Humphreys, W.F. 2003. *Groundwater ecosystems*. p. 45-53 *in* Report on the National Workshop on Groundwater Dependent Ecosystems: Policy and Management. 16-17 June 2003, Melbourne. Report prepared by the Centre for groundwater Studies in association with Sinclair Knight Merz. CGS Report No 106.

2.3.3 Groundwater ecosystems *(*W. F. Humphreys, Western Australian Museum)

Introduction

Globally, the subject of groundwater ecology is recent with the first international conferences and textbooks (Gibert et al. 1994), and recognition by the World Bank and under the Ramsar Convention occurring in the last decade. As recently as 1998, a lack of appreciation of the diversity and extent of aquifer ecosystems led to the severe underestimation of the extent and significance of groundwater dependent ecosystems in Australia. Strong advocation, especially overseas, and the requirement to include stygofauna in some environmental impact assessment and the application of fauna protection legislation to some stygal species and communities in Australia has raised considerably awareness of stygofauna to a broader public. For example, "... *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*" (ANZECC / ARMCANZ, 2000).

Groundwater ecosystems comprise underground waters and their contained physical, chemical, microbial and faunal elements. They are typically fuelled by imported (allochthonous) energy from the surface (particulate and dissolved organic carbon) either directly or along the groundwater flowpath. Less commonly, chemoautotrophic processes have been identified, usually associated with hydrocarbon or magmatic flows but also with anchialine systems: they are probably much more common than so far identified and operating at a range of scales.

Most microbial systems in groundwater have been identified by DNA finger printing because culturing, especially of exotic species, is often not possible. In contrast, faunal elements can be sampled and characterised by morphology, sometimes supplemented using molecular methods to obtain fine scale resolution of the composition of the faunal assemblage. There is very little information of either type for most Australian groundwaters. At the current state of knowledge, the resolution of groundwater ecosystems (biodiversity, taxonomic composition, habitat characteristics and spatial extent) is often synonymous with the state of knowledge of groundwater fauna or stygofauna. For this reason, this paper discusses stygofauna at some length. However, the absence of stygofauna from an area should not imply a non-functional groundwater system – anaerobic microbial communities may be playing a crucial role in such areas.

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 most surface ecosystems. 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, some stygal lineages have apparently been isolated underground in the Miocene by the onset of aridity, or by orogenic and eustatic events. Others have become separated from their relatives by the movement of continental plates, before or after their isolation underground — groundwater ecosystems may be very persistent through geological time and the stygofauna is expected to be a good indicator of ecosystem health in terms of overall diversity and for some particular species.

Groundwaters have received no national attention comparable to that devoted to surface waters despite the interconnected medium and processes represented. While great effort has been expended addressing the reservoir attributes of groundwater only minuscule effort has been addressed to groundwater as habitat; indeed, that groundwater is habitat has only recently been recognised. Understanding the diversity of aquatic life in the subsurface is a necessary step for incorporating current biological concepts within the framework of groundwater management (e.g. maintaining biodiversity and thereby ecosystem function to protect groundwater quality) and to facilitate this there is need to develop new monitoring tools such as biological indicators of groundwater ecosystem health (the European PASCALIS Project, 2001). Of particular importance is the ecotone between surface and subsurface waters because exchange and filtering occurs in this hyporheic zone.

Classification

There is a gradient of dependence of the fauna on subterranean existence, from occasional inhabitants to one of total dependence on groundwater. Stygofauna are animals inhabiting groundwater and, except in karst areas, they are invertebrates. They have various lifestyles and many animals occur in groundwater either by chance (termed *stygoxenes*) or with varying degrees of affinity for groundwater, inhabiting it on a permanent or a temporary basis (termed *stygophiles*, of which *amphibites* spend part of their life cycle in hyporheos and part in surface water). Only *stygobites* are obligate inhabitants of groundwater; animals in these several ecological types collectively comprise the *stygofauna*. This is associated with gradients in environmental conditions from light—dark; oxidising—reducing; epigean—stygobite; photosynthesis—organic matter respiration. Stygobites comprise elements of the ultimate groundwater dependent ecosystem and they are overwhelmingly crustaceans, but the fauna includes amongst others, worms, snails, mites, insects and fish.

Stygobites have convergent morphologies, exhibiting a reduction or loss of eyes, pigments and hardened body parts (they are commonly translucent), and they have enhanced non-optic sense organs. Stygobites generally have no resting or dispersal stages, are slow-growing, long-lived and have few young. These attributes make them very efficient bioaccumulators, 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.

