bien que la santé des communautés de macro-invertébrés benthiques puisse être dégradée avec une diminution de la diversité et une sélection des taxons les plus robustes, les effets ont été peu significatifs dant la plupart des rivières. Des pullulations algales ont eu lieu en certains endroits, en particulier dans des bassins versants agricoles de plaines, présentant des vitesses d'écoulement faibles et peu d'ombre. L'absence durable de débit de chasse peut être un problème important. La mortalité des poissons a été forte là où ils se sont trouvé piégés et isolés des cours d'eau principaux et où les refuges profonds manquaient. Des températures supérieures à 25°C peuvent également causer la mort des poissons isolés, mais la durée de ces fortes températures apparaît comme le facteur critique principal. Les effets négatifs de la sécheresse peuvent être étendus et sévères en certains lieux, mais sont relativement éphémères dans la mesure où les qualités sont rétablies rapidement après la reprise des écoulements. Cela indique une forte résilience des rivières par rapport à la sécheresse et aux étiages, et donc des impacts à long terme qui ne sont pas sévères.

Mots clefs fleuves; étiages sévères; sécheresse; qualité de l'eau; écologie des milieux aquatiques; Nouvelle-Zélande

Open for discussion until 1 April 2002

INTRODUCTION

Studies of the hydrological effects of climate change, El Niño Southern Oscillation (ENSO) events and drought on river flows have increased in recent years. Many studies have found that climate change and ENSO events might increase the magnitude and frequency of droughts and low river flows in some areas of the world (Jones, 1999), including parts of North America (Woolhiser *et al.*, 1993; Piechota *et al.*, 1997; Westmacott & Burn, 1997; Nigam *et al.*, 1999; EOS, 2000), Europe (Sefton & Boorman, 1997), and Australasia (Burn, 1994; Moss *et al.*, 1994; McKerchar & Pearson, 1994; Mullan, 1996; McKerchar *et al.*, 1998; Chiew *et al.*, 1998; Mosley, 2000).

There have been far fewer studies evaluating impacts of droughts and low river flows on water quality or aquatic ecosystems. The studies that have been performed have generally been geared toward modelling and discussing the potential effects of climate change on freshwater ecosystems and surface water quality (Schindler, 1997; Murdoch *et al.*, 2000), but have generally not evaluated impacts from actual drought conditions. Some work has focused on effects on fluvial erosion and sediment patterns. Zonge *et al.* (1996) found that sediment deposition can occur due to lower stream velocities on vegetated, moderately steep streambank slopes, and plants can establish at the toe or midslopes of banks in deposition areas. This vegetation can retard erosion, and augment bank recovery and stability. Climate change can have many different effects on sediment transport in rivers and can cause instability in the fluvial system. However, it appears that human management activities have a greater influence and will ultimately determine the consequences of climatic change on fluvial systems (Newson & Lewin, 1991). Kobayashi *et al.* (1990) evaluated diurnal fluctuations in streamflow and specific conductance during drought in winter and summer in a forested headwater basin. In summer, there was high diurnal fluctuation of flow and conductance caused by daytime evapotranspiration of trees in the riparian zone. The uptake of throughflow with high ion concentrations that discharges to streams reduced both streamflow and ion concentrations. Peterson & Cayan (1988) demonstrated that stream chemistry (dissolved solids) was correlated with streamflow fluctuations and atmospheric patterns, showing that a series of dry years in the normally wet Pacific Northwest of the US shifted stream chemistry behaviour towards that of the arid southwest.

Drought can be defined by meteorological, hydrological, agricultural, or economic conditions. In this study, drought is defined as a hydrological drought, which typically refers to periods of below-normal streamflow and/or depleted reservoir storage (Rasmusson *et al.*, 1993). Many parts of New Zealand experienced significant droughts during the summers of 1998 and 1999 that had considerable impacts on the regional and national economies. The Otago Region of the South Island was particularly hard hit by recent droughts, with precipitation and river flows in some areas the lowest on record. Although the drought appeared to have significant adverse environmental effects, the actual impacts on aquatic systems, particularly water quality and aquatic biota, are not well understood. In particular, the long-term significance of the effects and recovery are not known.

The 1998/99 summer drought provided a unique opportunity to study the actual effects of drought on low river flows and aquatic ecosystems. The Otago Regional

Council (ORC), the agency responsible for river management in the region, undertook a significant amount of flow, water quality and aquatic biological measurements throughout the region during the drought to supplement its ongoing monitoring programmes.

The objective of this study was to evaluate the effects of severe drought on regional river flows, water quality and aquatic biota, and recovery of these characteristics as the drought receded. This information is needed to assess the significance of the effects of drought and low flows, and to provide a scientific basis for setting minimum flows to protect in-stream values and uses.

FLOWS

Data collection

River flow was monitored at 12 flow gauging stations across the Otago Region that are representative of a range of climatic, hydrological, and ecological conditions (Fig. 1). These sites were chosen primarily on the basis that they are locations where minimum flow provisions in the ORC's Regional Water Plan are proposed (ORC, 1998). Flow data were collected using standard stage/discharge gauging techniques as part of the regional hydrological monitoring programme.

Analysis and results

Data for each station were stored in the ORC Time Dependent Database, TIDEDA, (Rodgers & Thompson, 1992), and hydrographs were produced to visually evaluate flows over time. For each station, the mean flow (Q_{mean}), mean annual 7-day low flow (*MALF*), 7-day low flow with a return period of 10 years ($Q_{7,10}$), and the duration of low flows during the 1998/99 drought below the *MALF* and $Q_{7,10}$ were computed in TIDEDA (Table 1). The lognormal distribution was used to estimate the $Q_{7,10}$. The *MALF* and $Q_{7,10}$ are standard indices for evaluating low flows, and use of the lognormal distribution is a common method for estimating low flows in New Zealand and many other areas of the world (Caruso, 2000a). Four stations (Catlins, Shag, Waikouaiti, and Waitahuna), however, had record lengths less than 10 years. Use of such short records provides only rough estimates of low flows for these stations (Caruso, 2000a).

The 1998/99 drought was extreme and produced flows in many rivers in the region that were extremely low for a considerable duration (four to six months) (Table 1, Figs 1 and 2). Flows in all rivers analysed were below average during the drought period (generally four months from 1 December 1998 to 1 April 1999).

The most extreme low flows occurred in northern and coastal Otago, while low flows in southern Otago and mountainous areas of the western part of the region were only slightly less than previous years. Rivers in the upper central part of Otago were intermediate but variable.

The lowest instantaneous flows recorded at gauging stations during the drought ranged from 18 l s^{-1} for the Shag River (historical Q_{mean} of 1270 l s^{-1}) to 2098 l s^{-1} for the Pomahaka River (historical Q_{mean} of 27 890 l s^{-1}) (Table 1). However, the Shag

