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# Modeling the improvement of ultrafiltration membrane mass transfer when using biofiltration pretreatment in surface water applications

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ABSTRACT

In surface water treatment, ultrafiltration (UF) membranes are widely used because of their ability to supply safe drinking water. Although UF membranes produce high-quality water, their efficiency is limited by fouling. Improving UF filtrate productivity is economically desirable and has been attempted by incorporating sustainable biofiltration processes as pretreatment to UF with varying success. The availability of models that can be applied to describe the effectiveness of biofiltration on membrane mass transfer are lacking. In this work, UF water productivity was empirically modeled as a function of biofilter feed water quality using either a quadratic or Gaussian relationship. UF membrane mass transfer variability was found to be governed by the dimensionless mass ratio between the alkalinity (ALK) and dissolved organic carbon (DOC). UF membrane productivity was optimized when the biofilter feed water ALK to DOC ratio fell between 10 and 14.

## 1. Introduction

Ultrafiltration (UF) membranes effectively protect consumers from exposure to microbial pathogens in drinking water (Alspach et al., 2005). However, UF membranes face operational challenges with fouling caused by the accumulation of particulate, colloidal, organic, or biological matter present in the feed water (Duranceau and Taylor, 2011; Gao et al., 2011). Membrane foulants can be removed from feed waters to improve UF productivity by incorporating pretreatment processes (Huang et al., 2009). UF pretreatment options include coagulation-clarification (conventional), activated carbon adsorption, magnetic ion exchange (MIEX®), ozone oxidation, and biofiltration (Gao et al., 2011; Huang et al., 2009). Of these technologies, biofiltration has recently emerged as a sustainable pretreatment option for removing biodegradable natural organic matter (NOM) and producing biologically stable water prior to UF membranes (Gao et al., 2011; Huang et al., 2009).

Huck and colleagues have conducted several bench and pilot scale studies on the direct biofiltration of synthetic and natural surface waters ahead of UF membranes (Wang, 2014; Rahman, 2013; Peldszus et al., 2012; Huck et al., 2011; Halle et al., 2009; Mosqueda-Jimenez et al., 2006; Basu and Huck, 2004). The bench and pilot scale results revealed that direct biofiltration pretreatment can increase a membrane's operating specific flux or mass transfer coefficient (MTC) by significantly removing turbidity, organics, and biopolymers from the feed water (Wang, 2014; Rahman, 2013; Peldszus et al., 2012; Huck et al., 2011; Halle et al., 2009; Mosqueda-Jimenez et al., 2006; Basu and Huck, 2004). Azzeh et al. (2015) and Sadreddini (2013) examined direct biofiltration of river water prior to UF membrane filtration and reported reductions in membrane resistance as compared to non-biologically treated river water. In similar studies performed by Huang et al. (2011), Persson et al. (2006), and Velten et al. (2011), biofiltration was found to effectively reduce turbidity, organic, and biological activity levels prior to UF membrane processes. UF operating parameters, including the membrane MTC, were not reported (Huang et al., 2011; Persson et al., 2006; and Velten et al., 2011). Duranceau and Tharamapalan (2013) demonstrated that a UF membrane process operated at a higher MTC when biofiltration was applied to pretreat the surficial groundwater source.

Although these bench and pilot scale studies have indicated that the use of biofiltration pretreatment for UF processes is effective,

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other biofiltration pretreatment studies (Wend et al., 2003; Netcher and Duranceau, 2015) have reported less promising results. Wend et al. (2003) determined that direct biofiltration reduced bacterial cell counts in the synthetic surface water, yet no significant improvement on the membrane's MTC was identified. As compared to direct biofiltration investigations, fewer studies have investigated the integration of biofiltration within conventional-UF processes. The research conducted by Lipp et al. (1998) suggests that combining coagulation, biologically-active sand filtration, and UF enhances turbidity removal and the membrane's MTC. Wei and researchers (2011) have also reported favorable results when integrating biofiltration ahead of a coagulation and UF process. However, recent work by the authors (2015) revealed that integrating biofiltration after conventional pretreatment and before a UF membrane process was not effective in enhancing membrane performance.

The majority of models available for predicting varying biofilter effectiveness are used to estimate the removal of substrate or biodegradable organic matter (Huck and Sozanski, 2008). For example, the steady-state biofilm model developed by Rittmann and McCarty (1980) serves as a model framework for other biofiltration models (Huck and Sozanski, 2008; Chaudhary et al., 2003; Metcalf and Eddy, 2003; Urfer et al., 1997; Zhang and Huck, 1996). Zhang and Huck (1996) built upon the steady-state biofilm model and developed the dimensionless empty bed contact time (EBCT) model. The dimensionless EBCT model has been shown to effectively describe the percent removal of substrate by biofilters under varying conditions (Huck and Sozanski, 2008). Nonetheless, Huck and Sozanski (2008) recognized that further model development is needed to apply the dimensionless EBCT concept for modeling the effectiveness of biofiltration on UF operating performance.

