NOM-removal by the SIX®-process

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Abstract

Some waters can have elevated concentrations of dissolved organic carbon (DOC), especially sources like surface waters that are under the influence of secondary effluent, recreation, heavy population, farming and industry. In a number of locations in north-west Europe, for example the United Kingdom and Scandinavia, DOC levels are increasing over time, most likely due to climate change effects and changes in land use. For these types of water, ion exchange (IX) is of interest as a pre-treatment option because the removal of colour and DOC by IX will increase the efficiency of all downstream processes, including: coagulation, membrane filtration, advanced oxidation processes (AOP) and granular activated carbon filtration (GAC). It will also lead to improved water quality (i.e., less by-product formation) and most likely improvements in biostability within the distribution network. Surface waters also contain suspended and colloidal matter, making it nearly impossible to use standard state-of-the-art, fixed bed IX columns. This is because these beds will foul quickly (i.e., head loss build-up) with suspended matter. When this happens, the IX bed starts to function as a filtration bed rather than as an adsorption media.

The newly developed suspended ion exchange process SIX® (suspended ion exchange, PWN Technologies, Netherlands) presents an advanced solution for a world-wide challenge: how to remove natural organic matter (NOM/DOC) as a first step in surface water treatment to improve the efficiency of downstream processes and water quality. In addition to the possibility to treat water that contains suspended matter, another advantage is that the process has advanced to an economically and technically feasible process, requiring low contact times and small resin inventories, with a large tolerance for flow fluctuations. Depending on the water source, adding a relatively low concentration of coagulant after IX removes even greater quantities of DOC, especially in the fraction of the high molecular weight organic carbon (whilst the IX primarily removed the humic and fulvic organic fractions). The most important advancement is that almost any commercially available resin can be used, creating the desired flexibility in resin suppliers for water supply companies. This paper describes the process and its advantages and disadvantages compared to conventional technologies. NOM-characterisation with size exclusion chromatography, liquid chromatography – organic carbon detection (SEC/LC-OCD) before and after this process showed the outstanding performance of the process, especially on water types which contain high colour/DOC-concentrations and low total dissolved solids, which are typical of the majority of the surface waters in the north-west of Europe.

Key words: DOC-removal, ion exchange, LC-OCD, NOM-removal, SIX

BACKGROUND

Natural organic matter (NOM) (also described as dissolved organic carbon (DOC) or dissolved organic matter (DOM)) describes a complex mixture of organic compounds, such as humic and...
hydrophilic acids present in natural water sources. Operationally, DOC is defined as comprising any organic compound passing through a 0.45 mm filter. The total amount of organic carbon prior to filtration is defined as the total organic carbon (TOC) concentration. The number of organic compounds present in surface water is effectively limitless, and it is thus impossible to provide a general chemical description of DOC. DOC might be harmless in itself but it can cause problems in water treatment by reducing the efficiency of processes, i.e. energy consumption for UV-processes (Martijn et al. 2010) or regeneration frequencies of carbon filters (Köhler et al. 2016) and by reacting with disinfectants (Metcalfe et al. 2015) such as chlorine to form disinfection by-products (DBPs). The effect of DOC on water treatment processes and methods for DOC characterisation have been well described in the literature (see almost the whole of the reference list at the end of this paper). Previous research has shown that high DOC concentrations negatively impact all water treatment processes. DOC-related challenges vary widely temporally and spatially, but where DOC concentrations are elevated, or the organic compounds are difficult to treat, the outcomes are similar: reduced efficacy of downstream treatment processes and issues with water quality such as elevated DBP concentrations and reduced biostability. Therefore, processes which can increase the removal of DOC provide potential benefits for water utilities to meet water quality and efficiency challenges. Four source waters in northwest Europe experience elevated DOC concentrations, and the following descriptions showcase their specific challenges.

**South West Water, the United Kingdom**

South West Water (SWW) is a water utility in south-west England, providing water and sewerage services in Devon, Cornwall, and small sections of Dorset and Somerset. SWW owns and operates 29 water treatment works (WTWs) to serve approximately 1.6 million residents. The majority of water (~95%) is supplied from surface waters (rivers and reservoirs), with groundwaters only making up around 5% of the supplies. SWW continues to meet and/or exceed drinking water quality regulatory requirements, but strives to continue to improve the quality of water provided to their customers. As such, SWW is interested in new treatment technologies which can provide better water quality. One of the future challenges is related to significant increases in the concentration of DOC in UK surface waters during the last few decades (Matilainen et al. 2010; Ritson et al. 2014), linked to reduced acid deposition, elevated temperature, changes in land use, altered precipitation patterns and increased frequency of extreme weather events associated with climate change. A study by Evans et al. (2004) showed that the average DOC concentration of 22 UK surface waters increased by 91% over a 15 year period. SWW have observed similar increases to those documented by Evans et al. (2004), with the concentration of NOM in many of the surface waters they utilise significantly increasing over recent times.

