Feasibility Study of Suspended Ion Exchange for Organic Matter Removal and Disinfection By-product Minimisation in UK Lowland Waters

Javier Fernandez-Lozano
Cranfield University, College Rd, Cranfield, MK43 0AL

Clair Dunn
Anglian Water, Ermine Business Park, Lancaster Way, Huntingdon, PE29 6XU

Adam Brookes
Anglian Water, Ermine Business Park, Lancaster Way, Huntingdon, PE29 6XU

Peter Jarvis
Cranfield University, College Rd, Cranfield, MK43 0AL

Irene Carra
(Corresponding author) Cranfield University, College Rd, Cranfield, MK43 0AL

Abstract

This investigation compared the performance of suspended ion exchange (SIX) and granular activated carbon (GAC) filtration for organic matter removal and reduction of trihalomethane (THM) and haloacetic acid (HAA) formation potential. SIX treatment resulted in increased organic matter removal (60%) when compared with GAC (45%). SIX treatment produced a stable treated water Dissolved Organic Carbon (DOC), while changes in brine concentration had no effect on the removal of organic disinfection by-product (DBP) precursors. Liquid chromatography organic carbon detection analysis (LC-OCD) showed that the differences in the organic matter removal by SIX in comparison to GAC were caused by the increased affinity of the SIX process towards the 1 kDa and 0.5-0.35 kDa organic matter size bands. These were the molecular weight fractions comprising most of the overall DOC. Organic matter removal was consistent with the minimisation of THM and HAA formation. THM formation was reduced by 50% and 65%, whereas HAA formation was lowered by 60% and 70% in comparison to the untreated water, after GAC and SIX treatment, respectively. A linear correlation between the Br:DOC ratio and the bromine substitution factor was found for THMs and HAAs, suggesting that the formation of Br-DBPs was not selective to the treatment but attributed to bulk organic matter removal and bromide content at source. The use of resin in chloride form increased the chloride to sulphate mass ratio and Larson Index suggesting a risk for increased corrosivity of SIX treated water in the distribution network.

Keywords: DBP precursors; corrosion; costs; HAAs; LC-OCD; SIX; THMs.

Introduction

This research was part of Anglian Water's long-term programme that aims to increase the resilience of water quality and supply in the region. The high alkalinity of water sources in the Anglian Water region limits the implementation of pH-optimised coagulation at most sites due to the high costs associated with application of chemicals for pH control. As a result, the scope for removal of organic matter from Anglian Water source waters is much lower than might otherwise be possible. Therefore, finding a process that enables organic matter reduction without pH adjustment is part of Anglian's long-term research. Prior to the research presented in this article, the use of suspended ion exchange (SIX) was assessed at laboratory scale for the treatment of different lowland sources within the Anglian region (Carra et al., 2021). Results were promising, motivating further research on SIX at pilot scale and investigation of regeneration chemicals.

Coagulation is the most widely applied treatment for the removal of organic matter due to its favourable balance between removal efficiency and total expenditure (TOTEX) costs (Jacangelo et al., 1995). In coagulation, a positively charged ion (typically a Fe or Al salt) links to negatively charged colloids by different mechanisms (entrapment, adsorption, complexation, and destabilization), promoting destabilisation and aggregation. The process is more selective towards higher molecular weight organic matter that carries negative charge (Finkbeiner et al., 2020). In terms of chemical dosing practices, charge neutralisation and sweep flocculation are the two methods used to remove contaminants via coagulation. When using charge neutralization, the pH is optimised to promote the presence of positively coagulant charged species. A stoichiometrical coagulant dose in relation to the organic matter charge is used, which destabilises the colloids and promotes organic matter removal. For sweep flocculation, an excess coagulant dose is used without altering pH, creating insoluble hydrolysis products that enmesh the pollutants (Crittenden et al., 2012).The net positive charge of the coagulant salt significantly decreases with increasing pH (Sharp et al., 2006). The increased chemical dosing required to modify the pH to achieve charge neutralisation in alkalinity buffered sources explains the widespread use of sweep flocculation for lowland surface waters. Sweep flocculation, however, is not as efficient as charge neutralisation for the reduction of Dissolved Organic Carbon (DOC). In addition, some types of organic matter are not well removed by coagulation despite pH and coagulant optimisation. For example, Sharp et al. (2006) demonstrated the relationship between the hydrophilic non-acid fraction of organic matter in raw water and the residual DOC obtained after coagulation.

In the UK, upland sources are characterised by an increased proportion of hydrophobic organic matter, whereas for lowland areas the inputs of microbial activity and effluent organic matter are more pronounced (Ritson et al., 2014). Typically, organic matter in upland sources has an increased proportion of hydrophobic moieties with compounds of a larger molecular weight. On the other side, lowland sources have high concentration of hydrophilic moieties with compounds of reduced molecular weight (Mergen et al., 2008; Ritson et al., 2014) that are typically not well removed by coagulation. This type of organic matter has been shown to have lower formation potentials for trihalomethanes (THMs) and haloacetic acids (HAAs). However, if not sufficiently removed, there is still a risk of forming disinfection by-products (DBPs) above the regulatory limits (Phetrak et al., 2016; Carra et al., 2021). This is a challenge common for surface waters within the Anglian Water region as they are all considered lowland sources.

