Deliberate omission or unfortunate oversight: Should stygofaunal surveys be included in routine groundwater monitoring programs?

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Introduction

With burgeoning global exploitation of groundwater, there is increasing urgency for sustainable groundwater management (Kalf and Woolley 2005). Escalating groundwater exploitation is outstripping social and scientific understanding of the sustainability of this resource. To date, groundwater management has largely concerned quantity and hydrological sustainability of supply, water quality and protection from pollution, and more recently, economic and social governance (see *Hydrogeology Journal*, Vol 14 (3), 2006). However, increasing public and political recognition of the importance of ecological sustainability heralds a new paradigm in groundwater management integrating hydrogeology and groundwater ecology (Hancock et al. 2005). This paradigm emphasises the close links between hydrogeology, biogeochemistry, and ecology in holistic management of water supply and quality, explicitly acknowledging the connectivity between surface and groundwaters, aquifers as biologically active systems (e.g., capable of bioremediation of pollutants, Gounot 1994) and the ubiquity of groundwater dependence in terrestrial ecosystems (Eamus et al. 2006).

Aquifers support interstitial assemblages of bacteria and associated biofilms as well as specialized obligate groundwater fauna termed "stygofauna". Full assessment of aquifer condition includes not only traditional sampling of physical and chemical variables but also consideration of the biota. This requires the combined expertise of hydrogeologists and ecologists, but as in any multidisciplinary field, successful collaboration is hampered by different knowledge structures, disciplinary paradigms, and field experiences (Boulton et al. 2005). Traditionally, managers of groundwater have hydrogeological and engineering backgrounds and work in resource management agencies responsible for water supply. Conversely, groundwater ecologists mainly work in universities, museums and conservation agencies, seldom have direct responsibility for groundwater management, and currently grapple with the uncertainties of an infant discipline (Gibert et al. 1994). Thus, the potential benefits of groundwater ecology to resource management are seldom readily accessible to groundwater managers despite some efforts to bridge the divide (Sophocleous 2002; Danielopol et al. 2003). Questions of whether the contents of a bore are representative of the aquifer community, how results can be compared among aquifer types, and how to interpret the data given gaps in taxonomic and ecological knowledge currently hamper acceptance of stygofaunal sampling in the toolbox of techniques for assessing and monitoring environmental impacts of groundwater exploitation.

This essay briefly reviews perceived values of stygofauna and benefits of their inclusion in hydrogeological surveys of groundwater, and summarises the legislative and policy framework for stygofaunal surveys. Although focused on Australia, the issues discussed are of broad, international concern. A staged approach to surveys is advocated where investigations progressively increase in complexity. This aims to overcome the current paradox of omitting stygofauna from groundwater monitoring because there is insufficient information for the interpretation of survey results—yet, if stygofauna are not sampled, then the information will never be collected to address the knowledge gaps.

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Stygofauna and their perceived values

The term stygofauna refers only to obligate groundwater fauna (stygobionts, Gibert et al. 1994). It excludes organisms which may occur in groundwaters but lack specialisations for the aquifer environment. Most stygofauna are unpigmented, elongate and small, adapted for life in dark and often confined spaces. Stygofauna include crustaceans, molluscs, worms, beetles and other less familiar invertebrates, and occur in many calcrete, alluvial and fractured rock aquifers. Surveys worldwide reveal stygofauna to be more widespread, abundant and diverse than previously expected (Sket 1999). Currently, stygofauna are valued as (1) a reserve of biodiversity, (2) potential providers of

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ecosystem goods and services, and (3) biological sentinels of the 'health' of groundwater ecosystems.

1. *Biodiversity*: Once considered "biological deserts", groundwaters are proving to be surprisingly rich in species, many of which are new to science (Danielopol et al. 2003). In Australia, stygofaunal biodiversity so far includes two species of fish (Humphreys 1999), 80 new species of diving beetles (Watts and Humphreys 2006) and about one-quarter of the world's ostracod genera (Humphreys 2006). Interest has been ignited by reports of "hotspots" of stygofaunal diversity where new species, some of great scientific significance, have been discovered in areas where groundwater extraction or mining is planned (Boulton et al. 2003; Humphreys 2006).
2. *Ecosystem goods and services*: Stygofauna probably contribute to ecological processes that potentially promote ecosystem goods and services (Boulton et al. 2003; Hancock et al. 2005). The role of aquifer bacteria in natural attenuation of some pollutants is well known (Gounot 1994) and stygofaunal grazing on bacteria and biofilm may stimulate these bioremediation processes (Mattison et al. 2005). Stygofaunal feeding, movement and excretion likely mediate the transfer of organic matter through aquifers (Hancock et al. 2005), helping to transform nutrients and maintain water quality.
3. *Biological sentinels*: Ecologically significant changes in inputs of energy, nutrients, water or contaminants may change stygofaunal community composition (e.g., Malard et al. 1996). As some stygofauna may be more sensitive than surface water fauna to chemical pollutants (Mosslacher 2000), groundwater quality criteria based on responses of surface water organisms may be insufficient to protect groundwater systems (Hose 2005). Sensitivity varies among species and depends upon length of exposure and the particular contaminant mixture (Canivet and Gibert, 2001; Canivet and Gibert, 2002), yet stygofauna offer promise as indicators of groundwater quality, and could be sampled in monitoring programs similar to those developed for river health assessment (Wright et al. 2000).