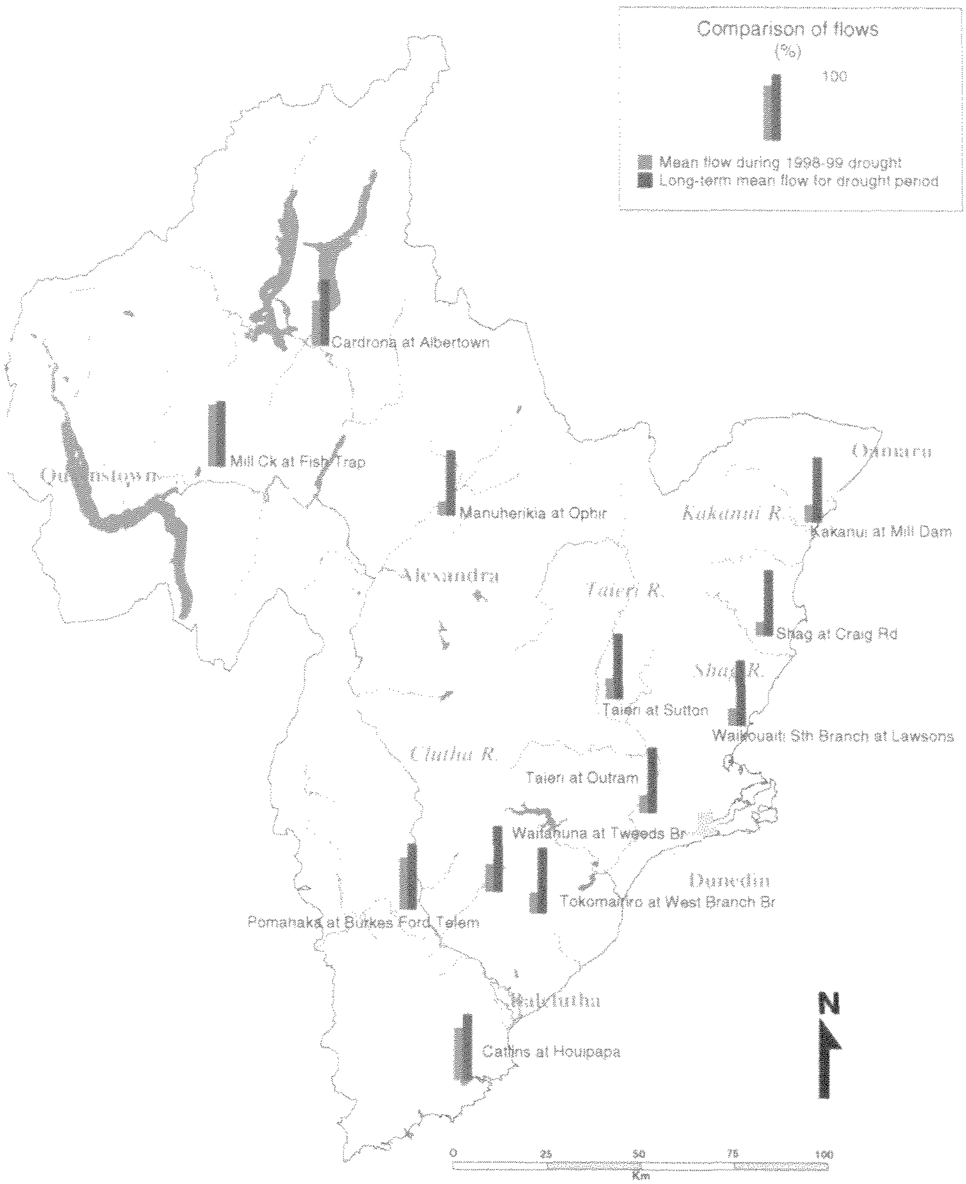

Fig. 1 Monitoring station locations in Otago for river flow, water quality and aquatic ecology and comparison of long-term mean flows (l s^{-1}) for period 1 December–1 April with 1 December 1998 to 1 April 1999.

River dried up and was a series of pools in some lower reaches downstream from the gauges in January. The smallest 7-day low flows ranged from 25 l s^{-1} for the Shag River (historical *MALF* of 284 l s^{-1} and $Q_{7,10}$ of 154 l s^{-1}) to 2224 l s^{-1} for the Pomahaka River (historical *MALF* of 4250 l s^{-1} and $Q_{7,10}$ of 2100 l s^{-1}). These values illustrate the range of size of rivers and associated flows monitored across the region.

Table 1 Historic and 1998/99 drought flow (l s^{-1}) characteristics.

Station		Period of record	Historic: Q_{mean}	*MALF*	$Q_{7,10}$	1998/99 Drought: Lowest Q	Lowest Q_7	No. days <*MALF*	No. days <$Q_{7,10}$	Rank*
Cardrona	Albert Town	1978/99	2 862	469	285	351	354	18	0	10
Catlins	Houipapa	1993/99	3 783	725	385	457	477	63	0	2
Kakanui	Mill Dam	1989/99	4 574	453	241	153	213	71	20	1
Manuherikia	Ophir	1971/99	15 307	2 200	820	4 112	592	63	20	2
Mill Creek	Fish Trap	1983/99	457	260	200	253	257	8	0	9
Pomahaka	Burkes Ford	1961/99	27 890	4 250	2 100	2 098	2 224	62	2	6
Shag	Craig Rd	1993/99	1 270	284	154	18	25	126	72	1
Taieri	Sutton	1978/99	19 650	2 640	1 250	725	884	87	53	2
Taieri	Outram	1978/99	29 100	5 490	2 500	947	1 042	98	52	1
Tokomairiro	West Branch	1981/99	820	190	109	49	58	120	43	1
Waikouaiti	Lawsons	1991/99	870	220	117	86	95	107	38	1
Waitahuna	Tweeds Bridge	1992/99	2 884	990	560	389	455	113	24	1

*Rank is the rank of low flows for 1998/99 in relation to all years, i.e. rank 1 is lowest flow on record and rank 2 is second lowest flow on record.

The duration of flows below the *MALF* and $Q_{7,10}$ was longest for the Shag River (126 and 72 days, respectively) (Table 1), and shortest for the Cardrona River and Mill Creek in the high country (0 days for both). Low flows and durations were also extreme in the Tokomairiro, Waikouaiti, Waitahuna, Taieri, Kakanui, and Manuherikia rivers, with the number of days below *MALF* greater than 60, and the number of days below $Q_{7,10} \geq 20$ at all of these sites (Table 1). Ranking of $Q_{7,10}$ values at each site showed that the 1998/99 drought resulted in the lowest or second lowest flows on record for these rivers (Table 1). Only four sites had 7-day low flows that were not the lowest or second lowest on record. Low flows in the Pomahaka and Catlins rivers in southern Otago were less than the *MALF* for long durations, but were not less than the $Q_{7,10}$ for any extended period.

There were many instances during the 1998/99 summer where permitted water abstractions were physically unable to be exercised because of lack of water in rivers. Some abstractors that could take water had to ration their water use to meet permit conditions, and some were required to cease abstracting due to minimum flow requirements. Most irrigation companies and municipal water supplies also rationed water.

A significant characteristic of the drought was the lack of any marked rainfall or freshes during January–March 1999, which resulted in the absence of any flushing flows in many catchments during these months and prolonged low-flow recessions without interruption.

Estimates of *MALF* and $Q_{7,10}$ after the 1998/99 drought at many stations also changed considerably compared to estimates prior to February 1998. For almost all stations estimates were lower as a result of the extreme nature of the drought. The largest reductions were for the Taieri River at Sutton and Outram.

Recovery Most river flows recovered or increased to values above *MALF* in mid to late April due to a series of storm events toward the end of March (Fig. 2). By June, flows in most rivers were well above *MALF* due to a series of larger storms in April and May. The storms and flows causing recovery during these months were generally

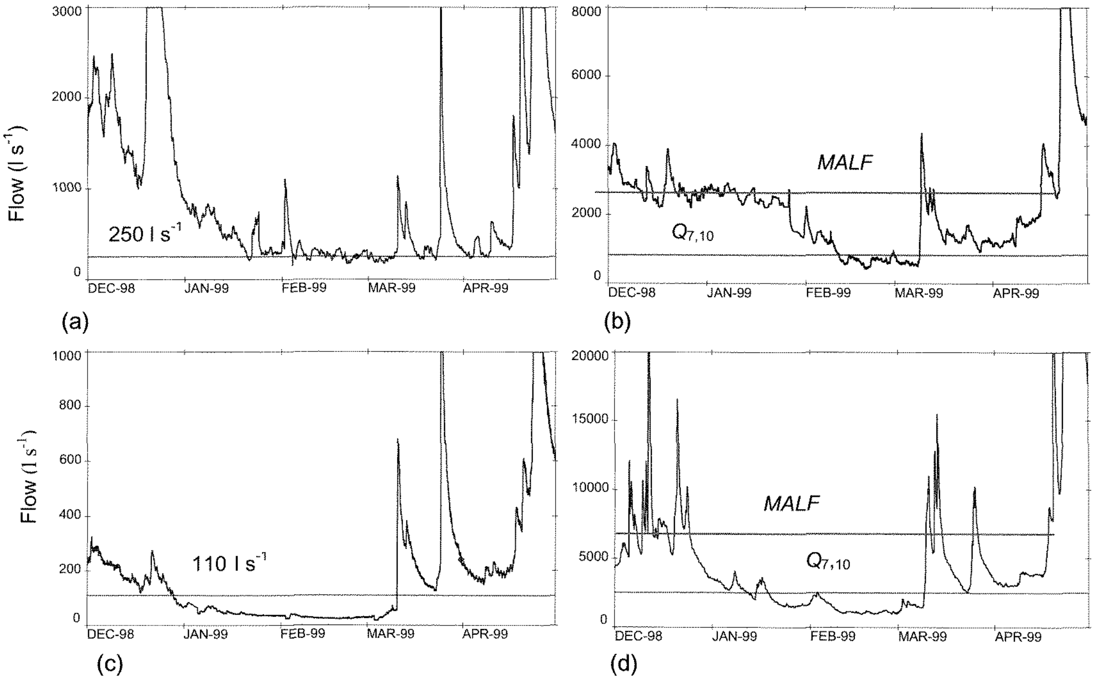

Fig. 2 River flow hydrographs at selected locations in Otago during 1998/99 drought: (a) Kakanui at Mill Dam, (b) Manuherikia at Ophir, (c) Shag at Craig Road and (d) Taieri at Outram.

not as large as historic storms and flows that occur at this time of year. During July and August, flows in southern Otago (Catlins and Pomahaka rivers) were near the long-term monthly averages. During July–September, flows in the Taieri River at Outram and the Manuherikia River were close to or higher than their mean flows, but still below the long-term averages for these months.

