Ultrafiltration membranes in managed aquifer recharge systems
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ABSTRACT

The natural organic matter (NOM) and color content of surface waters are increasingly becoming an issue for artificial groundwater recharge plants. Water from Lake Bolmen, in southern Sweden, had in 2017 an annual average NOM and color content of 8.6 mg/L total organic carbon (TOC) and 57 mg Pt/L respectively, and values ranging from 7.8 to 9.6 mg/L TOC and 50–70 mg Pt/L. Since water from Lake Bolmen will be used at Vomb Water Works, an artificial groundwater recharge plant, the high NOM-content of Lake Bolmen must be reduced prior to aquifer recharge. From experiences of full-scale operations of chemical flocculation, lamella sedimentation and rapid sand filtration using ferric chloride, three different pre-treatment methods were proposed; conventional precipitation, stand-alone direct precipitation before ultrafiltration (UF), and conventional precipitation with ultrafiltration after lamella sedimentation. In this study, a hollow fiber membrane (MWCO of 150 kDa) was used in different configurations during a 15 months pilot trial. The results showed the possibility to reduce NOM equal to conventional precipitation when a stable net-flux of 40 and 70 L/(m²·h) was used for direct precipitation before UF and conventional precipitation with UF, respectively. This paper presents these treatment methods and evaluates their viability as full-scale treatment steps.

Key words | coagulation, flocculation, natural organic matter (NOM), pre-treatment, ultrafiltration

INTRODUCTION

Three quarters of all drinking water produced in Sweden originates from surface waters, either through surface water treatment plants (WTPs) or artificial groundwater recharge plants (SWWA 2016). Similar numbers can be seen in Finland, but with a higher percentage of groundwater plants (FIDW 2008). The importance of the raw water source for drinking water supply can thus not be understated. Swedish and Finnish surface waters have high NOM concentrations that can reach 20 mg/L (Löfgren & Andersen 2017), measured as total organic carbon (TOC). Artificial recharge plants can, depending on the circumstances, reduce at least 50 percent of the NOM measured as TOC or chemical oxygen demand (COD) (Sundlöf & Kronqvist 1992; Kolehmainen et al. 2007; Jokela et al. 2017; Hägg et al. 2018b; Tanttu & Jokela 2018), although lower numbers reaching 40 percent have been recorded during winter (Kleja et al. 2009). Insufficient NOM removal rates, combined with growing populations and higher water consumption, have led artificial recharge plants to search for ways to pre-treat water before infiltration.

Common ways to accomplish pre-treatment in Sweden have been chemical flocculation in combination with either sedimentation or contact filtration, which are techniques also used by surface WTPs. Further, chemical flocculation synergizes well with infiltration due to the two different techniques’ ability to remove different fractions of NOM (Eikebrokk et al. 2018). Other techniques include membrane technologies, which are growing in popularity...
within the water supply industry (Salehi et al. 2007) because of their ability to remove particles and microorganisms (Iannelli et al. 2014). The different types of membranes typically used come with their own set of advantages and disadvantages depending on the context. Nanofiltration (NF) membranes, which have been combined with aquifer recharge (Yangali-Quintanilla et al. 2010), have the ability to remove large molecular compounds, such as humic acid, as well as low molecular weight organic material (MWCO ≤300 Da) (Meylan et al. 2007). However, for the purpose of pre-treatment, this might seem excessive. Ultrafiltration membranes, with higher molecular weight cut-off, combined with coagulation could be a better alternative.

