Upper thermal tolerances of twelve New Zealand stream invertebrate species

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Abstract  The upper thermal tolerances of 12 New Zealand freshwater invertebrate taxa were compared using a laboratory lethality testing protocol. Temperatures that were lethal to 50% of the test organisms (LT$_{50}$s), following acclimation to 15°C, generally declined over the 4 day period of the tests. LT$_{50}$ values after 48 and 96 h exposure ranged from 24.5 to $>$ 34°C and 22.6 to 32.6°C, respectively, indicating that temperatures that occur in summer in many NZ streams and rivers may limit the distribution and abundance of some of these invertebrate species. Larval insects included both the most sensitive species (a plecopteran and two Ephemeroptera) and the most tolerant (the larvae of the elmid beetle *Hydora* sp.) in this study. The two molluscs studied (*Potamopyrgus antipodarum* (Prosobranchia: Hydrobiidae) and *Sphaerium novaezelandiae* (Bivalvia: Sphaeriidae)) showed high thermal tolerance, whilst two crustaceans (*Paratya curvirostris* (Atyidae) and *Paracalliope fluviatilis* (Eusiridae)) were moderately tolerant. The effect of a higher acclimation temperature (20°C) on thermal tolerance was also investigated for the three most sensitive species. This appeared to increase the thermal tolerance of the two Ephemeroptera (*Deleatidium* spp. and *Zephlebia dentata* (both Leptophlebiidae)) but to reduce the tolerance of the plecopteran *Zelandobius furcillatus* (Gripopterygidae).

Keywords  benthic invertebrates; streams; temperature tolerance; lethality; thermal; laboratory tests

INTRODUCTION

Temperature is one of the primary factors influencing growth, metabolism, and survivorship of stream invertebrates (Hynes 1970; Sweeney 1978; Sweeney & Vannote 1986; Rempel & Carter 1987; Brittain 1991). A variety of human activities can affect thermal regimes in streams and rivers, including discharge of heated effluents from industry and thermal/geothermal power plants; impoundment discharges (Brooker 1981); abstraction (Dymond 1984); and removal of riparian shade (Beschta & Taylor 1988). Information on the effects of temperature on stream invertebrates is required for management of these activities and to understand the role of this prime forcing factor in determining invertebrate community structure and function.

The limited data available on thermal tolerances of New Zealand freshwater invertebrate species indicate a wide range of tolerances. Studies of the faunas of thermal and warm springs (Winterbourn 1968; Stark et al. 1976; James 1985) showed that some Coleoptera and Diptera can tolerate temperatures of 40–45°C and some other Diptera, Hemiptera, Odonata, Ostracoda and Pulmonata tolerate temperatures around 35°C. However, Plecoptera appear to be largely restricted to rivers with summer temperatures typically below 19°C (Quinn & Hickey 1990). Notably, the thermal tolerances of the vast majority of the common taxa in New Zealand streams and rivers are unknown.

Recently, Hickey & Vickers (1992) developed a standard 96 h LC$_{50}$ test for measuring the toxicity of substances to the mayfly *Deleatidium* spp. This
technique also has potential for screening thermal
tolerances of running water invertebrates. In
contrast to the elaborate artificial stream systems
used for testing thermal tolerances of stream
invertebrates by several previous workers (e.g.
Nebeker & Lemke 1968; Gaufin & Hern 1971; de
Kowalski & Bunting 1981), the method of
Hickey & Vickers (1992) has low establishment
costs and allows ample replication and concurrent,
parallel studies of a number of species. This study
aimed to evaluate the applicability of these methods
to measurement of thermal tolerances of stream
biota from a range of taxonomic groups (oligo-
chaetes, molluscs, crustaceans and insects) and to
provide information on the tolerances of a range of
the “common core” taxa that are found in
“unmodified” streams and rivers throughout New
Zealand.

MATERIALS AND METHODS

Most of the organisms were collected from a site
on the Waihou River (175° 49'E, 38° 1'S) in the
Waikato region of the North Island between July
and October 1992 by sampling the sediment and
macrophytes using a 500 µm mesh hand net.
Information on this spring-fed river’s thermal
regime is limited, but the similar Waimakariri River
(5 km east) has a mean annual temperature of
14.2°C with a typical summer maximum of 15.7°C,
and a winter minimum of 12.7°C (NIWA database,
Christchurch). Water temperature of the Waihou
River varied between 12.1°C and 14.3°C on the
sampling occasions. The thermal stability of the
sampling site allowed us to collect animals exposed
to similar thermal acclimation temperatures over
the four month period of the study.

