GROUNDWATER ECOSYSTEMS IN AUSTRALIA: AN EMERGING UNDERSTANDING

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Abstract: Metazoan communities, comprising obligate subterranean animals, occur in aquifers to a depth of at least one kilometre. Groundwater invertebrates are best known from cave studies but diverse groundwater ecosystems occur in anchialine systems, limestone caves, phreatic calcretes, fractured rock aquifers and coarse alluvial systems, as well as the ecotonal groundwater/surface water interface. Recently, a diversity of aquifer ecosystems has also been recorded in Australia. Groundwater ecosystems comprise an important component of biodiversity and they often support relictual taxa of high taxonomic order, and may be widely vicariant. Aquifer ecosystems are poorly understood but, by analogy with better known surface ecosystems, they are likely to provide a wide range of environmental services, both within aquifers and downstream. The development of awareness of groundwater ecosystems is outlined, both globally and in Australia.

I consider three major components that are essential to the functioning of groundwater ecosystems, each of which can be affected by the activities of hydrogeologists, and each of which, in turn, may have implications for hydrogeology. These are a place to live, oxygen and food (energy). This is followed by consideration of the pertinent heterogeneity in groundwater and some examples from Australia.

Two issues are bought to special attention. 1, Sharp gradients in physical and chemical conditions may occur through the water column, particularly in arid areas. Hence, the routine purging of boreholes before sampling for hydrochemical investigations extirpates information about the physicochemical structure of the water column, this most useful information pertaining to the groundwater fauna. Hence, physicochemical profiling of undisturbed groundwater may be required to understand groundwater ecology. 2, Water mining from deep palaeochannel sand aquifers, with a residence time in the order of 10^3-10^5 years, is becoming a widespread practice in arid Australia. The deep aquifers are coupled with the overlying phreatic calcrete in a manner not understood, and the latter are a source of water for pastoral, human and industrial consumption and support rich and diverse groundwater ecosystems. Hence, hydrogeological research and modelling is needed of the separate aquifer dynamics and their coupling to assess and to manage any impact that may occur. The maintenance of environmental flows to aquifer ecosystems in the face of sustainable water abstraction, water mining and dewatering presents a challenge to hydrogeologists.

Key Words: arid regions, karst, quality, ecosystem, stygofauna, Australia.

INTRODUCTION

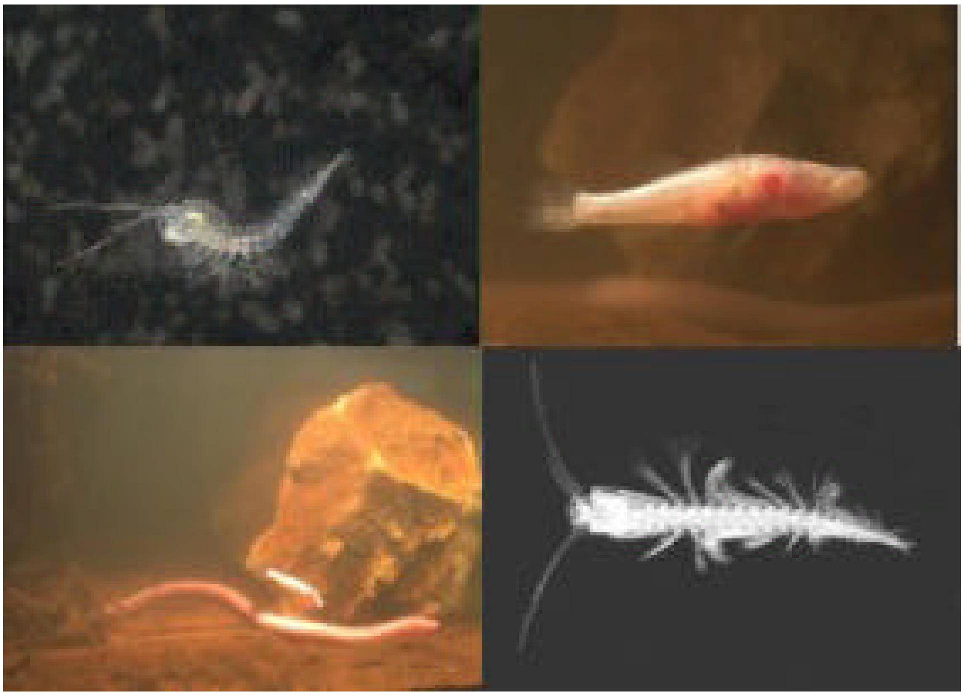
Balancing the groundwater budget serves, at the very least, to utilise the groundwater resource in a sustainable way to maintain the biodiversity and thereby ecosystem function to protect water quality. Enlightened groundwater mangers are concerned with the impact of environmental flows on surface ecosystems, such as phreatophytic vegetation, rivers and lakes. The implications of environmental flows to groundwater ecosystems have rarely been addressed, partly as those concerned with both aquifers and surface waters are largely unaware of the ecological complexity, biodiversity and local endemism that are contained in groundwater ecosystems, nor that these may be expected to provide significant environmental services. What does environmental flow mean in this context and how can it be addressed? What impact does water abstraction have in the context of, for example, water mining. or the sustainable drawing of water from an aquifer?