Flows in the Waikouaiti, Tokomairiro and Waitahuna rivers recovered more slowly. Flows remained lower than *MALF* in the Tokomairiro River until May, and in the Waitahuna River until June. The Waikouaiti River flows were still near $Q_{7,10}$ until mid July, when southerly and easterly fronts resulted in the eventual recovery of flows.

Although low flows resulting from one or two seasons of drought can be widespread and severe in many locations, they appear to be relatively short-lived with recovery of normal flow conditions occurring rapidly in autumn and winter at most locations. This indicates that potential impacts of drought on water quality and aquatic biota may also be short-lived and that, because flows can recover rapidly, aquatic communities may have a degree of resilience to drought and low flows with long-term impacts that may not be severe. The long-term effects of successive droughts over longer durations and multiple years or decades that could occur as a result of climate change might be much more severe. Riseby & Entekhabi (1996) found that a change to a drier or drought-prone climate could result in a more significant decrease in river flows than might be expected from observations of flows in isolated dry years.

WATER QUALITY

Data collection

As part of ORC's regional water quality monitoring programme, one stream grab sample was collected generally once every two months at or near each of the 12 flow stations. Analytes included total phosphorus (*TP*), total nitrogen (*TN*), faecal coliforms (*FC*), turbidity, dissolved oxygen (*DO*), pH, temperature and electrical conductivity (*EC*). Samples for *TP* and *TN* were collected in a 500-ml clear plastic bottle, refrigerated, frozen within 48 h and analysed at the Environmental Science and Research laboratory in Christchurch. Levels of *TP* and *TN* were analysed using the method discussed by Ebina *et al.* (1983). Faecal coliform samples were collected in a 500-ml sterilised bottle and analysed at the Cawthron Institute laboratory in Nelson within 24 h. Samples for turbidity were collected in a 1-l opaque plastic bottle, refrigerated and analysed within 48 h at Cawthron. Turbidity was analysed using the nephelometric method. Dissolved oxygen (YSI meter), pH (Orion 23A meter), temperature and specific conductivity (Orion 126 meter) were measured in the field.

Analysis and results

For each analyte and station, concentrations were plotted as a time series from winter/early spring 1998 to autumn/early winter 1999 and evaluated qualitatively for trends comparing values during the 1998/99 summer drought period (December–March) to values before and after the drought. For each analyte, data for all of the stations were also grouped together and nonparametric Kruskal-Wallis tests were performed to compare medians between the 1998/99 summer and the remainder of the 1998 year. These tests were also performed to compare medians for the 1998/99 summer and the medians for all previous summers for which concentrations were measured dating back to 1990. Sample sizes ranged from 25 to 30 for these tests. The 1997/98 summer was also a drought period, although it was not as severe as the 1998/99 drought. Therefore, Kruskal-Wallis tests were also performed excluding water quality data from the 1997/98 summer and comparing the 1998/99 summer to previous summers to determine if results changed or were influenced by the 1997/98 drought.

It is generally recognized that water quality variables may be auto- (or serially-) correlated when observations are taken less than about one month apart, and that they may not have significant autocorrelation when they are taken one month or more apart (Sanders *et al.*, 1983). Autocorrelation and small sample size can reduce the power of the Kruskal-Wallis tests. However, the water quality monitoring frequency of once every two months was selected for the regional program in large part to minimize serial correlation, but to still collect samples at a high enough frequency to allow for adequate evaluation of seasonal patterns and trend analysis. To confirm that autocorrelation was not a factor in significantly reducing the power of the hypothesis tests, the autocorrelation for each analyte and site was evaluated. It was found that the autocorrelation ranged from 0.008 to 0.45. The only values above 0.15 were for temperature and *DO*. Therefore most values were quite small and considered negligible for the purposes of hypothesis testing and interpretation of results. Although the Kruskal-Wallis tests were still used for temperature and *DO* to be consistent with the evaluation used for other analytes, the potential influence of the autocorrelation on the results was assessed.

In addition, the value of hypothesis tests can be enhanced by also reporting the estimated confidence interval around the difference between the two sample means, or by also reporting the *P* value of the test for the Type I error risk (Ward *et al.*, 1990). Therefore, the *P* values were reported for all significant test results. A power analysis was not explicitly performed as part of this study.

Temperature The highest temperatures during the drought were recorded in February at most sites, although the highest values occurred in January, or were elevated as early as December at a few sites (selected sites are shown in Fig. 3(a)). The only rivers that had temperatures exceeding 20°C were the Waitahuna, Shag, Kakanui and Taieri at Outram. The highest temperature recorded was 29°C on 8 February in the

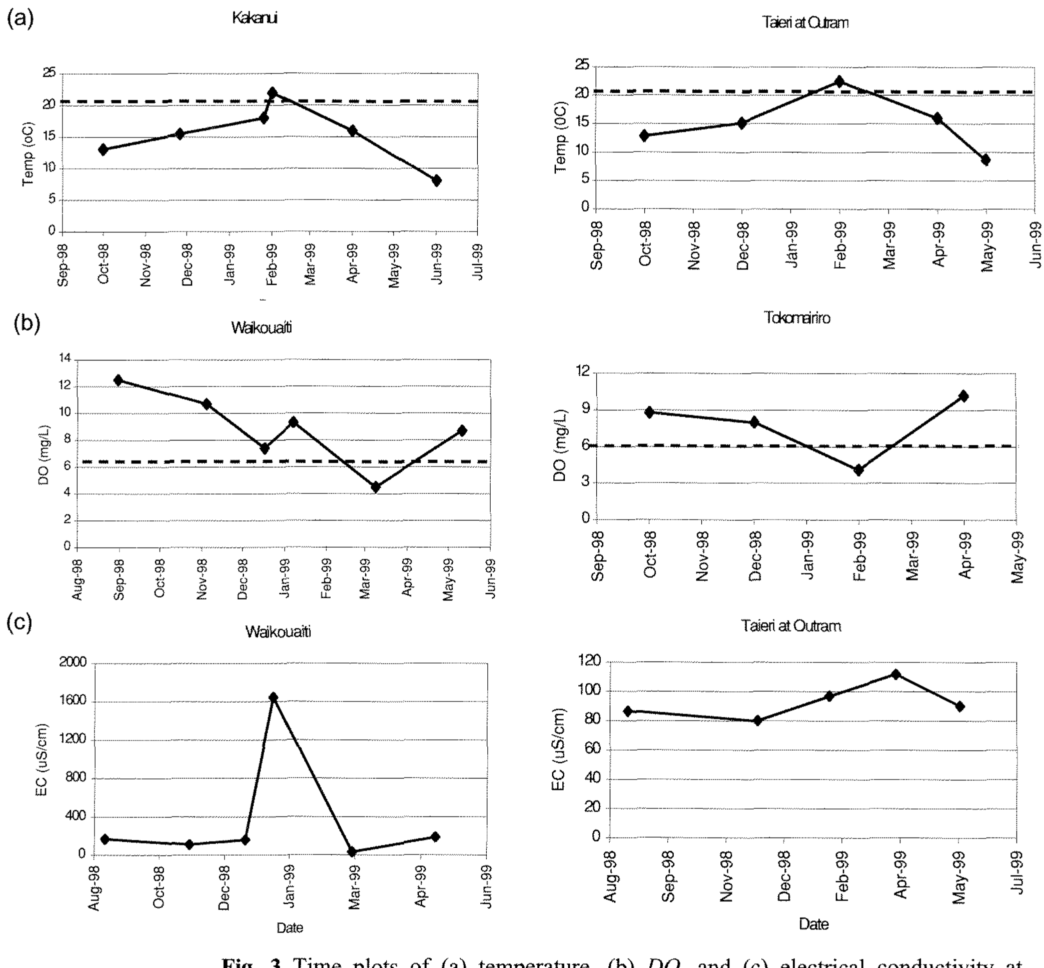

Fig. 3 Time plots of (a) temperature, (b) *DO*, and (c) electrical conductivity at selected stations during 1998/99 drought.