Current legislative and policy frameworks

Although stygofaunal surveys may be justified from the perspectives of both groundwater ecology and hydrogeology, to date most surveys have been driven by biodiversity considerations and have not been integral to groundwater management. For example, although the European Union Water Framework Directive is predicated on an integrated approach to water management, its supplementary Groundwater Directive focuses on physical and chemical monitoring and omits any reference to stygofauna (Danielopol et al. 2004). This is despite the development of standard methods for assessing groundwater biodiversity (Gibert et al. 2005) that provide fundamental baseline data on stygofaunal distribution and associations with environmental variables.

A rich hydrogeological literature about the semantics and practicalities of 'sustainability' (mainly quantity) of groundwater exists (review in Alley and Leake 2004), but only recently has this concept encompassed ecological sustainability and social objectives (Seward et al. 2006). One premise of sustainability is that the surface-groundwater resource should be managed holistically (Winter et al. 1998). Moreover, most groundwater ecosystems are not inert, isolated bodies of water but influence adjacent terrestrial, aquatic and marine ecosystems (Eamus et al. 2006).

In Australia, water-resource policy is co-ordinated through the Council of Australian Governments (COAG) which agreed in 1994 that water must be allocated for environmental use (ARMCANZ, 1996). All jurisdictions have implemented the COAG reforms by making legal provisions for environmental water and formulating approaches to setting environmental water requirements, including allocations for groundwater-dependent ecosystems (GDEs). For example, the *South Australian Natural Resource Management Act 2004* requires that decisions relating to water resource management "must take into account the needs of the ecosystems that depend on that resource for water". As stygofauna are, by definition, 100% groundwater-dependent (Humphreys 2006), it may be argued that stygofaunal surveys are essential to the determination of environmental water requirements for groundwater systems regardless of whether stygofauna have any ecological role that benefits humans.

Stygofaunal surveys may be warranted on other legislative grounds. There are obligations to conserve aquifer fauna from a biodiversity perspective if the provisions of the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* are triggered. Water resource legislation in most Australian States provides for assessment of the environmental impact of water extraction, although only Western Australia specifically requires stygofaunal surveys in assessment of environmental water allocations. In this State, a specific "guidance document" assists in environmental impact assessment where subterranean fauna are present (EPA 2003). DNA analyses are required in such assessment, and although expensive have proved worthwhile. In one case, mining below the water table was delayed for nearly 3 years while apparent diversity based on morphospecies was investigated. Analysis of genetic markers showed no evidence for multiple species within catchments (Finston et al. 2004).

Deliberate omission or unfortunate oversight?

Groundwater-dependent ecosystems may include river and lake systems, phreatophytic vegetation, marine ecosystems, and aquifer and cave ecosystems. In Australia, water-resource assessment now involves some level of assessment of GDEs, and there are several examples of comprehensive assessments of terrestrial GDEs instigated by groundwater management agencies (e.g., Cook et al. 1998). Despite their complete groundwater dependency, aquifer ecosystems have received far less attention than terrestrial GDEs, probably because impacts of excessive groundwater abstraction on surface GDEs are more readily apparent (Boulton and Hancock 2006; Eamus and Froend 2006). Conversely, the

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impact of human activities on stygofauna is poorly documented and not evident to the public.

Faced with the risk that finding stygofauna may delay or prevent resource exploitation, who would dare open this 'Pandora's Box'? 'The less we know, the better' may be a popular view, but is omission of stygofaunal sampling acceptable? There is certainly a lack of knowledge of stygofaunal taxonomy, distribution and ecology along with numerous uncertainties relating to sampling protocols. Analogous challenges faced water managers tackling national audits of river health in the 1980s and 1990s but most of these have been resolved by integrated strategic research (Wright et al. 2000). Questions directly relevant to groundwater management for stygofauna include:

1. Are stygofauna evenly distributed throughout aquifers or are they clustered in "hot spots" of high biodiversity? If they are clustered, their protection may be easier, involving targeted controls on drawdown in particular parts of the aquifer.
2. Are stygofaunal populations impacted by water-level decline? If so, is the rate of decline important? If stygofauna are sufficiently mobile, they may migrate downwards when the water table falls. Also, if stygofauna are distributed vertically throughout the aquifer, a relatively small decline in the water table may have little impact. Exceptions will arise where aquifer conditions (e.g., dissolved oxygen) change with depth so that deeper aquifer conditions do not resemble the environment close to the water table where stygofauna may be most diverse.