It still comes as a surprise to many hydrogeologists that aquifers are ecosystems, often in close continuity with surface waters. Hydrogeological decisions may both directly and indirectly affect these ecosystems and the ecosystems themselves may have hydrogeological impacts. This paper provides a brief background to this subject to provide a context to this session devoted to work occurring on groundwater fauna, largely in Australia.

Life forms may occur several kilometres below the Earth's surface and this subterranean world is the largest terrestrial biome (Gold 1992). A specialised invertebrate fauna, occasionally vertebrates, occurs in these subterranean ecosystems, the health of which is paramount as 97% of global liquid freshwater occurs as groundwater (Gibert et al. 1994). My references to groundwater ecosystems incorporates this wider view of subterranean ecosystems, rather than the microbial, occasionally protozoan, assemblages usually referred to in the context of, for example, groundwater remediation work, while acknowledging that in some aquifer ecosystems only microbial elements will occur (Malard and Hervant 1999). While the point is increasingly made that groundwater and surface water are a single interconnected resource (Winter et al. 1998), that this also comprises connected ecological systems (Boulton 2001) is less well understood and far from universally known (Boulton et al. submitted) even amongst environmental professionals.

What are stygofauna?

Stygofauna are animals inhabiting groundwater and, except in karst areas, they are invertebrates. They have various lifestyles and many animals occur in groundwater either accidentally (termed stygoxenes) or with varying degrees of affinity for groundwater, inhabiting it on a permanent or a temporary basis (termed stygophiles), but only stygobites are obligate inhabitants of groundwater; animals in these several ecological types collectively comprise the stygofauna (Gibert et al. 1994: 12). Stygobites comprise elements of the ultimate groundwater dependent ecosystem and they are overwhelmingly crustaceans, but the macrofauna include representatives of the Oligochaeta, Nematoda, Mollusca, Acarina, Insecta, Pisces and Caudata.



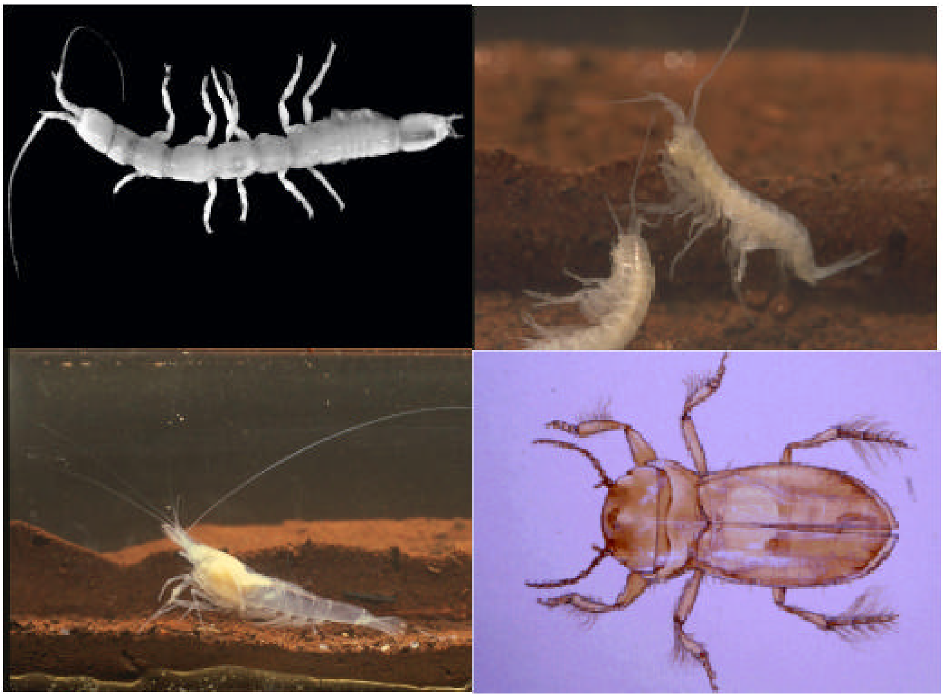
Stygobites have a convergent morphology (Figures 1 and 2) exhibiting a reduction or loss of eyes, pigments and hardened body parts (they are commonly translucent), and they have enhanced non-optic sense organs (Culver *et al.* 1995). Stygofauna generally have no resting or dispersal stages, are slow-growing, long-lived and have few young. These attributes make them very efficient bioaccumulators (Plénet *et. al.* 1992), slow to recover from reductions in their populations and difficult to study. Owing to these biological characteristics, the species inhabiting groundwater ecosystems are often locally endemic, that is, they are restricted to a small geographic area.

Biodiversity

In recent years stygofauna, and groundwater (or aquifer) ecosystems have become the focus of much attention both on account of the biodiversity they contain and their functional properties (Botosaneanu, 1986; Gibert *et al*., 1994; Juberthie and Decu, 1994, 1998; Culver *et al*., 1995; Wilkens *et al.,* 2000). Globally, subterranean fauna comprises a significant component of biodiversity (Rouch and Danielopol 1997; Sket 1999). Certain areas in both Australia (Humphreys, 2001; Boulton et al submitted) and globally (Rouch and Danielopol 1997; Culver and Sket 1999; Danielopol et al. 2000; Danielopol and Pospisal 2001) are known to contain particularly diverse stygofaunas, and these have been referred to as biodiversity "hot-spots". Groundwaters comprise complex ecosystems interacting with surface systems in a manner pertinent to both groundwater and surface water quality, but in ways as yet poorly understood (Gibert *et al*. 1994; Boulton 2000). As such, the groundwater fauna

(Figure 2) may maintain ecosystem function to protect groundwater quality; this is the rationale behind the global effort to conserve biodiversity.

