NIWA
Taihoro Nukurangi

Ecological effects of Waikanae Water Treatment Plant abstraction

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Contents

Tables

Figures

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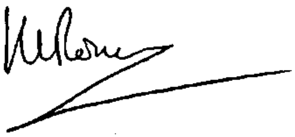

Helen Rouse

Executive summary

- The Kapiti Coast District Council (KCDC) contracted NIWA to review ecological information collected from the Waikanae River to determine whether abstraction for their water treatment plant (WTP) was having a demonstrable effect on algal and invertebrate communities. We hypothesised that abstraction could alter specific components of the hydrological regime, specifically the duration, magnitude or frequency of low flows, and that these alterations could potentially affect algal or invertebrate communities. We addressed this issue by examining 1) differences in flow indices above and below the WTP; 2) differences in algal biomass above and below the WTP, and the relationship between biomass and flow regimes; 3) differences to invertebrate communities above and below the WTP, and their relationship to flow regimes.

- Effects of abstraction on ecologically relevant flow indices was assessed, based on flows at the Greater Wellington Regional Council (GWRC) gauging site, and on synthesised flow data below the WTP. Abstraction was generally higher over late spring and summer, and the percentage abstraction of river flow was highest in late summer - early autumn, although there was considerable year-to-year variation. No significant changes were observed in hydrological flow indices above and below the WTP.

- Algal and invertebrate data from the Waikanae River, and other similar rivers in the region, were obtained from the GWRC. These data were analysed to determine whether communities differed above and below the WTP, or whether differences existed between communities below the WTP and those in other non-abstracted rivers in the region. Year-to-year variability in algal and invertebrate communities was examined to determine whether variability was higher above the WTP than below, or in other rivers not subject to abstraction. Relationships between hydrological variability and ecological variability were examined to determine whether abstraction was affecting variability in algal or invertebrate communities. Thus, a large variation in ecological communities was expected in dry years when relative abstraction was higher, compared to that in wetter years, if abstraction was having an ecological effect.

- Chlorophyll biomass data showed that abstraction was not associated with increased algal biomass, as observed values were similar to those naturally found in other sites with a similar landuse. The higher biomass found at the site below the WTP most likely reflected the assumed higher nutrient levels and increased sunlight at the lower site, which was dominated by pasture landcover. In contrast, biomass at the upper site was low, presumably reflecting increased shade, and the lower nutrient regime in the upper catchment which was dominated by native bush. Analysis of relationships between flow and chlorophyll biomass showed no significant effects of the preceding flow regime in either site in the Waikanae River.

- The Waikanae River supported a diverse invertebrate community, indicative of a river in a good ecological condition. Samples collected above the WTP differed to those from below the WTP. Invertebrate communities varied less above the WTP than below, but no relationships existed between variation in hydrology and invertebrate communities. Lack of such relationships suggested that no direct link existed between invertebrate communities and flow regimes at either location.

- Although not examined directly, it is unlikely that the WTP abstraction would limit fish communities in the river. The consented minimum flow is 750 L s^{-1}, and previous instream hydraulic habitat modelling done by GWRC showed that this flow supports a relatively high proportion of adult trout habitat. Even with the current abstraction, flows below the WTP fell below the consented minimum level only rarely (1.78% of the time), and so would have only minor effects on fish communities. Furthermore adult brown trout have a higher flow demand than many native fish, so adverse effects of the current flow regime on native fish are considered to be minor.

- Condition 8 of the Resource Consent (WGN050024[23848]) requires a monitoring programme to be implemented to determine the impacts of the WTP abstraction on water quality, algae, invertebrates and fish. Our analysis showed that the effects of abstraction on the ecological values of the Waikanae River appear minor, so the value of continued monitoring as required is questioned. Instead, it is recommended that the KCDC liaise with the GWRC to obtain a variation to the monitoring requirement, and on an algal monitoring program at two sites above the WTP and two sites below. Algal cover should be monitored fortnightly during the summer and autumn low flow period. This would not only allow successional changes of algal communities above and below the WTP to be monitored, but it would also provide useful baseline information should the river recharge with groundwater (RRwGW) option that the KCDC has been investigating go ahead.

1 Introduction

The Kapiti Coast District Council (KCDC) holds a Resource Consent (WGN050024[23848]) to take water from the Waikanae River at the Waikanae Water Treatment Plant (WTP) for public water supply purposes for Waikanae-Paraparaumu-Raumati communities. The WTP uses a run-of-river abstraction from the Waikanae River and is generally regarded as being a sound water source (Egyed~~,~~ et al. 2010). Like many run-of-river water supply schemes, it cannot cater for peak daily demand for the existing population during dry periods when the river flows are low. This is due to both the physical constraints of the river (i.e. low flows) plus the consented abstraction regime, which requires a residual minimum flow of 750 L s^{-1} in the river (unless the river naturally falls below this flow). The maximum consented take is 23,000 m^3 day^{-1} at a maximum rate of up to 463 L s^{-1} when river flows are above 1,400 L s^{-1}. Between river flows of 1,400 L s^{-1} and 1,100 L s^{-1}, the rate of take is reduced to only 350 L s^{-1}. Once the flows in the river drop below 1,100 L s^{-1}, the rate of take is required to drop proportionally such that a residual flow of 750 L s^{-1} is maintained in the river, unless the river naturally falls below 750 L s^{-1}.

Condition 8 of the Resource Consent requires preparation of a monitoring programme (Porter 2006) to determine the impacts of the water abstraction on water quality, native fish species and trout, including:

- Macroinvertebrate Community Index (MCI);
- Native fish and trout surveys;
- Monitoring methods, and frequency locations;
- Frequency and method of reporting the monitoring information to the Greater Wellington Regional Council (GWRC).

The aim of the monitoring plan was to gather biological data from 2 sites above the WTP intake and 2 sites below and to quantify any differences between these sites. The null hypothesis being tested was *there is no significant difference between measurements of any parameter between upstream and downstream sites.*

For various reasons, the proposed monitoring plan has not been undertaken. Consequently, KCDC contracted NIWA to undertake a review of all ecological information collected to date to determine whether the WTP abstraction has had a demonstrable effect on algal and invertebrate communities in the river. The scope of this work is rather different to that proposed by Porter (2006), which did not consider natural changes in the river above and below the treatment plant. Thus, if some differences in measured parameters were observed, they could have been attributed the abstraction, or to natural differences between sites. As such, a degree of ambiguity could exist on interpretation of results, as no comparison was made of other longitudinal changes in rivers without abstraction. Such a concern is particularly relevant when assessing potential changes due to abstraction, as such changes are likely to be more subtle than those associated with, for example, discharge of waste water into a river where there would be clear a priori reasons to expect differences above and below a specific point (e.g., Winterbourn and Stark 1978; Rosenberg and Resh 1993).

An alternative methodology to assess potential effects of the WTP abstraction would be to compare the temporal variability of algal and invertebrate communities in the Waikanae River (subject to abstraction) to communities not subject to abstraction either above the WTP, or in other rivers. A number of assumptions are needed for this approach, namely:

1. The degree of abstraction relative to upstream flows is not constant between years, so higher abstraction rates occur in some years, and lower rates in others;

2. If low flows were affecting algal or invertebrate communities, then the magnitude of this effect would be proportional to the level of abstraction;

3. The biota would respond in a continuous manner to changes in flow, and not to a specific flow thresholds, which would trigger changes only if passed;

4. Any effects of abstraction would manifest themselves by changing the variability of algal or invertebrate communities below the WTP, which would be greater below the WTP than above, and greater below the WTP than in rivers not affected by abstraction;

5. That each year was independent of the other years, and that the ecological communities were responding to the hydrological conditions only for the year prior to sampling, and not to previous years.

Of these assumptions, the first is easily tested by examining abstraction rates from the WTP. The second assumption – that the magnitude of this effect would be proportional to the level of abstraction – was based on examination of literature investigating interactions between invertebrate communities and low flow events. For example, habitat simulation methods (e.g. the PHABSIM part of the Instream Flow Incremental Methodology (IFIM)) model the quantity of the physical habitat at various flow levels for the species of interest (Bovee al. 1988). The basic tenet of these models is that individual taxa have specific hydraulic habitat suitability curves (e.g. Statzner and Higler 1986; Wetmore et al. 1990; Collier et al. 1995; Jowett 2000), so that the amount of suitable habitat changes with flow, which can be modelled. The resultant habitat suitability curves are used to set minimum flows to meet chosen objectives such as ensuring maintenance of sufficient habitat for specific fish species, or for maintenance of food-producing habitat for fish (e.g. Jowett and Mosley 2004).

1.1 Review of low effects

Dewson et al. (2007) conducted a review of 20 studies examining the effects of low flows on invertebrate communities. Half of these studies investigated the effects of at least a 50% reduction in flow. This represents an extreme situation that does not occur in the Waikanae River. Most of these studies also reported the effects of low flow events that had been operating over many months to years - comparable to the situation of the Waikanae WTP (in operation since 1977). Reduced discharge not surprisingly decreases water velocity, depth and wetted width. Reduced wetted width often decreases available habitat (Cowx et al. 1984; Stanley et al. 1997; Brasher 2003), lessens habitat diversity (Cazaubon and Giudicelli 1999), or generally contracts the available ecosystem size (Stanley et al. 1997).

