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Removal of both dissolved and particulate iron from groundwater

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Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

Iron is the primary source for discolouration problems in the drinking water distribution system. The removal of iron from groundwater is a common treatment step in the production of drinking water. Even when clear water meets the drinking water standards, the water quality in the distribution system can deteriorate due to settling of iron (hydroxide) particles or post-treatment flocculation of dissolved iron. Therefore it is important to remove dissolved and particulate iron to a large extent. This paper describes the study towards the current iron removal processes and experimental work towards improving removal of dissolved and particulate iron. The study was carried out at groundwater treatment plant Harderbroek, consisting of aeration, rapid sand filtration and tower aeration. The research contains two parts: 1) a particle fingerprint of the treatment, resulting in a quantification of particles breaking through the rapid sand filtration. 2) Small column experiments on the oxidation and filterability of iron. The fingerprint showed that operational events such as switching on/off of filters and backwashing have a significant impact on the volume concentration of particles breaking through the filter. A frequency plot of the different size ranges of particles indicates that mainly the filterability of the middle size ranges ($2-7\ \mu\text{m}$) of particles was influenced by switching a filter on/off. A backwash event mainly affects the bigger particle size ranges. The column experiments showed that in the cascade effluent the majority of the iron is dissolved iron(II), indicating that the oxidation of iron(II) to iron(III) is the rate determining step at Harderbroek, which is limited by pH. Dosing caustic soda resulted in a significant increase of the oxidation rate and improved the removal of iron(II) in the column. Crushed limestone filtration gave promising results, but the contact time applied was too short to completely oxidize iron(II).

DWESD

1, 87–115, 2008

Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



1 Introduction

Iron is removed during groundwater treatment. However, the iron removal is usually incomplete. Iron particles (consisting of Fe(III)oxides and hydroxides) in water supplies cause various aesthetic and operational problems including bad taste, discolouration and deposition and resuspension in the distribution system. In addition to particulate iron, dissolved iron (Fe(II)) can cause post-treatment flocculation forming extra iron particles.

In some publications on the corrosion of cast iron in potable water systems it is concluded that this is a major cause of discolouration (Smith et al., 1997; McNeill and Edwards, 2001). Recent studies (Prince et al., 2003; Vreeburg, 2007) suggest that other sources of particles play a role in the discolouration problem. Vreeburg (2007) states that particles in the drinking water leaving the treatment plant are in most cases the main source for deposits in the network. These deposits may cause discolouration (high turbidity) after resuspension, e.g. due to increased flow. In the Netherlands, the mandatory drinking water standard for iron is 0.2 mg/l. Verberk (2006) showed that even with a clear water concentration of 0.01 mg Fe/l, post-flocculation of dissolved iron can lead to a significant increase of particulate iron. In order to avoid post-flocculation and subsequent sedimentation of iron in the distribution network, companies should thus aim for a very low total iron concentration in the clear water.

Conventionally, iron is removed from groundwater by the processes of aeration and rapid filtration (O'Connor, 1971; Salvato, 1992). Different mechanisms may contribute to the iron removal in filters; flock filtration, adsorptive iron removal and biological iron removal. Which mechanism is dominant depends on the groundwater quality and the process conditions (Lerk, 1965; Hatva, 1989; Mouchet, 1992; Søggaard et al., 2000).

Iron present in anaerobic groundwater will be in the reduced state (Fe(II)). In the presence of oxygen, iron(II) will be oxidised to iron(III) (Lerk, 1965). The solubility product of iron(III)hydroxide is very low (2.0×10^{-39} at 25°C (Jones, 2000)) and hence the iron(III) will quickly hydrolyse to form iron(III) hydroxide flocks. Pin flocks are formed,

Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

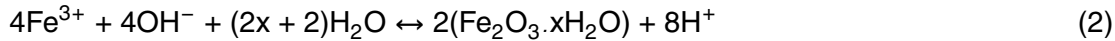
Printer-friendly Version

Interactive Discussion

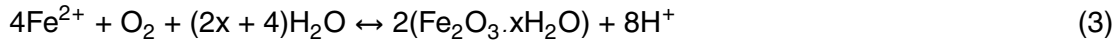


that will grow depending on residence time and G-values. These flocks will subsequently be removed by filtration.

The oxidation (1) and hydrolysis (2) reactions and the overall reaction equation are (Lerk, 1965):



The overall reaction equation becomes:



Oxidation and hydrolysis strongly depend on the pH. At low pH the reaction rate is low; the reaction rate increases with increasing pH. Depending on the pH value the formed colloids can become positively or negatively charged. Charged colloids do not flocculate very well.

