DO SPRINGS PROVIDE A WINDOW TO THE GROUNDWATER FAUNA OF THE AUSTRALIAN ARID ZONE?

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Abstract: Groundwater is an important resource for human populations as well as many invertebrate species. Consequently, there is potential for substantial conflict when attempting to protect the conservation values of springs, and other groundwater habitats, while also utilising the water that sustains them. Recognizing the role of springs as habitat for surface-water and groundwater fauna is a pre-requisite for groundwater management. This paper reports results of preliminary work on the invertebrate fauna of five springs in the Pilbara and interprets results in terms of the importance of springs for groundwater and surface-water invertebrates. A classification of Pilbara species in terms of their use of groundwater habitat and their geographic range is proposed as a framework for assessing the likely impacts of development projects that lower water-tables. Possible parallels in patterns of endemism of surface-water and groundwater invertebrates in Western Australia are also pointed out.

Keywords: arid regions, Australia, groundwater/surface-water relations, invertebrates, stygofauna

INTRODUCTION

Groundwater is an important resource, meeting about three-quarters of the water requirements of the human population in Europe, half in the USA (Gibert et al. 1994a) and between two-thirds and all the domestic and industrial requirement in south-west Western Australia, depending on annual rainfall (R. Stone pers comm.). Almost all the water supply of Karratha, the largest town in the arid Pilbara region of Western Australia, is currently being drawn from groundwater at Millstream (Fig. 1), an area containing biologically important springs that feed into the Fortescue River. Water extraction at Millstream has the potential to affect phreatophytic vegetation detrimentally, as well as impacting on the aquatic ecology of the major pools in the spring system.

Despite the ecological impacts of groundwater extraction on springs and underground ecosytems, the practice is likely to continue because most of the world's freshwater occurs below ground (Gibert et al. 1994a) and surface water resources are under even greater pressure in terms of maintaining the ecology of their ecosystems while meeting human, industrial and other water demands (Gleick 1993). Almost all rivers in south-eastern Australia are over-allocated, mostly to irrigate crops (Anon 2001), but little surface water has been utilised in the Pilbara because the flat topography means few sites are suitable for dam construction, rainfall is episodic and evaporation is high. A dam on the Harding River, built to supply Karratha, destroyed some of the most attractive river pools and springs in the region but failed to provide a reliable source of water for domestic use because of water quality issues, mostly associated with high turbidity.

In the Pilbara, however, the small size of the human population means that domestic use of groundwater does not have as significant an overall impact on water-tables as open-cut mining. The Pilbara supplies about half the iron ore used in Asia (Preston and Bachman 2001) and, when mining occurs below the water-table, de-watering of mine pits is necessary. This localised drawdown can have detrimental effects on the ecology of the groundwater systems, including the potential to cause extinction of locally endemic species (EPA 1998). Disposal of the drawdown water can also have significant, but much more easily managed, effects when it is pumped into adjacent rivers and creates permanent pools in areas that previously held water for brief periods only (see Kay et al. 1999).

The main reason for concern about the effects of groundwater drawdown on biodiversity is that the region appears to contain a very rich stygofauna by global standards, with high levels of endemism (Humphreys 1999, 2001). As is common with groundwater animals (Strayer 1994), many of the endemic species appear to have restricted ranges. Surveys suggest they occur mainly in karst, calcrete and alluvial groundwater systems (Humphreys 1999). However, little is known about the ecology of the Pilbara stygofauna, except for species that occur in surface waters as well as groundwater. For example, the ecological tolerances of the cyclopoid copepod *Mesocyclops brooksi*, which was described from samples collected in wells in the Ashburton catchment (Pesce et al. 1996a), are reasonably well understood on the basis of occurrences in fresh and brackish surface waters throughout the southern two-thirds of Western Australia (Halse et al. 2000a,b).

Much of the focus on stygofauna research in the Pilbara has been on animals occurring in deep (up to 40 m below water-table) groundwater in calcrete deposits (Humphreys 2001) or in caves (Humphreys 2000; Jasinska and Knott 2000). However, Boulton (2001) has emphasized the importance the hyporheic zone and the lack of Australian studies in this habitat. Northern Hemisphere research has shown that the largest numbers of groundwater animals occur in shallow groundwater of the hyporheos rather than the deeper phreatic zone (Marmonier et al. 1993; Rouch and Danielopol 1997) and few Northern Hemisphere studies have sampled groundwater as deep as much of the Pilbara sampling. The significance of different sampling strategies is unclear partly because groundwater species are often flexible in their habitat selection and choose a variety of geological formations; many species occur in surface water as well as at deeper groundwater (e.g. *Mesocyclops brooksi*) and classifications of groundwater species based on their known occurrence in different groundwater environments (Gibert et al. 1994a) are only indicative of likely distribution patterns in other situations.

