Water Practice & Technology

© 2024 The Authors Water Practice & Technology Vol 19 No 3, 977 doi: 10.2166/wpt.2024.025

Exploring source water mixing strategies to reduce chemical consumption and environmental footprint in surface water treatment

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ABSTRACT

Common methods for treating surface waters involve chemical flocculation, for which a significant factor contributing to the total cost and climate impact is the consumption of chemicals, chiefly coagulants and pH-adjusting chemicals. The amount of chemicals required for treating surface waters and achieving suitable flocculation pH depends greatly on the alkalinity of the source water. This study investigates the viability of mixing two surface waters with different chemical properties with the aim of reducing the amount of chemicals used during chemical flocculation. Bench-scale experiments were carried out, and the results were compared with full-scale operations at a surface water treatment plant (WTP). The WTP uses ferric chloride as a coagulant, which effectively removes natural organic matter, but consumes large amounts of hydroxide to manage pH before and after flocculation. As an alternative process, this study tested the use of aluminum sulfate, polyaluminum chloride and ferric chloride at varying dosages in combination with different source water mixtures to achieve suitable flocculation pH. The results showed that pH-adjusting chemicals could be omitted by adding a small amount of high alkalinity surface water to the primary source water, thereby reducing costs and climate impact substantially.

Key words: chemical consumption, climate impact, coagulation, flocculation, jar tests

HIGHLIGHTS

- Mixing raw waters with different properties could substantially reduce costs and climate impact.
- Aluminum sulfate offered potential cost savings of up to 40% and a reduction in climate impact by up to 36% compared to conventional ferric chloride precipitation.
- Polyaluminum chloride with high basicity offered a broader coagulant dosage range, reducing the need for pH adjustment and potentially allowing for higher dosages.

INTRODUCTION

Common methods for treating surface waters that are rich in organic compounds are artificial groundwater recharge (Dillon *et al.* 2009; Sprenger *et al.* 2017; Stefan & Ansems 2018) and coagulation and flocculation (Crittenden *et al.* 2017), where coagulants based on Fe^{3+} and Al^{3+} are often used to remove natural organic matter (NOM) due to their efficiency and low cost (Bratby 2016). The optimal pH range varies for these coagulants and depends on the specific impurities that are being targeted for removal (Naceradska *et al.* 2019). Fe^{3+} coagulants tend to have a lower optimal pH and be more effective at removing NOM than Al^{3+} coagulants, while Al^{3+} coagulants have a wider optimum pH range at higher pH values (Gillberg *et al.* 2003; Jarvis 2004). However, Al^{3+} coagulants have been shown to have different pH optimums with regard to coagulant residuals and NOM removal (Pivokonský *et al.* 2022). This could lead to concerns of residual aluminum when using Al^{3+} coagulants. However, this is generally not an issue around pH 6–6.5, depending on temperature, organic matter content, coagulant, basicity and coagulant dosage (Gillberg *et al.* 2003; Gao *et al.* 2006; Matilainen *et al.* 2010; Kimura *et al.* 2013; Pivokonský *et al.* 2022).

The Southern Sweden Water Supply (Sydvatten AB) is a municipality-owned water utility that produces potable water for over 950,000 inhabitants in southern Sweden. This is mainly done through two waterworks (WW), Ringsjö WW and Vomb WW. Over 90% of Sydvatten AB's climate impact comes from the production and

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transport of chemicals used for water treatment, which corresponds to about 70 kg CO_2 equivalent per cubic meter of water (see Sydvatten AB (2021a) for detailed descriptions of how climate impact is calculated). The largest contributor (about 50%) to the total chemical consumption is the coagulant, $FeCl_3$, followed by $Ca(OH)_2$, CO_2 and NaOH. NaOH is used for adjusting pH prior to coagulation, while the combination of $Ca(OH)_2$ and CO_2 is used to adjust the pH and increase alkalinity after flocculation (Sydvatten AB 2021b).

The chemicals used for water treatment also come at a significant price (Lidén & Persson 2016) and energy price increases, and global supply chain disruptions have caused prices to increase even more in recent years (LaBelle & Santacreu 2022). NaOH contributes to about 50% of the total chemical costs at Ringsjö WW in 2021, and the cost of NaOH increased by nearly 60% in 2022. Supply chain disruptions are a growing concern for water utilities that rely on these chemicals for water production. These disruptions can arise for many different reasons and can affect deliveries of chemicals, such as NaOH (EPA 2022). Thus, the importance of minimizing the WW reliance on these chemicals cannot be understated from cost, water supply security and climate impact perspectives.