As an example, Figure 1 shows significant seasonal variation and a near doubling of the average TOC concentration during a ten year period (2001–2010) within one of the upland reservoirs that is treated by SWW. SWW has a long term strategic goal to build a new WTW to replace the existing Crownhill WTW (Plymouth, UK). During the periodic review in 2014 (PR14), SWW reviewed and restated drinking water treatment goals for new WTWs to include:

- Provision of an absolute barrier to *Cryptosporidium*.
- Enhancement of water quality, particularly DOC removal and DBP reduction and effective removal of pesticides where present.
- Use of efficient design to realise improved operability (compact footprint, automation, reliability and robustness of processes).
- Sustainability (chemicals, energy, waste, life expectancy).
- Application of innovative, forward-looking technology where applicable.
The two primary goals for the selection of treatment processes for the new WTW were the desire to provide an absolute barrier to *Cryptosporidium* and reduce DOC and DBP formation. These goals were in part related to the company’s reliance on surface waters (95% surface water abstraction), the increasing challenge from raw water organic compounds and elevated *Cryptosporidium* risk related to the agricultural environment.

**Norrvatten, Sweden**

Water treatment plant (WTP) Görvälnverket of Norrvatten (125MLD) produces potable water from surface water that is under the influence of secondary effluent, recreation, population, farm land and industry. The water source for WTP Görvälnverket is Lake Mälaren, which has 1,100 km² of surface area, and is one of the largest fresh water lakes in Europe and serves as the source for drinking water for almost two million people. Besides Norrvatten, Stockholm Water also uses this source for their potable water production. The current treatment process for WTP Görvälnverket consists of a deep intake, micro-sieves, coagulation, sedimentation, sand filtration, carbon filtration, and UV disinfection followed by monochloramine and pH control with lime.

The biggest challenge that this current treatment process is facing is the increasing levels of DOC in the raw water, which is not sufficiently removed by the coagulation process. Figure 2 shows the increasing trend in the concentration of colour in the lake at a depth of 0.5 m (Lake Mälaren, Sweden) over the last 10 years.

There is no historical data of the DOC concentration at the intake, but recent experiments show that a good linear relationship exists between color and DOC (Figure 3). This indicates that for the last 6 years the DOC concentration is most likely on average around 10 mg/L or higher.

The increased level of DOC at this site results in blinding and fouling of the GAC (Köhler et al. 2016), which was developed as a treatment need when the micro contaminants started to increase during the late 1970s. The most likely cause of this increase in DOC concentration is related to climate change effects as well as changes in land use. Higher levels of DOC likely lead to inefficiencies with the existing treatment processes (i.e., coagulation, GAC and UV disinfection) and are already responsible for reduced biostability in the network.

Norrvatten is currently investigating DOC removal with direct nanofiltration in collaboration with 4 other interested utilities in Sweden. The advantage of direct nanofiltration compared to coagulation,
sedimentation and sand filtration according to Köhler et al. (2016) is its compactness, high retention of DOC and absolute barrier against colloids (independent of capacity and raw water quality) and the retention of a few micro-contaminants. Possible disadvantages are related to controlling membrane fouling to enable acceptable permeability, recovery, membrane integrity, membrane lifetime, and life cycle costs. NOM is effectively removed by nanofiltration, but NOM also has high fouling properties for this membrane process. At the moment, Norrvatten is seriously considering nanofiltration as a feasible supplement after the existing coagulation process, or if possible as an alternative for coagulation, sedimentation, and sand filtration. However, they want to compare this option with another feasible alternative.

Scottish Water, the United Kingdom

Scottish Water (SW) provides drinking water to 2.46 million households and 150,000 business customers in Scotland. Every day it supplies 1.34 billion litres of drinking water and takes away 847 million litres of waste water from customers for treatment prior to returning it to the environment. SW has 137 WTWs, over 80% of which serve small rural communities across the Scottish Highlands and Islands. Drinking water in Scotland comes from a number of sources, including upland reservoirs,
rivers, springs, and bore holes. All sources are treated to ensure that they comply with the regulatory standards. The extent and type of treatment required depends on the nature of the supply, its quality and any potential risks to quality that are present. All water in Scotland supplied by SW is disinfected, normally by chlorine disinfection.

It is not uncommon for raw waters in Scotland to have relatively high concentrations of DOC; anything between 5 to 15 mg/l would not be considered unusual and traditional coagulation and filtration techniques have proved an efficient treatment process for such water sources. However, where chlorine is used to disinfect potable water, NOM is recognised as the most important source of DBP precursors. The characteristics of NOM are therefore of great importance. The efficient removal of DBP precursors is essential to minimise subsequent formation of DBPs after disinfection. Different NOM fractions can also significantly influence the NOM removal efficiency of coagulation processes with hydrophilic, low molecular weight (LMW) organics typically being recalcitrant to the process. The chemical and physical properties of NOM therefore play important roles throughout the water treatment process, such as coagulation, filtration and disinfection, both in terms of NOM removal efficiency and achieving DBP compliance at customer taps. Therefore, NOM fractionation techniques, e.g. resin adsorption processes, etc, are being used by SW to assess the NOM removal efficiency of treatment processes, the impacts of seasonal variations and the resulting DBP formation potential.