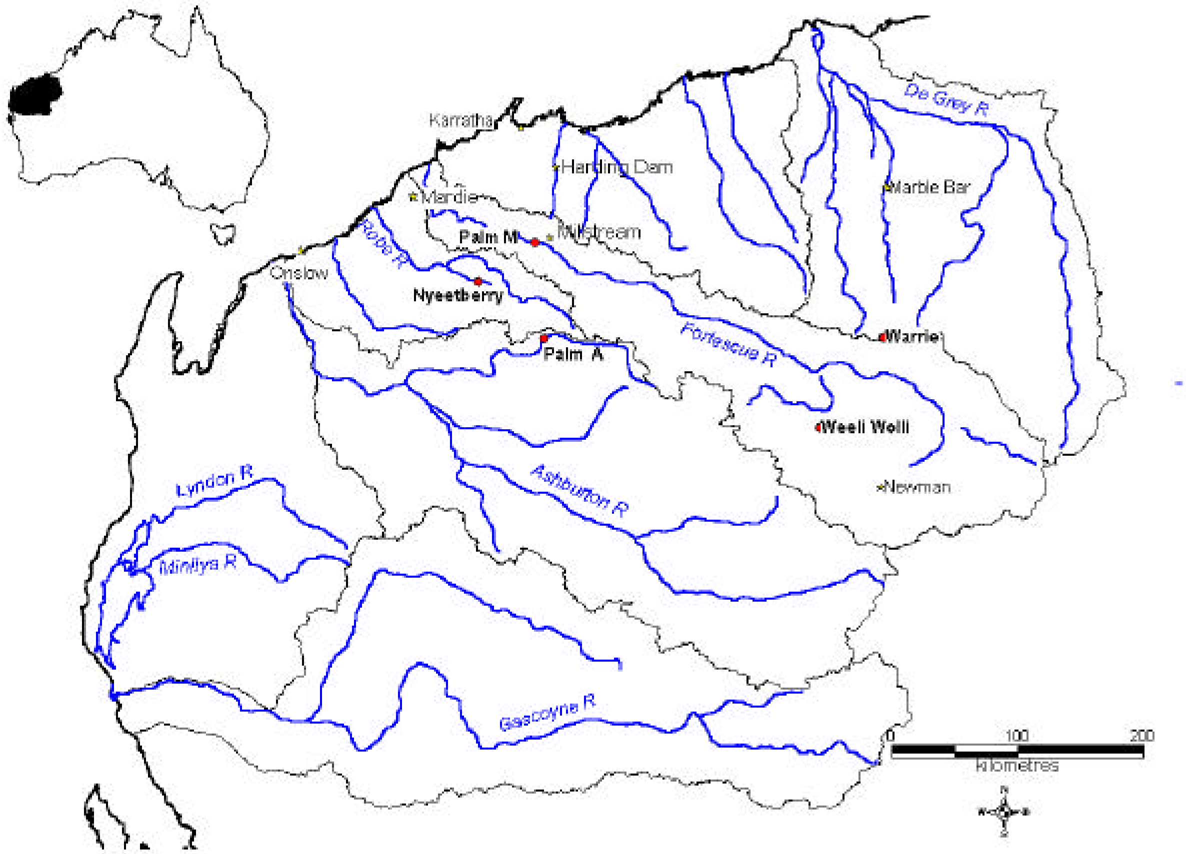

Figure 1. Major catchment basins and location of the five springs sampled in the Pilbara, Western Australia. Other places mentioned in text are also shown.

The acquisition of ecological information about stygofauna in calcrete and alluvial formations in the Pilbara has been hampered by the overall lack of survey effort, the focus on sampling deep groundwater with attendant logistical constraints, and the low abundance and patchy distribution of animals. A useful approach for collecting animals in karst systems has been to sample discharge zones (springs), where a high proportion of the fauna of the local aquifer can often be recovered (Gibert et al. 1994b). We are currently sampling springs to determine whether spring-sampling can be used successfully to collect species typical of the deeper groundwater fauna of alluvial and calcrete systems in the Pilbara. A second objective is to document groundwater species using the hyporheic zone of Pilbara streams. The third objective is to assess the importance of springs for surface-water invertebrates.

The aridity of the Pilbara means permanent surface water is scarce and restricted to springs and some permanent groundwater-fed pools in the beds of large rivers (Masini 1988; WRC 1997). Such predictable sources of water would be expected to have high conservation importance through supporting richer faunas than ephemeral water-bodies (Kay et al. 1999). They are also likely to be an important source of animals for colonisation of newly flooded pools and maintenance of populations of invertebrate species at the regional level.

STUDY AREA AND METHODS

Summer temperatures in the Pilbara often exceed 45 °C. The highest recorded maximum is 50.5 °C at Mardie and the highest average monthly temperature is 41.5 °C at Marble Bar in January (data from Bureau of Meteorology). Average monthly maximum temperatures during summer exceed 38 °C at two-thirds of weather stations. Rainfall is monsoonal, falling mostly in late summer and early autumn. The average annual precipitation varies from just over 300 mm near the coast to 200 mm inland (Gentilli 1972). However, the most marked characteristic of Pilbara rainfall is its variability: for example, the annual average rainfall at Mardie (Fig. 1) is 274 mm but the highest recorded daily and monthly falls are 364 and 675 mm, respectively. Annual evaporation is approximately 3000 mm and surface water quickly evaporates so that water-bodies are permanent only if supplied by groundwater. Masini (1988) and WRC (1997) provide general accounts of surface waters in the Pilbara, while groundwater resources are described by Allen (1997) and Johnson and Wright (2001).

In September 2001, we sampled aquatic invertebrates in the benthos and 'stream bed' of five permanent springs in four river systems (Fig. 1). Brief descriptions of the springs are given in Table 1 and photographs are shown in Fig. 2; all were located in water-courses and consisted of discharge areas and associated permanent pools. The springs occurred in alluvial sediments but extensive calcrete deposits were also visible. Around Weeli Wolli Spring and Nyeetberry Pool, rainfall was exceptionally high in the wet season of 2001, as it had been in 2000 (Bureau of Meteorology 2000, 2001), and aquifers were still discharging strongly over a broad area at the time of sampling. Most of the water in the two systems appeared to be coming from several kilometres up-stream of the sampling sites. The amount of water and flow at the other three sites were more typical of end-of-dry-season conditions and discharge areas probably occurred relatively close to the sampling sites. However, with the exception of one small area at Palm Spring on the Ashburton, we were unable to distinguish discharge and recharge zones at any of the sites.