Southern Sweden is a fast-growing region, and more municipalities are joining Sydvatten AB (Länsstyrelsen i Skåne Län *et al.* 2016). As a result, Sydvatten AB is planning to build a new source water pipeline transporting water to Vomb WW, an artificial groundwater recharge plant. Based on previous studies (Hägg 2020), the new raw water source originating from Lake Bolmen, requires pre-treatment through chemical flocculation prior to groundwater recharge. The water from Lake Bolmen is soft and has low alkalinity. Treatment of the water requires substantial pH adjustments before and after flocculation, especially when using $FeCl_3$ as a coagulant. In a series of jar tests, this study investigates the possibility of reducing the need for pH-adjusting chemicals by mixing water from Lake Bolmen with water from Lake Vomb, hard water with high alkalinity. The investigation includes three different coagulants (aluminum sulfate (ALG), polyaluminum chloride (PAX XL60) and ferric chloride (PIX 311)), and the results were compared to full-scale operations at Ringsjö WW based on cost and climate impact.

MATERIALS AND METHODS

Source water and water works

This study was conducted at Ringsjö WW, a surface water treatment plant, and Vomb WW, an artificial groundwater recharge plant, both located in southern Sweden (Figure 1). The primary treatment process at Ringsjö WW includes coagulation and flocculation with $FeCl_3$. NaOH is added prior to coagulation, due to the low alkalinity of the source water, to achieve a flocculation pH of about 5 (Table 1). The pH and alkalinity of the water is increased after flocculation by using $Ca(OH)_2$ and CO_2 (Figure A1). The source water is taken from Lake Bolmen, which is connected to the WW by an 80-km-long tunnel and a pipeline of about 30 km. Lake Bolmen is oligotrophic, and the catchment area around the lake is dominated by forest, bogland and iron-rich soil, which causes the lake water to have high UV absorbance$_{254nm}$ (35–45 m^{-1}), color (80–90 mg Pt/L) and specific UV absorbance (SUVA, around 4 L m^{-1} mg^{-1}) (Eikebrokk *et al.* 2018; SMHI 2018).

Vomb WW treats water from Lake Vomb using disc filters (40 μm) before pumping the water to infiltration basins excavated in the recharge field consisting of glacifluvial deposits. Treatment after well extraction includes aeration, softening and rapid sand filtration (Figure A2). Lake Vomb is hypertrophic due to runoff from the agricultural lands in the catchment area, which causes seasonal algae blooms (Skåne County 2012; Li 2020). The organic composition of source water from Lake Vomb has slightly higher dissolved organic matter originating from microbial sources as opposed to terrestrial sources (Hägg *et al.* 2021b). As a result, Lake Vomb has lower UV absorbance$_{254nm}$ (about 20 m^{-1}) and SUVA (around 2 L m^{-1} mg^{-1}) compared to Lake Bolmen.

The lake water extraction at Vomb WW is increasing due to the increased water demand. For this reason, a new source water pipeline, transporting water from Lake Bolmen, will be connected to Vomb WW within 10 years (Figure 1). The high NOM content and NOM composition in source water from Lake Bolmen makes the water suitable for coagulation and flocculation but not for biofiltration (Hägg *et al.* 2021a); consequently, a pre-treatment facility will also be built at Vomb WW. Once the source water pipeline is built, Vomb WW will pre-treat a mixture of water from Lake Bolmen and Lake Vomb through coagulation and flocculation prior to infiltration. It is expected that a mixture of the two waters will eliminate the need for the softening reactors after infiltration, due to the soft water from Lake Bolmen (Table 1). The combination of chemical flocculation

