MINISTRY FOR THE ENVIRONMENT:

GROUNDWATER INDICATORS PROJECT

GROUNDWATER INVERTEBRATES AS POTENTIAL INDICATORS

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by

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1.0 INTRODUCTION

The Ministry for the Environment (MfE) has made considerable progress towards its goal of establishing Environmental Performance Indicators for New Zealand that will "allow monitoring of the environment so that the current state, trends, and effects of human activity can be detected" and, ultimately, achieve better environmental outcomes. Having developed concepts for EPIs and defined requirements for and the nature of EPIs for air, fresh water (including goundwater) and land (MfE, 1997), now wishes to develop more specific EPIs for groundwater. Lincoln Environmental is undertaking this task and the present report contributes background information on invertebrate communities inhabiting groundwater and preliminary views on use of invertebrates as EPIs for groundwater. The report also provides a tentative indication of the work and resources required to establish reliable and effective invertebrate EPIs for New Zealand.

1.1 BRIEF

The brief for this report comprised four points:

1. Report on existing knowledge about types of invertebrates found in aquifers in New Zealand, their distribution, and the availability of quantitative data.

2. Comment on the resources needed to collect relevant data about these invertebrates.

3. Comment on sensitivities of these invertebrates to the likely effects (contamination or depletion of groundwater, etc.) of human activity.

4. Comment on the variability of such data from the point of view of natural trends and cycles against which the effects of human action would need to be detected.

The report addresses these points through a review of current knowledge of NZ groundwater invertebrates and a review of international literature on the topic.

1.2 GROUNDWATER, THE ECOLOGIST'S PERSPECTIVE

Research on the ecology of groundwaters spans a series of usually inter-linked habitats:

- interstitial faunas of river and lake margins,
- the hyporheos (animals living at depths of up to 0.5 m below stream and river beds and adjacent alluvial bed deposits),
- groundwaters in caves (mostly limestone or karst),
- groundwaters associated with other rocks (mostly karst) and
- subterranean waters flowing through alluvial deposits.

For the purposes of this report, attention is focused on true groundwaters, the latter three listed above. True groundwater (phreatic) environments tend to be inhabited by species specifically adapted to live in habitats lacking primary production by plants and mostly reliant on allochthonous (imported) organic matter as sources of energy (the few notable exceptions are beyond the scope of this report). Interstitial faunas of lakes and rivers and the hyporheos include many typical epigean (surface-dwelling) species. Epigean species are found in true groundwater habitats as accidental immigrants from the surface or adjacent rivers, especially in springs and at cave entrances, although a few inhabit both realms.

This report has, therefore, focused primarily on true groundwaters. Particular attention is given to the fauna and ecology of alluvial groundwater systems because these are the most extensive and most important economically of NZ's groundwater environments. However, much of our understanding of phreatic faunas and their ecologies is based on studies of caves, springs, deeper hyporheic and interstitial riverine habitats. Consequently, studies of all of these habitats are considered here (research on strictly hyporheic habitats is largely excluded).

2.0 THE NEW ZEALAND GROUNDWATER INVERTEBRATE FAUNA

2.1 EXISTING KNOWLEDGE

2.1.1 Groundwater biodiversity

The New Zealand groundwater invertebrate fauna is poorly known, despite very strong early interest by Charles Chilton, an early NZ naturalist. In the early 1970's, Dr W. Kuschel surveyed many wells through out the country, but just a few taxa from these collections were reported in publications. Consequently, more than 100 years since the presence of an abundant and diverse fauna was reported from NZ' groundwaters, very little is known of this fauna.

Published accounts of the NZ groundwater fauna report three (possibly four) species of amphipods Chilton, 1894; Chapman & Lewis, 1976; Hurley, 1975), five species of isopods (another 2-5 may be partly or largely subterranean)(Nicholls, 1944; Chapman & Lewis, 1976), five (possibly six) syncarids (very small crustaceans)(Schminke, 1978), 14 gastropod molluscs (Climo, 1974, 1977), two species of dytiscid beetles (Ordish, 1976), at least one species of flatworm (Chilton, 1894; Sinton, 1984) and two or more oligochaete worms (Chilton, 1894; Sinton, 1984). This gives a total of at least 29 species, 16 of which are crustaceans (Table 1).

Documented, but unpublished, accounts indicate significant additions to this fauna:

six amphipods (Fenwick, in prep.);
some 20 undescribed amphipods, including new genera (Bousfield, 1980);
one new species of amphipod is under investigation by an overseas worker;
harpacticoid copepods were present in collections made by Kuschel (unpublished) and Fenwick (unpublished);
nematode worms were found in collections from Canterbury (Fenwick, unpublished).