Over the last decade it has become increasing recognised that groundwater ecosystems are not semi-deserts, occupied by rare, effete lineages, but are dynamic systems comparable in complexity to surface ecosystems (Rouch 1977, Gibert *et al.* 1994). Notwithstanding, aquifers are living museums containing faunas that have been sampled from various geological periods. While a pattern of repeated colonisation—even recolonisation of surface habitats—is an active process (Culver *et al.* 1995), some stygal lineages have apparently been isolated underground in the Miocene by the onset of aridity (Humphreys, 1993; Cooper et al. submitted), or by orogenic and eustatic events (Stock 1980; Boutin and Coineau 1990; Notenboom 1991). Others have become separated from their relatives by the movement of continental plates, before or after their isolation underground (Schminke 1974; Poore and Humphreys 1992, 1998; Wilson and Keable 1999; Humphreys 2000), and have Gondwanan or even Pangaean affinities, or clearly mirror the Greater Tethys (Boxshall and Jaume 2000; Humphreys 2000; Jaume and Humphreys 2001; Jaume et al. 2001). Hence, hypogean ecosystems, especially groundwater ecosystems, may be very persistent through geological time (review Humphreys 2000).



In the 19th century Australasia was at the forefront of research on aquifer organisms (Hurley 1990.) but since then has lagged in the international league. Australia is not alone and "[o]nly very recently has the existence of groundwater animals ..... on this continent [North America] been recognised to represent a largely unappreciated reservoir of biodiversity" (Ward et al. 1992). Within the last decade, major conferences and reports failed to encompass groundwater ecosystems or their fauna (Australian Water Resources Council. 1992; Australian Geological Survey Organisation 1993). Thus, as recently as 1994, it was possible to write "Recognition ... of the biodiversity inherent in the fauna ... of groundwaters, their vulnerability to groundwater contamination, their functional role and their potential utility to hydrogeological investigations remains, in practice, unrecognized in Australia" (Humphreys, 1994). Even as late as 1998 a lack of appreciation of the diversity and extent of aquifer ecosystems (Hatton and Evans 1998) led to the severe underestimation of the extent and significance of groundwater dependent ecosystems in Australia, a dismissal now firmly rejected (T. Hatton and R. Evans, in lit. 1999). Only recently has subterranean fauna been included as a requirement for some environmental impact assessment (Western Australia— Hamilton-Smith et al. 1996; EPA 1998; Tasmania—Eberhard 1995, 1999; Tasmanian WHA 1999). The application of fauna protection legislation to a number of stygal species and communities (Western Australia: CALM 2001: Commonwealth, EPBC Act, 1999), has raised considerably awareness of stygofauna to a broader public (Playford 2001).

The last decade saw the first international conference of groundwater ecology (Stanford and Simons 1992) and a major textbook on the subject (Gibert et al. 1994). Internationally, groundwater ecosystems, especially those in karst, have gained recognition by the Council of Europe (Council of Europe 1992; Juberthie 1995; PASCALIS Project under the *Fifth Framework*

Programme, European Commission) and the World Bank (Vermeulen and Whitten 1999), and under the Ramsar Convention—*Convention on Wetlands of International Importance especially as Waterfowl Habitat, Ramsar, Iran, 1971*—(Brisbane, 1996; Humphreys 2000b). While, in Australasia:

> "Groundwater should be managed ... when it comes to the surface ... [such that] it will not ... compromise ... [its] designated environmental values. *An important exception is for the protection of underground aquatic ecosystems and their novel fauna. ... given their high conservation value, the groundwater upon which they depend should be given the highest level of protection*" [emphasis added] (ANZECC and ARMCANZ, 2000).

By analogy with surface ecosystems, invertebrates have numerous potential functional roles in groundwater systems, but as yet experimental evidence is largely lacking. These include the maintenance of voids — suggested also for protozoa (Haack and Bekins 2000) — the alteration of redox gradients, enhancing the release of organic carbon and the cycling of nutrients (which often limit bioremediation processes: Haack and Bekins 2000), promotion of biofilm activity (*inter alia* through grazing, nutrient cycling and improved hydraulic flow paths), the provision of favourable sites for microbial activity (see also Gebruk *et al.* 1997 below), the acceleration of cycling, movement and mass transfer of energy and materials through the sediments, alteration of population size and community structure through predation ("top-down" effects) and as prey ("bottom-up" effects). These issues are discussed and referenced more fully by Boulton (2000: Table II). While it is recognised that consortia of microorganisms can work, by mechanisms yet to be identified, to breakdown contaminant plumes (Haack and Bekins 2000), it has yet to be recognized that stygofauna may be expected similarly to interact with biofilms, and other expressions of microbial diversity, so as to promote or to restrict their activity and the community diversity in groundwaters (Humphreys 2000a).