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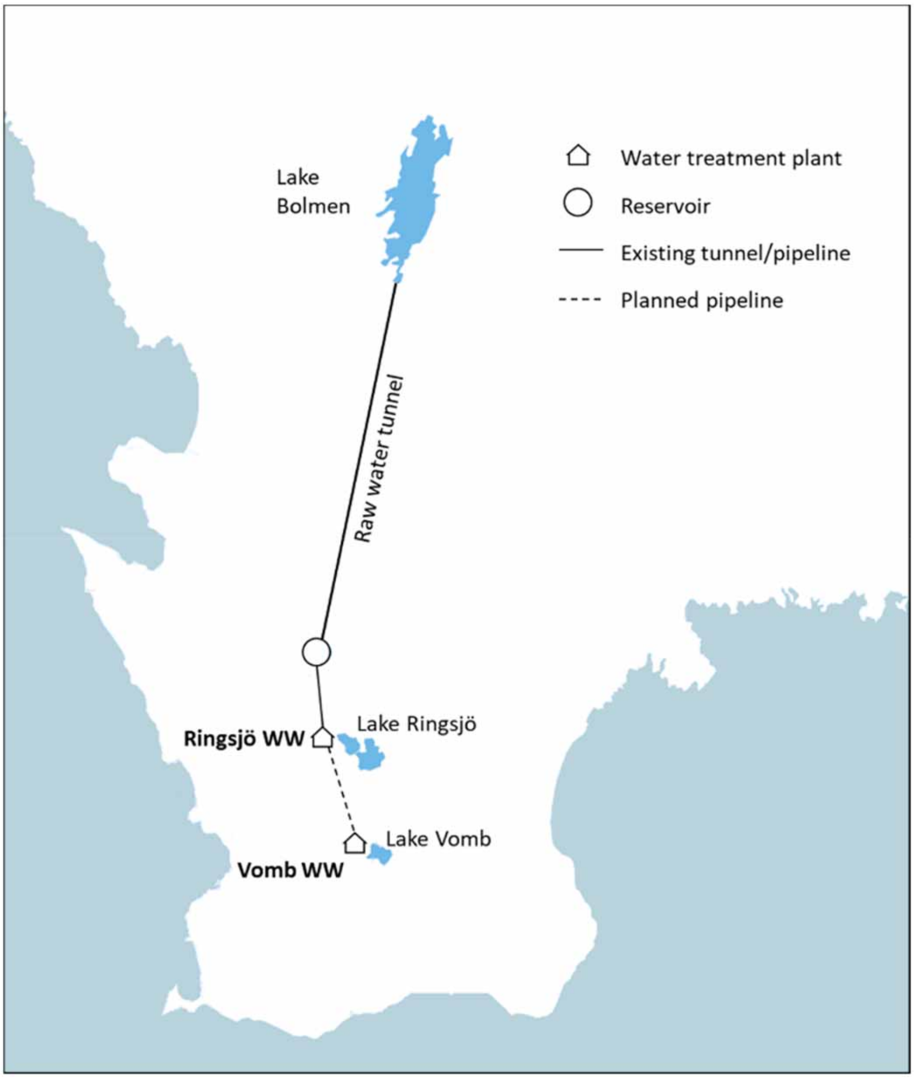

Figure 1 | Overview of Southern Sweden Water Supply's source, WWs and planned raw water pipeline. The figure shows the three raw water sources – Lake Bolmen, Lake Ringsjö and Lake Vomb – and the two main WW – Ringsjö and Vomb (adapted from Sydvatten (2018)).

Table 1 | Average water quality in Lake Bolmen and at Ringsjö WW intake after the Bolmen tunnel, Lake Vomb, and median drinking water quality after treatment at Ringsjö WW and Vomb WW (Sydvatten AB 2021b)

Sampling point	Color (mg Pt/L)	CODMn (mg/L)	TOC (mg/L)	pH	Alkalinity (mg HCO_3^-/L)	Hardness (°dH)
Lake Bolmen	84	N/A	10.1	6.9	7.32	N/A
Intake Ringsjö WW after the tunnel	66.3	11	9.5	6.9	12.6	1.2
Treated water Ringsjö WW	<5	1.4	N/A	8.1	45	3.5
Lake Vomb	23	6.0	7.6	8.3	161	10
Treated water Vomb WW	<5	1.7	N/A	8.2	140	6.5

and artificial recharge reduces the need for extensive NOM removal through the flocculation process, enabling the use of a wider range of coagulants that were not previously feasible for water treatment.

Chemical consumption and climate impact

Sydvatten AB's total annual climate impact is about 5,800 tons CO_2-eq, whereby over 90% comes from the production of chemicals used in the treatment process (Sydvatten AB 2021a). At Ringsjö WW, NaOH and $Ca(OH)_2$

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are used for pH adjustment before and after flocculation, while at Vomb WW, NaOH is used in the softening reactors. A significant part of the cost and climate impact comes from the use of these chemicals (Table 2).

Table 2 | The total chemical usage, cost and climate impact per chemical at Ringsjö WW (Sydvatten AB 2021a, 2021b)

WW	Chemical	Chemical consumption 2021 (ton)	Cost 2021 ($/ton)	Cost 2022 ($/ton)	Climate impact (kg CO_2-eq/ton)	Climate impact 2021 (ton CO_2-eq)	Application
Ringsjö WW	$FeCl_3$	3,597	154	188	0.400	1,439	Coagulant
	$Ca(OH)_2$	1,652	135	175	0.917	1,515	pH adjustment
	CO_2	901	95	99	0.625	563	Alkalinity adjustment
	NaOH (50%)	904	207	330	0.446	403	pH adjustment
Vomb WW	NaOH (50%)	2,921	207	330	0.446	1,303	Softening reactor
Jar tests	ALG	N/A	N/A	205	0.320	N/A	Coagulant
	PAX XL60[a]	N/A	N/A	227	0.447	N/A	Coagulant

Notes: The climate impact for each chemical depends on the supplier; therefore, national data from the Swedish Water and Wastewater Association (SWWA) is presented, rather than data specific to Ringsjö WW (SWWA 2022). Chemicals used at Ringsjö WW and Vomb WW that were not relevant for this study were not included, e.g. sodium hypochlorite.

