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Natural organic matter removal by ion exchange at different positions in the drinking water treatment lane

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Abstract

To guarantee a good water quality at the customers tap, natural organic matter (NOM) should be (partly) removed during drinking water treatment. The objective of this research was to improve the drinking water quality, including biological stability, by incorporating anion exchange (IEX) for NOM removal. Different placement positions of IEX in the treatment lane (IEX positioned before coagulation, before ozonation or after slow sand filtration) are compared on water quality as well as costs. For this purpose the pre-treatment plant at Loenderveen and production plant Weesperkarspel of Waternet were used as a case study. NOM removal can be done efficiently before ozonation and after slow sand filtration; it was found that the position in the treatment lane did not influence the NOM removal capacity. The operational costs were assumed to be directly dependent of the NOM removal rate and determined the difference between the IEX positions. The operational costs for IEX positioned before coagulation were higher than for IEX positioned after slow sand filtration, however the savings on following treatment processes caused a cost reduction compared to IEX positioned after slow sand filtration. IEX positioned before coagulation or ozonation were most cost effective and produced the highest water quality.

1 Introduction

Drinking water treatment consists of different steps, depending on the quality of the source water. The main purpose of a drinking water treatment plant is to produce safe water for human consumption. The presence of natural organic matter (NOM) can cause problems in drinking water treatment, as well as in the distribution of drinking water to customers. NOM can be a source of nutrients for bacteria present in the distribution system. When the source water contains high NOM concentrations, this should be removed to a high extend during drinking water treatment. NOM can be removed by coagulation, activated carbon filtration, membrane filtration and anion exchange (IEX).

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NOM in surface water can be removed by IEX, because the main part of NOM, humic, fulvic and organic acids, is negatively charged (Bolto et al., 2002; Cornelissen et al., 2008). IEX is a promising method for NOM removal, because empty bed contact times can be small and run times of IEX columns can be up to several weeks (van der Helm et al., 2009). IEX is relatively cost effective, easy to operate and a compact installation can be used due to the short contact times (Cornelissen et al., 2009). The efficiency of NOM removal by IEX depends on i.a. NOM concentration, NOM composition, type of IEX resin, empty bed contact time and configuration of the IEX installation. NOM fractions of low and high molecular weight (MW) are known to be removed by IEX (Croue et al., 1999; Bolto et al., 2002; Allpike et al., 2005; Boyer and Singer, 2005; Humbert et al., 2005). Weak base resins do not remove NOM as efficient as strong base resins (Croue et al., 1999) and bead size of the resin, water retention, capacity and functional groups of the resin (Cornelissen et al., 2008) will also influence the removal efficiency. IEX can be operated as a packed bed or in a fluidized mode, like Magnetic IEX (MIEX[®]) (Drikas et al., 2002), Fluidized IEX (FIX) (Cornelissen et al., 2009) or suspended IEX (SIX) (Galjaard et al., 2011). When the resin is exhausted, a 10 % sodium chloride solution can be used for regeneration of the resin; the NOM ions are exchanged to chloride ions. The residual or waste of IEX regeneration consists of water, salt (NaCl) and humic substances. The waste can be discharged to the sewer or directly to the waste water treatment plant. However, humic substances are not readily biodegradable and will substantially remain in the effluent of the waste water treatment. Additionally, high salt solutions could give problems in waste water treatment. To limit the residual, the brine can be reused (Schippers et al., 2004). Separating the salt from the humic substances is possible by membrane filtration. In that way the salt can be reused and only the higher concentration of humic substances is discharged to the sewer (Schippers et al., 2004; Kabsch-Korbutowicz et al., 2011).

The objective of this research is to improve the drinking water quality, including biological stability, by incorporating IEX for NOM removal. Different placement positions of IEX in the treatment lane are compared on water quality as well as costs. For this

purpose the pre-treatment plant at Loenderveen and production plant Weesperkarspel (WPK) of Waternet, the water cycle company of Amsterdam (NL) and surrounding areas, were used as a case study. The aim of Waternet is to lower the NOM concentration from a dissolved organic carbon (DOC) concentration of approximately 2.7 to 1 mgCl⁻¹. Because assimilable organic carbon (AOC) values below 10 µgCl⁻¹ have been derived as a reference value for biostable drinking water during distribution (van der Kooij, 1992), Waternet is aiming an AOC concentration removal from approximately 20 µgCl⁻¹ (Baghoth et al., 2009) to 10 µgCl⁻¹ before the water is transported to the customers.