Instead of oxidation followed by flocculation, iron(II) may also be removed by adsorptive filtration (Sharma, 2001): The ions are adsorbed onto the catalytic surface of the filter media. Subsequently, in the presence of oxygen, the adsorbed iron(II) is oxidised forming a new surface for adsorption; in this way the process continues.

The iron(II) adsorption capacity depends on the surface conditions of the filter material, the oxygen concentration and on the pH of the water. The capacity may also be influenced by other ions or organic matter present in the water (Mn^{2+} , Ca^{2+} , NH_4^+ and NOM) (Sharma et al., 2002). Calcium ions negatively affect the iron(II) adsorption. The performance of flock filtration iron removal from soft waters is, however, poor (Hult, 1973) due to the formation of weak flocks. Adsorptive iron removal is the dominant mechanism if pre-oxidation of iron(II) before filtration is minimal. This can be achieved by reducing the oxidant concentration or time available for the oxidation reaction (Sharma, 2001). Sharma (2001) compared flock filtration and adsorptive filtration in pilot research. In general, for single media fine sand filters, the filter run times were longer for adsorptive filtration than for flock filtration.

Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



As mentioned above, recent insights indicate that iron should be removed to concentrations well below the norm. Therefore, removal of both dissolved and particulate iron by the conventional treatment process is studied. By applying different methods, a complete picture of the iron removal at a typical groundwater treatment plant is obtained. The oxidation, particle formation and removal of particles is studied and in addition two hypothesis were tested:

1. Iron removal is not sufficient because the formed iron hydroxide flocks break down due to high turbulence in the cascade or filter inlet construction.
2. The oxidation of iron(II) to iron(III) does not perform well due to a too low pH of the cascade effluent.

In this study particle counters and filtration equipment are used and iron analyses are performed. The oxidation rate of iron (II) is shown to be low, but it may be increased by increasing the pH. Furthermore, breakdown of flocks after the cascade aeration does not seem to affect particles breaking through the filter, however, operational events such as a filter switch and a backwash, significantly affect the particle load to the distribution network.

2 Methods

2.1 Analyses

HCO_3^-/pH

Performed in the laboratory of Vitens in Utrecht. pH and HCO_3^- samples are collected in “special air removal bottles”. pH is analysed conform NEN 6411. HCO_3^- is determined by titration with hydrochloric acid.

Iron(II) analysis

Spectofotometric determination of iron(II). Dissolved iron(II) forms a purple complex with the reagent ferrozine. (3-(2-pyridyl)-5,6-diphenyl-1,2,4-triazine 4,4'-disulfonacid disodium salt. xH₂O). Iron(III) does not form complexes with this reagent. Thus only iron(II) is determined. Samples were taken in 100 ml bottles, containing 2 ml HCl for conservation. The acid results in a very low pH, limiting the oxidation reaction.

Iron total

Metal samples conserved with 2 ml HNO₃. The total iron concentration is determined with ICP-MS, in conformance with ISO 17294-2.

Iron(II) – iron(III) analysers

Applicon, type Alert 2004 colorimeters, installed at different locations and filter bed heights at treatment plant Harderbroek.

Particle counter

Pamas, type: WaterViewer, 8 channels, Size range 1–100 μm.

TILVS

The TILVS equipment consists of a pump (TrueDos M 209, Alldos) which maintains a constant flow through a filter, regardless the pressure building up due to filtration. The TILVS concentrates the particles from the water on a filter which can be used for determining the mass and chemical composition of the particles. For mass determination the TILVS filter was filtered with Milli-Q water, dried in an oven (105°C) and weighted before use. Afterwards, the filter with filtered particles is dried again for at least 16 hours in the oven (105°C) and weighted again. For the chemical composition the filter

Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



is digested in nitric acid and analysed by NPOC (Non purgable organic carbon) and an ICP-MS scan (Inductively coupled plasma – mass spectroscopy). The applied filters were glass micro fibre filters with a pore size of $0.7 \mu\text{m}$ (GF/F, Whatman).

2.2 Materials

5 2.2.1 Characteristics treatment plant Harderbroek

Drinking water at Harderbroek is produced from groundwater. The raw water quality is summarised in Table 1. A maximum flow of $1800 \text{ m}^3/\text{h}$ can be treated and the average production is $800 \text{ m}^3/\text{h}$. The treatment consists of three steps: cascade aeration (4 units, each $450 \text{ m}^3/\text{h}$, 5 steps), filtration (8 filters, average flow $220 \text{ m}^3/\text{h}$, filter bed depth 2 m, surface 24 m^2) and tower aeration (3 towers, each $320 \text{ m}^3/\text{h}$) The mean iron concentration in the clear water is 0.04 mg/l .