Invertebrates were collected by (a) stirring up the substrate in the stream or spring and then sweeping through the water column with a 250 µm mesh pond net, and (b) by digging up sediments with a shovel to a depth of 30 cm, placing the sediments in a bucket, agitating them and pouring the supernatant through 50 µm and 250 µm mesh pond nets. At Palm Spring on the Ashburton, a small quantity of up-welling water was collected and passed through a 50 µm mesh pond net. At each spring, we collected information on surface-water conductivity, pH, dissolved oxygen and water temperature using portable meters. Total dissolved phosphorus and nitrogen were measured in the laboratory using persulphate digestion.

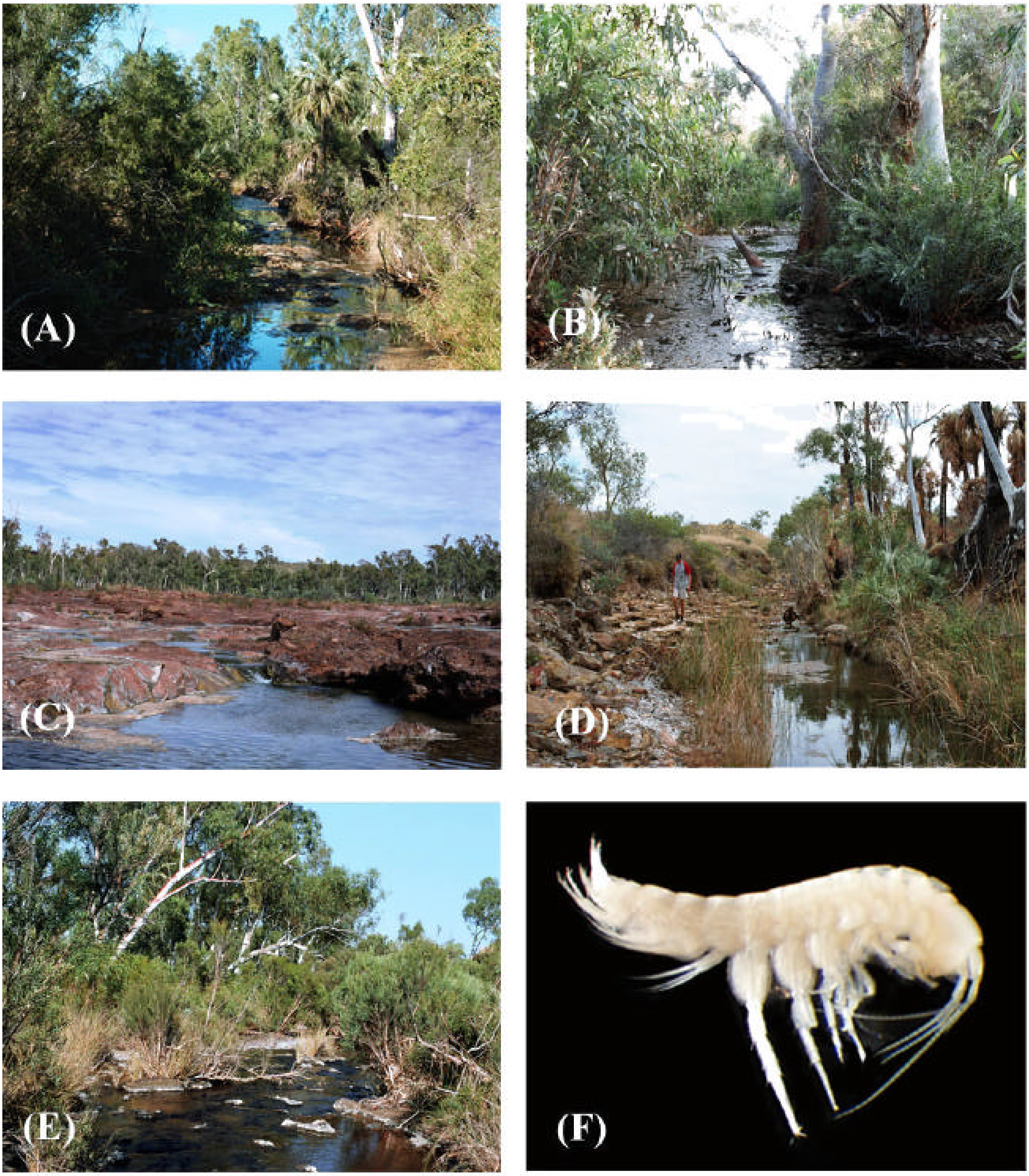

Figure 2. Springs sampled in the Pilbara and a species of stygofauna. (A) Palm Spring in the Ashburton catchment, (B) Warrie Spring in the De Grey, (C) Weeli Wolli Spring in the Fortescue, (D) Palm Spring in the Fortescue near Millstream, (E) Nyeetberry Pool in the Robe, (F) stygofaunal amphipod *Pilbarus millsi* from Weeli Wolli.