From the alternative technologies that have been considered for enhanced organic matter removal, ion exchange (IEX) (Levchuk et al., 2018) has received significant attention due to the high degree of charge associated with many types of organic matter found in source waters (Bolto, Dixon and Eldridge, 2004). IEX has been proven to achieve organic matter reduction in alkaline buffered sources without the need to alter pH (Caltran et al., 2020; Carra et al., 2021). For organic matter removal, strong and weak anion exchange resins are used (referring to the Arrhenius theory of dissociation). Typically, the process of IEX involves the stoichiometrical exchange of chloride for an ion with higher affinity to that displaced from the exchanger (Helfferich, 1995). IEX targets negatively charged organics regardless of the compound type (Smith et al., 2020), being particularly effective at removing low molecular weight organics, which diffuse better through the resin pores (Mergen et al., 2008; Bazri and Mohseni, 2016). In practice, this allows for the treatment of hydrophilic charged organics that are not readily removed either by coagulation or granular activated carbon (GAC), reducing the THM and HAA formation for sources with hydrophilic organic matter (Hanigan et al., 2013). In addition to organic matter, IEX also removes inorganic anions (e.g., nitrates or sulphates), which increases the resilience for treatment of source waters that contain elevated nitrate concentrations.

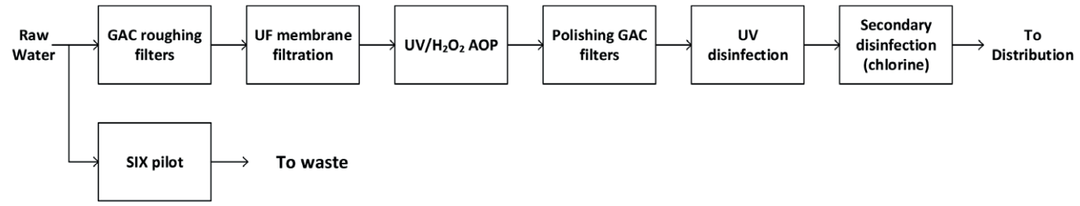
Of the different IEX alternatives commercially available, SIX was selected to undertake a pilot trial due to previous laboratory testing showing its high efficiency in the removal of organic matter from lowland source waters (Carra et al., 2021). Within the UK, the use of SIX at pilot scale has been benchmarked against the performance of coagulation processes at full scale water treatment works (WTWs) (Metcalfe et al., 2015; Finkbeiner et al., 2018). To the author's knowledge, there have been few, if any, studies that have compared SIX with roughing GAC filters at the front end of WTWs for treatment of surface waters. Some studies have compared the performance of activated carbon with IEX (Tan et al., 2008; Hanigan et al., 2013). However, these have been limited to bench scale comparisons, which may not be representative of full-scale conditions. In addition, most of the UK based studies that have been performed assessing the removal of organic matter by IEX have been focused on their application to upland sources (Mergen et al., 2008; Metcalfe et al., 2015; Finkbeiner et al., 2018). On this regard, this study is expected to bring insights into the long-term performance, scalability, and treated water quality for lowland sources.

The present study aimed to establish the long-term differences in organic matter treatability between GAC and SIX for a lowland river source not amenable to treatment by conventional coagulation. The efficiency of each process was examined based on the different organic matter size fractions removal and reduction of THM and HAA formation potential. In addition, the influence of the brine concentration on organic matter removal, DBP formation and inorganic anions removal was evaluated.

SIX pilot trial at Hall WTW

The pilot trial was located at Hall WTWs, which was built in 2014 to supply the increasing population in the Lincoln area. It abstracts water directly from the River Trent and has a maximum treatment capacity of 20 MLD. Previous tests at the design stage had identified that the organic matter in the source water was not amenable to coagulation and GAC filters were selected as the main organic matter removal process. The treatment flowsheet (Figure 1) is constituted by roughing GAC filters (Filtrasorb TL-830),

Figure 1. Hall WTW treatment train.



which are responsible for the removal of bulk organics, followed by a UF membrane system, an Advanced Oxidation Process for pesticides removal, polishing GAC filters to quench hydrogen peroxide from the oxidation process and adsorb by-products, and UV disinfection with final hypochlorite addition for chlorine residual in distribution. Each of the roughing GAC filters is regenerated in sequence every 2 months so that the overall regeneration is once per year.

This source was selected to undertake a SIX pilot trial as it was an example of a challenging water to treat. A SIX pilot plant (PWNT, Netherlands) was operated in parallel to the roughing GAC filters over 8 months from July 2019, including 3 weeks for commissioning and start up. The pilot plant had a treatment capacity of 7-12 m3/h. The pilot trial was started with fresh Lewatit S5128 resin with a gel type structure, acrylic backbone and quaternary ammonium as the ionogenic group, with Cl- as the mobile anion. The resin was selected by PWNT based on its good settleability and high selectivity towards organic matter (Caltran et al., 2020).

In the SIX process (Figure 2) the fluidised chamber where adsorption takes place behaves as a plug flow reactor (Galjaard and Kamp, 2014). The resin is separated after the fluidised bed through a lamella clarifier and it goes to the regeneration vessel, where it is regenerated every bed volume. The chloride brine was produced on site through the generation of a saturated chloride solution. In the SIX process the brine is reused 5 times prior to waste discharge. Thus, during a regeneration cycle the resin is washed with the 4x, 3x, 2x, 1x used, fresh brine and tap water rinse.

Figure 2. SIX pilot plant diagram.