Shag River at Goodwood Pump. Due to the bimonthly sampling regime, it is not known how long temperatures remained above 20°C at those sites. Other studies have indicated that water temperature can have significant spatial and temporal variability (Mosley, 1982). Variability in braided channels can be due in part to smaller tributaries sometimes having lower temperatures than the main channel, and low flows being cooler than higher flows, because of the seepage of cool underflow and groundwater from the streambed during baseflow conditions (Grant, 1977; Mosley, 1983). Such channels can serve as potential refuges for fish, for which the high temperatures elsewhere would be lethal.

A continuous temperature probe was installed during the drought in the Kakanui River at Clifton Falls (farther upstream of Mill Dam) to evaluate the temporal patterns and variability of temperature during the drought. Temperature measurements at that location fluctuated around, but were often higher than, 20°C from January to March, with considerable diurnal fluctuations (Fig. 4). Temperatures exceeded 20°C for 29 days, or 19% of the time, between 1 December 1998 and 30 April 1999. The mean temperature over this period was 16.5°C and the maximum was 25.6°C. Values decreased consistently below 20°C through April. These results reflect typical seasonal patterns and may not necessarily be directly related to the drought (Mosley, 1983). However, the duration of elevated temperatures, which could increase during drought, is a very important factor contributing to impacts on aquatic life, particularly native fish (Richardson *et al.*, 1994).

Results of the Kruskal-Wallis test indicated that there was no significant difference ($P < 0.05$) in median temperatures for the group of sites between summer 1998/99 and previous summers from 1990 to 1997/98. The test showed that, given the relatively small sample size (28), there were insufficient data to reject the null hypothesis that the median temperatures were equal. Results of the test did not change when data from summer 1997/98 were excluded. The autocorrelation of the temporal temperature data observed (average of 0.45 for all stations) can reduce the power and confidence of these test results. However, median and maximum temperatures at most stations during the drought were the highest on record.

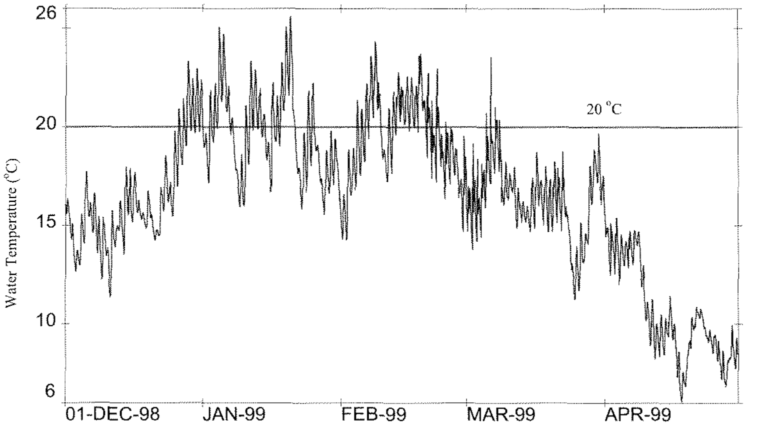

Fig. 4 Time plot of continuous temperature measurements from 1 December 1998 to 30 April 1999 in the Kakanui River at Clifton Falls.

Stream temperatures are influenced by direct radiation from energy sources such as the sun and atmosphere, thermal inertia of the stream, and ambient air temperature (Mosley, 1983). Thermal inertia (resistance to temperature change) of a stream increases with stream size/depth. High abstraction rates can reduce water depths and increase temperatures (Hockey *et al.*, 1982; Mosley, 1983). The degree to which abstractions during the drought increased stream temperatures would depend on the proportional amount of abstraction compared to streamflow and channel geometry/ riparian factors (Hockey *et al.*, 1982; Mosley, 1983). However, abstractions in many locations were minimal due to the extreme low flows.

Dissolved oxygen As for temperature, the expected seasonal pattern of decreasing *DO* during the summer in relation to increasing temperatures was observed at most sites (Fig. 3(b)). Although bimonthly sampling at individual stations does not provide a good quantitative basis for temporal trend analysis or comparisons, it does provide an indication of changes over time and conditions before, during and after the drought.

The timing of the lowest values varied among sites, ranging from January to March. The lowest values fell below the Australia and New Zealand Environment and Conservation Council (1999) guideline of 6 mg l^{-1} for aquatic life only in the Tokomairiro and Waikouaiti rivers. In the Shag River *DO* values decreased to just above 6 mg l^{-1} in March; they decreased only slightly and were relatively consistent in the Cardrona, Kakanui and Pomahaka rivers and in the Taieri at Middlemarch; and they increased at the Taieri River at Stonehenge. This latter location is far upstream in a tussock, high country catchment that was impacted by the drought. Therefore, the reason for the increase in *DO* is not known. On 3 March the water supply from the Shag River at the Goodwood Pump was discoloured grey due to very low *DO*.

As for temperature, the Kruskal-Wallis test indicated that there was no significant difference ($P < 0.05$) in median *DO* values between the summer of 1998/99 and previous summers. There were insufficient data to reject the null hypothesis that *DO* values were equal. Results were the same when data from the summer of 1997/98 were excluded. The autocorrelation of the temporal *DO* data measured (average of 0.4 for all stations) can reduce the power and confidence of these test results.

pH Results for pH varied considerably among sites. However, no values were outside the range acceptable for most beneficial uses (6.5–9.5). Values tended to increase in January or February with slight decreases later in the season at almost half of the sites, including the Kakanui River. For the other sites, such as the Shag River, pH generally decreased in January or February and either remained lower or increased slightly later in the season. Values remained steady in the Taieri River at Stonehenge and at Outram over the period.

There was no significant difference ($P < 0.05$) in median pH values for the group of sites between the drought and the rest of the year or other summers, including when the 1997/98 summer was excluded (Table 2). Differences could not be distinguished based on the data collected.

Electrical conductivity *EC* generally increased during the 1998/99 summer and showed a significant peak at many locations, although the exact timing of the peak varied between sites (Fig. 3(c)). The *EC* values increased somewhat in the Tokomairiro River, Taieri at Outram and Mill Creek in February and March compared

Table 2 Median values for surface water quality analytes and *MCI* by period, significant ($P < 0.05$) differences based on Kruskal-Wallis tests, and *P* values for differences.

Analyte	Period: Summer 1998/99	Winter 1998	Other* 1990/98	Significant diff. summer 1998/99 & winter 1998	*P* value	Significant diff. summer 1998/99 & other 1990/98	*P* value
Temperature (°C)	15.5	7.2	15	8.3	<0.0001		
DO (mg l^{-1})	9.95	11.7	9.9	1.75	<0.0001		
pH	7.6	7.5	7.5				
EC (µs cm^{-1})	106	106	93				
TP (mg l^{-1})	0.019	0.06	0.036	0.041	0.0034	0.017	0.0055
TN (mg l^{-1})	0.22	1	0.315	0.78	<0.0001		
FC (cfu 100 ml^{-1})	260	68	93	192	0.0007	167	0.0191
Turbidity (NTU)	1.8	6.8	1.9	5	<0.0001		
MCI	87.5	N/A	92*				

Analytes defined in text; *MCI* = Macroinvertebrate Community Index.
*Other for all analytes includes summers only (1 December–31 March), except *MCI* which includes all other data.

to December. These peaks probably resulted from a concentration of dissolved solids during the unusually low flows and from increased effects of evaporation, as well as greater effects of groundwater inputs with higher ion concentrations. They might also be caused by additional inputs into the river systems from point sources or stock accessing water during summer.

However, at three other sites that were not severely impacted by the drought and low flows (Cardrona, Catlins and Waitahuna), *EC* remained fairly constant from August to May. In the Cardrona River, which is representative of a high country river, *EC* remained between 75 and 100 µS cm^{-1}. In the Catlins River, which represents a lowland, non-agricultural and bush-covered catchment in southern Otago, *EC* remained between 9.5 and 12.5 µS cm^{-1} over the period.