Reduced flows can cause prolific algal and macrophyte growth, leading to dramatic diurnal variation in dissolved oxygen and pH from plant photosynthesis and respiration. Algal community composition can also change during reduced flows (McIntire 1966; Poff et al.

1990; Dewson et al. 2003; Biggs 1995), so abstraction from the Waikanae River may change algal and invertebrate communities (Suren and Riis 2010). However, relationships between reduced flow and algal communities are not always clear-cut. For example, Suren et al. (2003) found that responses of algae to reduced flow differed in rivers of contrasting enrichment. They measured substantial increases in filamentous green algae and cyanobacteria in a nutrient enriched river, whereas low biomass diatoms remained dominant throughout a 6 week period of low flow in a nearby un-enriched river.

If conditions during a low flow period become intolerable for a particular species, individuals can seek refuge, leave the stream, or die. Low flows can increase downstream drifting behaviour (e.g., Minshall and Winger 1968; Gore 1977), and invertebrates can move into the hyporheic zone (the interface between surface and ground waters) to avoid reduced flow impacts (e.g., Gilpin and Brusven 1976; Delucchi 1989). However, the responses of fauna to flow reduction are often inconsistent between streams (Armitage and Petts 1992; Castella et al. 1995; Rader and Belish 1999; Dewson et al. 2003). For example, evidence is equivocal as to whether invertebrate densities increase, decrease, or show no change with flow reduction. This is illustrated by Suren et al. (2003a) in a comparison of invertebrate densities in 2 New Zealand rivers of contrasting nutrient enrichment. Invertebrate densities increased significantly in the high enrichment river over the summer low flow period, as filamentous green algal cover increased. In contrast, the invertebrate community remained stable in a low-nutrient stream that was dominated by diatoms, the cover of which did not increase (Suren et al. 2003b).

It has also been suggested that community composition can change from one dominated by taxa preferring fast flows to one dominated by taxa suited to slower flows (Jowett 1997). However, Suren et al. (2003a) and Suren and Jowett (2006) found no large or consistent changes to either densities of individual taxa, or to biotic metrics, when invertebrate communities in the Waipara River, north of Christchurch, where exposed to flows below the Mean Annual Low Flow (MALF) which ranged for durations of 22 to 93 days. In addition, James and Suren (2009) also found that more prolonged low flows did not cause great changes to invertebrate communities. -These findings suggest that the duration of low flows may be unimportant in influencing invertebrate communities.

Given the above, we hypothesised that the WTP abstraction from the Waikanae River may alter specific components of the hydrograph and effect the duration, magnitude or frequency of low flows. This could have follow-on effects to algal and invertebrate communities. This report examines algal and invertebrate data obtained from GWRC from both the Waikanae River (with abstraction) to other rivers in the area (without abstraction). In this way, we could determine if samples collected from the Waikanae below the WTP (at Greenaway Rd) displayed any effects that could be attributed to abstraction.

This report examined three components:

1. Analysis of effects of abstraction on different hydrological indices, based on flows recorded at the GWRC flow site, and on synthesised residual flow data below the WTP;

2. Examination of algal data collected from the Waikanae River and other rivers in the region, and a comparison of samples collected below the WTP to other

samples collected above, and to other rivers without abstraction. If abstraction was affecting biomass, this would be higher below the WTP than above, and be higher below the WTP than in other rivers not subject to abstraction.

3. Repeat the above analysis using invertebrate data collected by the GWRC.

We compared year-to-year variability of algal biomass and invertebrate communities to determine whether variability was higher in the Waikanae River below the WTP than above, or at other sites. We also related within-river variability to calculated flow indices in the Waikanae River. In this way, we asked the question *what effect has the WTP on the overall temporal variability of algal and invertebrate communities, and does the abstraction affect this variability*? Thus, in drier years, when the relative abstraction is higher, we would expect a greater change to algal or invertebrate communities than in wetter years, if abstraction was affecting these communities.

2 Methods

2.1 Hydrological effects of abstraction

The GWRC maintains a hydrological monitoring site located immediately above the WTP that has been operating since March 1975. Records of cumulative water takes at five minute intervals have been kept since 2004. Abstraction rates were calculated from this data, and residual flows below the WTP were derived by subtracting the abstraction rates from the upstream flows. The residual flow was then compared to the upstream flow. Initial examination of the abstraction data showed many records (7.6% of the total number) of either zero values, or low abstraction rates (< 50 L s^{-1}). These most likely reflected errors in the data, and so were replaced with the default mean abstraction rate (161 L s^{-1}). Eleven ecologically relevant flow indices were calculated, including those summarising the river's overall flow regime (e.g., mean and median flow), the number of floods with a magnitude of three times the median flow (called FRE3) and low flows (both magnitude and duration). Low flow indices included the instantaneous low flow, the seven-day mean annual low flow, the minimum flow, a number of low flow events (defined as flows less than the seven-day minimum flow), and the duration of low flow events (Table 2-1).

Table 2-1: List of flow indices calculated from the hydrological monitoring station above the WTP. The same statistics were also derived for flows below the WTP, based on the natural flow record minus the recorded abstraction rates.

Type of flow index	Name	Abbreviation	Description
Flow	Max flow	Qmax	The maximum instantaneous flow
	Mean flow	Qmean	The mean annual flow (Jan – Dec)
	Median Flow	Q_{50}	The median annual flow (Jan – Dec)
Flood Frequency	FRE3 (floods/y)	FRE3	Number of floods > 3 × median flow per year
Low Flow Magnitude	7day MALF	MALF	The lowest mean 7-day low flow period
	Lower quartile	Q_{25}	Flows that are exceeded 75% of the time
	Lowest inst. flow	LowQ_Inst	The minimum instantaneous flow
Low Flow Duration	Ave duration <7d MALF	Dur_MALF	Average duration of flows less than the 7 day MALF
	Ave duration in lower quartile	Dur_{25}	Average duration of flows less than flows that are exceeded 75% of the time
	Max duration (days)	DurMALF_max	Maximum duration of a low flow event less than the 7 day MALF
	Max duration (days)	Dur_{25}_max	Maximum duration of a low flow event less than flows that are exceeded 75% of the time

Low flow indices were calculated as 'water years' from 1 July to 30 June, to encompass the summer and autumn when low-flows predominate. High flow indices were calculated from 1 January to 31 December, to encompass winter high flows. These statistics were calculated for both the flow above the WTP, and for the derived flow below. Paired *t*-tests were performed on the different flow indices using years as replicates to determine whether significant differences existed above and below the WTP. An ordination (Non-metric Multi-Dimensional Scaling: NMDS) was then performed on the flow indices (Clarke and Warwick 2001). This statistical technique graphically represents the location of samples based on the similarity of their measured flow indices. Samples with similar indices are grouped on an *x-y* graph, while samples with different indices are far apart. Another statistical technique, Analysis of Similarities (ANOSIM), was then used to test whether any significant differences existed between two or more groups of sampling units. In this case, the groups represented samples collected from above and below the WTP. ANOSIM produces a statistic, *R*, which indicates the magnitude of difference among groups of samples. An *R* of 1 indicates that the flow indices differed among defined groups, and an *R* of 0 indicates no difference among groups. The statistical significance of *R* was tested by permutation tests. Both ANOSIM and NMDS are based on calculations of similarity between samples, which were computed using the Euclidian distance measure. Prior to this, all flow indices were normalised according to their mean. Similarity indices such as Euclidian distance are used to quantify the compositional similarity (in this case the flow indices) between two different sites. This distance measure is not bounded by numerical limits: the more dissimilar two sites are, the higher their distance measure, while the more similar they are, the smaller the measure. Based on these analyses, and using professional judgement and the literature described in section 1 above, comments could be made on the likelihood of these flow changes having an ecological impact on the Waikanae River.

2.2 Ecological effects of abstraction

The GWRC monitors invertebrate and algal communities annually at 56 rivers throughout the region. Included in this monitoring program are two sites on the Waikanae River: an upper site near the Mangaone walkway above the WTP, and a lower site opposite Greenaway Rd below State Highway 1. Data obtained from these sites was compared to data from other rivers in the region to determine whether abstraction from the Waikanae was associated with demonstrable changes to ecological communities below the WTP. Samples were generally collected in late summer (February), and early autumn (March and April), making them ideally suited to assess likely impacts of abstraction, as this is the time when the Waikanae usually has the lowest flows. All monitoring sites were assigned to their respective River Environment Classification (REC) codes.

Table 2-2: REC classification levels, categories and their notation, mapping characteristics and class assignment criteria.

