Limnologica 42 (2012) 1–6

Contents lists available at SciVerse ScienceDirect

Limnologica

journal homepage: www.elsevier.de/limno

Review

What is groundwater and what does this mean to fauna? – An opinion

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ARTICLE INFO

Article history:
Received 3 August 2010
Received in revised form 9 August 2011
Accepted 12 August 2011

Keywords:
Groundwater ecosystems
Stygofauna
Groundwater fauna
Groundwater/surface water-interactions
Reference conditions

ABSTRACT

Many subsurface waters are considered groundwater but are influenced in shallow depths by hyporheic, parafluvial and/or soil interception water to such a degree that groundwater fauna (stygofauna) communities may be significantly altered. Recharge, even if spatially and temporally distinct, delivers input of dissolved oxygen, organic matter (OM), and nutrients that caters sustainably for ubiquists such as stygophiles and hyporheic fauna, but renders the life of uncompetitive stygobites difficult or impossible. The impact of recharge at shallow groundwater thus needs to be taken into account when determining groundwater fauna reference communities and when evaluating monitoring studies.

One of the main characteristics of groundwater is low OM concentration. In contrast, high OM concentrations are typical of hyporheic or parafluvial waters, which are enriched by OM from the river, the riparian soils and from interflow, and which contribute significantly to river OM balance. Consequently, for ecological studies on subsurface waters, both the origin of the water and OM, and the intensity of surface water interactions should be considered. Here, we discuss how groundwater spatial and temporal heterogeneity translates into faunal distribution patterns. In terms of the origin of water and OM, and from an ecological point of view, we need to distinguish between (i) shallow groundwater characterized by infiltrating precipitation and soil recharge, (ii) shallow groundwater interacting with surface water bodies such as continuously flowing and ephemeral streams and rivers, and (iii) "old" groundwater which has no recent connections to the surface and is thus largely secluded from input of nutrients and carbon. Water in the first two groups is characterized by high amounts of OM of varying quality, while water in the third group is characterized by low amounts of low quality OM. Consequently, stygophiles dominate in groups 1 and 2, with hyporheic fauna taking up a considerable proportion in group 2, while stygobites only dominate in group 3. Thus, for studies aiming to assess impacts on groundwater, only sampling sites of the third group should be used for reference sites as these are the most likely sites to have little surface impact and a stygofauna representative of the deeper aquifer.

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Introduction

Increasing recognition is being given to groundwater ecosystems, both as a habitat of vulnerable biotic richness and as a provider of ecosystem functions (Boulton et al., 2008).

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doi:10.1016/j.limno.2011.08.002

Subsurface aquatic fauna act as a biological sentinel for aquifer condition (Malard et al., 1996; Dumas et al., 2001; Humphreys, 2008) and are seen as promoters of ecosystem goods and services (Boulton et al., 2003; Danielopol and Griebler, 2008). In Western Australia, the occurrence of little-known groundwater species delayed mining because of concerns the species would become extinct, and groundwater ecological surveys are now required by government legislation for many developments that impact on aquifers (Boulton et al., 2003; Tomlinson and Boulton, 2010; Stein et al., 2010). However, fauna's distribution often appears patchy so a better understanding is needed of the conditions under which we can possibly expect fauna. Here, we distinguish three cases which are all part of groundwater but which potentially lead to very different faunal communities. Any practitioner using fauna occurrence and community distribution patterns as a measure for ecosystem quality, contamination, etc., will need to consider such reference cases.

Most groundwater systems are characterized by low exchange (Humphreys, 2009) and low – if any – autotrophy (self-sustained production of organic matter from inorganic substances; but see Sârbu, 2000 and Por, 2007, for examples of autotrophically sustained groundwater ecosystems). Thus, this huge ecosystem relies largely on allochthonous sources, i.e. organic matter, energy, and electron acceptors that originate from outside the ecosystem boundaries (Wilkens et al., 2000). It is well known that organic matter (OM) and nutrient concentrations of older groundwater are low (Gibert et al., 1994; Baker et al., 2000; Quinn and Stroud, 2002) and the input shapes groundwater ecosystems (Datry et al., 2005; Hahn, 2006; Schmidt et al., 2007a). In order to evaluate the occurrence of biota in this ecosystem in the framework of monitoring studies and when developing reference conditions, it is therefore paramount to characterize these inputs from the boundaries in terms of what they mean for fauna and for the ecosystem as a whole, at the sampled sites.

