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Ultrafiltration Pilot Plant at Görväln WTP

Purifying Carbon Filtrate to Evaluating Operation for the Future Treatment Plant

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Abstract

This project report describes an ultrafiltration pilot operation with direct coagulation. The UF step will be a part of the new water treatment process at the Görväln plant. Norrvatten is constructing the plant in phases to improve the capacity and microbial barrier of the treatment process. The NFVP, which manages the development and construction, requires a basis for the design and performance of UF with direct coagulation. Knowledge of the operation is also needed to understand what obstacles could occur during daily operations. *Inge DuPont* was chosen as the supplier of the membrane pilot plant for this study. They provided two parallel membrane lines with two vertical UF modules of the model *dizzler XL 0,9 MB 80 WT*.

The purpose of the project was to gain knowledge of the UF pilot plant, specifically, how the process is affected by various parameter settings and seasonal changes while using GAC filtrate as feed water. The goals of the project were:

- optimisation of the coagulant dosage at a given pH adjustment,
- attain experience from the pilot's operation at different fluxes,
- understand how variations in temperatures affect the membrane performance,
- find a sufficient coagulant retention time,
- Determine optimal chemical enhanced backwash sequence based on backwash interval and dosage of chemicals,
- evaluate the removal efficiency of natural organic matter over UF pilot.

The pilot operation confirmed acceptable operation of the UF pilot with direct coagulation using filtrate from the activated carbon filters.

The optimal coagulant dosage was found to be approximately 1,5 mg Al/L with a pH adjustment to 6,9 for stable permeability. However, a higher dosage was needed during seasonal variations. An immediate increase in permeability could be accomplished by temporarily increasing the coagulant dosage to 2,0 mg Al/L. The pilot was tested with higher flux rates of 85 and 100 lmh. The coagulant dosage needed to be increased to achieve stable operation at higher flux, and 2,0 mg Al/L was enough for stable operation for 85 lmh, but not 100 lmh.

The contact time between coagulant addition and UF filtration was adjusted to 42 s for ideal coagulation and floc formation on the membrane. This maintained the aluminium residue in the permeate below the internal limit of 0,03 mg Al/L at the Görväln plant, when the coagulant dose was set to 1,5 mg Al/L.

A normal backwash should also be implemented at the start of a chemically enhanced backwash, ensuring no suspended solids exceed 40 mg/L.

Operating the UF membrane pilot without coagulant addition resulted in a decreasing permeability profile. Even with the addition of chlorine in the CEB could the permeability not be recovered to similar stable operation conditions achieved with coagulant dosing.

When coagulant is dosed, the reduction of organic matter was, on average, between 10 – 20 % measured by UV_{254}. Operating the membranes without coagulant decreases the permeability and increases the TMP and does not appear to achieve a stable operation, and results in minimal organic reduction approximately a 1 – 2 % reduction in UV_{254}.

List of abbreviations

BW – Backwash

CEB – Chemical Enhanced Backwash

DOC – Dissolved organic carbon [mg/L]

feed – Filtrate from granular activated carbon dosed with coagulant and sodium hydroxide before the membrane filtration

Flux – Hydraulic loading rate based on flow of water through a membrane surface area [lmh/bar]

H_2SO_4 – Sulphuric acid

KF – Granular activated carbon filter

L1 – Membrane line 1

L2 – Membrane line 2

mPermeability – Mean permeability of a CEB cycle

NaOH – Sodium hydroxide

NOM – Natural organic matter

NaOCl – Hypochlorite

PAX-XL60 – Poly aluminium chloride ($Al_2Cl\ (OH)_5$), used as a coagulant

perm – Filtrate from the UF pilot plant

PDT – Pressure Decay Test

RT – Coagulant retention time (flocculation time)

source – Granular activated carbon filtrate used as feed water in the pilot before pH adjustment

TMP – The feed pressure minus the permeate pressure [mbar]