2.1.2. Distribution of groundwater fauna.

Information on the geographic distribution of NZ groundwater fauna is very incomplete and widely scattered, there being no published accounts of any detailed geographic surveys. Indeed, known distributions are based almost entirely on collections made by the few taxonomists who have examined the fauna. Information on the depth distributions of species are similarly poor.

To date, most collections of groundwater fauna have come from relatively shallow sites, but Hurley (1975) reported an amphipod from a well 700 feet (210 m) deep at Lake Taupo. It is well known that the alluvial gravels of some NZ plains (e.g. Canterbury) are very thick and aquifers are known at over 100 m depth. Many of these deeper aquifers are likely to be inhabited by invertebrates which feed on bacteria and or sub-fossil organic carbon sources buried when the gravels were deposited (see Pedersen, 1993, for review).

2.1.3. Quantitative data on groundwater fauna

A few workers have presented quantitative data on the hyporheos (fauna living within sediments up to 0.5 m beneath streams and rivers), but only two investigations provide any information on the abundances of NZ groundwater species or faunas. Sinton (1984) documented the larger invertebrates from ten wells at Templeton on the Canterbury Plains, reporting mean numbers of up to 250 crustaceans and 2 (oligocheates and turbellarians) per well for sewage contaminated wells and less than two animals per well for an uncontaminated well. The bulk of the crustaceans were a large isopod, *Phreatoicus typicus*. Four species of amphipods were present in these collections (Sinton, 1984). Fenwick (unpublished) found similar numbers of amphipods and isopods at this site and Wilson & Fenwick (in press) report on numbers of *Phreatoicus* from some of these wells.

TABLE 1. Identified invertebrates inhabiting New Zealand groundwaters and their reported distributions.

Species	**Geographic distribution**		**Habitat**
Crustacea: Amphipoda			
Paracrangonyx compactus	SI: North Canterbury		wells, 5-20 m
Paraleptamphopus subterraneus	SI: Southland, Fiordland, Otago, North Canterbury, Nelson.	NI: Taupo, Eketahuna, Whakau Island	in streams, ditches and wells to 20 m.
Phreatogammarus fragilis	SI: South & North Canterbury.		streams, wells to 20 m
Crustacea: Isopoda			
Cruregens fontanus	SI: North & South Canterbury;	NI: Wellington, Wairarapa, Hawkes Bay	river gravels, wells
Neophreatoicus assimilis	SI: South Canterbury		wells
Notamphisopus flavius	SI: Central Otago		springs
Notamphisopus littoralis	SI: eastern Otago		springs
Phreatoicus orarii	SI: South Canterbury		wells
Phreatoicus typicus	SI: North Canterbury		wells, 5-20 m
flabelliferan, n. sp.	SI: Nelson		caves
Crustacea: Syncarida			
Atopobathynella compagana	SI: Otago, Canterbury, Nelson	NI: Wairarapa	well
Hexabathynella aotearoae	SI: Westland		
Notobathynella chiltoni	SI: Canterbury		
Notobathynella hineoneae	SI: Southland		
Notobathynella longipes	SI: Nelson		well
Notobathynella sp.	SI: Nelson		well
Mollusca: Gastropoda			
Catapyrgus spelaeus	SI: Westland, Nelson		caves
Hadopyrgus anops	SI: Westland, Nelson.		wells, caves, river gravels
Hadopyrgus brevis	SI: Nelson		wells
Horatia nelsonensis	SI: Nelson		cave
Hydrophrea academia	SI: Canterbury, Nelson		wells, deep (2m) excavations
Kuschelita mica	SI: Nelson		wells
Kuschelita inflata		NI: Hawkes Bay	wells
Opacuincola caeca	SI: Nelson		pools, caves
Opacuincola kuscheli	SI: Westland, Nelson		caves
Opacuincola troglodytes		NI: King Country	spring
Paxilostium nanum		NI: Northland	seeps
Potamopyrgus cresswelli	Stewart Island. SI: Nelson	NI: Northland	seeps
Potamopyrgus troglodytes		NI: King Country, Northland	springs
Potamopyrgus subterraneaus	SI: North Otago, Canterbury		well, 15 m
Insecta: Coleoptera			
Kuschelydrus phreaticus	SI: Nelson		wells
Phreatodessus hades	SI: Nelson		wells

2.1.4 Conclusion

There are substantial difficulties in sampling the groundwater fauna and obtaining reliable estimates of the quantitative abundances of groundwater species is even more difficult because of the nature of the habitat. Usually, it is impossible to remove or sort representative samples of the substratum to collect the fauna. Wells provide access to the strata inhabited, but are an artificial situation, possibly serving as traps for individuals entering them and, perhaps, excluding others. For example, very few juvenile or brooding female *Phreatoicus* occur in wells (Wilson & Fenwick, in press).