First, pilot experiments were conducted with IEX positioned at two locations: (1) halfway the treatment lane, before ozonation and (2) after the treatment lane, before distribution. Experiments were conducted by two IEX configurations, namely FIX and MIEX[®]. Both IEX pilots were compared on NOM removal by LC-OCD characterization. Second, the effect on the biological stability of the produced water was researched for IEX at these two positions. Third, based on the results three possible positions in the treatment lane (IEX before coagulation was added) were compared to costs per cubic meter of treated water after the complete treatment lane.

2 Materials and methods

2.1 Treatment scheme

For this investigation pre-treatment plant Loenderveen and production plant Weesperkarspel were used as a case study. The production of WPK is approximately 30 Mm³ drinking water per year. At the pre-treatment plant surface water from the Bethune polder is treated by coagulation and sedimentation, followed by natural self-purification in a lake reservoir and rapid sand filtration. The pre-treatment plant removes suspended solids, phosphate, heavy metals, and pathogenic micro-organisms partially. It converts ammonium into nitrate and provides smoothing of peak loads. The

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pre-treated water is pumped to the production plant at WPK. There the water is treated by ozonation for disinfection, the hardness is reduced by pellet softening followed by removal of organic compounds in biological activated carbon (BAC) filtration. As a final treatment step, the water passes through slow sand filters (SSF) for the removal of pathogenic micro-organisms and for lowering the AOC concentration. The experiments were conducted at WPK pilot plant, owned and operated by Waternet. The pilot plant of WPK consists of 2 lanes of the same treatment processes and with similar contact times as in the full-scale treatment plant on a scale of approximately 1 : 200 compared to the full-scale treatment plant. The maximum flow in the pilot plant was $7 \text{ m}^3 \text{ h}^{-1}$ for each lane. The pilot plant was extended with a MIEX[®] pilot and a FIX pilot in one of the lanes. The MIEX[®] pilot used in this experiment is the high rate configuration. In this configuration, raw water fed to the base of the reactor vessel is mixed with the MIEX[®] resin, causing the ion exchange process to occur in a fluidized bed. In the fluidized bed the magnetic particles are attracted to each other to form large agglomerates that form a stable resin suspension. An agitator operating at low velocity keeps the resin/water suspension uniformly mixed. A small stream of resin is withdrawn from the reactor vessel, regenerated twice a week with a 12 % NaCl solution and returned to maintain the ion exchange capacity of the process. A series of plates (or tube settlers) at the top of the reactor vessel separate the resin from the water and treated effluent overflows (OricaWatercare, n.d.). To prevent resin carry-over a magnetic capture device was built in the MIEX[®] pilot plant. Additional, the MIEX[®] pilot plant was extended by a filter bag with pore size of $100 \mu\text{m}$ and a settling tank. The influent flow rate of the MIEX[®] pilot plant was 300 l h^{-1} . The contact time was 3 min. The fluidized bed volume in the contactor was 15 l. The volume ratio of resin to water was 210 ml l^{-1} . Fresh resin was pumped into the contactor with a flow of 12 ml min^{-1} . The resin service was 1984 bed volumes. The MIEX[®] pilot was placed before ozonation (for 4 weeks) and in one of the lanes after SSF (for 4 months).

The FIX pilot, as described by Cornelissen et al. (2009), was positioned prior to ozonation (for 4 months). Three FIX columns were operated in parallel with a flow of

4 m³ h⁻¹ each and contained Lewatit VP OC 1071 type resin, which is a strong-base gel resin with an acrylic (type 1) structure. This resin was the best performing resin for WPK feed water, according to a selection study on lab scale (Cornelissen et al., 2008). The height of the ion exchange bed was approximately 0.5 m, when fluidized it was approximately 1 m. The surface area was 0.3 m², each column was filled with 150 l of resin and the empty bed contact time was approximately 2.5 min. After a run time of 15 000 bed volumes the resin was regenerated with a 10 % NaCl solution.