Table 1. Descriptions of the five springs sampled in the Pilbara (see Fig. 1 for locations and Fig. 2 for photographs)

Palm A[1]	Ashburton River, 22° 16' 03"S 117° 02' 16"E, 2 channels each 2-20 m across, depth from seepage film to several metres, flow none to seepage, substrate silt and calcrete with a few pebbles, on pastoral lease with some cattle damage to vegetation
Warrie	De Grey River, 22° 15' 36" S 119° 42' 21" E, channel 2-10 m across, depth 15- 50 cm, flow none to seepage, substrate silt with calcrete outcrops outside channel, on pastoral lease with deserted homestead on creek bank and evidence of heavy grazing and eutrophication
Weeli Wolli	Fortescue River, 22° 54' 58"S 119° 12' 23"E, channel 10-50 m across, depth 20-50 cm, flow weak but obvious, substrate coarse alluvial sand (shale) and bedrock with some calcrete, on Crown land and in good condition
Palm M[2]	Fortescue River, 21° 34' 19"S 116° 57' 42"E, channel 1-3 m, depth 15 cm to several metres, flow none to weak, substrate silt, sand, cobbles and calcrete, on reclaimed pastoral lease and in good condition
Nyeetberry	Robe River, 21° 51' 31"S 116° 30' 58"E, channel braided 20-100 m across, depth 15-200 cm, flow none to moderate, substrate sand and pebbles, on pastoral lease and in good condition

[1] Palm Springs on Ashburton River, [2] Palm Springs on Fortescue River at Millstream

All invertebrates were identified to species (or morpho-species) level and we assigned them to the broad habitat categories of 'surface-water' or 'groundwater' based on morphology and published information on occurrence of the species or related taxa. In this paper, the groundwater category refers to invertebrate species thought to be restricted to the hyporheic zone of groundwater-dependent habitats or to species known to occur in deep groundwater habitats (even if they also occur in surface water). These species are stygophiles and stygobites *sensu* Gibert et al. (1994a). The surface-water category refers to species that principally occur in surface waters, although they may be benthic and occasionally invade the shallow hyporheos. Such species are usually stygoxenes *sensu* Gibert et al. (1994a). Our categories, and those of Gibert et al. (1994a), are somewhat arbitrary but may be useful in the context of assembling information on the importance of groundwater habitats for invertebrate biodiversity.

RESULTS AND DISCUSSION

Table 2 shows the variation in water chemistry at the springs. Warrie Spring was eutrophic, probably as a result of the old homestead on its banks and also because of low flow. This site and Palm Spring on the Ashburton, were the most saline sites and there appeared to be an inverse relationship between flow and salinity. Other than Weeli Wolli, all sites contained extensive fine sediment or silt. This was most pronounced at Warrie Spring.

Table 2. Water chemistry at the five springs in the Pilbara (measurements taken about 20 cm below water surface)

	Palm A	Warrie	Weeli Wolli	Palm M	Nyeetberry
Conductivity (µS cm^{-1})	2990	2580	890	1334	770
pH	8.36	8.02	8.55	8.00	8.01
Dissolved oxygen (%)	102	150	106	110	104
Temperature (°C)	20.1	19.3	17.7	19.9	20.4
Turbidity (NTU)	7.7	7	0.8	0.5	0.3
Colour (TCU)	2.5	5	2.5	2.5	2.5
Alkalinity (mg L^{-1})	480	505	340	405	325
Total nitrogen (mg L^{-1})	0.19	9.1	0.03	0.06	0.08
Total phosphorus (mg L^{-1})	0.01	0.03	0.005	0.01	0.005

Table 3 provides a breakdown of the fauna occurring in the five springs. A total of 159 invertebrate species were identified. Eighteen of them (11 % of the fauna) belonged to the groundwater category, with between 4 and 8 groundwater species being recorded from each spring. The groundwater species were copepods, ostracods, amphipods, isopods, bathynellids, oligochaetes and water mites. Between 40 and 85 % of the crustaceans at each site were groundwater species. Overall, however, the fauna at each site was dominated by insects. A complete species list for each spring is provided in Appendix 1.

Table 3. Total numbers of species of crustacean and insect and other invertebrates at the five springs in the Pilbara. Numbers of groundwater species are shown in parentheses

	Palm A	Warrie	Weeli Wolli	Palm M	Nyeetberry	Total
Other	6 (1)	7 (1)	6 (1)	5 (1)	7 (1)	29 (1)
Crustacea	13 (7)	10 (4)	6 (5)	12 (6)	10 (4)	33 (14)
Insecta	51	48	30	41	40	97
Total	72 (8)	66 (5)	44 (7)	58 (7)	62 (4)	159 (18)

Deep groundwater element

Considering the small number of springs sampled, a significant number of groundwater species known from deep calcrete and alluvial aquifers were collected during the study. Although they constituted a small proportion of the spring fauna and considerable searching among detritus and surface animals was required to find them, the yield of groundwater species (4-8) from the springs was comparatively high (typically bores yield 0-5 or 6 species, S.D. Anstee pers. comm.). Spring-sampling was an efficient method of collecting groundwater species.

