

The role of backwash in start-up of full-scale drinking water biofilters

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ABSTRACT

The purpose of backwashing during the start-up period of rapid biofilters at drinking water treatment plants differs significantly from the purpose of backwashing during normal operation. During start-up, finished water quality is secondary, detachment of microorganisms must be minimized, dust present in the original filter media must be removed and inherent inoculation of the biofilter with water used for backwashing must be considered. Investigations over a 9-week start-up period at a full-scale waterworks showed a strong correlation between suspended solids and turbidity, and that fine particles present in the original filter media were removed over a period of several weeks. In addition, after an initial period in which iron accumulated on the filter was not removed by backwash, iron was removed with 80% efficiency. Backwashing had 0% efficiency in removing manganese from the filter media. Practical conclusions include that shortened backwash procedures during start-up may be preferable, turbidity may be used as a surrogate for suspended solids in backwash effluent, filter media may be pre-treated by exaggerated backwashing to remove fine particles before start-up, and that a reasonable backwash procedure for future operation of the filter may be defined early in the start-up period.

Key words | backwash, drinking water, filter media, rapid biofilter, start-up

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INTRODUCTION

In the production of drinking water from groundwater, waterworks often use a simple treatment process consisting only of oxygenation followed by filtration in rapid granular biofilters (Rittmann 1995) to remove parameters such as iron, manganese and ammonium. Operation of these biofilters is highly dependent on periodic backwashes to clean the filter media. Focus in previous studies has therefore been on optimizing and testing different backwash procedures with regard to the effect on biofilter operation (Fitzpatrick 1997; Amburgey 2005; Slavik *et al.* 2013). Little attention has previously been given to observing the unique role of backwashing during start-up of biofilters in a full-scale waterworks.

Backwash is the name for the washing process between filter runs in which water is pumped backwards through the biofilters. The process may consist of several cycles such as a

compressed air scour cycle, a simultaneous air and water cycle, and a water-only cycle. The main purpose of backwash is to remove inorganic particles and excessive biomass from the biofilter to prevent excessive head loss and poor finished water quality (Amirtharajah 1993).

Optimal detachment of iron oxides and other inorganic particles from the filter media has been found to occur when simultaneous air and water backwashing leads to collapse-pulsing (Amirtharajah 1978, 1993), due to the high shear forces resulting from high filter media agitation (Fitzpatrick 1997). Following backwash, the first produced water often has a poor quality (Logsdon *et al.* 1985). As the filter run progresses, a period of ripening in which the quality of the produced water improves ensues. Filtrate quality can be improved by extending the terminal water cycle (Amburgey 2005), starting the next

filter run with a slow flow (Colton *et al.* 1996) and recirculation of the finished water.

Excessive biomass must be removed during backwash while leaving enough biofilm on the filter media to not compromise biological performance at the start of the subsequent filter run. Previous studies have indicated that collapse-pulsing does not remove the effective biomass or impact biological filter performance (Ahmad & Amirtharajah 1998; Emelko *et al.* 2006; Kim *et al.* 2014). This may be due to the fact that bacterial hydrophobicity provides an advantage for bacteria to attach to surfaces compared with many inorganic compounds (Ahmad & Amirtharajah 1998). Other studies, however, indicate a possible negative effect of backwashing on biofilter performance (Liu *et al.* 2001; Laurent *et al.* 2003).

Various filter media are utilized in biofilters for drinking water production. The backwash flow must be adjusted to fit with filter media properties such as size, density, and shape in order to avoid flushing the media out with the backwash effluent. High shear forces during backwash may form fine particles through media attrition and cause the subsequent loss of filter media. The degree of attrition also depends on the durability of the media. Attrition studies on sand and anthracite concluded that the loss of filter media due to backwash was acceptable (Humby & Fitzpatrick 1995).

The start-up period of drinking water biofilters consists of a complex, interconnected set of processes in which virgin filter media matures into a fully functional biofilter coated with inorganic precipitates and biofilm. During start-up, inorganic coatings consisting of e.g. iron and manganese oxides form on the filter media. This coating can be initiated on virgin filter media surfaces by the adsorption of iron (II) from the raw water and subsequent oxidation to iron (III) oxides in the presence of oxygen. Ions such as calcium in the raw water have been shown to interfere with the adsorption of iron (II) on virgin filter media, while continued adsorption and oxidation of iron (II) onto a previously formed coating is less influenced by such ions (Sharma *et al.* 2002).