[a]Cost and climate impact for PAX XL60 was taken from the manufacturer Kemira.

Jar tests

Prior to the jar tests, samples of raw water with added coagulant were pH tested (using a WTW pH-197, pH meter) to ensure the correct targeted pH during flocculation. The required NaOH or HCl amount was measured and used for chemical consumption calculations. Jar tests were conducted using a program-controlled flocculator (Flocculator 2000, Kemira; Helsingborg, Sweden). The setup consisted of six 1 L glass beakers and the jar test procedure was as follows:

1. Each beaker was filled with 1 L raw water.
2. NaOH or HCl solutions were added to the beakers prior to flocculation.
3. The flocculator program was initiated: 30 s rapid mixing (400 rpm), 20 min slow mixing (50 rpm) and 30 min sedimentation (0 rpm).
4. The coagulant was added when 5 s remained of the rapid mixing and the pH was measured during slow mixing.
5. Samples were taken with a 30 mL syringe 5 cm below the surface, when sedimentation was finished.

Coagulants and additives

ALG ($Al_2(SO_4)_3$) in solid state, PAX XL60 (PACl) in liquid state and PIX 311 solution ($FeCl_3$) were used as coagulants in this study. The ALG was a 9.1% by weight Al^{3+} dry product and was prepared by dissolving granules in distilled water to a 200 g/L solution. The PAX XL60 used was a 7.5% by weight Al^{3+} solution with a basicity of $40 \pm 5\%$. PIX 311 was a 40% by weight $FeCl_3$ and a 13.8% by weight Fe^{3+} solution. All three products were approved for drinking water treatment and produced by Kemira (Helsinki, Finland). A 0.36% NaOH and a 3.7% HCl solution were used to control the resulting pH during the jar tests.

Methodology

The future pretreatment plant at Vomb WW will treat a mixture of the two source waters, with approximately 10–30% water from Lake Vomb, to achieve the desired chemical properties (i.e., alkalinity) and ensure the distribution of non-corrosive (iron and copper) drinking water. In this study, the three coagulants (ALG, PAX XL60 and PIX 311) were used with different dosages and source water mixtures. The source water mixtures were 10, 20 and 30% Vomb water, and the results were compared to full-scale flocculation at Ringsjö WW, where flocculation pH is controlled by NaOH additions. A cost and climate impact estimation was conducted based on the chemical usage for each treatment option. A series of titration trials was also conducted with the

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different water mixtures to investigate the required amount of NaOH to reach a pH of 7 after flocculation. A pH of approximately 7 was assumed to be suitable for the infiltration ponds downstream of the chemical precipitation. The required amount of $Ca(OH)_2$, including 7% loss due to $CaCO_3$ impurities in the slaked lime product, was calculated based on the consumption of hydroxide from NaOH adjustment.

The selected residual UV_{254nm} absorbance and VIS_{436nm} absorbance targets were 10 and 0.7 m^{-1}, respectively, based on previously conducted jar tests using $FeCl_3$ and water from Lake Bolmen (Figure A3). High coagulant dosages and the resulting low pH could cause an increase in residual aluminum (Crittenden *et al.* 2017). Therefore, a minimum targeted flocculation pH of 6 was selected to mitigate the potential risk of residual aluminum (Yang *et al.* 2010). A common flocculation pH range for Fe-based coagulants is 4.5–6 (Matilainen *et al.* 2010), and, based on experience from full-scale operations, a minimum flocculation pH was set to 4.5 to minimize the risks of residual iron. Once these requirements were fulfilled, the resulting climate impact (measured as kg CO_2-eq/m^3 water) and cost (USD) of each option were calculated based on the chemical consumption. The costs were taken from the Swedish market, and the exchange rate used was 1 dollar (USD) to 11 Swedish kronor (SEK).

Waters sample analysis

Water samples before and after the jar tests were tested for UV–VIS absorbance using a spectrophotometer (DR 5000, Hach Lange, Loveland, CO, USA). The absorption was measured at $\lambda = 254$ and 436 nm using a 5-cm cuvette. The raw water temperature, pH and the UV–VIS absorbance varied depending on the raw water mixture used during the jar tests (Table 3).

