Waikato Regional Council Technical Report 2021/36

The distribution of biota from some geothermally influenced standing waters in the Taupo Volcanic Zone

www.waikatoregion.govt.nz
ISSN 2230-4355 (Print)
ISSN 2230-4363 (Online)

Waikato
REGIONAL COUNCIL
Te Kaunihera ā Rohe o Waikato

Prepared by:
Ian Duggan and Ian Boothroyd (National Institute of Water & Atmospheric Research Ltd (NIWA))

For:
Waikato Regional Council
Private Bag 3038
Waikato Mail Centre
HAMILTON 3240

February 2022

Document #: 1270173

Peer reviewed by:
Katherine Luketina Date January 2022

Approved for release by:
Mike Scarsbrook Date January 2022

The distribution of biota from some geothermally influenced standing waters in the Taupo Volcanic Zone

NIWA Client Report: EVW02226
May 2002

The distribution of biota from some geothermally influenced standing waters in the Taupo Volcanic Zone

Ian Duggan
Ian Boothroyd

Prepared for

Environment Waikato

Information contained within this report should not be used without the prior consent of the client

NIWA Client Report: EVW02226
May 2002

National Institute of Water & Atmospheric Research Ltd
PO Box 11-115, Hamilton
New Zealand
Tel: 07 856 7026
Fax: 07 856 0151

CONTENTS

Reviewed by: *Approved for release by:*

(Dr Martin Haase) *(Dr Kevin Collier)*

Executive Summary

This report discusses the occurrence and spatial dynamics of phytoplankton, zooplankton and macroinvertebrates from standing water bodies in the Taupo Volcanic Zone, a project jointly funded by Environment Waikato and NIWA.

The aims of this report are to:

- describe the phytoplankton, zooplankton and macroinvertebrate communities in a variety of standing water geothermal habitats;
- measure invertebrate community changes along geothermal stress gradients, and;
- examine the significant habitat and environmental factors influencing the diversity and distribution of aquatic geothermal invertebrate communities.

Samples were collected from water-bodies in five geothermal fields within the Taupo Volcanic Zone: Waiotapu, Orakeikorako, Golden Springs, Rotokawa and Waikite. Additional samples were collected from two non-geothermal waterbodies, Lakes Ngapouri and Ngahewa, to provide a comparison with geothermal sites.

The diversity of biota was typically low in the geothermally influenced waters compared with non-geothermally influenced waters. Biota were found to respond to gradients in environmental and habitat conditions within and between geothermal fields.

The phytoplankton of geothermal waters was dominated by diatoms or cyanobacteria. The spatial distributions of dominant algal groups in relation to physicochemical conditions appeared to be generally consistent with patterns observed in flowing water geothermal habitats. Water temperature and chemical composition (e.g., pH and sulphide concentrations) were generally important in determining distribution, with cyanobacteria dominating at higher temperatures but not in highly acidic waters. However, some cyanobacteria populations were found in some highly acidic, high sulphide sites in the Waiotapu and Rotokawa fields. However, algal biomass (chlorophyll *a*) was typically low at these sites.

Zooplankton were most commonly represented in geothermal waters by rotifers, cyclopoid copepods, and early instar chironomids. Monogonont rotifers were uncommon, but represented by *Lecane* species in two water-bodies, and *Synchaeta pectinata* in another. Bdelloid rotifers were ubiquitous in their distribution in the geothermal sites. The cyclopoid copepod *Paracyclops waiariki* was recorded from several ponds in the Waiotapu geothermal field, and appears to occur obligately in geothermal waters. *Eucyclops serrulatus* was recorded in warmer sites (up to 32.2 °C) with circum-neutral

pH. Differences in zooplankton composition were observed between the geothermal sites, with high temperature and acidity, compared to sites that had no geothermal influence.

Macroinvertebrates recorded in this survey were typical of those that had been recorded in geothermally influenced sites previously. Taxa richness declined with increasing temperature and acidity. The degree of acidity of each waterbody was also the dominant factor determining the community composition and abundance of macroinvertebrate species within geothermal fields and between sampling locations. Acidic sites were distinguished by having high relative abundances of *Neoscatella* sp., *Culex rotoruae*, *Liodessus deflexus*, *Anisops wakefieldi* and *Chironomus zealandicus*. The more alkaline lakes were also separated along a temperature gradient. Warmer, alkaline sites from Lake Ohakuri and Waikite were dominated by *Enochrus tritus*, *Chironomus* sp. a and *Paratrichocladius pluriserialis*. Annelids, *Paroxyethira hendersoni* and *Pisidium* were found to be more typical of non-geothermally influenced sites. Chlorophyll *a* and dissolved oxygen concentrations also appeared to be important in determining the distribution of macroinvertebrate species.

Overall, the fauna of geothermal sites comprised mainly thermo-tolerant or acid-tolerant species. However, several zooplankton and macroinvertebrate taxa were obligately restricted to or recorded most commonly from geothermal waters, and many taxa, particularly zooplankton, were recorded from a limited number of water bodies and in extremely low numbers. The combination of restricted distribution and low density is likely to make the geothermal fauna more vulnerable to extinction if significant changes were to occur in the geothermal resources. Furthermore, we believe that improved systematic knowledge and the application of genetic techniques in the future may indicate that endemism of some groups among geothermal sites is greater than indicated in the present study.

1. INTRODUCTION

On a world scale, the Taupo Volcanic Zone contains a high number of geothermal waters in a relatively small area. The landscape and water bodies overlying most geothermal fields are characterised by zones of high temperature and unusual pH conditions (Vincent & Forsyth, 1987). Within the Taupo Volcanic Zone the influence of geothermal activity on waterbodies varies widely, with waters between fields ranging in temperature and pH from hot and moderately alkaline to cold and highly acidic, with all ranges of variability in between.

The biodiversity of these unusual habitats is typically low, as species occurring here commonly need to be adapted to extremes in temperature, pH or toxicant levels (Vincent & Forsyth, 1987). In response to these conditions, a unique indigenous aquatic biota has evolved. This biota includes a few species or varieties only found in geothermal habitats, notable occurrences of species more commonly found in tropical or subtropical climates, and common stress-tolerant species (e.g., Winterbourn, 1968; Vincent & Forsyth, 1987; Duggan & Boothroyd, 2001). Collectively, this biota possesses high conservation and scientific values.

To date, most ecological studies of geothermal biota have focussed on recording distributions in relation to temperature or pH. For algae, the factors determining distribution are better known than for other groups of organisms, with water temperature, pH and sulphide concentrations being the most important determinants of algal distribution patterns (e.g., Stockner, 1967; Castenholz, 1976; Lamberti & Resh, 1985). Less is known about the quantitative responses of zooplankton and macroinvertebrate communities to gradients in the underlying geothermal resource, or whether the factors determining distribution within sites are also those responsible for distribution patterns between sites.

Duggan & Boothroyd (2001) examined the factors affecting spatial distributions of algae and macroinvertebrates in geothermal stream habitats in the Taupo Volcanic Zone within the regional boundaries of Environment Waikato. As expected, the distributions of benthic algal taxa were dependent on temperature and chemical composition (pH, sulphide concentrations). Macroinvertebrate composition and taxa richness were mainly determined by temperature and pH gradients in these flowing water environments. The macroinvertebrate communities in geothermal waters were mainly thermally tolerant species, although some specialist hot water taxa were also found. In addition, the tropical gastropod *Melanoides tuberculata*, presumably a release from a tropical aquarium, was recorded at Golden Springs.

The aim of this report is to examine the factors influencing the distribution of algae in the water column (phytoplankton), zooplankton and macroinvertebrates in geothermally influenced standing waters in the Taupo Volcanic Zone, within the Environment Waikato boundaries. To our knowledge, no study has previously examined environmental factors affecting the distribution of zooplankton among lentic geothermal waters. Specifically, this report aims to:

- describe the algal, zooplankton (primarily the rotifers and crustaceans) and macroinvertebrate communities in a variety of geothermal habitats with a particular emphasis on standing waters;
- measure invertebrate community changes along geothermal stress gradients, and examine the significant habitat and environmental factors influencing the diversity and distribution of aquatic geothermal biota.

For the purposes of this report, we define geothermal waters as those in which thermal or chemical (i.e., pH) conditions are influenced by natural volcanic activity. A better knowledge of the significant attributes in geothermal ecosystems will allow resource managers to focus effort on the important environmental features of these systems, measure changes in ecosystem health, and develop appropriate tools and indicators for monitoring. This knowledge is required to predict the effects of changes in geothermal fields on the aquatic biota.

2. METHODS AND SAMPLING SITES

2.1 Site locations and field methodology

Samples were collected from five geothermal fields in the Taupo Volcanic Zone between 9 and 16 November 2001 (Table 1). Sites were selected to represent a broad range of environmental conditions, including pH, temperature, and other habitat attributes. They comprised mainly small ponds and lakes with geothermal influence. Lake Ohakuri was sampled at a small embayment at the entrance to the Orakeikorako tourist area, which receives inputs from a geothermal stream and subsurface springs. One of the Waikite Valley sites was a section of stagnant water connected to the Otamakokore Stream, and the other in a shallow wetland adjacent to the stream with a water level less that 10 mm deep. Additional samples from small, cold (non-geothermally influenced or with extremely reduced influence) lakes were also collected from Lake Ngapouri and Lake Ngahewa, near the Waiotapu and Waikite geothermal fields. Lake Ngahewa is situated outside of extent of warm ground in the Waiotapu field, although it apparently has a spring of pH 6 in the centre of the lake that may provide limited influence (Lloyd, 1963).

Table 1. Key to the locations of standing water sites sampled in the current survey

Site nos.	Field	Named feature or site description	South	East
Geothermal sites				
1	Waiotapu	Lake Whangioterangi (Echo Lake)	3821.722	17622.39
2	Waiotapu	Pond near Lake Rotowhero	3819.836	17622.68
3	Waiotapu	Lake Rotowhero, southern shore	3819.396	17622.36
4	Waiotapu	Lake Rotowhero, eastern shore	3819.368	17622.45
5	Waiotapu	Pond on Mud Road	3820.535	17622.26
6	Waiotapu	Pond on State Highway 5	3820.566	17621.72
7	Waiotapu	Lake Ngakoro	3821.813	17622.14
8	Waiotapu	Pond on Rainbow Mountain	3819.148	17622.67
9	Orakeikorako	Lake Ohakuri	3828.441	17608.57
10	Orakeikorako	Lake Ohakuri	3828.440	17608.61
11	Golden Springs	Lower spring	3827.940	17618.64
12	Golden Springs	Upper spring	3827.860	17618.63
13	Rotokawa	Lake Rotokawa, northern shore	3837.346	17611.59
14	Rotokawa	Lake Rotokawa, western shore	3837.636	17611.59
15	Rotokawa	Pond at north-western edge of lake	3837.638	17611.59
16	Rotokawa	Pond at outflow of lake	3837.792	17611.76
17	Waikite	Side arm of Otamakokore Stream	3891.395	17618.60
18	Waikite	Wetland adjacent to Otamakokore Stream	3819.180	17618.75
Non-geothermal sites				
19		Lake Ngapouri, northern shore	3820.215	17620.22
20		Lake Ngahewa, western shore	3818.913	17622.51

Temperature, conductivity, dissolved oxygen, pH and substrate type were recorded at each site. Chemical factors were recorded using YSI 30 conductivity, YSI 60 pH, and YSI 95 dissolved oxygen meters. The proportion of the dominant substrate types (silt, sand/gravel, small cobble, large cobble, boulders, bedrock, and organic material) was visually estimated on a zero to 100% scale.

Approximately 250 mL of surface water (at approximately 150 mm depth) was collected for chlorophyll *a* analysis. Chlorophyll *a* was measured spectrofluorometrically from duplicate samples following acetone pigment extraction by the NIWA Hamilton Chemistry Laboratory. This analysis provided a measure of phytoplankton biomass.

Planktonic algal species were collected from the sites by taking a 250 mL sample of surface water. Samples were preserved (Lugols Iodine) and taxa identified by Cathy Kilroy (NIWA, Christchurch), and the dominant taxa were noted from each sample.

For zooplankton, a survey of 19 of the 20 sites was conducted using throw nets (37 µm mesh, 200 mm diameter opening). One site at Waikite Valley was not sampled because of low water levels in the wetland. Five throws of approximately 5 m each were made at each site. Zooplankton were enumerated under a stereo microscope until 300 animals were counted, or until the entire sample was complete. Copepod nauplii were enumerated concurrently, but not included in the total count for analyses because in some sites they could not be ascribed to species. Because the samples were collected qualitatively, zooplankton data were expressed as relative abundances (% composition) for statistical analysis.

For macroinvertebrates, a semi-quantitative survey of the 20 sites was undertaken on the shallow margins of each water body using triangular nets (250 µm mesh). At each site a consistent three metre sample length was taken with the aim of removing the surface sediment. Because samples were collected semi-quantitatively, animals were expressed as numbers per metre sampled.

