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Introducing sequential managed aquifer recharge technology (SMART) – From laboratory to full-scale application

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HIGHLIGHTS

- Sequential recharge by establishing multiple redox zones and substrate-limiting conditions.
- Full-scale application of sequential managed aquifer recharge technology (SMART).
- Improved trace organic chemical removal during SMART treatment.
- Effect of sorption to clay on trace organic chemical removal during recharge.

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ABSTRACT

Previous lab-scale studies demonstrated that stimulating the indigenous soil microbial community of groundwater recharge systems by manipulating the availability of biodegradable organic carbon (BDOC) and establishing sequential redox conditions in the subsurface resulted in enhanced removal of compounds with redox-dependent removal behavior such as trace organic chemicals. The aim of this study is to advance this concept from laboratory to full-scale application by introducing sequential managed aquifer recharge technology (SMART). To validate the concept of SMART, a full-scale managed aquifer recharge (MAR) facility in Colorado was studied for three years that featured the proposed sequential configuration: A short riverbank filtration passage followed by subsequent re-aeration and artificial recharge and recovery. Our findings demonstrate that sequential subsurface treatment zones characterized by carbon-rich (>3 mg/L BDOC) to carbon-depleted (≤1 mg/L BDOC) and predominant oxic redox conditions can be established at full-scale MAR facilities adopting the SMART concept. The sequential configuration resulted in substantially improved trace organic chemical removal (i.e. higher biodegradation rate coefficients) for moderately biodegradable compounds compared to conventional MAR systems with extended travel times in an anoxic aquifer. Furthermore, sorption batch experiments with clay materials dispersed in the subsurface implied that sorptive processes might also play a role in the attenuation and retardation of chlorinated flame retardants during MAR. Hence, understanding key factors controlling trace organic chemical removal performance during SMART allows for systems to be engineered for optimal efficiency, resulting in improved removal of constituents at shorter subsurface travel times and a potentially reduced physical footprint of MAR installations.

1. Introduction

The increasing demand for drinking water supplies has resulted in an increased interest in using impaired water sources (e.g., surface water receiving wastewater discharge; recycled water) to supplement aquifers via natural treatment processes such as managed aquifer recharge (MAR). Due to the interplay of hydro-

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geochemical and biological processes during MAR, opportunities exist to improve the water quality of infiltrating water. However, impaired water like recycled water often contains trace organic chemicals (TOrC) including pharmaceuticals, personal care products, household chemicals and emerging disinfection by-products, which are not efficiently removed during conventional biological wastewater treatment (Joss et al., 2006). While MAR is still considered a 'black-box' natural treatment technology, fundamental knowledge about the fate and transport of TOrC and pathogens during subsurface treatment in an aquifer is essential for the assessment and design of MAR facilities (Regnery et al., 2013).

Our previous research under controlled conditions at the laboratory-scale has suggested that the composition and availability of the primary substrate, namely the amount of biodegradable dissolved organic carbon (BDOC) in the recharged source water, plays a major role in influencing microbial community structure and function (i.e., xenobiotic biotransformation capability) in subsurface systems (Rauch-Williams et al., 2010; Li et al., 2012, 2013, 2016; Alidina et al., 2014a, 2014b). In these laboratory-scale soil column systems simulating MAR, lower primary substrate concentrations and a higher humic content in the recharged source water resulted in higher soil microbial diversity at the phyla and species level and promoted biotransformation rates of TOrC during recharge.

