

Comparison of physicochemical iron removal mechanisms in filters

Saroj K. Sharma, Joost Kappelhof, Martijn Groenendijk and Jan C. Schippers

ABSTRACT

Water supply companies are continually seeking means to improve the process efficiency of iron removal from groundwater in order to minimize the deposition of iron in distribution networks, backwash water use, and volume of the sludge produced. It is expected that the process efficiency can be optimized with a better understanding of the different mechanisms involved in the iron removal process and their optimal utilization. In order to investigate the options to improve the performance of an iron removal plant, pilot experiments were conducted with filters operating in two different iron removal modes, namely floc filtration and adsorptive filtration. The results were then compared with the performance of the full-scale plant Gilze, which operates mainly in the floc filtration mode. Results demonstrated that the performance of WTP Gilze in terms of ripening time, filter run time and filtrate quality (residual iron and turbidity) could be improved by operating the filters in (a) adsorptive mode with fine sand (0.5–0.8 mm) and low influent oxygen, or (b) in floc filtration mode with dual media (anthracite 0.8–1.2 mm and sand 0.5–0.8 mm). In general, for a single media fine sand filter, the adsorptive mode gave a longer run time than the floc filtration mode with comparable filtrate quality. In the adsorptive mode, oxygen content and pre-oxidation time should be kept as low as possible. However, to ensure sufficient removal of manganese and ammonium present in groundwater, a minimum oxygen concentration is required (about 2 mg l⁻¹ in case of WTP Gilze). Experimental results suggested that filters with coarser single media or dual media operating mainly under adsorptive mode with short pre-oxidation time could further improve filter performance and probably result in significant cost savings.

Key words | adsorption, filtration, floc filtration, groundwater, iron removal, mechanism

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INTRODUCTION

Iron in water supplies causes various aesthetic and operational problems including bad taste, discoloration, staining, deposition in distribution system leading to after growth and incidence of high turbidity (O'Connor 1971; Vigneswaran & Visvanathan 1995). The EC directive recommends that iron concentration in drinking water should be ≤ 0.2 mg l⁻¹ (EC 1998). In the Netherlands, the guideline value for iron in drinking water is ≤ 0.05 mg l⁻¹ (VEWIN 1993) and several water supply companies are aiming at iron levels below 0.03 mg l⁻¹ in order to minimize the distribution network maintenance costs.

Another important consideration is the minimization of the treatment costs. This can be achieved by lowering the percentage of backwash water used (e.g. in the Netherlands groundwater abstraction is charged with a tax of about euro 0.18 m⁻³) and by reducing the volume of sludge produced. In this context, several water supply companies are continually seeking the means to improve the efficiency of existing groundwater treatment systems.

Aeration followed by rapid sand filtration is the most commonly used method for the removal of iron from groundwater (O'Connor 1971; Salvato 1992). Different

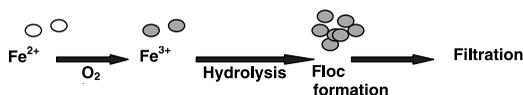
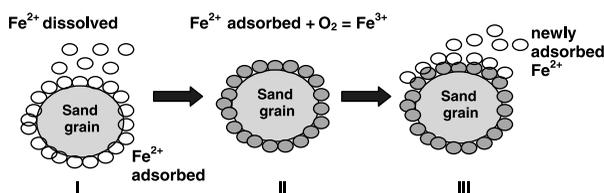
Oxidation-floc formation mechanism**Adsorption-oxidation mechanism**

Figure 1 | Physicochemical iron removal mechanisms.

mechanisms (physical, chemical and biological) contribute to the iron removal in filters and the mechanisms playing a predominant role depend on the groundwater quality and process conditions (Lerk 1965; Hatva 1988; Mouchet 1992). A better understanding of the different mechanisms involved in the iron removal process is therefore important to optimize the design and operation of iron removal filters in terms of run time, filtrate quality and overall treatment costs.

Physicochemical iron removal mechanisms

There are two main physicochemical mechanisms of iron removal in filters, namely the oxidation–floc formation mechanism (floc filtration) and the adsorption–oxidation mechanism (adsorptive filtration/catalytic iron removal), as illustrated in Figure 1.

In anaerobic groundwater, iron is commonly present in soluble iron(II) form. In the floc filtration mode of iron removal, commonly applied in many groundwater treatment plants, soluble iron(II) is first oxidized to insoluble iron(III) by aeration or chemical oxidation and the flocs formed are subsequently removed in a rapid sand filter (O'Connor 1971). In several conventional plants, however, oxidation is only partially achieved before filtration and, as a consequence, besides oxidation–floc formation, adsorption–oxidation plays a role as well. In addition to rapid head loss development and short filter runs, various

other practical problems associated with the conventional iron removal systems, like long ripening periods, iron passing through the filter and large volume of sludge produced, have been reported (Mouchet 1992).