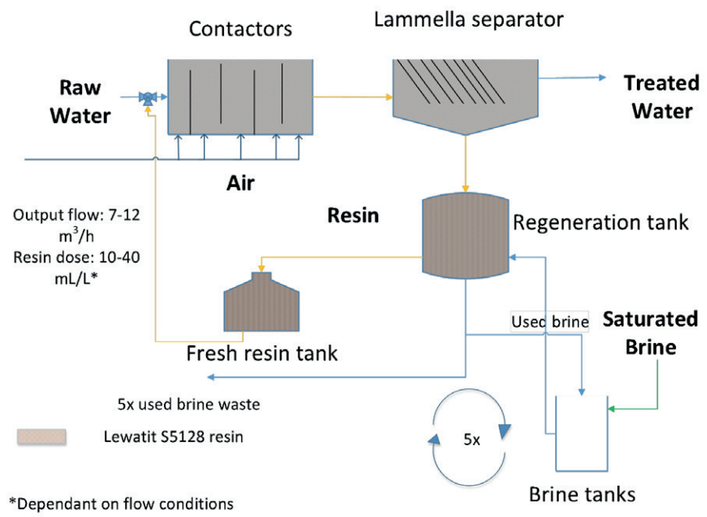
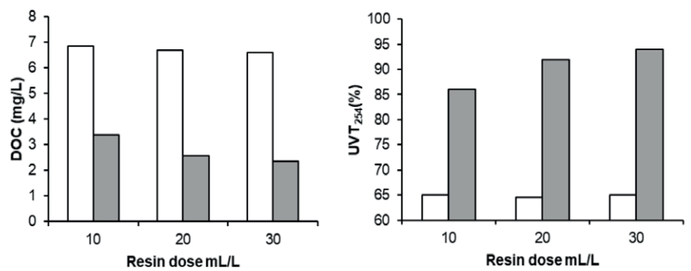


Figure 3. DOC and UVT results during matrix tests



Initial matrix tests and optimisation of resin dose

The resin dose for the pilot plant was determined through matrix tests performed during the first three weeks of trial where different resin doses (10, 20 and 30 mL/L) were used with a 30 min contact time (Figure 3). The SIX treated water DOC was reduced from 3.4 mg/L to 2.5 mg/L as the resin dose increased from 10 mL/L to 20 mL/L. Further increasing of the resin concentration to 30 mL/L only improved DOC removal by 0.2 mg/L. Similar trends were observed for UVT, with results using 10, 20 and 30 mL/L resin doses being 86%, 91% and 93%, respectively. Due to the similarities in DOC and UVT in the treated water between 20 ml/l and 30 ml/l, a resin dose of 20 mL/L was selected for the duration of the trial.

Organic matter removal and brine optimisation

During the first three months of operation (Aug-Oct 2019), the raw water quality remained stable with an average DOC of 6.6 ± 0.3 mg/L and UVT of 66 ± 2% (Figure 4). In the last four months of the trial (Nov 2019-Feb 2020), the DOC and UVT in the raw water decreased to a mean value of 5.7 ± 0.4 mg/L and 66 ± 2%, respectively. SIX treatment resulted in a DOC of 2-3 mg/L in the treated water for the entirety of the pilot trial. Changes in the raw water quality and brine optimisation did not change the DOC concentration in the treated water, with similar organic matter removal performance, 60% ± 6%, for the duration of the trial in comparison to 43% ± 10% for the GAC adsorption.

Although the removal of DOC by SIX and GAC were similar during the first three months of the trial (Aug-Oct 2019), each process removed different organic matter fractions. As an example, SIX resulted in higher UVT in the treated water in comparison to GAC treatment (91 ± 2% and 85 ± 1%, respectively), showcasing the higher removal of aromatic compounds and compounds with double C bonds by SIX.

As the trial progressed (Nov 2019-Feb 2020), the SIX treated water contained on average 1.5 mg/L DOC lower than seen in the GAC treated water, with a 6% higher UVT. Regeneration of the GAC beds did not have an observable effect on the treated water DOC and UVT, with similar results before and after regeneration. The regeneration programme encompasses the regeneration of one filter bed every two months, but the overall combined outlet of the six beds results in an averaged treated effluent where the regeneration of one filter does not influence the overall DOC and UVT.

A seasonality effect was observed (Figure 5) for summer and winter seasons, with temperatures of 11-16°C in the summer and 6-7°C in the winter. GAC performance was more affected by temperature, with higher DOC in the treated water in the winter than SIX. Similarly, UVT in the winter period was lower for the GAC treated water. This is attributed to the lower biological activity in the filters with colder temperatures. In the case of SIX, the fact that the resin is regenerated every bed volume allows for a lower impact of temperature on organic matter removal.

The differences in treatability for SIX and GAC were further explored by looking at the organic matter molecular weight fractions from LC-OCD analysis (Figure 6). This analysis allows for the determination of organic matter groups based on their molecular size -larger than 10 kDa; 1 kDa; 550-350 Da; and <350 Da. Organic matter with molecular weight > 10 kDa is suggested to include biopolymers such as proteins and polysaccharides (Huber et al. 2011). While this fraction is small in concentration in this source and other lowland sources, it is still relevant as it has the potential to form THMs (Carra et al. 2021). SIX showed limited removal of this particular fraction (<10%), in agreement with previously reported research, and attributed to size exclusion (Finkbeiner et al., 2020). On the other hand, GAC removed ca 50% of this fraction.

The next group, with 1 kDa, is associated with humic-like substances and compounds with unsaturated aromatic rings, and it showed the greatest differences between GAC and IEX. SIX removed 2,620 ± 300 µg/L, whereas GAC removed 1,510 ± 420 µg/L. It is thought that the high removal of this fraction by SIX is due to the high charge density of this group (Finkbeiner et al. 2018). The following group, 0.5-0.35 kDa, has been associated with breakdown

Figure 4. DOC concentration and UVT in the raw water and GAC and SIX treated water during the pilot trial at Hall WTW. GAC regeneration times and SIX brine optimisation are highlighted in the graph.