NOM fraction analysis has provided SW with new insights into the ability of traditional coagulation processes to remove the DBP precursors associated with certain NOM fractions. It became clear that, in some cases, there was a need to look at alternative processes to improve the NOM removal efficiency, especially the removal of LMW humics, which can form DBPs during the disinfection process. Following further investigation with Cranfield University, ion exchange (IX) processes were identified as a treatment option that required further investigation and assessment at pilot plant-scale was performed (Bond et al. 2011). A further challenge for Scottish Water is that there are a large number of small WTWs in remote rural areas, which are not always easily accessible. This means that treatment works need to be robust, reliable and efficient.

Water Supply Company PWN, the Netherlands

In 1920, when Water Supply Company North Holland PWN (PWN) was founded, the demand for drinking water was satisfied by groundwater extraction. However, due to growing drinking water demand, PWN was compelled to utilize surface water as an additional source. Therefore, in 1968 Water Treatment Plant Andijk (WTP Andijk) was constructed for the direct production of drinking water from the IJssel Lake (River Rhine). Originally the plant consisted of micro-straining, breakpoint chlorination, coagulation, sedimentation, rapid filtration and post disinfection with ClO₂. In 1978 the plant was upgraded with pseudo moving bed GAC filtration. In the beginning of the 90’s a minor improvement in water quality was made by softening the raw water reservoir by dosing NaOH in the intake from the IJssel Lake to the reservoir, followed by pH adjustment with CO₂ prior to the micro-strainers. After almost 40 years of operation, WTP Andijk still complied with all Dutch drinking water standards. Nevertheless a second large upgrade was desired to install a universal barrier against pathogenic micro-organisms such as protozoa and organic micro pollutants such as pesticides (Kruithof et al. 2000). This retrofit included the world’s first large scale application of advanced oxidation with UV/H₂O₂, which became operational in 2004 (Kruithof et al. 2005). This advanced oxidation process is placed between the existing pre-treatment and the GAC filtration process. The GAC treatment provides removal of residual H₂O₂ and easily assimilable organic carbon (AOC). Since the advanced oxidation with UV/H₂O₂ requires a higher UV dose (compared to standard UV disinfection), superior disinfection is provided and breakpoint chlorination can be abandoned (Kruithof et al. 2000, 2005). In a third phase, the existing
pre-treatment that dated from 1968 was renewed. The desire to retrofit the pre-treatment was based on a few challenges:

- increase the UV transmission (UVT) to improve the efficiency of the AOP;
- increase the removal of DOC to improve the efficiency of the AOP and to lower the formation of AOC;
- remove nitrate to improve the efficiency of the AOP and to lower the formation of nitrite;
- provide an absolute barrier to suspended and colloidal matter independent of the feed water quality;
- increase the overall capacity from 3,000 to 5,000 m³/h.

The requirement to remove all suspended matter quickly led to the idea of using micro- or ultrafiltration (MF/UF). A former PWN study (Galjaard et al. 2005) indicated that the direct treatment of IJssel Lake water with MF/UF was only possible after the removal of the LMW DOC fractions with an anion resin (at that time Magnetic Ion EXchange (MIEX®, Ixom Watercare, Australia, previously Orica)), which resulted in a high gross flux rate with almost no fouling. The use of anion exchange also increased UVT considerably and removed a large amount of nitrate and DOC.

The pre-treatment of IX followed by MF/UF looked promising to fulfill the needs for the downstream treatment and resulted in the first full scale SIX plant, which has been in operation since 2014 (120 MLD, Andijk III WTW). At the moment, research is still being conducted to see how the predicted increase in certain DOC fractions affects the process and what measures are possible to deal with any further increases in raw water DOC. Figure 4 shows the DOC concentrations at the WTW intake, which reveals a recent increase in the high molecular weight organic fraction (biopolymers).

![Figure 4](http://iwaponline.com/wpt/article-pdf/13/3/524/479459/wpt0130524.pdf)

**Figure 4** | DOC level (µg/L) in the IJssel Lake (the Netherlands) over the last 8 years.

**INTRODUCTION**

**Ion exchange (IX)**

Coagulation has been the most commonly applied process for NOM removal (within conventional water treatment processes). However, anion exchange processes have been identified as an efficient alternative or supplementary process to other NOM removal processes, such as coagulation, and activated carbon filtration. (Bolto et al. 2004; Bond et al. 2011; Watson et al. 2015).