2.2 Analyses

The water samples were analyzed for general physicochemical characteristics such as DOC, ultra violet absorbance at 254 nm (UV254), pH and temperature, which were determined using standard procedures following Eaton et al. (2005). Liquid chromatography with organic carbon detection (LC-OCD) with ultra violet (UV) and online organic carbon (OC) detection (UVD and OCD) was used for NOM characterization (Huber et al., 2011). Water samples were analyzed after filtration through 0.45 mm filters. LC-OCD separates chromatographable organic carbon (CDOC) into fractions of different molecular weights. The non-chromatographable organic carbon, which remains on the column, is referred to as hydrophobic organic carbon (HOC). CDOC is fractionated into (a) biopolymers (BP), which is a non-ionic, hydrophilic fraction with a high molecular weight ($\geq 10\,000\text{ g mol}^{-1}$); (b) humic substances (HS) ($450\text{--}1000\text{ g mol}^{-1}$) are a heterogeneous fraction of similar chemical composition but varying molecular size and aromaticity, (c) building blocks (BB), this fraction consists of breakdown products of HS, which is HS-like material of lower molecular weight ($300\text{--}450\text{ g mol}^{-1}$); (d) low-molecular weight (LMW) acids $\leq 350\text{ g mol}^{-1}$ and (e) low-molecular weight neutrals, this fraction has a low molecular weight and a low ion density and the fraction is hydrophilic to amphiphilic (Huber and Frimmel, 1996; Huber, 2005; Huber et al., 2011). For data acquisition and data processing of the LC-OCD data a customised software program (FIFFIKUS, DOC-LABOR, Germany) was used. This program integrates the

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different peaks to determine the concentration of different organic fractions. In Huber et al. (2011) it was explained that a small portion of HS, which is called the LMW-HS, is trapped in the LMW-acids zone. To distinguish between LMW-acids and LMW-HS the UV/OC ratio of HS is used to determine the concentration of LMW-HS, by assuming the same UV/OC ratio for LMW-HS as for HS. The concentration of LMW-acids is calculated by subtracting the concentration of LMW-HS from the total surface of the peak LMW-HS and LMW-acids. In this research the fractions were determined without correction for LMW-HS.

The change in relative signal response from the chromatograms of LC-OCD before and after treatment, is called a differential chromatogram. With a differential chromatogram small qualitative changes in NOM fractions are visualised. A similar differential spectrum analysis was used by Korshin et al. (1999) for light absorption spectra.

The aromaticity per DOC is used in this study and is determined by the specific UV254 absorbance ($SUVA = UV254/DOC$). $SUVA \geq 4 \text{ l mg C}^{-1} \text{ m}^{-1}$ indicates that mainly hydrophobic and especially aromatic material or humic substances are present, while $SUVA \leq 2 \text{ l mg C}^{-1} \text{ m}^{-1}$ represents hydrophilic material or non-humic material (Edzwald et al., 1985).

The concentration of AOC was determined, with growth measurements in water samples of 600 ml. Two pure cultures of bacteria were used by applying the simultaneous incubation of strains *Pseudomonas fluorescens* (strain P17), which is capable of utilizing a wide range of low-molecular-weight compounds at very low concentrations and *Spirillum* sp. (strain NOX), which utilizes only carboxylic acids. The AOC concentration was calculated from the obtained maximum colony counts of these strains, using their yield values for acetate. (van der Kooij et al., 1982; van der Kooij and Hijnen, 1984; van der Kooij, 1992). AOC was measured in duplicate and the average value was reported.

Biofilm monitors were used to determine the biofilm formation characteristics of drinking water (Van der Kooij et al., 1995). The biofilm monitor consists of a vertically-placed glass column containing glass cylinders on top of each other. Water flows

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through the column with a flow of 270 l h^{-1} . Every other week two cylinders were collected. The biomass attached to these cylinders was released by sonication and the ATP concentration was determined (Van der Kooij et al., 2003). A biofilm formation rate (BFR) below $10 \text{ pg ATP cm}^{-2} \text{ day}^{-1}$ reduces the risk of exceeding the Dutch guideline value for *Aeromonas* in the distribution system to less than 20 % (van der Kooij et al., 1999).

2.3 Cost comparison

In this section a technical-economical assessment was made using IEX in the WPK treatment on three positions. In Table 1 the DOC concentrations after every treatment step, in normal operation (without IEX treatment), are given (Baghoth et al., 2009). In order to obtain a DOC concentration of 1 mg Cl^{-1} after treatment, three positions were selected for NOM removal by IEX, namely before coagulation, before ozonation and as polishing step after SSF. For all positions the required DOC concentrations after IEX are given in Table 1. It was assumed that after IEX subsequent treatment processes remove DOC at the same rate as without IEX pre-treatment (coagulation 21 %, reservoir 8 %, rapid sand filtration 8 %, ozonation 5 %, pellet softening 5 %, biological activated carbon filtration 44 % and SSF 10 %).