Phytoplankton, macroinvertebrates and zooplankton were identified to the lowest taxonomic level practical (usually species for invertebrates and genera for algae). Invertebrate taxa were generally identified using the keys of Chapman & Lewis (1976), Shiel (1995) and Winterbourn et al. (2000).

2.2 Analyses of responses of invertebrates to environmental gradients

Relationships between macroinvertebrate taxa richness, pH and temperature were examined using linear regression analysis using log (x+1) transformed taxa richness data (SYSTAT, version 9, SPSS Inc., Chicago, U.S.A.).

Mulitdimensional scaling (MDS) and Canonical correspondence analysis (CCA) were used to elucidate patterns in zooplankton and macroinvertebrate community composition. MDS is an indirect ordination technique used to examine the relationships of the sample sites to one another. MDS is a method akin to Cluster analysis, in that the resulting diagram is constructed using a similarity matrix based on species composition between sites. However, MDS has advantages over Cluster analysis in situations where species respond to gradients in environmental conditions, rather than forming different communities based on distinct environmental conditions. MDS produces a two-dimensional map that attempts to satisfy all the conditions imposed by a similarity matrix. Samples are thus distributed on the map such that those with similar composition are found close together, and samples with dissimilar composition are distributed far apart from one another (Clarke & Warwick, 1994).

CCA is an ordination technique that is used to determine species groupings and infer environmental factors that are important in determining the distribution of species between sites. CCA is used when species show unimodal response patterns in relation to underlying environmental variables. The results of CCA are presented on an ordination diagram. The position of the sites and species on the ordination diagram indicate the association between species and samples, their distance from the centre of the ordination, and the strength of their association. Environmental variables with the longest arrows on the ordination plot are those most strongly associated with the variations in species composition (Ter Braak, 1987).

For multivariate analyses, zooplankton species were used only if they comprised >3% of any sample and were present in two or more samples, or if they were in single samples and comprised greater than 10% of the composition. Sites were removed from the analyses in which a total of <10 zooplankton were enumerated in samples. Sites 1, 7, 9, 12, 13, 14, 15 and 16 were thus removed from analyses (see Appendix 2). The removal of this large number of sites was necessary because the occurrence of taxa in these samples may largely be due to chance, and these taxa would have been given a high weighting in the analysis.

Dissolved oxygen values from the upper site at Golden Springs could not be recorded due to equipment limitations brought about by high temperatures, and data for this site were replaced with those from the lower site for CCA. MDS was based on the Bray Curtis similarity coefficient calculated on the log (x+1) transformed relative abundances of zooplankton taxa to downweight the effects of dominant species. Downweighting ensured that the results of the ordination not only reflected abundance differences of the dominant species between sites, but also the abundances of less common taxa. Some of the environmental variables were also log (x+1) transformed to improve normality of the data. All environmental data were standardised to zero mean and unit variance to remove the influence of different scales of measurement.

Analysis of the macroinvertebrate data was performed similarly. However, analyses were performed only on the abundances of those taxa comprising >3% of the composition in any sample and present in two or more samples, and only on sites with greater than 30 individuals per species. Sites 5, 7, 9, 11, 12 and 13 were therefore omitted from the analyses. MDS and CCA were performed using the Primer Routines in Multivariate Research statistical package (PRIMER, Primer-E Ltd., Plymouth, U.K.) and CANOCO 4.0 (Centre for Biometry Wageningen, Netherlands), respectively.

3. RESULTS

3.1 Habitat conditions

A range of habitat conditions that could potentially affect the distributions of zooplankton, macroinvertebrates and algae was recorded in the survey (Table 2). Temperature and pH varied widely (Figure 1). The lakes with little or no geothermal influence (Lakes Ngapouri and Ngahewa) were distributed on the top left of the graph, indicating a combined influence of colder temperatures and higher pH levels than the other sites. Lake Ngahewa (pH 6.68) was more acidic than Lake Ngapouri (pH 9.07), which was likely due to the dystrophic nature of the former lake (Forsyth & McColl, 1975). An acidic spring in the middle of the lake may also have influenced pH (Lloyd, 1963). However, this site had the lowest conductivity of all the sites (67.2 µS/cm at 25 °C), suggesting minimal geothermal influence. Of the geothermally influenced sites, the Waikite Valley and Lake Ohakuri sites were the least acidic (pH>6), but they were not outside of the range of the non-influenced sites. These sites along with the Wiaotapu and Rotokawa sites had moderate temperatures.

Lake Ohakuri was sampled at a small embayment that receives geothermally heated water inputs from a stream and from springs on the shore of the lake. The first site was close to the stream input, and the water varied widely in temperature between 25.3 and 32.4 °C within short time periods (seconds). This site had no submerged macrophytes. It was revisited on 12 December 2001 and was observed to be dry due to the fluctuating water levels created by the Ohakuri Power Station. The second site differed from all of the other sites in this survey by the presence of a patchy covering of submerged and floating macrophytes (*Egeria densa*, *Ceratophyllum demersum*, the waterlily *Nymphea mexicana*, *Azolla filiculoides* and the duckweed *Lemna minor*). At this site, the temperature was temporally stable, at least over short time periods, but a vertical cline existed between 29.8 °C in the surface waters to 25.5 °C in the bottom waters over a depth of approximately 45 cm.

Average habitat conditions for each geothermal field are given in Table 2, and a complete list of measurements is given for all sites in Appendix 1. Conductivity was extremely high in the geothermally influenced sites relative to that of the non-influenced sites. Conductivity in these standing water sites was also generally greater than the adjacent, or even adjoining, streams from our previous survey of geothermally influenced flowing waters (cf. Duggan & Boothroyd, 2001). The most acidic fields, Waiotapu and Rotokawa, had the highest conductivity levels. Dissolved oxygen levels were lower, on average, in the geothermally influenced sites than the non-influenced sites. However, extremely high oxygen levels were occasionally recorded in some of the individual geothermal sites (see Appendix 3).

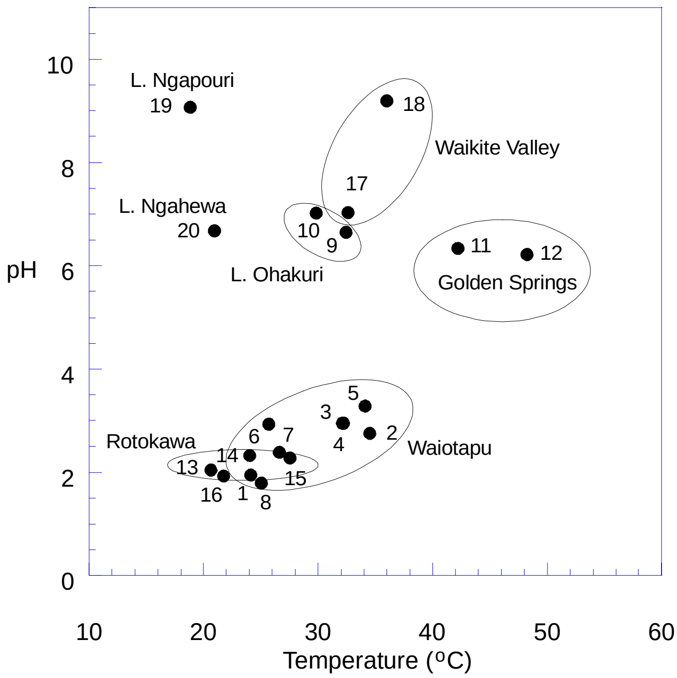


Figure 1. **Temperature and pH recorded from 20 standing water sites with various levels of geothermal influence in the Taupo Volcanic Zone (see Table 1 for site locations).**

Table 2. **Average physico-chemical variables from 20 standing water sites with various levels of geothermal influence in the Taupo Volcanic Zone.**

Geothermal Field	Site nos.	Temperature (°C)	pH	Conductivity (µS/cm @ 25 °C)	Dissolved oxygen (mg/L)	Oxygen saturation (%)	Chlorophyll *a* (mg/m^3)
Waiotapu field sites	1-8	29.3	2.7	2865.9	5.87	79.06	34.42
Lake Ohakuri	9-10	31.1	6.8	520	7.77	105.45	5.55
Golden Springs	11-12	45.2	6.3	1211.5	1.31	21.20	2.40
Lake Rotokawa	13-16	23.5	2.1	5557.5	8.31	97.13	4.30
Waikite Valley	17-18	34.3	8.1	1216.0	5.99	87.60	24.25
Non-influenced lakes	19-20	19.9	7.9	97.1	10.42	113.95	74.78

3.2 Algal composition and biomass

A list of the planktonic algal species recorded from the study sites, and an estimate of the algal biomass as assessed by chlorophyll *a* concentrations, is given in Table 3. The non-influenced lakes had, on average, the highest chlorophyll *a* levels. However, individually some geothermal sites had high algal biomass, in particular Lake Rotowhero (mean = 127.75 mg/m^3). Samples from the cooler, less acidic sites (e.g., Lakes Ohakuri and Ngahewa) generally possessed the greatest taxa richness, except Lake Ngapouri which had a dense monoculture of a *Ceratium* species. Cyanobacteria, diatoms, Euglenophyceae and Chlorophyceae were typical of the geothermal sites. Dinophyceae (*Ceratium* sp.) were found only in the non-geothermal Lake Ngapouri, and Chrysophyta (*Dinobryon* sp.) only in Lake Ohakuri where the geothermal influence was low. Most of the Waiotapu sites were dominated by Chlorophyceae, except Echo Lake (a diatom, *Gomphonema* sp.) and the Rainbow Mountain crater (a cyanobacterium, cf. *Spirulina* sp.). The small unidentified Chlorophyceae cells abundant in some of these sites were probably *Chlorella* species, as found in this lake by Forsyth & McColl (1974) and Cassie & Cooper (1989). The Lake Ohakuri sites (Orakeikorako field) were rich in species, particularly diatoms. A *Fragilaria* species dominated both sites, with the cooler site also having cf. *Spirulina* sp. (Cyanobacteria) and a *Fragilaria* species (Diatomophyceae) as dominants. Golden Springs was dominated by the cyanobacteria cf. *Phormidium* sp. (both sites) and the diatom *Aulacoseira* sp. The Rotokawa field sites were typically dominated by a *Euglena* species, except a small pond next to Lake Rotokawa in which *Euglena* was absent and a diatom dominated. The Waikite field sites were both dominated by diatoms (especially *Nitzschia* sp. and *Anomoeoneis* cf. *sphaerophora*), and no cyanobacteria were recorded.

3.3 Zooplankton

The zooplankton taxa collected from throw net samples (37 µm mesh) are listed in Table 4. No taxa were recorded from Echo Lake (site 1), and no sample was taken at site 18 (Waikite Valley), as low water levels precluded the use of a throw net. Taxa collected in the plankton comprised a variety of Rotifera, Cladocera and Copepoda species, as well as Ostracoda, Acarina and early instar Chironomidae. The non-geothermally influenced sites (19-20) generally had greater numbers of taxa than the geothermally influenced sites, except at the embayment of Lake Ohakuri, which also had a high number of taxa. In the geothermal sites, monogonont rotifers were recorded only occasionally. *Lecane* cf. *rhytida* was only recorded from Lake Rotowhero, and *Lecane luna* only from Golden Springs. Bdelloid rotifers were ubiquitous, being recorded at sites with high temperatures and low pH. Cyclopoid copepods were commonly found in geothermal sites. *Eucyclops serrulatus* was recorded from Waikite Valley and Lake Ohakuri, and *Paracyclops waiariki* from a number of sites in the

Waiotapu geothermal field. Mites and chironomids were common components of the zooplankton at geothermal sites.