Table 3 | Raw water quality parameters during jar tests

Vomb:Bolmen (%)	UV abs ($\lambda = 254$ nm, m^{-1})	VIS abs ($\lambda = 436$ nm, m^{-1})	pH	Temperature range (°C)
0:100	34.2 $\pm$ 0.2	2.3 $\pm$ 0.1	6.8	13–16
10:90	34.5 $\pm$ 0.2	2.3 $\pm$ 0.1	6.9	18–20
20:80	33.1 $\pm$ 0.6	2.3 $\pm$ 0.2	7.2	19–20
30:70	32.2 $\pm$ 0.9	2.4 $\pm$ 0.1	7.4	19–21

Note: The average UV–VIS absorbance, pH and temperature ranges of the source water mixtures area shown.

RESULTS AND DISCUSSION

Coagulant dosage effects on pH and residual NOM

Figures 2 and 3 show the results of the flocculation trials using ALG and PAX XL60 with different source water mixtures. For both coagulants, higher pH was observed for water mixtures that had higher ratios of Vomb water, attributable to the increase in alkalinity and pH. An adequate NOM removal using ALG was possible for coagulant dosages ranging from 148 to 370 mmol Al^{3+}/m^3 (Figure 2). However, ALG lowered pH significantly, and with a 10:90 water mixture, it was not possible to achieve a flocculation pH of 6 or above. With 20:80 and 30:70 water mixtures, the coagulant dosages that achieved the targeted pH were 148–185 and 185–259 mmol/m^3, respectively. The coagulant dosage range for ALG in this experiment was, therefore, 148–259 mmol Al^{3+}/m^3 (4–7 mg Al^{3+}/L), and the possible flocculation pH was 6.0–6.4. This is illustrated as the flocculation window in Figure 2.

PAX XL60 did not lower the pH to the same extent as ALG (Figure 3(b)), which is consistent with the findings from previous studies (Matilainen *et al.* 2010; Nowacka *et al.* 2014) and the information provided by the manufacturer (Kemira). Consequently, slightly higher dosages of PAX XL60 were required to reach the targeted residual UV_{254nm} absorbance and minimum pH. For this reason, additional trials were conducted with water only from Lake Bolmen. However, it was possible to achieve the targets only with a coagulant dosage of 148 mmol/m^3, and the residual UV_{254nm} absorbance increased significantly when the coagulant dosage was above 200 mmol Al^{3+}/m^3. A similar UV absorbance increase occurred with the 10:90 water mixture at around the same pH (approximately 5.5) but at a higher coagulant dosage (above 300 mmol Al^{3+}/m^3). This could be the result of restabilization caused by charge reversal or a bridging mechanism due to excessive surface coverage

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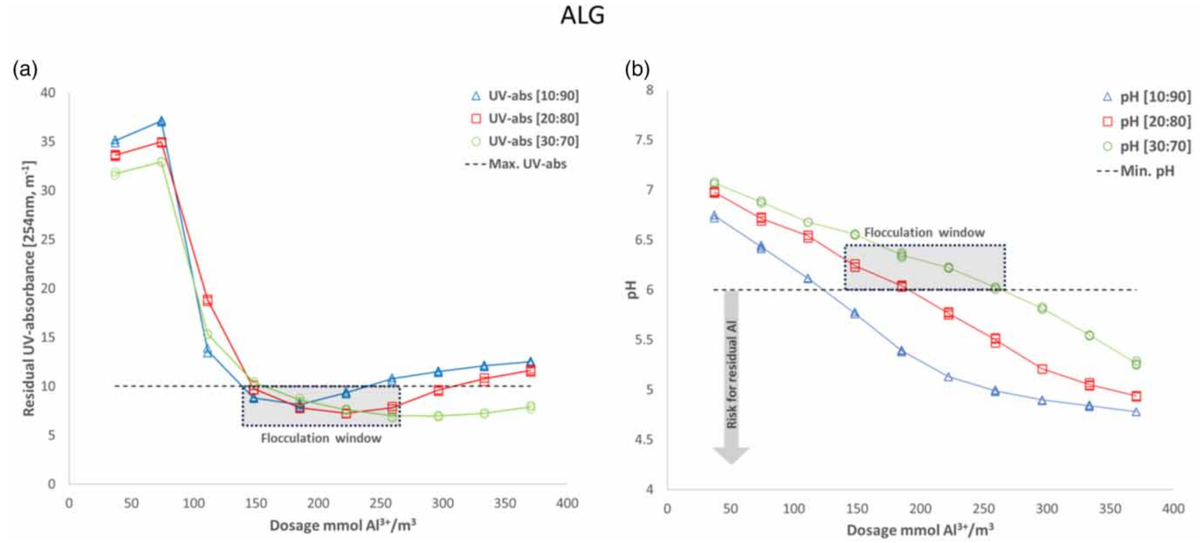

Figure 2 | Flocculation trials using $Al_2(SO_4)_3$ (ALG) without pH adjustment: (a) coagulant dosage effect on residual UV_{254nm} absorbance and (b) flocculation pH. The source water mixtures used were 10, 20 and 30% Vomb water, shown as [10:90], [20:80] and [30:70]. The flocculation window shows the possible range of coagulant dosage and flocculation pH.