In the adsorptive filtration, iron is mainly removed in the iron(II) form by adsorption onto the surface of the filter media. Adsorbed iron(II) is oxidized in the presence of oxygen to form an iron oxide coating on the filter media surface and hence the process continues. Adsorption–oxidation is one of the mechanisms responsible for removal of iron entering the filter in iron(II) form in conventional iron removal plants (Ghosh *et al.* 1967; Committee Report 1987) and is also the dominant mechanism in sub-surface iron removal (Rott 1985; Braester & Martinell 1988). For successful application of this mechanism, the design and operation of the process should ensure that the pre-oxidation of iron(II) is limited. When oxygen is present in the feed water, the oxidation of iron(II) during filtration cannot be avoided completely, therefore some flocs are formed and floc filtration inevitably plays a role. However, the extent of floc formation can be minimized by adapting the process conditions. It is expected that the adsorption–oxidation mechanism will result in lower head loss in comparison with the oxidation–floc formation mechanism, as adsorbed iron forms a compact coating rather than a voluminous floc. Thus the filter runs are expected to be longer and the backwash water requirement and volume of sludge produced are reduced.

Adsorption of iron(II) onto the surface of filter media or onto iron hydroxide flocs is a well-known process (Cox 1964; Hult 1973; Tamura *et al.* 1976; Sharma *et al.* 1999). Adsorption-based processes for heavy metal removal are receiving more attention these days as they have advantages over the conventional process in that they have high removal efficiencies and produce less or no sludge (Edwards & Benjamin 1989; Benjamin *et al.* 1996). However, no information is available on the effectiveness of the adsorption–oxidation mechanism when employed as the dominant mechanism of iron removal from groundwater in filters. In this study the performance of two filters, one operating predominantly in floc filtration mode and another predominantly in adsorptive mode, were compared at a pilot scale. The results of these experiments

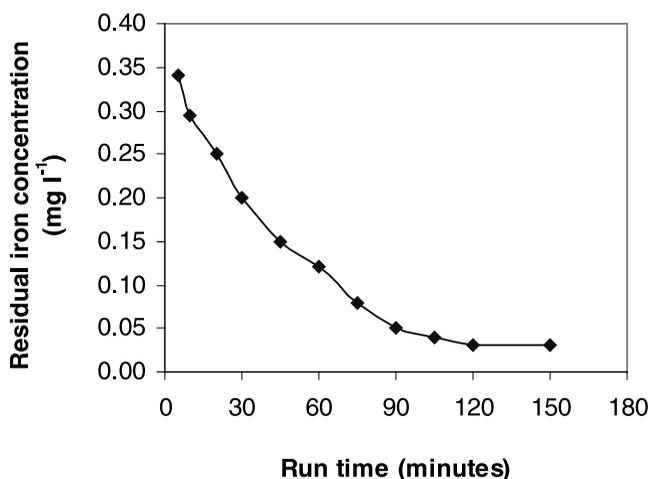


Figure 2 | Typical ripening curve of the full-scale filter at WTP Gilze after backwashing (filtration rate $\sim 8 \text{ m h}^{-1}$).

were compared with the performance of the full-scale ground water treatment plant (WTP) Gilze of N.V. Waterleiding Maatschappij 'Noord-West-Brabant' (WNWB), in southern Netherlands.

In WTP Gilze, the filtrate turbidity and iron concentrations after backwashing remain relatively high during the first 1.5–2 h (ripening period) (Figure 2). A similar problem is experienced after increasing the production rate (e.g. residual iron increases from 0.03 to 0.08 mg l^{-1} for more than 30 minutes when filtration rate increases from 10 to 15 m h^{-1}) (Figure 3). Additionally, the filtrate turbidity is relatively high ($\sim 0.3 \text{ NTU}$). The aim of this study was to explore the possibilities for more efficient iron removal in groundwater treatment plants and specifically to investigate the options to improve the performance of WTP Gilze. Therefore, pilot plant experiments were conducted to compare the performance of filters operating under two main physicochemical mechanisms of iron removal.

MATERIALS AND METHODS

Water Treatment Plant Gilze

Gilze is one of the smaller WTP of WNWB with a production capacity of 2 million m^3 per year. WTP Gilze uses

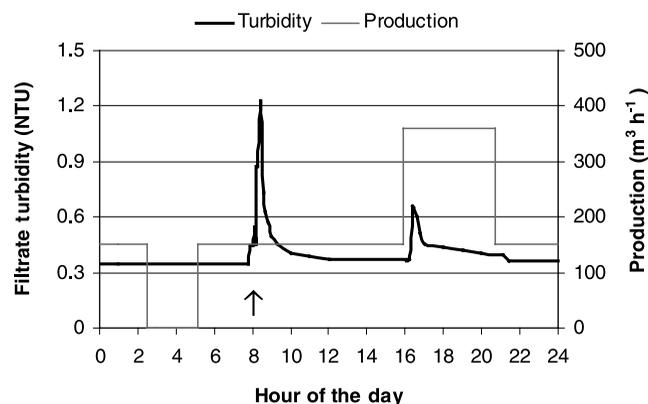


Figure 3 | Increase in filtrate turbidity with backwashing of filters and change in production rate at WTP Gilze (\uparrow three filters are backwashed subsequently around 8:00 a.m.).