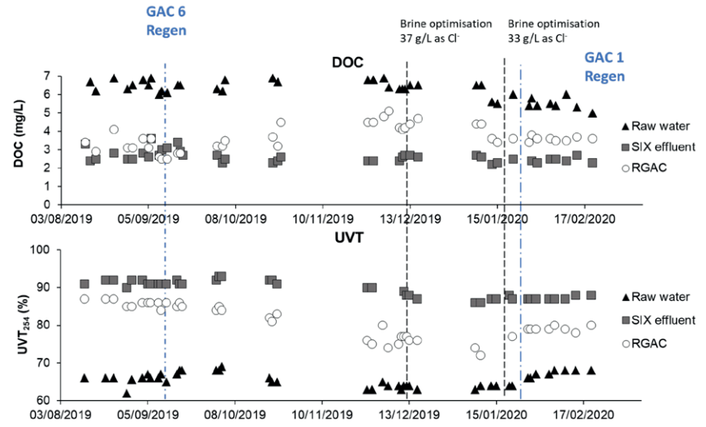


Figure 5. DOC and UVT for the treated water by SIX and GAC in the summer and winter months during the trial.

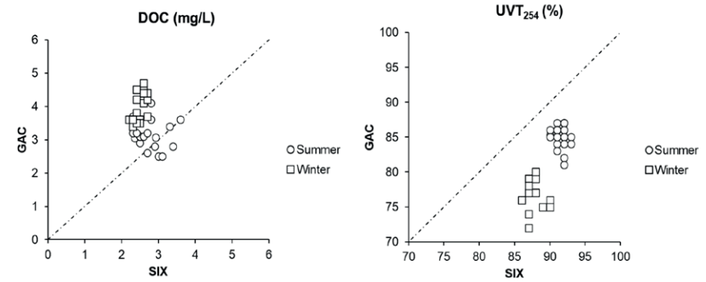
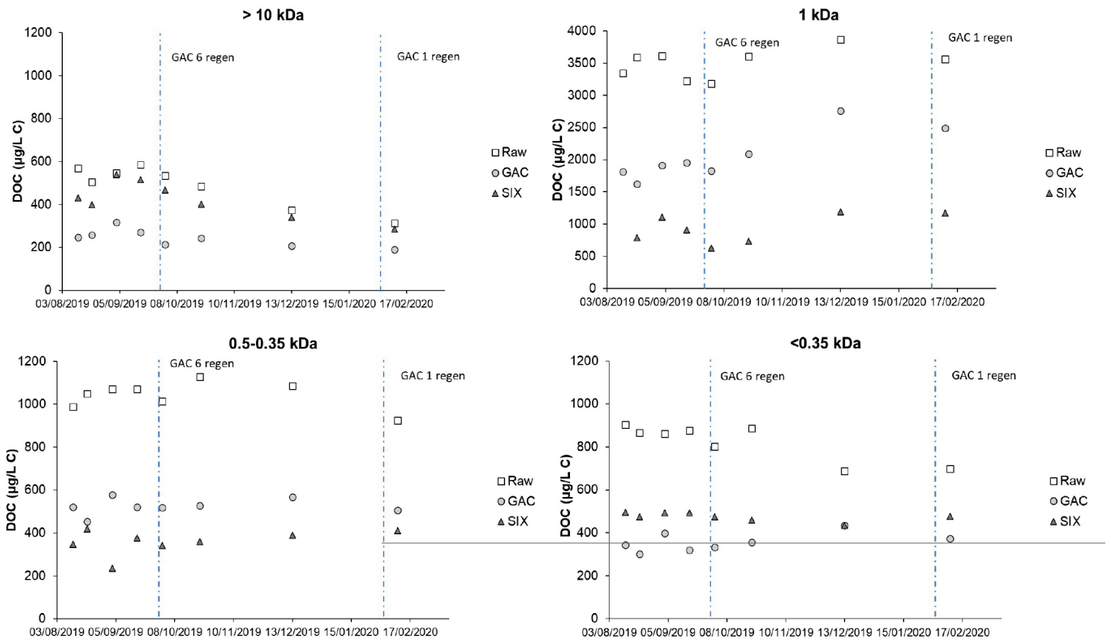


Figure 6. Organic matter molecular weight fractions in the raw water and GAC and SIX treated waters during the trial.



products from humic-like substances, with similar properties to them, explaining the higher removal obtained with SIX 685 ± 80 µg/L vs 540 ± 80 µg/L with GAC. The smallest group, with 350 Da, has been linked to hydrophilic and amphiphilic material, such as low molecular weight alcohols or amino acids and GAC showed higher removals than SIX (475 ± 90 with GAC vs 350 ± 80 µg/L with SIX). The lower amenability of removal by SIX were attributed to the reduced degree of charge of this fraction. The results evidenced the differences in the treatability of organic matter by GAC and SIX, where LC-OCD analysis highlighted that the differences in bulk organic removal (DOC) were related to the 1 kDa size group.

THMs and HAAs formation potential tests

One of the aims of the trial was to understand the THM and HAA formation potential of the SIX treated water and its comparison to GAC treated water. DBP formation tests were performed on raw water and SIX and GAC treated water. The formation tests were designed to simulate the conditions on site. Samples were chlorinated to achieve 0.9 ± 0.05 mg/L of free chlorine to achieve the target for the final water on site and for 7.5 hours contact time. This contact time aimed at mimicking the average residence time of the chlorinated water in the treated water service reservoir at the WTW.

In agreement with DOC removal, SIX was more efficient in eliminating DBP precursors than GAC (Figure 7). SIX treated water presented stable THM (49 ± 7 µg/L) and HAAs (34 ± 6 µg/L) formation potential during the trial, regardless of the raw water quality. On the other hand, GAC treated water showed an average formation of 70 ± 10 and 44 ± 6 µg/L, respectively, throughout the trial. DBP formation tests followed the reported trends for DOC removal (Figure 4), and whilst the GAC treated water reflected the changes observed in the raw water, with results within 50-100 µg/L for THMs and 34-55 µg/L for HAAs, the SIX treated water showed stable THM and HAA formation regardless of the raw water quality seasonality or brine optimisation.