The Waihou River originates in an area of native
and *Pinus* plantation forest on the Mamaku Plateau
but the unshaded sampling site is in an area of
pastoral agriculture. This site provides a wide range
of microhabitats, from gravel riffles to dense beds
of the macrophytes *Ranunculus fluitans* and
*Nasturtium officinale*, and has a highly diverse and
abundant invertebrate fauna. *Deleatidium* sp.
(Ephemeroptera: Leptophlebiidae), *Pycnoentrodes
aureola* (Trichoptera: Conoecucidae), *Aoteapsyche
colonica* (Trichoptera: Hydropsychidae), and
*Hydora* sp. (Coleoptera: Elmidae) were common
in the gravel riffle areas whereas *Potamopyrgus
antipodarum* (Prosobranchia: Hydrobiidae) and
*Lumbriculus variegatus* (Oligochaeta: Lumbrici-
culidae) were abundant in detritus-rich riffles
downstream of macrophyte beds. *Pycnocentria
evecta* (Trichoptera: Conoecucidae), *Zephlebia
dentata* (Ephemeroptera: Leptophlebiidae), and
*Zelandobius furcillatus* (Plecoptera: Gripop-
terygidae) were common on the macrophytes.
*Sphaerium novaezelandiae* (Bivalvia: Sphaeriidae)
were collected from near the outlet of Lake Rotoiti
(176° 21'E, 38° 1'S) using a bottom dredge in
October 1992, when an average water temperature
of approximately 15°C was expected (pers comm.
M. Gibbs). This species is widely distributed in
sandy areas of streams and rivers. The two
crustacean species (*Paracalliope fluvialilis*
( Amphipoda: Eusiridae), and *Paratya curvirostris*
(Decapoda: Atyidae)) were collected from a site
on the lower Waikato River opposite the power
station at Meremere (175° 4'E, 37° 18'S) in October
1992, when the water temperature was 14.7°C.

Middle to late instar specimens of the larval
insects and crustaceans, and medium to large
molluscs, were selected from the hand-net
collections, using wide-mouthed pipettes, and
transported back to the laboratory in continuously
aerated river water in 4 litre PVC pails. The river
water was replaced with preconditioned tap water
(treated Waikato River water) on arrival at the
laboratory. Initially, preconditioning of the water
involved aeration for at least 24 h, but later tests
were performed using a single large batch of water
that had been filtered through activated carbon and
aerated for one week. This water had alkalinity of
38 g m⁻³ (as Ca CO₃), hardness 41 g m⁻³ (as Ca
CO₃), conductivity 20 mS m⁻¹ and pH of 7.9.
Organisms were transferred to the preconditioned
tap water and kept under these conditions for 24 h
to allow gut clearance, which minimised fouling of
sample vessels, and to ensure acclimation to the
control temperature of 15°C, which was very close
to the stream temperature at the collection sites.
The organisms were then transferred to the
experimental apparatus in a laboratory with a
natural diurnal light regime provided by external
windows.

Two designs of incubation apparatus were used
in these experiments. In the first two experiments
five organisms were placed in 60 ml plastic cups
filled with 40 ml of preconditioned tap water at
15°C. These cups (five replicates per temperature)
were mounted in 5 cm diameter holes in polystyrene
sheeting (0.25 x 0.25 m) covered with Perspex™
sheeting and floating on the surface of waterbaths.
Aeration and current was supplied to each cup via
fine bore (0.6 mm ID x 50 mm) tubing through
hoses in the Perspex™ sheeting and connected via syringe needles (23 gauge) to larger tubing from an air pump.

This design was satisfactory in the first experiment which investigated three species of collector/browsers (Deleatidium spp., Pycnocentrodes aureola and Potamopyrgus antipodarum). Mortality was less than 10% in the controls and the organisms showed no signs of antagonistic behaviour. However, in the second experiment, involving the free-living caddisfly Aoteapsyche colonica, individual cups were used to isolate each individual organism and prevent the antagonistic and cannibalistic interactions which would normally be observed. In subsequent experiments twenty or thirty replicates in individual cups were used for all species at each temperature.

Five temperatures (c. 15, 20, 25, 30 and 35°C) were used to determine the thermal tolerance of each species. These were achieved by manually raising the temperature from 15°C by 2 to 4°C every hour until the desired temperature was reached. This procedure avoids inducing thermal shock without allowing time for acclimation to raised temperatures (Gaufin & Hern 1971). The water temperature was maintained at the desired temperature (± 0.2°C) using a proportional temperature controller (Yellow Springs Instrument model 72). Temperature of the baths was evenly distributed using a mechanical stirrer and recorded continuously. Half of the incubation water was removed and replaced with preconditioned tap water at the appropriate temperature every 24 h, for the first experiment and for the large shrimp Paratya curvirostris, and every 48 h in the other experiments.