groundwater as its source and employs the conventional treatment scheme: cascade aeration followed by rapid sand filtration. At WTP Gilze, 70 to 85% of iron is oxidized before entering the filter bed; hence oxidation–floc formation is the dominant iron removal mechanism. There are six sand filters (0.7–1.25 mm) with a total surface area of 37.8 m^2 and the filtration rates vary from 8 to 15 m h^{-1} depending on the production capacity (0, 150, 225, 375, 435 $\text{m}^3 \text{ h}^{-1}$). A typical daily production pattern (pumping rate) at WTP Gilze is presented in Figure 3. The depth of the supernatant water is 1.0 m and the bed depth is 1.8 m. The filters are backwashed after 48 to 72 hours at a backwash rate of 35–40 m h^{-1} as follows: water (7 min), air (5 min) and water (7 min).

Experimental set-up and process conditions

In this study, the experiments were carried out in two phases. In the first phase, two pilot filters were equipped with fine sand media (0.5–0.8 mm) and operated in two different modes: one predominantly in floc filtration mode and another predominantly in adsorptive mode with different feed water oxygen concentrations (0 mg l^{-1} , 0.5–0.7 mg l^{-1} and 1–2 mg l^{-1}). These options were compared with the existing full-scale filter equipped with coarser single media (0.7–1.25 mm), with respect to ripening time, filter run time, filtrate quality and production efficiency. The minimum acceptable run time of 48 hours

Table 1 | Raw water quality parameters at WTP Gilze, WNWB

Temp (°C)	pH	Conductivity (mS m ⁻²)	O ₂ (mg l ⁻¹)	Fe (mg l ⁻¹)	Mn (mg l ⁻¹)	CO ₂ (mg l ⁻¹)	HCO ₃ (mg l ⁻¹)	Ca (mg l ⁻¹)	Mg (mg l ⁻¹)	SO ₄ (mg l ⁻¹)	NH ₄ (mg l ⁻¹)	Cl (mg l ⁻¹)	TOC (mg l ⁻¹)
12	7.6	25.5	0.0	1.8	0.08	6.0	160	50	4.5	8	0.12	12	1.26

at the average filtration rate of 10 m h⁻¹ was set by WNWB based on operational consideration. The maximum allowable head loss in the filter bed was limited to 2.6 m and the guideline values for the filtrate quality, based on the VEWIN (Association of Water Works in the Netherlands) recommendations, were iron ≤0.05 mg l⁻¹, manganese ≤0.02 mg l⁻¹ and ammonium ≤0.04 mg l⁻¹ (VEWIN 1993). The WNWB guideline for iron concentration in drinking water entering a distribution system is ≤0.03 mg l⁻¹.

During the second phase, in an attempt to improve the performance of the filter operating predominantly under floc filtration mode, filter runs were conducted with the dual media filter (anthracite 0.8–1.2 mm and sand 0.5–0.8 mm).

The average water quality parameters of the raw groundwater at WTP Gilze are presented in Table 1, which shows that iron, manganese and ammonium concentrations in raw water are above the VEWIN guideline values.

The schematic diagram of the experimental set-up is shown in Figure 4. The pilot plant consisted of two plexi glass filter columns (300 mm internal diameter and 3 m high) provided with sampling and head loss measurement taps. Columns were provided with the automatic water level controller to maintain the constant supernatant level and filtration rate. Each column was equipped with a flow meter and a water meter to measure the rate of flow and the total production.

The details on the filter media used and process conditions applied are included in Table 2.

Experimental procedure

The filters were operated under different conditions to facilitate two different mechanisms of iron removal.

Influent to the ‘floc filtration column’ was the aerated water after the cascades of WTP Gilze so that most of the iron entered the filter bed in iron(III) form. Raw water from the wells was supplied to the ‘adsorptive column’ without aeration to ensure that the majority of the iron was in iron(II) form. The pilot filters were operated at filtration rates of 10 and 15 m h⁻¹. The run time of the filters was determined by either filtrate quality breakthrough (iron concentration >0.05 mg l⁻¹) or terminal head loss (>2.6 m). At the end of the filter run the columns were backwashed and the filter runs were started again.

