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Effects of dynamic operating conditions on nitrification in biological rapid sand filters for drinking water treatment

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ABSTRACT

Biological rapid sand filters are often used to remove ammonium from groundwater for drinking water supply. They often operate under dynamic substrate and hydraulic loading conditions, which can lead to increased levels of ammonium and nitrite in the effluent. To determine the maximum nitrification rates and safe operating windows of rapid sand filters, a pilot scale rapid sand filter was used to test short-term increased ammonium loads, set by varying either influent ammonium concentrations or hydraulic loading rates. Ammonium and iron (flock) removal were consistent between the pilot and the full-scale filter. Nitrification rates and ammonia-oxidizing bacteria and archaea were quantified throughout the depth of the filter. The ammonium removal capacity of the filter was determined to be 3.4 g NH_4–N m^{-3} h^{-1}, which was 5 times greater than the average ammonium loading rate under reference operating conditions. The ammonium removal rate of the filter was determined by the ammonium loading rate, but was independent of both the flow and influent ammonium concentration individually. Ammonia-oxidizing bacteria and archaea were almost equally abundant in the filter. Both ammonium removal and ammonia-oxidizing bacteria density were strongly stratified, with the highest removal and ammonia-oxidizing bacteria densities at the top of the filter. Cell specific ammonium oxidation rates were on average $0.6 \times 10^2 \pm 0.2 \times 10^2$ fg NH_4–N h^{-1} $cell^{-1}$. Our findings indicate that these rapid sand filters can safely remove both nitrite and ammonium over a larger range of loading rates than previously assumed.

List of abbreviations: A, Cross section area of column (m^2); ALR, Ammonium loading rate (g NH_4–N m^{-3} h^{-1}); AOA, Ammonia-oxidizing archaea; AOB, Ammonia-oxidizing bacteria; ARR, Ammonium removal rate (g NH_4–N m^{-3} h^{-1}); $c_{a,in}$, Influent ammonium concentration (mg L^{-1}); $c_{a,out}$, Effluent ammonium concentration (mg L^{-1}); $c_{n,in}$, Influent nitrite concentration; $c_{n,out}$, Effluent nitrite concentration; DWW, Drained wet weight; NOB, Nitrite oxidizing bacteria; NRR, Nitrite removal rate; NVOC, Non-volatile organic carbon; z, filter depth (m).

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1. Introduction

Biological rapid sand filters are a common treatment process for drinking water production, which combines rapid sand filtration for particle removal with biological processes. They are commonly used to remove biodegradable organic matter (BOM) and ammonium from drinking water (Rittmann et al., 2012). For example, in Denmark drinking water is produced solely from groundwater that is mostly anaerobic, and almost exclusively treated by aeration followed by biological rapid sand filtration. Ammonium can cause nitrification in the distribution system, which can lead to many problems including corrosion, aesthetic problems (taste and odor), decreases in pH, and biological instability (Rittmann et al., 2012). Incomplete nitrification can lead to nitrite accumulation (Wilczak et al., 1996), which is a toxic intermediate of the nitrification process. Ammonium can also negatively affect free chlorine or chloramine residuals, which can lead to insufficient microbial disinfection in distribution systems (Lytle et al., 2013). In regions or countries like Denmark, that do not use disinfectants in the treatment process or in the distribution system, ammonium removal becomes important at the works to prevent microbial after growth in the distribution network. The guideline values for ammonium and nitrite in the effluent of the waterworks in Denmark are 0.05 mg NH_4 L^{-1} (0.04 mg NH_4–N L^{-1}) and 0.01 mg NO_2 L^{-1} (0.003 mg NO_2–N L^{-1}) (Miljøministeriet, 2014), which are significantly lower than the EU drinking water directive of 0.5 mg L^{-1} for NH_4 and NO_2.

Nitrification is a two-step biological process conducted by autotrophic bacteria and archaea (Niu et al., 2013). First ammonia-oxidizing bacteria (AOB) or archaea (AOA) oxidize ammonium to nitrite, which is then oxidized to nitrate by nitrite oxidizing bacteria (NOB). In both steps oxygen is the electron acceptor (Metcalf et al., 2004).