It has been shown that NF and coagulation combined with UF can reduce NOM in similar ways (Lidén & Persson 2015), although at different costs (Lidén & Persson 2016). In both studies, aluminum-based coagulant was used, and this coagulant has also been used successfully in several other studies (Choi & Dempsey 2004; Kabsch-Korbutowicz 2006; Keucken et al. 2017; Ding et al. 2018). Iron-based coagulants, such as FeCl₃, in contrast are less commonly used in chemical flocculation techniques. One reason is that iron-assisted coagulation requires lower pH (around pH 5) and has a lower optimum pH range than aluminum-based coagulants (Gillberg et al. 2005). However, iron-assisted coagulation is successfully used at Ringsjö Water Works, a surface WTP in Southern Sweden, where this study was conducted. Konieczny et al. (2009) shows that, when comparing iron- and aluminum-based coagulants at similar pH (around pH 7) combined with UF membranes, the aluminum-based coagulant (aluminum sulphate) was more effective at reducing TOC, but it should be observed that the pH range was outside the optimum range for iron-based coagulation in this study. Iron-based coagulation and flocculation combined with microsieving has also been studied (Hägg et al. 2018a); however, more research is needed on the efficiency of iron-based coagulation with UF membranes, and how this compares to iron-based coagulation, flocculation and sedimentation.

This study investigates FeCl₃ assisted coagulation combined with UF membranes in two different configurations, (1) combining direct precipitation with UF and (2) UF of full-scale pre-treated water (coagulation, flocculation and lamella sedimentation), and compares these results with (3) the full-scale treatment with iron-based coagulation, flocculation, lamella sedimentation and rapid sand filtration presently used at Ringsjö Water Works. At Ringsjö, the effort is to use the WTP’s raw water source; that is, Lake Bolmen, as a new water source for Vomb Water Works, an artificial groundwater recharge plant 35 km southeast of Ringsjö WTP. Motivated by previous studies, indicating limitations in the infiltration fields’ ability to produce groundwater with high quality from the NOM-rich waters of Lake Bolmen (Hägg et al. 2018b), the water works are investigating ways to pre-treat the water before infiltration. Thus, the objective of this study was to evaluate the three methods and assess the possibility to utilize the different techniques as pre-treatment steps in artificial recharge.

MATERIALS AND METHODS

This study investigated two possible ways of implementing UF membranes in full-scale drinking water production through a two-part membrane pilot trial and comparing the results with conventional precipitation with rapid sand filters (RSFs). The first part of the tests was direct precipitation before UF and the second part was full-scale conventional precipitation combined with UF. The feasibility of these three methods was compared based on NOM removal, scalability, cost, and operational flexibility and security. For all three methods, the water quality and NOM removal efficiencies were determined by measuring UVA₂₅₄ nm (m⁻¹) using online sensors in the feed, filtrated and permeated water. To achieve successful flocculation pH, NaOH dosages during flocculation were controlled by online pH measurements. The capacity of the two treatment alternatives was compared with conventional precipitation using the actual net-flux and the temperature compensated permeability achieved during the pilot trials. Figure 1 shows the three different methods combined with artificial groundwater recharge.

Ringsjö Water Works

This study was conducted at Ringsjö Water Works, a surface WTP in southern Sweden operated by South Sweden Water Supply AB (Sydvatten AB). The current treatment process at...
the WTP includes coagulation with ferric chloride (FeCl₃), flocculation, lamella sedimentation, rapid and slow sand filtration, disinfection through UV-light and chlorination (Figure S1, Supplementary material).

The raw water is taken from Lake Bolmen and is transported for one week through an 80 km long tunnel and a 25 km long pipeline before it reaches the WTP (Sydvatten AB 2016). The quality of the water varies seasonally and daily depending on previous conditions at the water source. Lake Bolmen is an oligotrophic lake with a catchment area dominated by forest, bogland and iron-rich soil which causes the water to have high NOM and color content (Persson 2011; Eikebrokk et al. 2018; SMHI 2018).

Pilot plant

To investigate the possibility to pre-treat water from Lake Bolmen, a membrane pilot study was conducted from April 2017 to August 2018 at Ringsjö Water Works. This study presents the results from April to November 2017. The UF membrane used was an X-flow XIGA64 hollow fiber membrane from Pentair, with MWCO of 150 kDa and membrane area of 64 m² (Pentair 2018). The pilot plant was constructed in a moveable container including feed and permeate tank, strainer (AZUD Helix Automatic FT201 AA, Murcia Spain 300 μm), feed pump, backwash pump, panel PC, compressor and vertically installed membrane module.