Surface waters and groundwaters have important zones of exchange beneath (hyporheic zone) and alongside (parafluvial zone) water courses, and at groundwater estuaries along the coast and possibly saltlakes (playas). These dynamic ecotones between the river and groundwater exhibit sharp chemical and biotic gradients where light, nutrients and energy are filtered or exchanged. Water in the hyporheic zone exchanges with groundwater and the chemical and biotic environment varies markedly depending on whether it is a zone of downwelling (influx) or upwelling (efflux), and on the transmissivity and scale of the medium which affects the rates of exchange. Many surface waters rely on groundwater for supply and Australian rivers that rely on baseflow during drier periods are considered as groundwater-dependent ecosystems.

Assessing (in situ/remote)

There are no established general methods to assess groundwater ecosystems globally, or even stygofauna. The large PASCALIS Project aims to establish general methods applicable to Europe by considering Region, Hydrographic Basin, and various subsets of karst and alluvial aquifers (Table 3). While no such broadscale and detailed assessment has been conducted in Australia, some states have been partly sampled at the system level—karst in Tasmania, NSW and WA, groundwater calcretes in WA. In WA, CALM is currently doing a limited regional stygofauna survey of the Pilbara using standard sampling equipment but on non-standard bores. In Queensland a survey is planned of groundwater habitats in the Pioneer River as a prelude to formulating a standard protocol for GDE assessments in Queensland catchments. Most groundwater sampling outside caves has been conducted on a broad-scale in bores, pastoral wells and springs, to qualitatively characterise the diverse groundwater faunas, using mostly haul nets in

Level			
1	Regional		
2	Hydrogeographic Basin		
3	Unconsolidated sediments	Hyporheic zone	
		Groundwater zone	Unconfined
			Unconfined valley aquifers
			Confined aquifers
4	Karstic	Unsaturated zone	Epikarstic aquifer
			Slowly infiltrating water
			Exogenous rivers
			Endogenous rivers
		Saturated zone	

Table 3. Hierarchy of sampling units in the European PASCALIS project, as an example of multistate assessment effort.

access points. This method has been tested in Germany and found to be comparable to more complex methods but unbaited traps also permit detailed characterisation of the groundwater environment. For hyporheic zone sampling, fixed tubes (sampled by pumping, traps or haul nets), temporary tubes (Bou-Rouch pumps) or sampling the filtrate from holes dug in sediments (Karaman-Chappuis pits) can be used. Freeze coring has also proved useful because it simultaneously provides data on sediment size and packing.

Most species of Australian stygofauna are undescribed and any newly investigated area is likely to yield predominantly undescribed species. Although there is a large taxonomic hiatus, experience in Cape Range and in the Yilgarn and Pilbara has shown that with appropriate funding allocation for taxonomy within other projects that the taxonomic gap can be closed within the life time of a major project (3-5 years), at least sufficient to ascertain the uniqueness and range of the characteristic fauna. However, this experience has also shown that the convergent morphology characteristic of stygal species means that molecular methods may be required to understand the origin and affinities of the fauna (sometimes even species level determinations), attributes that may have management implications.

There is a pressing need for research into methodology suitable for regional and landscape scale assessment of subterranean faunas on a continent-wide basis. A coordinated thrust incorporating all types of landscape across the country would be advised, rather than the current piecemeal approach (emphasised also by NSW NCC, 1999). Effective use could be made of overseas experience as there is little background in Australia of such work. Concomitantly, there is a need to facilitate taxonomic work through funding and training programmes on stygal lineages to determine biodiversity, and to determine the range of scales that need to be considered—many Australian stygal species are small range endemic. We also need to think about concomitant environmental variables to measure – water quality, habitat factors, etc. to try and help us develop predictive models of what fauna we would expect to find in specific environments. This way, we can identify when there are key elements of the fauna missing and determine if this might be due to human activities or biogeographic reasons.

Quantification of stygal populations is fraught with problems the resolution of which is current research. Direct enumeration often may not be practicable or necessary and the pragmatic approach may be design sampling programmes that give repeatable results and leave the quantification to flux measurements which may be more achievable. It is important also to develop functional classifications in order to find out what the fauna *do*, as well as what they are.

Biodiversity conservation status

Groundwater animals, especially though inhabiting alluvial systems, are likely to have more extended distributions than terrestrial subterranean animals owing to their ability to move through groundwater that is interconnected along the hyporheic highway in space and time during landscape evolution. However, there is now much evidence that this is not the case in much of Australia which has a much older landscape than those areas (Europe and N. America) where such paradigms were established. Indeed the numerous small impounded karsts of NSW and Tasmania essentially contain unique fauna. The same occurs within segments of the Devonian reef system of the Kimberley. More surprisingly, in the groundwater calcrete habitats of the palaeovalleys in the Australian arid zone, each calcrete body examined contains a unique fauna.