TOC – Total organic carbon [mg/L]

UF - Ultrafiltration

UV_{254} – Absorbance at 254 nm [Abs/m]

WTP – Water treatment plant

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1. Introduction

This project involves an ultrafiltration (UF) pilot operation with direct coagulation. The UF step will be a part of the water treatment process at the Görväln plant. Norrvatten is gradually constructing a new water treatment plant (WTP) to improve the capacity and microbial barrier of the treatment process. The UF step will be placed after the granulated activated carbon filter (GAC filter). The results of the microbial barrier will be presented in a separate report (Holmer & Danielsson, 2023).

Several collaborators were a part of the project. The NFVP, which manages the development of Norrvatten new treatment plant, requires a basis for the dimension and performance of UF with direct coagulation when using carbon filtrate as feed water. The role of Process and Production at Norrvatten requests knowledge of the operation and seeks an understanding of what obstacles could occur during daily operations. Furthermore, to verify if placement after the GAC filter is suitable in contrast with the previous pilot study when sand filtrate was used as feed water (Köhler & Sekizovic, 2021). *inge Dupont* supplied the pilot plant. *inge* was chosen as the supplier as they met the need to provide two parallel membrane lines with two vertical UF modules. Furthermore, they delivered a different kind of hollow fibre membranes compared to previous pilot studies at Norrvatten, which gave a new understanding of performance using other UF modules. Inge also provided recommendations on how the pilot plant should be operated and interpreted trends when adjusting different parameters.

1.1. Purpose and Goals

The project's purpose is to gather knowledge for the standard operation of the UF pilot plant, specifically, how the process is affected by various parameter settings and seasonal changes while using GAC filtrate as feed water.

The goals of the project are:

- Optimisation of the coagulant dosage at a given pH adjustment.
- Find a sufficient coagulant retention time (RT).
- Attain experience from the pilot's operation at different fluxes.
- Understand how variations in temperatures affect the membrane performance.
- Construct a suitable chemical enhanced backwash (CEB) sequence based on the operation, involving CEB interval and dosage of chemicals.
- Evaluate the removal efficiency of natural organic matter (NOM) for the UF pilot.

1.2. Delimitations

The project was conducted for one year. The feed water used in the pilot plant was filtrate taken from carbon filters 2 (KF2) and 4 (KF4). Both membrane lines used filtrate from KF4 at the beginning of the project, which had a median RT of 5,1 min. KF4 was filled with saturated GAC covered with a biofilm called BAC filter from the manufacturing *Norit 830*. Then, feed water was switched to filtrate from KF2, with a median RT of 19,5 min. KF2 was previously filled with new activated carbon from the manufacturer *Brennsorb 830*. The use of coagulant in the project was limited to poly aluminium chloride and the brand PAX-XL60.

2. Implementation

The implementation of the project is described in chapters 2.1-2.4. It includes the pilot plant schematic design, operational setting, an experimental plan for the adjusted parameters, and data collection.

2.1. Pilot Design

The physical layout of the pilot plant consists of two containers provided by the membrane manufacturer *inge GmbH*, a part of the *DuPont* corporation. The first container includes two operational lines with membrane modules of the model *dizzler XL 0,9 MB 80 WT*. The membrane surface area is 80 m^2, and the pore size is 20 nm. The plant also contains pH adjustment, coagulant dosing, and dosing of cleaning chemicals. The second container is a neutralisation plant for adjusting the pH and neutralising chlorine substances of the effluent CEB before releasing it into the recipient.