Two different membrane pilot configurations were conducted during the trial period. The first part was direct precipitation before UF using two different coagulation configurations, inline and feed tank dosage. In the second part, pretreated water (after lamella sedimentation and before rapid sand filtration) from full-scale operations was combined with UF.

The cleaning of the membrane was conducted in three different ways, all using collected permeate from the permeate tank. Table 1 shows the hydraulic clean (backwash) and the two different chemical cleaning procedures used during the pilot trials.

Table 1 | Cleaning proceedings during the pilot trials

| Cleaning proceeding     | Chemical                     | Interval         | Duration | Procedure                  |
|------------------------|------------------------------|------------------|----------|----------------------------|
| Backwash (BW)          | None                         | 32 min<sup>a</sup> | 30 sec   |                            |
|                        |                              | 34–50 min<sup>b</sup> |
| Chemical enhanced backwash (CEB) | NaOH, NaClO (CEB A) H₃SO₄ (CEB B) | 12–24 h | 20 min | 1. Soak for 10 min (CEB A)  
2. Soak for 10 min (CEB B)  
3. Rinse |
| Cleaning in place (CIP) | CIP 1: Citric acid (C₆H₈O₇)≤  
CIP 2 & 3: Oxalic acid (C₂H₂O₄) and Ascorbic acid (C₆H₈O₆)≥ | 3 occasions | 24 h | 1. Overnight circulation  
2. flushed |

<sup>a</sup>Setting used during direct precipitation.  
<sup>b</sup>Setting used during conventional precipitation with UF.  
<sup>c</sup>Used during the first CIP.  
<sup>d</sup>Mixture used the second and third CIP.
The backwash was done every 32 minutes with permeate and without any chemicals, while the chemically enhanced backwash (CEB) was done by soaking for 10 minutes in a combination of sodium hydroxide and sodium hypochlorite (CEB A) followed by a 10 minutes’ soak in sulphuric acid (CEB B). During CEB A, the pH was 12 and the hypochlorite concentration 200 ppm, and during CEB B the pH was 2. The cleaning in place (CIP) was conducted three times over the course of the pilot trials and was done by circulating the cleaning solution through the membrane pilot for 24 hours. The first CIP was performed with citric acid but, because the permeability remained the same before and after, the method was abandoned and a combination of oxalic acid and ascorbic acid was used successfully instead.

**Direct precipitation before UF**

From 1 May to 15 September 2017, direct precipitation trials were conducted. Figure S2 shows the flow chart used during the pilot study. The two different coagulant dosage configurations used were: (1) inline coagulation and (2) feed tank coagulation.

The first part of the trial was inline coagulation, where FeCl₃ was added after the feed tank and before the feed pump to create adequate mixing. The 90 seconds dosage contact time was achieved by connecting a tube allowing for sufficient contact time for floc formation, and during the second part, FeCl₃ was added in a feed tank equipped with a stirrer, allowing for a 14 minute flocculation time. To achieve the same NOM removal as conventional precipitation, the flux and coagulant dosage was 50–60 L/(m²·h) and 5–6.5 ppm (mg Fe³⁺/kg water) respectively. The corresponding recovery rate for both configurations was about 88%. The coagulant dosage was determined based on the resulting UVA and the NaOH dosage in the feed tank was determined based on the measured pH after flocculation.

**Conventional precipitation with UF**

From September 2017 to August 2018, water supply from full-scale operations after lamella sedimentation was connected to the pilot, as seen in Figure S3. In this pilot configuration, the UF membrane replaces the rapid sand filtration function of separating residual flocs from the water. The flux was varied between 60 and 90 L/(m²·h) with a recovery rate of about 95%.

**Chemicals**

The coagulant used was a 40% by weight FeCl₃ solution produced by Kemira (PIX-311, Helsingborg, Sweden), and the coagulant dosage was presented as mg Fe³⁺/L of water (ppm). A H₂SO₄ (37%) and NaOH (25%) solution was used for pH adjustment and CEB to remove metal residues and organic matter respectively. A 12.5% sodium hypochlorite (NaClO) solution was used also for CEB. Citric, oxalic and ascorbic acid was used during CIP cleans.