Although the time plots showed that *EC* generally increased during the 1998/99 summer, results of the Kruskal-Wallis test indicated that, based on the data collected, there was no significant difference ($P < 0.05$) in median *EC* concentrations for the group of sites between the drought period and the rest of the year or previous summers. These results did not change when the results for the summer of 1997/98 were excluded.

Total phosphorus For most sites *TP* was either low, relatively constant, or decreased somewhat during the drought period (Fig. 5(a)). Values were below the Australia and New Zealand Environment and Conservation Council (1999) guideline of 0.1 mg l^{-1} for aquatic ecosystems for all of these cases. The lack of storm events and runoff inputs from diffuse sources, including fertilizers and livestock waste, could account for these results. However, the pattern was different for a number of other locations. In four locations *TP* values increased during March and April to values below the guideline. In the Tokomairiro River values increased considerably to 0.24 mg l^{-1} in February and were still elevated in April. These were the highest values observed during the drought. However, they decreased again below the guideline in June. This river appears to have a particular source of P, such as a point source

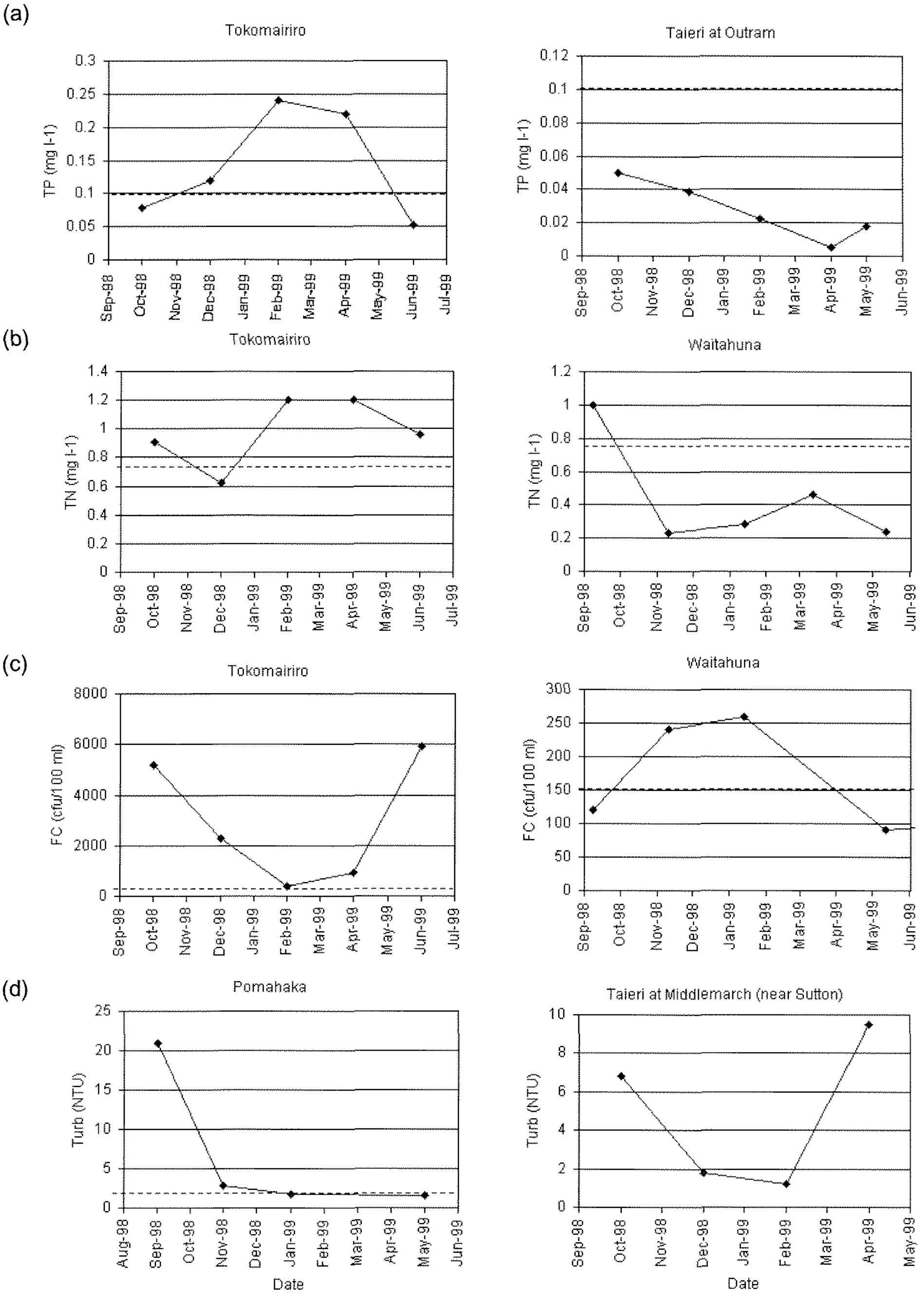

Fig. 5 Time plots of (a) *TP*, (b) *TN*, (c) *FC* and (d) turbidity at selected stations during 1998/99 drought.

discharge or livestock and/or animal waste in the stream, that impacts its water quality under low-flow conditions.

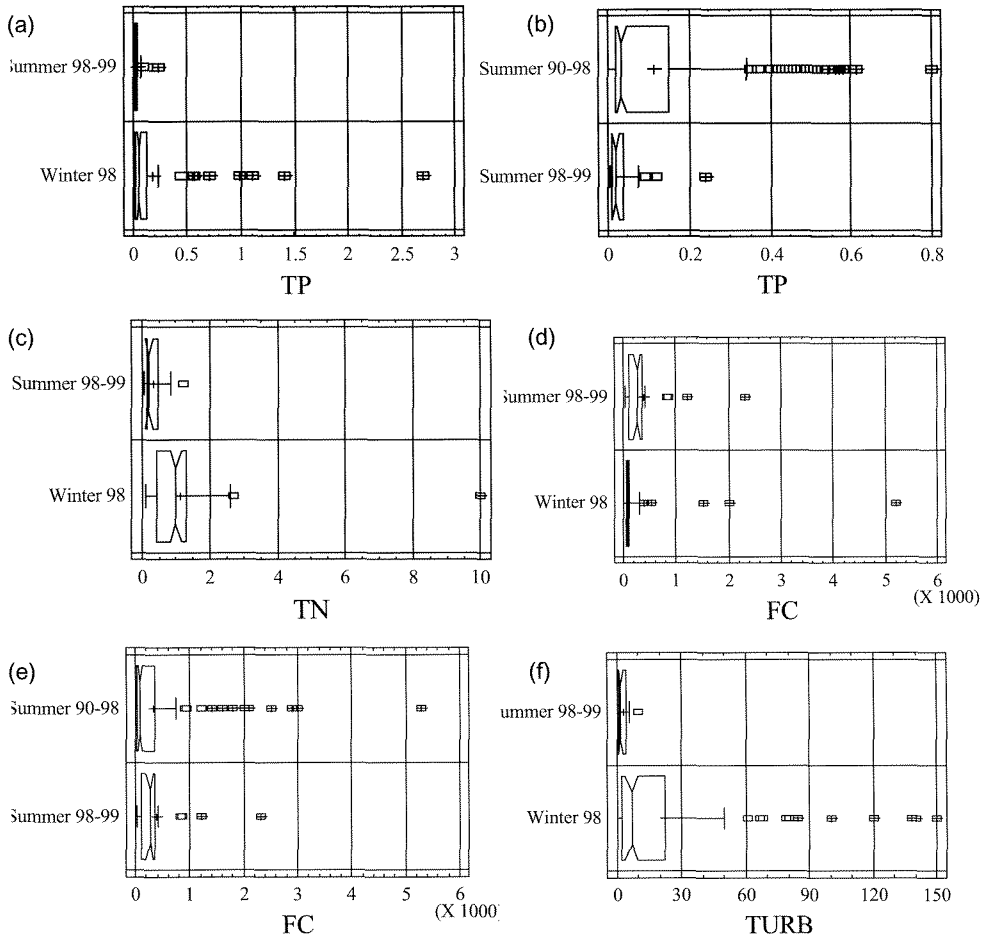

Fig. 6 Box plots of (a) *TP* concentrations (mg l^{-1}) for summer 1998/99 and remainder of year, (b) *TP* concentrations (mg l^{-1}) for summers 1990–1998 and summer 1998/99, (c) *TN* concentrations (mg l^{-1}) for summer 1998/99 and remainder of year, (d) *FC* concentrations (cfu 100 ml^{-1}) for summer 1998/99 and remainder of year, (e) *FC* concentrations (cfu 100 ml^{-1}) for summers 1990–1998 and summer 1998/99, and (f) turbidity concentrations (NTU) for summer 1998/99 and remainder of year.