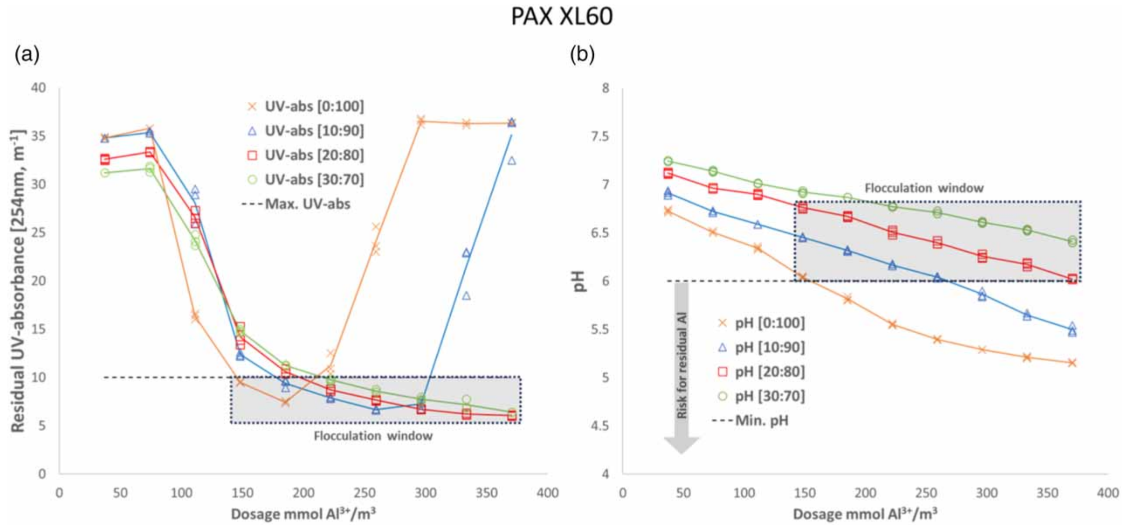

Figure 3 | Flocculation trials using pre-hydrolyzed PAX XL60 without pH adjustment: (a) coagulant dosage effect on residual UV_{254nm} absorbance and (b) flocculation pH. The source water mixtures used were 0, 10, 20 and 30% Vomb water, shown as [0:100], [10:90], [20:80] and [30:70]. The flocculation window shows the possible range of coagulant dosage and flocculation pH.

of $Al(OH)_4^-$ (Bratby 2016; Kong *et al.* 2021). With water mixtures of 10:90, 20:80 and 30:70, the targets were achieved at coagulant dosages of 185–259, 222–370 and 222–370 mmol/m^3, respectively. Therefore, a viable coagulant dosage range for PAX XL60 was 148–370 mmol Al^{3+}/m^3 (4–10 mg Al^{3+}/L) with a pH of 6–6.8.

PIX 311 lowered pH more than the Al-based coagulants and, depending on the water mixture, a possible pH range was 4.5–6 (Figure 4), which is consistent with the findings of Matilainen *et al.* (2010). The flocculation window for each water mixture widened considerably as alkalinity increased, because of higher Vomb water mixtures. Due to the narrow pH window of the coagulant, the residual UV absorbance rapidly increases outside of this range. Any result with a UV absorbance above 35 m^{-1} indicates that there was no floc-formation and PIX 311 only added to the absorbance of the raw water. All three water mixtures seemed to achieve the targeted UV absorbance when pH was increased to about 4.5. Furthermore, with higher ratios of Vomb water, the maximum flocculation pH was raised (approximately a pH of 6 with a 30% Vomb water mixture). The viable coagulant