Backwashing

When operated under anoxic conditions, the adsorptive column was backwashed only with water (45 m h⁻¹) for 15 minutes. In the filter runs when the adsorptive column

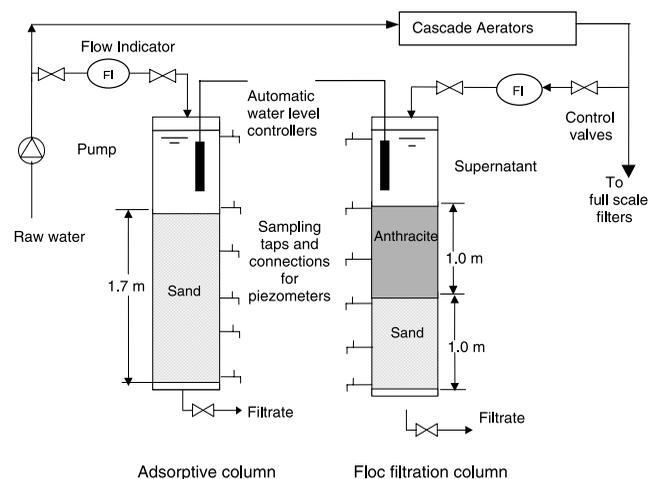
**Figure 4** | Schematic diagram of the pilot plant experimental set-up.

Table 2 | Experimental conditions

	Column 1	Column 2
Dominant mechanism	Oxidation–floc formation	Adsorption–oxidation
Filter media	Phase I: 1.8 m sand (0.5–0.8 mm) Phase II: 1.0 m sand (0.5–0.8 mm) + 1.0 m anthracite (0.8–1.2 mm)	1.7 m sand (0.5–0.8 mm)
Filtration rate	10 m h ⁻¹ , 15 m h ⁻¹	10 m h ⁻¹
Feed water	Aerated Gilze water	(i) Anaerobic Gilze well water (ii) Gilze water with 1–2 mg l ⁻¹ O ₂ (iii) Gilze water with 0.5–0.7 mg l ⁻¹ O ₂
Depth of supernatant	0.9–1.0 m	0.9–1.0 m

was operated with some oxygen in the influent, the back-wash procedure was as follows: (i) water (45 m h⁻¹) for 6 minutes, (ii) air (50 m h⁻¹) + water (10 m h⁻¹) for 4 minutes, and (iii) water (45 m h⁻¹) for 6 minutes. The dual media floc filtration column was backwashed as follows: (i) water (45 m h⁻¹) for 6 minutes, (ii) air (50 m h⁻¹) for 4 minutes, and (iii) water (45 m h⁻¹) for 6 minutes.

Measurements

Head losses along the filter columns were measured periodically with piezometers. The pH and the dissolved oxygen concentrations of influent and filtrate turbidity were monitored on-line continuously. Iron concentrations in influent, filtrate, and along the filter column were measured at different times during the filter runs. Iron(II), total iron, manganese and ammonium contents of the samples were measured immediately on site with a Dr. Lange ISIS 9000 MDA photometer using LCK 320, LCW 032, and LCK 302 cuvettes according to the methods prescribed by the supplier (Dr Lange Laboratories, Dusseldorf, Germany). Duplicate samples were taken frequently and concentrations of iron and manganese were also measured in the laboratory with a spectro-

photometer (Perkin Elmer 550 S) and an atomic absorption spectrometer (Perkin Elmer AAS 3110) to verify the results of field measurements (Standard Methods 1995). It was found that the field measurements were comparable with the laboratory results.

RESULTS

Single media filter in floc filtration mode

Preliminary experiments were conducted with a single media sand (0.5–0.8 mm) filter operating at a filtration rate of 10 m h⁻¹ in floc filtration mode. Under applied conditions, about 75% of the iron was entering the filter bed in iron(III) form. The residual iron concentrations were <0.05 mg l⁻¹ from the beginning of the filter run. The filter run time was, however, limited to only 22–24 hours due to excessive head loss (2.4 m in 24 hours). The full-scale filters at WTP Gilze have run times of 48–72 hours at a filtration rate of 10–15 m h⁻¹. This shows that sand media of 0.5–0.8 mm under floc filtration mode is not an acceptable option due to short run time. Hence this option was not investigated further.

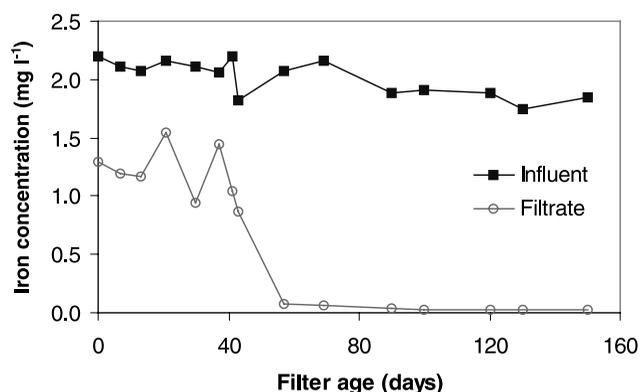


Figure 5 | Improvement in filtrate quality of the adsorptive filter operating under anaerobic conditions with filter age (filtration rate = 10 m h⁻¹, depth of supernatant = 1.0 m, samples taken one hour after backwashing).