A preliminary design for the IEX plant, independent of the location, is given in Table 2. The costs of an IEX installation consists of investment costs, capital costs, maintenance costs, chemicals, disposal costs, energy and staff. Except for chemicals and disposal costs, all costs are considered to be independent of the position of IEX in the treatment lane as well as independent of the removal rate and are given in Table 3. To compare the different positions of IEX in the treatment lane the breakthrough curve of one IEX pilot plant column, operated on WPK feed water, was taken as a starting point (Fig. 1). The design is based on 22 columns, see Table 2. When the filter run time of every individual column is 13500 BV, than every day one column is regenerated. The effluent DOC concentration of all the columns is the average DOC concentration

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of the effluent concentrations of the individual columns. The column just regenerated produces water with a lower DOC concentration than the column that runs already for 20 days. For a filter run time of 13 500 BV the average removal is 60 %, so 40 % of the influent DOC is found in the effluent. The average DOC concentration was calculated for filter run times of 3000 BV, 6000 BV, 13 500 BV, 25 000 BV and 50 000 BV and interpolated for other filter run times as is shown in Fig. 1. Different NOM removal rates can be obtained by applying different filter run times for 22 columns and thus different regeneration frequencies. The contact time is 2.5 min for all configurations. The NOM removal rate influences the operational costs, particularly costs for salt consumption and waste disposal. The cost for the discharge of waste were determined by the waste load expressed in pollution equivalents (PE) (van Lier, 2011). The PE is determined by: $PE = \frac{Q}{1000} \cdot \left(\frac{COD+4 \cdot KjN}{54.8} \right)$ in which Q = flow ($m^3 y^{-1}$), COD (chemical oxygen demand) = $3 \cdot DOC$ ($mg l^{-1}$) (DowChemicalCompany, 2011), KjN (Kjeldahl nitrogen) is assumed to be negligible). The costs per PE will be approximately 50 €. The waste will be transported by tanker trucks with a volume of $10 m^3$. The distance to the nearest waste water treatment plant was assumed to be 15 km. A tanker truck with driver will cost approximately $70 € h^{-1}$ and it will take 2 h per tanker truck to be filled, to drive and to discharge the water. With the assumptions made, the costs for transportation are $14 € m^{-3}$. The costs for salt are $0.1 € kg^{-1}$. For calculating cost savings of treatment processes following on IEX, numbers were taken from Barrios et al. (2008). They determined the environmental and financial impact of drinking water production plant Weesperkarspel and its pre-treatment plant Loenderveen. Barrios et al. (2008) calculated costs for the different treatment steps for 2002, for this research actual costs (2012) were calculated with an inflation of 1.7 % per year.

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3 Results and discussion

3.1 Comparison MIEX[®] and FIX

The MIEX[®] pilot positioned before ozonation caused an average DOC concentration decrease from 5.7 to 2.5 mgCl⁻¹. This is a decrease of 56.1% and a removal of 3.2 mgCl⁻¹. FIX removed DOC on average from 5.9 to 3.0 mgCl⁻¹ which is a removal of 2.9 mgCl⁻¹ or 49.2%. The removal of DOC by MIEX[®] after SSF was on average 57.7% or 2.2 mgCl⁻¹ (3.8 to 1.6 mgCl⁻¹). The removal rate at both locations was comparable however, the absolute removal was higher for water before ozonation. This can be explained by the fact that ion exchange from the water to the resin is based on equilibrium reactions.

The SUVA was lowered by both IEX treatment systems before ozonation from 2.6 to 1.6 lmgC⁻¹ m⁻¹ (38.4%), after SSF the decrease was from 1.5 to 0.9 lmgC⁻¹ m⁻¹ (40.0%), which is comparable to the decrease before ozonation. The decrease in SUVA means that the aromaticity of the water decreased (Edzwald et al., 1985); NOM with double bonds was removed to a higher extent than NOM with single bonds, and preferentially the higher molecular weight NOM was removed. In Fig. 2 the (differential) OCD chromatograms of the different water types are given. This figure shows that specifically the HS were removed from the water, independent of the water source. It also shows that MIEX[®] removed more of the lower MW NOM and FIX removed more of the HMW-HS. In Fig. 3 the concentrations of the different fractions are given. Although the decrease of the different fractions is higher for water before ozonation, the removal rates are of the same order of magnitude for both water types. Overall, MIEX[®] showed a higher removal of NOM (fractions) than FIX, which can be explained by the longer contact time of the MIEX[®] resin (3 min for MIEX[®] and 2.5 min for FIX). Figure 3b showed an increase in BP after FIX treatment and an increase in LMW-acids after MIEX treatment at the end of the treatment lane, however the concentrations of both fractions are very low, and the increase rate will not be significant.