The effectiveness in minimising THM and HAA formation potential was compared using DBP yield ratios (raw water DBP yield to GAC or SIX treated water DBP yield, µg DBP in the raw water per mg DOC / µg DBP in the treated water per mg DOC) to assess if the DBP minimisation was caused by selective removal of DBP precursors (Figure 8). The reduction in the DBP yield ratios achieved by SIX and GAC were similar for THMs and HAAs. For example, during the first three months of the trial (Aug-Oct 2019), SIX presented a ratio of 3.4 ± 0.5 and 3.5 ± 0.5 for THMs and HAAs, respectively. Equivalent results for the GAC treated water were 2.6 ± 0.3 and 2.6 ± 0.3 for THMs and HAAs. During the colder months the similarities between GAC and SIX ratios were maintained. There was an overall decrease in the THMs and HAAs ratio from the summer/autumn to the winter, caused by a reduction in the DBP formation potential of the raw water (Figure 7). Results evidenced limited reduction in the THM and HAAs reactivity treatment with both processes, in agreement with other author's findings (Metcalfe et al., 2015; Finkbeiner et al., 2018). Therefore, bulk organic matter removal was considered as the main cause for the THM and HAA formation potential reductions in either the SIX or GAC treated water.

Bromide is readily oxidised by free chlorine (Bond et al., 2014) and it is more reactive towards organic matter that chlorine (Symons et al., 1993). Low concentrations of bromide can increase the proportion of brominated DBPs which present an increased toxicity in comparison to their chlorinated equivalents (Sfynia, 2017). The influence of the bromide concentration on the speciation of THMs and HAAs was assessed by the Bromine Substitution Factor (BSF) (Hua and Reckhow, 2012). The BSF is defined as the bromine percentage of the total amount of halogen on each type of DBPs and it can differ from 0 to 1 (Hua and Reckhow, 2012) as defined below:

$$BSF(\%) = \frac{\sum_{i=1}^{n} br_i * molar\ concentration\ brominated\ species_i}{\sum_{o=1}^{p} h_o * molar\ concentration\ DBP\ species_o}$$

With Br defined as the number of brominated atoms in the DBP species, h_0 being the number of halogenated atoms (Br and Cl) in the DBP species, n is the number of brominated species and p the number of DBP species.

For THMs:

$$BSF_{THM} = \frac{[BDCM] + 2 * [DBCM] + 3 * [BF]}{3 * ([CF] + [BDCM] + [DBCM] + [BF])}$$

Where BDCM is bromodichloromethane; DBCM is dibromochloromethane; BF is bromoform; and CF is chloroform.

And HAAs:

$$BSF_{THM} = \frac{([BCAA]+[MBAA]+[BDCAA])+2*([DBAA]+[DBCAA])+3*[TBAA]}{\left(\begin{array}{c}([MCAA]+[MBAA])+2*([DBAA]+[DCAA]+[BCAA])\\+3*([DCBAA]+[DBCAA]+[TCAA]+[TBAA])\end{array}\right)}$$

Where BCAA is bromochloroacetic acid; MBAA is monobromoacetic acid; BDCAA is bromodichloroacetic acid; DBAA is dibromoacetic acid; DBCAA is dibromochloroacetic acid; TBAA is tribromoacetic acid; MCAA is monochloroacetic acid; DCAA is dichloroacetic acid; and DCBAA is dichlorobromoacetic acid.

Figure 7. THM and HAA formation from the raw water and GAC and SIX treated water.

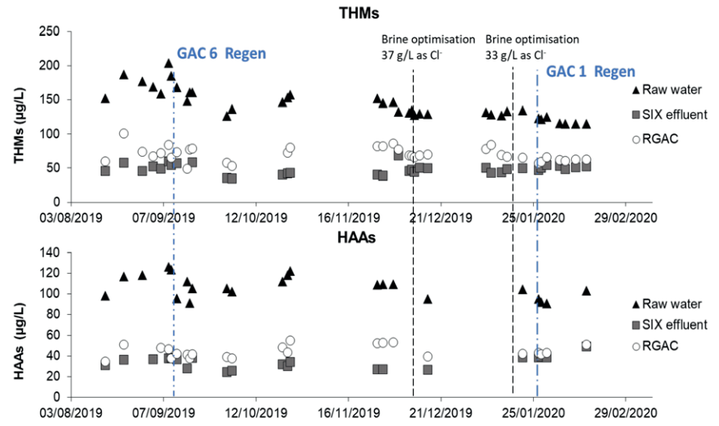


Figure 8. Raw water to SIX or GAC treated water DBP yield ratio during the trial.

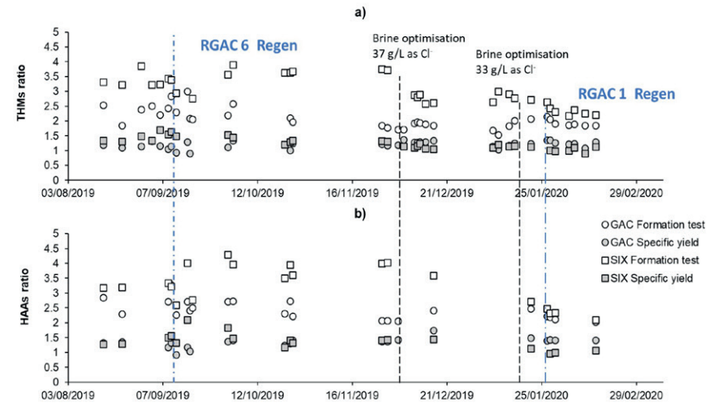
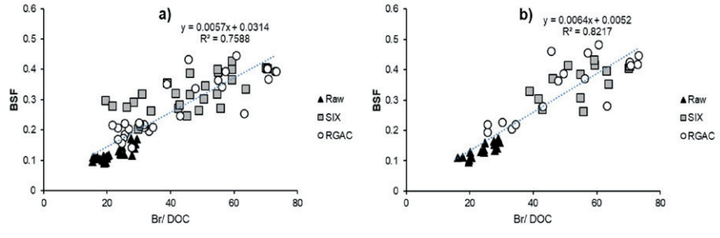


Figure 9. BSF for THMs (a) and HAAs (b) for the raw and treated waters by SIX and GAC.