Classification level	Classes	Notation	Mapping characteristics	Class assignment criteria
1. Climate	warm extremely wet Warm wet Warm Dry Cool extremely wet Cool wet Col Dry	WX WW WD CX CW CD	mean annual precipitation, mean annual potential evapotranspiration, and mean annual temperature	warm: mean annual temperature > 12℃ cool: mean annual temperature < 12℃ extremely wet: mean annual effective precipitation > 1500 mm wet: mean annual effective precipitation 500 – 1500 mm dry: mean annual effective precipitation < 500
2. Source of flow	Mountain| Hill Low elevation Lake	M H L Lk	Catchment rainfall volume in elevation categories, Lake influence index	M: > 50% annual rainfall volume above 1000 m ASL H: 50% bring forward following between 400 and 100 m ASL L: 50% rainfall below 400 m ASL Lk Lake influence index > 0.033
3. Geology	Alluvium Hard sedimentary Soft sedimentary Volcanic basic Volcanic acid Plutonic	Al HS SS Vb Va Pl	Proportions of each geological category in section catchment	Class = the spatially dominant geology category unless combined soft sedimentary geological categories exceed 25% of catchment area, in which case class = SS
4. Land Cover	Bare Indigenous forest Pastoral Tussock Scrub Exotic forest Wetland Urban	B IF P T S EF W U	proportions of each land cover category in section catchment	Class = the spatially dominant land cover category unless P exceeds 25% of catchment area, in which case class = P, or unless U exceed 15% of catchment area, in which case class = U

Examination of REC classes showed that the Waikanae River was found in the CW climate class, had a lowland source of flow, and was from a catchment dominated by hard sedimentary geology (i.e., it had a REC classification of CW/L/HS: See Table 2-2 for explanation of codes). Examination of the rivers monitored by GWRC showed that 19 others had a similar REC classification at the 3rd level. These other rivers were found throughout the Wellington region, from Otaki in the Northwest, Owhanga in the North East, through to Karori Stream in the south-west, and the Wainuiomata near Baring Head in the south-east (Figure 2-1). Within this class, there were 5 landuse types, of which Indigenous forest and Pasture were dominant in the upper and lower sites on the Waikanae respectively. Both algal and invertebrate data from these 19 rivers were thus compared to data obtained from the Waikanae River.

2.2.1 Statistical methods

Examination of the chlorophyll data showed it was highly skewed, so it was log transformed to achieve a normal distribution. Differences in chlorophyll biomass between sites above and below the WTP, and in other comparison streams of different landuse were assessed by ANOVA. Because chlorophyll biomass is strongly influenced by shading, all streams were assigned to one of three shade categories based on examination of aerial images of each site: open; semi-shaded and shaded. Differences in biomass between these shade classes were also assessed by ANOVA. Relationships between the preceding flow history and chlorophyll biomass at each site were also examined. For this analysis we calculated the size of the flood prior to algal sampling and the number of days since the last flood. We defined a flood as any time prior to sampling when flows had increased before decreasing again, as Biggs and Close (1989) showed how even relatively small floods can often remove algal biomass. The average flow 1 and 4 weeks prior to sampling was also calculated. These flow indices were calculated both above the WTP and below. Relationships between these flow indices and chlorophyll biomass were examined, and analysis of covariance used to determine whether these relationships differed between the two sites.

Invertebrate data was obtained from the 19 comparison rivers, and the two sites in the Waikanae. The following biological indices were calculated: total density; taxonomic richness; the hard-bottomed macroinvertebrate community index (MCI); its quantitative variant, the QMCI; the number of Ephemeroptera, Plecoptera, and Trichoptera taxa (i.e., EPT); and % EPT. The MCI is an index describing overall invertebrate community health, with high scores (e.g., MCI > 120) indicating pristine waters, while scores < 80 indicate probable organic enrichment, and streams in poor condition (Stark 1993). The number and % of EPT taxa also conveys information about overall invertebrate community composition and condition. For example, as nutrient or algal biomass increases, the number or % of EPT taxa often declines. These biological indices are useful for assessing both the current condition of the invertebrate community, and for monitoring changes in composition over time. We examined relationships between biological indices and flow indices to assess whether the WTP abstraction was associated with temporal changes to the invertebrate communities. The densities of the 12 most common invertebrate taxa were also examined to see how they differed between rivers of different REC classes, and at sites in the upper and lower Waikanae River. All biological data were checked for normality and fourth-root transformed where necessary to achieve normal distributions. All data was first analysed using analysis of variance (ANOVA) to determine whether there were any differences in biological indices describing invertebrate communities between the different river classes.

Figure 2-1: Map of the rivers monitored by the GWRC that were in the same REC class (CW/L/HS) as the Waikanae River (RS09 and RS10).

NMDS ordination and ANOSIM were then performed on the invertebrate data. For the ANOSIM, the groups tested represented samples collected from the two sites in the Waikanae River, and from the other 19 comparison rivers in the region. The main comparisons of interest for the ANOSIM were 1) between samples collected from above and below the WTP; 2) between samples from the upper Waikanae and those from other undisturbed catchments (i.e., either indigenous forest or scrub; 3) between samples from the lower Waikanae and those from other catchments dominated by pasture. We were not interested in comparisons of invertebrate communities collected between different land-use types of the other rivers, and so these comparisons were omitted from the results. The Bray-Curtis similarity measure was calculated for the biological data, as it is more appropriate for biological data than flow data. The Bray-Curtis measure quantifies compositional similarity between two different sites, and is bound between 0 (two sites have no species in common) and 1 (two sites have the same composition).

Lastly, we compared the year-to-year variation of samples collected from above and below the WTP to each other, and to that of samples collected from the other 19 rivers. A year-by-year similarity matrix (using Bray-Curtis) was constructed. This matrix showed how similar the communities at a particular site in a particular year were to other samples from the same site for different years. A similar year-by-year similarity matrix was calculated for flow indices at each site to assess the degree of change in flow indices between years. Correlations were made between the annual similarity of invertebrate communities and annual similarity of flow indices. The underlying assumption here was that if flow indices at a site differed greatly in a particular year (and therefore displayed low similarity to other years), then the invertebrate communities at this site at this time would show a corresponding decrease in similarity to the communities in other years, if they were responding to flow.

3 Results

3.1 Hydrological effects

Analysis of flow and abstraction data showed significant differences in abstraction rates over time, and significant differences in the percentage of flow abstracted. The average abstraction rate was 166 L s^{-1}, but was generally higher in late spring and summer, and slightly lower during other months (Figure 3-1). The percentage abstraction of river flow was highest in late summer - early autumn (February, March and April), and lowest during winter and early spring (July to October: Figure 3-1). Considerable year-to-year variation was observed, with some years (2007, 2008 and 2009) having higher abstraction rates than other years (2004 and 2005). The percentage of flow abstracted also varied yearly, and was highest in 2005 and 2007 (Figure 3-2).

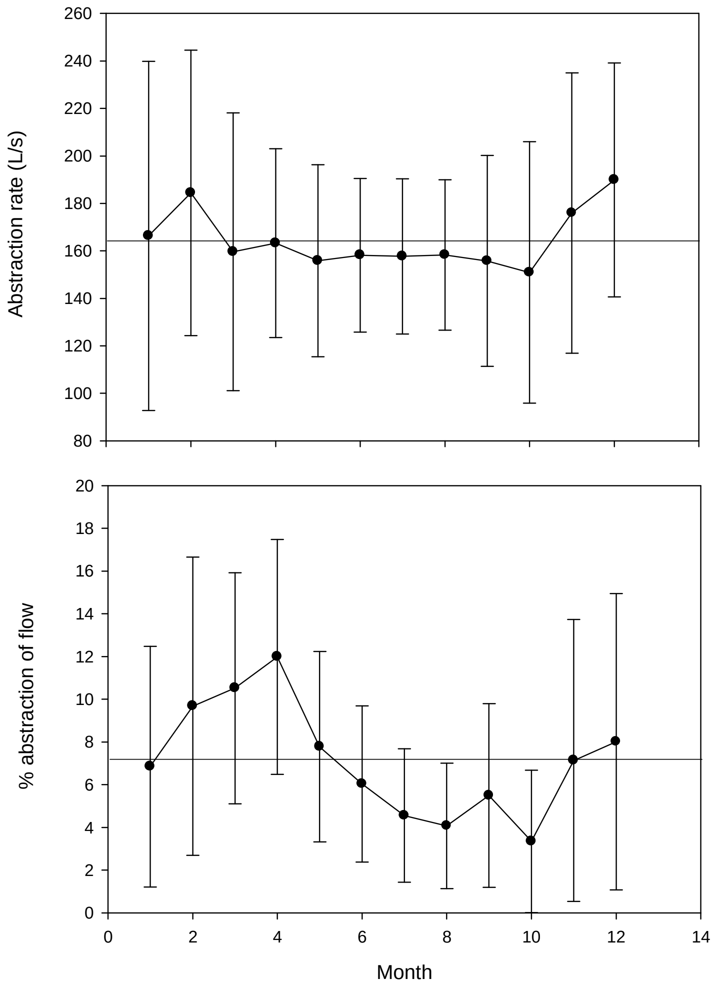

Figure 3-1: Average monthly abstraction rate (L s^{-1}) and average percentage abstraction of flow from the Waikanae River (x + 1 sd).