2.2.2 Fingerprint

At Harderbroek the presence and removal of particles in the treatment plant is determined, the so-called fingerprint. A distinction is made between normal treatment and operational events. A particle size distribution is obtained by using the 8 channel particle counters from PAMAS, type Waterviewer. Particles are counted during a complete filter run (32 h). At the same time TILVS were continuously filtering filter effluent. After the filter run the backwash water was analysed, to obtain a mass balance of the filtration process.

20 In order to quantify the contribution of operational events on the total volume load, particle counts ($\#/ \text{ml}$) are converted to particle volumes in $(\mu\text{m})^3/\text{ml}$ and in parts per billion (ppb). The volume concentration during stable operation is compared with the volume concentration after an operational event. With this method it is possible to evaluate particle breakthrough of a rapid filter quantitatively.

Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



2.2.3 Column set-up

Four identical columns, with a diameter of 9 cm are used. They are flow controlled with four separate flow control meters. The applied flow was 60 l/h per column, which corresponds to a filtration velocity of 10 m/h. They are operated by hand and filled with ripened filter material from the Harderbroek filters. The available filter bed height was 25 cm. Before starting the experiments the columns are flushed for 8 h with clear water to wash out most dirt.

The filterability is determined by measuring turbidity, iron concentrations (iron(II) and total iron separately) and a particle counter. Samples were taken 1 h and 4 h after the start-up of the filtration experiment. After an experiment (4 h) the filters were back-washed. The backwash is performed with drinking water. The applied backwash flow was 350 l/h (55 m/h) for 10 min. The expansion during a backwash event was between 20% and 28%.

2.3 Experiments

2.3.1 Fingerprint

During the fingerprint measurements two situations are distinguished: stable operation and operation in which “events” occur. For particle behaviour during operational events, only the particle count data are used. In order to compare particle counting data and TILVS, they are installed in parallel throughout the treatment plant. Table 2 shows a schedule of the measurements on each location.

2.3.2 Column experiments

With the four-column set-up research is executed, concerning the filterability of iron. The first part is focussed on testing the first hypothesis. For this the pre-treatment of the filter influent water is changed. These pre-treatments may also be able to improve

Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



the iron(III) hydroxide flock formation and removal. During the first part of the column experiments the influent water treatment is varied resulting in four different water types, see Table 3. Mixing intensity, residence time, iron(II) concentration in the influent and the type of aeration were varied. The second part is focussed on adjustments in the filtration process, in order to test hypothesis 2 and to test improvement of the oxidation and the removal of iron in the filter. With caustic soda dosage and crushed limestone filtration the pH is increased.

Water type 1 is the reference. Cascade effluent water was mixed with a stirrer, which simulates the filter inlet construction of the filter in the treatment plant. The water type 2 originates directly from the cascade, without a mixing phase (as the hypothesis is that the mixing intensity in the inlet was so high that flocks are broken up again). Water type 3 is mixed water; a part of the water is cascade effluent water, and the rest is raw water (ratio 2:1 and 1:1, to limit pre-oxidation and hydrolysis)). Type 4 is raw water which passed a combination of spray and bubble aeration.

During the second part of the column experiments pH adjustments were performed, in order to investigate the kinetics of the iron oxidation processes at Harderbroek. With a membrane pump caustic soda (0.01 M) is dosed in one of the two influent pipe lines, feeding columns 1 and 2. The dosing point was situated 2 m before the columns, which gives a residence time of 5 s in the tubing before the filter columns and another 100 s in the supernatant water. To study the effect of crushed limestone on the pH in two of the four columns the filter material is removed and replaced by crushed limestone. The applied grind is Jura Perle grains, in the size range 1.1–1.8 mm.

Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



3 Results and discussion

3.1 Fingerprint

3.1.1 Particle counter in filter effluent during events

During stable treatment operation, the particle volume concentration is measured and summarised in Table 4.

The particle counts in the filter effluent during events are shown in Figs. 1 and 2. At the start of the experiment filters 2 and 3 were in operation. When the particle counter shows a stable value, filter 1 is switched on. A clear peak in particle number (Fig. 1a) and particle volume concentration (Fig. 1b) is detected. Figure 2a shows the particle counts during a complete filter run, starting immediately after the filter was backwashed. At the start of the filter run the numbers are higher compared to stable operation. Figure 2b clearly shows the higher particle volume during 4 h.

The squares in the volume graphs indicate the contribution of the event to the total volume, compared to the contribution of the stable operation.

During stable operation, lasting for 24 h, the particle volume load was 15.7 ml. As a result of switching the filter, the particle volume during the peak, which lasts for 30 min, was 2.4 ml. So, in only 2% of the time 15% of the total particle load is breaking through the filter (Table 5 and Fig. 1b).

