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Reducing natural organic matter and disinfection by-product precursors by alternating oxic and anoxic conditions during engineered short residence time riverbank filtration: A laboratory-scale column study

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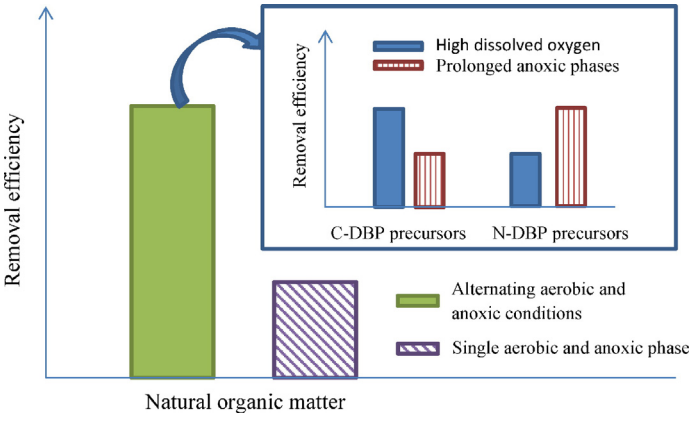
HIGHLIGHTS

- Engineered river bank filtration was tested with 6 days retention time.
- Organic matter and disinfection by-product precursor removal ranged from 40 to 90%.
- Alternating oxic and anoxic conditions increased overall performance.
- High dissolved oxygen availability favours C-DBP precursor removal.
- Prolonged anoxic phases favour N-DBP precursor removal.

GRAPHICAL ABSTRACT



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ABSTRACT

Riverbank filtration (RBF) with days to months of residence time has been successfully used as treatment or pre-treatment process to improve water quality for decades. However, its feasibility depends on the local hydrogeological conditions. Therefore, for sites unsuitable to traditional RBF, a smaller engineered RBF may be an option. This study evaluates the performance of engineered short residence time RBF on improving water quality, focusing on the removal of natural organic matter (NOM) and the reduction of precursors of carbon and nitrogen disinfection by-products (DBP).

Acronyms: BCAN, bromochloroacetonitrile; BDCM, bromodichloromethane; BDOC, biodegradable dissolved organic carbon; BIF, bromine incorporation factor; C-DBPs, DBPs containing carbon, but no nitrogen; CH, chloral hydrate; DBAN, dibromoacetonitrile; DBCM, dibromochloromethane; DBP, disinfection by-product; DBP FP, disinfection by-product formation potential; DCAN, dichloroacetonitrile; DO, dissolved oxygen; DOC, dissolved organic carbon; EEM, excitation emission fluorescence matrix; GC-ECD, gas chromatograph with ^{63}Ni electron capture detector; HAAs, haloacetic acids; HANs, haloacetonitriles; HAN4, sum of the concentrations of TCAN, DBAN, BCAN, DCAN; HKs, haloketones (halopropanones); HK2, sum of the concentrations of 1,1-DCP and 1,1,1-TCP; HNMs, halonitromethanes; HNM2, sum of the concentrations of TCNM, TBNM; HOBr, hypobromous acid; HOCl, hypochlorous acid; SEC-UV-OCD, size exclusion chromatography with ultraviolet absorbance and organic carbon detection; N-DBPs, DBPs containing nitrogen; NOM, natural organic matter; RBF, riverbank filtration; $SUVA_{254}$, specific UV absorbance at 254 nm; TBM, tribromomethane (bromoform); TBNM, tribromonitromethane; TCAN, trichloroacetonitrile; TCM, trichloromethane (chloroform); TCNM, trichloronitromethane; THMs, trihalomethanes; THM4, sum of the concentrations of TCM, BDCM, DCBM and TBM; TDN, total dissolved nitrogen (inorganic and organic); UV_{254}, ultraviolet absorbance at 254 nm; WTP, water treatment plant; 1,1-DCP, 1,1-dichloropropanone; 1,1,1-TCP, 1,1,1-trichloropropanone.

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Disinfection by-product precursors

Lab-scale experiments were conducted with surface feed water from a drinking water plant. The results showed that within 6 days hydraulic retention time (HRT), 60–70% dissolved organic carbon (DOC) and 70–80% ultraviolet absorbance at 254 nm (UV_{254}) could be removed. During the whole filtration process, biodegradation was responsible for the removal of organic matter, and it was found that alternating redox condition between oxic and anoxic was beneficial for the overall performance of the RBF. Dissolved oxygen (DO) had a substantial impact on the removal of DBP precursors. For carbon-containing DBP (C-DBP) precursors' removal, re-aeration after a sequence of oxic and anoxic conditions could further increase the removal efficiencies from 50%, 60%, and 60% to 80%, 90%, and 80% for trihalomethanes (THMs), chloral hydrate (CH), and haloketones (HKs). Prolonged anoxic conditions were however beneficial for the removal of nitrogen-containing DBP (N-DBP) precursors.