Table 3. **Phytoplankton biomass (chlorophyll *a*) and species recorded from geothermal and non-geothermal standing water habitats in the Taupo Volcanic Zone. Numbers refer to the relative abundance of algal taxa assessed by eye for their relative contribution to the biomass of the sample on a scale of 8 (dominant) to 1 (rare).**

	Echo Lake	Waiotapu pond	Lake Rotowhero	Lake Rotowhero	Waiotapu	Waiotapu	Lake Ngakoro	Rainbow Mountain crater	Lake Ohakuri	Lake Ohakuri
site	1	2	3	4	5	6	7	8	9	10
Chlorophyll a (mg/m^3)	0.2	3.8	125.5	130.0	4.0	5.5	5.7	0.7	3.1	8.0
Class Cyanophyceae/ Cyanobacteria										
cf. *Leptolyngbya* sp.		3	3			5				
cf. *Phormidium* sp.										
cf. *Spirulina* sp.			2					8		8
unknown branched species										
Class Diatomophyceae/ Bacillariophyceae										
Achnanthes cf. *exigua*										3
Achnanthidium lanceolatum										
Achnanthidium spp.						1		3	5	5
cf. *Achnanthidium* sp.		4								
Amphora sp.										
Anomoeoneis cf. *sphaerophora*				1						
Aulacoseira sp.					1				3	3
Cocconeis sp.			1							
Cocconeis placentula									5	6
Cyclotella sp.									2	
Cymbella aspera										
Cymbella kappi										1
Cymbella sp.									1	
Epithemia sorex										4
Eunotia sp.						1				
Fragilaria sp. (chains)									8	8
Frustulia sp.		1								
Gomphonema truncatum										
Gomphonema sp.	8	4	1		3	3		6		
?*Gomphonema* sp.				1		5				2
Mastogloia sp.									1	
Melosira varians									6	6
Navicula cf. *avenacea*										
Navicula cf. *cryptocephala*										
Navicula sp.					1				2	
Nitzschia spp.	1					1			2	
Pinnularia sp.			1						3	3
Placoneis sp.									1	
Rhapalodia cf. *operculata*									1	
Rhapalodia novae-zealandiae			1					1	1	
Sellaphora sp.									3	3
cf. *Sellaphora sp.*										
Surirella sp.									2	
Synedra cf. *acus*									4	4
Class Chlorophyceae										
Closterium sp.										
Microspora sp.					8		2		6	
cf. *Mougeotia* (filaments)								5		
Oedogonium sp.									3	
Scenedesmus sp.										
Spyrogyra sp.									7	5
Staurastrum sp.										
small unicells		8	8	8			8			
small narrow cells						8				
Class Euglenophyceae										
Euglena sp.										
Class Dinophyceae/ Dinoflagellates										
Ceratium sp.										
Class Chrysophyceae										
Dinobryon sp.										2

Table 3 cont.

site	Golden Springs (lower) 11	Golden Springs (upper) 12	Lake Rotokawa 13	Lake Rotokawa 14	Pond near Lake Rotokawa 15	Lake Rotokawa outflow 16	Waikite Valley 17	Waikite Valley 18	Lake Ngapouri 19	Lake Ngahewa 20
Chlorophyll *a* (mg/m^3)	4.0	0.8	10.1	2.2	0.3	4.7	18.3	30.2	138.5	11.1
Class Cyanophyceae/ Cyanobacteria										
cf. *Leptolyngbya* sp.		6								
cf. *Phormidium* sp.	8	8								
cf. *Spirulina* sp.				6		5				
unknown branched species										1
Class Diatomophyceae/ Bacillariophyceae										
Achnanthes cf. *exigua*	3						7			
Achnanthidium lanceolatum										2
Achnanthidium spp.								3		
cf. *Achnanthidium* sp.										
Amphora sp.								6		
Anomoeoneis cf. *sphaerophora*							6	7		
Aulacoseira sp.		8					1			8
Cocconeis sp.										
Cocconeis placentula										
Cyclotella sp.										
Cymbella aspera										5
Cymbella kappi		1								
Cymbella sp.										
Epithemia sorex		3								2
Eunotia sp.										
Fragilaria sp. (chains)										5
Frustulia sp.										
Gomphonema truncatum										3
Gomphonema sp.										
?*Gomphonema* sp.		3	4		8	5				
Mastogloia sp.										
Melosira varians										4
Navicula cf. *avenacea*										1
Navicula cf. *cryptocephala*										1
Navicula sp.										
Nitzschia spp.	3	5			1		8	8		2
Pinnularia sp.							3			3
Placoneis sp.										
Rhapalodia cf. *operculata*					1		5	3		
Rhapalodia novae-zealandiae		6								2
Sellaphora sp.										
cf. *Sellaphora sp.*							6			
Surirella sp.										
Synedra cf. *acus*										
Class Chlorophyceae										
Closterium sp.							4			
Microspora sp.										3
cf. *Mougeotia* (filaments)							3			
Oedogonium sp.										
Scenedesmus sp.							2			
Spyrogyra sp.										
Staurastrum sp.										2
small unicells				6		5	6			
small narrow cells										
Class Euglenophyceae										
Euglena sp.			8	8		8				
Class Dinophyceae/ Dinoflagellates										
Ceratium sp.									8	
Class Chrysophyceae										
Dinobryon sp.										

Table 4. Zooplankton species recorded from geothermal and non-geothermal standing water habitats in the Taupo Volcanic Zone. P = present.

site	Waiotapu pond 2	Lake Rotowhero 3	Lake Rotowhero 4	Waiotapu 5	Waiotapu 6	Lake Ngakoro 7	Rainbow Mountain crater 8	Lake Ohakuri 9	Lake Ohakuri 10
Rotifera									
Asplanchna priodonta									
Brachionus quadridentatus									P
Colurella uncinata									P
Cephalodella gibba									P
Cupelopagis vorax									P
Dicranophorus forcipatus									P
Euchlanis dilatata									P
Filinia longiseta									
Hexarthra mira									
Keratella cochlearis									
Keratella tropica									
Lepadella acuminata									P
Lecane closterocerca									P
Lecane decipiens									P
Lecane luna									
Lecane lunaris									
Lecane bulla									P
Lecane cf. *rhytida*		P							
Pompholyx complanata									
Synchaeta pectinata	P								
Testudinella patina									P
Trichocerca rattus									P
Trichotria tetractis									P
Trichocerca similis									
Bdelloids	P	P	P	P	P	P	P	P	P
Cladocera									
Bosmina meridionalis									
Ceriodaphnia dubia									
Chydoridae									P
Chydorus sp.									P
Simocephalus vetulus									
Copepoda									
Acanthocyclops robustus									
Calamoecia lucasi									
Eucyclops serrulatus								P	P
Paracyclops waiariki		P	P	P	P				
Copepod nauplii		P	P	P	P	P			P
Ostracoda									P
Acarina									
Orbatei				P					
Hydracarina									
Chironomidae		P	P		P		P		P

Table 4 cont.

site	Golden Springs (lower) 11	Golden Springs (upper) 12	Lake Rotokawa 13	Lake Rotokawa 14	Pond near Lake Rotokawa 15	Lake Rotokawa outflow 16	Waikite Valley 17	Lake Ngapouri 19	Lake Ngahewa 20
Rotifera									
Asplanchna priodonta								P	
Brachionus quadridentatus									
Colurella uncinata									
Cephalodella gibba									
Cupelopagis vorax									
Dicranophorus forcipatus									
Euchlanis dilatata									P
Filinia longiseta								P	P
Hexarthra mira								P	
Keratella cochlearis								P	
Keratella tropica								P	
Lepadella acuminata									
Lecane closterocerca									
Lecane decipiens									
Lecane luna	P	P							
Lecane lunaris									P
Lecane bulla									
Lecane cf. *rhytida*									
Pompholyx complanata								P	
Synchaeta pectinata									P
Testudinella patina									
Trichocerca rattus									
Trichotria tetractis									
Trichocerca similis								P	P
Bdelloids	P	P	P	P	P	P	P		P
Cladocera									
Bosmina meridionalis									P
Ceriodaphnia dubia									P
Chydoridae									
Chydorus sp.									P
Simocephalus vetulus									P
Copepoda									
Acanthocyclops robustus									P
Calamoecia lucasi									P
Eucyclops serrulatus							P		
Paracyclops waiariki									
Copepod nauplii							P	P	P
Ostracoda									
Acarina									
Orbatei			P		P		P		
Hydracarina									P
Chironomidae				P		P	P		P

3.4 Zooplankton community dynamics

Lake Ngakoro, Lake Ohakuri near the inflow stream, the upper Golden Springs site, and all of the sites in the Lake Rotokawa field were not included in the multivariate zooplankton community analyses due to the extremely low numbers of individuals recorded in these samples. MDS was used to find natural groupings of samples based on species composition and abundance, and to detect changes in community composition that may occur along environmental gradients. The extremely low stress value of the MDS (0.04) indicates that this diagram provides an excellent representation of the similarity of zooplankton distribution between sites.

The MDS ordination (Figure 2) revealed that the composition of zooplankton communities was generally more similar within than between geothermal fields, as indicated by the fairly discrete, non-overlapping distributions of samples. Samples from the coldest sites were found on the left hand side of the ordination. Lake Ngahewa (site 20) was distributed closer to the geothermally influenced sites, possibly due to the acidic nature of this dytrophic lake (Forsyth & McColl, 1975), or because of mild geothermal influence.

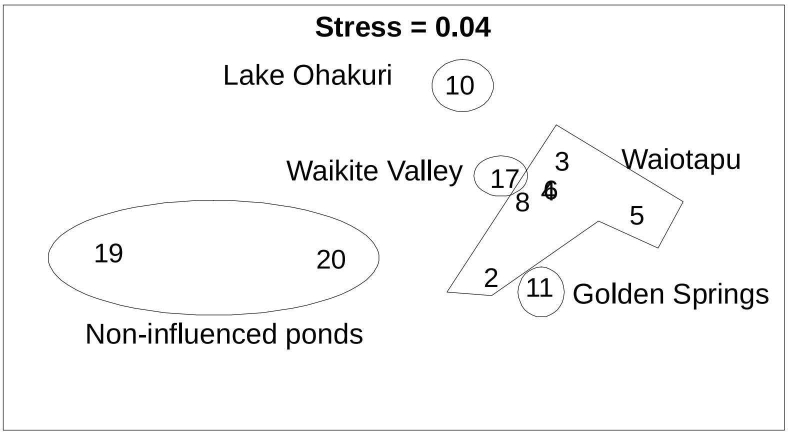


Figure 2. Ordination diagram based on MDS of zooplankton species composition from 11 standing water sites with varying degrees of geothermal influence in the Taupo Volcanic Zone. Numbers correspond to sites (see Table 1 for locations).

CCA was used to detect species groupings and the environmental variables important in determining the patterns in community composition found in the MDS. Samples were in general distributed similarly in the CCA (Figure 3) as they were in the MDS ordination, allowing us to have confidence in the representation given by the CCA ordination, and that the environmental variables examined adequately explain species distribution. Samples from the cooler sites (the lakes with no geothermal influence and Lake Ohakuri) were distributed on the right hand side of the ordination. The remaining sites (Golden Springs, Waiotapu and Waikite Valley) were distributed on the left hand side of the ordination. The more alkaline sites were generally distributed on the bottom left of the ordination, while the more acidic sites (Waiotapu) were on the top left of the ordination. However, the alkaline Golden Springs site was also located amongst the acidic ponds from Waiotapu, indicating that these sites had a similar species composition despite differences in environmental conditions. Species most strongly associated with the cooler sites (right side of the ordination) were the rotifers *Synchaeta pectinata*, *Euchlanis dilatata*, *Lecane bulla*, *Filinia longiseta*, *Trichocerca similis* and *Keratella cochlearis*, and the cladoceran *Chydorus* sp. Taxa most strongly associated with the remaining sites were *Lecane luna*, *L*. cf. *rhytida* and the bdelloid rotifers, Acari, chironomids, and the copepod *Paracyclops waiariki*.

Conductivity explained the largest proportion of variability in zooplankton community composition between sites (lambda A = 0.62, $P < 0.05$), indicating that the major differences in taxa composition between sites are due to the presence or degree of geothermal activity (i.e., ion concentrations in the water). Samples with the greatest degree of geothermal influence are distributed on the left side of the ordination, and those with the least influence on the right. Geothermal versus non-geothermal differences therefore mainly drove these patterns.

3.4 Macroinvertebrate composition and dynamics

A list of macroinvertebrate species recorded in the sites is listed in Table 5. No taxa were recorded from one of the Waiotapu ponds, Lake Ngakoro, or the upper spring at Golden Springs (sites 5, 7 and 12). Regression analyses (Figure 4) indicated that taxa richness significantly decreased with increasing temperature ($R^2 = 0.206$; $F = 4.682$; $P = 0.044$), but no significant relationship existed for pH ($R^2 = 0.142$; $F = 2.985$; $P = 0.101$). Multiple linear regression indicated that the predictive ability using both factors was highly significant ($R^2 = 0.493$; $F = 8.249$; $P = 0.003$).