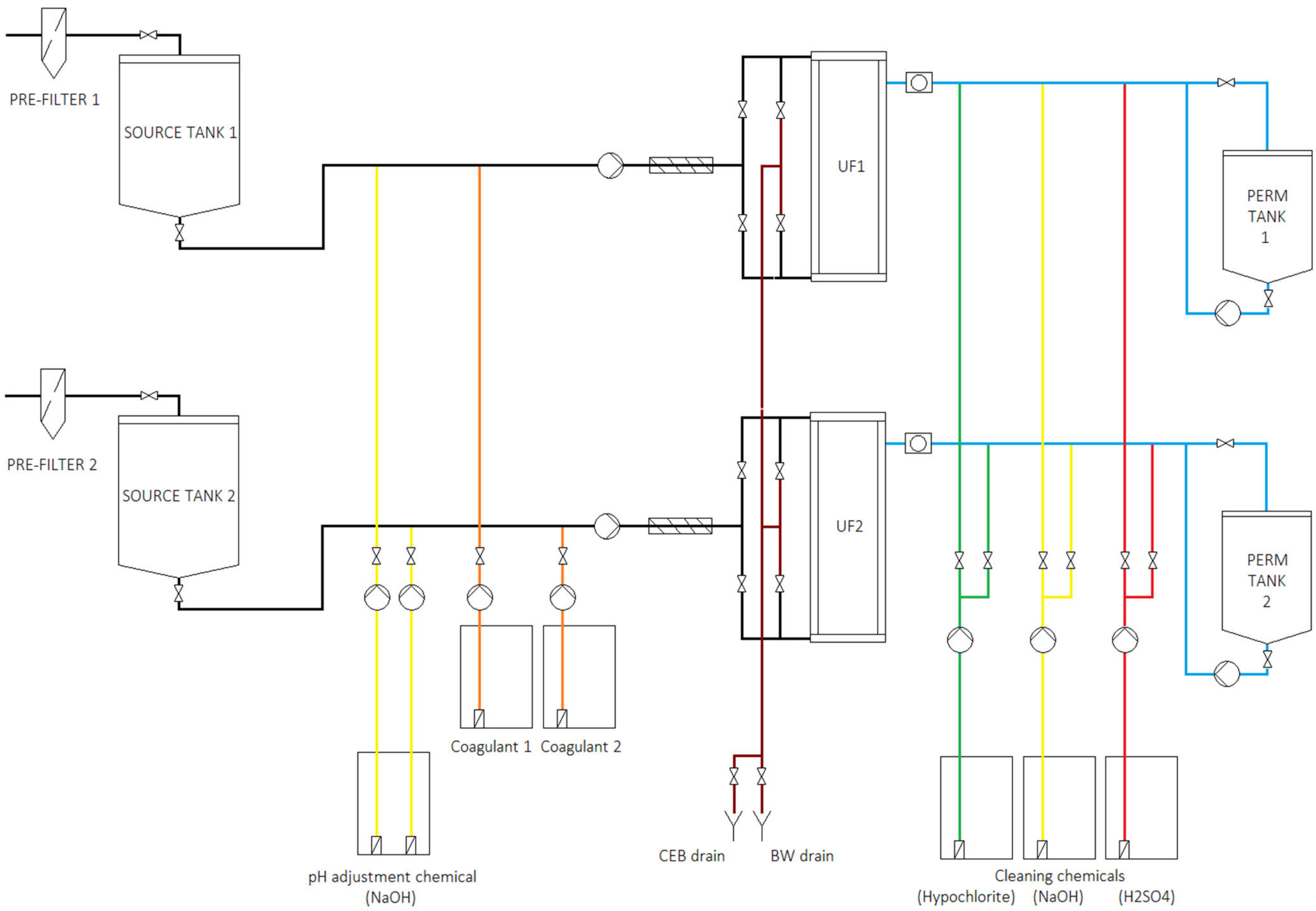

Figure 1. Schematic design of the pilot plant.

Figure 1 presents a schematic design of how the water is treated in the pilot plant. The water is filtered in two separate lines, membrane lines 1 (L1) and 2 (L2). The feed water (*source*) is pumped from carbon filters inside the WTP. Then, it passes through a pre-filter with a 200 µm mesh to remove larger particles. The water is filled up in a feed tank inside the pilot plant. The water (*feed*) is then pH adjusted with sodium hydroxide (NaOH) and dosed with (PAX-XL60) as a coagulant, which is then mixed in an inline static mixer.