For a backwash event the load from the peak is compared to the load of the total filter run (32 h). The load during the first 4 h is 18.7 ml, while the total load during the stable part of the filter run time (28 h) is 22.6 ml. Thus, in 13% of the time, 45% of the particle volume load is added to the filter effluent (Table 5 and Fig. 2b).

A frequency curve indicates which volume concentration occurs during which time fraction. Such a curve is plotted of the particle volumes calculated at every data point during a filter run. This was done for the different size ranges of particles separately (Fig. 3). A steep S-curve indicates a uniform concentration during the filter run. A more flat S-curve indicates some variation in the measured particle concentration during the

Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



measured time interval (more peaks).

In Fig. 3a the S-curve for a filter switch is plotted. The curves for the size ranges 1 to 1.5 and 1.5 to 2 μm and 10–15, 15–20 and >20 μm show a steep S-shape. These particle sizes occur in a constant volume over the measured time interval. But the size ranges 2–5 , 5–7 and 7–10 μm show a less steep S-curve. The smaller particles (1 and 1.5) are removed to a smaller extent by filtration compared to other size ranges, so an event does not significantly influence the filterability of these particles. The larger particles (10, 15 and 20 μm) have such a high filterability that they are always well removed, also during an event. The particles in the middle size ranges (2–10 μm) are significantly influenced by the event.

In Fig. 3b the frequency curves for the complete filter run (after a backwash) are plotted. In this graph the curves for the size ranges 10–15 and 15–20 show a less uniform volume concentration. After a backwash event mainly the larger particles break through. This can be explained by the settling properties of particles. Larger particles have better settling properties and are therefore hardly removed by backwashing. These particles stay in the filter bed and break through when filtration is started. These larger particles are undesired in the distribution system, because of their good settling properties.

3.1.2 TILVS and particle counter throughout the treatment

Table 6 shows the results for the TILVS and the particle counters, installed in the same time period. From the mass on the filter in the TILVS filtration equipment and the known volume that passed the filter, the average particle concentrations are calculated. With the NPOC ICP-MS scan the iron concentration of the residual is determined. As expected, both methods show the formation of particles during cascade aeration and the removal of particles during filtration. To relate the data of the TILVS measurements and the particle counts, a density is calculated by dividing the concentration (in mass) from the TILVS by the concentration (in volume) from the particle counter data.

The estimated density varies a lot for the different treatment steps. Furthermore,

Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



the values are much higher than expected. Verberk (2006) reported a floc density of 1037 kg/m^3 , which is a more realistic value. If the particles were present as iron hydroxide flocs, these could have had a loose structure, which probably gives a density only slightly higher than that of water. However, as will be shown later, oxidation and hydrolysis were very slow, which may have resulted in adsorptive iron removal. The iron particles formed in this way, may have a higher density. Nevertheless, the average density value of 7130 kg/m^3 then still seems to be much too high. This can only be explained by differences between the methods. E.g. the TILVS filters had a pore size of $0.7 \mu\text{m}$, while the particle counter starts measuring only from $1 \mu\text{m}$. Thus, it might be that small particles are accumulated on the filter, which are not measured by the particle counter. It even can occur that smaller particles than $0.7 \mu\text{m}$ were retained by the TILVS filter, due to cake filtration and pore blocking. This may have resulted in a much higher mass-pbb measured with TILVS, compared to volume-ppb measured with the particle counter, which results in an overestimation of the density.

The latter effect can also explain the differences in densities throughout the treatment. In the raw water a lot of small particles are present, so probably also a lot of particles below $1 \mu\text{m}$, which are not counted by the particle counter, but are retained by the TILVS filters. This will result in a too high density. At measuring locations where small particles and low particle concentration are expected, such as raw water and filter effluent, the calculated density is high. This can be due to a relative bigger deviation between the particle counter and the TILVS.

The particle counter and the TILVS are both strong tools which enable to investigate particles on composition and changes. But in this research, it seemed to be hard to combine the results from both methods for density estimation. Nevertheless, it is useful to apply both methods in parallel, because the particle counter data mainly give information about variation in particle concentrations for example by operational events, while TILVS gives an average concentration over the measured time interval and can be used to measure the absolute mass of particles.

Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



3.2 Column experiments part 1

In the first part of the column experiments, the different influent water types, did not show significant differences. Thus, hypothesis 1 was not rejected. The iron in the cascade effluent water consists mainly of iron(II) (Fig. 4), while it is expected to find mainly iron(III) after the aeration step. pH measurements gave reason to assume that this is due to a slow oxidation rate (pH=7.5). Figure 5 shows the (slow) oxidation of Fe(II) in the supernatant of a filter, which was out of order after it was backwashed. The iron(II) concentration does decrease, but this process takes hours. For the flock filtration at Harderbroek the oxidation of iron(II) is thus the rate determining step, limited by the pH.