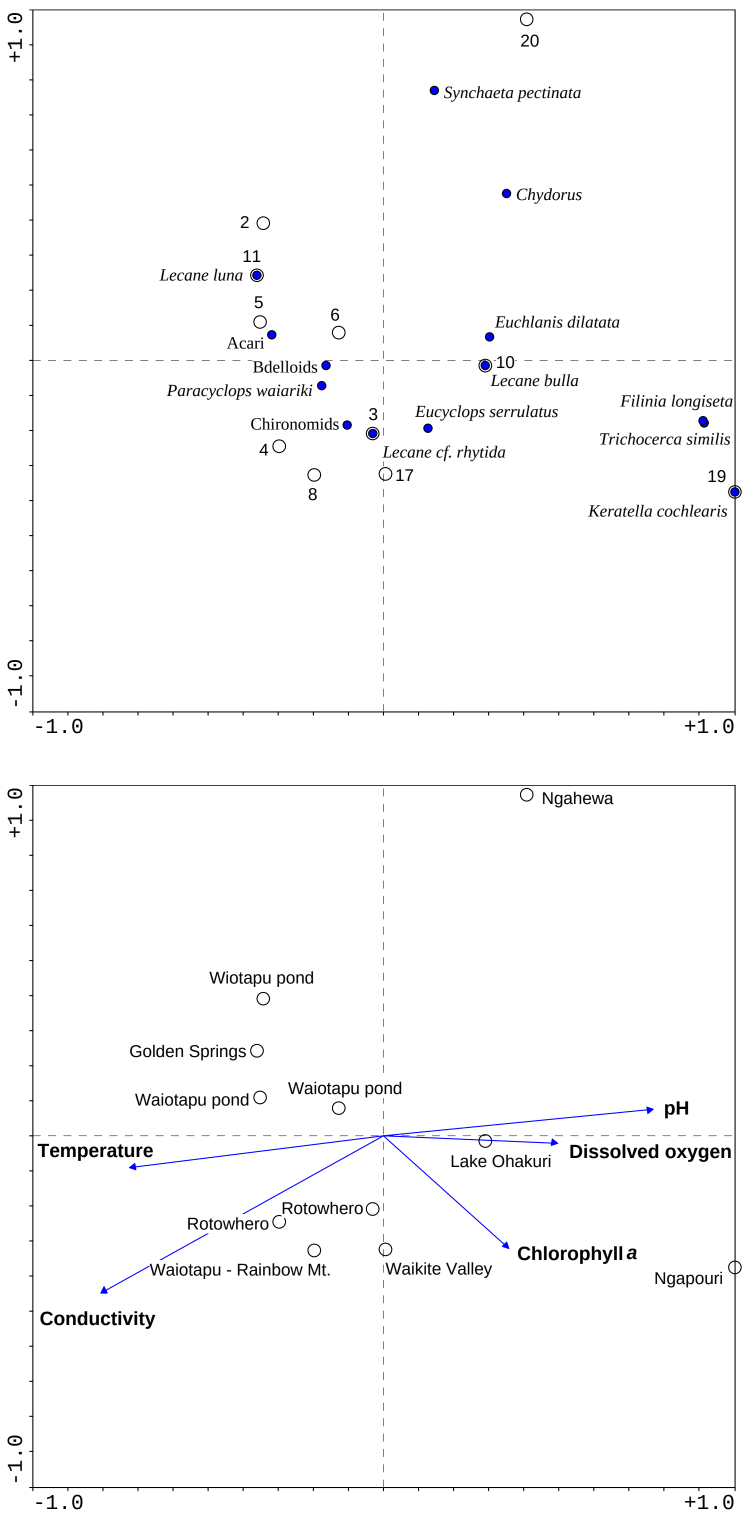


Figure 3. **Ordination biplots based on CCA of zooplankton composition from 11 standing water sites with various levels of geothermal influence in the Taupo Volcanic Zone. The site (open circles) and species (closed circles) biplot is above, and the site and environmental variable (arrows) biplot is below. Numbers correspond to sites (see Table 1). Eigenvalues for axes 1 (horizontal) and 2 (vertical) = 0.738 and 0.475 respectively.**

The MDS ordination (Figure 5) showed that the composition of macroinvertebrate communities was, in general, similar in waterbodies within each geothermal field. However, sites in the Waiotapu field had a wide range of invertebrate compositions between sites. The non-influenced sites were distributed on the left hand side of the ordination. The more alkaline sites, Lake Ohakuri and Waikite Valley, were most closely associated with the non-geothermally influenced sites. The more highly acidic sites, from the Waiotapu and Rotokawa fields, were in general found to associate closely with one another, except for sites 2 and 8. The low stress value of the MDS (0.07) indicates that this diagram provides a good representation of the similarity relationships between sites.

The CCA ordination of macroinvertebrate distributions (Figure 6) showed a broadly similar distribution of samples as the MDS. Samples from the non-geothermally influenced ponds were found together at the top right of the ordination, and the remaining more alkaline sites (Waikite Valley and Lake Ohakuri) were also distributed on the right side of the ordination. All of the acidic Lake Rotokawa and Waiotapu sites are distributed on the left side of the ordination, except one Waiotapu pond (site 2).

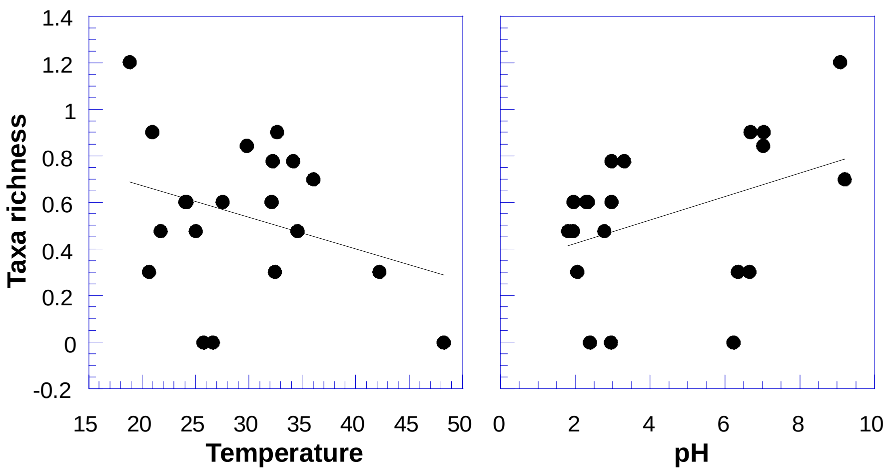


Figure 4. Log (x+1) taxa richness from 20 standing water sites with various levels of geothermal influence in the Taupo Volcanic Zone against temperature (^{o}C) and pH.

Three groups of species are apparent in the ordination. Species most strongly associated with the non-geothermal sites (Lakes Ngapouri and Ngahewa) were *Lumbriculus*, *Pisidium* sp., *P. hendersoni* and Tubificidae. Species most strongly associated with the group comprising site 2 (Waiotapu), and more greatly with the Lake Ohakuri and Waikite Valley samples, were *Enochrus tritus*, *Chironomus* sp. a and *Paratrichocladius pluriserialis*. Species most strongly associated with the acidic

Rotokawa and Waiotapu field samples were *Chironomus zealandicus*, *Anisops wakefieldi*, *Liodessus deflectus*, *Culex rotoruae*, and *Neoscatella* sp.

The pH of the water bodies explained the greatest proportion of variability in macroinvertebrate composition (lambda A = 0.67, $P < 0.01$). pH was strongly positively associated with both Axes 1 and 2 (top right of the ordination). Conductivity was strongly negatively associated with Axis 2 (bottom of the ordination) and less strongly negatively associated with Axis 1. The most alkaline water bodies with low conductivity (i.e., the non-geothermally influenced lakes) werethus distributed on the top right of the ordination. Those sites which were more alkaline but with high conductivity, and hence with geothermal influence, are distributed on the bottom right of the ordination. Temperature and the percentage of silt substrates are both found on the bottom right of the ordination. This thermal and substrate gradient seems to strongly influence the species composition and abundance between the more alkaline sites, with the warmer Waikite Valley sites and Lake Ohakuri with silt beds separating from the cold water non-geothermal sites with coarser grained beds along this gradient. Chlorophyll *a* and dissolved oxygen were both positively associated with Axis 2 (top of the ordination); the non-geothermal sites generally had high values of both of these variables, and the geothermal sites generally had lower values.

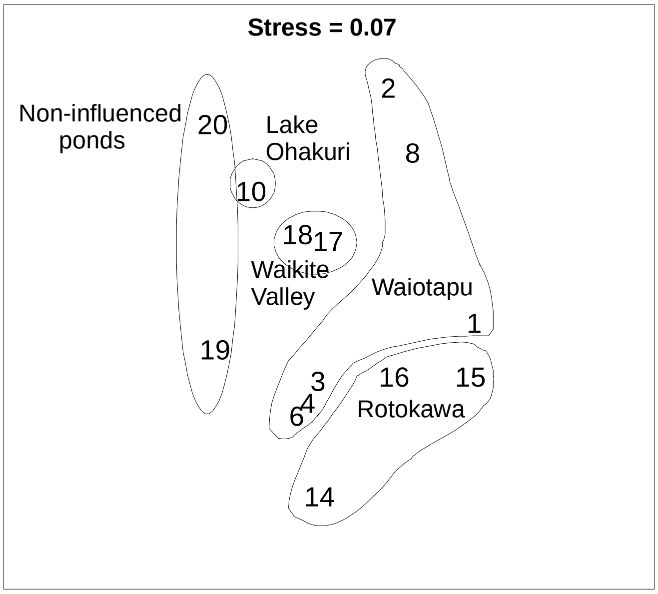


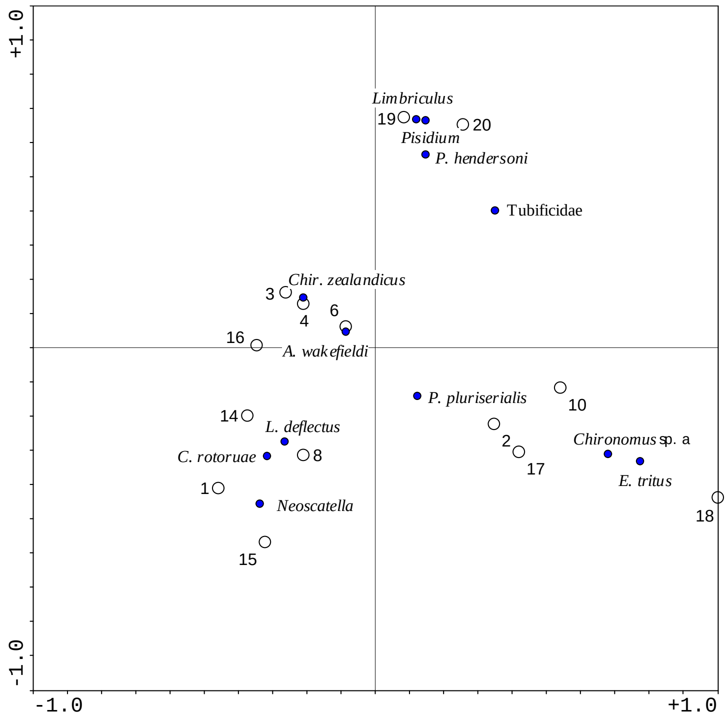
Figure 5. **Ordination diagram based on MDS of macroinvertebrate species composition from 14 standing water sites with varying degrees of geothermal influence in the Taupo Volcanic Zone. Numbers correspond to sites (see Table 1 for locations).**

Table 5. Macroinvertebrate species recorded from geothermal and non-geothermal habitats in the Taupo Volcanic Zone. P = present.

	1 Echo Lake	2 Waiotapu pond	3 Lake Rotowhero	4 Lake Rotowhero	6 Waiotapu pond	8 Waiotapu Pond - Rainbow Mt.	9 Lake Ohakuri	10 Lake Ohakuri
Odonata								
Antipodochlora braueri								
Austrolestes colensonis					P			
Ischnura aurora								
Procordulia grayi								
Xanthocnemia zealandica					P			
Trichoptera								
Triplectides cephalotes					P			
Coleoptera								
Antiporus ?strigosulus								
Enochrus tritus			P					
Hydraenidae								
Laccobius arrowi	P		P			P		
Liodessus deflectus	P	P						
Scritidae								
Hemiptera								
Anisops wakefieldi			P	P	P			
Saldula stoneri								
Sigara sp.			P	P				P
Diptera								
Ceratopogonidae								
Chironomus zealandicus			P	P	P			
Chironomus sp. a								P
Cricotopus aucklandensis								
Culex rotoruae	P							
Muscidae								
Neoscatella sp.								
Oxyethira albiceps							P	
Paratrichocladius pluriserialis		P				P		P
Paroxyethira hendersoni								P
Polypedilum sp.								
?*Tanytarsus* sp.								
Crustacea								
Ostracoda								
Mollusca								
Glyptophysa variabilis								
Gyraulus kahuica								
Physa sp.								
Pisidium sp.								
Planorbarius corneus								P
Potamopyrgus antipodarum								
Acari								
Oligochaeta								
Lumbriculus sp.								
Tubificidae								P
Hirudinea								
Platyhelminthes								

Table 5 cont.