Furthermore, several studies identified redox conditions as one of the important driving factors for removal of chemical contaminants in subsurface systems like MAR. Based on extensive field studies, Wiese et al. (2011) stated that redox conditions have the most important impact on removal efficiency of TOrC but added that additional factors such as subsurface travel time, residual threshold concentrations or field site specifics may contribute to removal or might even exceed the importance of predominant redox conditions. The relationship between redox conditions and subsurface travel time, however, and their influence on attenuation is complex and often variable over the range of contaminants and environmental conditions (Regnery et al., 2015a). During simulated MAR at the laboratory-scale, the majority of TOrC show enhanced removal under oxic redox conditions (Burke et al., 2014; Regnery et al., 2015a). Although anoxic to anaerobic subsurface conditions are beneficial for the removal of nitrate (Rivett et al., 2008) or certain substance groups such as certain disinfection by-products (Pitoi et al., 2011), iron, manganese, and other inorganic trace elements are mobilized under reducing subsurface conditions and usually require post-treatment of the recovered groundwater. Main driving factors for redox zonation in MAR systems are the availability of oxidizing agents such as oxygen and nitrate, of reducing agents (organic matter, reduced mineral phases), nutrients, the biological activity of the soil microbial community, and subsurface travel time (Grützmacher and Reuleaux, 2011; Regnery et al., 2013). These drivers are controlled by many natural, site-specific as well as design and operation-related variables. Site-specific variables are among others aquifer geochemistry, indigenous soil microbial community, temperature, or natural groundwater recharge, whereas design and operation-related variables comprise factors such as carbon composition of the recharged source water, distance between infiltration basins and wells, well depth, pumping rate etc. Moreover, a thorough understanding of the role of sorptive processes in MAR may provide opportunities to enhance the attenuation capabilities of MAR facilities. In case of low soil organic carbon (f_{oc}), other sorptive processes such as interactions with mineral surfaces (e.g., clay) gain importance and can increase the effective travel time of compounds (e.g., ionic compounds) compared to the hydraulic residence time, allowing microbes more time for biotransformation and/or mineralization of substances.

The concept of stimulating the indigenous microbial community by manipulation of the primary substrate and establishing sequential redox conditions in the subsurface for enhanced removal of compounds with redox-dependent removal behavior is an approach aiming for optimal residence times based on the degradation kinetics of contaminants present in impaired source water (Regnery et al., 2013). Our goal is to advance this concept from laboratory-to full-scale application by introducing sequential managed aquifer recharge technology (SMART). We hypothesize that a multi-sequence configuration, featuring carbon-rich and predominantly anoxic subsurface conditions followed by carbon-depleted and predominantly oxic conditions, can result in an optimized treatment performance of impaired water related contaminants. As outlined in our previous literature review (Regnery et al., 2013) and illustrated in Fig. 1, a logical and cost-effective treatment train at full-scale features an initial treatment via short riverbank filtration (RBF) passage for the depletion of BDOC and nutrients, exhibiting a transition from oxidizing conditions in the river to reducing conditions in the riverbank. The initial treatment is followed by re-aeration of the recovered RBF water through surface spreading or engineered aeration, returning to a predominantly oxic subsurface passage, but under carbon-depleted conditions for enhanced attenuation of less-degradable compounds. For shallow groundwater, the lifting energy requirement during pumping is in general low and re-aeration can usually be achieved during surface spreading. However, at full-scale application several aspects of surface spreading MAR design must be taken into consideration for maintaining rapid infiltration rates in infiltration basins to prevent algae growth and clogging-related issues.

To validate the concept of SMART at full-scale, we chose a full-scale MAR facility in Colorado that featured the proposed sequential configuration motivated by local water right issues: A short RBF passage, which is subsequently followed by artificial recharge and recovery (ARR) via surface spreading basins. We extensively monitored water quality changes at the full-scale RBF facility during previous studies (Hoppe-Jones et al., 2010; Betancourt et al., 2014; Regnery et al., 2015b) and moreover characterized subsurface heterogeneities (e.g., dispersed clay) and flow paths at the full-scale ARR facility (Parsekian et al., 2014). Here, we evaluate and compare the removal efficiencies of the sequential treatment steps that exhibit distinct differences during groundwater recharge (e.g., redox conditions in the aquifer, organic carbon load in the source water) and discuss further implications for MAR operation using SMART. Besides bulk organic parameters, 19 TOrC were selected for the performance assessment based on their physiochemical properties, occurrence in South Platte River water, and potential to serve as performance indicators for sequential MAR treatment (Drewes et al., 2008; Regnery et al., 2015a). Due to the occurrence of dispersed clay aggregates throughout the MAR site, we performed additional laboratory batch experiments with two different soils from the ARR facility and montmorillonite clay to investigate the role of sorption to clays in attenuation of TOrC during MAR. While different clay materials provide different sorption capacities, it was beyond the scope of this study to develop sorption isotherms or to further characterize the clay materials.

2. Experimental approach

2.1. Field site description

After facing severe drought conditions over a period of several years, the city of Aurora, Colorado, launched the Prairie Waters Project in 2009/2010 to supplement its drinking water supply. A MAR system consisting of RBF galleries and an ARR facility as part of an advanced water treatment train was constructed along the South Platte River in Brighton, Colorado (Regnery et al., 2015b). A