While distributional information about groundwater species is still limited, and the high proportion of endemism and small geographic ranges of most deep groundwater species recorded in the Pilbara has been emphasized (Humphreys 2001), this study suggested substantial elements of the fauna are widespread geographically, as well as in terms of the groundwater habitats they utilise (Table 4). For example, the amphipod *Pilbarus millsi*, which was collected in enormous numbers at Weeli Wolli Spring, was first collected from pools at Millstream (Bradbury and Williams 1997) and subsequently from bores in the Fortescue and the Ashburton catchments over a distance of 200-300 km and (S.D. Anstee pers. comm.). Of the other groundwater species in the springs, the new species of *Vestenula* ostracod and the copepod *Microcyclops varicans* have been collected from deep wells in the Ashburton catchment by W.F Humphreys (see Martens and Rossetti 2002 and Pesce et al. 1996a) and undoubtedly occur in groundwater throughout the Pilbara (*M. vaicans* occurs throughout Australia). Some other groundwater copepod species known from bores in the Pilbara or adjacent regions (*Metacyclops mortoni*, *Halicyclops spinifer* and *Mesocyclops brooksi*), although not collected in this study, occur in springs on Mandora Marsh just north of the Pilbara and are likely to have groundwater ranges covering at least north-western Australia (Table 4).

The undescribed isopod *Pilbarophreatoicus* was previously collected only from groundwater bores adjacent to Palm Spring at Millstream by W.F. Humphreys. It may well have a localised distribution but occurs in the spring as well in the under-lying aquifer. It seems likely that many localised species will also show a broad vertical distribution.

Table 4. Distributional data for selected groundwater species found in the Pilbara and adjacent areas

	This study	Pilbara bores[1]	Mandora springs[2]	Distribution[3]
Oligochaeta				
Phreodilidae spp.[4]	1	1		Several species in springs and bores
Ostracoda				
Vestenula marmonier	1		1	Oceania
Vestenula n. sp.	1	1		Pilbara
Candonopsis tenuis	1	1	1	Australia
Limnocythere dorsosicula	1		1	Australia
Copepoda				
Microcyclops varicans	1	1		Australia
Metacyclops mortoni		1	1	North-west Australia
Halicyclops spinifer		1	1	Oceania
Mesocyclops brooksi	1	1	1	Australia
Ectocyclops rubescens	1		1	Australia
Amhipoda				
Pilbarus millsi	1	1		Fortescue and Ashburton Rivers
Isopoda				
Pilbarophreatoicus n. sp.	1	1		Lower Fortescue River
Tainisopus sp.[5]	1	1		Several species in Pilbara bores

[1] collecting by W.F Humphreys in Pilbara and Ashburton catchment; [2] collecting by A.W Storey et al.; [3] based on mostly literature cited in text; [4] species from bores immature and cannot be identified; [5] probably a species collected from bores

Composition of the hyporheic groundwater fauna

The sampling methods used in this study collected epigean species at least as effectively as hyporheic ones. In fact, some planktonic species may also have been collected as the water column was swept. Therefore, we can only speculate about the composition of the hyporheic fauna, based on observations made while collecting, known habitat preferences, and morphological traits of some species.

Boulton (2001) analysed hyporheic assemblages from around the world, using the Gibert et al.'s (1994a) classification, and suggested most species were there by accident (stygoxenes) or occasional users of the hyporheic zone (a category of stygophile), although in a few situations species spending all their life-cycle in the hyporheos formed the largest portion of the assemblage (other stygophiles and stygobites). Such analyses are obviously affected by sampling methods, available information on life history and the way the classification categories are interpreted. We tentatively assigned the fauna of the Pilbara springs to the categories used by Boulton and found 56 % of species were either stygoxenes or likely to be in surface water when collected, 30 % were occasional hyporheos stygophiles, 8 % amphibite or permanent hyporheos stygophiles, and 5 % stygobites. This distribution accords with other studies in that < 20 % of species collected in hyporheic habitats were likely to be directly dependent on groundwater for their persistence as a species. Given that the hyporheos is an ecotone between productive, species-rich surface-water systems and nutrient-poor groundwater systems with lower numbers of species per sampling unit, it is not surprising that the hyporheos is dominated by species with some affinity for surface water.

An example of an occasional hyporheos stygophile in the Pilbara is Baetid genus 1 WA sp. 1, which occurred in large numbers in the benthos and hyporheos at Weeli Wolli. We regard it as a surface-water species. It occurs widely in north-western Australia (Suter 1997). The distribution of most of the permanent hyporheos stygophiles in the springs that, so far, are known only from shallow groundwater is wide-ranging (Table 4). The copepod *Ectocyclops rubescens* occurs throughout Australia (Morton 1990) as do the ostracods *Limnocythere dorsosicula* and *Veslenula marmonier* (De Deckker 1981, Martens and Rossetti 2002). Similar results have been obtained in other regions of Western Australia, with collections from the hyporheos of Cockleshell Gully in south-west Western Australia by P.M Davies and Mandora Marsh in the southern Kimberley by A.W. Storey containing the widespread Northern Hemisphere groundwater copepod genera *Parastenocaris* and *Leptocaris*, respectively (S.A. Halse unpubl. data). We predict many of the species will eventually be found to occur in deeper groundwater as well.

Surface-water animals

The number of invertebrate species collected from each spring varied between 44 and 72 (Table 3). While 11 % of the fauna could be classified as groundwater species, the overall number of surface water species at these sites was high in comparison with that recorded at other river sites, particularly considering that only the benthos and hyporheos were sampled intensively. Seven river sites sampled more intensively in the southern Carnarvon Basin, just south of the Pilbara, contained an average of only 38 species each sampling occasion with a maximum richness of 53 (Halse et al. 2000b).