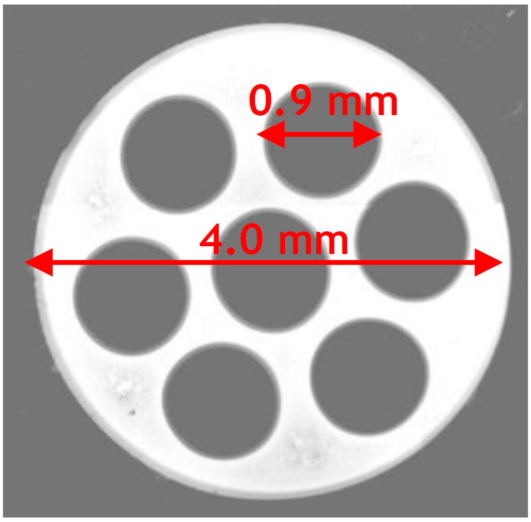

Figure 2. Membrane module of the model dizzler XL 0,9 MB 80 WT and cross-section of a membrane fibre (inge GmbH, 2019).

The *feed* is filtered in a vertical hollow fibre UF module with a multi-bore structure of seven capillaries. The fibres are 4 mm in diameter, and each capillary has a diameter of 0,9 mm, which is illustrated in Figure 2.

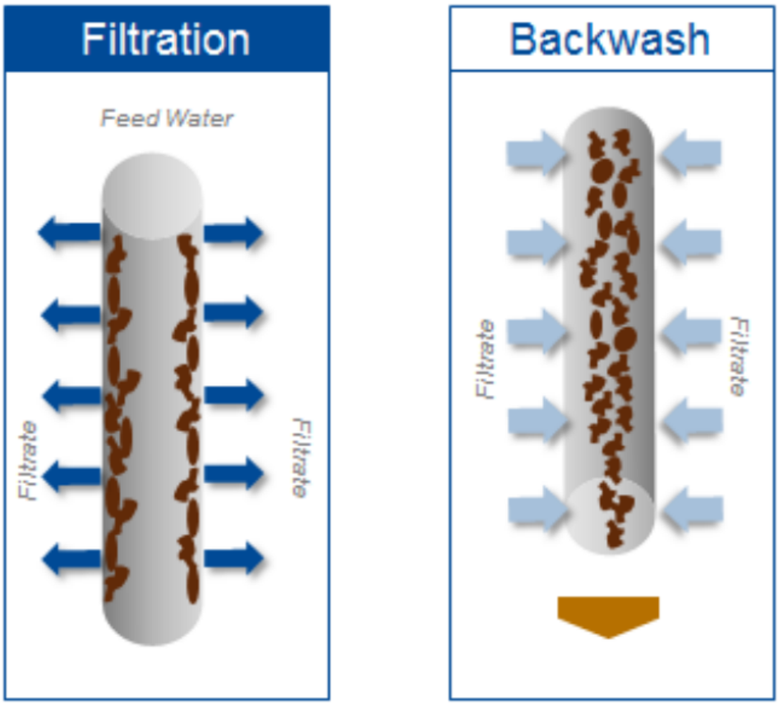

Figure 3. Membrane fibre during the mode's filtration and backwash (inge GmbH, 2019).

The separation occurs through inside-out filtration and dead-end mode, as seen in Figure 3. The treated permeate (*perm*) is gathered in a permeate tank, also used to wash the membranes during backwash (BW) and CEB.

2.2. Operational Settings

The UF process operation is monitored by assessing trends in permeability and TMP at constant flux, which is set by adjusting the water flow. The permeability has internal limits where the pilot plant shuts down at a permeability of 190 lmh/bar, alternatively, a TMP of 700 mbar. The shutdown occurs at 190 lmh/bar as the membrane's critical permeability is passed after 200 lmh/bar on recommendations by inge.