Table 1: The distribution of some widely disjunct higher taxa new to the southern hemisphere that have been found recently to inhabit groundwaters of northwest Australia.

Taxon	New to southern hemisphere	Distribution[1]
Halosbaena (Thermosbaenacea)[2]	Order	Genus: Caribbean, Canaries
Haptolana (Isopoda: Cirolanidae) [3]	Genus	Genus: Cuba, Somalia
Lasionectes (Remipedia)[4]	Class	Class: Caribbean, Canaries Genus: Turks and Caicos
Danielopolina (Ostracoda: Thaumatocypridae)[5]	Family	Genus: Galapagos, Caribbean, Canaries
Bunderia (Calanoida: Epacteriscidae)[6]	Family	Genus: closest Bermuda
Stygocyclopia (Calanoida: Pseudocyclopiidae)[7]	Family	Genus: Balearics, Canaries, Phillipines
Speleophria (Misophrioida)[7]	Order	Genus: Galapagos, Bermuda, Canaries, Balearics, Palau.
Spelaeogriphacea	Order	Order: Table Mtn., S. Africa; Mato Grosso, Brazil
Tiramideopsis (Acari) [9]	Genus	Genus: India

[1]Canaries refers only to Lanzarote; [2]Poore and Humphreys, 1992; [3]Bruce and Humphreys, 1993; [4]Yager and Humphreys, 1996; [5]Danielopol et al., 2000; [6]Jaume and Humphreys, 2001; [7]Jaume et al., 2001. [8]Poore and Humphreys, 1998; [9]Harvey, 1998.

As this conference is in Australia, it is appropriate, at this point, to provide some pointers to studies of groundwater biology in this arid continent. Surprisingly, it is the arid zone that is yielding some of the most interesting groundwater faunas (Humphreys 2001; Watts and Humphreys 1999, 2000, in press; Taiti and Humphreys 2001; Cooper et al. submitted). However, as elsewhere, great diversity is found in classical karst (Thurgate et al. 2001a, 2001b), anchialine (Humphreys 1999a; 2000b, 2000c; Jaume and Humphreys 2001; Jaume et al. 2001) and alluvial settings (Boulton et al. 1998) yielding stygofauna of unexpected diversity and affinity (Table 1). Boulton et al. (submitted) advocated protection aimed at the habitat or ecosystem scale and identified three common themes in particular reference to Australian subsurface biodiversity:— 1, an ignorance of the invertebrate biodiversity of the various groundwater environments; 2, a high degree of small scale endemism in the Australian stygobites known to date, and 3, the intimate link between surface and subsurface aquatic ecosystems, the latter two themes being common world-wide (e.g., Danielopol et al. 1997, 2000; Marmonier et al., 1997, Sket, 1999a, and reviews in Gibert et al., 1994; Winter et al., 1998).

Aquifer attributes for stygofauna

I want to consider three major components that are essential to the functioning of the groundwater ecosystem *sensu lato*, each of which can be affected by the activities of hydrogeologists, and each of which in turn may have implications for hydrogeology. These are a place to live, oxygen and food (energy). This is followed by consideration of pertinent heterogeneity in groundwater and some examples from Australia.

1, A place to live

Subterranean waters may conveniently be separated into groundwater and the hyporheic waters that occur below river channels (Jones and Mulholland 2000) and which form a broad ecotone between surface water and groundwater. Animals are mostly restricted to the upper parts of subterranean ecosystems, nonetheless, diverse stygofaunas, even including vertebrates (Longley 1992), may be found at depths of up to one kilometre (Essafi *et al*. 1998) in karst systems. Groundwater animals inhabit megavoids, such as large caves, but they are particularly evident in the mesocaverns in karst and basalts, and they also occur widely in alluvial aquifers where the size of the interstices may limit the distribution of many species (Pospisil 1994). In general, it appears that the greater the distance of the groundwater habitat from epigean influence the greater is the affinity of the fauna to the groundwater. This "distance" occurs in four dimensions, as vertical depth in groundwater, distance from the bank in parafluvial aquifers, and distance or time along groundwater hyporheic flowpaths (Dole-Olivier et al. 1994: fig. 9). Recently, the widespread occurrence of locally endemic stygal communities has been described from unconfined groundwater calcrete aquifers in the palaeodrainage channels of the Australian arid zone (Humphreys 1999b, 2001; Watts and Humphreys 1999, 2000, in press; Cooper et al. submitted).

Adverse effects on a place to live

Some anthropogenic effects are overtly detrimental to stygofauna, for example removal of the matrix itself (mineral mining), or widespread removal of the groundwater (water mining or dewatering operations during civil engineering or mining projects). The effect of these activities on biodiversity will depend on whether species are restricted to the area of impact (small-scale endemicity: Boulton et al. submitted; Cooper et al. submitted), and the magnitude of the dewatering operations. These activities have recently received some attention in Western Australia (Playford, 2001) and resolution of such issues is dependent on access to a comprehensive information on the nature and composition of the stygofauna.