IX is considered to be both an adsorption process and a sorption process (Wachiniński 2006). The term ion exchange describes the unit process of IX, which is widely used in water treatment to remove unwanted contaminants. The most common application of IX is softening, but there are many kinds
of resin, and anion IX resins can be used for the removal of anions such as nitrate, DOC, and arsenate. IX has been introduced by the World Health Organization (WHO) as a nitrate removal technology and approved as the Best Available Technology (BAT) for nitrate removal by United States Environmental Protection Agency (US EPA). Cation IX refers to the removal of cations, such as calcium and magnesium. Wachinski and others argue that the role of IX in water treatment is changing. This is because of the proposed brine discharge legislation in California, Montana, and Texas and also because of advanced membrane technologies, AOP and the need for many utilities to lower DBP formation potential. Anion IX offers a very good opportunity for enhanced removal of organic matter for source waters that contain medium to high concentrations of NOM as the majority of compounds which make up NOM are negatively charged.

The size exclusion liquid chromatography–organic carbon detection (SEC-LC-OCD) method is a powerful analytical tool to characterize organic matter and to observe relative differences in DOC. The SEC broadly groups the organics into five fractions: biopolymers (MW > 20,000 Da), humics (MW ~ 1,000 Da), building blocks (MW 300–500 Da), LMW acids and LMW neutrals (MW < 350 Da) (in the order of retention time). Two detectors: an organic carbon detector (OCD) and ultraviolet detector (UVD) detect the organics. The OCD spectrum is used to determine the total mass of organic carbon, whereas the UVD spectrum detects only the UV adsorbing species (i.e., double bond carbon), the so-called chromophoric DOM. Figure 5 shows an example of an OCD signal where the same surface water is treated with enhanced coagulation and anion IX. It is clear that enhanced coagulation removes a part of the biopolymer fraction (around 30 minutes retention time) and a small portion of humics (around 40 minutes retention time). The IX removed most of the humics with the highest molar absorption coefficients and LMW fractions (around 40 and 50 minutes retention time) but it had almost no impact on biopolymer removal. As a result, the UVT 254 nm for enhanced coagulation was 82% while anion IX achieved a treated water UVT of 94%.

![Figure 5](http://iwaponline.com/wpt/article-pdf/13/3/524/479459/wpt0130524.pdf)

**Figure 5** | SEC-OCD chromatogram of ion exchanged and in-line coagulated IJssel Lake water.

**Ion exchange and related challenges**

Currently available technologies to treat surface waters containing suspended and colloidal matter with IX are based on fluidized bed reactors or on totally-mixed reactors with very high concentrations of resin (>400 mL/L), like in the MIEX® process or in suspended plug flow reactors like in the SIX® process of PWN Technologies. The SIX® process was developed to overcome the disadvantages of the fluidised bed and MIEX® processes. The MIEX® process has several different process configurations, but the main two are: the classical dual-stage MIEX® process and the high-rate MIEX® process. In the
classical dual-stage MIEX® process, one or two totally mixed contactors in series are fed with raw water and resin, leading to an average resin concentration of 20 to 40 mL/L of resin in the contactors. Approximately 5 to 10% of the settled resin is pumped to a regeneration station, regenerated and re-loaded to the remaining 90 to 95% resin.

In the case of the high-rate MIEX® process, the resin concentration in the contactors is 200 to 500 mL/L. The resin stays in the contactor and the water flows through. Only a very small amount (~0.1%) of the resin is pumped to regeneration vessel while, at the same time, regenerated resin is pumped into the contactors. From the available literature on the high-rate MIEX® process (Verdickt et al. 2011) it is not exactly clear how much resin is pumped to the regeneration system over the course of time, as the 0.1% of the total resin is being regenerated without a direct correlation to time or capacity. Based on the information reported by end users and customers, one concludes that the effective resin concentration in the process is between 1 to 2.5 mL/L. This theoretically yields a number of bed volumes (BV) treated of 400–1,000 before regeneration and a resin residence time 1,000 times higher than the hydraulic residence time, which is not known. This may explain why the process has been called high-rate. The hydraulic residence time and contact time of the water may be short (although not confirmed in the literature) compared to the dual-stage process, but the resin inventory and residence time until regeneration are much larger (Verdickt et al. 2011).

The fluidised bed and the MIEX® process treat a high number of BVs (i.e., >1,000 volumes of water per volume of resin) until the resin is regenerated (Sluksi et al. 1999). Under some water quality conditions, this approach could present quite a few disadvantages that would make the technology less economically attractive. For example, the anion exchange MIEX® process used to remove DOC from raw surface waters is sometimes not efficient due to nutrients such as nitrates and phosphates in the water, which adsorb to the resin during the long retention times (designed to minimize the number of regenerations) and, along with the existing carbon and porous characteristic of the resin beads, create an ideal environment for bacterial growth. The biofilm formed on the resin ‘blinds’ the active sites of the resin, resulting in serious operational and performance challenges. In addition, the loss of adsorption capacity (Wachinski 2006) requires a higher resin concentration or longer contact time (Cornelissen et al. 2009; Verdickt et al. 2011); factors which increase the operational costs and/or lower the plant capacity. Another real problem is that eventually the biofilm releases organic matter or adenosine triphosphate, both known to be detrimental to downstream water treatment processes, particularly to membranes (Cornelissen et al. 2010).