Thus, there is a conspicuous paucity of information on the biodiversity of NZ's groundwater fauna. Quantitative data on groundwater fauna are difficult to obtain and difficult to extrapolate to the *in situ* groundwater habitat. At best, abundance data from well sampling may provide indications of the relative abundances of selected species only.

2.2 EXPECTED FAUNA

2.2.1 Biodiversity

Based on overseas work and reports of apparently undescribed species in existing collections, the biodiversity of the NZ groundwater fauna is expected to be considerably greater than indicated by present published accounts. This greater biodiversity is expected to be spread among all of the taxa so far recorded from the NZ groundwater and include some taxa not yet reported. Note, vertebrates (fishes) and decapods (shrimps and crayfish) are not included because, although common in some North American aquifers, they are consistently associated with limestone strata and there is no evidence of their presence in NZ groundwaters.

Protozoa	(Barr, 1968; Harvey et al., 1992; Stanford et al., 1994; Strayer, 1994; (Sinclair & Ghiorse, 1987)
Cnidaria*	(Ward et al., 1992; Dole-Olivier et al., 1994)
Nematoda	(Hakenkamp & Palmer, 1992; Ward et al., 1992; Dole-Olivier et al., 1994; Stanford et al., 1994; Notenboom et al., 1996)
Rotifera	(Hakenkamp & Palmer, 1992; Ward et al., 1992; Notenboom et al., 1996)
Turbellaria	(Hakenkamp & Palmer, 1992; Longley, 1992; Dole-Olivier et al., 1994)
Nemertina	(Dole-Olivier et al., 1994)
Annelida:	Archiannelida (Ward et al., 1992; Dole-Olivier et al., 1994; Stanford et al., 1994)
	Oligochaeta (Barr, 1968; Hakenkamp & Palmer, 1992; Ward et al., 1992; Dole-Olivier et al., 1994; Stanford et al., 1994; Notenboom et al., 1996)
Mollusca:	Gastropoda (Barr, 1968; Longley, 1992; Dole-Olivier et al., 1994)
Tardigrada	(Ward et al., 1992; Notenboom et al., 1996)

Crustacea:	Ostracoda (Barr, 1968; Danielopol et al., 1992; Longley, 1992; Ward et al., 1992; Dole-Olivier et al., 1994;; Stanford et al., 1994; Notenboom et al., 1996)
	Cladocera* (Ward et al., 1992; Dole-Olivier et al., 1994)
	Copepoda (Barr, 1968; Danielopol et al., 1992; Hakenkamp & Palmer, 1992; Ward et al., 1992; Dole-Olivier et al., 1994; Stanford et al., 1994; Notenboom et al., 1996)
	Isopoda (Barr, 1968; Danielopol et al., 1992; Longley, 1992; Dole-Oliver et al., 1994; Stanford et al., 1994; Notenboom et al., 1996)
	Amphipoda (Barr, 1968; Danielopol et al., 1992; Longley, 1992; Ward et al., 1992; Dole-Olivier et al., 1994; Stanford et al., 1994; Notenboom et al., 1996)
	Syncarida (Ward et al., 1992; Longley, 1992; Dole-Olivier et al., 1994)
Arachnida:	Acarina (Hakenkamp & Palmer, 1992; Ward et al., 1992; Dole-Olivier et al., 1994; Stanford et al., 1994; Notenboom et al., 1996)
Insecta:	Coleoptera (Barr, 1968; Longley, 1992; Dole-Olivier et al., 1994; Notenboom et al., 1996)
	Diptera* (Ward et al., 1992; Notenboom et al., 1996)
	Ephemeroptera* (Ward et al., 1992; Notenboom et al., 1996)
	Plecoptera (Notenboom et al., 1996; Stanford et al., 1994)
	Trichoptera* (Notenboom et al., 1996)

* Species of these taxa reported from groundwater may be epigean or riverine species found occasionally in shallow groundwaters, especially near rivers.

World-wide, crustaceans, especially amphipods, are the most widespread, abundant and diverse groundwater invertebrates (Holsinger, 1993), making them ideal candidates for indicators of groundwater quality. Research on Australian groundwater amphipods provides an indication of the likely biodiversity of this group in NZ. Forty-five species have been described, most from central Western Australia, southern New South Wales and Tasmania (Bradbury & Williams, 1997). A similar diversity of amphipods is expected in NZ because of the diversity of habitats and the geological isolation of the numerous pockets of favoured habitats.