Other human activities may be less overt in their effects on subterranean ecosystems. In both hyporheic systems and cave streams it seems that the mobilisation of fine sediments, for example by dredging, quarrying or removal of vegetation, can clog sediment spaces (‘internal colmation’, Brunke and Gonser, 1997) and smother surfaces. Such effects may also be expected to impact similarly on aquifer ecosystems. The resulting disruption of hydrological exchange reduces dissolved oxygen concentration (DO) and may lead to the extirpation of stygal populations (Boulton 2000a; Boulton et al. in press). Debate as to whether the macrofauna can maintain void space, and thus the hydrological functioning within aquifers, by their movements through sediments is unresolved and may be site dependent (Danielopol et al. 2000).

Groundwater abstraction has numerous effects on the groundwater ecosystem. Overtly, the water table may be lowered regionally or locally (Longley 1992). The groundwater surface may be dimpled both spatially and temporally by drawdown cones of adjacent wells. Concomitantly any interface with underlying sea water will be similarly dimpled in mirror image to that of the groundwater surface but magnified about forty fold owing to the Ghyben-Herzberg principle (Ford and Williams 1989).

The mixing between meteoric water and seawater produces brackish to saline water in many coastal aquifers, the extent of which is a function of transmissivity of the aquifer at various depths and the rate of groundwater flow. The mixing zone may vary from a few metres in sand dunes (McLachlan et al. 1992), to many kilometres in karst (Iliffe 2000). In an important paper, Moore (1999) termed these *groundwater estuaries* and considered the analogy between subterranean and surface estuaries from a hydrogeochemical perspective. However, he does not draw the comparison at the microbiological and faunistic level that is needed to integrate anchialine ecosystems into this analogy (Humphreys 1999a, in press). Seawater intrusion through these subterranean estuaries as a result of water abstraction in near coastal areas may have profound chemical consequences resulting in long term loss damage to the aquifer. These subterranean estuaries are the very focus of the anchialine ecosystems, which occupy certain types of groundwater estuaries (karstic and volcanic coasts), and which contain unique assemblages of taxa restricted to anchialine systems and which have widely vicariant distributions (Sket 1996; Humphreys 1999a, 2000c; Iliffe 2000). Many of the principles, processes and findings from groundwater estuaries may be applicable to inland salinity stratified groundwaters of the type common, for example, in the palaeodrainage channels of the Yilgarn Craton, Western Australia (Watts and Humphreys 2000; Humphreys 2001).

Covertly, pumping induces low flow velocity in the groundwater, without which hypogean fauna may be sparse (Gibert et al. 1995). However, prolonged pumping completely modifies the groundwater habitats and the faunal assemblages around the pumping well (Dole and Chessel 1986). By reducing the downstream flow volume, water abstraction will reduce the flux of oxygen and of dissolved organic carbon (DOC) at downstream stations in the aquifer, alter the redox gradients and change the vertical and lateral gradients in the flux of DO and DOC (Figure 3).

A further indirect impact may result from leakage between aquifers. In the Australian arid zone water mining is rapidly expanding from deep sand aquifers in palaeochannels, which may have a residence time in the order of 10^5 years (Johnson et al. 1999)**.** The deep sand aquifers are coupled, *inter alia*, with the overlying phreatic calcrete aquifers in a manner not understood (S. Johnson, Water and Rivers Commission, pers. comm., 3 May, 2000; R. Martin, Anaconda Nickel Ltd., pers. comm. 21 August 2000). The calcrete aquifers are habitat for numerous stygal systems containing many short-range endemic species (Humphreys 1999b, 2001; Watts & Humphreys 1998, 1999, in press; Cooper et al. submitted; Taiti and Humphreys 2001), and are a source of water for pastoral, human and industrial consumption. Hence, knowledge of the separate aquifer dynamics and the nature and dynamics of the coupling between them is required to assess both the likelihood of impact of the mining on stygofauna and its subsequent management. The maintenance of environmental flows to aquifer ecosystems in the face of water mining and dewatering operations presents a major research challenge.