Single media filter in adsorptive mode

Filter run with anaerobic well water

Development of the iron oxide coating

Pilot plant experiments were started with new virgin sand. Under applied conditions, about 95% of the iron was entering the filter bed in iron(II) form. At the end of each run the filter was backwashed to regenerate the adsorption sites and to remove any flocs formed. Initially the iron removal was poor. The filtrate quality improved considerably with the development of iron oxide coating on the filter media as the iron(II) adsorption capacity of the media increased with the coating development (Figure 5). It took several weeks to develop an effective iron oxide coating and to achieve good performance under adsorptive filtration mode. After about 75 days of operation, the residual iron concentrations were consistently <0.05 mg l⁻¹.

That a rather longer time was required for the development of the coating is probably due to the operation of the adsorptive column under anoxic conditions, in which the oxidation of adsorbed iron and regeneration of the adsorption sites takes place during backwashing only. The development of the coating would probably be faster if the feed water contained a small amount of oxygen, which would speed up the process of the coating development with the continuous oxidation of adsorbed iron and consequent regeneration of the

adsorption sites. The conditions governing the development of the catalytic iron oxide coating need, however, to be investigated further.

Ripening after backwashing

After the coating development, the ripening time after backwashing was shortened to ≤30 minutes and the residual iron concentrations were consistently <0.05 mg l⁻¹. This is much faster than in the full-scale filter where filter ripening takes about 1.5–2 hours.

Filtrate quality and run time

The first few runs, after the development of the coating, produced filtrate of good quality (iron <0.05 mg l⁻¹, turbidity <0.1 NTU) with the run lengths ranging from 75 to 80 hours at a filtration rate of 10 m h⁻¹. However, further filter runs were inconsistent with respect to filtrate quality. During the later stage, filter run time varied between 24 and 30 hours. At WTP Gilze, there are regular night supply shutdowns of variable duration (Figure 3). This might have introduced oxygen into the filter, which most likely regenerated the catalytic iron oxide coating occasionally by oxidizing the adsorbed iron and consequently resulted in the variable filter run times. The conditions governing the adsorption capacity and regeneration of the adsorption sites need further detailed investigation.

In all filter runs, the head loss development in the adsorptive column was very slow as compared with the floc filtration column (Figure 6) and the filter runs were terminated due to residual iron breakthrough. Under applied conditions, there was no manganese and ammonium removal.

Filter run with 1–2 mg l⁻¹ oxygen in influent

It was hypothesized that continuous regeneration of adsorption sites with the introduction of some oxygen in the feed water would increase the run time of the filter. Therefore, oxygen-rich treated water from WTP Gilze was mixed with anaerobic well water to get feed water with an oxygen concentration of 1–2 mg l⁻¹. This water was introduced at the top of the filter column; this resulted in a

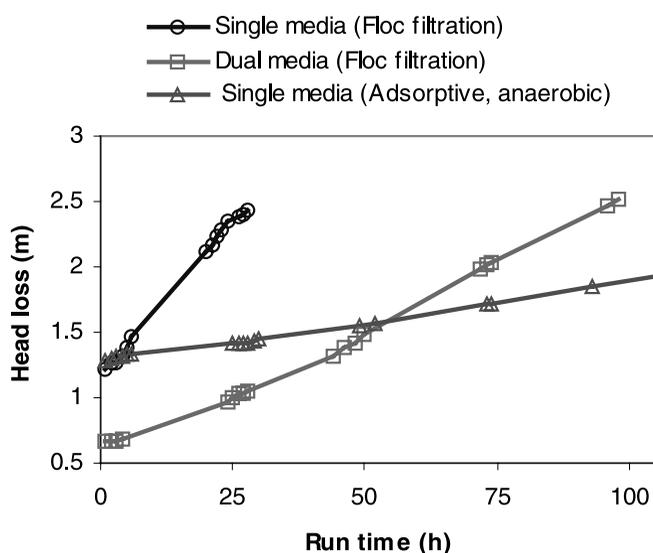


Figure 6 | Head loss development under different operational conditions (filtration rate = 10 m h^{-1} and depth of supernatant = 1.0 m).

pre-oxidation time of about 8 minutes. Under these conditions, about 10–15% of the iron was entering the filter bed in iron(III) form.

With this modification, the ripening time after back-washing was 45–60 minutes and the average filter run time was 44 hours. The filter runs were consistent and reproducible. Residual iron and turbidity were consistently $<0.05 \text{ mg l}^{-1}$ and $<0.1 \text{ NTU}$, respectively, with an additional advantage of ammonium and manganese removal (from 0.15 to 0.06 mg l^{-1} and from 0.08 to 0.04 mg l^{-1} , respectively). Filter runs were terminated due to excessive head loss (2.6 m in 44 hours). From the Stumm and Lee iron oxidation rate equation it was calculated that, under the applied conditions and oxidation rate constant $k = 1.14 \times 10^{13} \text{ l}^2 \text{ mol}^{-2} \text{ atm}^{-1} \text{ min}^{-1}$, 16–29% of the dissolved iron entering the filter bed is oxidized within the filter (Stumm & Lee 1961). Therefore, the introduction of oxygen coupled with a relatively long pre-oxidation time in the supernatant, very likely resulted in substantial floc formation in the supernatant and in the filter bed, thereby causing the rapid head loss development and shortening filter runs.