Survival was recorded at 24, 48 and 96 h after the target temperature was reached. Organisms showing no obvious movement, or gaping bivalves, were gently prodded or “jetted” with water from a pipette to check for life. Mollusc mortality was confirmed after each experiment.

If 90% control survival was obtained, LT50 values (the temperature at which 50% of the organisms were killed) and 95% fiducial limits were calculated for each time period by probit analysis (Finney 1971) following the EPA flowchart procedure of the ToxCalc programme (Anon 1993). A trimmed Spearman-Karber analysis was used to estimate the LT50 values in cases where the data did not fit the probit model, except when 100% survival and 100% mortality occurred at consecutive temperatures in which case the LT50 values were set at the geometric mean of the two bracketing temperatures.

After initial estimates of LT50 values had been obtained, experiments were run to obtain more precise estimates for the more sensitive taxa whose LT50 values indicated the greatest potential for temperature to significantly restrict distributions in New Zealand streams. This was achieved using a narrower range of temperatures, especially around the initial LT50 value.

Three species (Zelandobius furcillatus, Deleatidium spp. and Zephlebia dentata) were used to investigate how acclimation to higher temperatures affected thermal tolerance. Survival at 26°C (near the 48 h LT50 for 15°C acclimated organisms of these species) was compared for organisms held in the laboratory for 1 week at 15.4 ± 0.4°C or 20.0 ± 0.4°C in aquaria (0.3 x 0.4 x 0.3 m) containing Waihou River water, stones with epilithon attached, detritus and macrophytes. During acclimation, aeration stones located behind a baffle at the end of the aquarium provided a gentle current over the bottom of the aquaria. After acclimation, the test organisms were held at their acclimation temperature in food-free water for 24 h and then transferred to the experimental apparatus where lethals were recorded after 24, 48 and 96 h at 26°C.

**RESULTS**

The LT50 values and 95% confidence limits for all species tested are summarised in Table 1. The LT50 progressively decreased with time for most species, with the 96 h LT50 values ranging from 22.6°C to 32.6°C.

The insect species varied widely in their upper thermal tolerances. Larvae of the elmid Hydora sp. and the mayfly Deleatidium spp. yielded the highest and lowest median lethal temperatures at 96 h, respectively. The LT50 values declined with the period of exposure for both Deleatidium spp. and Z. dentata, indicating short-term tolerance of higher temperatures. The stonefly Z. furcillatus had a similar high level of temperature sensitivity to the two mayflies. Repeated measurements for these three species gave similar LT50 estimates.

Of the caddisfly larvae tested, Pycnocentrodes aureola had the highest LT50 at 96 h, whereas the other two species, Pycnocentricia evecta and Aoteapsyche colonica, had much lower values.
The snail *Potamopyrgus antipodarum* and the clam *Sphaerium novaezelandiae* had similar, relatively high, upper thermal tolerance. The two crustaceans tested had similar thermal tolerances to each other, that declined only slightly with time. In contrast, the LT$_{50}$ of the oligochaete *Lumbriculus variegatus* declined by 5°C between 48 and 96 h.

The thermal acclimation results are shown in Fig. 1. These indicate that individuals of the two mayfly species (*Z. dentata* and *Deleatidium* spp.) that were acclimated at 20.4°C had higher tolerance to elevated temperature than those acclimated at 15.4°C. However, the stonefly *Z. furcillatus* showed lower thermal tolerance after acclimation at 20°C.

**DISCUSSION**

The apparatus used in these experiments allows ample replication and provides a convenient means of testing thermal tolerance of aquatic invertebrates from a variety of taxonomic groups including Ephemeroptera, Trichoptera, Plecoptera, Crustacea, Mollusca and Oligochaeta. Separate containers for housing individual organisms were found necessary to avoid stress effects due to antagonistic interactions between some species. These also avoid the possible effects on water quality of rapid degradation following death of “companion” animals in shared containers at high temperatures.

