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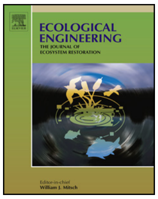

The use of crustaceans as sentinel organisms to evaluate groundwater ecological quality

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ABSTRACT

Criteria for the evaluation of groundwater quality are essentially based on the physical and chemical characteristics of the water, but biological and ecological indicators are needed to estimate groundwater ecosystem disturbance correctly. Such ecological evaluations may use communities (of micro- or macro-organisms) as disturbance indicators, but the density and diversity of groundwater fauna can be too low to permit effective evaluation. In these cases, the use of sentinels (i.e., caged organisms in situ) may complement physical and chemical indicators in the assessment of subterranean ecosystems. We tested the use of aquatic crustaceans (Amphipoda and Isopoda) as sentinel organisms by caging and exposing them in piezometers. In a first step, four species were tested in six piezometers located in the east Lyon aquifer, located upstream and downstream of three urban storm-water infiltration basins. In a second step, we used two species: the epigean Amphipoda *Gammarus pulex* for a short-duration exposure (one week) and the stygobite *Niphargus rhenorhodanensis* for a long-duration exposure (one month). Sentinels were tested in four infiltration basins, using upstream (control) and downstream (impacted) piezometers, on three occasions in 2010 and 2011 and in the laboratory using three types of water with increasing pollution. Infiltration of storm water induced a decrease in dissolved oxygen (DO) and an increase in dissolved organic carbon (DOC) between control and impacted piezometers. We therefore proposed a Water-Quality Index (WQI) based on the ratio of DO to DOC concentrations in groundwater. We measured the survival rates and the levels of body stores (glycogen and triglyceride) at the end of the exposure period. The survival rates of both species, when significantly different, were lower in impacted than in control piezometers, but body-store levels did not change with location. We propose an Ecophysiological Index (EPI) that combines the survival rate and the state of body stores. The EPI of sentinels at the end of each exposure period was negatively correlated with DOC concentrations and positively correlated with WQI for both species; this measure was also positively correlated with DO concentrations for *N. rhenorhodanensis*. Short-term exposure (i.e., one week) of an epigean species (such as *G. pulex*) may be used to assess acute toxic disturbance, while a longer exposure (i.e., one month) of a stygobite organism (here *N. rhenorhodanensis*) may be used to assess diffuse organic pollution and for a global evaluation of groundwater ecological quality if the appropriate ecophysiological indicators are used to estimate stress during exposure.

1. Introduction

Groundwater is a major source of potable and irrigation water in several countries (Zektser and Everett, 2004), but these water resources are under threat due to agriculture (Bohlke, 2002; Legout et al., 2005, 2007: Martin et al., 2006), industry and urbanisation (Datry et al., 2005; Foulquier et al., 2010, 2011; Lerner and Barrett, 1996; Trauth and Xanthopoulos, 1997). All of these

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human activities may endanger groundwater ecosystem health, i.e., a system that can sustain its ecological structure and function (biodiversity, ecological processes) while sustainably providing ecosystem services (Korbel and Hose, 2011). An extensive evaluation of groundwater quality is needed to develop a coherent and efficient protection strategy and to plan restoration programs (Boulton, 2005). Evaluation criteria are principally based on the physical and chemical characteristics of the water (e.g., EU-GWD, 2006; Moura et al., 2011; Wendland et al., 2005, 2008), but many authors and environmental agencies advocate the development of biological and ecological indicators to assess groundwater quality in an ecosystem context (Danielopol et al., 2004, 2006a, 2008; EPA, 2003; Griebler et al., 2010; Stein et al., 2010; Korbel and Hose, 2011). Ecological evaluations of groundwater ecosystems may use communities (of micro- or macro-organisms) as disturbance indicators (Boughrous et al., 2007; Danielopol et al., 2006b, Griebler et al., 2010; Hahn, 2006), but in several cases, the density and diversity of groundwater fauna are too low for efficient evaluation (Deharveng et al., 2009). This difficulty is especially true in areas where freezing in the last glacial period led to depopulation of the groundwater fauna (Castellarini et al., 2007; Dole-Olivier et al., 2009; Gibert et al., 2009). In these cases, sentinels (i.e., caged organisms in situ) may complement the use of physical and chemical indicators in assessing groundwater ecosystems.

Sentinel organisms caged in rivers and streams are regularly used to monitor surface water (Maltby et al., 1990, 2002; Xuereb et al., 2009) post-evaluation. The methods consist of exposing caged organisms for a defined period of time to local physical and chemical stressors in real-life exposure assessments (Schmitt et al., 2010) that evaluate the environment quality after the exposure period. These indicators are generally based on several health status criteria: survival rate (Brown, 1980, Gust et al., 2010), feeding activity (Coulaud et al., 2011; Crane et al., 1995; Forrow and Maltby, 2000), physiological rates (e.g., respiration, Gerhardt, 1996; vitellogenesis, Xuereb et al., 2011) and life-history traits (e.g., reproduction, Gust et al., 2011; Schmitt et al., 2010). The organisms used in monitoring surface water in situ are very diverse and include molluscs (Schmitt et al., 2010; Taleb et al., 2009), crustaceans (Coulaud et al., 2011; Debourge-Geffard et al., 2009; Maltby, 1995; Maltby and Crane, 1994) and fish (Hanson, 2009). Macro-faunal communities in groundwater ecosystems are dominated in most cases by crustaceans (Gibert and Culver, 2009). If caged sentinels are used to monitor groundwater, macrocrustaceans are the most appropriate species to sample and manipulate for field exposure.