**Methodology**

To be able to compare and determine the performance of the membranes in the different configurations, the results from full-scale precipitation at Ringsjö Water Works was used as a benchmark for water quality during the pilot study. Another important aspect is the targeted infiltration water quality when introducing pre-treatment of water before infiltration. Table 2 shows the yearly water quality averages of Lake Bolmen, the finished drinking water, the

| Sampling point          | COD ort [mg/L] | Color [mg Pt/L] | Turbidity [FNU] | pH     | Alkalinity [mg HCO₃/L] |
|-------------------------|----------------|----------------|-----------------|--------|------------------------|
| Lake Bolmen             | 6.7            | 41.9           | 1.2             | 7.0    | 15.5                   |
| Drinking water          | 1.3            | <5.0           | <0.10           | 8.2    | 44                     |
| Targeted infiltration   | <4ᵇ            | <10ᵇ           | <0.1ᶜ           | 6.5–8  | n/a                    |
| Regulatory limit        | 4              | 15             | 0.5             | >7.5, <9 | n/a                   |

The table also shows the estimated infiltration water quality needed to reach groundwater of drinking water quality based on experiences from Vomb Water Works and other artificial groundwater recharge plants in Sweden.  
bData reflects average and median annual values from Ringsjö WTP taken from Sydvatten AB’s annual rapport (Sydsvatten AB 2018).  
cBased on Swedish experiences and estimated to a reduction of 60% (Hägg et al. 2018b).  
dBased on the microbial risk assessment used in Sweden (Pott & Odegaard 2015).  
eSwedish regulatory limit for drinking water (Livsmedelsverket 2001).
estimated infiltration water and the regulatory limits for drinking water quality.

The table shows the water quality parameters that are required to produce both finished drinking water and treated water with sufficient quality to be used as infiltration water. This distinction is useful when determining if the pre-treated water is adequate for drinking water, meaning it can be used without artificial groundwater recharge. Note that the estimated water quality for the infiltration water does not take into account issues related to maintenance of infiltration basins; for example, increased clogging of infiltration basins due to high turbidity (Schuh 1990; Hansson 2000).

The water quality from Lake Bolmen varies daily and seasonally, which affects the coagulant dosage and usage of hydroxide. For this reason, yearly averages for chemical consumption were used to determine chemical consumption and cost, and current coagulant dosages were used for comparisons between full-scale precipitation and the membrane pilot. Once the targeted water quality was achieved, maintenance cost, chemical consumption, performance and stability were estimated based on the production of 1 m³ of water, and the investment cost was calculated for a facility with a 2 m³/s production capacity. Because some costs were taken from the Swedish market, an exchange rate of 1 $ (US) to 9 SEK was used. The investment cost of membranes was estimated from retailers and experiences from other water utilities. The relationship between total membrane surface, production volume and investment cost were assumed to be non-linear. Instead, an estimation was done where the investment cost per membrane surface area ($/m²) for a membrane facility decreased with increased production according to Huehmer (2016) and experiences from Swedish water utilities. The cost for chemicals and energy consumption was taken from present costs at Ringsjö Water Works and Lackarebäck Water Works, with a large scale UF facility in Sweden. The study also considered changes in permeability and the need for cleaning when comparing the capacities of the membranes.

**RESULTS**

In this section, the results from the pilot study and the economical evaluation are presented. As previously mentioned, the water quality, measured as UV-absorbance, from conventional precipitation was the target for the membrane pilot. The results from full-scale operation show that the water quality of the treated water remains around 5 m⁻¹ despite fluctuations in raw water quality. However, the result depends on sufficient coagulant dosage, and when NOM content increases in the raw water, the coagulant dosage is increased. The results from full-scale operations can be seen in detail in Figure S4.

**Hollow fiber UF membrane performance**

This section describes the performance of the membrane in the different configurations. The first section presents the results from direct precipitation where the coagulant was applied at two different stages; inline and feed tank precipitation (see Figure S2). The second section shows the results from conventional precipitation combined with UF, where treated water from full-scale operation was used as feed water in the membrane pilot (see Figure S3).