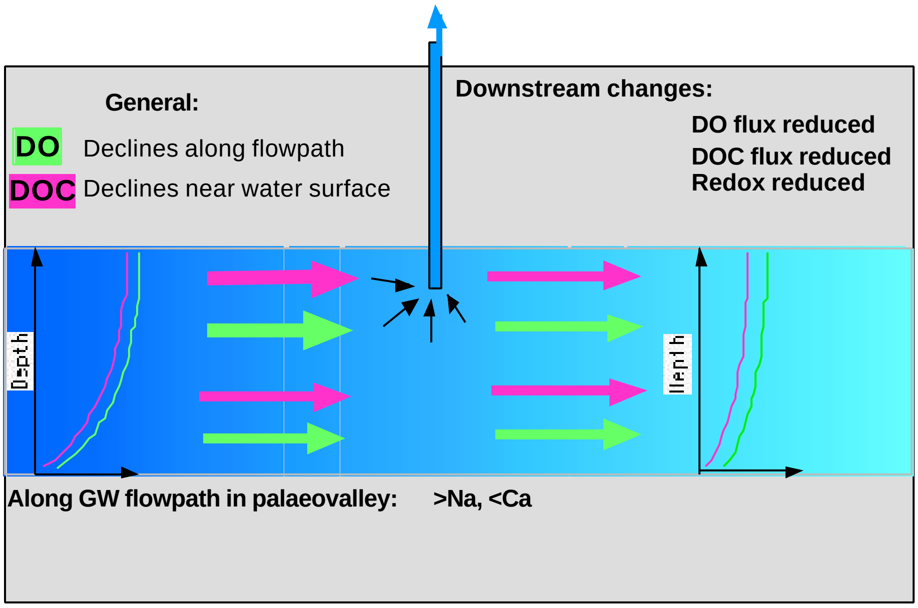
2, Food or energy sources

Except in special cases, bacteria are dependent on the fluxes in organic carbon and on the availability of labile organic compounds (see Danovaro et al. 2001). Hence, as groundwater ecosystems are perpetually dark, except in the special case of chemoautotrophic energy fixation, they are dependent for their energy on imported organic matter (Fisher and Likens 1973). Whatever the energy source, microorganisms (mostly bacteria and fungi) capture the energy (utilizing either heterotrophic or chemotrophic pathways) and the resulting biofilms are grazed by the stygal animals, thus supporting the groundwater ecosystem, *sensu lato*. Energy is largely derived from the downward movement of photosynthetically derived particulate or dissolved organic carbon (DOC) reaching the water table through the overlying matrix, or transported laterally within the groundwater flow. The DOC in groundwater is generally low (median 0.7 mg L^{-1} DOC in 100 samples from 27 USA States, Leenheer et al 1974 cited in Malard and Hervant 1999) and is often limiting to microbial activity—they appear to suffer nutritional stress (Anderson and Lovley 1997)—and ecosystem metabolism, as, for example, under base flow conditions in New Mexico, USA (Baker et al. 2000). Generally much lower levels of energy are contained in sedimentary organic carbon (SOC).

Recent work has shown that a variety of stygal ecosystems may also be dependent on energy derived *in situ* along chemoautotrophic pathways, being fixed, for example, by methanogens and sulphur bacteria. In the artesian Edwards Aquifer, Texas (Longley 1992), and in Movile Cave in Romania (Sarbu 2000), sulphides, respectively of petroleum and magmatic origin, support chemoautotrophic ecosystems (Poulson and Lavoie 2000). These ecosystems are analogous with those associated with deep sea cold seeps and hydrothermal vents respectively (Gebruk *et al*. 1997). Chemoautotrophy has also been implicated in anchialine systems of Mexico and Australia (Humphreys 1999b, Pohlman *et al*. 2000) and in Frasassi Cave, Italy (Sarbu *et al*. 2000). With these few exceptions, so far, subsurface rates of chemoautotrophic primary production are low compared to surface environments (Chapelle and Lovley 1990; Jones et al. 1995).

3, Dissolved oxygen

Dissolved oxygen (DO) in groundwater is one of the prime ecological factors governing the occurrence and spatio-temporal distribution of hypogean animals (Malard and Hervant 1999). DO concentration in groundwater depends on the rate of oxygen transport from the atmosphere and the rate of oxygen consumption within the groundwater. DO concentration generally decreases with depth in the groundwater—it tends to be rapidly consumed in the upper layers owing to incomplete degradation of soil-generated labile DOC in vadose zone (Ronen et al. 1987a). DO is gradually consumed along the groundwater flowpaths, often dependent on sedimentary organic carbon, but the resulting DO gradient may vary by several orders of magnitude (Malard and Hervant 1999) and in confined aquifers may be consumed over 10^1 to ^{4} years (Figure 3). Spatially heterogeneity, exhibited at the macro (km), meso (m) and micro (cm: Ronen et al. 1987a) scales, is a reflection of both the aquifer structure and composition, the groundwater flow velocity, organic matter content, and the abundance and activity of microorganisms and stygofauna. This heterogeneity may have a temporal component owing to varying rates of recharge owing to meteorological and climatic variation, and be influenced by stygal animals responding to lowered DO by migrating to more oxic zones (Malard and Hervant 1999).