The pilot plant runs in three modes during operation: filtration, BW, and CEB. The filtration cycle runs for 60 min, the BW for 50 s after every filtration cycle, and the CEB for 50 min, usually after every 48 hours.

During filtration, the default setting of the pilot plant at the commissioning was set with the flux 70 lmh, the RT 21 s, 48 h interval between CEB, and pH adjustment was set to 6,7. The RT at 21 s was determined by the length of the pipes at flux 70 lmh. The pH adjustment was established by an inline sensor in the *feed,* which measured the pH and sent a feedback signal to the pH adjustment dosage. Subsequently, NaOH dosage was adjusted according to a pH of 6,5. Additionally, laboratory samples were analysed to control the correct pH. pH analysis in the *feed* is presented in Figure 17 in Appendix 1.

Aluminium dosages were based on previous pilot studies by Köhler and Sekizovic, 2021. Setpoint aluminium concentration in the stream was controlled by laboratory samplings, where concentrations observed in the *feed* were compared between the setpoint and actual value. Laboratory samples were also taken of the *perm* to ensure that the value did not exceed the internal limit of 0,03 mg Al/L (Norrvatten, 2003). Furthermore, the BW's chlorine and aluminium concentrations were measured to confirm the correct aluminium dosing. Figures 18 and 19 in Appendix 1 present aluminium concentrations throughout the operation.

The process modes for BW and CEB were set on a predetermined sequence, recommended by inge. The BW was flushed from the outside, through the pores, first from the top of the module for 25 seconds and then from the bottom for 17 seconds. Then, the membrane was switched back to filtration mode.

The CEB sequence was run in three phases and constantly with a regular BW before the sequence started:

1. The membrane was backwashed with permeate and NaOH from the top and bottom, then soaked for 15 min. Alternatively, the first step in the CEB was backwashed with permeate, NaOH, and hypochlorite (NaOCl). The chlorine concentration was based on previous pilot studies to 200 mg/L and approved by inge (Köhler & Sekizovic, 2021).
2. The membrane was rinsed from chemicals with permeate and flushed in filtration mode for 15 min.
3. The membrane was backwashed with permeate and sulphuric acid (H_2SO_4) from the top and bottom and soaked for 15 min. Afterwards, the membrane is rinsed before going back into filtration.

pH was set to 11,95 in the caustic wash step of the CEB and 2,25 in the acidic wash step. The *feed* pH was monitored to correctly adjust the dosage of chemicals in the CEB, presented in Figures 20 and 21 in Appendix 2. The pH setpoint must be reached to achieve adequate chemical backwash, but also that the pH does not exceed the upper limit of 11,95, which could lead to precipitation of calcium carbonate during soaking and a less beneficial cleaning.

The effluent CEB was treated in a neutralisation plant before being released to the recipient. The neutralisation was conducted on a set interval for redox potential and pH. The process started after a CEB and when the neutralisation tank reached a level of 30 %. First, the effluent was mixed by recirculation. After that, pH and redox were measured. If the values were outside the acceptable limit, sodium metabisulphite was added to decrease the redox potential, and NaOH or H_2SO_4 was dosed to adjust the pH. The cycle was then repeated until the parameters were within the setpoint interval. Afterwards, the CEB effluent was discharged down to 15 % from the tank. Settings for neutralisation are listed in Table 11 in Appendix 2.

2.3. Experimental Plan

The experimental plan involved six periods, which are presented in Table 1. The membrane lines were adjusted after a specific tested parameter. L1 was used as a testing line, while L2 was used as a reference line with constant parameter settings to observe seasonal changes. The experimental plan had a few modifications during the projects, and the initial schedule and goals are listed in Table 20 in Appendix 7.

