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Examining biological sand filters for drinking water treatment as biofilm reactors: experimental and modeling approach

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Rapid sand filtration is a widespread technology in drinking water treatment. Operation is simple and aims to retain particles and remove compounds such as NH_4^+, Fe and Mn. Filter design and operation is mainly based on rules of thumb. Lack of knowledge on the specific processes taking place in the filters limits optimization of filter performance. NH_4^+ is removed biologically by autotrophic microorganisms attached on the sand grains. The conventional approach considers a rapid sand filter as a homogenous unit and nitrification rate is averaged over filter depth. In this study we approach a rapid sand filter as a biofilm reactor aiming to interpret and predict filter performance. The study was composed of NH_4^+ depth profiling in a full scale filter, core sampling of sand and nitrification activity measurements in different depth layers with a lab scale assay. Experimental observations were interpreted with a biofilm model ultimately used to predict full scale filter performance.

Islevbro waterworks, Denmark was selected for the experimental investigations. The facility consists of two filtration stages. Influent NH_4^+ is mostly removed in the after filters to comply with the guideline value (0.05 mg/L). A multi level water sampler was installed in the full scale filter. Water samples were collected every 5-10 cm depth up to 40 cm to construct the NH_4^+ depth profile in the filter (Figure 1). Influent NH_4^+ was removed within the upper 10 cm of the filter in all sampling rounds.

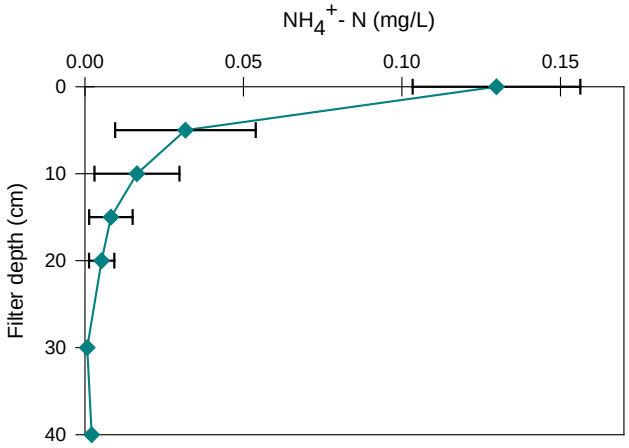

Figure 2: NH_4^+ depth profile in the full scale filter

Sand was sampled from three depths of the full scale filter: 0-10 cm, 20-30 cm and 35-50 cm with a core sampler. Nitrification activity of the three filter regions was quantified in a lab scale assay. The experimental set up consisted of three independent columns, each packed with sand from one depth layer. Column dimensions were small (5 cm bed height and 2.6 cm inner diameter) to avoid stratification of nitrification activity within the lab-scale column. The columns were continuously fed with a 1 mg/L NH_4^+ solution and the influent flowrate was adjusted to obtain the same NH_4^+

volumetric loading rate of in the full scale filter. The effluent was monitored for all nitrogen species and dissolved oxygen.

To determine nitrification kinetics, the loading rate was increased for short periods of time (3-5 h) by increasing the influent flowrate. Volumetric removal rate was calculated from the NH_4^+ flux normalized over the packed sand volume in the for the three investigated filter depths (Figure 2).

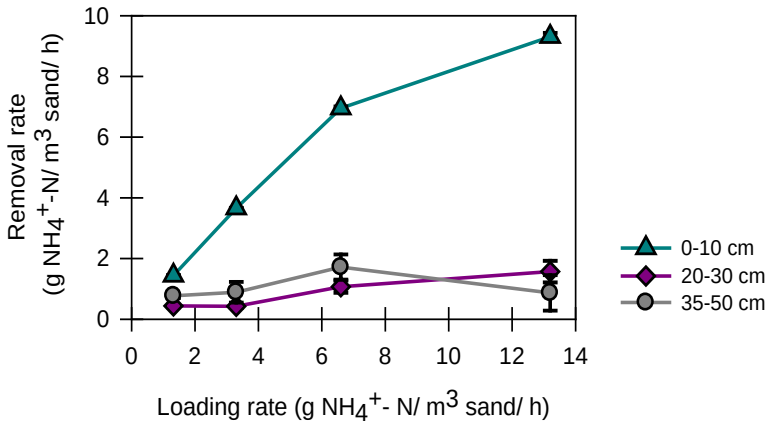

Figure 2: Volumetric NH_4^+ removal rate observed in the lab scale assay for sand obtained from three full-scale filter depths.

Sand from the top 10 cm was significantly more active than deeper layers of the filter reaching removal rates up to 10 times higher compared with the middle and bottom filter layers. This clearly showed that nitrification activity was stratified with filter depth. These observations were supported by the full scale filter NH_4^+ profile, where NH_4^+ was mainly removed in the top 10 cm. Lower nitrification rates in the deeper layers were a result of low substrate concentration available for nitrifying microorganisms in these depths. However, nitrification activity detected here may function as extra nitrification capacity in case NH_4^+ is pushed deeper in the filter.

The lab scale observations were interpreted by a model that considered a biofilm attached on the external surface of the sand grains. Biofilm thickness was 30 µm as estimated by microscopic images. Cell abundance of specific microorganisms (ammonium and nitrite oxidizers) as determined by qPCR measurement was used to define the biofilm composition. The model assumed diffusion of substrates (NH_4^+ and O_2) through a boundary layer with a calculated thickness of 40 µm. Two step nitrification with intermediate NO_2^- production was considered and the model was fitted to the experimental results to estimate kinetic parameters.

The next step aimed to combine the lab scale column models for the different depth layers into a full scale filter model. Conceptually the full scale filter can be split into fractions, each of them approximated by one lab scale column model. Connecting the models of the different depths in series can simulate the performance of the full scale filter, predicting the NH_4^+ and NO_2^- effluent concentrations at a range of influent loading rate conditions. Loading rate variations are common due to switching between abstraction wells that have different water quality. These variations are a suspected cause of NH_4^+ breakthrough in several filters.

In this study we examined nitrification activity stratification in a filter. This differs from the traditional column approach, where NH_4^+ removal is averaged over filter depth. Nitrification activity was concentrated at the top of the filter. Physical observations were used to build a biofilm reactor model that interprets and predicts filter performance.