The conservation status of stygofauna cannot be adequately addressed in the absence of any data from most of Australia and an absence of historical data from most of those systems that have been studied. Many karst areas are in the conservation estate but their groundwater is not necessarily protected, especially if they have linkages to surface waters. So protection of groundwater must extend to surface waters as well, even to overlying terrestrial infiltration zones. A few stygal species and communities are specially listed under both State and Commonwealth endangered species legislation.

Some entire karst systems have been entirely mined, probably together with unique fauna. Sediment infilling is likely to have seriously impacted fauna in the hyporheic zone as has interception of groundwater by pumping from alongside rivers and coast which effect the dynamics of the hyporheic zone and groundwater estuaries.

As in surface systems, invertebrate biodiversity is likely to be a useful indicator of hyporheic health but we presently lack fundamental data on the composition and ecological requirements of most of the constituent species. The few studies of Australian and New Zealand hyporheic fauna indicate that diversity declines in response to agricultural activities, forestry and salinisation. Overseas, the functional composition of the interstitial invertebrate assemblage has been shown to change due to human disruption of the hyporheic zone. This indicator has yet to be properly tested (is the response limited to few species or the community at large?) and to do so requires better sampling methodology to obtain comparable samples. The assessments of aquatic indicator species that might typify GDEs requires baseline data and developed sampling protocols, geographic distributions and taxonomies.

Is it time to review our protocols for assessing the health of GDEs and rivers and are we yet technically capable? As recommended elsewhere (Nature Conservation Council of NSW - NCC,1999) there is a need for a manual to collate groundwater dependent indicator species, development of sampling protocols and approaches that could be used nationally, and additional research on management strategies (once the resource can be quantified).

Currently, the NSW Department of Infrastructure, Planning and Natural Resources (DIPNR) is trialling the inclusion of hyporheic indicators in its 'Integrated Monitoring of Environmental Flows' program in the Hunter River. A monitoring program to measure the effectiveness of the rules is being developed for both surface and subsurface components to examine the 'health' of the ecosystem as a whole rather than confining it to surface water and catchment conditions.

Methodologies for determining EWRs (level of dependence etc).

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 (duration, timing, rate of drawdown/recharge) have in the context of, for example, water mining or the sustainable drawing of water from an aquifer? Recent work in the hyporheic zone of the Hunter River has demonstrated substantial responses by microbial and hyporheos to environmental flow releases and simulated flow pulses, including changes in nutrient regeneration pathways in parafluvial zones.

Recognition and maintenance of appropriate environmental flows to aquifer ecosystems in the face of such perturbations presents a major research challenge. Given the scale of the task and the long time course expected of many responses, the only practical approach in many cases, as well as the most informative, may be to use Adaptive Environmental Management (AEM) in which the system is experimentally manipulated and responses assessed. AEM requires that environmental flow can be restored when found to have been reduced beyond a critical level. Such experiments must be well designed for best effect, and this will require development of methodology and need to take into account the longer time frames over which this response might occur, although pragmatic considerations will often lead to compromise. However, in this context well thought out experiments leading to modeling are useful —stygofauna need a place to live, food and oxygen.

A place to live: The greater the hydrological 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 in space or time along groundwater flowpaths. This is correlated with decreases in DOC and DO and population density. However, locally endemic stygobitic communities comprising highly stygomorphic species can occur in the arid zone.

Some anthropogenic effects are overtly detrimental to stygofauna, for example removal of the matrix itself (e.g. mineral mining which converts groundwater to surface water and offers ingress for nutrients), 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-range endemics), and the magnitude of the dewatering operations.

In both hyporheic systems and cave streams it seems that the mobilisation of fine sediments—an issue now more widely addressed in surface waters—for example by gravel extraction, dredging, quarrying or removal of vegetation, can clog sediment spaces and smother surfaces. Such effects may also be expected to impact similarly on aquifer ecosystems and do impact the hyporheic zone. The resulting disruption of hydrological exchange reduces dissolved oxygen concentration (DO) and may lead to the extirpation of stygal populations. Debate as to whether macrofauna can maintain void space by their movements through sediments, thus assisting with maintenance of the hydrological functioning within aquifers, is unresolved and may be site and scale dependent.