The BSF is linked to the formation of brominated DBP species, and Figure 9 links it to the Br:DOC ratio (µg Br/mg DOC) (Figure 9). Neither SIX nor GAC removed bromide, and thus, the bromide:DOC ratio increased after treatment. A linear correlation was observed for the BSF and the Br/DOC ratio for THMs (R^2 =0.76) and HAAs (R^2 =0.82), supporting the fact that DBP speciation was strongly influenced by the Br:DOC ratio (Figure 9). Results agreed with the findings from Boyer and Singer (2008) who reported increases of dibromochloromethane from 7.4 to 15 µg/L, when comparing the formation of the raw and MIEX treated water, outlining the influence of the bromide concentration in the speciation of the DBPs.

Brine optimisation and corrosion indexes

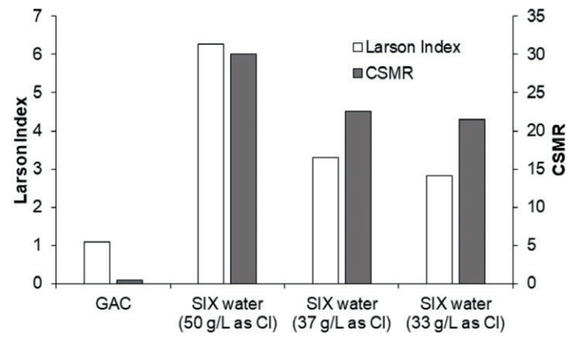
Optimising the brine usage is key not only from an economic perspective, but also to reduce the brine waste (Maul et al., 2014). Brine optimisation was carried out by reducing the fresh brine chloride concentration during the trial from 50 g/L to 33 g/L as chloride (Figure 10). Although the brine optimisation did not impact organic matter removal, there was a decrease in the uptake of inorganic ions. In particular, nitrate and alkalinity were removed 28-30% less.

Sulphate was removed below LOD in all cases. IEX resins preferably exchange the ion with the smallest solvated equivalent volume (i.e. hydrated radii normalised by the ion's valence), which explains the general preference for polycharged anions in detriment of single charged ones (Helfferich, 1995). For example, the solvated equivalent volume of sulphate is 0.17 nm (Tansel, 2012) whereas for nitrate and bicarbonate is 0.34 and 0.36 nm, respectively (Volkov et al., 1997; Kiss et al., 2013). The resin used on this study, was regenerated in Cl- form, has a gel type structure with quaternary ammonium as the fixed anion, and a high capacity per L (1.25 eq/L according to the manufacturer), which favours the exchange of polycharged anions (Helfferich, 1995; Lanxess, 2016).

The removal of inorganic ions affect the water chemistry. Chloride to sulphate mass ratio (CSMR) values higher than 0.5 have been linked to increased lead release via galvanic corrosion (Nguyen et al., 2011; Willison and Boyer, 2012). Galvanic attack of the lead soldering in copper pipes due to the electromigration of chloride to the lead anode surface, impedes the formation of a passivating scale, increasing plumbosolvency, which does not occur with sulphate (Nguyen et al., 2011; Willison and Boyer, 2012).

In addition, previous research has linked the proportion of corrosive agents (chloride and sulphate) to inhibitory agents in domestic waters (bicarbonate) to the corrosivity of natural waters on mild cast iron pipes (Larson and Skold, 1958). Larson and Skold (1958) showed that increased concentrations of chloride and sulphate relative to alkalinity may interfere with the formation of this film, increasing the corrosion rates.

Figure 10. Larson-Skold index and CSMR for the GAC treated water, final water and treated water by SIX for the different brine concentrations tested (50, 37 and 33 g/L as Cl-)



The Larson Index (LI)(Larson and Skold, 1958) is defined as the ratio between the sum ofchloride and sulphate milliequivalents divided by the alkalinity. A LI value higher than 0.8 indicates the potential for corrosion.

$$LI = \frac{[Cl^-] + 2 * [SO_4^{2-}]}{[Alk]}$$

The purpose of this assessment was to determine the risk of corrosion for SIX treated water. The LI was slightly above the 0.8 threshold for the GAC treated water (Figure 10), suggesting some degree of aggresivety towards cast iron pipes. The use of SIX under optimised conditions, increased the LI by a factor of 3 in comparison to the GAC treated water, suggesting a high risk of corrosion.

A similar trend was observed for the CSMR, where results increased from 0.4-0.5 for the GAC treated water in comparison to 23-30 for the SIX treated water. The results indicate that SIX treated water will be more aggressive with respect to plumbosolvency than for GAC treated water. A survey in the USA considering >100 sites countrywide, effectively related increases in the CSMR with risk of concentrations >10 µg/L as lead (Stets et al., 2018), supporting the findings. Furthermore, for an equivalent CSMR, increased anion concentrations also increase lead solubility (Willison and Boyer, 2012). The use of bicarbonate-form resin is proposed as an alternative regenerant to minimise the risk of corrosion, due to the mild inhibiting effect of on corrosion (Nguyen et al., 2011).