Although nitrification in biological filters is a commonly used treatment technology for removing ammonium from drinking water, the process can experience problems. Incomplete ammonium or nitrite removal can be caused by several factors including temperature (Aa et al., 2002; Andersson et al., 2001; Kors et al., 1998), insufficient oxygen (Lytle et al., 2013), phosphate (nutrient) limitations (De Vet et al., 2012), and improper design and operation of filters (Lopato et al., 2013). Filters can also experience problems with nitrification due to ammonium loading rates that exceed the maximum removal rates of the filter. For groundwater, temperatures are quite stable, but filters can often operate under other dynamic conditions, and can experience sudden, large shifts in hydraulic and ammonium loading rates that could exceed the nitrification capacity of the filters, causing elevated levels of ammonium and nitrite in the effluent. Lopato et al. (2013) observed that the inlet ammonium concentration and hydraulic loading rate more than tripled in a matter of hours in biological rapid sand filters treating groundwater. These sudden changes can be caused by filter hydraulics, changes to operating parameters in upstream processes, shifts in abstraction wells, and consumer demand.

Several methodological approaches have been applied to study nitrification in drinking water filters. Tatari et al. (2013) used lab scale column assays, without backwashing, to determine nitrification biokinetics. Others have studied nitrification using lab scale batch experiments (De Vet et al., 2012; Kihn et al., 2000), pilot columns, and full scale filters (Kihn et al., 2002; Lopato et al., 2011). This study employs a pilot scale rapid sand filter designed to replicate full-scale filter performance, with the ability of obtaining depth profile information.

The aim of this research was to examine the effects of sudden increases of ammonium loading on nitrification, and to determine a safe operating window, in terms of influent ammonium concentrations and hydraulic loading rates, in which these filters could operate and still produce water that meets regulatory guidelines. The pilot rapid sand filter was set up at a local waterworks (Islevbro, Copenhagen Denmark), which supplies drinking water to the Copenhagen metropolitan area. After validation of the pilot rapid sand filter, short term ammonium upshift experiments were conducted at varying influent ammonium concentrations and hydraulic loading rates. The maximum ammonium removal rates (ARR) were determined, and quantification of AOB using real-time quantitative PCR (qPCR) was used to directly quantify AOB on the filter media.

2. Materials and methods

2.1. *Islevbro water works and pilot plant*

Islevbro water works treats anaerobic groundwater, with the main compounds of concern being ammonium and reduced forms of iron and manganese. The full-scale treatment train consists of aerators, followed by a contact chamber that provides an additional hour of contact time for iron oxidation. The aerated water then passes through up-flow primary filters designed to remove the majority of the iron from the water. After this the water flows through down-flow submerged biological rapid sand filters designed to remove ammonium and manganese, and which serves as a polishing filter for any residual iron. The secondary filters have an active depth of 0.7 m on top of 0.3 m of coarse grained support material, and are operated at an average hydraulic loading rate of 4.0 m h^{-1} (volumetric flow rate (m^3 h^{-1}) divided by the cross sectional area of the column (m^2)). Specific operating and design parameters for the full scale filter and pilot column are shown in Table 1A in the supplementary information and in Lee et al. (2013).

The hydraulic loading rate and water quality varied in the full-scale waterworks filters. An example of the changing ammonium concentration in the inlet water of the pilot and full-scale filters is shown in Fig. 1. Ammonium varies rapidly, by almost a factor of five, and the hydraulic loading rate of the full-scale filters has been observed to double in a few hours. Average influent concentrations (with standard deviations) to the full scale after filter were 0.13 ± 0.05 mg NH_4–N L^{-1}, 0.38 ± 0.16 mg Fe L^{-1}, and 0.04 ± 0.01 mg Mn L^{-1}, and NVOC was approximately 2.4 mg L^{-1} in the influent and effluent of the waterworks. NVOC is generally not highly removed in these filters. Other influent and effluent water parameters, for the full-scale filters and pilot column, are shown in Table 1.