3.3 Column experiments part 2

In part two of the column experiments, the pH is adjusted. With caustic soda dosage the influent pH is changed, while during crushed limestone filtration the pH changes during filtration. The results for the measured iron(II) and iron(III) concentration are plotted in Fig. 6. The pH in the influent of the columns after the NaOH dosage is about 8.0. The iron(II) concentration in the influent water is decreased compared to the reference, from 1.2 mg/l to 0.8 mg/l. The iron(II) concentration in the effluent is decreased from 0.4 mg/l to less than 0.1 mg/l. During the backwash procedure after the caustic soda dosage experiment, the backwash water showed a deep brownish red colour, indicating the presence of iron hydroxide flocks.

The crushed limestone filtration experiment results in a slight increase of the pH in the effluent water, from 7.5 to 7.65. The contact time between the water and the crushed limestone was too short for the required pH increase. But still a slight improvement of the iron removal is noticed. The iron(II) concentration in the effluent in decreased from 0.4 mg/l to 0.2 mg/l. The measured iron(II) concentration in the most right reference column is unexpectedly low. The total iron concentration however, is the same as the other reference column in the same experiment, so probably an error

Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



occurred during the iron(II) analysis.

The results of the column experiments to test hypothesis 2 are presented in Fig. 6. The red (lowest) bars indicate iron(II) and the blue (uppest) bars indicate iron(III). The straight bars show the results of the dosage experiment, the striped bars show the results of the reference experiments. From the caustic soda dosage experiment, it can be concluded that an increase of pH by the dosage of caustic soda results in less iron(II) in the influent water. The oxidation of iron(II) into iron(III) has increased. The effluent iron(II) concentration is decreased compared to the reference columns. A pH increase results in better oxidation and iron(II) removal. The iron(III) concentration in the effluent columns is remarkable, which is increased compared to the reference experiment. Removal of iron(III) hydroxide flocks needs attention in further research. For the crushed limestone experiment there is no difference in the influent concentration, because the pH is only increased during filtration. The iron(II) as well as the iron(III) removal seems to be slightly better than the reference experiment, but this is not significant. Crushed limestone filtration seems to be a promising alternative, but the contact time in the columns was too short to obtain reliable results. Extended experiments with longer contact time are recommended.

Thus at Harderbroek after cascade aeration, the majority of the iron is present as dissolved iron(II) because of the slow oxidation rate. The treatment is not designed for adsorptive removal.

To improve the iron removal at Harderbroek the following may be suggested: (i) Caustic soda dosage (NaOH) in the cascade step, to achieve a good mixing. This dosage is easy to implement. However, due to the low buffering capacity it will be very sensitive for pH variations and will be difficult to control; (ii) Crushed limestone filtration. Although during the experiments the contact time was too short, Oomen et al. (1983) reported crushed limestone filtration to be the most convenient process for the treatment of iron containing aggressive groundwater. The implementation of crushed limestone filtration is more expensive than introducing a caustic soda dosage. But the advantage is that calcium carbonic acid equilibrium will automatically be reached within

Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



the process. Therefore it is stable and there is no need for operation and control. An undesired side effect from this process can be an increase of small particles in the filter effluent, caused by dissolving calcium; (iii) A last alternative is to move the aeration tower to be applied directly on raw water. More intensive aeration (and removal of CO₂) of raw water will increase the pH. Some extra pipelines and pumping are necessary. An advantage of this alternative is the absence of chemical dosages. It can be expected that fouling of the aeration tower can be controlled, because of the low particle load of the raw water. Alternative (i) and (ii) have the positive side effects of an increase in the SI (Saturation Index) resulting in less aggressive water and an increase of the buffering capacity.

4 Conclusions

The aim of this research was to study the removal of both dissolved and particulate iron by the conventional treatment process. By applying different methods, a complete picture of the iron removal at a typical groundwater treatment plant is obtained. The oxidation, particle formation and removal of particles are studied and in addition two hypotheses were tested.

The fingerprint showed that operational events have a significant impact on the volume concentration of particles breaking through the filter. Switching on/off of filters influences mainly the middle size ranges (2–10 μm). A backwash event mainly affects the breakthrough of particles >10 μm. The backwash resulted in a peak in volume load for 4 h. During this peak in 13% of the filter run time, 45% of the volume load is added to the effluent. The majority of this volume exists of the larger particles with good settling properties, which are undesired in the distribution system. Recirculation of the filtrate during the first hours may result in an improvement of the treatment at Harderbroek and the volume load will probably be significantly decreased.