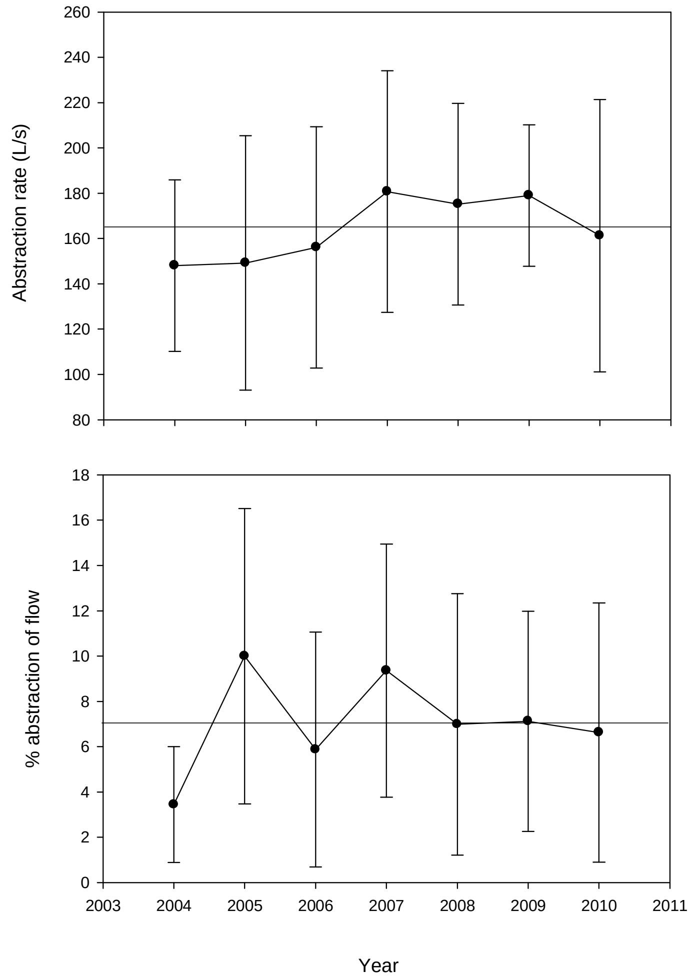

Figure 3-2: Average annual abstraction rate (L s^{-1}) and average percentage abstraction of flow from the Waikanae River (x + 1 sd).

Analysis of the corrected residual flow data showed that the average abstraction rate was relatively small, with only approximately 7% of river flow, or a median of only 5.5% being taken Abstraction rates were highly variable between years. For example, during a dry-period in 2005, more than 20% of upstream flows were abstracted for c. 10% of the time. In contrast, 2004 was much wetter, and so this proportional volume of water was never abstracted.

Calculation of percentage differences above and below the WTP showed that half the flow indices differed by 10% or less. The greatest difference (almost 70%) occurred for the maximum duration of flows below the 25th percentile, which was higher below the WTP. Despite these differences, no statistically significant changes were observed for any of the calculated flow indices (Table 3-1). Although the magnitude of low flow indices was lower below the WTP than above, the reduction was not statistically significant. Similarly, even though some of the duration indices (e.g., Dur-MALF) had doubled below the WTP, this increase was not statistically significant over the 7 year period. Thus, the WTP abstraction was having little significant impacts on ecologically relevant flow indices.

Table 3-1: Average of the 11 summary flow indices calculated from a 7-year flow period (2004-1020) above and below the WTP. The table also shows the % difference in calculated indices, as well as the results of t-tests between flows above and below the WTP.

Type of flow statistic	Abbrev	Above WTP	Below WTP	% Difference	T-test, p-value
Flow	Qmax (L s^{-1})	193524	182536	5.4	t = 0.199, P = 0.845
	Qmean (L s^{-1})	5585	5345	4.7	t = 0.225, P = 0.826
	Q_{50} (L s^{-1})	3104	2999	4.1	t = 0.162, P = 0.874
Flood Frequency	FRE3 (no. per year)	12.03	11.64	3.4	t = 0.208, P = 0.838
Low Flow Magnitude	MALF (L s^{-1})	981	846	13.1	t = 1.016, P = 0.330
	Q_{25} (L s^{-1})	1808	1642	10.3	t = 0.400, P = 0.696
	LowQ_Inst (L s^{-1})	932	771	16.6	t = 1.310, P = 0.216
Low Flow Duration	Dur_MALF (days)	22.3	40.9	-71.1	t = -1.341, P = 0.206
	Dur_{25} (days)	108	118	-12.4	t = -0.295, P = 0.773
	DurMALF_max (days)	10.3	14.1	-24.9	t = -0.759, P = 0.463
	Dur_{25}_max (days)	23.5	24.9	-7.67	t = -0.258, P = 0.801

Examination of the NMDS ordination of flow indices showed large yearly variation, but smaller differences above or below the WTP (Figure 3-3). These NMDS patterns were confirmed by ANOSIM, which showed significant differences in flow indices over time (R = 0.932, P = 0.003), but no differences in flow indices above and below the WTP (R = -0.092, P = 0.079).

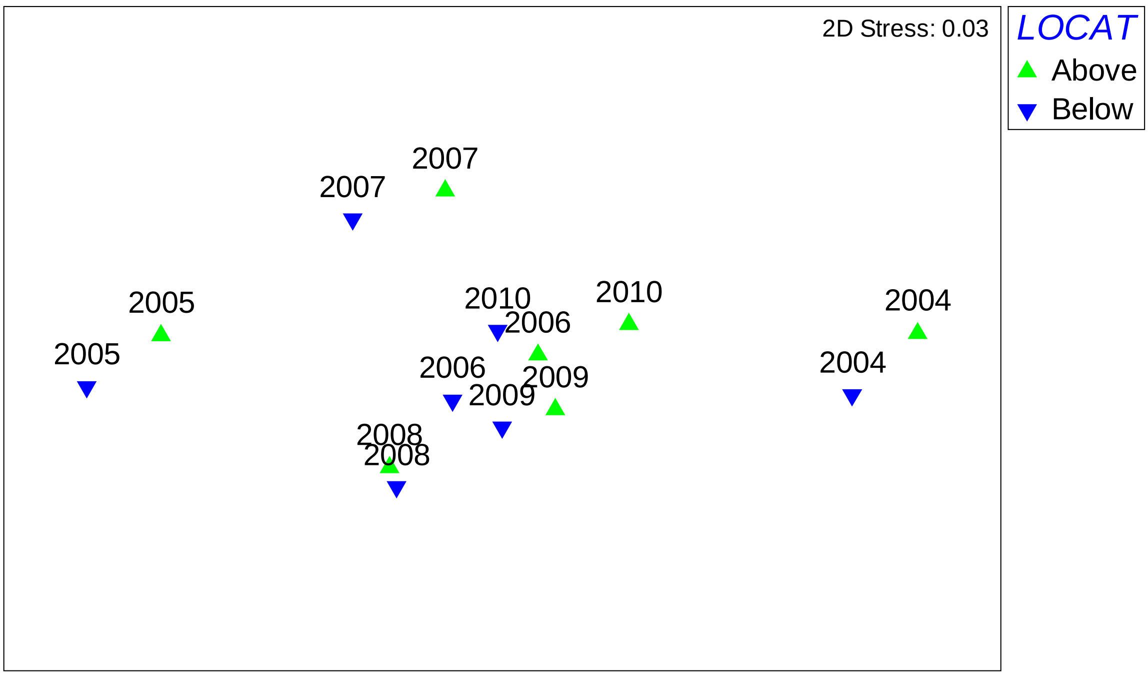

Figure 3-3: NMDS ordination of flow data from the Waikanae River at locations (LOCAT) above and below the WTP. Note the generally small difference between the two locations, but the large year-to-year variation.

3.2 Ecological effects – algae

Chlorophyll biomass was significantly higher below the WTP (mean = 44.3 mg m^{-2}) than above (mean = 3.6 mg m^{-2}). Biomass was also significantly different between samples collected in the Waikanae and in the other comparison streams. When coded for land cover, chlorophyll biomass was significantly lower at the site above the WTP, and at sites draining scrub and exotic forestry than the site below the WTP, and higher at sites draining catchments dominated by pasture and urban land cover (Figure 3-4). The site below the WTP had a similar chlorophyll biomass to other pasture sites in the region, suggesting that any abstraction from this site was not causing algal biomass to increase to levels higher than that naturally found in streams draining catchments with a similar landuse.