Based on the data collected, the Kruskal–Wallis test indicated that the median *TP* concentration during the 1998/99 drought (0.019 mg l^{-1}) was significantly lower ($P < 0.05$) than during the remainder of 1998 (0.06 mg l^{-1}) (Table 2 and Fig. 6(a)) and previous summers, including the 1997/98 summer (0.036 mg l^{-1}) (Fig. 6(b)).

Total nitrogen Like *TP*, *TN* was either low, relatively constant, or decreased somewhat in most rivers during the drought (Fig. 5(b)). For all of these cases, values were below the Australia and New Zealand Environment and Conservation Council (1999) guideline of 0.75 mg l^{-1} for aquatic ecosystems. Again, the lack of storm events and runoff inputs from diffuse pollution sources could explain these results. For three locations, however, the pattern was different. Values increased slightly above the guideline in February in Mill Creek, and increased to 0.48 mg l^{-1} in the Taieri River at Stonehenge. Values increased to 1.2 mg l^{-1} in February and April in the Tokomairiro River, which was the highest value measured during the drought. By June *TN* decreased to 0.98 mg l^{-1} at this location. As for *TP*, these rivers could have point source discharges or livestock/animal waste in the stream increasing values during low flows.

The Kruskal-Wallis test indicated that, using the data collected, the median *TN* value during the drought (0.22 mg l^{-1}) was significantly lower ($P < 0.05$) than during the rest of the year (1.0 mg l^{-1}) (Table 2 and Fig. 6(c)), but not lower than during previous summers, including the 1997/98 summer.

Faecal coliform *FC* increased considerably during the drought and low flows at most stations, with many locations exceeding the guideline for contact recreation/ bathing (median of 150 colony forming units [cfu] 100 ml^{-1} over the bathing season; Australia and New Zealand Environment and Conservation Council, 1999) (Fig. 5(c)). Values typically started to increase in December and were highest in January or February. In the Catlins River, values were low through January and increased to >1200 cfu 100 ml^{-1} from March to May. In Mill Creek, values increased to >800 cfu 100 ml^{-1} in December and did not decrease below that value until April. Elevated values could result from reduced river assimilation capacity during low flows, individual pollution events, and direct access to streams by livestock and waste deposition in or near the watercourses, particularly when the animals used the waterways as a drinking water source during the hot, dry summer drought conditions. Although livestock accessing watercourses during drought can increase *FC* numbers considerably in many rivers, they do not appear to increase *TP* and *TN* values in most locations. High concentrations of these analytes appear to be derived mainly from diffuse sources outside of the channels during higher flows.

The Pomahaka River and the Taieri River at Outram were unusual in that *FC* numbers were very high prior to summer and decreased to below the guideline during the drought. In addition, the Tokomairaro River was extremely high in October (>4000 cfu) and decreased to concentrations only slightly greater than the guideline in February. Values increased considerably again in June. The reason for the different *FC* characteristics of these rivers is not clear. One possibility is that livestock are not accessing these rivers directly and animal waste is not accumulating and causing increases in *FC* during low flows in summer. This could be particularly true for the Pomahaka and Taieri rivers, which are larger, deeper rivers that livestock do not access as much as smaller streams. Livestock in these areas might be restricted to grazing in paddocks adjacent to or farther away from the rivers. In these cases, *FC* counts might only be high when storm events occur and surface runoff transports contaminants from diffuse animal waste sources to the watercourses.

Based on the monitoring results, the Kruskal-Wallis test indicated that the median *FC* concentration was significantly higher ($P < 0.05$) during the 1998/99 drought (260 cfu 100 ml^{-1}) than during the rest of the year (68 cfu 100 ml^{-1}, Fig. 6(d)) and previous summers (median of 93 cfu 100 ml^{-1}, Fig. 6(e)). These results did not change when the results for summer 1997/98 were excluded.

Turbidity Turbidity results during the drought varied considerably across the region. At most locations turbidity decreased during the summer when flows were low, in some cases to below the Australia and New Zealand Environment and Conservation Council (1999) guideline of 2 nephelometric turbidity units (NTU) for aesthetics and aquatic ecosystems (Fig. 5(d)). This pattern can result from the lack of storm events that cause runoff and associated erosion of solids transported to the watercourses during the drought period. However, the lowest values in the Waitahuna, Catlins (which decreased during early summer and then increased), Manuherikia and Pomahaka rivers still generally exceeded the guideline.

For two stations, turbidity followed a similar pattern to *FC*, increasing and peaking during the summer and low-flow conditions. This relationship can result from bacteria associated with animal waste that forms part of the particulate matter load in some rivers. Turbidity values increased in the Shag River and in the Taieri River at Stonehenge (where it also exceeded the guideline during summer).

Turbidity in Mill Creek increased only slightly during the summer and was consistently above the guideline. For the Taieri River at Outram, results varied considerably over the period around the guideline. Turbidity had a consistent decreasing trend in the Tokomairiro River through the period, but was always above 2 NTU. Values were generally highest during the drought period in Mill Creek and in the Catlins River. Mill Creek can be turbid as a result of livestock in the channel and stream bank erosion and sediment transport (Caruso, 2000b). High turbidity in the Catlins River can be a natural characteristic resulting from decaying vegetation and organic inputs from the predominantly bush catchment.

Based on the data collected, the Kruskal-Wallis test indicated that the median turbidity for the group of stations was significantly lower ($P < 0.05$) during the drought (1.8 NTU) than during the remainder of the year (6.8 NTU, Fig. 6(f) and Table 2), but was not different from that in previous summers.

Recovery Although water temperatures were relatively high during the 1998/99 drought, they decreased following the typical annual pattern with values dropping below 20°C in April (Fig. 3(a)). The highest temperatures during the drought at the Kakanui site lasted only one to two days (Fig. 4). The extremely high values of short duration did not appear to delay temperature recovery. The low *DO* values in the Tokomairiro and Waikouaiti rivers increased above the guideline in April (Fig. 3(b)).

Total nitrogen and *TP* values in the Tokomairiro and Pomahaka rivers decreased by May or June (Figs 5(a) and (b)). These decreases could have resulted from dilution of concentrations from moderate precipitation and runoff that did not cause additional nonpoint source loadings to the rivers. The common elevated *FC* concentrations decreased significantly and/or complied with guidelines at most sites by April (Fig. 5(c)). The exceptions were the Tokomairiro and Catlins rivers and Mill Creek. It is suspected that unauthorised discharges or stock in the waterways continued to cause high values at these sites, although values in the Catlins River are not easily explained. Turbidity tended to return to pre-drought values in most locations by June, with the exception of the Tokomairiro, Pomahaka, Waitahuna and Cardrona rivers, where values remained relatively low through April and June (Fig. 5(d)). The low values at these locations could reflect the dilution of solids with only moderate precipitation and runoff restoring flows, without the large storms that could cause more erosion and sediment loading to the rivers.

AQUATIC ECOLOGY

Data collection

Aquatic biology was monitored at or near the water quality/flow stations twice per year in March/April and September/October. At some locations, however, additional monitoring was performed specifically during the 1998/99 drought period. At each site, stream habitat conditions and changes over time were assessed and recorded, including the substratum, current velocity, depth of water, cover, vegetation, and shade. Kick sampling in riffles was used to collect single (400 ml volume) samples of streambed fine matter at each site. This involves disturbing the stream substrata by foot, covering as many microhabitats as possible. Samples of the disturbed material are collected by placing a 0.5 mm mesh net immediately downstream as the substrata are disturbed. Fine material is retained for the sample. Analysis was performed at ORC and involved identification of macroinvertebrate and algal taxa under a microscope, which were recorded semi-quantitatively.

The percentage cover of periphyton was also recorded at each station. The abundance of fish species, fish movement to pool refuges, fish strandings, and fish kills were all observed at each location. Reports from other organizations and the public on fish and other water quality problems (such as algal blooms, discoloration, and odours) were also encouraged and followed up by site visits.