Conclusions

The applicability of SIX has been assessed for a lowland river source with high inorganic ion concentration and compared to GAC filtration. The major conclusions of this work are:

- SIX reduced organic matter 15% more on average than GAC and up to up to 30%, mainly because of the increased affinity of IEX towards the 1-0.35 kDa organic matter fraction.
- The SIX process was more robust than GAC to the impact of water quality variability, achieving similar final DOC levels for the duration of the trial. The stability observed for DOC was also seen for THM and HAA formation, with 49 ± 7 µg/L and 34 ± 6 µg/L for THMs and HAAs, respectively. Higher concentrations were observed for GAC treated water, with 70 ± 10 µg/L for THMs and 44 ± 6 µg/L for HAAs.
- Reducing the brine concentration from 50 to 33 g/L as Cl^- did not have an impact on organic matter removal or DBP formation, although the removal of nitrate and alkalinity were up to 30% lower.
- A linear correlation between the Br:DOC ratio and the BSF was found for THMs (R^2=0.76) and HAAs (R^2=0.82), evidencing the relationship between the bromide content of the source and the bromo-DBP formation. This would suggest that the formation of Br-DBPs was not selective to the treatment but attributed to bulk organic matter removal.
- The increase in the LI and CSMR for the SIX treated water presents a risk of corrosion in the distribution network, potentially impacting the solubility of metal from iron and lead pipes.

Next steps of the research include further testing and modelling on the use of bicarbonate as a regenerant.

Acknowledgements
The authors would like to acknowledge Anglian Water, who funded and supported the work; Anglian Water Laboratories, for the provision of water analysis; and PWN Technologies, Netherlands, for the technical support throughout the project.

References

AW (2019) Water resources management plan. Available at: https://www.anglianwater.co.uk/siteassets/household/in-the-community/revised-dwrmp-2019.pdf.

Bazri, M. M. and Mohseni, M. (2016) 'Impact of natural organic matter properties on the kinetics of suspended ion exchange process', Water Research, 91(1), 147–155. doi: 10.1016/j.watres.2015.12.036.

Bolto, B., Dixon, D. and Eldridge, R. (2004) 'Ion exchange for the removal of natural organic matter', Reactive and Functional Polymers, 60(1), 171–182. doi: 10.1016/j.reactfunctpolym.2004.02.021.

Bond, T., Huang, J., Graham, N. J. D. and Templeton, M. R. (2014) 'Examining the interrelationship between DOC, bromide and chlorine dose on DBP formation in drinking water - A case study', Science of the Total Environment, 470–471(1), 469–479. doi: 10.1016/j.scitotenv.2013.09.106.

Boyer, T. H., Singer, P. C. and Aiken, G. R. (2008) 'Removal of dissolved organic matter by anion exchange: Effect of dissolved organic matter properties', Environmental Science and Technology, 42(19), 7431–7437. doi: 10.1021/es800714d.

Caltran, I., Heijman, S. G. J., Shorney-Darby, H. L. and Rietveld, L. C. (2020) 'Impact of removal of natural organic matter from surface water by ion exchange: A case study of pilots in Belgium, United Kingdom and the Netherlands', Separation and Purification Technology, 247(1), p. 116974. doi: 10.1016/j.seppur.2020.116974.

Carra, I., Fernandez Lozano, J., Johannesen, S., Godart-Brown, M., Goslan, E. H., Jarvis, P. and Judd, S. (2021) 'Sorptive removal of disinfection by-product precursors from UK lowland surface waters: Impact of molecular weight and bromide', Science of The Total Environment, 754, 142–152. doi: https://doi.org/10.1016/j.scitotenv.2020.142152.

Crittenden, J. C. et al. (2012) MWH's Water Treatment: Principles and Design: Third Edition. Chapter 9: Coagulation and Flocculation. Hoboken, New Jersey: John Wiley & Sons, Inc. doi: 10.1002/9781118131473.

Finkbeiner, P., Redman, J., Patriarca, V., Moore, G., Jefferson, B. and Jarvis, P. (2018) 'Understanding the potential for selective natural organic matter removal by ion exchange', Water Research, 146(1), 256–263. doi: 10.1016/j.watres.2018.09.042.

Finkbeiner, P. et al. (2020) 'The combined influence of hydrophobicity, charge and molecular weight on natural organic matter removal by ion exchange and coagulation', Chemosphere, 238(1), p. 124633. doi: 10.1016/j.chemosphere.2019.124633.

Galjaard, G. and Kamp, P. (2014) EP2850034B1: Ion exchange process with plug flow conditions and short residence times. Andijk, Netherlands: NV PWN Waterleidingbedrijf Noord-Holland.

Hanigan, D., Inniss, E. and Clevenger, T. E. (2013) 'MIEX® and PAC for removal of hydrophilic DBP precursors', Journal - American Water Works Association, 105(3), E84–E92. doi: 10.5942/jawwa.2013.105.0019.

Hua, G. and Reckhow, D. A. (2012) 'Evaluation of bromine substitution factors of DBPs during chlorination and chloramination', Water Research, 46(13), 4208–4216. doi: 10.1016/j.watres.2012.05.031.

Huber, S. A., Balz, A., Abert, M. and Pronk, W. (2011) 'Characterisation of aquatic humic and non-humic matter with size-exclusion chromatography - organic carbon detection - organic nitrogen detection (LC-OCD-OND)', Water Research, 45(2), 879–885. doi: 10.1016/j.watres.2010.09.023.

Jacangelo, J. G. et al. (1995) 'Selected processes for removing NOM: An overview', Journal / American Water Works Association, 87(1), 64–77. doi: 10.1002/j.1551-8833.1995.tb06302.x.

Kiss, A. M., Myles, T. D., Grew, K. N., Peracchio, A. A., Nelson, G. J. and Chiu, W. K. S. (2013) 'Carbonate and Bicarbonate Ion Transport in Alkaline Anion Exchange Membranes', Journal of The Electrochemical Society, 160(9), F994–F999. doi: 10.1149/2.037309jes.

Lanxess (2016) Product Information Lewatit ® s 5128. Lenntech. Available at: https://www.lenntech.com/Data-sheets/Lewatrit-S-5128-L.pdf (Accessed: 10 March 2021).