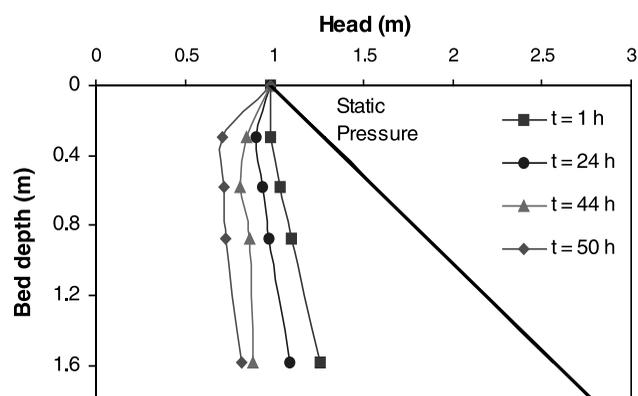


Figure 7 | Lindquist diagram of adsorptive filter with feed water oxygen of $0.5\text{--}0.7 \text{ mg l}^{-1}$ (filtration rate = 10 m h^{-1} , depth of supernatant = 0.94 m).

Filter run with $0.5\text{--}0.7 \text{ mg l}^{-1}$ oxygen in influent

To further prolong filter run length by reducing head loss, the adsorptive column was operated with an influent oxygen concentration of about $0.6 \pm 0.1 \text{ mg l}^{-1}$ and feed water was introduced 10 cm above the surface of the filter media to shorten the pre-oxidation time to 1 minute. Under these conditions, the amount of iron entering the filter bed in iron(III) form was reduced to about 8–10%.

Under these conditions, the ripening time after back-washing was 30–60 minutes and the average filter run time further increased from 44 hours to above 50 hours. At the filtration rate of 10 m h^{-1} , residual iron concentration and turbidity were $<0.05 \text{ mg l}^{-1}$ and $<0.1 \text{ NTU}$, respectively. Ammonium removal was rather good (from 0.15 to 0.01 mg l^{-1}) but manganese removal was rather poor (from 0.08 to 0.07 mg l^{-1}). Head loss development was still limiting the filter run length to 50–72 hours. Calculations using the Stumm and Lee equation show that under the applied operating conditions only 8–12% of the iron entering the filter bed is oxidized within the filter (Stumm & Lee 1961). This explains why the head loss development in this run was much slower than in the filter run with $1\text{--}2 \text{ mg l}^{-1}$ of oxygen.

Head loss development was substantial in the first 0.4 m of the filter bed (Figure 7) due to deposition of flocs (Figure 8) and thereafter in the deeper layers head loss increased very gradually. It is clear from the Lindquist

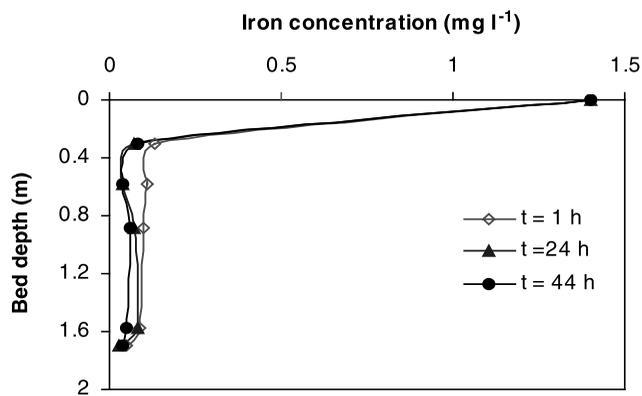


Figure 8 | Iron removal profile for adsorptive filter with 0.5–0.7 mg l⁻¹ of oxygen in feed water (filtration rate=10 m h⁻¹, depth of supernatant=0.94 m).

diagram (Figure 7) that filter runs much longer than 50 hours are possible without developing negative pressure.

Table 3 summarizes the established evaluation criteria and results obtained with pilot filters equipped with single sand media (0.5–0.8 mm) operating under different process conditions, and compares them with the results obtained with the full-scale filter. For all the options examined, the ripening time was shortened to ≤60 minutes. It is evident from Table 3 that, under given conditions, the adsorption–oxidation mechanism is a better option than the oxidation–floc formation mechanism, despite the fact that the bed depth is 10 cm smaller in the case of the adsorptive filter. The adsorption–oxidation mechanism results in longer filter runs, lower head loss development and lower sludge volume, therefore reducing the amount of backwash water used and sludge treatment and disposal costs. The single media fine sand filter operating under adsorptive mode with 0.5–0.7 mg l⁻¹ of oxygen in the influent satisfies the WNWB filter run time criterion. However, in pilot filters operated under

Table 3 | Overview of comparison criteria and results for the single media filters