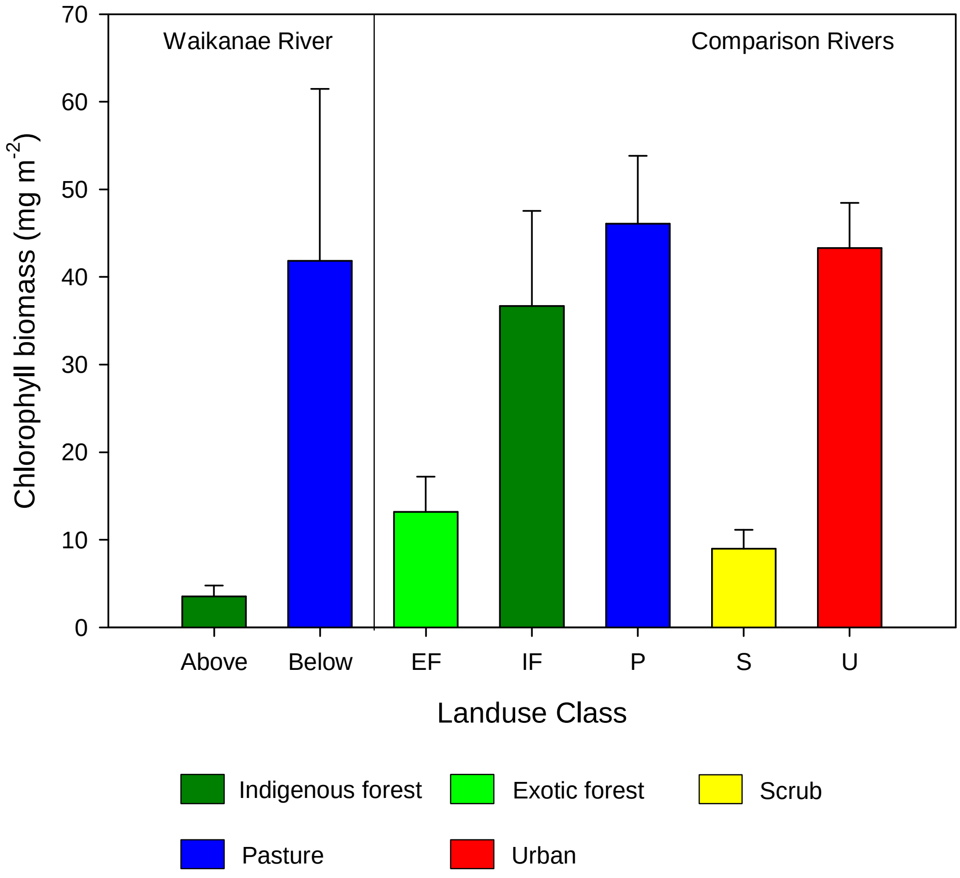

Figure 3-4: Average chlorophyll biomass from rivers in different REC land cover classes (*x* ± 1 SE).

As expected, significant differences existed in chlorophyll biomass with respect to the degree of streaming shading. Biomass was lowest in the shaded sites, both above the WTP and in the other shaded comparison sites, and highest in open sites (Figure 3-5), and the site below the WTP.

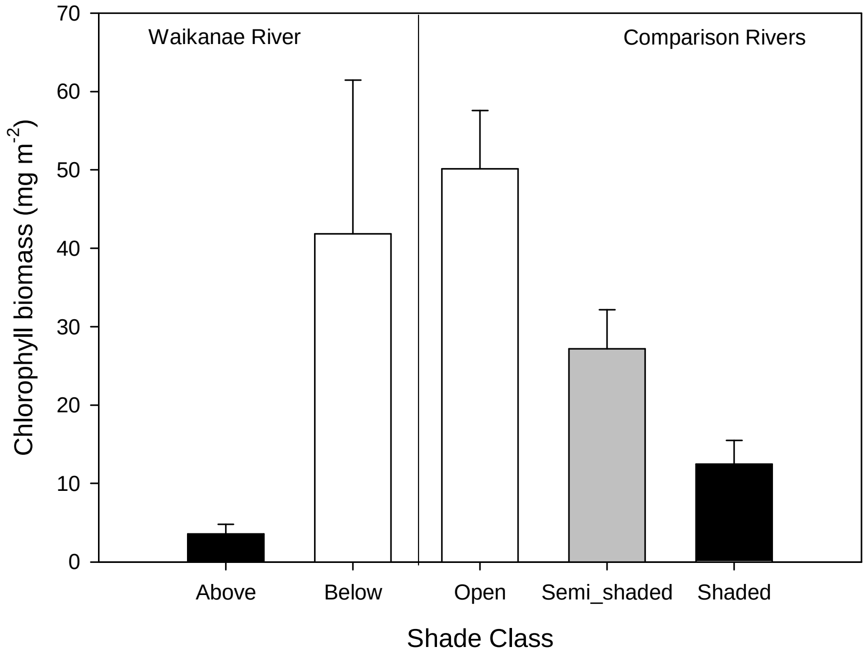

Figure 3-5: Average chlorophyll biomass from rivers in different a priori defined shade classes (x + 1 SE).

Flow regimes prior to the annual summer/autumn algal sampling differed greatly between years. For example, the size of the antecedent flood prior to sampling ranged from 8 m^3 s^{-1} in 2004 through to 381 m^3 s^{-1} in 2005. The number of days following a flood and the time of sampling also varied greatly, from a minimum of five days (2004) to 77 days (2005). The magnitude of the seven-day low flow prior to sampling also differed between years, from a low of 0.8 m^3 s^{-1} below the treatment plant in 2005 to 2.2 m^3 s^{-1} in 2009. Despite the wide range of antecedent flow conditions, ANCOVA showed no significant effects of the preceding flow regime on chlorophyll biomass, but consistent differences in algal biomass above and below the WTP. Lack of any significant relationships between the preceding flow regime and algal biomass in the 2 sites suggests that the flow regime during the summer and autumn was having no effect on the algal communities.

3.3 Ecological effects – invertebrates

3.3.1 Community composition

A total of 139 invertebrate taxa were found in the two Waikanae River sites and the other 19 comparison rivers. The fauna in all rivers was dominated by the mayflies *Deleatidium* and *Coloburiscus*, Elmid riffle beetles, the snail *Potamopyrgus*, four caddisflies (*Aoteapsyche*, *Pycnocentrodes*, *Olinga*, and *Oxyethira*), three midges (Orthocladiinae, *Tanytarsus*, Tanytarsini), and the amphipod *Paracalliope*. With the exception of *Paracalliope*, all these invertebrates were common (i.e., relative density greater than 1%) in both sites. The relative abundances of the 12 most common taxa were compared between the two Waikanae sites. Only three of taxa had a significantly higher relative abundance in the site above the WTP than below, and only two had significantly higher relative abundance in the site below. Relative abundances of the other seven common taxa were similar between these two sites.

Examination of the five biotic indices showed that the upper Waikanae site had higher values for the MCI, number of EPT taxa, and QMCI than the lower site. This was not surprising, and most likely reflected differences in the dominant land use between the upper catchment (unmodified indigenous forest) and the lower catchment (dominated by pasture). The upper site also had higher values of these indices when compared to the other 19 rivers, including those of a similar catchment landuse. This site, and other rivers draining catchments dominated by indigenous forest or scrub, also had the highest values for the percentage EPT, and taxonomic richness. The high indices indicate that the Waikanae River has a high ecological value within the region.

Despite being in a catchment classified as pasture, the lower Waikanae site had significantly higher MCI, numbers of EPT taxa, QMCI and %EPT than the other pastures streams in a similar REC class in the region. This suggested that the lower site was also in good ecological condition compared to other similar streams in the region draining pasture-dominated catchments. These results were mirrored by the NMDS ordination (Figure 3-6). Invertebrate communities collected from rivers in the different landuse categories showed clear differences. For example, samples collected from urban catchments had distinctive communities when compared to other landuse types, and samples collected from catchments dominated by indigenous forest appeared quite distinctive to those from pasture. Pasture streams had the widest spread of ordination scores, suggesting a wide variation in invertebrate community composition. Samples collected from the upper Waikanae were clustered with samples from other rivers from catchments dominated by indigenous forest or scrub (Figure 3-6), while samples from the lower Waikanae were clustered more with rivers from catchments dominated by pasture. There was no overlap between samples collected above or below the WTP, suggesting that overall community composition differed greatly between these two sites.

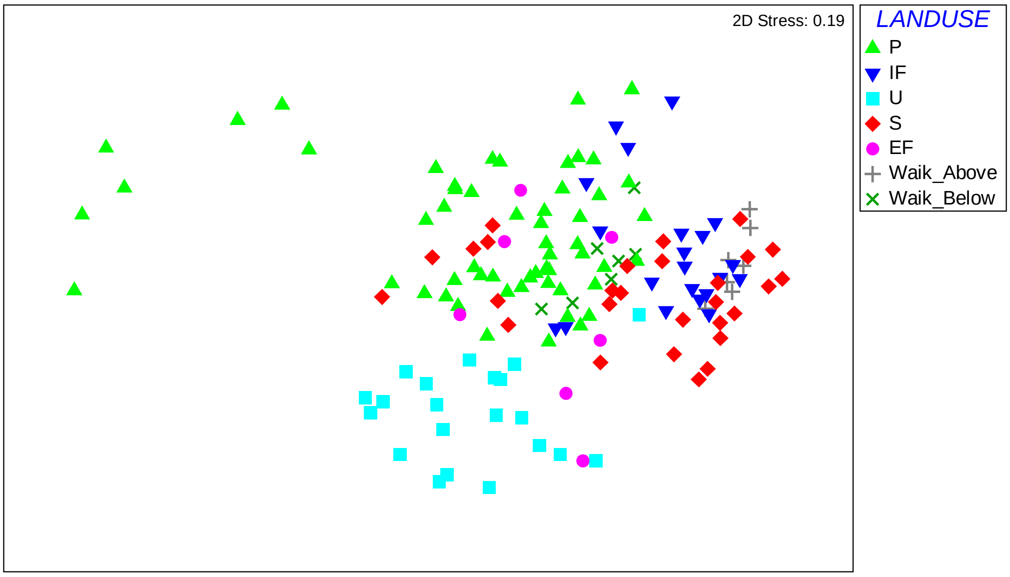

Figure 3-6: Results of NMDS ordination of invertebrate communities collected from the Waikanae River above (Waik_Above) and below (Waik_Below) the WTP. Also shown are the communities in 19 other rivers of a similar REC classification throughout the Wellington region from catchments dominated by different landuse: P = pasture; IF = indigenous forest; U = Urban; S = scrub; EF = exotic forest.