The most geographically complete aquatic invertebrate sampling program in the Pilbara, the National Assessment of River Health (Halse et al. 2002), identified invertebrates only to family level but also found that springs contained significantly richer assemblages than other types of river pools (26.1±2.5 vs 20.4±2.0 families, unpubl. data). Thus, it appears that springs are an important habitat for surface-water species as well as groundwater ones. It is also likely that springs provide an important refuge for many surface-water species during drought and have a significant role in maintaining regional populations of these species (Boulton 1989). In this respect, springs are probably particularly important sites for coleopterans, dipterans, trichopterans, odonates, hemipterans and hydracarines, all of which were abundant in the springs and usually lack a drought-resistant life-stage.

The relationship between stream flow and invertebrate abundance in groundwater habitats is variable but floods that scour the streambed usually result in a reduction in number of interstitial groundwater species (Marmonier et al. 2000). In the Pilbara, with its occasional high intensity floods resulting from monsoonal rainfall, the post-flood reduction in species richness of the surface-water fauna can be even more dramatic (Davies 1996). In this study, the lowest overall species richness at the five springs was recorded at Weeli Wolli (Table 3), where antecedent floods had caused pronounced changes in channel morphology and washed away many mature riparian trees. Richness was also relatively low at Nyeetberry Pool, the other site of substantial antecedent flooding. Valves of several ostracod species not represented in the live fauna were found at both these sites, suggesting a richer ostracod fauna occurs under lower-flow conditions or at other times of the year.

Vertical and horizontal distribution of groundwater animals

It is evident from limited work in the Pilbara, and from the much more extensive work in the Northern Hemisphere (Dole-Olivier et al. 1994), that many species can occupy a considerable range of vertical habitats. The various classification schemes for groundwater (Gibert et al. 1994a) reflect this, although they do not highlight the large variability that can occur within a species at different sites. For example, *Mesocyclops brooksi* can occur only in surface water, in a stream-bed where the same animal is moving between surface water and groundwater (a stygophile) and in deep groundwater where the entire life-cycles of many generations will be underground (a stygobiont). Considerably more sampling is required to define the vertical distribution of invertebrates occurring in Pilbara groundwater. Most of the sampling to date has been in deeper aquifers (Humphreys 1999, 2001) and may have resulted in a biased understanding of distributions.

From the viewpoint of assessing likely impacts of groundwater abstraction and de-watering on the groundwater fauna, vastly better information about the below-ground occurrence of individual groundwater species is required, as well an understanding of the factors controlling vertical and horizontal distributions. Discharge (up-welling) zones usually contain many more species than recharge (down-welling) zones but some species are more likely to be found in recharge areas (Dole-Olivier et al. 1994). Phreatoicid isopods are strongly associated with discharge areas (G.D.F. Wilson pers. comm.) and the failure to collect *Pilbarophreatoicus platyarthricus* from Nyeetberry Pool, despite it being recorded previously by Knott and Halse (1999), was probably the result of being unable to locate an up-welling zone.

To provide a framework for assessing the impacts of de-watering and groundwater abstraction, as well as to stimulate discussion about stygofauna distributions, we hypothesize that the groundwater fauna of the Pilbara consists of four distribution types:

(1) widespread species with body shapes, behaviour and ecological tolerances that enable them to utilise both surface water and groundwater. Many species of cyclopoid copepods provide extreme examples of flexibility with respect of water source and can occur as surface water species, stygophiles and stygobionts, using deep as well as shallow groundwater. Baetid genus 1 WA sp 1 is an example of a species that can occur as a stygophile in shallow groundwater

(2) widespread stygophiles. Such species are restricted to groundwater and associated habitats and have appropriate morphological adaptations. They use deep as well as shallow groundwater and include many

ostracods and the copepod *Ectocyclops rubescens*. The amphipod *Pilbarus millsi* is an example that is probably widespread only at the river basin or regional scale

(3) locally restricted stygophiles. The isopods *Pilbarophreatoicus* spp. appear to belong to this group, having been recorded only within small parts of river basins (all sites < 50 km apart)

(4) locally restricted stygobionts. These species are found only in groundwater, usually at depth. None was collected during the study but Humphreys (1999, 2001) lists likely examples, including the amphipods *Nedsia* and *Chydaekata*.

The above classification applies the terms stygophile and stygobiont to the species as a whole and individual animals may have a more restricted vertical distribution than the classification implies (see earlier comments about Gibert et al's classification). Determining the proportion of the Pilbara groundwater fauna in each group will require extensive survey and the collection of autecological information (see Claret et al. 1999) but we hope it will focus debate about the conservation status of particular species and sites by facilitating predictions of the risk posed by de-watering, groundwater abstraction and other perturbations.

Endemism

One cannot assume that, because a species is collected from groundwater, it is likely to have a restricted distribution. Groundwater is used by species that are widespread in surface water (eg *Mesocyclops brooksi*, *Microcyclops varicans*) and interstitial habitats (eg *Vestalenula marmonier*, *Halicyclops spinifer*). In many cases small-scale patchiness in the distribution of groundwater species, combined with low animal abundance in this low-energy environment, will result in species appearing to be more restricted than they are. Rouch and Danielopol (1997) found that > 140 samples were required to document the full range of cyclopoid copepod species using a single stream over time. Even allowing for temporal turnover, it suggests the sampling effort required to document instantaneous species richness of the groundwater fauna is much greater than contemplated in almost any study.