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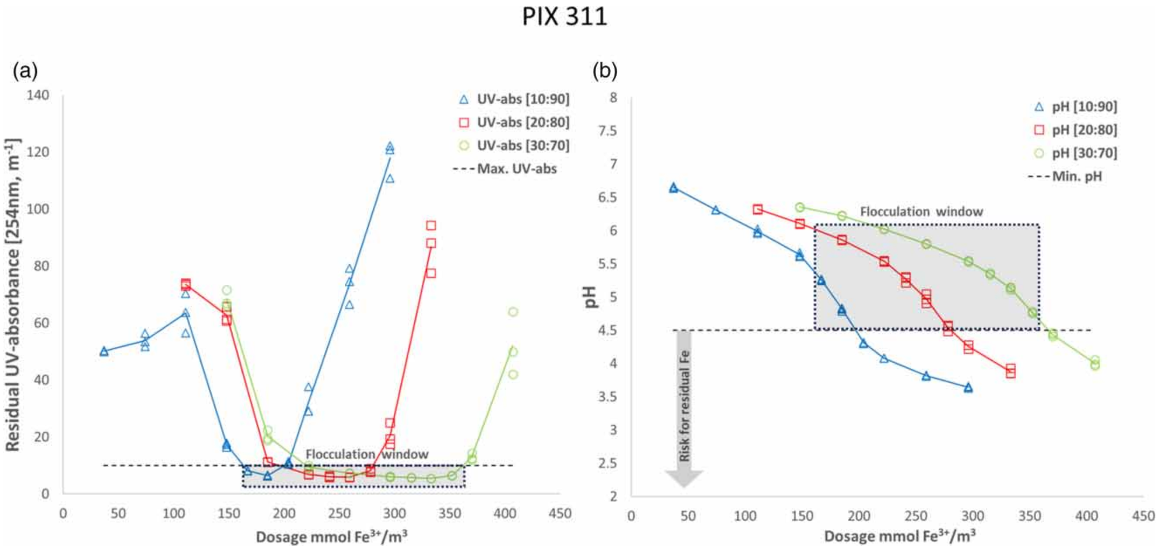

Figure 4 | Flocculation trials using PIX 311 without pH adjustment: (a) coagulant dosage effect on residual UV_{254nm} absorbance and (b) flocculation pH. The source water mixtures used were 10, 20 and 30% Vomb water, shown as [10:90], [20:80] and [30:70], respectively. The flocculation window shows the possible range of coagulant dosage and flocculation pH.

dosages were 167–352 mmol Fe^{3+}/m^3 (10–20 mg Fe^{3+}/L), and the pH range was 4.5–6 for the tested water mixtures.

Chemical consumption, costs and climate impact*

The chemical consumption, costs and climate impact were calculated to optimize for operational reliability and for low chemical consumption separately (Table 4). The configuration with the lowest cost and chemical consumption for each coagulant is presented in parentheses. For these configurations, a coagulant dosage at the lower end of the flocculation window was chosen: 148 mmol/L for ALG, 185 mmol/L for PAX and 167 mmol/L for PIX 311. The results show that ALG had the lowest cost and climate impact compared to other options, including the reference (full-scale operations at Ringsjö WW). PAX XL60 and PIX-311 had similar costs, but PIX-311 had a significantly higher climate impact due to the increase of $Ca(OH)_2$ post-flocculation.

Table 4 | Summary of the chemical consumption from the jar tests and the reference, Ringsjö WW (annual data 2021)

Chemical	ALG	PAX XL60	PIX-311	Ringsjö WW
Coagulant (mmol M^{3+}/m^{3+})	185 (148)	222 (185)	241 (167)	194
Coagulant (mg M^{3+}/L)	5 (4)	6 (5)	13.4 (9.3)	10.8[a]
Flocculation pH	6 (6.2)	6.2 (6.3)	5.3 (5.3)	5.0
NaOH (50%) (tons/year)	0	0	0	904
$Ca(OH)_2$ (100%) (tons/year)	740 (570)	440 (350)	1,210 (850)	550
Vomb:Bolmen (%)	20:80 (20:80)	10:90 (10:90)	20:80 (10:90)	0:100
Residual UV abs (254 nm/m)	7.8 (9.8)	7.9 (9.4)	6.1 (8.2)	5[b]
Total cost 2022 (USD)	0.65M (0.52M)	0.92M (0.77M)	1.06M (0.74M)	1.07M
Climate impact (ton CO_2-eq)	1,500 (1,180)	2,070 (1,710)	2,920 (2,040)	2,350

Notes: The annual chemical consumption was calculated based on Ringsjö WW annual water production 2021 (46.6 Mm^3) (Sydvatten 2021b). The cost and climate impact were obtained from the manufacturer (Kemira) and SWWA (2022). The results shown are optimized for operational reliability, while the results optimized for cost and climate impact are shown in parentheses.
[a]Average $FeCl_3$ dosage from full-scale treatment.
[b] After rapid sand filtration.