Filter media also supply a surface for the attachment of microorganisms, the initial step in the development of a biofilm (de Vet *et al.* 2009). Microorganisms present in the raw water generally provide an inoculation of the filter media. Although this inherent inoculation may be sufficient,

development of a mature biofilm on the filter media is time-consuming. Therefore, proactive inoculation using mature filter sand (Zeng *et al.* 2010) or backwash sludge (Štembal *et al.* 2004; Cai *et al.* 2015) from another waterworks is often used to ensure a more rapid start-up. The start-up period may be considered complete when finished water concentrations of treatment parameters such as iron, manganese and ammonium are in compliance with drinking water criteria. Simultaneous biofiltration of iron, ammonium and manganese is a complex process. In general, iron is removed within the first hours of the start-up of virgin biofilters by simple aeration (Tekerekopoulou *et al.* 2006) while ammonium removal takes weeks and requires development of biofilm. Biologically mediated manganese removal occurs after ammonium removal, since complete nitrification is found to be a prerequisite (Frischherz *et al.* 1985).

During the start-up period, backwash has a significantly different purpose from that during normal operation. The importance of good finished water quality during start-up is secondary, since the water is typically discharged to a surface water recipient instead of distributed to consumers. This means that the goal for backwashing during start-up is limited to reducing head loss rather than obtaining high drinking water quality with respect to e.g. turbidity and suspended solids. In addition, although loss of media during backwashing is undesirable, removal of very fine particles present as dust in virgin filter media should be accomplished. Therefore, exaggerated backwashing is often included as a filter media pre-treatment in the beginning of the start-up period (Humby & Fitzpatrick 1995). Also, since biofilm development is critical in the start-up period, backwash during this period must not cause excessive detachment of relevant microorganisms (Ahmad & Amirtharajah 1998). Finally, the microorganisms in the water used to backwash the filter can supplement the microorganisms in the raw water to provide inherent inoculation of the biofilter (de Vet *et al.* 2009) when the water used for backwashing contains no disinfectant.

Backwash effluent is often characterized by elevated levels of suspended solids and turbidity. Such measurements are often used to evaluate the duration and efficiency of the backwash process and thereby filter performance (Ahmad & Amirtharajah 1998). However, such measurements may also be used to follow the progress of

the start-up processes, supplementing finished water analyses. When treatment parameters such as iron and manganese start to be removed in the biofilters, the inorganic precipitates build up on the filter media grains. These compounds may end up in the backwash effluent, and chemical analysis of these specific compounds may be another way of using backwash water for monitoring the progress of the start-up. Deposits that are not removed by backwash may accumulate in the biofilter, and may be quantified by mass balance calculations. Measurement of microorganisms in backwash effluent during start-up is a complementary approach to study the changes taking place during start-up.

The objective of the present study was to observe the role of backwash during start-up of virgin full-scale biofilters. For this, backwash water was analyzed in a full-scale waterworks containing two rapid biofilters in series through a period of 9 weeks. The investigation focused on suspended solids and turbidity, as well as the chemical composition of backwash effluent. These measurements were correlated with the progress of the start-up as measured in the finished water through chemical analyses.

METHODS

Waterworks and operation

This study was carried out during July–September 2014 on Production Line 1 at Truelsbjerg waterworks (Aarhus Water Ltd, Denmark). The water treatment process starts with the addition of 93–95% pure oxygen to the raw water. Oxygenation is followed by filtration through two stainless

steel pressure filters in series (Filter 1 and 2). Each filter has an area of 8.95 m² and a bed height of 2.29 m excluding the support layers. Filter 1 is composed of granular calcium carbonate, and Filter 2 of granular quartz sand with a layer of manganese oxide on the top (Table 1). No disinfectant is used during the water treatment process.

The source water is anaerobic groundwater abstracted from eight wells. During the start-up period, the source water had average concentrations of iron of 1.40 mgL⁻¹ ± 0.19, manganese of 0.45 mgL⁻¹ ± 0.07, and ammonium of 0.21 mgL⁻¹ ± 0.04. In general, the source water is saturated with calcium carbonate (89 mgL⁻¹ ± 5 calcium, 7.6 mgL⁻¹ ± 0.3 magnesium, 282 mgL⁻¹ ± 4 hydrogen carbonate). The redox conditions are reduced (no oxygen or nitrate, but traces of methane and hydrogen sulfide) and the pH averages 7.3.