These results were confirmed by examination of the ANOSIM pairwise comparisons (Table 3-2). Samples collected above and below the WTP differed significantly from each other (R = 0.883). Samples collected above the WTP were similar to those collected from other unmodified catchments dominated by indigenous forest or scrub, but significantly different to samples collected from rivers in catchments dominated by pasture, exotic forest, or urban development (Table 3-2). In contrast, samples collected below the WTP were similar to those collected from rivers in catchments dominated by pasture, indigenous forest and scrub, and different to those collected from streams and dominated by urban or exotic forest.

Table 3-2: Results of ANOSIM showing the pairwise differences in similarity of samples collected from different locations.

Site	R statistic	Significance level %	Possible permutations	Actual permutations	Number observed
Waik_Above, Waik_below	**0.883**	**0.1**	1716	999	0
Waik_Above, P	**0.483**	**0.2**	5532700671	999	1
Waik_Above, U	**0.906**	**0.1**	1184040	999	0
Waik_Above, IF	0.018	36.4	1184040	999	363
Waik_Above , S	-0.087	78.1	6724520	999	780
Waik_Above, EF	0.932	**0.1**	1716	999	0
Waik_Below, P	-0.108	81.4	5532700671	999	813
Waik_Below, U	**0.476**	**0.1**	1184040	999	0
Waik_Below, IF	0.056	25.6	1184040	999	255
Waik_Below , S	-0.041	64.8	6724520	999	647
Waik_Below, EF	**0.575**	**0.2**	1716	999	1

3.3.2 Temporal variability

Similarity of invertebrate communities was higher above the WTP (75% similarity) than below (69% similarity). Year-to-year similarity above the WTP was generally stable over time, with the exception of 2010 when the community similarity decreased (Figure 3-7). Similarity below the WTP varied more over time, and displayed a slight increase in year-to-year similarity (Figure 3-7).

No significant correlations were observed between calculated similarity of flow indices and similarity of the invertebrate communities at either site above or below the WTP (Figure 3-8). Lack of any relationships suggested that no direct links existed between invertebrate communities and flow at either location. Thus, any year-to-year changes in flow regime caused by, for example, relatively more abstraction of flow from the Waikanae River was not having any demonstrable effect on the invertebrate communities below the WTP. This suggests that any temporal changes to the invertebrate communities were due to non-flow related parameters.

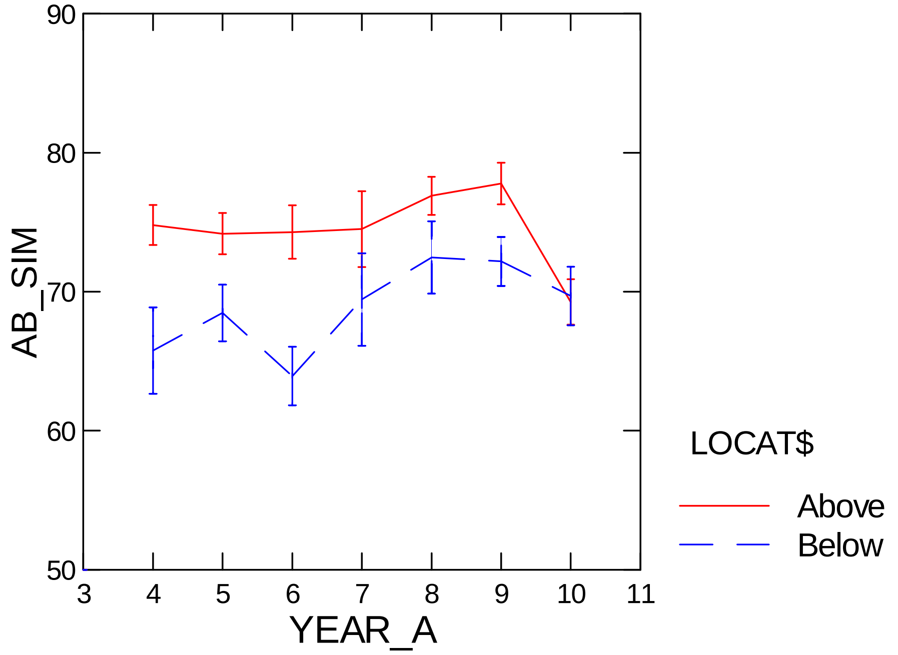

Figure 3-7: Calculated Bray-Curtis similarity of invertebrate communities above and below the WTP yearly since 2004. The similarity of communities at each year was compared to the similarity of communities at every other year.

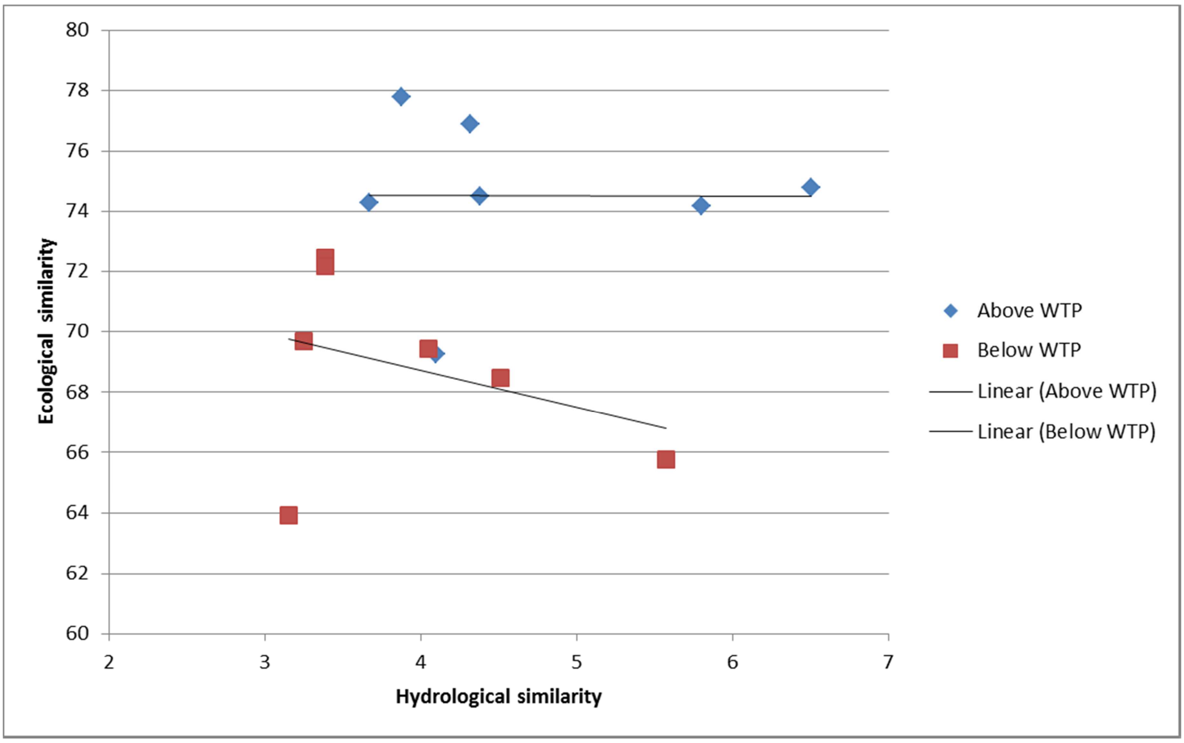

Figure 3-8: Relationships between calculated year-to-year similarity of flow indices and similarity of invertebrate communities at sites above and below the WTP. Note the lack of any significant relationships, suggesting that changes in flow regime were having little effect on invertebrate communities at either site.

4 Discussion

The aim of this study was to determine whether the WTP abstraction had a demonstrable effect on algal and invertebrate communities in the Waikanae River. It was based on three key questions:

1. analysis of differences to flow indices calculated from recorded flows above the WTP, and from synthesised flows below
2. comparisons of chlorophyll biomass above and below the WTP, and to other similar rivers
3. comparisons of invertebrate communities above and below the WTP, and in other similar rivers

It was also based on the premise that abstraction from the WTP would alter biologically relevant flow indices, which in turn would affect algal or invertebrate communities. Such alterations were hypothesised to be greatest below the WTP as a result of abstraction.

4.1 Effects on flow indices

We analysed 11 ecologically relevant flow indices that summarised both flood and low flows, and which affect ecological communities in rivers (Suren et al. 2003; Suren and Jowett 2006). When analysed over the seven year period, the WTP had no effect on any of the calculated flow indices such as reducing flow magnitude, or increasing the duration of low flows. Lack of any significant changes to any of the calculated flow indices in itself suggests that abstraction from the WTP would be very unlikely to cause ecological effects. The size of the abstraction was also too small to influence any of the high flow indices such as the frequency or magnitude of flushing flows. Such flushing flows are important parts of a river's flow regime in that they maintain low algal biomass. Lack of differences to any of the high flow indices further reinforces the contention that the abstraction would unlikely have ecological effects.