The main objectives of this work were (1) to establish a new method for the evaluation of groundwater ecological quality based on organisms caged in situ, (2) to test the efficiency of this method in an urban aquifer disturbed by storm-water infiltration, and (3) to propose an ecophysiological index based on sentinel survival rate and ecophysiological state (body store levels). We tested four different crustacean species, of which we used two upstream and downstream of four storm-water infiltration basins in the eastern Lyon aquifer (France). In this area, infiltration basins are widely used to drain storm water from urban areas because of the lack of superficial watercourses or nearby sewer networks and the high hydraulic conductivity of the soil. In France, they are most often used to reduce peak flows and volumes of downstream surface waters or sewers (limitation of flood effects) and/or to favour groundwater recharge. They are also used for their proposed role in the efficient removal of pollutants, especially heavy metals and some hydrocarbons (Barraud et al., 1999; Dechesne et al., 2004; Le Coustumer et al., 2007). However, the impact of infiltration systems on groundwater quality over time remains to be verified, and monitoring systems have yet to be developed. Addressing this question is one of the challenges of this work.

2. Site description

Four infiltration basins (artificial recharge systems) were used in this study. They are located in the eastern and southern parts of the city of Lyon, France (Fig. 1). The first infiltration basin (IUT, 45.7870 N, 4.8825 E) is located near the University Technological Institute of the University Lyon 1 Campus; it has an unsaturated zone of 2.8 m depth and a catchment area of 2.5 ha, with teaching and research buildings, parking lots, roads and lawns. The infiltration surface is 0.08 ha, with an annual recharge of 9.7 $m^3 m^{-2}$. The Django–Reinhardt infiltration basin (DjR, 45.7366 N, 4.9577 E) has an unsaturated zone 13 m in depth and a catchment area of 185 ha, which is composed of industrial buildings and roads; the infiltration surface is approximately 0.8 ha, and the annual recharge is 73.5 $m^3 m^{-2}$. The Minerve infiltration basin (MIN, 45.7153 N, 4.9154 E) has an unsaturated zone 3.2 m in depth and a catchment area of 270 ha. It is dominated by urban land use (commercial centres, lawns and large roads), and its infiltration surface is 0.39 ha, with an annual recharge of 202 $m^3 m^2$. Finally, the Granges Blanches infiltration basin (noted as GB, 45.6581 N, 4.8954 E) has an unsaturated zone 1.7 m in depth and a catchment area of 100 ha, which is mostly covered by intensive cultures (corn and wheat), small houses and roads. Its infiltration surface is 0.4 ha, and the annual recharge is 73.1 $m^3 m^{-2}$. All of the catchments are drained by a separate storm-water sewer network, the outlets of which are the infiltration basins.

3. Material and methods

3.1. Groundwater quality

To evaluate groundwater quality, water was sampled using a hand-pump technique based on the Bou–Rouch pumping method (Bou, 1974; Bou and Rouch, 1967). After 40 L was pumped to wash the piezometer completely, the temperature, electric conductivity, dissolved oxygen, and pH were measured (HQ20, HACH^{TM}, Dusseldorf, Germany) and 1 L of groundwater was sampled, stored in a cooler box and returned to the laboratory for chemical analyses. We measured seven chemical parameters: alkalinity (by potentiometry, Radiometer), chloride, sulphate, nitrate (ionic chromatography, Dionex DX120), ammonium, soluble reactive phosphorus (SRP, by spectrometry, Smartchem 200) and dissolved organic carbon (DOC, Pyrolysis and InfraRed detection, Bioritech OIA 1010 and Shimadzu TOC V). In addition, 42 volatile organic compounds (VOCs, head-space gas chromatography/mass spectrometry (HS-GC/MS), Agilent Technologies) and 24 polycyclic aromatic hydrocarbons (PAHs, GC/MS after solid-phase extraction (SPE), Agilent Technologies) were measured in the groundwater in triplicate (using three different piezometers) at the beginning and at the end of each exposure period ($n = 6$ for each mean value), except for the DjR basin where only one (upstream location) or two piezometers (downstream location) were available ($n = 2$ and $n = 4$, respectively).

Pesticides are difficult to detect in groundwater, especially in urban areas, because of their low concentrations (Gonzalez et al., 2008); we thus decided to test an integrative sampling technique (Polar Organic Chemical Integrative Sampler, POCIS, Pharm-sorbent, Exposmeter SA, Tavelsiö, Sweden) during the last study period, upstream and downstream of the four infiltration basins. This method allows a wide screening of targeted pesticides below standard detection limits (Kot et al., 2000). Two successive exposure periods of two weeks each were used (i.e., from the