Data analysis and results

The macroinvertebrate community index (*MCI*; Stark, 1985) was calculated for each station. This index reflects water quality and physical habitat conditions using the known tolerance of aquatic benthic macroinvertebrates. Time series plots of *MCI* values were constructed for selected stations and evaluated qualitatively comparing values before, during and after the 1998/99 drought. Values of *MCI* for selected stations were also plotted against the low flow on the date sampled (as a proportion of *MALF*), and linear regression was performed to evaluate the relationship between these variables and the influence of low flows on *MCI* values. The *MCI* data for all stations were also grouped together and Kruskal-Wallis tests performed to compare values between the 1998/99 summer and previous summers. The percent cover of periphyton, abundance of fish species, fish movement to pool refuges, and fish strandings and kills were assessed over time at each location. Reports from other organisations and the public on fish and water quality problems were also received and evaluated.

Macroinvertebrate community index *MCI* values generally decreased at most sites during the drought and were somewhat lower (10–15%) than values during non-drought periods. The Kakanui, Tokomairiro and Pomahaka rivers had the most obvious decreasing trends (Fig. 7). Values for the Kakanui, Shag, Tokomairiro and Manuherikia rivers during the drought were the lowest ever recorded. Values did not decrease in Mill Creek nor in the Cardrona and Catlins rivers. Although quantitative, site-specific analyses were limited by the small number of biological sampling events (six) at each site, there appear to have been only moderate (not significant) decreases in *MCI* as flows fell below *MALF*.

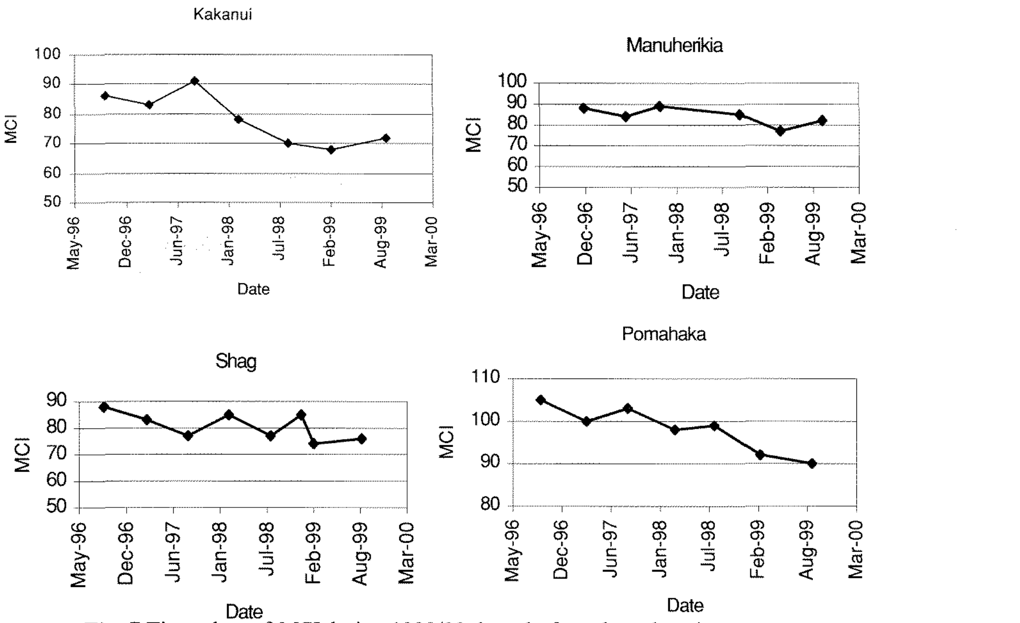

Fig. 7 Time plots of *MCI* during 1998/99 drought for selected stations.

Relationships between *MCI* and flow on sample date/*MALF* at four of the sites evaluated were generally not strong. The highest R^2 value was 0.76 for the Kakanui River, and the lowest was 0.23 for the Shag River (Fig. 8). Because *MCI* does not appear to be directly related to flow, Otago macroinvertebrate communities may have a degree of resilience to drought conditions.

There was evidence of a region-wide decrease in *MCI* values during the summer of 1998/99 based on mean *MCI* values for each year: 85.4 for 1996/97, 88.3 for 1997/98, and 84.0 for 1998/99. This is based on 153- 160 samples each year, the majority of which were from long-term sampling sites sampled at approximately the same time each year. Based on this large dataset, however, the Kruskal-Wallis test showed that the median *MCI* for the 1998/99 drought was not significantly different ($P < 0.05$) than the median for the pre-drought period for the group of selected stations analysed.

High temperatures during summer and drought periods can also influence benthic macroinvertebrate populations and *MCI* values. Quinn *et al.* (1994) found that the upper thermal tolerances (temperatures that were lethal to 50% of the test organisms) of 12 New Zealand invertebrate species ranged from 24.5 to >34°C. This suggests that temperatures occurring in summer in many Otago streams and rivers can limit the abundance and distribution of some species. However, benthic communities in Otago during the 1998/99 drought do not appear to have been significantly affected by high temperatures.

Algae Algal blooms were observed in several rivers during the drought period. The worst case covered 80% of the Shag River bed at the Goodwood Pump in early February. Algae covered approximately 50% of the bed of some reaches of the

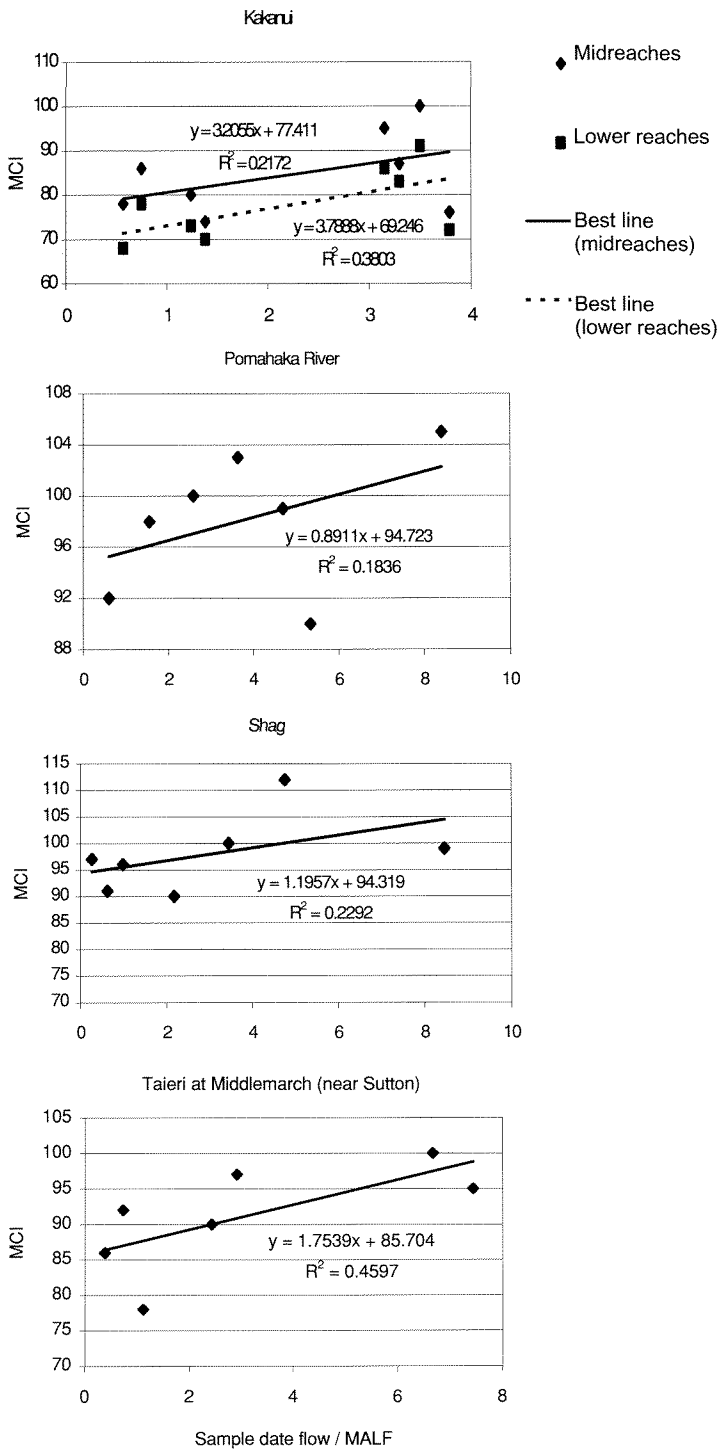

Fig. 8 *MCI vs* flow proportion of *MALF* for selected stations.