**Direct precipitation**

Figures 2 and 3 show the results from the first weeks of inline precipitation and feed tank precipitation, respectively. As seen in Figure 2, the inline configuration resulted in an unstable performance due to fouling and rapid and great decreases in permeability. The initial flux used was 60 L/(m²·h) but was decreased to 50 L/(m²·h) after two days in an attempt to stabilize the permeability. After the first couple of days, CEB intervals were increased from once to twice a day. In the last part, pH was gradually increased, which resulted in a more stable performance regarding permeability. However, permeate quality, measured as UV absorption, deteriorated with increasing pH. The results from the first two weeks shows that the overall permeability decreases from around 500 to less than 200 L/(m²·h-bar).

During feed tank precipitation, the result showed a more stable performance in regard to permeability (Figure 3). The initial coagulant dosage was 6 ppm and was gradually increased to 7.5 ppm. As a result, the UV-absorption of the permeate decreased from around 7 to 5 m⁻¹. During the three-week trial, the overall permeability decreased from around 500 to 450 L/(m²·h-bar).
During the last period of the trial, the capacity of the membrane was tested (Figure 4). Figure 4(a) shows the results from inline precipitation with two different coagulant dosages, 6.25 and 5.25 ppm. The pH was set to 5.1 and the flux was constant at 50 L/(m²·h) during the whole period. The results show that it was possible to decrease the coagulant dosage and still achieve the desired permeate quality (UVA ≤ 5 m⁻¹). The results from the capacity study of feed tank precipitation can be seen in Figure 4(b). During this study, the flux was gradually increased from 50 to 60 L/(m²·h) and the pH was constant at 5.1. The results show that the permeability decreases as the flux increases and stabilizes when the flux is decreased back to 50 L/(m²·h).

The performance for both settings of direct precipitation resulted in a flux of 50 L/(m²·h), with CEB intervals of 12 hours resulting in a recovery rate of 88% and a net-flux of
40 L/(m²·h). For a membrane facility capable of producing 2 m³/s, this would require 180,000 m² membrane area. Comparing the coagulant dosage needed for direct precipitation with conventional treatment, resulted in a potential chemical saving of up to 15% (from 6–7 ppm to 5–6 ppm).

**Conventional precipitation with UF**

During a two month period, pre-treated water from full scale operations was used as feed water for the membrane pilot. The results can be seen in Figure 5. In this study, most of the flocs were already removed in the sedimentation basins which allowed for higher fluxes. During the first week, the flux was gradually increased from 50 to 80 L/(m²·h), which resulted in a rather stable permeability the following month. However, there was a slight decrease in permeability on 15 October that coincided with a brief but strong turbidity increase in the feed water. The loss in permeability persisted after the event. The flux was further increased to 90 L/(m²·h) during the last couple of weeks, which resulted in a permeability decrease to between 300 and 400 L/(m²·h, bar).

Even though it was possible to have a flux of 90 L/(m²·h) for shorter periods of time, it was more sustainable when flux was 80 L/(m²·h), which translates to a net flux of 70 L/(m²·h) with a recovery rate of 95%. An important result was that the net flux was achieved with CEB intervals of 24 hours instead of 12 hours, which was the case with direct precipitation. The decrease in cleaning frequency results in close to four times decrease in CEB-chemical consumption, due to nearly half the membrane surface being required and the time between cleaning intervals can be twice as long. A membrane facility with a net-flux of 70 L/(m²·h) with a 2 m³/s production capacity would require 102,900 m² membrane surface area.

**Membrane area and lifetime**

A membrane facility capable of producing 2 m³/s with net-flux of 40 and 70 L/(m²·h) would require 180,000 m²
(direct precipitation) and 102,900 m² (conventional precipitation with UF) membrane surface area, respectively. An additional 12% membrane area would be required for direct precipitation for BW waste treatment, estimated from the observed recovery rate of 88%, which results in a total membrane area of 201,600 m². This secondary membrane treatment step would not be required for conventional precipitation with UF, due to the possibility to return the back-wash water waste to the previous treatment step.