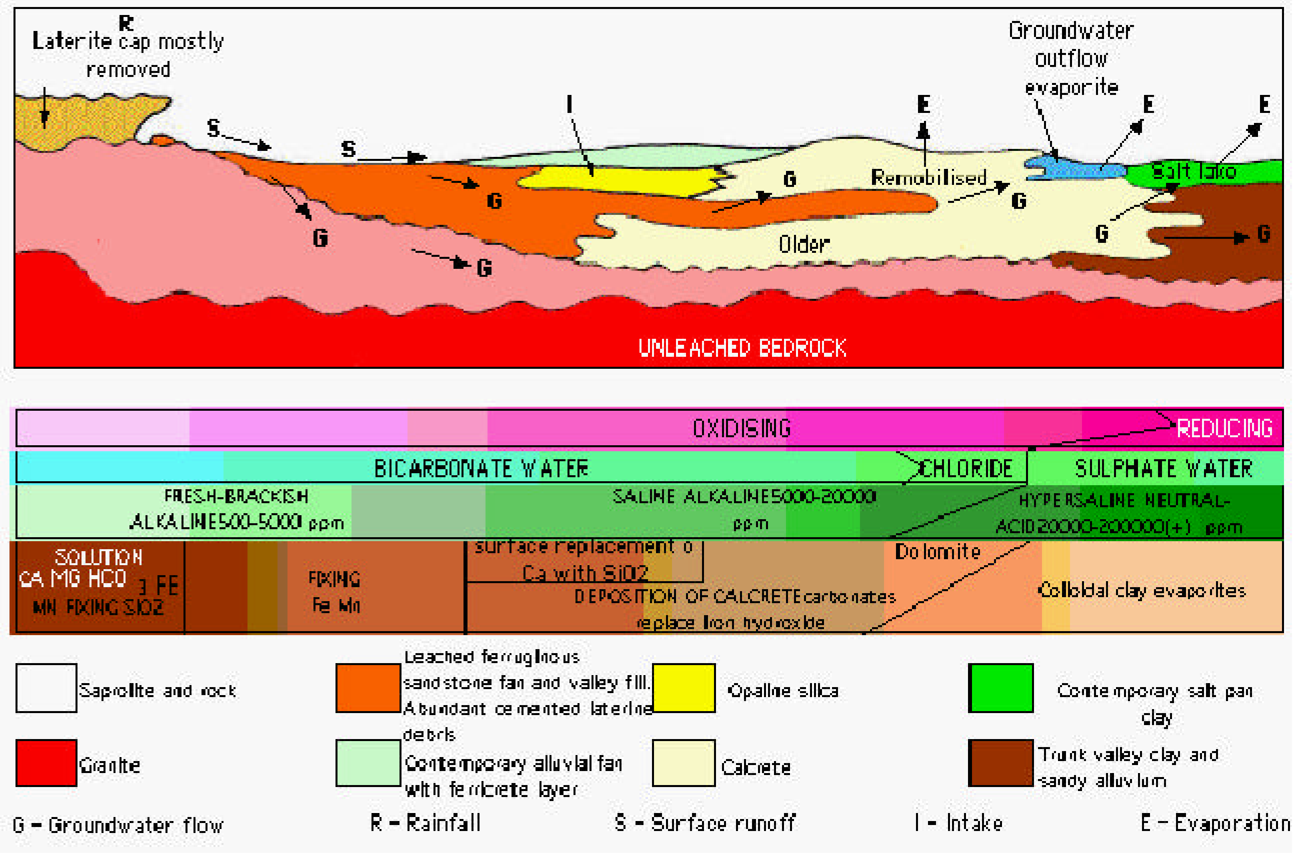
The available flux of oxygen in groundwater is much slower than in surface waters and DO concentrations of <1 mg L^{-1} are common in groundwater and many groundwater organisms withstand dysoxic waters (0.3-3.0 ml L^{-1}) for long periods. Stygofauna can exploit dysoxic areas rich in DOC owing to their efficient use of food (carbon) (Malard and Hervant 1999). Some stygofauna, which Sket (1986) called subthiobites, are even found beneath layers of hydrogen sulphide (Sket 1996; Pohlman et al. 1997; Humphreys 1999a; Iliffe 2000).

4, Physico-chemical heterogeneity

Groundwater calcrete aquifers in the Australian arid zone

In the Australian arid zone, large spatial and temporal changes in groundwater quality occur that result from the hydrogeochemical processes in the groundwater flow (Figure 4) that result in the deposition of groundwater calcretes (Mann and Deutscher, 1978; Mann and Horwitz, 1979), which harbour geographically restricted stygofaunas (Humphreys 1999b, 2001). Episodic rainfall, characteristic of the arid zone, may rapidly recharge unconfined calcrete aquifers causing the groundwater table to fluctuate widely accompanied by large changes in salinity in the upper layers of the groundwater (Watts and Humphreys 2000), and probably in oxygen. Such rapid recharge may be expected to have important effects on the biogeochemistry (Baker *et. al.* 2000), as well as stygofauna.

Figure 5: Generalised longitudinal section of the northern part of the Raeside and Carey Palaeorivers showing dissected regolith to the north (left side) with a south facing erosion escarpment and accompanying pediment eroded into the saprolite layer. This feature is followed southwards (right side) by a sedimentary facies of ferricrete-cementec colluvial/alluvial fan, entering the palaeochannel sequence of calcrete, silica, lake basin clay, overlain by evaporites at the groundwater outflow at the salt lake. At the base are shown the changes to the physico-chemical conditions along the groundwater flowpath. This represents a single cycle of a series of hydrochemical cycles that occur along the length of the palaeochannel and which are associated with the saltlakes. Redrawn after Morgan (1993) by permission.



Very sharp gradients in both physical and chemical conditions may occur through the water column (Ronen et al. 1986), even at the microscale, caused by anthopogenic inputs and suspected to be generally applicable (Ronen et al. 1987b). Such stratification is also seen in salinity stratified waters in both continental (Watts and Humphreys, 1999), karstic and anchialine systems, examples of which are shown in Figure 6 and Humphreys (1999a). Consequently, in aquifers that exhibit strong physico-chemical structure (stratification) in the water column, the routine purging of boreholes before sampling for hydrochemical investigations, will extirpate the most useful and important information pertaining to the groundwater fauna, namely, the physicochemical structure of the water column. It would appear that obtaining physico-chemical information from groundwater of utility both to hydrogeologists and biologists might be incompatible and that routine physicochemical profiling of undisturbed groundwater may often be required to understand groundwater ecology.