	Golden Springs (lower) 11	Lake Rotokawa 13	Lake Rotokawa 14	Pond near Lake Rotokawa 15	Lake Rotokawa outflow 16	Waikite Valley 17	Waikite Valley 18	Lake Ngapouri 19	Lake Ngahewa 20
Odonata									
Antipodochlora braueri									P
Austrolestes colensonis									
Ischnura aurora						P			
Procordulia grayi						P			
Xanthocnemia zealandica								P	
Trichoptera									
Triplectides cephalotes									
Coleoptera									
Antiporus ?strigosulus	P						P		
Enochrus tritus							P		
Hydraenidae							P		
Laccobius arrowi									
Liodessus deflectus									
Scritidae							P		
Hemiptera									
Anisops wakefieldi						P			
Saldula stoneri			P						
Sigara sp.								P	
Diptera									
Ceratopogonidae								P	
Chironomus zealandicus		P	P		P			P	
Chironomus sp. a						P	P		
Cricotopus aucklandensis									P
Culex rotoruae				P	P	P			
Muscidae				P					
Neoscatella sp.			P	P					
Oxyethira albiceps									
Paratrichocladius pluriserialis								P	P
Paroxyethira hendersoni								P	
Polypedilum sp.						P			
?*Tanytarsus* sp.						P			
Crustacea									
Ostracoda								P	
Mollusca									
Glyptophysa variabilis									
Gyraulus kahuica								P	
Physa sp.								P	P
Pisidium sp.								P	P
Planorbarius corneus									
Potamopyrgus antipodarum								P	
Acari								P	
Oligochaeta									
Lumbriculus sp.								P	P
Tubificidae									P
Hirudinea								P	
Platyhelminthes								P	



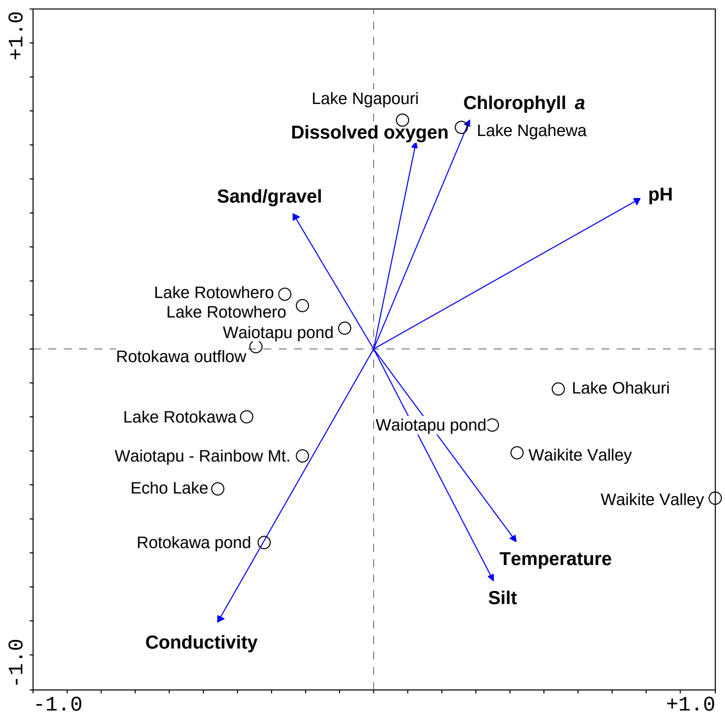


Figure 6. **Ordination biplots based on CCA of macroinvertebrate composition from 14 standing water sites with various levels of geothermal influence in the Taupo Volcanic Zone. The site (open circles) and species (closed circles) biplot is above, and the site and environmental variables (arrows) biplot is below. Numbers correspond to sites (see Table 1 for locations). Eigenvalues for axes 1 (horizontal) and 2 (vertical) = 0.736 and 0.685 respectively.**

4. DISCUSSION

4.1 Algal composition

Although the factors determining the distribution patterns of benthic algae in geothermal streams are well known, little attention has been given to factors important for planktonic algae of geothermal standing waters. Important variables controlling the distribution of benthic species in flowing waters are temperature, pH and sulphide concentration (Stockner, 1967; Castenholz, 1976; Lamberti & Resh, 1985; Brock, 1985). Standing water cyanobacteria are able to grow at higher temperatures than any other group, although this group is not successful in acidic waters, whereas diatoms generally dominate in cooler waters (Stockner, 1967; Brock, 1985). Brock & Brock (1970) have noted that cyanobacteria in flowing water systems do not grow below pH 4.8.

These expectations were all met in our study of benthic algae of geothermal flowing waters in the Taupo Volcanic Zone (Duggan & Boothroyd, 2001). In the current study, planktonic cyanobacteria were found to dominate standing waters in the hot (42.2-48.2 °C), alkaline Golden Springs sites. None of the other sites reached such high temperatures. In addition, the cooler, alkaline Waikite Valley sites were dominated by diatoms, and cyanobacteria were absent. Contrary to expectations, however, cyanobacteria (cf. *Spirulina* and cf. *Leptolyngbya* species) were recorded from a number of the highly acidic, high sulphide, Waiotapu and Rotokawa sites. A cyanobacteria species (cf. *Spirulina*) was found to dominate in the highly acidic (pH 1.8) Rainbow Mountain crater (Waiotapu field). In our previous study of flowing waters, cyanobacteria were absent from Hakereteke Stream (pH ~3) within the Waiotapu field (Duggan & Boothroyd, 2001).

Euglena anabaena was found to be prominent in the plankton of standing waters from in Lake Rotokawa (Forsyth, 1977), and Forsyth & McColl (1974) found *Chlorella* species in Lake Rotowhero. Neither study recorded cyanobacteria from either of these lakes. However, a lack of planktonic cyanobacteria from acidic geothermal waters, or from these lakes, is not universal. Cassie & Cooper (1989), for example, recorded the cyanobacterium *Phormidium tenue* from Lake Rotowhero at pH 4. It is also important to note that, at the acidic sites where cyanobacteria were of greatest relative importance (e.g., Rainbow Mountain), chlorophyll *a* was generally low, indicating that these taxa are likely to be found in low abundances at these sites.

4.2 Zooplankton composition

Very few zooplankton taxa have been recorded from geothermally influenced waters in New Zealand, or globally, to date. Major groups recorded from geothermal habitats in the current study are discussed below.

4.2.1 Rotifera

Monogonont rotifers (e.g., *Lecane* and *Synchaeta* species) were recorded infrequently in the geothermal sites. Two individuals of a *Lecane* species, similar to *L. rhytida*, were recorded from Lake Rotowhero. This taxon has been reported from this lake previously by James (1995). The specimens examined here have a projecting foot pseudo-segment with lateral projections, and toes tapering to a point from the midpoint, which are typical of this species. However, they differ from the nominate species by not possessing obvious ornamentation of the lorica, and by being smaller in size (cf. Segers, 1995). *L. rhytida* sensu stricto is known from Central and South America, Nigeria, and Papua New Guinea (Segers, 1995). This species has not been recorded from non-geothermal sites in New Zealand (Shiel & Green, 1996), and thus appears to be an obligate geothermal form here.

Lecane species may be common components of geothermal waters worldwide, with Jana & Sarkar (1971) and Jana (1973) recording a species from Swetgaga, a geothermal stream in west Bengal, India, at temperatures as high as 44 °C. In addition, Green & Kramadibrata (1988) recorded a *Lecane* species as the only rotifer from Lake Goang (pH 2.5), a geothermally influenced lake in Indonesia. *Lecane luna* was recorded at high temperatures (42.2 and 48.2 °C) from Golden Springs. This species is cosmopolitan, and is widely distributed in New Zealand (Sanoamuang & Stout, 1993; Duggan et al., 1998). The specimens fit the description of this species by Segers (1995). However, Perez-Legaspi & Rico-Martinez (1988) found populations of this species could not be sustained in the laboratory for more than two weeks at 30 °C, although they survived at lower temperatures. The population at Golden Springs may thus be genetically adapted for survival at these high temperatures.

A single individual of *Synchaeta pectinata* was recorded at a Waiotapu pond (site 2) at pH 2.76 and 34.5 °C. Berzins & Pejler (1987, 1989) recorded this species up to 27 °C in Swedish waters, and in waters as low as pH 4.5, although no thermally influenced waters were sampled in their survey. That there was only one individual recorded suggests that contamination of the sample was possible. However, we feel this is unlikely due to the net having previously been used in Echo Lake, where no rotifers were recorded, and because the animal appeared to be in good condition.

Bdelloid rotifers were in general not identified with greater taxonomic resolution due to the need to observe live individuals. However, these rotifers were almost ubiquitous in the geothermal sites, being absent only from those sites where no zooplankton were recorded. From a live sample collected from Lake Rotowhero on 12 December 2001, the bdelloids collected were identified as an *Adineta* species. In European hot springs, *Adineta gracilis* and *Adineta glauca* have been recorded at temperatures between 40 and 45 °C, along with another bdelloid, *Rotaria rotatoria* (Pax & Wulfert, 1941, 1942). Given their ubiquitous nature in the geothermally influenced sites, greater attention should be given to the identification of bdelloids in these habitats in the future. Bdelloid species composition is likely to vary along gradients of temperature and pH, with the potential for the presence of obligate geothermal forms to exist in some sites.

4.2.2 Copepoda

Paracyclops waiariki was recorded from Lake Rotowhero and several ponds within the Waiotapu geothermal field. This species was originally described from Lake Rotowhero, and also recorded from a warm swamp alongside Soda Springs, Lake Rotoehu by Lewis (1974). This is the only copepod recorded that appears to occur obligately from geothermal sites in New Zealand. A *Paracyclops* species has also been recorded from the geothermally influenced Lake Guang, Indonesia, at pH 2.5 (Green & Kramadibrata, 1988).

Eucyclops serrulatus was found in warmer sites (up to 32.6 °C), with fairly circum-neutral pH. This species is a common component of New Zealand ponds and the littoral zones of lakes (Chapman & Lewis, 1976), and the temperatures recorded here are not greatly higher than what might be expected in these habitats in summer. This species is cosmopolitan in distribution (Chapman & Lewis, 1976).

Zooplankton of Lake Ohakuri

A number of other rotifers, cladocera, and an ostracod were also recorded from Lake Ohakuri at 29.8 °C; temperatures approaching this might occur in the littoral zones of some northern New Zealand lakes in summer. Most of the rotifer species recorded were typical summer-autumn occurring forms. It would be interesting, therefore, to examine whether these year-round elevated temperatures inhibit the seasonality typical in other zooplankton communities. Most of the rotifer species recorded here were also typical littoral species, and are likely to live in association with the macrophytes present at this site (Duggan et al., 1998). Although vertical gradients in temperature were apparent at this site, zooplankton samples were collected from throughout the water column (avoiding contact with the bottom sediment), and zooplankton are likely to have been surviving at these elevated temperatures.

4.3 Patterns in zooplankton distribution

Increasing temperature and decreasing pH were important predictors of zooplankton distribution. Different taxa occurred in the geothermal and non-geothermally influenced sites, and composition in the geothermal sites was apparently similar regardless of whether they were hot, cold, acid, or alkaline. The conclusion that similar taxa appear to occur in geothermal sites regardless of temperature or pH is likely to partly reflect the fact that we were unable to identify or distinguish immature larval chironomid or bdelloid species. Both of these groups were typical of the geothermal sites, although they are likely to change in species composition along physico-chemical gradients. The low numbers of individuals generally encountered in the geothermal sites, and the low richness of taxa in these sites overall, are likely to have affected the resulting patterns in the multivariate analysis in the current study.

Records of zooplankton in New Zealand geothermal waters are rare. In Lake Rotokawa, Forsyth (1977) recorded only dead chironomids from zooplankton hauls. Forsyth & McColl (1974) recorded rotifers from the mud and water in Lake Rotowhero, and Winterbourn & Brown (1967) recorded rotifers from Waipahihi Stream, although these taxa were not identified with greater taxonomic resolution. In contrast, Forsyth & McColl (1975) recorded a species assemblage from the non-geothermal Lake Ngahewa in 1973 similar to the one we recorded in the current survey. Zooplankton species recorded from the non-geothermal sites were typical of species from North Island lakes in general (e.g., Duggan et al., 2001).

In the current study we have a sampling gap in the pH range between 4 and 6. We therefore had a sharp decline in the number of zooplankton species observed in the geothermally influenced sites relative to the non-geothermal sites between these pHs. Forsyth & MacKenzie (1981), however, recorded some more typical zooplankton species, *Bosmina meridionalis*, *Macrocyclops* sp., and the rotifers *Brachionus* sp. and *Polyarthra* sp. from Opal Lake at pH 4.3 at ambient temperatures. It seems apparent, therefore, that zooplankton species richness should increase as pH approaches neutrality from acidic conditions, with tolerant species appearing, such as *B. meridionalis* which is common in non-geothermal waters.

4.4 Macroinvertebrate community composition

Taxa richness in the sites surveyed generally decreased with increasing temperature or acidity. No taxa were recorded at the warmest site, the upper spring at Golden Springs (48.2 °C), and macroinvertebrates are typically not recorded at temperatures above 50 °C (Vincent & Forsyth, 1987). Lakes of high acidity and temperature are commonly found to be species poor compared with non-geothermally lakes in the Taupo Volcanic zone (Forsyth & McColl, 1974, 1975; Michaelis, 1982).