Although some researchers (Ma et al., 2015; Netcher and Duranceau, 2015; Ren et al., 2010; Hozalski et al., 1995) note the importance of alkalinity in biological processes, few if any studies have fully examined the role of alkalinity on biofiltration performance when applied as pretreatment for UF membranes. In prior work by the authors (2015), it was suggested that biofilter pretreatment effectiveness may have been influenced by the low alkalinity (2 mg/L as $CaCO_3$) of the natural surface water. Therefore, alkalinity could play a key role in understanding the effectiveness of biofiltration as pretreatment to UF membranes. This work aims to develop a simple, yet practical approach for modeling biofilter effectiveness relative to UF membrane mass transfer, where alkalinity is considered.

## 2. Materials and methods

### 2.1. Model framework development

Motivated by the suspected influence of alkalinity (Netcher and Duranceau, 2015) and known importance of organic substrate (Velten et al., 2011; Huck and Sozanski, 2008; Chaudhary et al., 2003) on bio-stabilization processes, an alternative modeling approach was developed to describe biofilter effectiveness. The modeling concept was based on the empirical relationship between the ratio of inorganic carbon (alkalinity) to dissolved organic carbon (DOC) and the corresponding impact on the UF membrane's MTC. Converting the alkalinity units from mg/L as $CaCO_3$ to mg/L as C, as shown in Eq. (1), allowed for the development of a dimensionless alkalinity to DOC (ALK/DOC) ratio. The ALK/DOC ratio was calculated according to Eq. (2). For Eq. (1), it was assumed that the equivalent weights of carbon ($EW_C$) and calcium carbonate ($EW_{CaCO3}$) were 6 and 50 mg/milliequivalent, respectively.

$$Alkalinity\left(\frac{mg}{L}C\right) = Alkalinity\left(\frac{mg}{L}CaCO_3\right) \times \frac{EW_C}{EW_{CaCO_3}} \tag{1}$$

$$\frac{ALK}{DOC}(dimensionless) = \frac{Alkalinity(mg\ C/L)}{DOC(mg\ C/L)} \tag{2}$$

The impact on UF operating performance was quantified according to the improvement on the UF MTC. The MTC improvement (Eq. (3)) was calculated using the temperature corrected specific flux (Eq. (4)) for the membrane with ($MTC_{biofiltration}$) and without ($MTC_{control}$) biofiltration pretreatment (Alspach et al., 2005). In Eq. (4), Q is the flow through the membrane (L/h); A is the membrane surface area ($m^2$), ΔP is the transmembrane pressure (TMP; bar); T is the measured temperature (°C); and $\mu_{20}$ is the absolute viscosity at 20 °C (1.002 cP).

$$MTC\ Improvement(\%) = \frac{MTC_{biofiltration} - MTC_{control}}{MTC_{control}} \times 100 \tag{3}$$

$$\mathrm{MTC} = \mathrm{J}_{\mathrm{SP,20^\circ C}} = \frac{\mathrm{Q/A}}{\Delta P} \times \frac{1.777 - 0.052\mathrm{T} + 6.25 \times 10^{-4}\mathrm{T}^2}{\mu_{20}} \tag{4}$$

### 2.2. Modeling parameters and analysis

To develop the empirical relationship between the ALK/DOC ratio and MTC improvement, a survey of the literature relative to biofiltration pretreatment for UF membrane processes was conducted. A summary of biofilter feed water quality and membrane MTC data is presented in Table 1. The data in Table 1 excludes results from studies that conducted experiments in-series with reportedly variable source water quality (Halle et al., 2009) or did not report data needed to calculate the ALK/DOC ratio and MTC improvement (Huck et al., 2011; Huang et al., 2011; Persson et al., 2006; Velten et al., 2011).

The biofiltration data was examined graphically by plotting the MTC improvement versus the ALK/DOC ratio. Based on observations from the scatter-plot analysis, mathematical equations were identified to describe the graphical relationship between MTC improvement and ALK/DOC ratio. The identified mathematical equations were used to model the MTC improvement and ALK/DOC data using curve fitting with non-linear regression in the Minitab® 17 software (Minitab, 2010).

## 3. Results and discussion

### 3.1. Modeling results and validation

The scatter-plot analysis of the MTC improvement versus ALK/DOC ratio is illustrated in Fig. 1. The scatter-plot analysis revealed that the relationship between MTC improvement and ALK/DOC ratio exhibits a parabolic shape. Thus, the biofiltration data may be fitted to a quadratic equation as defined in Eq. (5). In Eq. (5), $c_1$, $c_2$, and $c_3$ are model parameters that define the parabola's curve steepness, x-axis translation, and y-axis translation.

For a quadratic model, boundary conditions would be defined by the range of input data, which includes ALK/DOC ratios between zero and approximately 24. Beyond an ALK/DOC ratio of 24, MTC improvement would approach a parabolic negative infinity. Alternatively, it may be assumed that for ALK/DOC values greater than 24, the MTC improvement approaches a boundary level. This assumption may be modeled using a normal or Gaussian distribution, expressed in Eq. (6). In Eq. (6), $c_1$, $c_2$, $c_3$, and $c_4$ are model