Without good answers to these questions, our ability to consider stygofauna in groundwater management is limited. Therefore, groundwater managers are likely to see little value in paying for stygofaunal assessments. However, our knowledge of stygofaunal ecology will not advance sufficiently quickly if it relies only on scientific research funding. To abandon stygofaunal sampling is to risk losing valuable data that may be essential to ecologically sustainable groundwater management. To solve this dilemma, the authors advocate a 'staged approach' to stygofaunal sampling.

A staged approach to sampling

The first stage is to establish the presence of stygofauna. Simple, low cost sampling of bores, wells, and springs will provide evidence for the presence or absence of stygofauna. Techniques are fully reviewed in Malard et al. (2003) but weighted plankton nets lowered down a well, pumped water filtered through fine mesh (e.g., 0.063 mm), or even simple 'traps' left for several days (Masciopinto et al. 2006) will collect stygofauna. Often the fauna can be seen with the naked eye, so the existence of this GDE can be determined in the field. Of course, the absence of fauna even after microscopic examination cannot guarantee there are no stygofauna, and apparent absence should not be misinterpreted as an endorsement of reckless exploitation. Absence of stygofauna does not preclude a microbially active aquifer (see Goldscheider et al. 2006 for a review of methods) and the staged approach described here is only for stygofauna. Even this small effort would alert the public to the presence of life in aquifers, confirm the GDE, and stimulate research and management attention towards groundwater ecology.

The second stage is to identify the main types of invertebrates. Stygofauna should be preserved in 100% ethanol (enabling DNA analysis, EPA 2003) in a fully labeled container. Details of the bore characteristics and if possible, simultaneously collected water-quality data should be recorded. In the laboratory, animals can be sorted under a microscope into similar-looking 'morphotypes'. Although stygofauna are notoriously similar-looking (due to the selective pressures of subterranean life), the number of morphotypes is often a rough indication of diversity and enables broad comparisons over time in a region. With minimal training, it is possible to distinguish major groups. This is useful because early indications are that these groups differ in their tolerance to water-table fluctuations (Moya Tomlinson, University of New England, unpublished data, 2007) and other functional traits (Claret et al. 1999). Even if the samples are not sorted at this stage, retention of the preserved specimens with full details of sampling location and conditions provides an invaluable reference collection against which later material might be compared. Such long-term data are essential for assessing changes to groundwater resources. For example, Masciopinto et al. (2006) demonstrated long-term deterioration in groundwater quality of the Salento peninsula, southern Italy, by comparing current samples with collections since the 1960s. Over time, accumulation of such studies would help answer questions about stygofaunal distribution within aquifers.

The final stage entails specialist taxonomists, quantitative sampling and more detailed studies. Conservation issues and assessment of true biodiversity requires this more costly stage (Eberhard et al. 2005; Gibert et al. 2005). Such data can be used to address sophisticated questions of spatial and temporal variations of species abundance and diversity, correlations of community composition with physical and chemical variables, and application of these data in determining environmental water requirements.

Conclusions

Although stygofaunal surveys in Australia so far have been driven by biodiversity conservation issues and environmental impact assessment (e.g., Eberhard et al. 2005), they may also assist in: (1) determining groundwater 'sustainability' in conjunction with hydrogeological data, (2) setting environmental water requirements for aquifer GDEs, (3) monitoring ecological effects in connected alluvial aquifers affected by river regulation and environmental flows, and (4) biologically indicating aquifer condition. Without legislative 'prodding', few managers might dare to open the 'Pandora's Box' of stygofaunal sampling. Yet to ignore this aspect is to risk mismanagement of a precious resource, regardless of concerns for biodiversity or potential goods and services of stygofauna. This essay is a first step to encourage hydrogeologists and water managers to consider whether stygofauna

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are present in aquifers. The sooner this begins, the better. An inventory of GDEs necessitates survey of stygofauna to at least the first level described above. Retaining stygofaunal samples and gathering data now will provide the long-term data set essential to holistic management of groundwater. By combining their expertise, hydrogeologists and groundwater ecologists offer the most promise for truly sustainable groundwater management.

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