3.2 Biological stability

The AOC concentration in the water before ozonation was approximately $7 \mu\text{gCl}^{-1}$. After FIX the concentration was lowered to approximately $3.5 \mu\text{gCl}^{-1}$, a reduction of 50%. By extending the treatment lane with FIX columns before ozonation, the ozonation formed less AOC than without FIX treatment ($54.5 \mu\text{gCl}^{-1}$ instead of $115.8 \mu\text{gCl}^{-1}$), see Fig. 4. Because of this lower AOC concentration after ozonation, the AOC concentration after SSF was lower as well ($14.3 \mu\text{gCl}^{-1}$ instead of $38.1 \mu\text{gCl}^{-1}$). By extending the treatment lane with MIEX[®] at the end of the treatment, the AOC concentration was decreased from 38.1 to $13.6 \mu\text{gCl}^{-1}$. Removing approximately 50% of DOC concentration before ozonation or 58% of DOC concentration after SSF resulted in the same AOC concentration after treatment.

The BFR of the water after SSF (before the MIEX[®] pilot) was $6.6 \text{ pgATP cm}^{-2} \text{ day}^{-1}$. Immediately after starting up the experiment the ATP values for determining the BFR were much higher after the MIEX[®] pilot than after SFF ($200 \text{ pgATP cm}^{-2}$ versus 8 pgATP cm^{-2}). The ATP values after MIEX[®] treatment increased from $200 \text{ pgATP cm}^{-2}$ to $500 \text{ pgATP cm}^{-2}$ and varied for the rest of the experimental period between these two values, which made it impossible to calculate a BFR for the biofilm monitor positioned after MIEX[®]. The tube settlers and the magnetic capture device of the MIEX[®] pilot plant did not remove all spent resin and polluted the biofilm monitor. The MIEX[®] pilot plant caused an average increase in turbidity from 0.1 NTU to 1.5 NTU. This increase in turbidity after MIEX[®] treatment was also noticed by Singer and Bilyk (2002); Cornelissen et al. (2010) found an increase in ATP content after FIX. The higher ATP values after MIEX[®] treatment were probably caused by ATP on the resin that polluted the biofilm monitor. This problem can be solved by adding an extra (magnetite) filter. This filter should remove the resin before the water is transported to the consumers. The BFR of the finished water of the FIX-lane was $2.0 \text{ pgATP cm}^{-2} \text{ day}^{-1}$ (Grefte et al., 2011), which is an improvement compared to the existing values.

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3.3 IEX cost comparison

Three positions were selected for NOM removal by IEX: (1) before coagulation, (2) before ozonation and (3) as a polishing step after SSF. IEX added before coagulation is expected to remove DOC from 9.0 to 3.5 mgCl⁻¹, which is a removal rate of 61 %.

From Fig. 1 the run time of every column can be determined; for a removal rate of 61 % the run time is approximately 11100 BV. The flow through every column is approximately 220 m³ h⁻¹, which means that every column should be regenerated every 18.9 days. When IEX is positioned before coagulation, the DOC removal is 5.5 g C m⁻³. From 30 Million m³ treated water 165 000 kg C needs to be discharged. In Table 4 the regeneration and waste characteristics of the three possible positions of the IEX plant are given. It is shown that because of the higher regeneration frequency more brine and rinse water will be produced and more salt will be used when IEX is placed after SSF, than when IEX is placed before coagulation or before ozonation. The amount of DOC in the brine is very high for water treated by IEX before coagulation because of the high required (absolute) DOC removal at this position. In Table 5 the estimated operational and fixed costs are given. The highest IEX costs are 0.0656 € m⁻³ when IEX is placed before coagulation. The costs for waste are 34 % of the total costs. Brine treatment by NF, which means 90 % waste reduction (Schippers et al., 2004), will reduce the price. The cheapest option is to place IEX before ozonation.

3.4 Expected costs savings on subsequent treatment processes

The addition of an IEX installation in the treatment lane will influence subsequent treatment processes in operation and quality as well as costs. Removing NOM before coagulation will save coagulant, even when the main purpose of coagulation is turbidity removal (Singer and Bilyk, 2002). Currently, coagulation removes 1.9 mgCl⁻¹, when IEX is incorporated before coagulation DOC removal is only 0.75 mgCl⁻¹. DOC removal will be lowered by 60 %, assumed is a linear dependency of the coagulant dose and sludge production on DOC, therefore these can be reduced by 60 % as well (White

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et al., 1997). This will save 0.0037 € m^{-3} (Barrios et al., 2008). The purpose of coagulation at Loenderveen is also removal of phosphate for preventing eutrophication of the lake reservoir. The effect of NOM on phosphate removal is unknown, therefore the reduction in coagulant dose at Loenderveen could be less than 60 %.