4.2 Effects on algal biomass

If abstraction from the WTP was reducing flows below the WTP, or increasing their duration, then algal biomass would be expected to be higher below the WTP than above (e.g., Biggs and Price 1987; Biggs and Close 1989; Biggs 2000). Furthermore, algal biomass below the WTP would be higher than in other non-abstracted rivers. Although we observed higher biomass below the WTP than above, this was very unlikely to reflect any differences in flow regime, as all flow indices were similar between the two sites. Furthermore, the site above the WTP was more shaded than below, and this shade would have naturally reduced algal biomass. Finally, nutrient levels in the lower site would likely have been higher than above the WTP, reflecting the greater proportion of the catchment dominated by pasture.

Algal biomass below the WTP was also similar to that of other pasture streams where abstraction was not occurring. Most of these streams were open to full sunlight, and also supported high algal biomass. The fact that algal biomass below the WTP was no higher than in these other streams is further evidence that abstraction from the Waikanae River was having little, if any effect on algal communities.

4.3 Effects on invertebrate communities

The invertebrate community composition in the upper Waikanae River was dominated by taxa indicative of rivers with very high ecological condition. The lower Waikanae River also supported invertebrates indicative of rivers in good ecological condition, especially when compared to other similar streams in the region draining pasture-dominated catchments. Porter (2003) also examined the invertebrate communities at six sites in the Waikanae River, five of which were below the WTP. Despite sampling during a period of very low flow (726 L s^{-1}), they found the invertebrate community at all sites was representative of a river in good ecological condition. Porter also recorded a reduction in the number of EPT taxa at the sites downstream of the WTP, and suggested that this decline reflected differences in habitat conditions rather than any effects of flow regime. Our analysis and interpretation of the GWRC invertebrate data agreed with Porter's assertion, particularly as none of the flow indices differed above or below the WTP. Furthermore, lack of significant correlations between year-to-year similarity of flow indices and year-to-year similarity of invertebrate communities suggested no links between invertebrate communities collected in late summer – early autumn and flow regimes.

MALF is often used by regulatory agencies within New Zealand in setting low-flow levels in rivers (e.g., MfE 1998). This study showed that abstraction from the WTP reduced the magnitude of MALF by 13%, from 981 L s^{-1} to 846 L s^{-1}. However, in the context of the naturally variable flow regime from 2004 – 2011, this reduction was not statistically significant. Even if abstraction was reducing MALF, invertebrate communities appear relatively stable at flows at, or below MALF (e.g., Suren and Jowett 2006; James and Suren 2009). Potential reductions in flow as a result of abstraction may thus have little effect on invertebrate communities. Despite the lack of response between flow variables and invertebrate communities, temporal shifts are predicted to occur in invertebrate community composition as a result of non-hydraulic changes to instream habitat arising from plant growth during low flow (Suren et al. 2003; Suren and Riis 2010). Indeed, Suren et al. (2011) observed changes to the invertebrate community in the Waikanae River over summer that were attributable to periphyton growth. These changes reflected natural successional patterns associated with the warm water temperatures, and the mostly stable flows encountered during their study, which were independent of the operation of the WTP.

4.4 Effects on fish

It is acknowledged that the effects of the WTP abstraction on fish communities have not properly been examined in this report, despite the fact that low flows influence fish communities. For example, Jowett et al. (2005) found that native fish densities were adversely affected by flows < MALF in the Waipara River, North Canterbury, with reductions in abundances of fast-water fish such as Canterbury galaxias, torrentfish and shortfin eels. Furthermore, Jowett et al. (2005) suggested that the duration, not magnitude, of a low flow event was a critical factor in regulating fish densities. Given the lack of significant differences to any of the low flow indices examined in this study, it appears unlikely that the flow regime below the WTP would limit fish communities in the Waikanae River. Furthermore, Porter (2003) examined fish communities in the Waikanae during a period of very low flow in April 2003, and found no significant difference in either fish species or abundance above or below the WTP, and no relationships between fish density and flow measured at each of the six sampling sites. From this, they concluded that *there appears to be no significant adverse ecological effects which can directly be attributed to the abstraction at the time of the survey*.

The consented minimum flow in the Waikanae River is currently 750 L s^{-1}. Previous hydraulic habitat assessments using IFIM model have shown that this flow is predicted to retain 81% of adult trout habitat at MALF (Watts 2003). Examination of the flow hydrograph (January 2004 – January 2011) has shown that the instantaneous residual flow (i.e., recorded every 5 minutes) below the WTP fell under this threshold for only 2.7% of the time. A large proportion of this was only for short periods, which were then interspersed with periods above 750 L s^{-1}. When mean hourly flows were calculated (as opposed to instantaneous flows), and when flows less than 750 L s^{-1} for less than a 12h period were omitted, then only 45 days out of the entire record of 2528 days (1.78%) had less than the 750 L s^{-1} minimum flow. A figure of 12 h was chosen for this analysis as this seemed a reasonably long enough time for which to exert potentially adverse effects on benthic communities, or fish. The highest number of days in any month when flows dropped below 750 Ls^{-1} for more than 12 h was 11 and 12, in March (2008) and April (2005) respectively (Table 4-1). That flows less than 750 L s^{-1} below the WTP occur so rarely, combined with the fact that a relatively high proportion of adult trout habitat is retained even at this low-flow magnitude further suggests that the current flow regime in the Waikanae River is unlikely to be severely constraining fish communities. This statement is made in the context of adult brown trout, which have a higher flow demand than many native fish. Consequently, adverse effects of the current flow regime on native fish are thought to be even less.

Table 4-1: Calculated number of days when flows fell to less than 750 L s^{-1} for a 12 hour or more period. Analysis based on the flow hydrograph from January 2004 to January 2011.

Year	Month	Number of days with 12 h periods with flow < 750 L s^{-1}
2005	March	1
	April	12
	November	6
	December	1
2006	January	5
2008	January	3
	February	6
	March	11

Condition 8 of the Resource Consent (WGN050024[23848]) requires a monitoring programme be implemented to determine the impacts of the WTP abstraction on water quality, algae, invertebrates, native fish species and trout. The monitoring plan suggested by Porter (2006) was to determine if there were any significant differences between measurements of any parameter between upstream and downstream sites. The work presented by this report differed to that suggested by Porter (2006), and is based instead on the ability to detect changes in flow indices above and below the WTP, as well as detecting relationships between measured biological communities (algae and invertebrates) and flow indices.

Absence of any detectable effect of the WTP abstraction on ecologically relevant flow indices, combined with lack of any relationships between measured flow indices and observed algal or invertebrate communities suggest that the WTP abstraction was having little impact on these communities in the Waikanae River. Moreover, examination of the flow record has shown that residual flows below the WTP only rarely fell below the established minimum flows. As such, the effects of the water abstraction on fish communities are also considered minimal. Given this, the effects of the WTP abstraction on the ecological values of the Waikanae River are regarded as minor. This is the same conclusion as reached by Porter (2003) in their survey of invertebrate and fish communities in the Waikanae River.

If the effects of abstraction are minor, then the value of continued monitoring as per the methodology developed by Porter (2006) are questionable. We recommend that the KCDC consult with GWRC to obtain a variation to their consent to allow for a change to the proposed monitoring.. This recommendation is based on the fact that:

1. Our analysis of flow regimes above and below the WTP, and on algal and invertebrate communities failed to detect an effect of the WTP abstraction

2. Recent work being done by the KCDC to improve the security and certainty of the water supply for the area has recommended that the River Recharge with Groundwater (RRwGW) option be implemented (Egyed et al 2010).

As part of studies investigating the RRwGW option, Suren et al (2011) recommended a monitoring programme be implemented at sites above and below the WTP to obtain data on algal growth in the river. This was recommended to start this summer to obtain data of natural successional changes in algal cover at sites above and below the WTP to act as comparative baseline data should the RRwGW option proceed. Suren et al (2011) recommend that any algal monitoring be done following the standard MfE (2009) protocols for monitoring cyanobacteria (and all other algae), such that:

- monitoring be done using consistent methods as highlighted in section 4.4 of the MfE (2009) cyanobacterial monitoring guidelines;
- select at least two sites above the WTP, and at least two sites below, but above the State Highway. A further two sites could be selected below the State Highway, and at Jim Cooke Park;
- sites should be selected to have as similar substrate composition, water velocity and shade as possible;
- monitoring be done by as few people as possible to minimise inter-operator variability;
- commence fortnightly monitoring in early January, and continue until late autumn, or until the occurrence of the first large, post-summer flood that removes any excess algal build-up;
- Where possible, incorporate any monitoring into existing monitoring schemes currently undertaken by the GWRC as part of their SOE work.

Obtaining such a variation would allow the KCDC to better monitor any potential effects of abstraction on algal communities with a greater spatial and temporal resolution than recommended by Porter (2006), as algal communities are arguably the first to respond to changes in flow regime, and because of their close linkages to other parts of the river ecosystem such as invertebrates (Suren and Riis 2010). It would also allow them to commence a routine long-term algal monitoring programme that would feed into potential resource consent conditions for the RRwGW option.