Groundwater fauna as indictors of the health of aquifers

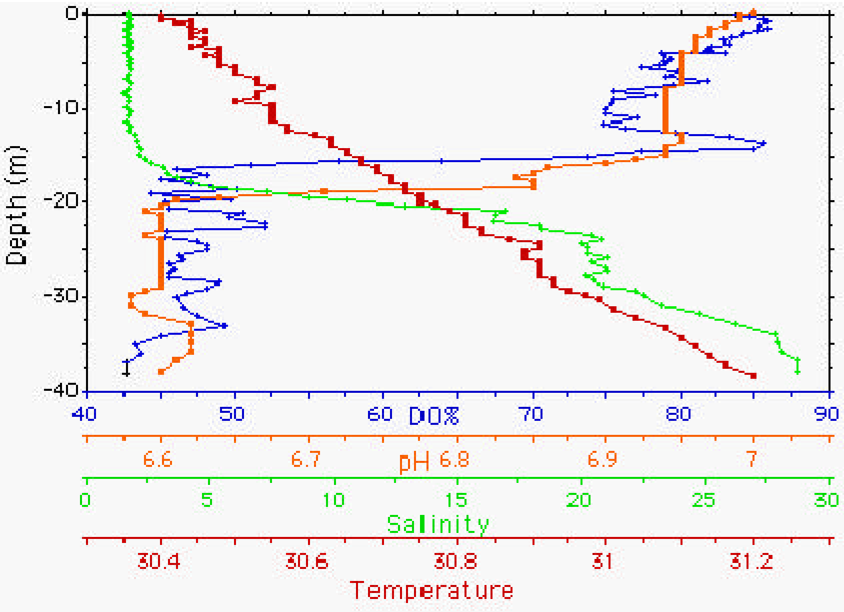
The most clearly groundwater dependent ecosystem is that occurring in the groundwater itself (Hatton and Evans 1998). Despite this, while there is some familiarity with the impact of groundwater abstraction on groundwater dependent ecosystems at the surface (e.g. in US, Loftus et al. 1992; in Australia, Hatton and Evans 1998), little is known about the impacts of water abstraction on the ecosystems within aquifers (Rouch et al. 1993), especially deep aquifers (Longley 1992).

Groundwater invertebrates have intimate connections with their milieu and cover a range of trophic types (filters, grazers, browsers, carnivores) and life cycles (few months to many years). Hence groundwater animals directly perceive changes in the nutrient content of groundwater whereas on the surface such changes are buffered and attenuated by the aquatic vegetation. In addition, different higher taxa may be differentially affected by pollutants (Malard et al. 1996a). As such they respond directly or indirectly through competition or predation, to changes in the properties of the various constituents of the subsurface environment, such as DO, the type and amount of organic matter, and particle size. Hence, hypogean invertebrates are in a comparable position for monitoring the health of subsurface ecosystems as are benthic invertebrates for the monitoring the health of surface ecosystems (Malard et al. 1996a).

Table 2: The distribution of crustacea and oligochaetes, and animals having an obligate (stygobites) or no affinity (stygoxenes) with groundwater in sewage-polluted and unimpacted sites in the Lez Basin karst system, Hérault, France. Data extracted from Malard et al. (1996a).

Organisms	Unimpacted sites	Sewage-polluted sites
Crustacea (% of invertebrates)	92-98	56-90
[1]Stygobites (number of species)	15-24	3-7
Stygobites (% of invertebrates)	48-81	2-12
Oligochaetes (% of invertebrates)	0-6	8-40
[2]Stygoxenes (number of species)	3-8	20-34
Stygoxenes (% of invertebrates)	3-5	10-88

[1]**Stygobite**: species that are specialized subterranean forms, obligatorily hypogean. Some are widely distributed in all kinds of groundwater systems (both karst and alluvia), and sometimes they are found very close to the surface. [2]**Stygoxenes**: organisms that have no affinities with the groundwater systems, but occur accidentally in caves or alluvial sediments. Nevertheless, stygoxenes can influence processes in the groundwater ecosystems—for example, by functioning either as predators or prey.



Groundwater ecology is not solely of academic interest but increasingly is of practical use. Groundwater fauna, especially stygofauna, are extremely sensitive to the environmental characteristics of the water they inhabit and thus are potentially useful indicators of groundwater health (monitors). A variety of studies suggest that stygofauna are useful for monitoring some types of pollution (Notenboom et al. 1994), either by its affect on communities, populations, or simply parts of an organism (Committee 1991). Changes in the spatio-temporal distribution of organisms in stygal communities can be good indicators of groundwater contamination by heavy metals (Malard et al. 1996b) and sewage (Table 2). Importantly, when information is available on characteristic changes associated about a given class of anthropogenic input, prior knowledge of a particular site may not required (Malard et al. 1996b). Consequently, Malard et al. (1996b) suggested that biological investigations should be incorporated into groundwater monitoring, management and protection programmes, rather than relying solely on hydrodynamical, physico-chemical and bacteriological data.

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