An additional cost that comes with UF facilities is replacing of the membrane modules after several years. The average lifetime of the membranes is typically 10 years if the CEB frequency is once per day and it is estimated to be 5–7 years if the CEB frequency is increased to twice per day, according to the manufacturers, after which the modules needs to be replaced.

Chemical consumption

One important aspect for water utilities and for sustainability is the usage of chemicals. Table 3 shows the amount of chemicals used to treat 63 M m³ (2 m³/s) of raw water for each alternative in tons per year.

The chemical flocculation steps for all alternatives have the highest chemical demand. This includes the coagulant but also sodium hydroxide which is used to increase the pH of the raw water to ensure the right flocculation pH. The results show the benefit of direct precipitation with the techniques ability to reduce the need for coagulant. The reduction of coagulant dosage would also reduce the need for hydroxide, and in this case the reduction was 40%. However, the need for cleaning chemicals is high, which results in an overall hydroxide consumption of 996 tons/year. The total yearly CEB chemical amount for conventional precipitation with UF is around 215 tons and around 841 tons for direct precipitation.

| Chemical | Conventional precipitation | Direct precipitation | Conventional precipitation with UF |
|----------|-----------------------------|----------------------|-----------------------------------|
| FeCl₃ (40%) | 4,023 | 3,420<sup>a</sup> | 4,023 |
| NaClO (12.5%) | 0 | 277<sup>b</sup> | 71 |
| NaOH (25%) | 1,159 | 695<sup>c</sup> + 301<sup>b</sup> | 1,159 + 77 |
| HCl (25%) | 0 | 263<sup>b</sup> | 67 |

The consumption of FeCl₃ and NaOH were based on yearly averages from full-scale precipitation at Ringsjö Water Works 2016. CEB chemical consumption was based on the pilot study and calculated by the membrane manufacturer.

<sup>a</sup>Calculated based on a 15% coagulant savings.
<sup>b</sup>Calculated value based on twice the CEB frequency and approximately double membrane area (201,600/102,900).
<sup>c</sup>Calculated based on a 40% savings.
Operational and investment costs

The feasibility to transform the alternatives to full-scale operations also depends on the operational and investment cost for each configuration. The operational costs for conventional precipitation, direct precipitation and conventional treatment with UF are summarized in Table 4. The data are taken from operational experience and estimated values from the pilot study, and only reflects costs associated with the pre-treatment of raw water before infiltration.

The results show that conventional precipitation is the cheapest option, $0.014/m³, where the coagulant cost contributes the most to the price followed by sodium hydroxide. Direct precipitation on UF membranes manage to reduce the cost of the coagulant and hydroxide used for pH adjustment significantly; however, the need for cleaning chemicals, the energy cost and replacement of the modules increases the price to 0.028 $/m³. The high replacement cost, compared to conventional precipitation with UF, comes from the increased number of modules that needs to be replaced and the more rapid deterioration associated with higher CEB frequencies. The price to pre-treat water with conventional precipitation with UF was 0.023 $/m³, 60% more than conventional precipitation. The cost for the cleaning chemicals was minor compared to the coagulant and hydroxide cost. Bisulphite cost, used to neutralize hypochlorite waste after cleaning cycles, was not included.

The investment costs for the membranes are based on a net-flux of 40 and 70 L/m²-h for direct precipitation and conventional precipitation with UF, respectively. This translates to a required membrane surface of 201,600 m² and 102,900 m² to achieve a yearly production of 63 Mm³ (2,000 L/s). As previously mentioned, it was expected that the investment cost per membrane surface would decrease with an increasing amount of membrane modules. This is due to the saving in other installments in the membrane facility, such as pumps and chemical facilities and so on. The price per membrane surface area for a 201,600 m² membrane facility was estimated to be 10–15% less than a facility with 102,900 m² based on Huhmmer (2016), which corresponds to approximately 290 $/m² (with 12.5% cost reduction) and 330 $/m², respectively. The costs for the membrane facility are based on experiences from water utilities in Sweden and from Huhmmer (2016). Table 5 shows the estimated costs for each alternative including shared costs such as building, sludge management and chemical facilities.