Single physical or chemical factors have only irregularly shown correlations with all subsurface fauna occurrence. Faunal communities have been observed to vary according to multivariate patterns of physical and chemical features (Schmidt et al., 2007a; Bork et al., 2009; Dole-Olivier et al., 2009). We interpret these multivariate patterns as reflecting hydrological exchange in general, which influences the whole ecosystem and thus the biota within. For example, the stygobitic (i.e. obligate inhabitants of groundwater; Gibert et al., 1994) taxa *Troglochaetus beranecki*, *Bathynella*, *Stygobromus* and *Crangonyx* occurred directly beneath or below the stream in the South Platte River gravel bar (Pennak and Ward, 1986), and several taxa occurred below two karstic streams (Rouch, 1988). In both of these cases, the shallow groundwater was strongly influenced by surface water interaction. Contrasting with this, hyporheic and thus stream-dependent fauna are sometimes found kilometres from the surface channel, reflecting the subsurface flow paths in alluvial floodplains (Stanford and Ward, 1988). This means that in the complex of groundwater recharge origin (hyporheic vs. soil), age ("how long since recharge", or rather: "how long since precipitation"), and depth ("how far from the surface") mediated by passage through systems that are sink and source of OM in themselves, all aspects are important. Such a complex is of course difficult to define and this is why the Groundwater Fauna Index (GFI; Hahn, 2006) was developed as a tool to simplify the multivariate complexity into one index. It has proven to be the only reliable predictor of faunal communities (e.g. Bork et al., 2009).

However, while the GFI may be used as a proxy for recharge, it does not provide information on which type of recharge dominates. Here, we argue that two types of recharge, as opposed to virtual lack of recharge, shape different faunal distributions, only some of which should actually be called stygobitic communities. When interpreting subsurface fauna occurrences, it is thus important not only to relate the observations with physical and chemical characteristics at the site, e.g. summarized by the alimony as in the GFI, i.e. food and oxygen supply (*sensu* Hahn, 2006), but also with the less-easy-to-describe exchange and recharge patterns characterizing the respective part of the aquifer. These three groups of varying type and quality of recharge are intertwined due to spatial and temporal heterogeneity.

Hydrological definitions of groundwater

"Ground water means different things to different people" (Holmes, 2000). Technically, one definition of groundwater is: "cohesive subsurface water that moves as a result of gravity" (DIN (German Institute for Standardization), 1994; 4049, part 3). However, major parts of some rivers that flow largely subsurface correspond to this definition as well and still cannot convincingly be classified as groundwater from a biological point of view. Another definition is: "Ground water (is) any water that has not yet exchanged with surface water" (Holmes, 2000). By this definition, only water entering from the ground through infiltration is classified as groundwater, and water recharging from stream or lake beds is not. While usually there is a net discharge of groundwater to streams, seasonal floods will turn around the flow direction for limited periods of time, facilitating the exchange with surface water. Consequently, the majority of groundwater bodies receive input from surface waters at least temporally and this temporal inflow shapes the subsurface water at the respective site sustainably. According to the latter definition, large parts of alluvial groundwater reserves would then be actually surface water reserves below the surface. Instead, we favour the statement that there are "different groundwater layers in the alluvium... that have relatively complex relationships with the surface water" (Négrel et al., 2003).

Except for extreme cases, the starting point of groundwater is upgradient recharge from precipitation. Recharge from precipitation and interception through soil (we use the term soil-derived recharge here) is slow. In temperate regions, it may be approximately estimated as 30% of the annual rainfall (Lerner, 1996). With temperate annual rainfall around 900 mm/y, these 30% would amount to around 0.0008 m/d, but this recharge occurs over most groundwater/surface ecotones where there are no confining layers. Recharge from rivers, streams and lakes occur only at the specific interfaces, so is generally more concentrated than recharge at the groundwater/vadose zone ecotone. However, because sediments at these interfaces are often not consolidated but rather are characterized by gravels, this recharge may be comparably fast (0.01 m/d; Conant, 2004). It also occurs usually only during specific periods, because usually the net flux of groundwater is directed towards the surface, not *vice versa*. However, where and when recharge from rivers occurs, it replenishes the subsurface sustainably and this recharge, although spatially and temporally discrete, may shape that zone of the aquifer to a greater distance. Of course, precipitation does not stop at a river's or lake's shores and thus, these two types of recharge may also overlap in space and time.

While the recharge velocity from interception is usually low, the area over which the two different recharge types occur may differ so immensely in size that the net recharge from interception via soil is probably much higher on the aquifer scale than that from stream/surface water interactions. Exceptions are dry regions and confined aquifers. However, at the spatially restricted zones where recharge from streams occurs, the high exchange intensity may override other parameters such as geology, water chemistry, and climate. The latter factors will probably play the major role in soil interception recharge zones because the exchanges are slower.

This complexity in hydrological and subsequent physical/chemical features stretches over spatial and temporal scales. In our opinion this complexity can, however, be split into three