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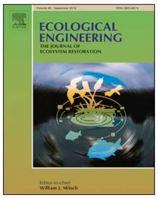

Does the efficiency of grazer introduction to restore and preserve the hydraulic performance of infiltration basins depend on the physical and biological characteristics of the infiltration media?

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ABSTRACT

Groundwater constitutes the principal source of drinking water in Europe but the increase of urbanized impervious surfaces reduced the natural recharge of aquifers. To bypass this problem, infiltration systems have been largely developed for groundwater recharge. Nevertheless, the hydraulic performance of these systems is often altered by physical and biological clogging. The present study aimed to experimentally quantify the impact of a grazer (*Viviparus viviparus*) on hydraulic conductivity of three infiltration basins differentially clogged by benthic algal mat. The influence of the gastropod was also measured on the physical (proportion of silt and clay particles) and biological (algal biomass, bacteria abundance, total organic carbon, gross photosynthetic and hydrolytic activities) of the top layer of the infiltration media. We expected that grazers would have the highest influence on hydraulic performance of basin presenting the highest algal biomass. Our results showed that: (i) the grazers had a positive influence on hydraulic conductivity in the three basins; (ii) these positive effects were not significantly influenced by the initial conditions (algal biomass) in the three basins; and (iii) the impact of the grazers on hydraulic conductivity was not restricted to the removal of biofilm biomass by trophic action but may be also associated with bioturbation activities (pelletization and sediment reworking of the top sediment layer). While management practices developed to improve hydraulic performance of infiltration basins mainly focus on costly and non-environmentally friendly actions (e.g. mechanical sediment scraping), this study highlights the opportunity to consider alternative ecological solutions using the trophic and/or the bioturbation activities of animals.

1. Introduction

Groundwater constitutes the principal source of drinking water for Europeans as about 75% of the inhabitants of the EU rely on groundwater for their water supply (Gibert, 2001). Nevertheless, groundwater quantity and quality are threatened by increasing pressures due to growing populations and human activities (agriculture, industrial activities). In addition, increases of impervious surfaces associated with urbanization reduced the natural recharge of aquifer by soil infiltration. To circumvent this problem, infiltration systems are used worldwide in urban areas for groundwater recharge from various sources such as stormwater or surface water (Dillon, 2005). Managed aquifer recharge (MAR) using infiltration basins has been largely developed in metropolitan areas to optimize and increase groundwater resources (Bouwer, 2002). Nevertheless, the hydraulic performance of infiltration systems is often altered by clogging (Knowles et al., 2011).

Clogging can be caused by physical (pore occlusion by fine inorganic particles), biological (excessive biofilm growth) or chemical (e.g. calcium carbonate precipitation) processes. A short-term solution to increase infiltration capacities is to mechanically remove the clogged layer of infiltration medium, but the cost of soil/sediment scraping is high (Gette-Bouvarot et al., 2015). Moreover, the top layer of the soil/sediment in these systems plays a key role in organic matter (OM) decomposition and nutrient cycling (Abel et al., 2014; Battin and Sengschmitt, 1999), and its replacement can alter the water purification capacities of the infiltration system. To prevent these negative aspects associated with the management of infiltration basins, ecological solutions have recently been explored to improve the hydraulic performance of clogged infiltration basins by manipulating ecological processes such as bioturbation or trophic interactions. For example,

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tubificid worms could be efficient actors in aquatic sediments impacted by clogging of the top sediment surface with fine particles (Navel et al., 2011; Nogaro et al., 2006). By their bioturbation activities (i.e. creation of galleries), worms create water pathways in the clogged sediment layer, thus increasing hydraulic conductivity. More recently, Gette-Bouvarot et al. (2015) showed that introduction of grazers could limit clogging of infiltration systems impacted by the proliferation of phototrophic biofilms at the sediment surface, forming a microbial mat (so-called algal mat) mainly composed of algae and bacteria (Geesey et al., 1978). Although literature already reported significant reduction of benthic algal development due to grazing (e.g., Steinman, 1996; Hillebrand et al., 2007), the study of Gette-Bouvarot et al. (2015) was the first to demonstrate that increasing grazing pressure could be an efficient way to ameliorate hydraulic performance of infiltration systems impacted by bioclogging. Nevertheless, this positive role of grazers on hydraulic performance has been only demonstrated in one infiltration basin characterized by a particular clogging due to benthic algal biofilms. We can expect that the influence of organisms on hydraulic conductivity of infiltration systems is highly dependent on soil/sediment properties. Indeed, the role of benthic organisms which act as ecosystem engineers (i.e., organisms that modify the physical environment and regulate the availability of resources for other species, Jones et al., 1994) at the water-sediment interface has been shown to be significantly modulated by the sedimentary context (e.g., Navel et al., 2012). For example, Nogaro et al. (2009) and Nogaro & Mermillod-Blondin (2009) showed that the effects of tubificid worms on hydraulic conductivity were only positive when sediment characteristics (grain size distribution, quantity of OM) allowed worms to produce stable and vertical galleries in the clogged sediment layer. Navel et al. (2012) also demonstrated that the positive influence of ecosystem engineers on hydraulic conductivity was at its highest in the most clogged systems.