Humphreys (1999, 2001) has shown, however, that there is considerable endemism in the Pilbara groundwater fauna. The increasing importance of international conventions for the protection of habitat and biodiversity (eg Ramsar and Bonn), and Commonwealth and State programs to conserve threatened species and communities, means that this endemism has implications for the planning of nature conservation and resource development. The Environment Protection Authority has already focussed on the protection of stygofauna communities in assessment of proposed mine sites (e.g. EPA 1998). While the ecosystem-service functions of much of the biota remain poorly documented, environmental assessment and protection will remain based on centred on concepts such as endemism and species protection.

Global lack of information about stygofauna makes it difficult to rank the Pilbara in a world list of important areas for stygofaunal biodiversity, in the way that has been done for vascular plants and vertebrates (e.g. Myers et al. 2000). Within the Australian context, there is considerable stygofaunal biodiversity in south-eastern Australia that is poorly recognised (Thurgate et al. 2000a,b). Taxonomic studies on both sides of Australia are still in their infancy and it is difficult to compare the characteristics of the two faunas but, if the groundwater fauna of the Pilbara proves to have higher levels of endemism (which is the current expectation), it will fit with the pattern exhibited by surface-water crustaceans with drought-resistant life stages. For this group, the western half of the continent has greater endemism than the east (Frey 1998; Geddes 1981; Halse 2002; Halse and McRae 2001). Just as relict species are present in groundwater of the Pilbara, species with Gondwanan links are present in surface water of the arid zone (Halse et al. 2000b).

Management issues

This study reports results from preliminary work on springs and conclusions are somewhat tentative. However, we suggest that the nature of previous sampling in the Pilbara, which largely had the aims of demonstrating the uniqueness of the region's stygofauna and its evolutionary ancestry, has overstated the importance of deep (up to 40 m below water-table) groundwater. In many cases, drilling logs were not available for bores (W.F. Humphries pers. comm.) and depth at which bores were slotted was unknown, making it impossible to determine the depth at which animals entered the bore and the depth of the bore itself had to be used as a *de facto* estimate. Northern Hemisphere studies and our results from springs suggest many species will be found at shallower depths and that very localised endemism (<< 1 km) may be the exception rather than the rule. This increases the likelihood that groundwater abstraction and de-watering can be undertaken in ways that will not greatly threaten stygofaunal biodiversity although, by analogy with surface-water invertebrate distributions, hotspots of endemism are likely to occur.

The study provided further evidence that springs are biologically rich sites for aquatic invertebrates, containing a range of groundwater and surface-water species, as well supporting many plant species and being a focal point for terrestrial animals. Their conservation is important and may depend as much on appropriate groundwater management as on management of the terrestrial and surface-water environment. Without further research, it is difficult to identify management parameters for groundwater, however, other than avoiding eutrophication and contamination and ensuring that groundwater levels, and the volumes of groundwater reaching the springs, remain within natural boundaries. Maintenance of up-welling zones is likely to require more than regional studies of groundwater movement, however.

For many Pilbara springs, the effect of floods after monsoonal rains provides a dominant visual impact. Floods probably have the capacity to scour contaminated springs and re-set them biologically (Smith et al. 1999), although they can also result in large-scale loss of riparian vegetation and erosion, with subsequent siltation of the stream-bed. The detrimental effects of flooding are probably greatest when springs and surrounding land are over-grazed and many springs would benefit from stock and feral animals being fenced out. To reduce the likelihood of siltation after stream-flow, it is probably important to fence off creek-lines well up-stream of the site of the spring. Watering points for stock could be provided outside the fence. In addition to removing vegetation, cattle cause pugging and increase turbidity.

The above comments are largely based on first principles because of the current lack of detailed information about the ecology of springs in the Pilbara and their biota. The aquisition of more information should itself be a management priority.

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Appendix 1. Species of invertebrate collected at each spring in the Pilbara. Groundwater species are marked with an asterisk

	Palm A	Warrie	Weeli Wolli	Palm M	Nyeetberry
NEMATOMORPHA					
Gordioidea					
Gordiidae		1			
MOLLUSCA					
Gastropoda					
Melanoides (Stenomelania) sp. 1	1				
Austropeplea lessoni	1	1		1	
Gyraulus sp.		1			1
Annelida					
Hirudinea					
Glossiphoniidae			1		
Oligochaeta					
Phreodrilus sp. WA12 *					1
Phreodrilidae sp. *			1		
Phreodrilus sp. WA7 *		1		1	
Allonais ranuana		1			
Allonais paraguayensis	1				
Pristina sp.			1		
ARTHROPODA					
Acarina					
Limnochares australica			1	1	
Hydroma sp.			1		
Oxus orientalis					1
Frontipoda nr *tasmanica*					1
Unionicola longiseta					1
Unionicola crassipalpis					1
Koenikea n. sp. (nr timmsi)	1				1
Recifella sp.		1			1
Gretacarus bifalcisetus	1				1
Limnesia sp. *	1		1		
Australiobates sp.	1		1		1
Australiobates n. sp. (nr mutates)				1	
Coaustraliobates longipalpis					1
Aspidiobates pilbara					1
Axonopsella sp.				1	
Diplodontus sp.		1			
Trombidioidea		1	1		
Oribatida	1				
Cladocera					
Alona macrocopa					1
Alona nr *poppei*		1			
Alona sp.					1
Simocephalus heilongjiangensis	1				
Ostracoda					
Vestenula marmonier *	1				1
Vestenula n. sp. *		1	1		
Canonopsis tenuis *	1	1			
?*Candona* sp. 782 *				1	
Limnocythere dorsosicula *	1			1	
Cypridospidae sp. 757 *					1
Ilyodromus sp. 805	1			1	
Cypretta sp. 759				1	1
Cyrpricercus sp. 442		1			
Cyprinotus sp. 804	1				
Ostarcod Sp 781				1	
?*Heterocypris* sp. 758					1
Ostracod Sp 788		1			
Ostracod Sp 807					1
Copepoda					
Microcyclops varicans *	1	1	1	1	
Ectocyclops rubrescens *	1	1	1	1	
Mesocyclops darwini	1	1			
Eucyclops nr *australiensis*	1	1			1
Paracyclops sp. 6	1				
Paracyclops sp. 7		1		1	1
Paracyclops nr *chiltoni* *	1			1	
Diacyclops sp. *			1		
Cyclopoida			1		
Nitocra sp.				1	
Bathynellacea					