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1. Introduction

At the beginning of the 20th century, chlorine was widely introduced as a disinfectant in drinking water production to prevent waterborne diseases such as cholera, dysentery and typhoid. Nevertheless, chlorine reacts with natural organic matter (NOM) to form the so-called disinfection by-products (DBPs), such as trihalomethanes (THMs), haloacetic acids (HAAs), haloacetonitriles (HANs), haloketones (HKs) and halonitromethanes (HNMs) (Krasner et al., 2006), among others. Some of these DBPs have been linked to bladder cancer (Costet et al., 2011) and reproductive defects (Nieuwenhuijsen et al., 2000). Due to these health concerns, most countries specify maximum allowable concentrations of DBPs in treated drinking water. Although some alternative disinfectants, such as chloramine, chlorine dioxide, ozone, and ultraviolet radiation, have been used to reduce the formation of halogenated DBPs in treated water, their extensive application is limited and chlorine is still the predominant disinfectant used worldwide. The main reason is that almost none of these disinfectants fulfils each of the three most important requirements of a disinfectant: effectiveness, relatively low cost and the ability to provide a residual in the distribution system to prevent regrowth of microorganisms (Tibbetts, 1995). The only exception of that is chloramine, which has though been linked to the formation of toxic nitrogen-containing DBPs (N-DBPs) (Sedlak and Von Gunten, 2011). Although the concentrations of N-DBPs are normally lower than that of common halogenated DBPs (Krasner et al., 2006), e.g. THMs and HAAs, increasing attentions are paying to N-DBPs in recent years for their higher cytotoxicity and genotoxicity (Plewa et al., 2002) and, for example, in Australia *N*-nitrosodimethylamine (NDMA) had been included in Australian Drinking Water Guidelines 6 (2011) at a maximum concentration of 100 ng/L.

Reduction of NOM therefore remains an important approach to minimize DBP formation. Conventional coagulation-filtration-based water treatment is widely applied to remove NOM in drinking water production. Modern treatment plants sometimes apply additional methods such as activated carbon adsorption (Velten et al., 2011) or membrane filtration (Cho et al., 1999; Zularisam et al., 2006). Recently, the long-established approach of bank or riverbank filtration (RBF) has attracted attention for its relatively low cost and reliable performance in improving the quality of surface waters (Tufenkji et al., 2002). RBF is a natural water treatment process that has been used in Europe and the U.S. since the 1870s (Ray et al., 2003). During RBF, river water or other surface water passes through banks and proceeds to the groundwater table naturally or through the inducement of a pressure gradient by extraction in pumping wells (Kuehn and Mueller, 2000). During this process, aquifer sediments and microbial communities supported by them act as a natural filter removing various contaminants, including pathogens, taste- and odour-causing compounds, organic micropollutants, microcystins, NOM and DBP precursors (Dillon et al., 2002; Grünheid et al., 2005; Maeng et al., 2012; Weiss et al., 2003). The removal mechanisms involve physical filtration, microbial degradation, ion exchange, precipitation, and sorption. Dilution with groundwater may also happen and reduce contaminant concentrations (Ray et al., 2002).

Although RBF was shown to have good performance in removing NOM and could improve water quality greatly (Grünheid et al., 2005; Hoppe-Jones et al., 2010), the effective application of RBF relies on the availability of locally suitable hydrogeological conditions. Therefore, for places not suitable for natural RBF, an engineered RBF may be a good option. In a natural RBF system, the residence time varied from several days to up to five months (Grünheid et al., 2005; Weiss et al., 2003). Considering the cost of construction and land use, engineered RBF with retention time of several days should be feasible, especially for smaller communities, where positive trade-offs for robust performance and low maintenance costs can be anticipated. Compared with conventional slow sand filtration system, the residence time for the engineered RBF is still longer and redox conditions can change from oxic to anoxic during soil passage potentially enhancing the removal of NOM that is sensitive to redox conditions. Although alternatively anoxic and oxic operation of activated sludge is widely used in wastewater treatment to achieve both organic matter and nitrogen removal (Tchobanoglous et al., 2003). Redox conditions have also been shown to be an important parameter for DOC and trace organic contaminant removal in artificial groundwater recharge with secondary effluent (Grünheid et al., 2005), but no evaluation of this process has been made in drinking water treatment practices with the aim of reducing natural organic matter and DBP precursors.

Therefore, the aim of this work was to study the performance of engineered short residence time RBF in removing NOM with hydraulic retention times (HRT) investigated from 2 h to 6 days. Specifically, the fate of DBP precursors along the whole filtration process was also studied with a focus on the impact of alternating oxic and anoxic conditions in the filter. This study compares the evolution of formation potential of carbon-only based C-DBPs (e.g. THMs, HKs) and nitrogen-containing disinfection by-products (N-DBPs, e.g. HANs, HNMs), with little information being available about the biodegradability of their precursor molecules.

2. Materials and methods

2.1. Raw water

Raw water used in this study was collected from a surface water reservoir, which is the source water for a drinking water treatment plant (WTP) in South East Queensland, Australia during December 2012. 400 L raw water were collected onsite and concentrated with a lab-scale reverse osmosis system using 2.5″ spiral wound reverse osmosis membrane (RO ESPA2540, Hydranautics, USA) to around 40 L (concentration factor of 10) for increased ease of storage in the freezer for future use. The analytical parameters of the studied water include dissolved organic carbon (DOC), ultraviolet absorbance at 254 nm (UV_{254}), DBP formation potential (DBP FP), size exclusion chromatography (SEC), biodegradable DOC (BDOC), dissolved oxygen (DO), inorganic nitrogen species (NH_4^+, NO_3^-, NO_2^-) and sulphide (HS^-).

2.2. Experimental setup

The experimental reactors used in this study consisted of three PVC columns in series, 2 m length and 2 cm diameter each (Fig. 1).

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