For animals acting as grazers, such context-dependent effect has never been demonstrated in infiltration systems clogged by benthic algae while understanding the interactions between herbivore pressure and biofilm characteristics is essential to provide sustainable ecological solutions (Bulleri et al., 2012). The present study therefore aimed to assess the influence of grazers on hydraulic conductivity under various physical and biological characteristics of the infiltration medium. Then, we measured the grazing effects of a gastropod on phototrophic biofilm and associated hydraulic conductivity in three contrasted infiltration basins. A field experimental approach based on *in situ* enclosures was used to measure the influence of the gastropod prosobranch *Viviparus viviparus* (L.) on hydraulic properties, sedimentary and benthic biofilm characteristics of the three basins. We coupled *in situ* measurements of hydraulic conductivity with abiotic (grain size distribution) and biotic (algal biomass, total bacterial abundance, total organic carbon, photosynthetic activity, hydrolytic activity) analyses. These analyses were performed on the top layer of sediment structure (0–1 cm), involved in the clogging of infiltration basins (Gette-Bouvarot et al., 2014; Gette-Bouvarot et al., 2015). According to context-dependent responses observed for ecosystem engineers (Gutiérrez et al., 2003; Navel et al., 2012), it is expected that the highest influence of grazers on hydraulic conductivity would be obtained in the system the most clogged by algal biomass.

2. Materials and methods

2.1. Study site

The experiment was set up in the pumping well field of «Crépieux-Charmy» (375 ha) which provides drinking water for the metropolitan area of Lyon (1,280,000 inhabitants supplied). Infiltration basins have been built to recharge aquifer with river water. All basins are fed with water from the "Vieux Rhône" channel of the Rhône River. To test the context-dependent effect of grazers on infiltration capacities, we selected three infiltration basins (called A, B, C) highly contrasted in terms of hydraulic conductivity and benthic biofilm characteristics (see section 3.1). Although several benthic invertebrates occurred in these basins (Gette-Bouvarot et al., 2015), the introduced species *V. viviparus* was not present at the start of the experiment.

During the course of the experiment, the artificial supply of water has been maintained in the three basins to ensure a water column varying from 1.0 to 1.8 m according to usual basin management. Monitoring of *in situ* temperature showed comparable fluctuations (between 14.7 and 24.6 °C) for the three basins during the experiment. We also measured weekly *in situ* conductivity, pH, and dissolved oxygen (DO) concentrations in the water column of the basins to characterize the physico-chemistry of the water column. These measurements were performed with HQ40D multiparameter probe (HACH). Mean (± standard deviation) of conductivity, pH and DO were 337 (± 13) $\mu S.cm^{-1}$, 8.3 (± 0.3), and 9.4 (± 0.5) $mg.L^{-1}$, respectively. Nutrient concentrations were also weekly measured and obtained from filtered water (0.7 µm) conserved at 4 °C before analysis within 24 h with a sequential analyzer (SmartChem 200, AMS Alliance, Frépillon, France) using colorimetric methods (Grasshoff et al., 1983). Comparable oligotrophic conditions were found in the three basins with concentrations of NO_3^-, NH_4^+ and PO_4^{3-} of 4.4 (± 0.9) $mg.L^{-1}$, 42.1 (± 25.9) $\mu g.L^{-1}$ and 37.7 (± 28.4) $\mu g.L^{-1}$, respectively.

2.2. Experimental design

The experiment lasted for 6 weeks, from the 17th of September to the 22nd of October 2014. Each of the three selected basins were equipped with 12 *in situ* enclosures (see the description in Gette-Bouvarot et al., 2015), allowing to test two treatments (presence/absence of *Viviparus viviparus*) with six replicates per treatment. Briefly, enclosures consisted of stainless steel cylinders (internal diameter of 30 cm, height of 14 cm) firmly buried in the sediment at a depth of 11 cm and covered with nylon nets (0.5 cm mesh size). They were disposed in the center of the basins to prevent from bank effects and to select a zone with a homogeneous colonization of benthic biofilm. The enclosures receiving *V. viviparus* (6 enclosures per basin) were randomly selected at the start of the experiment. Introduced specimens of *V. viviparus* were collected in a cut off channel of the Rhône River located at less than 1 km from infiltration basins. They were acclimated in aquariums filled with sediment and water from the basins for 15 days before the start of the experiment. A density of 100 $individuals.m^{-2}$ was introduced per enclosure (5 individuals per enclosure) to mimic natural densities observed in freshwater habitats (Jakubik, 2012).

Measurements were performed at the start (t_0) and at the end (t_f) of the experiment to determine mean hydraulic conductivity, grain size distribution (percentages of fine particles < 63 µm that could be responsible for hydraulic conductivity reduction) and biological characteristics (algal biomass, bacterial abundance, total organic carbon, microbial enzymatic activity and photosynthetic activity) of the sedimentary interface for each enclosure. For grain size distributions and biological analyses, the top layer (0–1 cm) of sediments was randomly cored in each enclosure at t_0 and t_f using cut syringes (internal diameter = 15 mm). Fifteen samples were collected, mixed and homogenized per enclosure to obtain representative sediment sample for each enclosure and date (t_0 and t_f). In addition, one intact core was collected for evaluating the physiological state of the algal biofilm (gross photosynthetic activity). Sampling was conducted just after the hydraulic measurements, with water in the basin, to prevent any drying and disturbance of sediment and biofilm. All samples were then stored in a cool box during transport to the laboratory within 4 h.

2.3. Hydraulic conductivity measured in enclosures

In situ infiltration measurements were performed in each enclosure under saturated conditions at the start and the end of the experiment before sediment and biofilm samplings. Measurements were done