The results show that the alternative with the lowest and highest investment costs are conventional precipitation and direct precipitation, respectively. The reason why direct precipitation is the most costly is because the most expensive treatment step is being scaled up; that is, the membrane modules. For conventional precipitation with UF, the investment in flocculation and sedimentation steps is saving investment costs in the membrane modules; however, the alternative still costs more than conventional precipitation. Both membrane alternatives have no need for rapid sand filters, which is one of the highest costs for conventional precipitation. In the end, conventional precipitation would cost $62,000,000; direct precipitation would cost $77,000,000; and conventional precipitation with UF would cost $69,000,000.

Table 4  | Operational costs for the three alternatives presented in $/m³ treated water

| Process                              | FeCl₃ | NaClO | NaOH | HCl | Energy cost¹ | Membrane replacement | Total cost | Relation |
|--------------------------------------|-------|-------|------|-----|--------------|----------------------|------------|----------|
| Conventional precipitation with RSF | 0.011 | 0.0031| 0    | 3.1e-4| 0            | 0.014                | 0          | +100%    |
| Direct precipitation on UF           | 0.009 | 9.0e-4| 0.0019+8.1e-4 | 3.4e-4b | 0.0039 | 0.011³         | 0.028      | +60%     |
| Conventional precipitation with UF   | 0.011 | 2.5e-4| 0.0031+2.1e-4 | 8.7e-5b | 0.0040 | 0.004⁴         | 0.023      | -60%     |

¹Costs were based on an energy consumption of 290 kWh/day for flocculation and sedimentation basins, 200 kWh/day for rapid sand filters, and 0.035 kWh/m² for the UF membranes. Energy cost was estimated at $0.11/kWh, based on the Swedish market.
²Cost for cleaning chemical.
³Calculated from a 7 year module lifetime and 201,600 m² membrane surface area.
⁴Calculated from a 10 year module lifetime and 102,900 m² membrane surface area.
The results from the pilot study shows that it is possible to achieve the same NOM removal with both membrane configurations to the same degree as conventional precipitation. In this case, exceeding the minimum estimated water quality for infiltration water and reaching drinking water quality. This leads to other considerations when evaluating the different treatment methods, the first being the amount of chemicals needed to treat the water. During the direct precipitation trials, it was possible to reduce the coagulant dosage by a significant amount (15%) and therefore also the need for hydroxide (40%). The coagulant reduction that was achieved with direct precipitation could add up to around 600 tons per year, which would have a large impact on sludge management. The reduction in coagulant usage would also reduce the need for hydroxide, which is used to increase the pH before chemical flocculation. In this case, a 40% reduction, which would reduce the hydroxide usage from 1,159 to 695 tons per year. However, the CEB frequency caused hydroxide consumption to be almost equivalent to conventional precipitation, around 1,000 tons per year. Comparing the reduction in flocculation chemicals (FeCl₃ and NaOH) with the increase of cleaning chemicals (NaOH, NaClO and HCl) for direct precipitation, resulted in a slight reduction in overall chemical usage. The cleaning chemical consumption for conventional precipitation with UF was about 4 times less than that of direct precipitation, but the technique does not benefit from savings in flocculation chemicals. As a result, conventional precipitation with UF had the highest chemical consumption followed by conventional precipitation and direct precipitation.

The second aspect, which is tied into this, is the production cost of 1 m³ water. In this case, producing 1 m³ using the two different conventional treatment configuration costs of $0.014 and $0.023 for conventional precipitation and conventional precipitation with UF, respectively. When producing water with direct precipitation, the price goes up to $0.028/m³, which does not seem like much; however, when producing 2 m³/s the resulting cost increase compared to conventional precipitation is around $880,000 per year. The large price increase comes from the increased energy demand and the expensive replacement of the modules, even when calculating with the already generous expected module lifetime of 7 years. The other part is the investment cost of each treatment method, where conventional precipitation also is the cheaper option. Comparing the two membrane configurations, direct precipitation is the most expensive alternative due to the increased membrane area needed. Both methods become comparable with conventional treatment only because of the reduction in price from the unused rapid sand filters, which costs more than the chemical flocculation and sedimentation step combined. For conventional precipitation, the rapid sand filters are important to ensure the infiltration basins functionality and must be included. It is clear that the membrane facilities are more expensive than conventional precipitation, so the question becomes, can the increased investment and operational costs be justified?