Macroinvertebrate taxa recorded in geothermally influenced habitats were in general typical of those recorded in similar habitats previously sampled in New Zealand (e.g., Vincent & Forsyth, 1987). Most of the taxa recorded in the current survey were also common taxa of non-geothermally influenced habitats, indicating that they can tolerate high temperatures or unusual pH rather than being obligate geothermal species. Taxa characteristic of the more geothermally influenced sites are discussed in detail below.

4.4.1 Odonata

A single individual of *Austrolestes colensonis* and several individuals of *Xanthocnemis zealandica* were recorded at a Waiotapu pond (site 6) at 25.7 °C and pH 2.94. *A. colensonis* has been recorded previously from Waipahihi Stream at 24 °C (Vincent & Forsyth, 1987). This species is widely distributed in still, non-geothermal waters throughout New Zealand (Winterbourn et al., 2000). *X. zealandica* was also recorded from the non-geothermal Lake Ngapouri. This species has been recorded previously from acidic streams within the Waiotapu geothermal field by Forsyth (1983a) and Duggan & Boothroyd (2001).

A single individual of *Procourdulia grayi* was recorded from Waikite Valley at 32.6 °C and pH 7.03. This species has been recorded from geothermally influenced waters previously at Opal Lake at 29 °C and pH 3 (Vincent & Forsyth, 1987).

Ischnura aurora was recorded from Waikite Valley (site 17) at 32.6 °C and pH 7.03. This species was recorded by Duggan & Boothroyd (2001) from Otamakokore Stream, Waikite Valley, at high temperatures and circum-neutral pH, but also from the acidic Lake Rotowhero (Forsyth & McColl, 1974). Further distribution details for this group are given in Duggan & Boothroyd (2001).

4.4.2 Trichoptera

Triplectides cephalotes was recorded at a Waiotapu pond (site 6) at 25.7 °C and pH 2.94. This species has been recorded previously from the highly acidic Opal Lake (pH 4) (Forsyth & MacKenzie, 1981) and from Hakereteke Stream, Waiotapu (pH 4.14) (Duggan & Boothroyd, 2001).

4.4.3 Coleoptera

Liodessus deflectus was recorded from the acidic Waiotapu sites Echo Lake, Lake Rotowhero and the pond at Rainbow Mountain (Waiotapu) (sites 1, 3, 8). This species has been recorded at temperatures up to 35 °C (Stark et al., 1976; Vincent & Forsyth, 1987), but is apparently not a typical dweller in geothermal habitats. A congeneric species, *L. plicatus*, has been recorded previously from the Lake Rotowhero outlet stream by Forsyth (1983a).

Enochrus tritus was recorded from Lake Rotowhero (site 3) and Waikite Valley (site 18). This species was not recorded in the survey of flowing water sites by Duggan & Boothroyd (2001). *E. tritus* is the commonest hydrophild in New Zealand's thermal waters with a known temperature range of 28-45 °C for adults and 33-45 °C for larvae (Winterbourn 1970).

Laccobius arrowi was recorded from Waikite Valley (site 18) at 36 °C and pH 9.2. This species is a common component of thermal water communities. It has been recorded by Winterbourn (1973) near the Copeland River from warm springs and pools between 27 and 33 °C. Winterbourn (1970) also recorded this species from the Waipuwerawera and Waipahihi Streams between 29-37 °C and pH 3.7-8.0. Most records of this species are from thermal waters (Winterbourn et al. 2000).

Sciritidae were recorded in highly acidic waters from Echo Lake (site 1; temperature 24.0 °C, pH 2.33) and Lake Rotowhero (site 3; 32.2 °C, pH 2.96). A scirtid species is also known from acid coal mine drainages (Winterbourn, 1998).

Antiporus cf. *strigosulus* (previously *Antiporus wakefieldi*) was recorded at Golden Springs at 36 °C and at Lake Ohakuri at temperatures up to 42.2 °C. Hydraenidae were also recorded at Lake Ohakuri at temperatures up to 42.2 °C, although due to vertical temperature gradients at this site it may have been living at temperatures somewhat cooler.

4.4.4 Hemiptera

Hemiptera were absent from our previous survey of flowing waters (Duggan & Boothroyd, 2001). Here, were recorded *Anisops wakefieldi* (sites 3, 4, 6, 17), *Sigara* sp. (sites 3, 4, 9, 19) and *Saldula stoneri* (site 14). The two former species have been recorded previously from moderate temperatures (37 °C) and high acidity (pH 3) from Lake Rotowhero (Vincent & Forsyth, 1987). Saldidae, such as *S. stoneri*, are common representatives of thermal waters around the world (Pritchard, 1991), with *S. stoneri* associated with North Island thermal areas (Winterbourn et al., 2000).

4.4.5 Diptera

Chironomus zealandicus was recorded mainly in the more acidic sites. This species is a commonly represented in geothermal waters and can tolerate extreme acidity (as low as pH 1.8) (Forsyth, 1983b; Boothroyd, 2002). It was the only chironomid recorded in Lakes Rotokawa and Rotowhero, despite Lake Rotokawa being a cold lake (Forsyth, 1983b). *C. zealandicus* has also been recorded from streams near Waiotapu (41.4 °C, pH 3.75) (Duggan & Boothroyd, 2001).

Chironomus sp. a was recorded only from the more alkaline sites (Lake Ohakuri pH 6.8, Waikite Valley pH 8.1). It has also been recorded from Otamakokore Stream (28.3-55.7 °C, pH 8.07-9.6), Hakereteke Stream (19.4-33.7 °C, pH 3.1-5.14) and Orakeikorako (14.7-25.3 °C, pH 8.72-8.92).

Paratrichocladius pluriserialis was recorded in ponds near Lake Rotowhero and at Rainbow Mountain. *P. pluriserialis* is extremely common and abundant in the central North Island, being found in a variety of habitats, from cold springs to the sinter terraces of Orakei Korako (IKB pers. obs.).

An undescribed species of *Polypedilum* was recorded from the side arm of Otamakokore Stream (pH 8.1, Temp. 34°C). Although *Polypedilum* species are common throughout New Zealand, they have rarely been recorded in geothermal water. A *Polypedilum* species was also recorded from Hakereteke Stream (1.4-28.8 °C, pH 3.1-5.4) by Duggan & Boothroyd (2001).

Culex rotoruae was recorded from the margins of Echo Lake, and Lake Rotokawa and associated ponds and outlets. *C. rotoruae* is confined to mineralised waters of the TVZ (Vincent & Forsyth, 1987; Winterbourn et al., 2000).

The ephydrid fly *Neoscatella* was recorded from Lake Rotokawa and an adjacent pond (sites 14 and 15). *N. vittithorax* has been recorded from surface waters up to 47 °C (Vincent & Forsyth, 1987), and in Waipahihi Stream over 45 °C by James (1985). Ephydrids are common in geothermal waters worldwide (Pritchard, 1991).

Muscidae were recorded from a small pond in the Rotokawa geothermal field (site 15). Muscidae are recorded as an uncommon component of thermal waters in Iceland (Pritchard, 1991).

4.4.6 Non-insect taxa

The mollusc *Planorbarius corneus* and Tubificidae were recorded from Lake Ohakuri. Due to the vertical thermal gradient at this site, both may have potentially been sampled from reasonably ambient temperature and pH levels on or within the sediment. However, *P. corneus* is known to tolerate temperatures up to 35 °C (Vincent & Forsyth, 1987). No other mollusc species were recorded from the geothermally influenced sites, despite being species rich in the previous survey of running waters (Duggan & Boothroyd, 2001). No leeches were recorded in the current study, despite Forsyth (1977) recording these on one occasion in Lake Rotokawa.

4.5 Patterns in Macroinvertebrate Community Composition

A range of environmental conditions affected the distribution of macroinvertebrates in the current study. CCA indicated that pH was the most important variable determining the macroinvertebrate community composition between sites, with the acidic Waiotapu and Rotokawa sites having generally different species composition than the more alkaline lakes. The acidic sites were distinguished by the presence or increased abundances of *Neoscatella* sp., *Culex rotoruae*, *L. deflectus*, *A. wakefieldi* and *Chironomus zealandicus.* These species have all been recorded as components of geothermal communities previously (see above section). Forsyth (1977) has previously noted great similarities in macroinvertebrate composition between Lakes Rotokawa and Rotowhero.

The alkaline sites were also separated along a temperature gradient, with Lake Ohakuri and the Waikite Valley sites having dissimilar composition than the colder non-geothermally influenced sites. Species associated with the geothermally influenced sites were *Enochrus tritus*, *Chironomus* sp. a and *Paratrichocladius pluriserialis*. The annelids (*Lumbriculus,* Tubificidae), *Paroxyethira hendersoni* and the mollusc *Pisidium* were more typical of the non-acidic, non-geothermal sites. Other annelid species have been recorded from warm non-acidic geothermal sites previously, for example in Otamakokore Stream (Duggan & Boothroyd, 2001). However, of this group, only the leeches appear to be able to tolerate low pH, as recorded by Forsyth (1977) from Lake Rotokawa. Molluscs are unable to tolerate acidities below pH 6 due to dissolution of their carbonate shells.

Different species have different optima and tolerance ranges to temperature, largely determined by the temperature specific enzyme systems of each species (Pritchard, 1991). It has thus long been noted that different groups of biota have markedly different tolerances to water temperature, and that this can often result in an abrupt zonation of species (Vincent & Forsyth, 1987). The variation along this gradient may have also been influenced by the sizes of substrate in these sites, with the Waikite Valley and Lake Ohakuri sites having predominantly silt substrates, while those of Lakes Ngapouri and Ngahewa had predominantly sand, gravel or small cobble substrates. Macroinvertebrate communities from New Zealand non-geothermal streams, and probably also standing waters, are also influenced by substrate size (Quinn & Hickey, 1990; Death, 2000).

Chlorophyll *a* and dissolved oxygen were associated with the composition of invertebrate communities, mainly because they were higher in the non-geothermal than geothermal sites.

5 CONCLUSIONS

The species richness of phytoplankton, zooplankton and macroinvertebrates recorded from the geothermal standing waters in the current study was low compared with non-geothermal systems. The fauna comprised mainly thermo-tolerant or acid-tolerant species. However, several of the macroinvertebrate taxa recorded appear obligately restricted to or most commonly occurring in geothermal waters, e.g., *Culex rotoruae* and *Laccobius arrowi*. An undescribed *Polypedilum* is possibly also an obligate geothermal species. Responses in macroinvertebrate community composition were distinguished along pH and temperature gradients, with different faunas occurring at the extremes of each gradient.

The geothermal waters sampled also harboured unique zooplankton species. *Paracyclops waiariki,* recorded from a number of the Waiotapu sites, is known only from geothermal waters. Other obligate geothermal water species may have been present but were not recognised using available taxonomic information. The bdelloid rotifers, for example, were ubiquitous in these waters, and in New Zealand this group is known to have a high degree of endemism (Shiel & Green, 1996). In addition, other species of zooplankton and macroinvertebrates may be cryptogenic, with those occurring in the geothermal water bodies resembling, but being genetically distinct from those of non-geothermal sites. *Lecane luna*, for example was recorded up to 48.2 °C, despite in laboratory cultures only surviving at 30 °C for less than a week (cf. Perez-Legaspi & Rico-Martinez, 1988). *Lecane* cf. *rhytida* did not conform exactly to the nominate species, has not been recorded from non-geothermal waters in New Zealand, and may be a separate species. To better assess the degree of endemicity of fauna within New Zealand geothermal waters, systematic and genetic comparison of taxa between the two systems may be required.

This study is the first to examine zooplankton distribution among geothermally influenced water bodies. However, the extremely low numbers of zooplankton generally recorded from the sites made it difficult to determine the most important gradients influencing the distribution of the species. However, community composition did vary with degree of geothermal activity, as indicated by changes in fauna associated with conductivity. In addition, many of the zooplankton taxa recorded were not found in more than one or two of the waterbodies. The extremely low numbers of zooplankton in each waterbody, combined with the apparent uniqueness of some of the taxa between sites, may make this fauna more vulnerable to local extinction if significant changes were to occur in the geothermal resources.

Acknowledgements

We thank Glenys Croker for enumeration and identification of most of the macroinvertebrates, and Cathy Kilroy for algae identifications. We thank David Speirs (Environment Waikato) and Ashley Cody for aid in site selection. Reece Fowler (Kingett, Mitchell and Associates) and Jason Crozier (Environment Waikato) aided in the field. This project was jointly funded by Environment Waikato and by NSOF augmenting programme C01X0017.