Prior to start, the filters were disinfected with a recirculating mixture of hydrochloric acid and hydrogen peroxide (3 liter CARELA[®] BIO-DES, CARELA GmbH, Germany, per 10 m³ filter media) for 24 hours, followed by a double backwash. During the start-up, the rapid biofilters were operated with an average flow of 45 m³h⁻¹ and a filtration rate of 5.0 m³ m⁻² h⁻¹. For the first 8 days of operation, both filters were backwashed daily. After this initial period, a programmed backwash was carried out every 4 days. The water used for the backwash was treated water from another waterworks. In general, Danish water supplies use no disinfectant, so the backwash water contained viable microorganisms. At the end of each filter run, Filters 1 and 2 were backwashed successively. Each backwash consisted of three cycles: Cycle I, air scour performed under water saturated conditions; Cycle II, combination of air and water; and Cycle III, water only.

Table 1 | Filter composition and filter media properties at Truelsbjerg waterworks

Parameter	Filter 1	Filter 2	Both filters	
Description	Calcium carbonate	Manganese oxide	Quartz sand	Support material
Particle density (kgL ⁻¹)	2.4	3.3	2.5	–
Porosity (%)	40	44	45	–
Grain size (mm, 10–90% fractile)	2.3–4.1	1.6–3.2	0.5–0.8	3–5/1.6–2.5
Layer thickness (mm)	2290	200	2090	310

Sampling of water

Unfiltered, 40 ml water samples were collected manually throughout the start-up period using standard procedures (DS/ISO 5667-5:2006) from before and after Filter 1. All samples were stored at 5 degrees Celsius and analyzed for iron, manganese and ammonium within 24 hours.

Unfiltered, 40 ml samples of backwash effluent were collected each minute of the Filter 1 backwash starting with Cycle II and continuing until the end of Cycle III, giving a total of 21 samples. The same procedure was used to collect sets of samples during the course of six backwashes (0.7, 10.7, 34.7, 38.7, 42.7 and 66.7 days after the start of flow on Production Line 1). These samples were analyzed for turbidity and total suspended solids.

A total of 13 composite backwash effluent samples from backwash of Filter 1 were collected throughout the start-up period. Each composite was assembled manually in a flow proportionate manner by combining 40 ml samples taken each minute of Cycle II and 120 ml samples taken each minute of Cycle III. Within 24 hours, each composite sample was carefully subsampled and analyzed for turbidity, suspended solids, iron, manganese and calcium.

Analyses

Iron, manganese and ammonium were analyzed spectrophotometrically (DR 3900, Hach Lange Ltd, Denmark), according to the manufacturer's instructions, with the kits LCK321/521, LCK304, and LCW532, respectively. Total suspended solids and turbidity analyses followed standard methods SM 2540 Solids (D) and SM 2130, respectively. Turbidity was measured using a Hach 2100AN Laboratory Turbidimeter. Calcium, iron and manganese were analyzed by ICP/OES using standard method SM 3120. All standard methods were performed according to *Standard Methods* (APHA/AWWA/WEF 2012).

In-line flow measurements of water during operation, backwash air and backwash water were carried out continuously during the investigation.

Precipitates and mass balance calculations

Calculations were used to compare the concentration of suspended solids to the concentrations of specific ions in the

backwash effluent. Here, it was assumed that all iron, manganese and calcium in the backwash effluent were present as the precipitates $\text{Fe}(\text{OH})_3$, MnO_2 , and CaCO_3 , respectively. Using these compounds' molecular weights, a factor of 1.91, 1.58 and 2.50 grams precipitate per gram iron, manganese and calcium, respectively, was used. However, since the degree of hydration of the precipitates is unknown, these factors are only estimates. Since the water used for backwash was treated water from another waterworks, it contained calcium, but no iron or manganese. The water's concentration of calcium was therefore subtracted from the backwash effluent results.

Mass balances for iron and manganese were calculated on a kilogram basis to determine the potential accumulation of these substances in Filter 1 during a filter run and subsequent backwash. The following equation was used:

$$\text{Accumulated} = \text{Filter influent} - \text{Filter effluent} - \text{Backwash effluent} \quad (1)$$

Where Accumulated is the mass remaining in Filter 1 after a filter run and subsequent backwash (kg); Filter influent is the mass entering Filter 1 with the raw water during a filter run (kg); Filter effluent is the mass leaving Filter 1 with the filtrate (kg); and Backwash effluent is the mass removed from Filter 1 during the backwash procedure (kg).

RESULTS AND DISCUSSION

Backwash analyses were performed at a full-scale waterworks during the start-up period in two rapid biofilters in series. This study is focused on the backwash of Filter 1, however, since Filter 2 was largely superfluous for the water treatment processes.

