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A novel bench-scale column assay to investigate site-specific nitrification biokinetics in biological rapid sand filters

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ABSTRACT

A bench-scale assay was developed to obtain site-specific nitrification biokinetic information from biological rapid sand filters employed in groundwater treatment. The experimental set-up uses granular material subsampled from a full-scale filter, packed in a column, and operated with controlled and continuous hydraulic and ammonium loading. Flowrates and flow recirculation around the column are chosen to mimic full-scale hydrodynamic conditions, and minimize axial gradients. A reference ammonium loading rate is calculated based on the average loading experienced in the active zone of the full-scale filter. Effluent concentrations of ammonium are analyzed when the bench-scale column is subject to reference loading, from which removal rates are calculated. Subsequently, removal rates above the reference loading are measured by imposing short-term loading variations. A critical loading rate corresponding to the maximum removal rate can be inferred. The assay was successfully applied to characterize biokinetic behavior from a test rapid sand filter; removal rates at reference loading matched those observed from full-scale observations, while a maximum removal capacity of 6.9 g NH_4^+–N/m^3 packed sand/h could easily be determined at 7.5 g NH_4^+–N/m^3 packed sand/h. This assay, with conditions reflecting full-scale observations, and where the biological activity is subject to minimal physical disturbance, provides a simple and fast, yet powerful tool to gain insight in nitrification kinetics in rapid sand filters.

1. Introduction

Biological rapid sand filtration is widely used in drinking water production to remove ammonium, iron and manganese from groundwater. Ammonium is sequentially oxidized by autotrophic microorganisms to nitrite and nitrate with oxygen as the electron acceptor. Complete nitrification is required in the treatment to limit microbial growth in the distribution system (Chu et al., 2005), to prevent accumulation of toxic nitrite (Lytle et al., 2007) and potential consumption of oxygen and disinfectant residual (Zhang et al., 2009).

Nitrification performance is often evaluated based on effluent concentration with little focus on the actual nitrification mechanism (Zhu et al., 2010). As a result, filter design and operation are mostly based on empirical rules (Lawler and Nason, 2006). Similarly, cases of poor filter performance are in

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List of abbreviations

A	Cross sectional area (cm^2 for lab-scale, m^2 for full-scale)
B_V	Volumetric NH_4^+ loading rate (g NH_4^+–N/m^3 packed sand/h)
D	NH_4^+ diffusivity in water at 10 °C (cm^2/h)
d	Filter depth (m)
d_p	Filter material particle diameter (cm)
δ_{ext}	External mass transfer boundary layer thickness (μm)
$F(\theta)$	Normalized tracer concentration
θ	Normalized time
ε	Porosity
k	1st order fitting constant (m^{-1})
N	Tanks in series
Q_{IN}	Influent flowrate (mL/h for lab-scale, m^3/h for full-scale)
$Q_{C,R}$	Lab-scale recirculation flowrate (mL/h)
R	Recirculation ratio
R_L	External mass transfer resistance (h/cm)
r_V	Volumetric removal rate (g NH_4^+–N/m^3 packed sand/h)
$r_{V,P}$	Full-scale volumetric removal rate predicted by 1st order decrease in NH_4^+ concentration with depth (g NH_4^+–N/m^3 packed sand/h)
Re	Reynolds number
S	Effluent NH_4^+–N concentration (mg/L)
S_{IN}	Influent NH_4^+–N concentration (mg/L)
S_P	NH_4^+–N concentration at 0.1 m filter depth predicted by 1st order decrease in NH_4^+ concentration with depth (mg/L)
S_T	Tracer concentration (mg/L)
$S_{T,0}$	Injected tracer concentration (mg/L)
Sc	Schmidt number
Sh	Sherwood number
t	Time (h)
τ	Hydraulic retention time (h)
u	Superficial velocity (m/h)
V	Packed sand volume (cm^3 for lab-scale, m^3 for full-scale)
V_d	Packed sand volume of a full-scale filter section with depth d (m^3)
*	Subscripts used: "$_{FS}$" for full-scale and "$_C$" for lab-scale column

general not thoroughly investigated but experience based remedial solutions are attempted, even though they may not resolve the problem. Stronger insight in nitrification kinetics can reveal potential process limitations, and diagnostic tools are necessary to help a targeted optimization strategy.

Kinetic insights can be derived from full-scale investigations (Parker et al., 1997; Lopato et al., 2012), although these studies are typically limited in the narrow range of operational conditions. On the contrary, with offline experimentation a wider range of conditions can be tested according to specific objectives. In these cases, sampling of filter material from the full-scale filter is required and the obtained kinetic characterization is site-specific. Site-specific investigations can, for example, seek to provide information on the distribution of nitrification activity with depth in a filter, detect inactive filter zones or quantify nitrification potential in deep filter regions.

Molecular diagnostic tools are being explored to identify the presence and abundance of nitrifying communities in biological filters (de Vet et al., 2011). However, kinetic information cannot be extrapolated from microbial abundances, but requires monitoring of the specific biological response to a change of target substrate. Furthermore, in rapid sand filters the biological activity is associated with the filter material forming some type of biofilm with specific characteristics that potentially affect or control nitrification kinetics (Rittmann, 1982; Chen et al., 2006). To obtain truly representative kinetic information on the processes in a filter, it is therefore essential to maintain the biofilm structure and other physical system properties during the assay. Several lab-scale assays use mechanical stirring of the filter material (Kihn et al., 2000; de Vet et al., 2009), but here it is likely that the microbes are gradually lost by mechanical abrasion and shear. Certainly, methods where the biomass is intentionally detached before the biokinetic measurements (Madoni et al., 2001) cannot capture the surface associated microbial activity. Instead, assays are needed where biofilm integrity and physical properties are maintained.

Biofilm-based degradation kinetics for a specific substrate can be derived in packed column set-ups from the response to short-term loading rate changes (Rittmann et al., 1986; Smets et al., 1999). This approach is applied in the present study to develop a bench-scale assay that minimizes alteration of biofilm properties and maintains antecedent conditions encountered in full-scale rapid sand filters. The assay aimed to quantify nitrification activity at full-scale relevant conditions and to identify the critical ammonium loading where the maximal nitrification activity is observed for the investigated filter sample. The approach uses a small packed-bed column, filled with sampled filter material and operated at steady and transient ammonium loading levels. The assay employed well controlled hydraulic conditions, and the inferred nitrification behavior was compared to full-scale observations.

2. Materials & methods

2.1. Design of the bench-scale assay

The assay was designed to be conceptually a mixed biofilm reactor, where surface associated biomass properties are maintained and mixed hydraulics prevent localization of nitrification activity. The experimental set-up consisted of a downflow plexiglas column packed with material from a full-scale rapid sand filter, a recirculation loop and a mixing vessel (Fig. 1). These three elements composed the mixed biofilm system with boundaries point B for the influent and point F for the effluent (Fig. 1). Column dimensions were small to