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6 References

Armitage, P.D.; Petts, G.E. (1992). Biotic score and prediction to assess the effects of water abstractions on river macroinvertebrates for conservation purposes. *Aquatic Conservation: Marine and Freshwater Ecosystems 2*: 1-17.

Biggs, B.J.F. (1995). The contribution of flood disturbance, catchment geology and land use to the habitat template of periphyton in stream ecosystems. *Freshwater Biology 33*: 101-120.

Biggs, B.J.F. (2000). New Zealand Periphyton Guideline: Detecting, Monitoring and Managing Enrichment of Streams. Wellington, Ministry for the Environment.

Biggs, B.J.F.; Close, M.E. (1989). Periphyton biomass dynamics in gravel bed rivers: the relative effects of flows and nutrients. *Freshwater Biology 22*: 209-231.

Biggs, B.J F.; Price, G.M. (1987). A survey of filamentous algal proliferations in New Zealand rivers. *New Zealand Journal of Marine and Freshwater Research 21*: 175-191.

Bovee, K.D.; Lamb, B.L. Bartholow, J. M., Stalnaker, C.B., Taylor, J.G., Henriksen, J. (1988). Stream Habitat Analysis Using the Instream Flow Incremental Methodology, Biological Resources Discipline Information and Technology Report USGS/BRD-1998-0004: 131.

Brasher, A.M.D. (2003). Impacts of human disturbances on biotic communities in Hawaiian streams. *Bioscience 53*: 1052-1060.

Castella, E.; Bickerton, M;. Armitage, P. D.; Petts, G. E. (1995). The effects of water abstractions on invertebrate communities in U.K. streams. *Hydrobiologia 308*: 167-182.

Cazaubon, A.; Giudicelli, J. (1999). Impact of the residual flow on the physical characteristics and benthic community (algae, invertebrates) of a regulated Mediterranean river: the Durance, France. *Regulated Rivers: Research & Management 15*: 441-461.

Clarke, K.R.; Warwick, R.M. (2001). Change in marine communities: an approach to statistical analysis and interpretation. PRIMER-E. Plymouth, UK.

Collier, K.J.; Croker, G.F.; Davies-Colley, R. J.; Rutherford, J. C.; Smith, C. M.; Williamson, R. B. (1995). Effects of hydraulic conditions and larval size on the microdistribution of Hydrobiosidae (Trichoptera) in two New Zealand rivers. *New Zealand Journal of Marine and Freshwater Research 29*: 439-451.

Cowx, I.G.; Young, W.O.; Hellawell, J.M. (1984). The influence of drought on the fish and invertebrate populations of an upland stream in Wales. Freshwater Biology 14: 165-177.

Delucchi, C.M. (1989). Movement patterns of invertebrates in temporary and permanent streams. Oecologia 78: 199-207.

Dewson, Z.S.; Death, R.G.; James, A.B.W. (2003). The effect of water abstractions on invertebrate communities in four small North Island streams. *New Zealand Natural Sciences 28*: 51-65.

Dewson, Z.S.; James, A.B.W.; Death, R.G. (2007). A review of the consequences of decreased flow for instream habitat and macroinvertebrates. *Journal of the North American Benthological Society 26*: 401-415.

Egyed, N.; Mandeno, K. Watson, A.; Pollock, G.; Baker, N.; Bazalo, N. Stroud, P. (2010). Kapiti Water Supply Ranked Options - summary report. G. Pollock. Wellington, CH2M Beca: 38 pp.

Faith, D.P.; Humphrey, C.L.; Dostine, P.L. (1991). Statistical power and BACI designs in biological monitoring: comparative evaluation of measures of community dissimilarity based on benthic macroinvertebrate communities in Rockhole Mine Creek, Northern Territory, Australia. *Australian Journal of Marine and Freshwater Research 42*: 589-602.

Gilpin, B.R.; Brusven, M.A. (1976). Subsurface sampler for determining the vertical distribution of stream-bed benthos. *The Progressive Fish-Culturist 38*: 192-194.

Gore, J.A. (1977). Reservoir manipulations and benthic macroinvertebrates in a prairie river. *Hydrobiologia 55*: 113-123.

James, A.B.W.; Suren, A.M. (2009). The response of invertebrates to a gradient of flow reduction – an instream channel study in a New Zealand lowland river. *Freshwater Biology 54*: 2225-2242.

Jowett, I.G. (1997). Environmental effects of extreme flows. Pp. 104-116. *In:* Floods and droughts: the New Zealand experience. M. P. Mosley, M.P.; Pearson, C.P. (Eds.). Christchurch, The Caxton Press.

Jowett, IG. (2000). Flow Management. Pp. 289-312. *In:* New Zealand stream invertebrates: ecology and implications for management. Collier, K.J.; Winterbourn, M.J. (Eds.).. Christchurch, New Zealand Limnological Society.

Jowett, I.G.; Mosley. M.P. (2004). Analysis of instream values. Pp. 43.41-43.20. *In:* Freshwaters of New Zealand. Harding, J.S.; Mosley, M.P.; Pearson, C.P.; Sorrell, B.K. (Eds.). Christchurch, New Zealand Hydrological Society and New Zealand Limnological Society.

Jowett, I.G.; Richardson, J.; Biggs, B. J. F.; Hickey, C. W.; Quinn, J. M. (2005). Relationship between flow regime and fish abundances in a gravel-bed river, New Zealand. *Journal of Fish Biology 66*: 1419-1435.

McIntire, C.D. (1966). Some effects of current velocity on periphyton communities in laboratory streams. *Hydrobiologia 27*: 559-570.

MfE (1998). Flow Guidelines for instream values. Wellington, Ministry for the Environment.

MfE (2009). New Zealand guidelines for cyanobacteria in a recreational freshwaters - interim guidelines. Ministry for the Environment and the Ministry of Health, Wellington. 1-82 p.

Minshall, G.W.; Winger, P.V. (1968). The effect of reduction in stream flow on invertebrate drift. *Ecology 49*: 580-582.

Poff, N.L.; Voeltz, N.J.; Ward, J.V. (1990). Algal colonisation under four experimentally-controlled current regimes in a high mountain stream. *Journal of the North American Benthological Society 9*: 303-318.

Porter, S. (2003). Waikanae River ecological report. Prepared for Kapiti Coast District Council, Opus International consultants: 1-21p.

Porter, S. (2006). Ecological Monitoring Plan Waikanae River. Resource Consent WGN050024 [23848]. Prepared for the Kapiti Coast District Council, Opus International Consultants Limited: 1-9.

Rader, R.B.; Belish, T.A. (1999). Influence of mild to severe flow alterations on invertebrates in three mountain streams. *Regulated Rivers: Research and Management 15*: 353-363.

Snelder, T.; Biggs, B.J.F. (2002). Multiscale river environment classification for water resources management. *Journal of the American Water Resources Association 38*: 1225-1239.

Stanley, E.H.; Fisher, S.G.; Grimm, N. B. (1997). Ecosystem expansion and contraction in streams - desert streams vary in both space and time and fluctuate dramatically in size. *Bioscience 47*: 427-435.

Stark, J.D. (1993). Performance of the Macroinvertebrate Community Index: effects of sampling method, sample replication, water depth, current velocity, and substratum on index values. *New Zealand Journal of Marine and Freshwater Research 27*: 463-478.

Statzner, B.; Higler, B. (1986). Stream hydraulics as a major determinant of benthic invertebrate zonation patterns. *Freshwater Biology 16*: 127-139.

Suren, A.M.; Biggs, B.J.F.; Duncan, M.; Bergey, L. (2003a). Benthic community dynamics during summer low-flows in two rivers with contrasting enrichment 2. Invertebrates. *New Zealand Journal of Marine and Freshwater Research 37*: 71-83.

Suren, A.M.; Biggs,B.J.F.; Kilroy, C.; Bergey, L. (200b). Benthic community dynamics during summer low-flows in two rivers of contrasting enrichment 1. Periphyton. *New Zealand Journal of Marine and Freshwater Research 37*: 53-69.

Suren, A.M.; Jowett, I.G. (2006). Effects of floods versus low flows on invertebrates in a New Zealand gravel-bed river. *Freshwater Biology 51*: 2207-2227.

Suren, A.M.; Riis, T. (2010). The effects of plant growth on stream invertebrate communities during low flow: a conceptual model. *Journal of the North American Benthological Society 29*: 711-724.

Suren, A.M.; Wech, J.A. Gadd, J. (2011). The effects of groundwater discharge on the algal, invertebrate and fish communities of the Waikanae River. *NIWA Client Report CHC2011-055*: 86 p.

Watts, L. (2003). Instream habitat assessment for the Waikanae River. Greater Wellington Regional Council, Resource Investigations Department, Wellington.

Wetmore, S.H.; Mackay, R.J., Newbury, R.J. (1990). Characterisation of the hydraulic habitat of *Brachycentrus occidentalis*, a filter feeding caddisfly. *Journal of the North American Benthological Society 9*: 157-169.