Finished water quality during start-up

The start-up period lasted 66 days, after which the concentrations of iron, ammonium and manganese in the raw water were removed sufficiently to meet national drinking water criteria of 0.1 mg L^{-1} , 0.05 mg L^{-1} and 0.02 mg L^{-1} , respectively. Table 2 shows that iron was completely removed on Filter 1 already from the first sampling event (day 4),

Table 2 | Concentration of iron, ammonium and manganese in water samples before and after Filter 1 during start-up

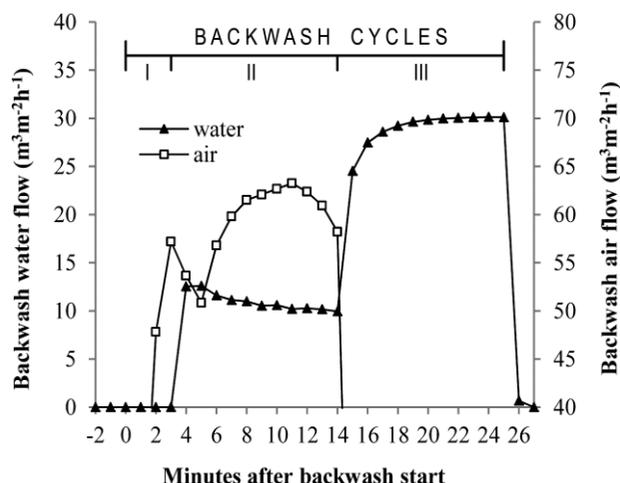
Sampling point	Compound	Days after operation start										
		4	10	18	26	34	38	42	50	58	66	69
Before Filter 1	Fe ²⁺	1.48	1.56	0.859	1.36	1.35	1.38	1.37	1.27	1.21	1.36	1.51
	Mn ²⁺	0.463	0.470	0.394	0.495	0.448	0.448	0.455	0.598	0.497	0.497	0.528
	NH ₄ ⁺	0.240	0.190	0.219	0.230	0.230	0.203	0.233	0.238	0.147	0.215	0.191
After Filter 1	Fe ²⁺	0.021	0.008	0.003	0.001	<0.01	<0.01	0.04	0.202*	<0.01	<0.01	<0.01
	Mn ²⁺	0.437	0.430	0.469	0.450	0.464	0.436	0.365	0.900*	1.56*	0.046	0.037
	NH ₄ ⁺	0.227	0.170	0.217	0.210	0.165	0.131	0.088	0.212*	<0.015	<0.015	<0.015

*The increase in iron, manganese and ammonium for the period days 50–58 was caused by a fault in the system supplying oxygen to the filter. These results show no influence on later results as concluded in a previous study (Soborg et al. 2015). Bold indicates concentrations below national drinking water criteria.

indicating that chemical oxidation was responsible for the removal. Ammonium concentration in water after Filter 1 was shown to meet drinking water criteria after 58 days. Manganese removal in Filter 1 began after ammonium removal, and 90% of the manganese in the raw water was removed at the end of the start-up period (day 66). At this time, the drinking water criterion for manganese was met in the water after Filter 2. Ammonium and manganese were removed on Filter 1 only after a period of >8 weeks, indicating that the removal of these compounds required a period of biofilm development and was mediated biologically.

Flow of air and water during a backwash event

Filter 1 was backwashed 22 times during the start-up period. Backwash air and water flow is shown in Figure 1 for the three backwash cycles of a typical backwash event. Cycle I

**Figure 1** | Flow of air and water during the three cycles (I, II, and III) of a backwash event.

had a duration of 3 minutes, with an air flow increasing to 60 m³ m⁻² h⁻¹, Cycle II had a duration of 11 minutes, with an air flow of 60 m³ m⁻² h⁻¹ and an average water flow of 11 m³ m⁻² h⁻¹, and Cycle III had a duration of 10 minutes, with an average water flow of 29 m³ m⁻² h⁻¹, far below the minimum fluidization velocity.

Pressure filters preclude visual examination of the filter media during backwash. Therefore, it could not be confirmed whether collapse-pulsing actually took place during Cycle II. Neither could the degree of bed expansion during Cycle III be observed. However, calculations based on Amirtharajah (1993) showed that collapse-pulsing conditions are not likely to be fulfilled due to the large particle size of the filter media and the low backwash water flow during Cycle II.