We observed a wide range of upper thermal tolerances amongst stream invertebrates. The general pattern of tolerances amongst families was consistent with observed distributions of invertebrates in New Zealand thermal and warm spring waters, which also indicate that Coleoptera are particularly tolerant (observed at temperatures of 34 to 45°C), Prosobranchia (*Potamopyrgus antipodarum*) moderately tolerant (observed at up to 28°C) and Lumbriculidae were relatively sensitive (observed at up to 24°C) (Winterbourn 1968). Notably, the upper limit of the natural distribution of *P. antipodarum* in the field (Winterbourn 1968; James 1985) is approximately 4°C lower than the upper lethal limit observed in this study and by Winterbourn (1969). This was explained by Winterbourn’s (1969) finding that

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<th>Table 1 LT$<em>{50}$ values with associated 95% fiducial limits (where given by probit analysis) for freshwater invertebrates at 24, 48 and 96 hours. $$ =$ no data due to power failure. † = LT$</em>{50}$ calculated as geometric mean of lower temperature (0% lethality) and upper temperature (100% lethality). * = confidence limits provided by lower temperature (0% lethality) and upper temperature (100% lethality). $$ = data excluded due to 15% mortality in controls.</th>
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<td><em>Lumbriculus</em> variegatus</td>
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the snail's activity began to decline above 28°C. If this response is typical of other species, it suggests that 96 h LT50 temperatures may be a few degrees higher than the temperatures limiting distribution in the field.

Selective pressures could result in greater thermal tolerance amongst populations of invertebrate species from streams with high summer temperatures than the same species in the relatively cool Waikato River, where most of the experimental animals were collected. The aerial dispersion of adult insects would be expected to reduce the likelihood of such local variations developing, but further work to examine this issue is warranted.

Comparison of the LT50 data in Table 1 with the maximum temperatures recorded at 255 New Zealand river sites (Moseley 1982) indicates that temperature stress may be important in determining the distributions of several of the species investigated (Fig. 2). In particular, the maximum recorded temperatures exceeded the 96 h LT50 values of the mayflies Deleatidium spp. and Z. dentata at 39%, and 35% of these sites. High temperature is more likely to be an important factor limiting lotic invertebrates in the North Island than in the South Island sites (Fig. 2).

Thermal stress is expected to affect distributions of invertebrates most commonly in lowland reaches of rivers, because maximum temperatures typically

Fig. 1 Comparison of survival of three invertebrate taxa at 26°C after acclimation at 15.4°C (open bars) and 20.4°C (shaded bars) for 1 week.
increase progressively from headwaters to the mouths of rivers (Ward 1985). However, due to their shallow depth, headwater streams are particularly prone to heating if riparian vegetation is removed (Brown & Krygier 1970; Quinn et al. 1992), so that temperature effects on distribution are also possible in these situations.

The relatively low 96 h LT₅₀ values recorded for the stonefly and mayfly taxa are consistent with the finding of Quinn & Hickey (1990) that Plecoptera and Ephemeroptera were much less abundant in rivers where typical summer temperatures exceeded 19°C and 21°C, respectively. The 96 h LT₅₀ values of two of the New Zealand trichopteran species tested in this study were within the range of 21.8 to 30.1°C observed for six North American trichopteran species (Gaufin & Hern 1971), whereas Pycnocentrod.es aureola was more tolerant.

Acclimation to temperatures higher than 15°C may increase LT₅₀ values somewhat (Cossins & Bowler 1987). When acclimation temperature was increased from 10 to 20°C, upper lethal temperatures of various freshwater Crustacea increased by up to 1.9°C (Spoor 1955; Sprague 1963) and 0.75°C for the stonefly, Paragnetina media (Heiman & Knight 1972). The increases we observed in survival of Zephlebia dentata and Deleatidium spp. at 26°C after acclimation at 20°C rather than 15.4°C also indicate relatively small acclimation effects on upper lethal temperatures. On the other hand, the lower 24- and 48-h survival of Zelandobius furcillatus acclimated at the higher temperature indicates that continued exposure of this species to temperatures approaching the incipient lethal temperature increased its sensitivity to high temperature. If the inability of this stonefly to acclimate to higher temperatures is typical for other New Zealand stonefly species, it may explain the more restricted distribution of stoneflies than mayflies in relation to maximum seasonal temperature in New Zealand rivers (Quinn & Hickey 1990), despite the similar 48 h LT₅₀ values of the mayfly and stonefly species in this study (Table 1). However, other factors, such as differences in the thermal sensitivities of the eggs and sublethal effects could also be involved.

The results of this study provide both a ranking of a variety of common stream invertebrates in terms of their upper thermal tolerance and information on the upper bound of their tolerance to constant temperatures. In natural streams, however, temperature usually has diurnal and annual fluctuations, so that comparisons of the effects of exposure to constant and diurnally varying temperatures would help application of the results to nature. Sublethal temperature increases can also affect the length of invertebrate life histories and the size and fecundity of emerging adult insects, which affects their reproductive output (e.g., Sweeney & Vannote 1986; Brittain 1991; Sweeney 1993). Longer-term studies on such sublethal effects would provide a better understanding of the effects of temperature increases and hence a sounder basis for temperature management. Nevertheless, the present methodologies and findings provide a useful starting point for such studies.

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