When a linear relation between ozone dosage per DOC concentration and disinfection capacity is adopted, the ozone dosage can be reduced from 2.0 to 0.75 mg l^{-1} . This will save 0.0040 € m^{-3} (Barrios et al., 2008).

Currently, the contact time in the BAC filters is 52 min, approximately 15 out of 26 filters are regenerated per year. The run time of each filter is approximately 1.7 yr. When IEX is incorporated in the treatment lane before BAC, the DOC removal can be reduced by 66 %. Assuming an increase in runtime of 66 %, only 9 columns need to be regenerated per year, resulting in a saving of 0.0089 € m^{-3} (Barrios et al., 2008).

Comparing the net costs (Table 6) shows that IEX before coagulation and IEX before ozonation are the most cost effective options because of the savings on coagulation, ozonation and BAC. IEX before ozonation will be the most cost effective option for the pre-treatment plant at Loenderveen and production plant Weesperkarspel of Waternet. Because removal of phosphate must be sufficient, the reduction in coagulant and thus the cost savings on coagulation will be less than calculated. IEX positioned after SSF does not influence other treatment steps and therefore the net costs are the highest.

3.5 Environmental impact

Pellet softening is the main contributor to the environmental impact at Waternet (Barrios et al., 2008) due to the use of sodium hydroxide (NaOH). The softening process will not be improved by IEX. The second largest contributor to the environmental impact is coagulation because of the use of ferric chloride. By incorporating IEX before coagulation, the coagulant dose can be reduced together with the environmental impact. Furthermore, regeneration of BAC determines for a large part the height of the environmental impact for BAC. The regeneration frequency of BAC will be decreased, by prior

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NOM removal by IEX and hence the environmental impact. Although the reduction of ozone dosage influenced the costs, it will have a negligible effect on the environmental impact (Barrios et al., 2008). It is expected that the environmental impact of an IEX plant would be mainly determined by energy cost, in that way the environmental impact of an IEX treatment will be comparable with rapid sand filtration, which had a very low environmental impact (Barrios et al., 2008). Extending the treatment lane with IEX before coagulation and ozonation will decrease the (already low) environmental impact of the drinking water treatment.

4 Conclusions

The drinking water quality, including biological stability, was improved by incorporating IEX for NOM removal. Different placement positions of IEX in the treatment lane (IEX positioned before coagulation, before ozonation or after slow sand filtration) and two IEX configurations (MIEX and FIX) were compared on water quality as well as costs. For this purpose the pre-treatment plant at Loenderveen and production plant Weesperkarspel of Waternet were used as a case study.

Both, MIEX[®] and FIX were able to remove NOM (mainly the HS fraction) to a high extent, which improved the water quality. NOM removal can be done efficiently before ozonation and after slow sand filtration, the position in the treatment lane did not influence the NOM removal percentage.

MIEX[®] used as polishing step after the treatment lane caused a decrease in AOC. Unfortunately, the tube settlers and the magnetic capture device did not remove all spent resin, resin was found in the effluent. This caused pollution of the biofilm monitor, which gave higher biofilm results in treated water by the MIEX[®] pilot plant, than without MIEX[®]. By adding an extra (magnetite) filter it should be possible to use MIEX[®] as a polishing step and increase the biological stability of the water. FIX treatment before ozonation improved the biological stability (Grefte et al., 2011).

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The operational costs were assumed to be directly dependent of the NOM removal rate and determined the difference between the IEX positions. The operational costs for IEX positioned before coagulation were higher than for IEX positioned after SFF, however the savings on following treatment processes caused a cost reduction compared to IEX positioned after SSF. IEX positioned before coagulation or ozonation were most cost effective and produced the highest water quality.

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Table 1. The expected variation of dissolved organic carbon (DOC) across the treatment train (based on Baghoth et al., 2009).

DOC concentration (mg C l ⁻¹)	Actual	Before coagulation	Before ozonation	After SSF
Raw surface water	9.0	9.0	9.0	9.0
IEX effluent	–	3.5	–	–
Coagulation effluent	7.1	2.7	7.1	7.1
Surface reservoir effluent	6.5	2.5	6.5	6.5
Rapid sand filtration effluent	6.0	2.2	6.0	6.0
IEX effluent	–	–	2.2	–
Ozonation effluent	5.7	2.1	2.1	5.7
Pellet softening effluent	5.4	2.0	2.0	5.4
Biological activated carbon filter effluent	3.0	1.2	1.2	3.0
IEX effluent	–	–	–	1.0
Treated water	2.7	1.0	1.0	1.0

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Table 2. Design of IEX treatment.