To overcome the ‘resin blinding’, fixed bed reactor systems are flushed regularly with a high pH solution to destroy the biofilm as much as possible. In the case of the MIEX® processes, which use hydrophobic resins, it is not possible to use high pH solutions to control the biofilm formation since the resin is not resistant to alkaline agents, and eventually the resin will be degraded, thus shortening the lifetime of this relatively expensive resin.

A PWN study (Galjaard et al. 2005) showed that the direct treatment of IJssel Lake water with MF/UF was only possible after the removal of the LMW DOC fractions with an anion resin. Consequently, PWNT pursued further research studies, which resulted in the development of a new IX process, namely the suspended ion exchange process (Galjaard et al. 2009). Unlike other IX processes treating waters with a high content of suspended matter, the ‘single pass’ or ‘suspended’ IX process (SIX®) developed by PWNT achieves full control of the adsorption process, minimising ‘blinding’ of the resin or producing biomass. The process uses almost any commercially available resin, and all resins tested to date can be treated with alkaline solutions for biofilm control, if necessary. In the SIX® process, the resin is dosed from a dosing tank into the raw water at a low concentration of 4 to 20 mL resin/L, depending on the raw water quality, desired treated water quality and resin type. This mixture then flows through plug flow contactors. In these contactors, the resin has the same residence time as the treated water, because the resin travels together with the water through these contactors. This is different to MIEX®, in which the resin is retained in the contactors. The
number, shape, and design of the contactors play an important role in the adsorption kinetics. The aim of design is to approach the ideal contactor conditions of a plug-flow reactor, characterized by the shorter residence time of the resin, and therefore shorter contact time. After the contact time in the contactors, the resin is separated from the treated water using a customized lamella settler. The resin collects in the hopper, and is then immediately regenerated and returned to the dosing tank (Figure 6).

Knowing the exact residence time of the resin makes it possible to regenerate all of the resin equally, leading to an equally low number of regenerations. The relatively short contact time (e.g., 10 min < t < 30 min) of the treated water with the resin before the regeneration procedure overcomes the problematic issues of bacteria growth and resin blinding, and ensures that the resin operates continuously at stable adsorption kinetics.

Another advantage of this process is that because the resin is not fully loaded prior to starting the regeneration, the regeneration (which is an equilibrium process) requires less salt and lower contact times for the regeneration procedure. The regeneration of the resin (time and volume) and the discharge of the brine are the primary factors which drive the costs for these IX processes.

**PROBLEM DESCRIPTION**

SWW, Norrvatten (in close co-operation with Stockholm Vatten), Scottish Water and PWN are investigating new approaches to lower the amount of DOC at the beginning of the treatment works to such an extent that:

- low pressure membranes as a barrier for suspended matter and colloids can be used without severe fouling problems (CIP frequency >3 months);
- blinding or fouling of carbon filtration at the end of the treatment process is minimized such that it leads to economically acceptable backwash frequencies and regeneration frequencies (BW > 1/month and regeneration >2 years);
- efficiency of the UV or advanced oxidation processes are increased;
- DBP formation potential in final product is reduced (trihalomethanes < 25 μg/L);
- biostability within the network is increased (AOC < 25 μg/L).

For these reasons all parties are interested in the feasibility of the SIX® process and the use of an in-line coagulant dose after the SIX® process to increase the removal of DOC further. The following objectives are listed to achieve an initial assessment of feasibility:

- Analysis of raw feed water quality (for the SIX® process);
- Establish a correlation between UV254 and DOC concentration;
- Determine absolute removal rate of DOC with IX;
- Establish a model for the removal rate to generate initial design parameters for the SIX® process (i.e. the resin concentration and contact time);
- Determine the desorption rate to define initial design parameters for the regeneration of the resin;
- Determine water quality after the SIX® process and after the CeraMac® process (ceramic membranes, PWNT) with and without in-line coagulation

**MATERIAL AND METHODS**

Raw water samples were taken from the different sites and brought to the PWNT research facility in Andijk, Netherlands. These samples were subjected to a series of laboratory and bench-scale experiments. Furthermore, samples were periodically taken from the current treatment processes for each individual treatment step in order to verify how the NOM composition is being affected by these treatment processes. On the occasions where pilot studies have already begun, further insight could be achieved on the economic feasibility.

**Anion exchange resin**

Lewatit® S5128 (Lanxess, Cologne, Germany) was selected for the experimental research. This resin is a food grade, gelular, strongly basic anion exchange resin (type 1) based on an acryldivinylbenzene copolymer, with a homogenous size distribution and especially suitable for NOM removal from surface waters. The resin is from a so called chloride form, i.e. the counter anion that is being exchanged with other anions such as sulphate or nitrate is the (weakly) absorbable chloride anion. This acrylic gel resin has been chosen above available macroporous resins because of its characteristics, which result in relative ease of regeneration. The adsorption kinetics are potentially slower in comparison to macroporous resin but the resin needs less contact time and a lower salt concentration for regeneration (to exchange all adsorbed anions for chloride). In practice this means that the resin concentration in the contactors are likely to be higher, but the overall inventory is reduced, including the volume that needs to be regenerated, leading to a smaller regeneration facility requirement.