Turbidity and suspended solids in backwash effluent

As seen in Figure 2(a), the turbidity of the effluent from Filter 1 on the first backwash event (day 0.7) was <100 NTU at all times, while the turbidity of all the other backwash events was much higher (falling from around 4,000 NTU in the beginning of Cycle II to below 20 NTU at the end of Cycle III). To understand this difference it should be noted that the duration of the filter run preceding this first backwash event was unusually short (<1 day) compared to the normal filter run length of 4 days. Further, the turbidity of the influent water used for backwashing was <1 NTU. At the end of the start-up period (day 66.7) manganese was being successfully removed on Filter 1. However, this was not reflected in an increase of turbidity in backwash effluent. This indicates that the

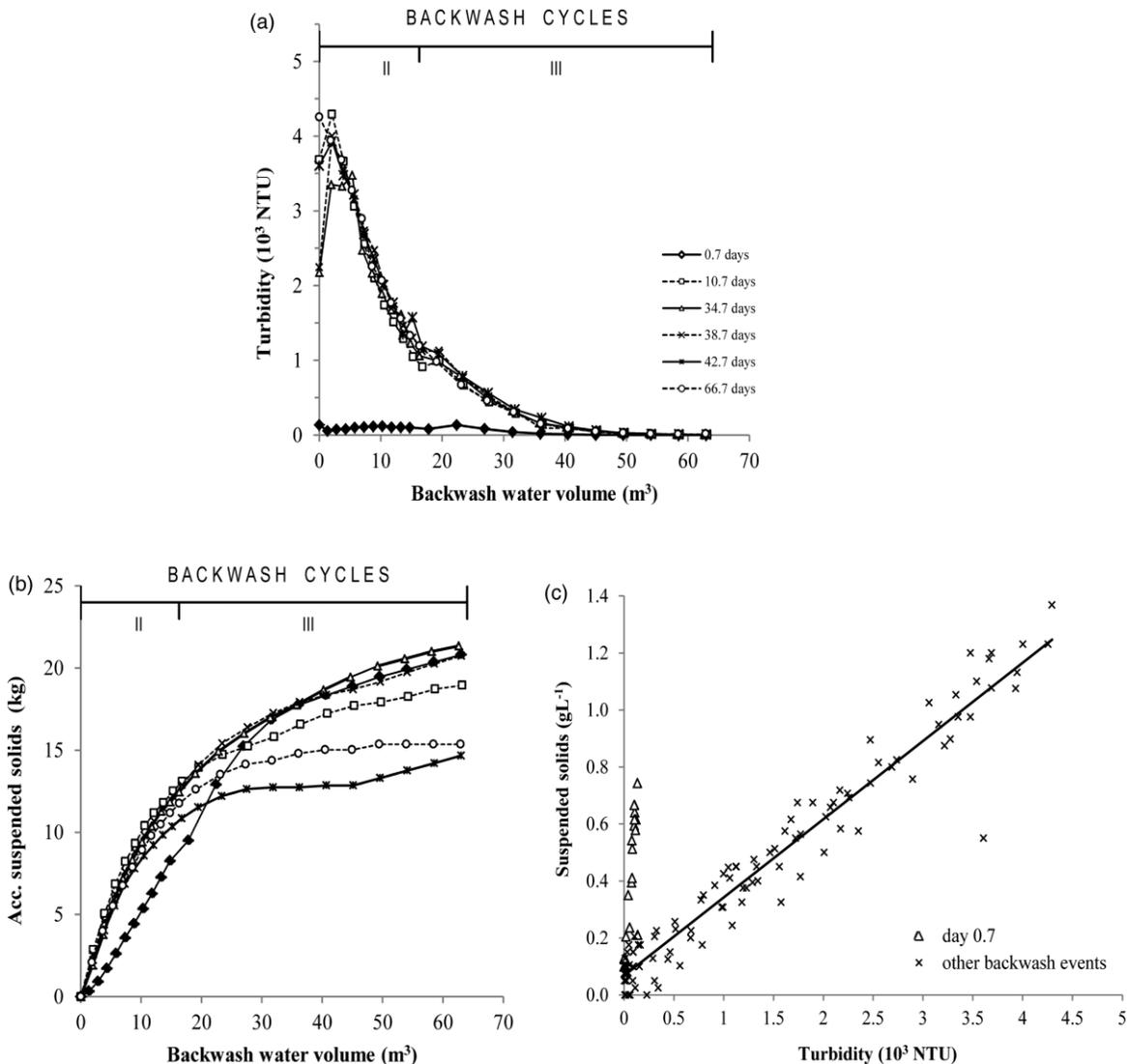


Figure 2 | Results for backwash effluent for six backwash events from Filter 1 during start-up. (a) turbidity; (b) accumulated suspended solids; (c) ratio between turbidity and suspended solids ($y = 0.000274x + 0.0692$ and $R^2 = 0.9469$).

removed manganese is accumulated in the filter media (see Figure 3).