The benefits of conventional precipitation come from over 30 years of operational experience (Sydvatten AB 2016) and as seen in Figure S4, the consistent treatment result despite peaks in organic matter from the raw water source. Based on the results from direct precipitation, the membrane had issues with fouling and operational stability, and it seems unlikely that this treatment option will be able to handle strong variations in NOM, which are common after storms, let alone

**DISCUSSION**

Table 5 | Investment costs for the three alternatives in M $

| Treatment step                        | Conventional precipitation | Direct precipitation on UF | Conventional precipitation with UF |
|---------------------------------------|-----------------------------|----------------------------|-----------------------------------|
| Flocculation basins and lamella sedimentationa | 16                          | 0                          | 16                                |
| Rapid sand filtersa                   | 27                          | 0                          | 0                                 |
| Chemical facility and storagea        | 6                           | 6                          | 6                                 |
| Sludgea                               | 3                           | 3                          | 3                                 |
| Membrane                              | 0                           | 58b                        | 34c                               |
| Construction planning and developer costd | 10                          | 10                         | 10                                |
| Total                                 | 62                          | 77                         | 69                                |

aCost based on experiences from previous projects at Sydvatten AB.
bCalculated from the base cost 290 $/m² taken from retailer with 12.5% discount.
cTaken from an estimated cost from previous experiences from WTPs in Sweden and literature (Huelmer 2016).
dCost commonly set at 20% of the total cost of the facility. In this case, the average cost for each alternative was used is therefore the same.
long-term trends of brownification of Lake Bolmen. Also, based on the organic and inorganic load the membrane modules need to withstand, the average lifetime will likely be significantly less. Direct precipitation is most likely not suitable for high production facilities combined with NOM-rich source waters. The treatment method lacks operational stability which is paramount for drinking water producers. Conventional precipitation with UF showed a more stable performance than direct precipitation, and during short periods of time it was possible to increase the gross-flux to 90 L/m²·h. This could provide more flexibility and allow for higher water production when peaks of water consumption occur, for example during warm periods in summer.

Taking everything into consideration, direct precipitation is not a viable option for treating water from Lake Bolmen. Based on production capacity and NOM removal, both conventional precipitation and conventional precipitation with UF were sufficient. Both techniques are also expected to be better equipped to handle increases in NOM content, which is predicted to occur in Lake Bolmen in the future (Persson 2011; de Wit et al. 2016). Conventional precipitation was the cheapest option, however, UF membranes comes with other benefits. One benefit that a membrane facility provides is the extra microbial barrier, which would protect the groundwater supply in Vomb infiltration fields from outbreaks originating upstream. Another safety benefit comes from the operational security of being able to bypass artificial recharge with a sufficient microbial barrier during a crisis, if the infiltration field is compromised because of contaminates, e.g. chemical and oil spills, etc.

CONCLUSIONS

This study showed different ways of applying chemical flocculation and UF membranes in managed aquifer recharge. The main findings can be summarized as follows:

- Conventional precipitation combined with UF was deemed the most suitable choice for full-scale operations due to the increased flexibility and security provided by UF membranes.
- Sufficient water quality can be achieved with all three methods (UVA254 nm below 5 m⁻¹).
- Conventional precipitation had the lowest installation cost followed by conventional precipitation with UF and lastly direct precipitation.
- Treating water using direct precipitation and conventional precipitation with UF increased the production cost of the drinking water ($/m³) by 100 and 60%, respectively, compared with conventional precipitation.
- Direct precipitation resulted in minor coagulant savings (around 15 percent) but with higher consumption of cleaning chemicals.
- A net flux of 40 and 70 L/m²·h was achieved with direct precipitation and conventional precipitation with UF, respectively.
- The CEB intervals were decreased from 12 to 24 hours when using treated feed water in the membrane pilot.

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CONFLICT OF INTEREST

None.

SUPPLEMENTARY MATERIAL

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