Larson, T. E. and Skold, R. V. (1958) 'Laboratory Studies Relating Mineral Quality of Water To Corrosion of Steel and Cast Iron', CORROSION, 14(6), 43–46. doi: 10.5006/0010-9312-14.6.43.

Levchuk, I., Rueda Márquez, J. J. and Sillanpää, M. (2018) 'Removal of natural organic matter (NOM) from water by ion exchange – A review', Chemosphere, 192(1), 90–104. doi: 10.1016/j.chemosphere.2017.10.101.

Maul, G. A., Kim, Y., Amini, A., Zhang, Q. and Boyer, T. H. (2014) 'Efficiency and life cycle environmental impacts of ion-exchange regeneration using sodium, potassium, chloride, and bicarbonate salts', Chemical Engineering Journal. doi: 10.1016/j.cej.2014.05.086.

Mergen, M. R. D., Jefferson, B., Parsons, S. A. and Jarvis, P. (2008) 'Magnetic ion-exchange resin treatment: Impact of water type and resin use', Water Research, 42(8–9), 1977–1988. doi: 10.1016/j.watres.2007.11.032.

Metcalfe, D., Rockey, C., Jefferson, B., Judd, S. and Jarvis, P. (2015) 'Removal of disinfection by-product precursors by coagulation and an innovative suspended ion exchange process', Water Research, 87(1), 20–28. doi: 10.1016/j.watres.2015.09.003.

Nguyen, C. K., Clark, B. N., Stone, K. R. and Edwards, M. A. (2011) 'Role of chloride, sulfate, and alkalinity on galvanic lead corrosion', Corrosion, 67(6), 065005–1–065005–9. doi: 10.5006/1.3600449.

Phetrak, A., Lohwacharin, J. and Takizawa, S. (2016) 'Analysis of trihalomethane precursor removal from sub-tropical reservoir waters by a magnetic ion exchange resin using a combined method of chloride concentration variation and surrogate organic molecules', Science of the Total Environment, 539(1), 165–174. doi: 10.1016/j.scitotenv.2015.08.111.

Ritson, J. P., Graham, N. J. D., Templeton, M. R., Clark, J. M., Gough, R. and Freeman, C. (2014) 'The impact of climate change on the treatability of dissolved organic matter (DOM) in upland water supplies: A UK perspective', Science of the Total Environment, 473–474(1), 714–730. doi: 10.1016/j.scitotenv.2013.12.095.

Sfynia, C. (2017) Minimisation of regulated and unregulated disinfection by-products in drinking water. Imperial College London.

Sharp, E. L., Jarvis, P., Parsons, S. A. and Jefferson, B. (2006) 'Impact of fractional character on the coagulation of NOM', Colloids and Surfaces A: Physicochemical and Engineering Aspects, 286(1–3), 104–111. doi: 10.1016/j.colsurfa.2006.03.009.

Smith, A. J. R., Moore, G., Semiao, A. J. C. and Uhrin, D. (2020) 'Molecular level characterisation of ion-exchange water treatment coupled to ceramic membrane filtration', Environ. Sci.: Water Res. Technol. The Royal Society of Chemistry, 6(1), 1495–1504. doi: 10.1039/C9EW01042D.

Stets, E. G., Lee, C. J., Lytle, D. A. and Schock, M. R. (2018) 'Increasing chloride in rivers of the conterminous U.S. and linkages to potential corrosivity and lead action level exceedances in drinking water', Science of The Total Environment, 613–614, 1498–1509. doi: https://doi.org/10.1016/j.scitotenv.2017.07.119.

Symons, J. M., Krasner, S. W., Simms, L. A. and Sclimenti, M. (1993) 'Measurement of THM and Precursor Concentrations Revisited: The Effect of Bromide Ion', Journal AWWA. John Wiley & Sons, Ltd, 85(1), 51–62. doi: https://doi.org/10.1002/j.1551-8833.1993.tb05921.x.

Tan, Y., Kilduff, J. E. and Karanfil, T. (2008) Disinfection By-Products in Drinking Water Occurrence, Formation, Health Effects, and Control. Chapter 17: Natural dissolved organic matter removal and subsequent disinfection by-product formation: A comparison of ion exchange and activated carbon. Washington: American Chemical Society. doi: 10.1021/bk-2008-0995.ch017.

Tansel, B. (2012) 'Significance of thermodynamic and physical characteristics on permeation of ions during membrane separation: Hydrated radius, hydration free energy and viscous effects', Separation and Purification Technology, 86, 119–126. doi: https://doi.org/10.1016/j.seppur.2011.10.033.

Volkov, A. G., Paula, S. and Deamer, D. W. (1997) 'Two mechanisms of permeation of small neutral molecules and hydrated ions across phospholipid bilayers', Bioelectrochemistry and Bioenergetics, 42(2), 153–160. doi: https://doi.org/10.1016/S0302-4598(96)05097-0.

Willison, H. and Boyer, T. H. (2012) 'Secondary effects of anion exchange on chloride, sulfate, and lead release: Systems approach to corrosion control', Water Research, 46(7), 2385–2394. doi: 10.1016/j.watres.2012.02.010.



https://dspace.org/

Feasibility study of suspended ion exchange for organic matter removal and disinfection by-product minimisation in UK lowland waters

Fernandez-Lozano, Javier; Jarvis, Peter; Dunn, Clair; Carra, Irene; Brookes, Adam

2021-12
Institute of Water
https://library.myebook.com/InstituteofWaterMagazine/journal-autumn-2021/3699/#page/5
Fernandez-Lozano J, Jarvis P, Dunn C, et al., (2021) Feasibility study of suspended ion exchange for organic matter removal and disinfection by-product minimisation in UK lowland waters. Institute of Water Journal, Issue 6, 2021, pp. 4-11

Downloaded from a DSpace repository. https://dspace.org/