As seen in Figure 2(b), approximately 15–20 kg of suspended solids were removed from Filter 1 per backwash event. These solids may consist of inorganic material collected during the previous filter run, biofilm, and fine particles of filter media. The total suspended solids in backwash effluent of day 0.7 were comparable to the total suspended solids of the remaining backwashes, even though Figure 2(a) showed a very low turbidity for this backwash. This can be explained if the suspended solids in this

backwash event consisted mainly of fine particles of the filter media, whereas subsequent backwash events consisted of even finer particles of iron oxides (Figure 3). It is well known that differences in particle size, as well as shape, color, composition, and refractive index etc., change turbidity response (Ahmad & Amirtharajah 1998). Larger particles produce less intense scattering of light for a given suspended solids concentration (Merton et al. 2014).

Backwash Cycle II and III each removed approximately 10 kg of suspended solids from Filter 1. However, different slopes were observed for the suspended solid curves

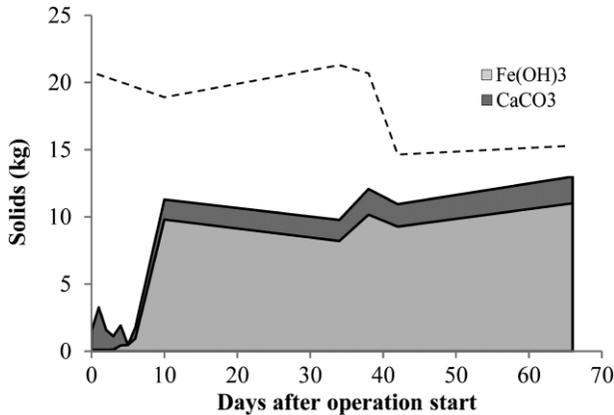


Figure 3 | $\text{Fe}(\text{OH})_3$ and CaCO_3 (12 backwash events) and total suspended solids (dashed line, 6 backwash events), in backwash effluent of Filter 1 during the start-up period. Presence of MnO_2 in backwash effluent was nearly zero.

(Figure 2(b)), with a greater amount of suspended solids being removed per volume of water used (measured in kg m^{-3}) during Cycle II.

A high correlation (0.95) between turbidity and suspended solids measurements on day 10.7 and all following backwash events is shown in Figure 2(c), with a turbidity–suspended solids ratio of approximately 3,600 NTU per g L^{-1} . The first backwash event after operation started (day 0.7) showed a lower correlation between turbidity and suspended solids (0.72) with a ratio of 250 NTU per g L^{-1} . The low ratio in this first backwash event suggests that the removed suspended solids may be composed of larger particles that produce less intense light scattering. This indicates that turbidity may be used as a surrogate for suspended solids in this system except in the very beginning of the start-up period.

Based on the turbidity measurements, it appears that the length of the backwash cycles was suitable for normal operation. During a start-up period, however, a shorter backwash may entail some advantages since there are no concerns regarding a short ripening period and producing drinking water of low quality with excessive suspended solids and turbidity. Advantages of a shorter backwash include reduced risk for detaching microorganisms during the critical stage of biofilm development as well as water and energy savings.

Chemical composition of backwash effluent

Figure 3 compares the chemical composition of backwash effluent from Filter 1 (measurements from 12 backwash

events) with the total suspended solids (measurements from six backwash events) during the start-up. As the graph shows, the total suspended solids measurements were always greater than the calculated sum of the compounds iron oxide, manganese oxide and calcium carbonate. This suggests that additional compounds may be present in the suspended solids.

The difference between total suspended solids and the calculated sum decreased over time, indicating that the unidentified suspended solid may be fine flint particles found as impurities in the calcium carbonate filter media and fine quartz particles in the original quartz supporting layer in Filter 1 (Table 1). An even more exaggerated amount of unidentified suspended solids was seen in backwash effluent of Filter 2 (data not shown). In Filter 2, an even lower ratio between turbidity and suspended solids was found on day 0.7 (22 NTU per g L^{-1}). This supports the hypothesis that the unidentified suspended solid is quartz and flint particles. These results reinforce the effect of backwash on the removal of fine particles from the original filter media during the start-up period.