To optimize for operational reliability, configurations were chosen for each coagulant to allow for a wider flocculation window, while keeping chemical consumption at a reasonable level. The coagulant dosages chosen for ALG, PAX XL60 and PIX 311 were 185, 222 and 241 mmol/L, respectively. In this configuration, both ALG and

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PAX XL60 had lower cost and climate impact than PIX 311 and the reference. PIX-311 had similar cost and higher climate impact than the reference, suggesting that source water mixing might not be viable when using this coagulant. ALG was cheaper than PAX XL60, despite the fact that ALG required more calcium hydroxide to increase pH up to 7, due to the increased buffer capacity of the water mixture. Moreover, compared to PAX XL60, ALG had a lower cost per ton and a higher aluminum content, 9.1% versus 7.5%. A PACl product with higher aluminum content would likely reduce the coagulant dosage and be more cost-effective.

Overall, compared to conventional precipitation with PIX 311 and pH adjustments prior to coagulation, choosing an aluminum-based coagulant in combination with harnessing source water mixtures could potentially reduce costs by as much as approximately 40% and lessen the climate impact by up to approximately 36%. It should be noted, however, that PIX 311 removed NOM more effectively than the aluminum-based coagulants.

Operational reliability and water quality

It was possible to achieve the targeted UV_{254nm} absorbance and VIS_{436nm} absorbance for all coagulants. The VIS_{436nm} absorbance target was more readily reached and therefore not included, see Figure A4. PIX 311 was the most effective at removing NOM and was cost-efficient in combination with low-alkalinity source waters (10% Vomb water). However, the flocculation window was very narrow, which could increase operational risks due to the natural variation of source water qualities and the lack of precision in pH control through source water mixing. Configurations with PIX 311 and 20% Vomb water mixtures did not have this issue but instead came at very high costs and climate impact. PAX XL 60 had a broader coagulant dosage range, and there were indications that higher dosages beyond 370 mmol Al^{3+}/m^3 (10 mg Al^{3+}/L) were viable with the tested source water mixtures. PAX XL60 lowered pH less than ALG and PIX 311, which enabled flocculation at higher pH and thereby required less pH buffering through NaOH additions or increased amounts of Vomb water. The reason for this is that pre-hydrolyzed PACl with high basicity, such as PAX XL60, lowers alkalinity to a lesser degree than other coagulants (Crittenden *et al.* 2012). However, the residual UV_{254nm} absorbance might increase when the coagulant dosage is high and if pH gets below roughly 5.5. Increased residual UV_{254nm} absorbance also occurred when using PIX 311 at a pH around 4.5. This could be amended by increasing the alkalinity of the raw water mixture or by NaOH additions to increase pH. In full-scale operations, the flocculation pH would be managed toward higher pH, and this would not be a concern. Lower dosages of ALG were needed to reach the targeted UV absorbance compared to PAX XL60, which lowered the cost and climate impact of this option. ALG lowered pH more and narrowed the flocculation window but not to the same extent as PIX 311. The new treatment facility at Vomb WW will combine chemical flocculation with artificial groundwater recharge, which will reduce the NOM removal requirements after flocculation. Therefore, an aluminum-based coagulant could be used, even though it is not as effective as PIX 311 at removing NOM.

It is preferable that drinking water production be based on a process that has minimal dependence on chemicals from foreign countries. In addition, various solutions should be prepared in the process design to handle unexpected shortages. In this article, it has been shown that aluminum-based coagulants, both in solid and liquid state, with sulfate or chloride as counter ions, and whether polymerized or not, can be used to reach the required quality of the water. Furthermore, by adjusting the mixture of raw water from Bolmen and Vomb, the need for pH-adjusting chemicals can be minimized. In cases of deteriorating source water quality (e.g. due to increased NOM content or turbidity), whether temporary or long-term, a higher coagulant dosage would be used and the need for pH-adjusting chemicals could be amended by using a suitable mixture of the two raw waters. The flexibility in this process design gives the required tools to handle future variations in the global chemical market and lake water qualities in a very effective way and allows for substantial reduction of the carbon footprint of Sydvatten.

CONCLUSIONS

This study showed that it was possible to substantially reduce the costs and climate impact associated with chemical consumption for water treatment by mixing raw waters with different chemical properties. Increasing raw water alkalinity removed the need for pH-adjusting chemicals prior to flocculation, but it also increased the need for calcium hydroxide post-flocculation due to the increased buffer capacity. Adding 10–30% lake water with high alkalinity could reduce costs by approximately 40% and climate impact by around 36%, compared to conventional precipitation with PIX 311. However, this approach does result in lower NOM removal

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efficiencies. The iron-based coagulant was more effective at removing NOM than aluminum-based ones, but they had a higher cost and climate impact.

ACKNOWLEDGEMENT

The authors would like to acknowledge Anders Pålsson at Kemira for their support and fruitful discussions throughout the project.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 15 November 2023; accepted in revised form 28 January 2024. Available online 9 February 2024

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