6. REFERENCES

Berzins, B.; Pejler, B. (1987). Rotifer occurrence in relation to pH. *Hydrobiologia 147*: 107-116.

Berzins, B.; Pejler, B. (1989). Rotifer occurrence in relation to temperature. *Hydrobiologia 175*: 223-231.

Boothroyd, I.K.G. (2002). Extreme midges: chilled, heated and acidified. *Biodiversity Update 5*: 4-5.

Brock, T.D. (1985). Life at high temperatures. *Science 230*: 132-138.

Brock, T.D.; Brock, M.L. (1970). The algae of Waimangu Cauldron (New Zealand): distribution in relation to pH. *Journal of Phycology 6*: 371-35.

Cassie, V; Cooper, R.C. (1989). Algae of New Zealand thermal waters. *Bibliotheca Phycologica. 78*: 1-159.

Castenholz, R.W. (1976). The effect of sulphide on the blue green algae of hot springs. I. New Zealand and Iceland. *Journal of Phycology. 12*: 54-68.

Chapman, M.A.; Lewis, M.H. (1976). An introduction to the freshwater Crustacea of New Zealand. William Collins (New Zealand) Ltd. Auckland. 261pp.

Clarke, K.R.; Warwick, R.M. (1994). Change in marine communities: An approach to statistical analysis and interpretation. National Environment Research Council, U.K. 144p.

Death, R. (2000). Invertebrate-substratum relationships. In: New Zealand stream invertebrates. Collier, K.J.; Winterbourn, M.J. (eds.). New Zealand Limnological Society, Christchurch. pp. 157-178.

Duggan, I.C.; Green, J.D.; Thompson, K.; Shiel, R.J. (1998). Rotifers in relation to littoral ecotone structure in Lake Rotomanuka, North Island, New Zealand. *Hydrobioloia 387/388*: 179-197.

Duggan, I.C.; Green, J.D.; Shiel, R.J. (2001). Distribution of rotifers in North Island, New Zealand, and their use as bioindicators of lake trophic state. *Hydrobiologia 446/447*: 155-164.

Duggan, I.C.; Boothroyd, I.K. (2001). The distribution of biota from some geothermally influenced waters in the Taupo Volcanic Zone. NIWA Client Report EVW01226.

Forsyth, D.J. (1977). Limnology of Lake Rotokawa and its outlet stream. *New Zealand Journal of Marine and Freshwater Research 11 (3)*: 525-539.

Forsyth, D.J. (1983a). The effect of geothermal waters on stream invertebrates. DSIR Taupo Research Laboratory file report 57.

Forsyth, D. J. (1983b). The distribution of chironomids in geothermal water in New Zealand. *Memoirs of the American Entomological Society 34*: 115 - 123.

Forsyth, D.J.; MacKenzie, A.L. (1981). Limnology of Opal Lake. *New Zealand Journal of Marine and Freshwater Research 15 (3)*: 279-283.

Forsyth, D.J.; McColl, R.H.S. (1974). The limnology of a thermal lake: Lake Rotowhero, New Zealand: II. General biology with emphasis on the benthic fauna of chironomids. *Hydrobiologia 44*: 91-104.

Forsyth, D.J.; McColl, R.H.S. (1975). Limnology of Lake Ngahewa, North Island, New Zealand. *New Zealand Journal of Marine and Freshwater Research 9*: 311-332.

Green, J.; Kramadibrata, H. (1988). A note of Lake Goang, and unusual acid lake in Flores, Indonesia. *Freshwater Biology 20*: 195-198.

James, M.R. (1985). Changes in the faunal composition of two thermal streams near Taupo, New Zealand. *New Zealand Journal of Marine and Freshwater Research 19*: 439-443.

James, M.R. (1985). A comparison of microzooplankton in aquatic foodwebs with special emphasis on ciliates. Unpublished PhD thesis. The University of Otago. 234pp.

Jana, B.B. (1973). The thermal springs of Bakreswar, India: Physico-chemical conditions, flora and fauna. *Hydrobiologia 41*: 291-307.

Jana, B.B.; Sarkar, H.L. (1971). The limnology of “Swetganga” - A thermal spring of Bakreswar, West Bengal, India. *Hydrobiologia 37*: 33-47.

Lamberti, G.A.; Resh, V.H. (1985). Distribution of benthic algae and macroinvertebrates along a thermal stream gradient. *Hydrobiologia 128*: 13-21.

Lewis, M.L. (1974). *Paracyclops waiariki* n. sp. (Copepoda: Cyclopoida) from thermal waters in Rotorua. *New Zealand Journal of Marine and Freshwater Research 8*: 275-281.

Lloyd, E. F. (1963). Thermal activity at Waiotapu. In: Waiotapu Geothermal Field. New Zealand Department of Scientific and Industrial Research, Bulletin 155. pp 42-49.

Michaelis, F.B. (1982). The lakes of Tongariro National Park. *Mauri Ora 10*: 49-65.

Pax, F.; Wulfert, K. (1941). Die Rotatories deutscher Schwefelquellen und Thermen. *Archiv fur Hydrobiologie 38*: 165-213.

Pax, F.; Wulfert, K. (1942). Die Radertiere der deutschen Thermen. *Lotos 88*: 246-262.

Perez-Legaspi, I.A.; Rico-Martinez, R. (1988). Effect of temperature and food concentration in two species of littoral rotifers. *Hydrobiologia 387/388*: 341-348.

Pritchard, G. (1991). Insects in thermal springs. *Memoirs of the Entomological Society of Canada 155*: 89-106.

Quinn, J.M.; Hickey, C.W. (1990). Magnitude of effects of substrate particle size, recent flooding, and catchment development on benthic invertebrates in 88 New Zealand rivers. *New Zealand Journal of Marine and Freshwater Research 24*: 411-427.

Sanoamuang, L.; Stout, V.M. (1993). New records of rotifers from the South Island lakes. *Hydrobiologia 255/256*: 481-490.

Segers, H. (1995). Rotifera. Volume 2: Lecanidae (Monogononta). *Guides to the identification of the microincertebrates of the continental waters of the world 6*: 1-223.

Shiel, R.J. (1995). A guide to the identification of rotifers, cladocerand and copepods from Australian inland waters. Albury, N.S.W., Co-operative Research Centre for Freshwater Ecology, Murray-Darling Freshwater Research Centre. 144pp.

Shiel, R.J.; Green, J.D. (1996). Rotifera recorded from New Zealand, 1859-1995, with comments on zoogeography. *New Zealand Journal of Zoology 23*: 193-209.

Stark, J.D.; Fordyce, R.E.; Winterbourn, M.J. (1976). An ecological survey of the hot springs area, Hurunui River, Canterbury, New Zealand. *Mauri Ora 4*: 35-52.

Stockner, J.G. (1967). Observations of thermophilic algal communities in Mount Rainier and Yellowstone National Parks. *Limnology and Oceanography 12*: 13-17.

Ter Braak, C.J.F. (1987). Ordination. In: Data analysis in community and landscape ecology. Jongman, R.H.G.; Ter Braak, C.J.F.; Van Tongeron, O.F.R. (eds.). pp 90-169.

Vincent, W.F.; Forsyth, D.J. (1987). Geothermally influenced waters. In: Inland Waters of New Zealand. Viner, A.B. (ed.). *New Zealand Department of Scientific and Industrial Research Bulletin 241*. pp 349-377.

Winterbourn, M.J. (1968). The faunas of thermal waters in New Zealand. *Tuatara 16:* 111-122.

Winterbourn, M. J. (1970). The Hydrophilidae (Coleoptera) of New Zealand's thermal waters. *Transactions of the Royal Society of New Zealand 12*: 21-28.

Winterbourn, M. J. (1973). Ecology of the Copland River warm springs, South Island, New Zealand. *Proceedings of the New Zealand Ecological Society 20*: 72-78.

Winterbourn, M.J. (1998). Insect faunas of acidic coal mine drainages in Westland, New Zealand. *New Zealand Entomologist* 21: 65-72.

Winterbourn, M.J.; Brown, T.J. (1967). Observations on the faunas of two warm streams in the Taupo thermal region. *New Zealand Journal of Marine and Freshwater Research 1*: 38-50.

Winterbourn, M.J.; Gregson, K.L.D.; Dolphin, C.H. (2000). Guide to the aquatic insects of New Zealand. *Bulletin of the Entomological Society of New Zealand 13*. 103 pp.

Appendix 1. Locations and environmental data for the 20 standing water sites sampled in the Taupo Volcanic Zone.

	site	date	pH	Temperature (°C)	Dissolved oxygen (mg/L)	Oxygen saturation (%)	Conductivity (µS/cm)	Conductivity (µS/cm @ 25 °C)	Chlorophyll a (mg/m^3)	Southings	Eastings
Echo Lake	1	09/11/2001	2.33	24	1.02	12.1	3170	3228	0.2	3821.722	17622.387
Pond below Rotowhero	2	09/11/2001	2.76	34.5	7.93	119.2	1904	1864	3.8	3819.826	17622.679
Lake Rotowhero	3	09/11/2001	2.96	32.2	12.93	173.8	1788	1570	125.5	3819.396	17622.358
L. Rotowhero	4	13/11/2001	2.96	32.1	5.7	77.8	1613	1427	130	3819.368	17622.454
Wiaotapu pond	5	09/11/2001	3.29	34.1	5.15	75.2	2636	2273	3.95	3820.535	17622.259
Waiotapu pond	6	16/11/2001	2.94	25.7	6.53	80.3	1436	1422	5.5	3820.566	17621.716
L. Ngakoro	7	16/11/2001	2.39	26.6	1.14	14.2	4628	4493	5.7	3821.813	17622.139
Rainbow Mountain crater	8	16/11/2001	1.8	25	6.57	79.9	6690	6650	0.7	3819.148	17622.667
Lake Ohakuri (surface)	9	13/11/2001	6.65	32.4	7.71	103.1	526	465	3.1	3828.441	17608.568
Lake Ohakuri (surface)	10	13/11/2001	7.02	29.8	7.82	107.8	628	575	8	3828.440	17608.605
Golden Springs (lower)	11	13/11/2001	6.34	42.2	1.31	21.2	1536	1154	4	3827.940	17618.636
Golden Springs (upper)	12	13/11/2001	6.22	48.2			1827	1269	0.8	3827.860	17618.625
Lake Rotokawa	13	15/11/2001	2.05	20.6	9.48	105.6	5120	5590	10.05	3837.346	17611.590
Lake Rotokawa	14	15/11/2001	1.95	24.1	9.92	118.7	5420	5530	2.15	3837.636	17611.587
Pond, NW end Rotokawa	15	15/11/2001	2.28	27.5	3.8	48.7	6040	5750	0.3	3837.638	17611.588
Lake Rotokawa outflow pond	16	15/11/2001	1.93	21.7	10.06	115.5	5030	5360	4.7	3837.792	17611.760
Waikite Valley	17	15/11/2001	7.03	32.6	1.37	18.7	942	788	18.3	3819.395	17618.595
Waikite Valley 2	18	15/11/2001	9.2	36	10.6	156.5	1958	1644	30.2	3819.180	17618.749
L. Ngapouri	19	16/11/2001	9.07	18.8	12.52	134.4	111.2	126.9	138.5	3820.215	17620.215
Lake Ngahewa	20	09/11/2001	6.68	20.9	8.32	93.5	61	67.2	11.05	3818.913	17622.508

	site	date	Silt (% substrate)	Sand/gravel (% substrate)	Small cobble (% substrate)	Bedrock (% substrate)	Organic matter (% substrate)	*C. demersum* (% coverage)	Filamentous green algae (% coverage)
Echo Lake	1	09/11/2001	80	20					
Pond below Rotowhero	2	09/11/2001	100						
Lake Rotowhero	3	09/11/2001		95	5				
L. Rotowhero	4	13/11/2001	100						
Wiaotapu pond	5	09/11/2001	99				1		
Waiotapu pond	6	16/11/2001							
L. Ngakoro	7	16/11/2001	60	20	20				
Rainbow Mountain crater	8	16/11/2001	50		20		30		
Lake Ohakuri (surface)	9	13/11/2001	95	5					
Lake Ohakuri (surface)	10	13/11/2001	95	5				40	20
Golden Springs (lower)	11	13/11/2001	60	30			20		
Golden Springs (upper)	12	13/11/2001							
Lake Rotokawa	13	15/11/2001		95	5				
Lake Rotokawa	14	15/11/2001	5	20		55	20		
Pond, NW end Rotokawa	15	15/11/2001	65	35					
Lake Rotokawa outflow pond	16	15/11/2001	40		5		55		
Waikite Valley	17	15/11/2001	100						
Waikite Valley 2	18	15/11/2001	100						
L. Ngapouri	19	16/11/2001		80	20				
Lake Ngahewa	20	09/11/2001		10	10		80		

Appendix 2. Zooplankton data (raw counts) for the 20 standing water sites sampled in the Taupo Volcanic Zone