The combination of particle counters and TILVS is seen as a method which can give a lot of information, but the interpretation of the data is still difficult. It is hard to be

Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



sure the particle counter and the TILVS are measuring the same fraction of suspended matter. Nevertheless, they give complementary information. A particle counter can be used to measure variation in particle concentration, while TILVS can be used to measure the absolute mass of the particulate material.

5 Column experiments showed mainly iron(II) in the aerated water. pH measurements gave reason to assume a slow oxidation rate. After NaOH dosage, the oxidation and the subsequent removal by filtration of iron(II) increased. For the flock filtration at Harderbroek the oxidation of iron(II) is the rate determining step, limited by the pH.

10 Good possibilities for improving the iron removal at Harderbroek are caustic soda dosage or crushed limestone filtration. Both alternatives will result in a higher pH and therefore a better oxidation of iron. An alternative without dosing a chemical is to make tower aeration the first treatment step (instead of the last step). When tower aeration is applied on raw water, the pH of the aerated water will probably be higher than currently is the case with only cascade aeration.

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Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

Table 1. Average raw water composition at treatment plant Harderbroek and (former) Vewin recommendation of maximum values in clear water.

Parameter	Unit	Raw water	(former) Vewin recommendation
Temperature	°C	12.9	25
Acidity	pH	7.47	7.8<pH<8.3
Saturation index	SI	-0.68	-0.2<SI<0.3
Conductivity	mS/m	16.4	80
Bicarbonate	mg/l	84.9	>60
Chloride	mg/l	7.5	150
Sulphate	mg/l	8.44	150
Sodium	mg/l	6.39	120
Potassium	mg/l		12
Calcium	mg/l	25.8	150
Magnesium	mg/l	2.07	50
Total hardness	mmol/l	0.729	1.0<TH<2.5
Ammonium	mg/l	<0.040	0.05
Nitrite	mg/l	<0.0070	0.05
Nitrate	mg/l	<0.50	25
Iron	mg/l	1.4	0.05
Manganese	mg/l	0.122	0.02

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

Table 2. Measurement scheme TILVS and particle counter through treatment plant.

Location	Date	TILVS Filtered volume [litre]	Particle counter Measured time [hour]
Raw water	06-03-07	91.85	60.4
Cascade effluent	20-02-07	19.2	40.7
Filter influent	20-02-07	19.2	82.6
Filter effluent (combined)	20-02-07	64 and 77.5	220.53
Aeration tower effluent	27-02-07	93.35	227.7
Clear water tank effluent	27-02-07	118.35 and 118.35	420.96
Distribution network	08-12-06	–	72.7

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

Table 3. Settings column experiments.

part	#	water source	device	settings
1	1a	Cascade	–	$\tau=2$ min
	1b		vessel	$\tau=7$ min V vessel=20 l
	2a	Cascade	Vessel, stirrer	$\tau=7$ min Rpm: 500 G=1000 l/s
	2b		Vessel, stirrer	$\tau=7$ min Rpm: 900 G=1800 l/s
	3a	Raw and cascade	Flow meters	$\tau=2$ min Raw: cascade=1:2
	3b		Flow meters	$\tau=2$ min Raw: cascade=1:1
4a	Raw water	Vessel, air pump	$\tau=7$ min RQ=0.5 Q air=200 l/h	
4a		Vessel, air pump	$\tau=7$ min RQ=1 Q air=400 l/h	
2	5a	Cascade	NaOH pump	$\tau=2$ min pH=8.0
	6a	Cascade	Crushed limestone	$\tau=2$ min pH=7.8 τ bed=2 min

Title Page

[Abstract](#) [Introduction](#)
[Conclusions](#) [References](#)
[Tables](#) [Figures](#)

⏪ ⏩
◀ ▶

[Back](#) [Close](#)

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

Table 4. Particle volume concentration in filter effluent during stable operation.

Particle size range (μm)	Average particle concentration ($\#/ml$)	Average particle volume (ppb)
1–2	332	0.492
2–5	7.38	0.122
5–7	0.28	0.030
7–10	0.14	0.044
10–15	0.07	0.064
15–20	0.03	0.094
20–50	0.03	0.457
50–100	0.02	3.567
total	340	4.871

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

Table 5. Volume load during a peak and during stable operation.

	Backwash	Switch
Total time [h]	32	24
Peak	4	0.5
Stable	28	23.5
Average concentration [ppb]		
Peak	19.9	19.4
Stable	3.44	2.62
Flow rate [m ³ /h]	235	250
Volume load [ml]		
Peak	18.70	2.43
Stable	22.66	15.70

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

Table 6. Results for TILVS and particle counter throughout the treatment plant, during stable operation.