Parameter	Reference criteria	Full-scale filter (existing)	Single media fine sand filter (Pilot)			
			Oxidation–floc formation	Oxidation–floc formation	Anaerobic	0.5–0.7 mg l ⁻¹ oxygen
Dominant removal mechanism					Adsorption–oxidation	
Ripening time (min)	≤60	90–120	< 30	< 30	30–60	45–60
Run time (h)	> 48	48–72	22–24	24–30	50–72	40–44
Head loss (m)	< 2.6		2.2–2.4	1.4–1.5	1.7–2.5	2.2–2.6
Run time criteria		Fixed time	Head loss	Filtrate quality	Head loss	Head loss
Filtrate quality						
Fe (mg/l) ^a	< 0.05	0.03	0.03	0.03	0.04	0.02
Mn (mg/l) ^a	< 0.02	0.02	NM	0.07	0.07	0.04
NH ₄ ⁺ (mg/l) ^a	< 0.04	0.05	NM	0.15	0.01	0.06
Production efficiency (%) ^b	≥98	97	96	96	98	98

^aAverage concentrations.

^bCalculated as difference between total filtered water (100%) and % of water used for backwashing.

NM=not measured.

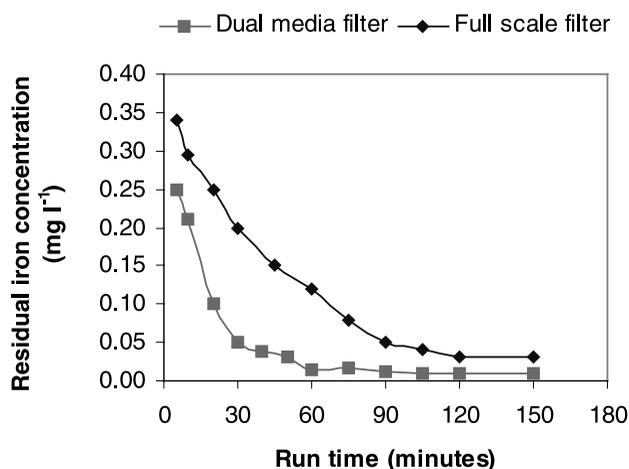


Figure 9 | Ripening of the dual media filter in floc filtration mode and full-scale filter after backwashing (dual media filter, filtration rate=10 m h⁻¹; full-scale filter, filtration rate =8 m h⁻¹).

adsorptive mode, manganese and ammonium were not sufficiently removed.

Dual media filter in floc filtration mode

Additional filter runs were conducted with the pilot filter equipped with the dual media (anthracite and sand) in order to reduce the head loss development and increase the run time. Under applied conditions, about 75% of the iron was entering the filter bed in iron(III) form.

Ripening after backwashing

Under these conditions, the ripening time was reduced to about 30–60 minutes. Figure 9 clearly shows that the ripening of the dual media filter is much faster than that of the full-scale filter, probably due to the polishing effect of the fine sand layer.

Filtrate quality and run time

The residual iron concentrations and turbidity after ripening were <0.05 mg l⁻¹ and <0.1 NTU, respectively, throughout the filter run. The filter run time was determined by the head loss development. At the filtration rate of 10 m h⁻¹, the filter runs were typically 85–90 hours, with a production efficiency of about 99%. A typical

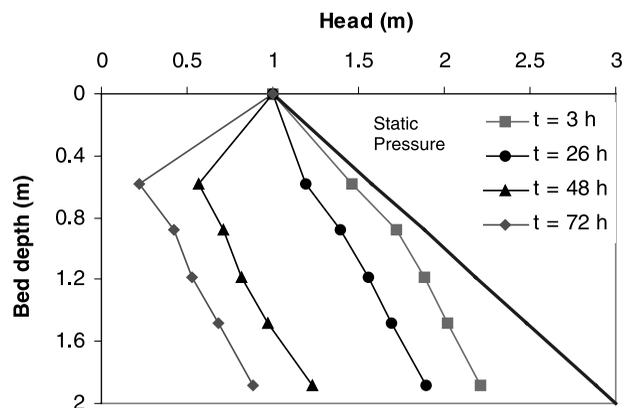


Figure 10 | Typical Lindquist diagram of the dual media filter operating under floc filtration mode (filtration rate=10 m h⁻¹, depth of supernatant=1.0 m).

Lindquist diagram (Figure 10) shows that most of the head loss is developed in the anthracite layer. It was also observed that, in this case, most of the iron removal occurs in the anthracite layer while the sand bed serves as a polishing step. For this option, the residual manganese and ammonium concentrations were also well below the guideline values (VEWIN 1993).

Effect of changing production rate

An increase in the filtration rate from 10 to 15 m h⁻¹ during the filter run resulted in only a slight temporary increase in residual iron concentration (from 0.02 to 0.04 mg l⁻¹) for about 20 minutes. A similar increase of the filtration rate in the existing full-scale filter resulted in an increase of residual iron from 0.03 to 0.08 mg l⁻¹, which lasted for more than 30 minutes.

These results show that use of dual media improved the performance of the filter operating under floc filtration mode and satisfied all the evaluation criteria. Hence, the dual media filter operating under floc filtration mode might be an attractive alternative for WTP Gilze.