2.2.2 Depth distributions

Beyond NZ, invertebrates are known to inhabit groundwater in caves more than 100 m below the earth's surface (Strayer, 1994) and Protozoa have been recorded from alluvial coastal plain aquifers (i.e. similar to many important aquifer-bearing sediments in NZ) in the USA to depths of 550 m (Sinclair & Ghiorse, 1989). Longley (1992) reported two species of catfish known only from wells that have their water source between 400 and 600 m below the ground, indicating that an entire fauna, including invertebrates, exists to these depths in Texas. Recent work bacteria using alternative metabolic pathways to survive in deep or otherwise unusual groundwater situations and support highly specialised faunas (Stevens & McKinley, 1995; Sarbu et al., 1996). Consequently, specially adapted animals may exist in deep and very deep groundwaters in NZ.

2.2.3. Conclusion

Diverse and abundant groundwater faunas exist in Europe, North America and Australia, although they remain relatively poorly researched. Nonetheless, knowledge of these faunas indicates that NZ's groundwater fauna will be much more diverse than present published accounts indicate. Groundwaters through out NZ are likely to support communities of invertebrates.

3.0 SENSITIVITY OF GROUNDWATER INVERTEBRATES TO HUMAN ACTIVITY

3.1 ECOLOGY OF NZ GROUNDWATER INVERTEBRATE COMMUNITIES

3.1.1 Review of research to date

Two studies investigated a groundwater invertebrate community's responses to pollution at varying distances downstream from the disposal area for domestic sewage oxidation pond effluent at Templeton, Canterbury. The original work reported dramatic increases in the abundance of phreatic crustaceans immediately downstream of the disposal area compared with an up-stream control site, with attenuation in numbers over about 900 m downstream (Sinton, 1984). Three crustaceans exhibited these marked responses, the isopod *Phreatoicus typicus* and two amphipods, *Paracrangonyx compactus* and *Phreatogammarus fragilis*. The increases in abundance for these crustaceans ranged between one and two orders of magnitude over mean values for the control site. Other species appear to have responded variously, but their numbers were insufficient to draw any conclusions (Sinton, 1984). Periodic massive kills of the fauna due to heavy pollution from unusual effluent irrigation events were also noted in some wells (Sinton, 1984; Fenwick, in prep.).

Differences in abundance of the main species appeared correlated with the increased numbers of faecal and total coliform bacteria observed at each well. The most abundant species, *Phreatoicus*, was found to ingest coliform bacteria. Based on data for an epigean amphipod from North America and a series of assumptions concerning species' densities and available habitat space, Sinton (1984) estimated that populations of the three crustaceans beneath the disposal site may be assimilating 20 % of the calorific value of the sewage effluent applied to the area.

Further work at the same site investigated organic carbon flows within the groundwater (Fenwick, in prep.). Immediately downstream of the disposal area, dissolved organic carbon levels and total coliform bacteria increased compared with levels at the upstream control well. Isotope tracer (^{14}C-glucose) experiments revealed increased organic carbon uptake rates by sediments in the more contaminated wells, apparently through microbial activity.

In further experiments, layers developed rapidly on artificial substrata (ceramic tiles) to reach near maximum organic carbon contents after 30-60 days (higher in winter than in spring). Layer biomass after four months' development was greater in the contaminated wells. Caging experiments showed that grazing by groundwater animals significantly reduced the organic carbon contents of layers and tended to reduce rates of oxygen uptake and ^{14}C-glucose uptake by layers. Differences in the extent and nature of layers developed in the control and contaminated wells were apparent from visual examination by scanning electron microscopy. Layers from control the well contained very rare bacteria loosely bound into irregular patches of fine particles covering about 25-30% of available surfaces after two months, with little change after four months. Layers from contaminated wells covered about 40 % of surfaces after just one month and contained infrequent bacteria bound into a matrix of slime and fine particles.

Layers protected from grazing differed. In the control well, protected (ungrazed) layers covered more of the surface, were denser and thicker than unprotected layers, but slime was still not obvious and bacteria scarce. Protected layers from contaminated wells developed an almost complete, moderately dense cover of unbound particles within one month. After four months, particles and bacteria bound into irregular patches over a relatively dense, homogeneous basement layer.