**NOM determination and chemical analysis**

NOM composition was determined at the certified laboratory ‘Het Waterlaboratorium (HWL)’ (Haarlem, Noord-Holland) according to the LC-OCD procedure, described by Huber et al. (2011). NOM, bicarbonate, DOC, and colour were measured at HWL.

**NOM adsorption kinetics**

Raw water samples were used for both one series of jar tests and a bench-scale test. With the jar tests DOC removal kinetics were investigated for several (pre-rinsed) virgin resin concentrations. See Tables 1 and 2 for more details. DOC was measured in-house using a spectrophotometer (Hach DR6000, Hach Lange, Düsseldorf, Germany) and Hach Lange (LCK 321) cuvette test tubes. For more accurate DOC analysis the samples were sent to the HWL. In addition, UV transmission (UVT) at 254 nm was measured in-house, using a Hach Lange DR 6000 spectrophotometer. Normally, UV measurements correlate well with DOC, giving the opportunity to estimate DOC levels from UVT254 values.

Immediately after the bench-scale adsorption experiment, the loaded resin was collected by decanting the supernatant. The loaded resin was subjected to a series of desorption jar tests.
About 20 L of the supernatant was collected and used for another jar test experiment aimed at further removal of residual NOM by coagulation with polyaluminum chloride (PACl). Table 3 describes an example experimental procedure that was used.

### RESULTS AND DISCUSSION

#### UV transmission and DOC correlations

Figure 7 shows the relationship (trendlines with R² values above 99%) between the UVT at 254 nm and the DOC concentrations measured during and after SIX® treatment mimicked at lab- and bench-scale. UVT254 was first measured after the samples were filtered through a 0.45 μm filter. The main reason to make this relation is to use UVT254 as a guide parameter for DOC during the anion adsorption process for a given resin concentration and contact time. It also provides valuable information about the DOC characteristics, in particular the UV absorbing compounds of the DOC during IX. This extra information should be regarded as complementary to the LC-OCD analysis with the UV detector in combination with the OCD.

### Table 1 | Jar test protocol for batch adsorption tests for different resin concentrations

<table>
<thead>
<tr>
<th>Jar</th>
<th>Resin conc. (g/L)</th>
<th>Sampling intervals (min)</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>0.2,6,10,14,20,30,24 h</td>
<td>Initial volume = 1.5 L; mech. stirring at 200 rpm</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>0.2,6,10,14,20,30,24 h</td>
<td>Initial volume = 1.5 L; mech. stirring at 200 rpm</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>0.2,6,10,14,20,30,24 h</td>
<td>Initial volume = 1.5 L; mech. stirring at 200 rpm</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>0.2,6,10,14,20,30,24 h</td>
<td>Initial volume = 1.5 L; mech. stirring at 200 rpm</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>0.2,6,10,14,20,30,24 h</td>
<td>Initial volume = 1.5 L; mech. stirring at 200 rpm</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>0.2,6,10,14,20,30,24 h</td>
<td>Initial volume = 1.5 L; mech. stirring at 200 rpm</td>
</tr>
</tbody>
</table>

### Table 2 | Bench scale protocol for batch adsorption kinetic studies for a selected resin concentration

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Resin conc. (g/L)</th>
<th>Sampling intervals (min)</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15°°, 20°°, 30°°mL/L</td>
<td>0.2,6,10,14,20,30</td>
<td>Initial water volume = 60 L; stirring with blade impeller at rotation speed, suitable for equal resin distribution over water volume.</td>
</tr>
</tbody>
</table>

\[ t = 0 \text{ min and } 30 \text{ min samples were send to the lab (HWL) for NOM analysis} \]

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About 20 L of the supernatant was collected and used for another jar test experiment aimed at further removal of residual NOM by coagulation with polyaluminum chloride (PACl). Table 3 describes an example experimental procedure that was used.

### Table 3 | Jar test protocol for the simulation of residual NOM removal by in-line coagulation with polyaluminum chloride (Sachtoclar; 5.35% Al; density 1.21 g/mL)

<table>
<thead>
<tr>
<th>Jar</th>
<th>Coagulant dosage As PACI (ppm)</th>
<th>As Al³⁺ (ppm)</th>
<th>Mixing Rapid (s/rpm) Slow (min/rpm)</th>
<th>0.2% HCl dosage mL</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>0.8</td>
<td>10/400</td>
<td>20/40</td>
<td>0.5</td>
</tr>
</tbody>
</table>