Table 1. Plan of testing periods and specific adjustment of parameters from week 41, 2022, to week 27, 2023.

Period and week	Testing parameter	Membrane line 1				Membrane line 2			
		Dosage [mg Al/L]	Flux [lmh]	Retention time [s]	CEB [h]	Dosage [mg Al/L]	Flux [lmh]	Retention time [s]	CEB [h]
1A (41-45)	Optimal dosage	0,5-2,0	70	21	48	1,0	70	21	48
1B (46-49)	Effect of new carbon filtrate	0,5-2,0	70	21	48	1,0	70	21	48
2 (50-5)	Flux and retention time at lower temperatures	1,5	70-100	21-30	48	1,5	70	21-42	48
3 (6-10)	Operation without coagulant	0	70	42	48	1,5	70	42	48
4 (12-14)	CEB effluent analysis	1,5	70	42	48	1,5	70	42	48
5 (15-21)	CEB adjustment	0-2,0	70	42	48+Cl	1,5	70	42	48
6 (22-27)	Flux during lower water quality	1,5	70-100	30-42	48	1,5	70	42	48

At the end of each period, a Pressure Decay Test (PDT) was conducted to ensure that the membranes were intact before starting a new period. After period 2, a manual CEB with chlorine was conducted at the end of each period for L1. The extended treatment step was done to restore the operational starting position.

2.4. Data Collection

Data was gathered by online sensor measurements and lab samples taken at different sampling points. Sampling points were taken separately for L1 and L2 at *source*, *feed*, *perm*, BW, and CEB. Tables 12, 13 and 14 in Appendix 3 list measured parameters and sampling points.

Data gathering includes:

- Constant measurements taken for TMP, permeability, and *feed* pH.
    - $TMP = P_f - P_p$; is measured in mbar, where P_f is the pressure on the *feed* side and P_p is the pressure on the *perm* side of the membranes.
    - $Permeability\ at\ 20\ ℃ = \left(\frac{Flux/_{TMP}}{0{,}01007}\right) \cdot \left(17{,}91 - 0{,}6T_f + 0{,}013{T_f}^2 - 0{,}00013{T_f}^3\right) \cdot 0{,}001$; is measured in lmh, and where is T_f the actual temperature of the *feed*,
- Online measurements taken every 60 s for turbidity, UV_{254}, temperature, pH, and conductivity.
- Lab samples taken 2 – 3 times per week for chemical analysis.
- Microbiological analyses are taken once per week in addition to chemical analyses. The microbial analysis included bacterial growth, flow cytometry, occasional virus tests and fungal growth.

External analysis was performed by Eurofins laboratory for samples of the CEB effluent. The results of the analysis are presented and discussed in Period 4.

The permeability and TMP data results are presented as mean values during a CEB cycle and only for data representing stable trends.

- Mean permeability (mPermeability) is the average value between permeability before and after the BW in the median of a CEB cycle.
- Delta permeability (ΔPermeability) is defined as the difference between permeability at the beginning and end of a CEB cycle.
- Permeability drop rate is the difference in permeability after a CEB, divided by the number of days passed between the values.