Gut analyses showed that *Phreatoicus* ingests very fine sediments and digests associated bacteria (epifluorescence microscopy). Further experiments using ^{14}C-labelled layers on sediments determined that adult *Phreatoicus* ingest 32-100 ug of organic carbon per day, assimilating about 90 % of this. Thus, each adult *Phreatoicus* cleans 0.01-0.02 g of sediment per day from a surface area of 1.2-3.9 cm^2. Using Sinton's (1984) density estimates, *Phreatoicus* beneath the 14 hectare disposal site ingest 98-196 tonnes of organic carbon per year, assimilating 31-98 tonnes of this, converting it into animal tissue and carbon dioxide. Assuming similar ingestion and assimilation rates for the other two large species of sediment-browsing amphipods and using Sinton's (1984) density estimates, a further 12-37 tonnes of organic carbon will be assimilated beneath the site. Thus, the three species together assimilate 43-135 tonnes total (or 3.1-9.6 tonnes per hectare) of organic carbon beneath the site each year.

The environmental management implications of these findings are profound (Fenwick, in prep.). The crustaceans clearly play an important role in the removal of organic contaminants and maintenance of groundwater quality. This occurs in at least three ways. First, potentially harmful bacteria and fungi are converted into relatively harmless animal tissue. Second, although conversion of contaminant material to animal tissue does not remove it from the system, conversion inefficiencies and respiration mean that significant amounts of the contaminant organic carbon are lost from the groundwater ecosystem as carbon dioxide through respiration. Third, the effect of grazing organic layers from particle surfaces also has the effect of helping to maintain very fine pore spaces within the aquifer system. Conceivably, removal of the all grazing animals would result in steady clogging of pores, slowing of groundwater flow rates and reducing its oxygen content, creating conditions disastrous for groundwater quality.

It is notable that both workers reported periodic massive kills of the crustaceans at this site, indicating sensitivities to some human input, presumably excess organic carbon.

Thus, these crustaceans hold potential as bioindicators. However, more work must be done to understand their sensitivities and distributions.

3.1.2 Conclusion

Within alluvial groundwater beneath Canterbury Plains, dissolved and fine particulate organic carbon is rapidly bound into organic layers on sediment particles. Layer formation is enhanced by additional organic carbon from sewage effluent and bacteria become more abundant in these layers. Numbers of phreatic crustaceans inhabiting the system are dramatically increased at sites affected by sewage inputs. These crustaceans play a very substantial role in maintaining and remediating groundwater quality, removing large quantities of organic carbon from the system by feeding on organic layers and digesting adherent bacteria. Excessive amounts of organic carbon apparently entering the groundwater periodically result in massive kills to the crustacean populations.

3.2 OTHER STUDIES ON SENSITIVITIES OF GROUNDWATER INVERTEBRATES TO HUMAN ACTIVITY

Although there is a moderate literature on bioindicators and ecotoxicology of marine and freshwater invertebrates, this report focuses almost entirely on the scant research in these areas specifically on groundwater animals. Literature on true phreatic environments is very limited, but studies of species in karstic, cave, spring and interstitial riverine habitats provide useful insights. There is no available research into the NZ groundwater fauna other than the two investigations described above (published investigations of hyporheos are not considered here).

3.2.1 Organic pollution

Groundwater habitats are generally carbon-limited; that is, the scarcity of a fundamental energy source in the form of organic carbon limits the size of species populations that can develop. Thus, pollution that adds organic carbon often increases populations of phreatic species (Sinton, 1984; Notenboom et al., 1994; Fenwick, in prep). However, because diffusion of oxygen into groundwater is often slow, especially in porous systems, microbial degradation of the added organic carbon can rapidly deplete available oxygen, decimating or eliminating larger invertebrates when enrichment is too great (Holsinger, 1966; Sinton, 1984). Thus, a study in the Fulda River (Germany) demonstrated a positive correlation between groundwater invertebrate densities and a combination of oxygen concentrations and organic enrichment (Husmann, 1975).

In a survey of interstitial faunas near rivers, densities of total phreatic faunas down-stream of sewage pollution were similar to those at an up-stream site, whereas surface and hyporheic faunas, overall, increased in abundance with pollution, although changes in individual species responses differed (Ward et al., 1992). Similar changes occur in karst cave habitats. Holsinger (1966) found dramatic increases in densities of cave invertebrates with contamination by septic tank effluent. With excessive organic

enrichment, however, diverse aquatic cave faunas may be exterminated and replaced by surface-dwelling species (Sket, 1973; Culver et al., 1992).
Organic pollution can, therefore, increase abundances of groundwater species or remove them completely when excessive.