Total production	30 Mm ³ yr ⁻¹
Empty bed contact time	2.5 min
Reactor	22 columns
Total bed volume	200 m ³ resin
Bed volume per column	9 m ³ resin
Flow per column	220 m ³ h ⁻¹
Salt solution	10 % NaCl
Regeneration	1.8 BV brine
Rinse	2.4 BV water

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Table 3. Total fixed costs.

Subject	Amount	Unit	Costs (€ yr ⁻¹)	
Depreciation			Interest (Linear) 5 %	702 000
Civil construction	1 750 000	€	30 yr	102 000
Installation construction	6 600 000	€	20 yr	495 000
Engineering construction	1 000 000	€	30 yr	58 000
Intern process construction	800 000	€	30 yr	47 000
Maintenance				207 000
Civil	7 750 000	€	0.5 %	9000
Installation	6 600 000	€	3 %	198 000
Chemicals				220 000
Resin-Lewatit VP OC 1071	40 000	l yr ⁻¹	5.50 € l ⁻¹	220 000
Energy	900 000	kWh yr ⁻¹	0,09 € kWh ⁻¹	81 000
Staff	0.25	FTE	55 000 € yr ⁻¹ FTE ⁻¹	14 000
Total fixed costs				1 224 000

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Table 4. Regeneration and waste characteristics of three possible positions for the IEX plant in the treatment lane.

	Before coagulation	Before ozonation	After SSF
DOC removal rate	61 %	62 %	67 %
Regeneration after (BV)	11 100	10 500	6800
Regeneration after (Days)	18.9	17.9	11.6
Regenerations per year	424	448	692
Brine per year (m ³)	6868	7257	11 210
Rinse water per year (m ³)	9158	9677	14 947
Salt per year (kg)	686 880	725 760	1 121 040
DOC (kg C yr ⁻¹)	165 000	114 000	60 000

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Table 5. Total costs of IEX at three different positions in the treatment lane.

Costs (€)	Before coagulation	Before ozonation	After SSF
Waste transport	224 364	237 076	366 198
Waste discharge	451 642	312 044	164 234
Salt	68 688	72 576	112 104
Fixed costs	1 224 000	1 224 000	1 224 000
Total	1 968 694	1 845 696	1 866 536
€ m ⁻³	0.0656	0.0615	0.0622

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Table 6. Expected savings of downstream processes because of IEX and the calculated net cost.

Costs (€ m ⁻³)	Before coagulation	Before ozonation	After SSF
Costs	0.0656	0.0615	0.0622
Savings			
Coagulation	0.0037	–	–
Ozonation	0.0040	0.0040	–
BAC	0.0089	0.0089	–
Net cost	0.0490	0.0486	0.0622

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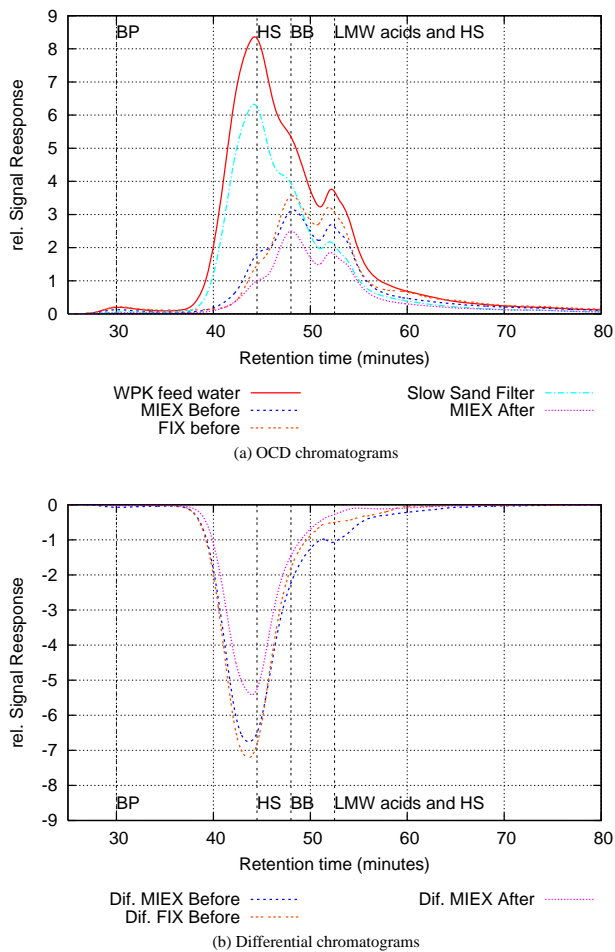


Fig. 2. LC-OCD (differential) chromatograms of the different water qualities.