Figure 2(b) shows that the amount of suspended solids removed during Cycle II is nearly equal to the total amount of iron removed in the backwash effluent. In addition, Figure 2(b) shows that the amount of suspended solids removed in Cycle III is nearly equal to the total amount of unidentified suspended solids removed in the backwash effluent. Therefore, it may be hypothesized that iron oxide is composed of smaller particles which are removed during Cycle II, while the unidentified suspended solid is composed of larger particles which are removed during Cycle III.

Daily backwashes were carried out on the first 8 days, whereas later backwashes were carried out every 4 days. Therefore, one might expect a factor-four increase in the mass of iron removed during the backwash after this initial period. Figure 3, however, shows an even greater increase. This may suggest that the initial adsorption of iron to the new filter media is stronger than subsequent adsorption to already-formed iron oxide coatings. During the rest of the start-up period, iron oxides were the dominant solids in the backwash effluent (Figure 3).

Manganese concentrations in the backwash effluent were insignificant throughout the start-up, even when 90% manganese removal was achieved (day 66). This is supported by the turbidity measurements in which no turbidity increase is seen on day 66 (Figure 2(a) and Figure 3).

The calcium carbonate removed during backwash events was modest and remained constant throughout the start-up period (Figure 3). It was not determined whether this calcium carbonate came from fine particles in the original filter media, attrition or variation in influent calcium concentration.

Mass balance of iron and manganese

The amount of iron and manganese accumulated on Filter 1 was calculated by a mass balance. Figure 4 shows that nearly

100% accumulation of iron on the filter media was seen initially, as little iron was found in the water after Filter 1 or in the backwash effluent. For the remainder of the start-up period, however, approximately 80% of the iron entering Filter 1 was removed via backwashing, while 20% was accumulated on the filter media.

Manganese passed through Filter 1 without being removed for the majority of the start-up period (Table 2). After successful removal of manganese on Filter 1 (from day 66), manganese was almost completely retained on the filter media, and almost none was removed via backwashing (Figure 4).