Location	TILVS		Particle counter		
	Particle concentration [mg/l]	Particle concentration [mass-ppb]	Iron concentration [μ g/l]	Average total particle volume [volume-ppb]	Density [kg/m^3]
Raw water	2.2×10^{-3}	2.2	2.6	0.145	15 170
Cascade effluent	1.03	1030	106	223.17	4620
Filter influent	1.07	1070	–	155.01	6900
Filter effluent	0.048	48	8.0	4.87	9860
Aeration tower effluent	0.036	36	7.8	21.56	1670
Clear water tank effluent	0.035	35	8.5	14.71	2380
Distribution network	–	–	–	1.11	–

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

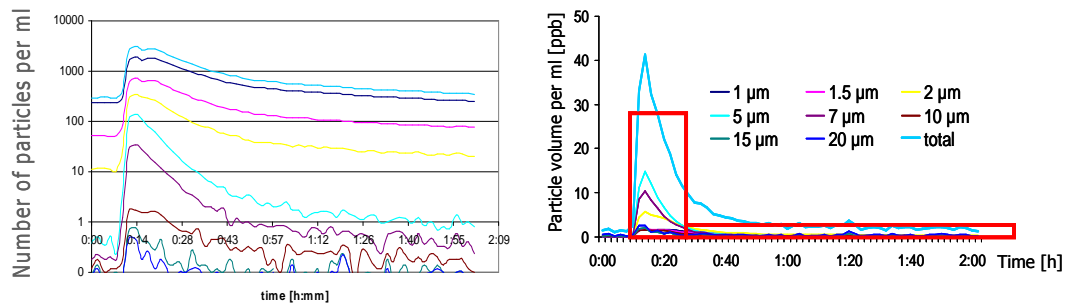


Fig. 1. Results from the particle counter in filter effluent after a switch of a filter: **(a)** number of particles and **(b)** particle volume concentration.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	



Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

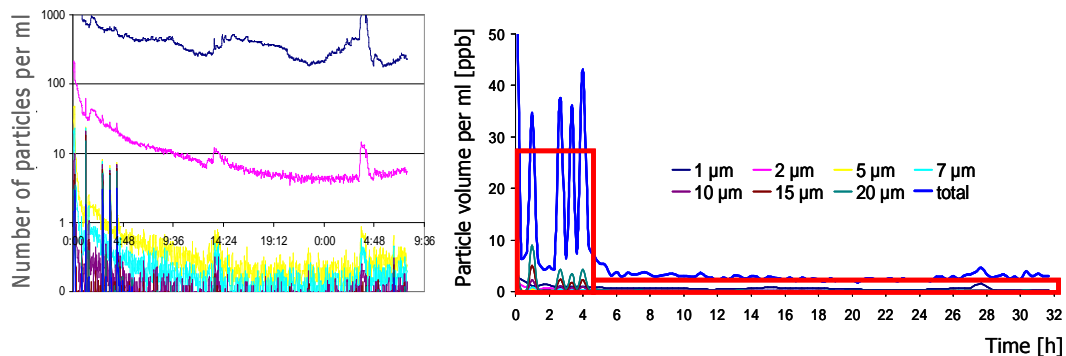


Fig. 2. Results from the particle counter in filter effluent after a backwash event: **(a)** number of particles and **(b)** particle volume concentration.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

⏪ ⏩

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

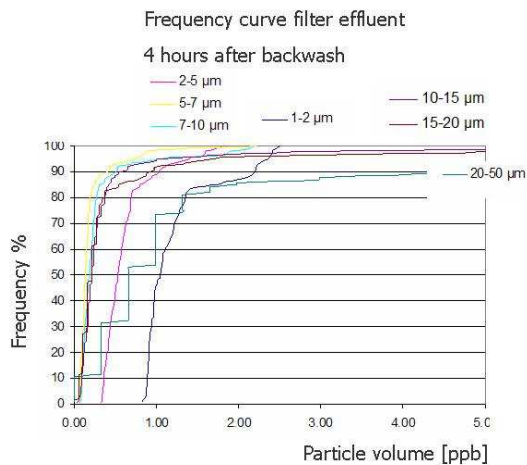
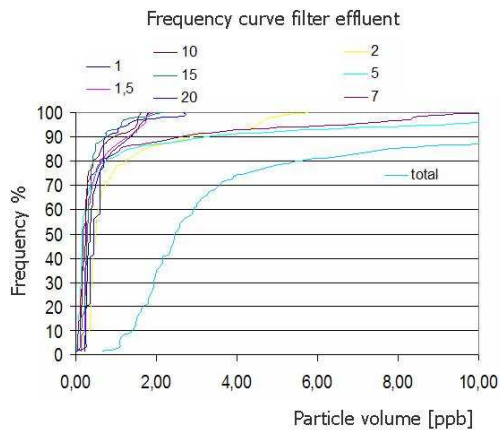