3.2.2 Pesticides, heavy metals and other pollutants

There are very few published accounts of the effects of such pollutants on groundwater species and nothing is known about the NZ fauna in this respect. Results are available for a few species from overseas work, but will not be reviewed in detail because of the complexities of test responses and test conditions used. A recent detailed review is available in Notenboom et al. (1994).

a. Effects on individuals.
The acute toxicities of species (mostly European or North American) of some common groundwater invertebrate groups to a few common pollutants have been investigated. The taxa and pollutants are listed below (see Notenboom et al. (1994) for references):

Amphipods	2 species	zinc, cadmium	Meinel & Krause, 1988
		copper	Plenet, 1994
Isopods	3 species	zinc, cadmium,	Meinel & Krause, 1988
		copper, chromium	Meinel et al., 1989
		TRC	Bosnak & Morgan, 1981a
			Bosnak & Morgan, 1981b
Decapods	1 species	TRC	Mathews et al., 1977
Copepods	1 species	zinc, cadmium,	Notenboom et al., 1992
		PCP, 3,4-DCP,	
		Aldicarb, Thiram	Notenboom & Bossenkool, 1992
Oligochaetes	1 species	zinc, cadmium	Meinel & Krause, 1988
			Meinel et al., 1989

Bioaccumulation, the net accumulation of a chemical or element by an organism during its life, is another aspect of pollution considered to pose considerable ecological risks, especially in communities comprising several trophic levels. Its importance in groundwater systems should not be under-estimated, however, in view of potential sub-lethal effects. Two investigations found that crayfish and copepods accumulate zinc and copper, but that epigean species accumulated less than did the hypogean (groundwater) species (Dickson, et al., 1979; Plenet, 1995). One of the hypogean amphipods was capable of regulating its body zinc and copper concentrations (Plenet, 1995).

Apparently, different taxa within an interstitial riverine invertebrate community are differentially affected by metals in water and sediments. Unpublished findings (Plenet, 1993, in Notenboom et al., 1994) from France report changing abundances of interstitial invertebrate taxa at different points along the Rhone River in response to differing concentrations of copper and zinc. Increasing pollution of this nature appears to eliminate amphipods and insects from these habitats, whereas ostracods and cladocerans persist (Notenboom et al., 1994).

b. Effects on populations and communities
Sublethal effects of pollutants on species populations and whole communities may be as catastrophic as sudden mass kills of species in the medium to long term. It is well known that various pollutants interfere with individual growth, development, reproduction and, hence, species populations' abilities to perform their normal ecological and bio-remediation roles (Underwood 1995). Interference with the normal functioning of one of these processes is, therefore, likely to disturb the functioning of the community as a whole. There is, however, no published information on such effects for groundwater species either in NZ or elsewhere, although reported changes in species abundances and total faunas with increased pollution, especially chemical pollution (Dickson, 1979; Notenboom et al., 1994; Plenet, 1995), probably result from such effects.

3.2.3 Groundwater depletion

No information is available on the effects of groundwater depletion on groundwater faunas. However, given that groundwater faunas comprise aquatic forms adapted for life in water, species are unlikely to withstand drying. Most taxa reported from groundwater are motile; the larger crustaceans tend to be highly mobile and capable of active retreat as water depletion. Smaller species also seem likely to be capable of some degree of active retreat and others may be carried along with surface tension, unless adhering to particles.

Probably more important is the removal of habitat space, especially food, as water levels in the system decline. The likely effect is that densities of animals increase beyond the carrying capacities of the available habitat and food resources as water levels recede, leading to declines in the population through density dependent factors. Thus, the fauna will move towards a new equilibrium. If water levels rise again, however, available habitat volume and food will increase. Some re-colonisation may be immediate, but densities of invertebrates, especially the larger ones, will take some time to attain original levels because groundwater species characteristically have low reproductive rates compared with those of epigean aquatic species (Holsinger, 1966; Gibert et al., 1994; Notenboom et al., 1994; Wilson & Fenwick, in press).

3.2.4 Conclusion

Because groundwater communities are typically low in species diversity and comprise species with low genetic plasticities and low population densities, often with a fairly restricted geographic distributions, seeking sparse, usually patchy food sources, they may be more susceptible to pollution than epigean communities (Gibert et al., 1994). Indeed, possibilities for recovery and re-colonisation may be limited for these reasons and because groundwater invertebrates tend to have low reproductive rates.