	Palm A	Warrie	Weeli Wolli	Palm M	Nyeetberry
?*Atopobathynella* sp. *	1				
Isopoda					
Tainisopus sp. *					1
Pilbarophreatoicus n. sp. *				1	
Amphipoda					
Pilbarus millsi *			1		
Decapoda					
Caridina indistincta				1	
Coleoptera					
Laccophilus sharpi					1
Hyphydrus elegans	1				
Hydroglyphus orthogrammus	1	1	1		
Hydroglyphus leai	1	1	1		
Liodessus sp.	1				
Hypodes sp.	1			1	1
Sternopriscus sp.	1				
Necterosoma regulare		1	1		
Necterosoma sp.		1			
Platynectes decempunctatus	1	1			1
Platynectes sp.	1	1			
Copelatus irregularis	1	1			
Hydaticus sp.	1				
Austrodytes insularis				1	
Cybister tripunctatus					1
Gyrinidae				1	
Hydrochus sp.	1	1	1	1	1
Berosus dallasae					1
Berosus pulchellus	1	1			
Berosus sp.	1				
Regimbartia attenuata	1				
Enochrus elongatus		1			
Enochrus deserticola	1				
Helochares tatei	1	1	1	1	
Paracymus spenceri		1			
Coelosoma fabricii		1		1	
Scirtidae sp. 1	1	1	1		1
Scirtidae sp. 2	1	1			
Elmidae sp. 1					1
Elmidae sp. 2					1
Hydrochus lateviridus			1	1	1
Diptera					
Tipulidae	1	1	1	1	1
Anopheles annulipes	1	1			1
Culex (Culex) annulirostris		1			
Culex (Culex) bitaeniorhynchus		1			
Bezzia sp. 2	1		1	1	1
Bezzia sp. 1		1	1		
Clinohelea sp.	1		1	1	
Nilobezzia sp.		1		1	
Simulium ornatipes	1			1	1
Simuliidae			1		
Tabanidae	1	1			
Stratiomyidae	1	1		1	1
Ephydridae	1	1			
Procladius paludicola	1	1	1	1	1
Larsia ?*albiceps*		1	1	1	1
Thienemanniella sp.				1	
Cricotopus brevicornis				1	
Orthocladiinae S03 sp.					1
Chironomus aff. *alternans* (V24)		1			
Dicrotendipes conjunctus				1	1
Dicrotendipes flexus				1	
Polypedilum watsoni	1	1	1	1	1
Cryptochironomus griseidorsum	1		1	1	1
Cladopelma curtivalva				1	
Harnischia K1				1	
Ephemeroptera					
Cloeon sp.	1	1			
Baetid genus 1 WA sp. 1 sensu Suter	1		1	1	1
Thraulus sp.				1	
Tasmanocoenis arcuata	1	1	1	1	1
Hemiptera					
Hebrus nourlangiei	1				
Microvelia oceanica	1	1			

	Palm A	Warrie	Weeli Wolli	Palm M	Nyeetberry
Microvelia peramoena			1	1	
Rhagadotarsus anomalus					1
Limnogonus fossarum gilguy	1			1	1
Laccotrephes tristis	1				
Ranatra sp.	1				
Diplonychus eques		1			
Ochterus sp.	1	1			
Nerthra luteovaria			1		
Micronecta annae annae		1			
Micronecta sp.		1			1
Anisops hackeri		1			
Pleidae		1			1
Lepidoptera					
Pyralidae	1	1	1	1	1
Odonata					
Agriocnemis kunjina	1			1	1
Ischnura aurora aurora	1				
Pseudagrion microcephalum	1				
Coenagrionidae					1
Eurysticta coolawanyah	1	1		1	
Hemianax papuensis		1			
Austrogomphus gordoni	1	1	1	1	1
Austrogomphus mjobergi				1	
Diplacodes haematodes	1	1	1		
Diplacodes sp.					1
Nannophlebia injibandi				1	
Orthetrum caledonicum	1	1	1		
Libellulidae				1	
Trichoptera					
Hellyethira litua	1		1	1	1
Hellyethira sp.			1		
Chimarra sp AV18	1	1	1	1	1
Cheumatopsyche wellsae	1		1		1
Cheumatopsyche sp. AV11				1	
Paranyctiophylax sp AV5				1	1
Ecnomus pilbarensis	1	1			1
Ecnomus sp.			1	1	
Oecetis sp.		1			1
Triplectides australis		1			
Triplectides parvus		1			1
Triplectides ciuskus seductus	1		1	1	1