	2 Waiotapu pond	3 Lake Rotowhero	4 Lake Rotowhero	5 Waiotapu	6 Waiotapu	7 Lake Ngakoro	8 Rainbow Mountain crater	9 Lake Ohakuri	10 Lake Ohakuri
Rotifera									
Asplanchna priodonta	0	0	0	0	0	0	0	0	0
Brachionus quadridentatus	0	0	0	0	0	0	0	0	1
Colurella uncinata	0	0	0	0	0	0	0	0	12
Cephalodella gibba	0	0	0	0	0	0	0	0	1
Cupelopagis vorax	0	0	0	0	0	0	0	0	9
Dicranophorus forcipatus	0	0	0	0	0	0	0	0	2
Euchlanis dilatata	0	0	0	0	0	0	0	0	77
Filinia longiseta	0	0	0	0	0	0	0	0	0
Hexarthra mira	0	0	0	0	0	0	0	0	0
Keratella cochleris	0	0	0	0	0	0	0	0	0
Keratella tropica	0	0	0	0	0	0	0	0	0
Lepadella acuminata	0	0	0	0	0	0	0	0	5
Lecane closterocerca	0	0	0	0	0	0	0	0	1
Lecane decipiens	0	0	0	0	0	0	0	0	3
Lecane luna	0	0	0	0	0	0	0	0	0
Lecane lunaris	0	0	0	0	0	0	0	0	0
Lecane bulla	0	0	0	0	0	0	0	0	44
Lecane cf. *rhytida*	0	2	0	0	0	0	0	0	0
Pompholyx complanata	0	0	0	0	0	0	0	0	0
Synchaeta pectinata	1	0	0	0	0	0	0	0	0
Testudinella patina	0	0	0	0	0	0	0	0	23
Trichocerca rattus	0	0	0	0	0	0	0	0	2
Trichotria tetractis	0	0	0	0	0	0	0	0	9
Trichocerca similis	0	0	0	0	0	0	0	0	0
Bdelloids	9	6	28	5	10	2	6	5	62
Cladocera									
Bosmina meridionalis	0	0	0	0	0	0	0	0	0
Ceriodaphnia dubia	0	0	0	0	0	0	0	0	0
Chydoridae	0	0	0	0	0	0	0	0	6
Chydoris sp.	0	0	0	0	0	0	0	0	12
Simocephaus vetulus	0	0	0	0	0	0	0	0	0
Copepoda									
Acanthocyclops robustus	0	0	0	0	0	0	0	0	0
Calamoecia lucasi	0	0	0	0	0	0	0	0	0
Eucyclops serrulatus	0	0	0	0	0	0	0	1	27
Paracyclops waiariki	0	8	5	2	7	0	0	0	0
Copepod nauplii	0	38	1	1	12	1	0	0	29
Ostracoda	0	0	0	0	0	0	0	0	19
Acarina									
Orbatei	0	0	0	18	0	0	0	0	0
Hydracarina	0	0	0	0	0	0	0	0	0
Chironomidae	0	4	9	0	2	0	4	0	5

Appendix 2 cont.

	Golden Springs (lower) 11	Golden Springs (upper) 12	Lake Rotokawa 13	Lake Rotokawa 14	Pond near Lake Rotokawa 15	Lake Rotokawa outflow 16	Waikite Valley 17	Lake Ngapouri 19	Lake Ngahewa 20
Rotifera									
Asplanchna priodonta	0	0	0	0	0	0	0	14	0
Brachionus quadridentatus	0	0	0	0	0	0	0	0	0
Colurella uncinata	0	0	0	0	0	0	0	0	0
Cephalodella gibba	0	0	0	0	0	0	0	0	0
Cupelopagis vorax	0	0	0	0	0	0	0	0	0
Dicranophorus forcipatus	0	0	0	0	0	0	0	0	0
Euchlanis dilatata	0	0	0	0	0	0	0	0	1
Filinia longiseta	0	0	0	0	0	0	0	168	3
Hexarthra mira	0	0	0	0	0	0	0	1	0
Keratella cochleris	0	0	0	0	0	0	0	59	0
Keratella tropica	0	0	0	0	0	0	0	8	0
Lepadella acuminata	0	0	0	0	0	0	0	0	0
Lecane closterocerca	0	0	0	0	0	0	0	0	0
Lecane decipiens	0	0	0	0	0	0	0	0	0
Lecane luna	8	1	0	0	0	0	0	0	0
Lecane lunaris	0	0	0	0	0	0	0	0	1
Lecane bulla	0	0	0	0	0	0	0	0	0
Lecane cf. *rhytida*	0	0	0	0	0	0	0	0	0
Pompholyx complanata	0	0	0	0	0	0	0	5	0
Synchaeta pectinata	0	0	0	0	0	0	0	0	252
Testudinella patina	0	0	0	0	0	0	0	0	0
Trichocerca rattus	0	0	0	0	0	0	0	0	0
Trichotria tetractis	0	0	0	0	0	0	0	0	0
Trichocerca similis	0	0	0	0	0	0	0	51	2
Bdelloids	127	6	3	4	1	1	130	0	2
Cladocera									
Bosmina meridionalis	0	0	0	0	0	0	0	0	18
Ceriodaphnia dubia	0	0	0	0	0	0	0	0	5
Chydoridae	0	0	0	0	0	0	0	0	0
Chydoris sp.	0	0	0	0	0	0	0	0	11
Simocephaus vetulus	0	0	0	0	0	0	0	0	P
Copepoda									
Acanthocyclops robustus	0	0	0	0	0	0	0	0	3
Calamoecia lucasi	0	0	0	0	0	0	0	0	P
Eucyclops serrulatus	0	0	0	0	0	0	39	0	0
Paracyclops waiariki	0	0	0	0	0	0	0	0	0
Copepod nauplii	0	0	0	0	0	0	4	394	7
Ostracoda	0	0	0	0	0	0	0	0	0
Acarina									
Orbatei	0	0	2	0	3	0	1	0	0
Hydracarina	0	0	0	0	0	0	0	0	1
Chironomidae	0	0	0	2	0	3	25	0	1

Appendix 3. Macroinvertebrate numbers collected in three metre sample sweeps for the 20 standing water sites sampled in the Taupo Volcanic Zone

	1 Echo Lake	2 Waiotapu pond	3 Lake Rotowhero	4 Lake Rotowhero	6 Waiotapu pond	8 Waiotapu Pond - Rainbow Mt.	9 Lake Ohakuri	10 Lake Ohakuri
Odonata	0	0	0	0	0	0	0	0
Antipodochlora braueri	0	0	0	0	0	0	0	0
Austrolestes colensonis	0	0	0	0	1	0	0	0
Ischnura aurora	0	0	0	0	0	0	0	0
Procordulia grayi	0	0	0	0	0	0	0	0
Xanthocnemia zealandica	0	0	0	0	3	0	0	0
Trichoptera	0	0	0	0	0	0	0	0
Triplectides cephalotes	0	0	0	0	1	0	0	0
Coleoptera	0	0	0	0	0	0	0	0
Antiporus ?strigosulus	0	0	0	0	0	0	0	0
Enochrus tritus	0	0	1	0	0	0	0	0
Hydraenidae	0	0	0	0	0	0	0	0
Laccobius arrowi	0	0	0	0	0	0	0	0
Liodessus deflectus	2	0	1	0	0	41	0	0
Scritidae	5	1	0	0	0	0	0	0
Hemiptera	0	0	0	0	0	0	0	0
Anisops wakefieldi	0	0	8	12	7	0	0	0
Saldula stoneri	0	0	0	0	0	0	0	0
Sigara sp.	0	0	14	2	0	0	0	1
Diptera	0	0	0	0	0	0	0	0
Ceratopogonidae	0	0	0	0	0	0	0	0
Chironomus zealandicus	0	0	3294	2565	188	0	0	0
Chironomus sp. a	0	0	0	0	0	0	0	42
Cricotopus aucklandensis	0	0	0	0	0	0	0	0
Culex rotoruae	709	0	0	0	0	0	0	0
Muscidae	0	0	0	0	0	0	0	0
Neoscatella sp.	0	0	0	0	0	0	0	0
Oxyethira albiceps	0	0	0	0	0	0	1	0
Paratrichocladius pluriserialis	0	179	0	0	0	147	0	1
Paroxyethira hendersoni	0	0	0	0	0	0	0	1
Polypedilum sp.	0	0	0	0	0	0	0	0
?*Tanytarsus* sp.	0	0	0	0	0	0	0	0
Crustacea	0	0	0	0	0	0	0	0
Ostracoda	0	0	0	0	0	0	0	0
Mollusca	0	0	0	0	0	0	0	0
Glyptophysa variabilis	0	0	0	0	0	0	0	0
Gyraulus kahuica	0	0	0	0	0	0	0	0
Physa sp.	0	0	0	0	0	0	0	0
Pisidium sp.	0	0	0	0	0	0	0	0
Planorbarius corneus	0	0	0	0	0	0	0	1
Potamopyrgus antipodarum	0	0	0	0	0	0	0	0
Acari	0	0	0	0	0	0	0	0
Oligochaeta	0	0	0	0	0	0	0	0
Lumbriculus sp.	0	0	0	0	0	0	0	0
Tubificidae	0	0	0	0	0	0	0	6
Hirudinea	0	0	0	0	0	0	0	0
Platyhelminthes	0	0	0	0	0	0	0	0

Appendix 3. cont.

	Golden Springs (lower) 11	Lake Rotokawa 13	Lake Rotokawa 14	Pond near Lake Rotokawa 15	Lake Rotokawa outlow 16	Waikite valley 17	Waikite valley 18	Lake Ngapouri 19	Lake Ngahewa 20
Odonata	0	0	0	0	0	0	0	0	0
Antipodochlora braueri	0	0	0	0	0	0	0	0	1
Austrolestes colensonis	0	0	0	0	0	0	0	0	0
Ischnura aurora	0	0	0	0	0	2	0	0	0
Procordulia grayi	0	0	0	0	0	1	0	0	0
Xanthocnemia zealandica	0	0	0	0	0	0	0	8	0
Trichoptera	0	0	0	0	0	0	0	0	0
Triplectides cephalotes	0	0	0	0	0	0	0	0	0
Coleoptera	0	0	0	0	0	0	0	0	0
Antiporus ?strigosulus	1	0	0	0	0	0	1	0	0
Enochrus tritus	0	0	0	0	0	0	23	0	0
Hydraenidae	0	0	0	0	0	0	41	0	0
Laccobius arrowi	0	0	0	0	0	0	P	0	0
Liodessus deflectus	0	0	0	0	0	0	0	0	0
Scritidae	0	0	0	0	0	0	0	0	0
Hemiptera	0	0	0	0	0	0	0	0	0
Anisops wakefieldi	0	0	0	0	0	3	0	0	0
Saldula stoneri	0	0	1	0	0	0	0	0	0
Sigara sp.	0	0	0	0	0	0	0	1	0
Diptera	0	0	0	0	0	0	0	0	0
Ceratopogonidae	0	0	0	0	0	0	0	1	0
Chironomus zealandicus	0	2	27	0	22912	0	0	325	0
Chironomus sp. a	0	0	0	0	0	246	431	0	0
Cricotopus aucklandensis	0	0	0	0	0	0	0	0	1
Culex rotoruae	0	0	0	432	640	4	0	0	0
Muscidae	0	0	0	2	0	0	0	0	0
Neoscatella sp.	0	0	7	112	0	0	0	0	0
Oxyethira albiceps	0	0	0	0	0	0	0	0	0
Paratrichocladius pluriserialis	0	0	0	0	0	0	0	20	4
Paroxyethira hendersoni	0	0	0	0	0	0	0	75	0
Polypedilum sp.	0	0	0	0	0	1	0	0	0
?*Tanytarsus* sp.	0	0	0	0	0	5	0	0	0
Crustacea	0	0	0	0	0	0	0	0	0
Ostracoda	0	0	0	0	0	0	0	6	0
Mollusca	0	0	0	0	0	0	0	0	0
Glyptophysa variabilis	0	0	0	0	0	0	0	0	0
Gyraulus kahuica	0	0	0	0	0	0	0	4	0
Physa sp.	0	0	0	0	0	0	0	2	1
Pisidium sp.	0	0	0	0	0	0	0	9	3
Planorbarius corneus	0	0	0	0	0	0	0	0	0
Potamopyrgus antipodarum	0	0	0	0	0	0	0	88	0
Acari	0	0	0	0	0	0	0	22	0
Oligochaeta	0	0	0	0	0	0	0	0	0
Lumbriculus sp.	0	0	0	0	0	0	0	471	4
Tubificidae	0	0	0	0	0	0	0	0	53
Hirudinea	0	0	0	0	0	0	0	1	0
Platyhelminthes	0	0	0	0	0	0	0	1	0