Fig. 3. Frequency curve filter effluent after (a) a filter switch and (b) after a backwash event.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

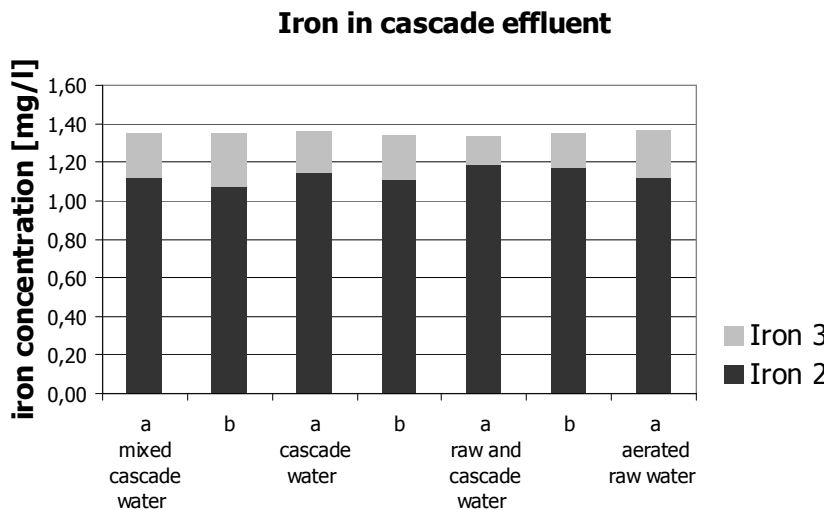


Fig. 4. Iron(II) and iron (III) in aerated cascade effluent water measured during column experiments.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

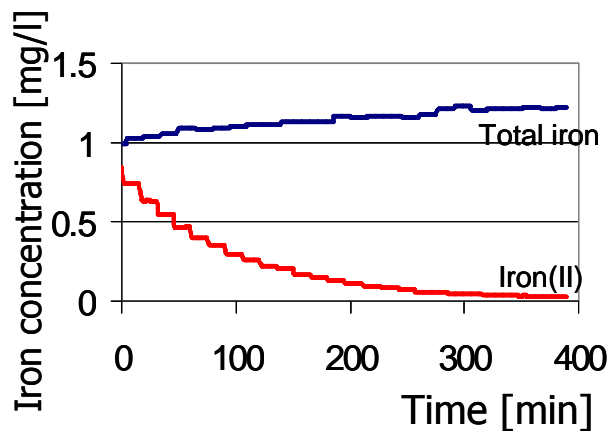


Fig. 5. Iron(II) and total iron concentration measured with applicon iron analyser in supernatant filter water.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Removal of dissolved and particulate iron from groundwater

K. Teunissen et al.

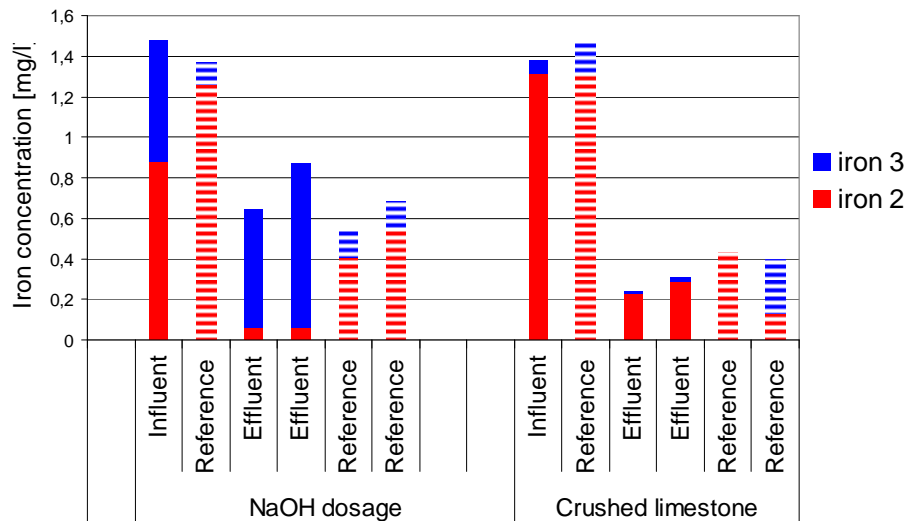


Fig. 6. Iron(II) and iron(III) concentration in column experiments for dosed columns and reference columns (striped bars).

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