Groundwater abstraction has numerous effects on the groundwater ecosystem and it is important to consider both the magnitude as well as the rate of change of the water table. Overtly, the water table may be lowered regionally or locally. The groundwater surface may be dimpled both spatially and temporally by drawdown cones of adjacent wells. Concomitantly any interface with underlying salt water will be similarly dimpled in mirror image but amplified about forty-fold due to the Ghyben-Herzberg effect. There may also be thermal effects of drawdown that then flow on to respiration rates, etc.

Covertly, pumping induces low flow velocity in the groundwater, without which hypogean fauna may be sparse. However, prolonged pumping may completely modify the groundwater habitat and the faunal assemblage around the pumping well. 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, DOC and macronutrients.

A further indirect impact may result from leakage between aquifers. In the arid zone water mining from deep sand aquifers in palaeochannels, which may have a residence time in the order of 10^5 years, is rapidly increasing. The deep sand aquifers are coupled with the overlying phreatic calcrete aquifers in a manner not understood. The calcrete aquifers are habitat for numerous stygal systems containing many short-range endemic species, as well as supporting phreatophytes. 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 the GDE's and its subsequent management.

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. 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. 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. 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 (and often refractory) and increasing it or its lability through contamination may allow epigean species to displace hypogean species.

Dissolved oxygen (DO) in groundwater is one of the prime ecological factors governing the occurrence and spatio-temporal distribution of hypogean animals. DO concentration generally decreases with depth in the groundwater as oxygen is gradually consumed along groundwater flowpaths. Spatial heterogeneity exhibited at the macro (km), meso (m) and micro (cm) 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. The flux of oxygen in groundwater is much slower than in surface waters and DO concentrations of <1 mg L^{-1} are common in groundwater. 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). Some stygofauna are even found beneath layers of hydrogen sulphide.

Factors that affect DO are therefore of importance. For example, changing flow rates and thus DO flux, upconing of denser water may shift boundary of low DO water, injected water may have low or high DO, oxidation of added organic matter. Abstraction or injection of water may thus influence the quality, quantity and rate processes within the aquifer and so the hyporheic zone. Of likely special importance in Australia owing to the generally arid climate, are salinity, recharge rate and nutrient input, but also human contaminants – hydrocarbons, organochlorines, and other toxicants.

Very sharp gradients in both physical and chemical conditions may occur through the water column in continental, karstic and anchialine systems. 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. Also, there is the possibility of creating 'new' habitat by macropores of boreholes!

Key threatening processes

- Removal of matrix (excavating below the water table makes GW into surface water and opens sink for nutrients), changing of permeability.

- Occlusion of void space by sediment - Australian examples in karst systems, hyporheic zone of river gravels and work in the Hunter Valley implies that environmental releases are not very good at flushing the sediments to any great depth.

- Remove or add water, either too much or too fast (alter level of groundwater; flux and gradients of nutrients, DO, DOC, redox, etc.)

- Changing vector or rate of groundwater flow by abstraction or injection which changes groundwater topography (e.g. dimpling in borefield. amplified 40 fold at saltwater interface, spring discharge, recharge, saltwater intrusion).

- Changing hyporheic zone dynamics by pumping alongside or beneath rivers especially when river flow ceases.

- Landscape scale changes affecting hydrological cycle (silation, salinity, water balance, magitude and rate of infiltration)

Groundwater ecology is not solely of academic interest but increasingly is of practical use in the provision of 'ecosystem services'—the rationale for the conservation of biodiversity—and stygofauna, especially stygobites, are potentially useful indicators of groundwater health (monitors). Effective water management requires an understanding of both surface water and groundwater ecosystems, and their effects on each other mediated by the hyporheic zone.

3. Towards Best-practice Management of GDEs

Following more formal presentations, and identification of a range of current issues, the workshop participants split into three groups to consider the following key issues

- Generic Framework for Management of GDEs
- Best-Practice Management Tools
- Impediments to GDE Management

The outcomes from these discussions are summarized below.

3.1 Generic Framework for Management of GDEs

The following dot-point issues were raised by the groups. These are listed singly or grouped with explanatory text.

- Integrate Groundwater (Water) Management with Land Management
- Identify key planning frameworks

States should aim to develop comprehensive integrated catchment management, for management and protection of land, surface water and groundwater, with nationally agreed principles. Integrated catchment management would include Water/ groundwater management plans which include protection of GDEs, and land management plans. These should address both water quantity, flux and level criteria and water quality criteria. Consideration of water quality criteria in relation to GDE health would seem to be patchy at best.

- Develop State and National Registers of GDEs within a consistent format (methodologies for characterision, dependency on groundwater, prioritized, mapping [GIS], cross-linkages, scale etc)
- Investigate / raise the establishment of Statutory Reserves for highest priority GDEs