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#### Results and Discussion

**UV transmission and DOC correlations**

Figure 7 shows the relationship (trendlines with R² values above 99%) between the UVT at 254 nm and the DOC concentrations measured during and after SIX® treatment mimicked at lab- and bench-scale. UVT254 was first measured after the samples were filtered through a 0.45 μm filter. The main reason to make this relation is to use UVT254 as a guide parameter for DOC during the anion adsorption process for a given resin concentration and contact time. It also provides valuable information about the DOC characteristics, in particular the UV absorbing compounds of the DOC during IX. This extra information should be regarded as complementary to the LC-OCD analysis with the UV detector in combination with the OCD.
As can be seen from Figure 7, the relationship between IJssel Lake, Lake Mälaren, Burrator reservoir and Lake Invercannie seems to be more linear compared to Burncrooks and North-Hoy raw water. However, this linear relationship is also present at Burncrooks and North Hoy for UVT values higher than about 60%. The remarkable differences between the various water qualities with regard to UVT254 and DOC content are rather dependent on the NOM matrix of the various waters and the extent to which it changes during anion exchange. Both Mälaren and IJssel Lake raw waters have a much higher UVT for a given DOC content, which means that the UV-absorbing fractions of the DOC have a lower specific UV absorbance (SUVA) than the other raw waters. Further, it is notable that Invercannie, IJssel Lake and Mälaren raw waters have a relatively high residual DOC content at 100% transmission, which, in turn, means that a significant part of the DOC does not absorb UV light at 254 nm at all. For IJssel Lake water the latter can be explained by the presence of a high molecular weight biopolymer fraction, especially in the residual DOC fraction after SIX treatment. For IJssel Lake it was determined that the biopolymer fraction does not absorb UV light at 254 nm (Koreman & Galjaard 2016).

Chloride exchange

During sorption, chloride ions are exchanged not only with NOM molecules, but also with sulfate, nitrate, and bicarbonate, which are the most dominant anion constituents for many natural waters. The selectivity of anion exchange resins for different anions is typically as follows: \( \text{SO}_4^{2-} > \text{NO}_3^- > \text{Cl}^- > \text{HCO}_3^- > \text{OH}^- \) (Wachinski 2006). In addition, for IJssel Lake water it was determined that the order of desorption rate during regeneration holds: \( \text{SO}_4^{2-} > \text{HCO}_3^- > \text{NO}_3^- > \text{DOC} \) (Im et al. 2015). This order cannot be directly derived from the selectivity order, since we also have to take into account the total amount of the various anions that are being adsorbed onto the resin, which is not only dependent on adsorption rate but also on initial concentration. For the IJssel Lake this implies that the total chloride exchanged during SIX adsorption/desorption is mainly determined by \( \text{SO}_4^{2-} \) and \( \text{HCO}_3^- \) and to a much lesser extent by the target ‘anions’ DOC and \( \text{NO}_3^- \). This can be explained by the higher initial concentrations for \( \text{SO}_4^{2-} \) and \( \text{HCO}_3^- \) and highest removal efficiency for \( \text{SO}_4^{2-} \) (sulfate for more than 95%).
In the Scottish Water locations the situation differs. During bench-scale adsorption experiments, chloride increase was determined and converted to desorbed meq Cl-/L resin and compared with total amount of adsorbed SO$_4^{2-}$, HCO$_3^-$ and NO$_3^-$ meq/L resin, while for these anions molar anion equivalencies are assumed to be 2, 1 and 1 respectively. Since these are by far the most dominant anions within the water matrix, the gap between both curves in Figure 8 is likely to be (mainly) related to DOC adsorption (see Figure 8(a) and 8(b)).

![Figure 8](http://iwaponline.com/wpt/article-pdf/13/3/524/479459/wpt0130524.pdf)

Figure 8 | (a) Chloride desorption versus anion adsorption during bench-scale adsorption tests expressed as meq/L for Invercannie raw water (30-6-2015). (b) Chloride desorption versus anion adsorption during bench-scale adsorption tests expressed as meq/L for Burncrooks (23-6-2015).

It can be seen in Figure 8(b) that especially for Burncrooks, the chloride efficiency, i.e. the amount of chloride that is involved in the DOC sorption process, is very high because of the low total anion and high DOC content. Moreover, the total amount of meq/L for SW raw waters involved in anion sorption with Lanxess Lewatit S 5128 resin is 10–20 fold lower compared with IJssel Lake water (150–200 meq/L resin). An intermediate position must be assigned to Lake Mälaren raw water, where 80 meq/L resin are exchanged during SIX® treatment and regeneration. The lower the amount, the
lower the total chloride consumption and, as a consequence, the salt (NaCl) demand during regeneration.

Optimization of the regeneration process at PWNT research facility (Andijk) has resulted, among other things, in a drastic reduction of the total salt consumption due to controlled blinding (0.2–0.3 kg NaCl/m$^3$ SIX effluent) (Koreman & Galjaard 2016). Based on this finding and due to the much lower anion content compared to Andijk, it is to be expected that for the investigated SW locations this amount will be lower than 0.02 kg NaCl/m$^3$ and lower than 0.1 kg NaCl/m$^3$ for Lake Mälaren.