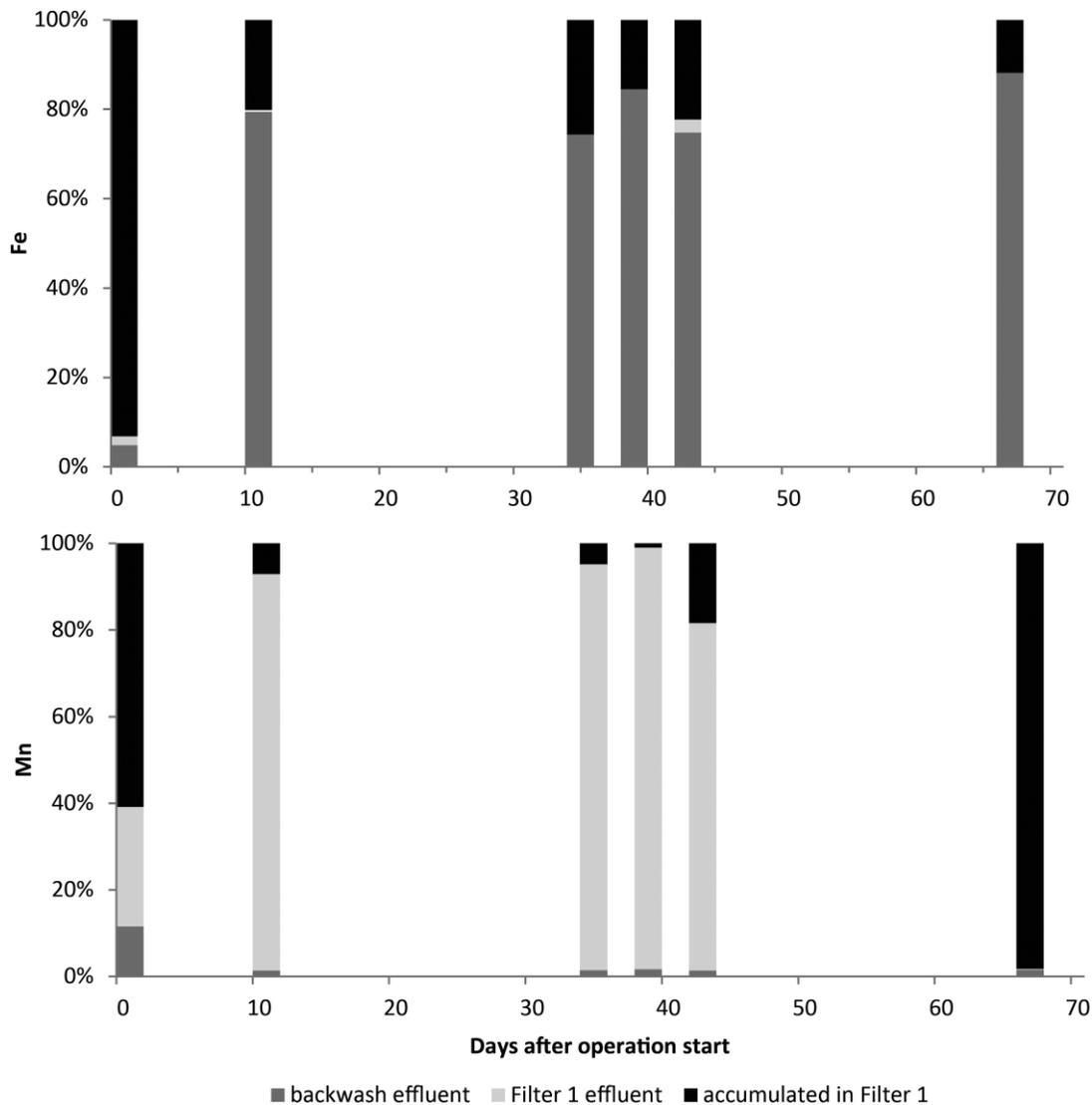


Figure 4 | Mass balance for iron and manganese on Filter 1 based on six backwash events during the start-up period.

These results demonstrate that the backwash procedure preferentially removes iron, although not obtaining 100% removal. The inorganic coating on the filter media will therefore increase over the coming years of operation and be mainly composed of manganese oxides.

CONCLUSIONS

The purpose of backwashing during the start-up period of a drinking water biofilter differs significantly from the purpose during normal operation. The objective of this study was to observe the role of backwash during the start-up of full-scale biofilters.

In the biofilters of this study, the start-up period lasted 66 days, after which the concentrations of iron, manganese and ammonium in the raw water were removed sufficiently to meet national drinking water criteria. During this time, both filters were backwashed 22 times. Except for the backwash that was carried out 0.7 days after the start of operation, all backwashes shared a very similar pattern with regard to turbidity and suspended solids in the backwash effluent. There was a high correlation ($R^2 = 0.95$) between turbidity and suspended solids (slope of 3,600 NTU per g L^{-1} of suspended solids), meaning that turbidity may be used as a surrogate for suspended solids.

Suspended solids in the backwash effluent of Filter 1 exceeded the calculated sum of iron oxides, manganese oxides and calcium carbonate. Since the difference decreased over time, it was suggested that the main cause was fine particles of flint initially present as impurities in the calcium carbonate filter media and fine quartz particles in the quartz supporting layers. Since removal of these fines is one of the purposes of backwashing during start-up, pre-treatment of the filter media by exaggerated backwashing to remove fine particles before start-up may be recommended.

Most of the iron oxide found in the backwash was removed during Cycle II, while fine particles present in the original filter media were removed in both Cycle II and III. This suggests that Cycle III may be applied as an intensive pre-treatment step before the start of operation until the filter media fines in the virgin filter are removed. This also suggests that following an initial pre-treatment, a backwash

procedure consisting only of Cycle I and II may be adequate for backwashing during the start-up period.

Analyses of iron in the backwash effluent of Filter 1 indicated that iron was entirely retained on the filter media during the first 3 days of the start-up, while 80% was removed in the backwash effluent in subsequent backwashes. In contrast, manganese passed through Filter 1 in the first part of the start-up. When 90% of the manganese in the raw water was removed by Filter 1, no manganese appeared in the backwash effluent, suggesting that 100% of the manganese was accumulated on the Filter 1 media.

It was suggested that the backwash could be shortened to prevent detachment of microorganisms, since the goal of backwash during start-up is to remove inorganic particles and excessive biomass from the preceding filter run to prevent excessive head loss rather than to ensure high quality of the finished water.

The removal of suspended solids during a backwash cycle (see Figure 2(b)) followed a similar pattern for all backwash events between day 10.7 and day 66.7. Therefore, a reasonable backwash procedure for the long-term operation of the filter following the start-up period apparently may be defined early in the start-up period. However, periodic checks of the backwash procedure are recommended, as development of the filter media continues after the start-up period.

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