Quantification of iron passing the filters

The average concentration of iron passing through filters operating under different conditions during the entire filter run (quantified by computing the area under the

Table 4 | Iron passing through the filters (filtration rate=10 m h⁻¹)

Filter	Iron passing (mg l ⁻¹) ^a
Full scale filter No. 1 ^b	0.03
Dual media filter in floc filtration mode	0.02
Single media adsorptive filter (0.5–0.7 mg l ⁻¹ O ₂)	0.04
Single media adsorptive filter (1–2 mg l ⁻¹ O ₂)	0.02

^aAverage for a filter run.^bFiltration rate 8 m h⁻¹.

residual iron concentration versus time curve) is presented in Table 4. The dual media filter operating in floc filtration mode and the adsorptive filter with influent oxygen of 1–2 mg l⁻¹ resulted in the lowest amount of iron passing the filter and could, consequently, provide savings in terms of operation and maintenance of the distribution network as well as reduce ‘red water’ incidents. The full-scale filter and the adsorptive filter with influent oxygen of 0.5–0.7 mg l⁻¹ also satisfy the VEWIN guideline value of 0.05 mg l⁻¹ but slightly exceed the WNWB guideline for iron concentration in drinking water entering a distribution system (<0.03 mg l⁻¹).

DISCUSSION

Experimental results strongly suggest that adsorptive iron removal is an attractive iron removal alternative for some groundwaters. The influent oxygen concentration has a strong influence on the removal efficiency of iron, manganese and ammonium. Theoretically, a minimum of 1.0 mg l⁻¹ of oxygen is needed for the complete oxidation of iron, manganese and ammonium present in the groundwater of Gilze. Therefore it is very likely that nitrification and manganese removal, in the filter runs in adsorptive modes with 0 and 0.5–0.7 mg l⁻¹ of influent oxygen, were limited due to a lack of oxygen. Consequently, to improve manganese and ammonium removal in Gilze, it

is advisable to operate an adsorptive filter with a feed water oxygen concentration of about 2 mg l⁻¹, assuming that filter design is optimized with respect to head loss development and filter run time. To reduce iron oxidation and subsequent floc formation, the feed water should be introduced just above the media surface thus reducing pre-oxidation time to a minimum. In addition, the head loss development in the filter bed can be reduced and, consequently, the filter run time can be prolonged by facilitating deep bed filtration with the use of the dual media or the coarser single media as used in the full-scale filters.

Results obtained strongly suggest that the dual media filter operating mainly under adsorptive mode with a short pre-oxidation time is an attractive option worth further investigation for WTP Gilze. Another promising alternative is to run two filters in series at a high filtration rate of 20 m h⁻¹. The first filter equipped with coarser media operating in the adsorptive mode with very low oxygen concentration would remove the majority of the iron, and the second filter with finer media operating in the floc filtration mode would remove manganese, ammonium and the remaining iron.

Rapid development of an effective iron oxide coating that will reduce the ripening time of new media is important for successful implementation of this mechanism. Secondly, the media of filters operating in adsorptive mode will grow with time. Hence, long-term experiments are required to determine the method of rapid development of an effective coating and to assess the rate of growth of media and the required frequency of the filter media replacement.

CONCLUSIONS

1. The filter with fine sand (0.5–0.8 mm) operating under floc filtration mode gave better filtrate quality and a much shorter ripening time than the full-scale plant. However, filter run times were unacceptably short.
2. Single media filter with fine sand running in adsorptive mode produced filtrate with low iron

concentrations and had short ripening times. However, manganese and ammonium removal were not satisfactory. In general, for the single media fine sand filter, the adsorptive mode gave a longer run time than the floc filtration mode. The filter run times of the adsorptive filter were, however, influenced by the influent oxygen concentrations. Filter run time criteria established for WTP Gilze (48 hours) were easily fulfilled at influent oxygen concentration of 0.5–0.7 mg l⁻¹ while at influent oxygen concentration of 1–2 mg l⁻¹, the filter run times were slightly shorter (40–44 hours).

3. Use of dual media (anthracite 0.8–1.2 mm and sand 0.5–0.8 mm) considerably prolonged the run time of the filter operating under floc filtration mode and the filtrate quality satisfied all the evaluation criteria.
4. Three options considered to be attractive to improve the performance of WTP Gilze are: (i) dual media filter in floc filtration mode; (ii) single media filter in adsorptive mode with coarser material (e.g. 0.7–1.2 mm) and low influent oxygen concentration (about 2 mg l⁻¹); (iii) dual media filter in adsorptive mode with low influent oxygen concentration (about 2 mg l⁻¹) and limited pre-oxidation time. The experimental results suggest that the third option would result in the best performance in terms of both productivity and quality. However, for filters running under adsorptive mode, the process conditions need to be selected carefully to ensure sufficient manganese and ammonium removal as well. Additionally, the growth of filter media in adsorptive filters and related practical implications should be assessed.

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