**NOM adsorption**

Figure 9 shows the NOM removal as a function of contact time during SIX$^{\text{®}}$ treatment. The graphs clearly demonstrate that, except for Burncrooks, the adsorption is still in a non-equilibrium state. But after 30 minutes contact time the vast majority of the adsorbable NOM seems to have been removed. Hence the adsorption can be regarded as being in a near equilibrium state, as is also the case with Lake IJssel SIX$^{\text{®}}$ treated water (Koreman & Galjaard 2016).

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Besides Invercannie, over-all DOC removal for the Scottish Water locations is at least 75% and even 85% for Burncrooks (Figure 10). DOC removal for Invercannie and Burrator reservoir is somewhat lower, most likely due to the much lower initial DOC concentrations (i.e., $\leq$2.0 mg C/L), since the adsorption rate is proportional with the DOC load, i.e. $[\text{DOC}(t) - \text{DOC}_{\text{equilibrium}}]$. Against this background, Andijk (45–58% removal) might be considered as an intermediate situation ($4.5 \text{ mg/L} < \text{DOC}_{\text{initial}} < 5.5 \text{ mg/L}$).

**SIX-affected NOM fractions**

Again, the OCD relative signal response at various retention times allows a more comprehensive interpretation of which NOM fractions are being affected during SIX$^{\text{®}}$ treatment. Figure 11 is illustrative for all investigated locations. From this figure and available literature (i.e. Bond et al. 2011) it can be denoted that anion exchange will be capable of very substantial NOM removal over a wide range of LMW NOM ($<1$ kDa apparent molecular weight). The removal of the high molecular weight fraction ($>20$ kDa) is however much lower. According to the LC-OCD detection method this fraction is characterized as the ‘biopolymers’ fraction.
Figure 11 gives the relative differences between the different raw water sources, showing clear similarities in the different NOM fractions and relative differences in quantities. Further, it will be obvious that post coagulation after SIX further reduces humics, but in particular this HMW biopolymer fraction. ‘In-line’ coagulation with polyaluminum chloride was mimicked with jar test experiments. As a result of applying in-line coagulation on SIX-treated water, DOC levels can be further reduced using low Al³⁺ doses of about 1 ppm to 0.4–2.3 mg C/L, depending on raw water quality (Figure 12).

**CONCLUSIONS**

The surface waters examined all have elevated concentrations of DOC. These DOC levels are increasing, most likely due to climate change effects. This increase differs and fluctuates depending on location, but is in the range of 10–50% over the last 10 years. For these types of waters, IX is of interest as a pre-treatment option because the removal of colour and DOC by IX will increase the efficiency of all downstream processes, including coagulation, membrane filtration, AOP and GAC. In addition, it will improve water quality (reduced by-product formation) and most likely improve biostability within the distribution network. These waters however contain significant amounts of suspended and...
colloidal matter, which makes it nearly impossible to use standard state-of-the-art, fixed bed IX columns. This is because these beds will foul quickly (i.e., head loss build-up) with the suspended matter leading to frequent backwashing or damage to the resin and resin blinding.

Overall, the SIX process functions very well and seems to be a potential solution for removal of DOC. The higher removal of DOC and other negatively-charged ions theoretically impacts water quality and the efficiency of all the downstream processes. This has already been demonstrated in Andijk (Martijn et al. 2010) and Plymouth (Metcalfe et al. 2015). The advantages of SIX compared to existing IX processes and enhanced coagulation/sand filtration systems (ECSFs) are:

- no (significant) resin ‘blinding’;
- capable of using almost any available commercial resin;
- low resin concentration and inventory;
- high effluent quality;
- costs comparable or lower to ECSF

From the results of the bench-scale SIX study performed on different raw waters the following can be concluded:

- Depending on the regeneration regime, suspended ion exchange (SIX) results in substantial removal of NOM (55–85%) and colour (60–80%) for moderate resin concentrations (10–20 mL/L) and contact times (20–40 minutes).
- NOM reduction could be further improved relative to SIX pretreatment alone, by applying coagulation at low coagulant dosage (0.4–2.5 ppm as Al3+) and short contact time (2.5 minutes). This was especially important for the reduction of the residual biopolymer fraction after SIX treatment.
- The amount of salt necessary to regenerate the resin is relatively low compared to other IX methods. Most likely the highest salt concentration in the fresh brine solution will not exceed 20 g Cl/L (Andijk, because of its relative high anion content, is excluded) meaning that after dilution (counter current regeneration over 5 brine vessels) and adsorption of chloride, the brine that needs to be discharged will have an estimated concentration of 1–5 g Cl/L.

The scenario of SIX, in combination with coagulation or not, followed by ceramic MF can therefore be a serious alternative for NOM reduction and suspended matter control next to NF polishing for all utilities. The advantages and disadvantages of this process compared to existing treatment processes, including nanofiltration, are being further studied within a pilot study at Scottish Water and

![Figure 12](http://iwaponline.com/wpt/article-pdf/13/3/524/479459/wpt0130524.pdf)
Norrvatten in close co-operation with Stockholm Vatten, begun in 2016, while it has already led to full-scale design at PWN and South West Water.

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REFERENCES