Kakanui River. However, no complaints were received by ORC from the public regarding unsightly algal growth over the summer period.

The time period between freshes is possibly the most important limiting factor for algal growth in rivers. Clausen & Biggs (1996, 1997) found that the average annual frequency at which flows exceed three times the median flow (FRE_3) is the most useful statistic for classifying rivers according to the habitat for benthic biota (periphyton and invertebrates). Therefore, FRE_3 is a measure of the frequency of floods and freshes that affect river biota. In many rivers in Otago the period January–March exhibited a relatively consistent recession of flows with limited freshes. The controlling factor in these rivers appears to be the occurrence of storms that produce significant runoff, rather than the level of abstraction. However, small flushing flows lower than FRE_3 could benefit benthic populations and habitat.

Fish Although temperatures were elevated in many locations, widespread fish kills were not observed or reported in rivers in the region. This was probably due to the presence of fish refuges in pool habitats where temperatures decrease with depth. Cooler water in some areas from underflow through gravels and groundwater inputs could also play a role (Mosley, 1983). Richardson *et al.* (1994) reported that upper lethal temperatures for eight common New Zealand native fish species range from 28.3 to 39.7°C. Church *et al.* (1979) reported that lethal temperatures for brown and rainbow trout are 23.8 and 29.4°C, respectively. Lethal temperatures depend on time of exposure and other water quality factors at the time of exposure. Therefore, although 20°C is not preferred for some species of native fish and trout, it is not necessarily lethal. In general, water temperatures in most rivers during the drought were not high enough for a long enough period to cause a significant number of fish kills.

However, some adverse effects, including isolated fish kills, were reported in specific locations. In March the lower Shag River was a series of isolated pools with some fish strandings and kills reported, including trout and native species. Although some lower reaches of the Shag River dried up, there were higher concentrations of fish (and reports of good fishing) due to migration to pool refuges in mid reaches. Fish deaths (natives and freshwater crayfish) were reported in several tributaries of the Taieri River from January to March with flows well below $Q_{7,10}$. Trout and eel deaths were reported in the upper Taieri River at Middlemarch and near Hyde in mid February. In the lower Taieri River, dead fish were reported near Outram in January when flows were below $Q_{7,10}$. In the Manuherikia River some trout, particularly juveniles, were stranded in backwaters along the entire river that were no longer connected to the mainstem in January and February. The only fish deaths, however, involved adult trout at Alexandra in January. No effects on fish were reported in the Kakanui River, but damage to banks and beds due to increased stock pressure was observed in some areas. Fishing generally remained good in the Pomahaka River throughout the period, and no adverse effects occurred in the other rivers in southern Otago or the mountainous western areas.

Fish and habitat data for trout, salmon and natives, their preferred habitats, food producing areas, and the flows required to sustain these fisheries are generally not available for most Otago rivers. Campbell & Scott (1984) found that most brown trout moved to pools in the Silverstream, a tributary of the Taieri River, when the flow velocity decreased to a threshold value of 0.30 m s^{-1}. Information from other parts of

New Zealand suggests that minimum habitat requirements for trout can be below *MALF* (Jowett, 1993, 1997). In addition, the National Institute of Water and Atmospheric Research (NIWA) recommended 300–350 l s^{-1} to maintain trout populations in the Kakanui River (ORC, 1998). The *MALF* is 453 l s^{-1} at Mill Dam and 590 l s^{-1} at Clifton Falls, approximately 30 and 40% higher, respectively, than the minimum flow recommended by NIWA. However, smaller river systems that have not been analysed usually require higher minimum flows in relation to *MALF* than large rivers for habitat maintenance (Jowett, 1997).

Recovery Although each river monitored has exhibited slightly different patterns in *MCI* over time, some general patterns can be observed from biomonitoring results since the end of the drought. Generally the 1999 *MCI* results were slightly lower than those of 1996–1998 and there was no significant upward trend in *MCI* values between the drought period (early 1999) and spring 1999.

Recolonization of streambed habitats by sensitive (high scoring) invertebrate species following periods of low flow would typically result in an increase in *MCI* values. During high flow events, increased current velocities scour excessive algae and sediment from the bed and redistribute sensitive invertebrate species throughout the river. During spring 1999, however, many rivers were again at relatively low flows or they had not had any recent high flow events.

In several cases the more recent decline in *MCI* values has been the result of quite minor changes in invertebrate community composition. The *MCI* data from the lower Pomahaka River, for example, shows a decline since the 1998 (pre-drought) surveys, but the changes in invertebrate community composition causing this decline have been minor. The September 1999 Pomahaka River survey results showed no significant change compared to February 1999 during the drought (Fig. 7). All surveys to date have shown high numbers of taxa (34–37), including many of the generally sensitive taxa and "healthy" *MCI* values (90 to 106) for an agricultural catchment.

Other studies have found that recovery of benthic macroinvertebrates from very dry stream conditions (Kennedy, 1955; Waters, 1964), as well as from large floods (Scrimgeour *et al.*, 1988), can be relatively rapid. Sagar (1983) demonstrated that recolonization of previously dry channels by stream invertebrates in the braided Rakaia River in New Zealand was affected mostly by flow fluctuations (freshes and floods) with drift as the main source of colonising animals and recovery in summer occurring in as little as 15 days. Therefore, the recovery time since the last flushing flow is important.

Algal blooms at several sites during the drought have been reduced or removed during the winter of 1999, but visible (normal) algal growths had begun to re-establish by spring 1999. This is a seasonal occurrence. For example, several algal taxa had become abundant on the bed of the Kakanui River (mid and lower reaches) by September 1999. Eventually such algal growths can smother river bed habitats, which can lead to reduced *MCI* values. These continuing algal growths may be limiting the recovery of the invertebrate fauna, hence the lack of significant improvement in *MCI* values.

Limited observations have shown that native and introduced fish species generally recovered fairly quickly from the drought conditions and no long-term impacts have been noted.

CONCLUSIONS

The findings of this study are consistent with many of those of other, limited studies on the effects of low flows on river ecosystems. This assessment, however, has also provided some interesting findings for specific water quality analytes and a range of biota during extreme drought and low-flow conditions on a regional scale and across a diversity of rivers and catchments. River flows that decrease significantly for prolonged periods during severe drought can affect river ecosystems in various ways that can be "river specific" and depend on the biophysical characteristics of the rivers and their catchments.

In predominantly agricultural/pastoral catchments, increased widespread bacterial contamination of rivers can occur due to greater livestock use of waterways and the lack of dilution and flushing flows during drought/low flows. This has potentially significant public health consequences. For other contaminants, particularly nitrogen and phosphorus, concentrations and loadings can decrease in many locations due to the lack of rainfall and runoff events capable of transporting these contaminants to waterways from various sources in the catchment outside of channels. Some analytes, such as total dissolved solids and pH, may not change to any considerable degree, or can be quite spatially variable.

The physical habitat and water quality changes during low flows can adversely affect aquatic biota in the short term. Although the general health of benthic macroinvertebrate communities can decrease with a lower diversity and fewer sensitive taxa, the effects do not appear to be significant in most rivers. Algal blooms will occur and can be significant in some locations with severe low flows and high temperatures, particularly in lowland agricultural catchments with low water velocities and little shade. Nutrient concentrations do not appear to be a primary contributing factor to excessive algal growth during drought because concentrations are relatively low. Greater uptake of nutrients by prolific algal growth, however, can also contribute to the lower nutrient concentrations observed. The duration of droughts appears to be a very important factor affecting the proliferation of algae. The prolonged lack of flushing flows to scour periphyton from river beds during sustained droughts is a significant problem in some locations. Fish kills can occur primarily where fish become stranded and isolated from the main flow and where there is a lack of deeper pool refuges. Temperatures in excess of 25°C can also result in isolated fish kills, but the duration of these high temperatures appears to be the most critical factor.

Although adverse effects from one or two seasons of drought on river ecosystems can be widespread and severe in some locations, they appear to be relatively short-lived with recovery occurring rapidly with increasing flows in autumn and winter at most locations. This recovery indicates a degree of resilience of aquatic ecosystems to drought and low flows with long-term impacts that are not severe. However, the long-term effects of successive droughts over longer durations and multiple years or decades that could occur as a result of climate change might be much more severe and requires further research and modelling.

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