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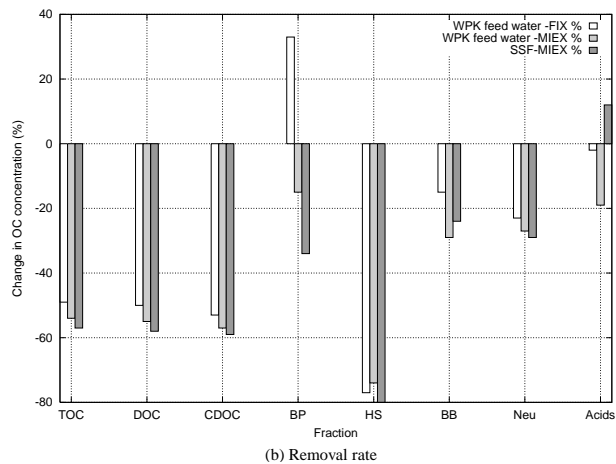
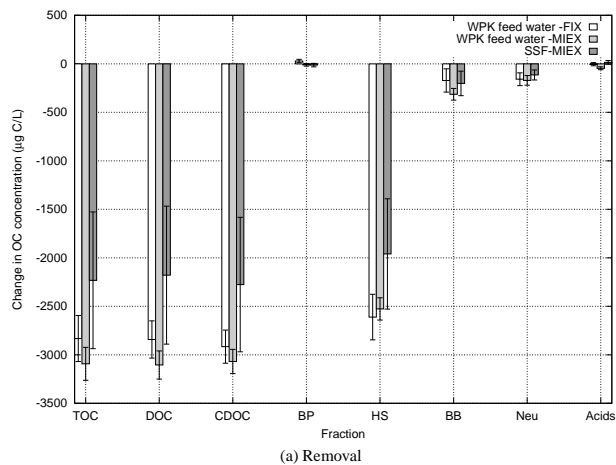


Fig. 3. Change in NOM fraction concentrations in the different water types by MIEX[®] and FIX.



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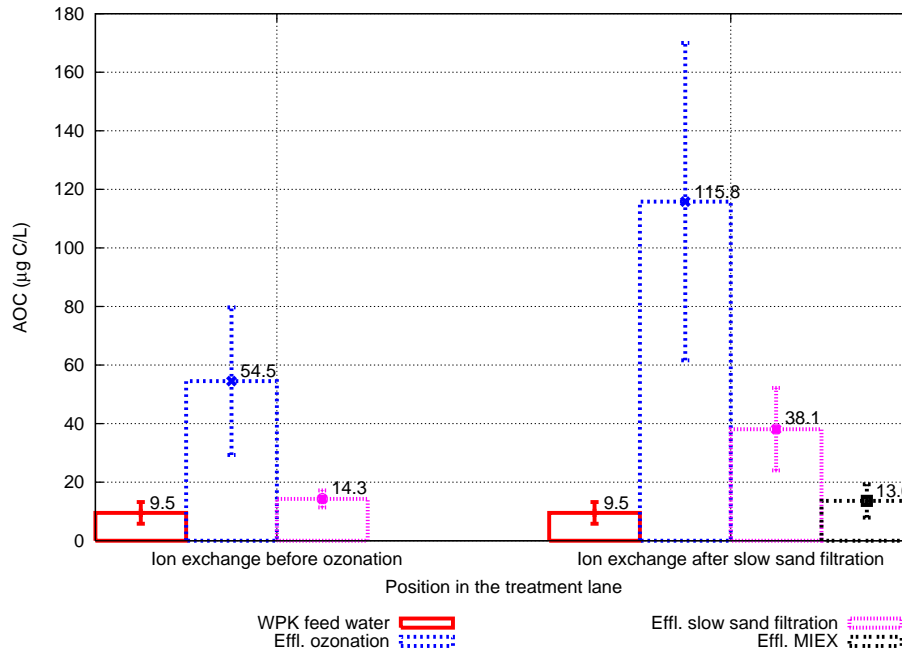


Fig. 4. AOC concentrations in the treatment lanes when FIX was positioned before ozonation or MIEX was positioned after SSF.

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