4.0 NATURAL VARIABILITY OF GROUNDWATER INVERTEBRATE POPULATIONS

One of the universal characteristics of faunas, regardless of situation, is their spatial and temporal variabilities in abundance and diversity over most scales, often for no apparent reason (Stewart & Loar, 1993; Underwood, 1992). Groundwater is no exception. Many workers regard groundwater environments, generally, and alluvial groundwater environments, in particular, as well as their faunas, as very heterogeneous over relatively short distances (Hakenkamp & Palmer, 1992; Dole-Olivier et al., 1994; Vanek, 1997) and between times at the same site (Hakenkamp & Palmer, 1992).

4.1 NEW ZEALAND GROUNDWATER FAUNA

Results from research in NZ demonstrate the heterogeneity of a local alluvial groundwater fauna. In Sinton's (1984) seminal study, variations in numbers of the three dominant species from the same well at different times were so large that standard deviations exceeded mean values ($n = 4$) for 60-80 % of the ten wells sampled.

4.2 OTHER GROUNDWATER FAUNAS

Variation was a feature of most other investigations of groundwater faunas. Abundances of some species of the Rhone River interstitial faunas varied dramatically between repeat samplings (Marmonier et al., 1992; Dole-Olivier et al., 1994). Similarly, abundances of interstitial invertebrates in the hyporheos of the Rhone River fluctuated dramatically between samplings within samplings just 13 days apart (Chafiq et al., 1992). Similar variation occurred in North American groundwater also. In their investigation of the effect of pollution on riverine interstitial faunas, Ward et al. (1992) found considerable variation in the pattern of effects between pairs of sites above and below sewage sources. Although they collected replicate samples at each site, no measures of variation between replicates were provided (Ward et al., 1992).

Meiofauna discharged by springs in the Netherlands also displayed wide variations in abundance (numbers per unit volume of discharge)(Notenboom et al., 1996). Numbers of an amphipod and an isopod collected by filtering discharge from a groundwater seep fluctuated very widely, even when normalised for water discharge (Edler & Dodds, 1992).

In a methodologically weak investigation, Hakenkamp & Palmer (1992) examined variation in the fauna from arrays of wells, as well as comparing two sampling methods. Sampling by pumping from the wells extracted a very different fauna to that collected from cages of substratum suspended in wells for a month. Repeated samplings of wells by pumping on the same day and on alternate days resulted in decreasing numbers of individuals and taxa represented in samples, even though there were no associated changes in chemical parameters within each well. Thus, different methods sample different elements of the fauna and repeated sampling of the same well may be inappropriate replication. Three wells spaced 10 m apart did not serve as satisfactory replicates, but the fauna from an array of 12 such wells did not differ significantly, indicating that effective replication can be achieved using larger numbers of wells (Hakenkamp & Palmer, 1992).

4.3 CONCLUSION

These studies, then, indicate that there is considerable variation in groundwater population densities and community compositions over time and space at the same site, as well as between locations that appear to be ecologically equivalent. These variations were not immediately correlated with observed physico-chemical factors in most of the above studies. In fact, wide fluctuations in some of these factors are common to the various studies reported above. Thus, reliable quantitative sampling to detect human impacts on groundwater faunas requires further refinement of sampling methods and procedures. Establishing causal relationships between changes in the fauna and human activities may be even more demanding than in epigean aquatic, terrestrial and marine environments.

5.0 INVERTEBRATES AS MONITORS OF GROUNDWATER IN NZ

Research reviewed in this report provides an understanding of the functioning of the groundwater ecosystem and the role of various components in this. Invertebrates are the only element of this system with the capacity to respond in the short to medium term to a broad spectrum of pollutants at high and low concentrations, arriving in brief pulses or pervading the system over longer periods. Chemical monitoring is, of economic and logistic necessity, restricted to a small proportion of the harmful chemicals in the environment, whose effects on the fauna and ecosystem are largely unknown (Patrick, 1993; Butterworth, 1995). Nor is chemical monitoring continuous. Thus, important contaminants may be missed, simply because their arrival could not be predicted or because the pollution event was brief and occurred between samplings. Bacteriological surveys are not appreciably better. Potentially important bacteria may be missed because culture conditions did not promote their growth. Bacteria tend to be more tolerant of pollution and their very brief generation times mean that affected populations may recover from a pollution event between samplings. In addition, bacteria are often tolerant of conditions that are harmful to higher organisms and humans. Finally, because bacteria are low in the groundwater trophic system, their biodiversity and numbers may be a poor reflection of the system's functioning and Life Supporting Capacity (*sensu* MfE, 1997).

Use of groundwater invertebrates as monitors of groundwater holds substantial promise, but just how environmental change caused by human activity can be measured or predicted has no easy answer. The fundamental reason for this is the innate variability of natural systems (Underwood, 1995), including groundwater systems, and the diversity of levels at which pollution may influence individuals and populations, especially invertebrate population numbers and communities' quantitative compositions. In addition, the groundwater environment is relatively inaccessible and apparently quite heterogeneous (Hakenkamp & Palmer, 1992; Gibert et al., 1994; Vanek, 1997), especially in alluvial aquifers, making the task even more difficult. Therefore, efforts to establish invertebrate biomonitors for NZ groundwater should follow a structured plan to ensure resources are focused on developing biomonitors giving increasingly more detailed and specific information as knowledge of the fauna and its responses develops.

5.1 ROLE OF GROUNDWATER INVERTEBRATES AS INDICATORS

Invertebrates hold promise of serving as extremely valuable indicators of groundwaters' Life Supporting Capacity and suitability for human uses (*sensu* MfE, 1997), although substantial research is required to establish appropriate indicators for the whole country. The above review shows that some groundwater invertebrates can satisfy most of the established criteria for good indicators (MfE, 1997) in much the same way as aquatic, terrestrial and marine invertebrates. Indeed, groundwater invertebrates are almost certain to prove more useful as indicators of this habitat and resource than invertebrates in aquatic or marine environments. The remoteness of many groundwater environments mean that many of the usual ways of first detecting (dying fish or plants) and evaluating environmental quality (e.g. visual inspection and direct observations by scientists) cannot be employed. Invertebrates, therefore, provide one of the only ways of assessing both the life-supporting capacity of groundwater and its suitability for human uses, specifically, human consumption, in the face of potential contamination from too many combinations of harmful substances for continuous monitoring by any other means.

5.2 DEVELOPMENT OF GROUNDWATER BIOINDICATORS

The most appropriate way forward seems to be working towards establishing a Groundwater Invertebrate Index (GII) that includes all common and readily identifiable species. This should be similar to the Macroinvertebrate Community Index (MCI) as adapted from the British model for NZ aquatic systems (Stark, 1993). Development of such an index requires extensive surveys of the groundwater fauna throughout NZ, best focussed on key regions initially. Undisturbed and disturbed (polluted) situations must be included. The aim of this initial work should be to determine the biodiversity of groundwaters and to ensure that the taxonomic work is in place to support on-going surveys and definition of species distributions. Effective procedures for quickly sampling the fauna must also be developed at this stage. NIWA will commence work of this nature in Canterbury and Hawkes Bay in mid 1998.

The next stage of the work should involve simultaneously monitoring groundwater invertebrate populations, probably key species, and collecting of physico-chemical and, perhaps, bacteriological, data. Again, both polluted and unpolluted sites must be included. The results would establish baseline invertebrate population levels and community biodiversities under known physico-chemical conditions at each locality. Refinements to species used in future monitoring and the development of a robust GII should result. In addition, this stage should provide data for developing an initial predictive model of species and community responses to different levels of various pollutants.

Further work should seek to understand the biologies of key indicator species so that longevities and reproductive capacities can be incorporated into predictive models. Rates of pollutant accumulation, especially harmful metals and pesticide residues, by key species should be determined. Changes to species' reproductive and feeding rates and behaviours should be included also to add finer detail to the monitoring tool and ensure that predictive models accommodate such potential changes.

6.0 RESOURCES NEEDED TO COLLECT RELEVANT DATA

Resources required to establish effective groundwater biomonitors centre mostly on developing the required expertise and knowledge. This includes:

Taxonomic expertise and resources to define the species that will comprise the basis of the monitoring technology.

Development of efficient methods for collecting and monitoring groundwater invertebrates.

Support to establish networks of wells that are accessible for this work and suitable for long-term sampling groundwater invertebrates. At present few, if any of the wells monitored by regional authorities are immediately suitable for sampling by present methods. The first wells investigated will be in Canterbury and Hawkes Bay. As work proceeds, wells in most other regions of NZ must be identified and indefinite access for sampling negotiated. Access to all regional authority monitoring wells in the vicinity of land fills, sewage treatment/ disposal areas and other potential sources of pollutants would be extremely useful.

Establishing wells at points along two or more catchments to determine how groundwater faunas change from groundwater source to the sea.

Continuing access to and support for invertebrate (crustacean) taxonomists, invertebrate ecologists, water chemists and technical assistance is required.

Continuing access to the well fields at Templeton and Burnham should be secured as nationally significant scientific sites for on-going experimental work.

Resources to establish one or more well fields for future scientific investigations may be required.

Support for ecological investigations into key groundwater species to establish life history parameters as a means of predicting resilience after pollution events.

Support for toxicity testing and heavy metal uptake investigations of key species to refine predictive models and understand sublethal effects.

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