3. Water Quality in Raw Water, *Source*, and *Perm*

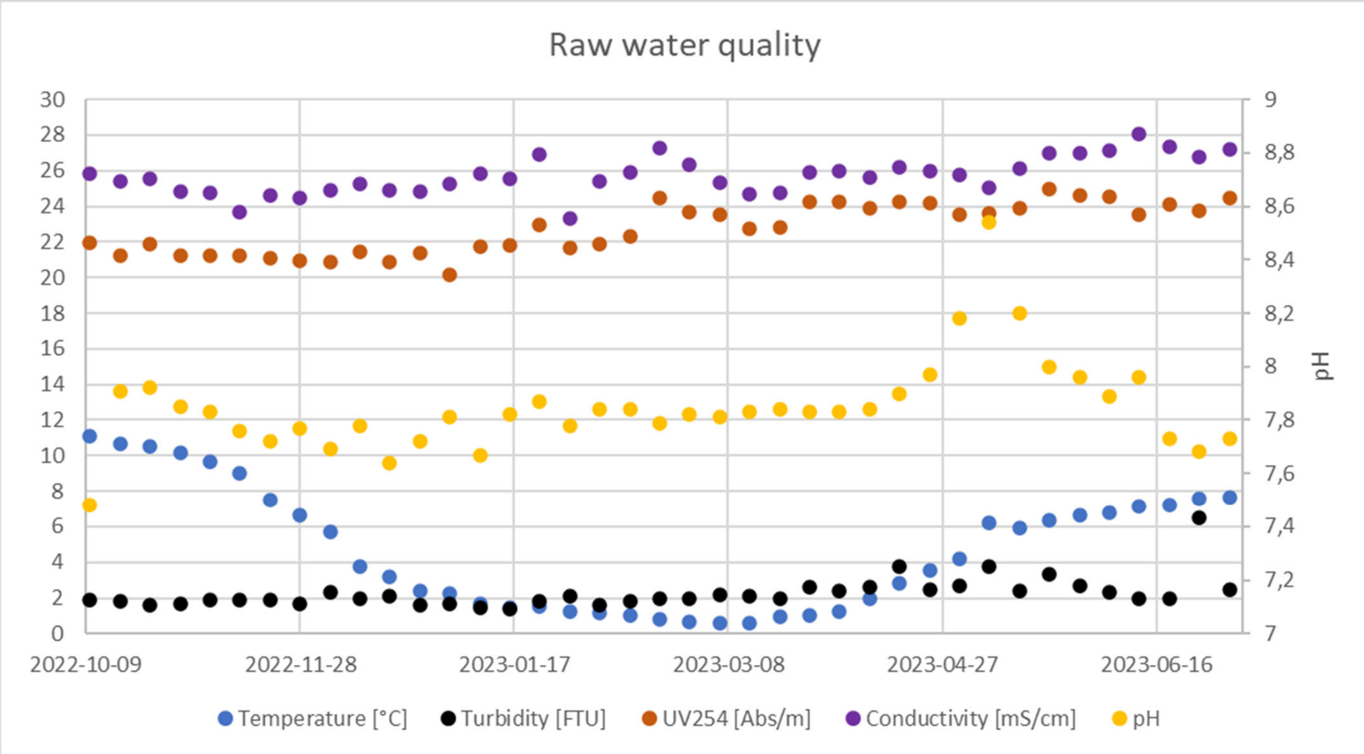

Figure 4. Raw water quality (into the DWTP) between 20231010 - 20230703. Trending temperature, turbidity, UV_{254}, conductivity, and pH.

The raw water (into the DWTP) quality trends were gathered from aCurve and plotted in Figure 4. The trends presented in the piloting project are a comparison to the feedwater and filtrate of the UF. The lowest raw water temperatures occurred between the start of December and the end of April. The temperatures were between 1 and 6 °C.

During the pilot trials, the *source* and *perm* water quality are presented as turbidity, UV_{254}, pH and conductivity. The results are shown in Figures 22 – 29 in Appendix 4.

The *source* turbidity was generally below 0,1 FNU during the piloting, with occasional turbidity spikes. The *perm* turbidity varied between 0,01 and 0,05. Online turbidity results were inconclusive, likely because of air bubbles in the stream.

The UV_{254} *source* was between 7,5 and 8,0 abs/m, where the trend correlated with raw water quality, and UV_{254} was the lowest during lower water temperatures. The UV_{254} *perm* differed between periods and membrane lines, connected to the specific parameter setting of L1 and L2.

The pH was between 6,8 - 6,9 in the *source*, then increased to 6,9 – 7,0 in the *perm*. The increase in *perm* can result from NOM reduction with an acidic characteristic.

Both *source* and *perm* had similar conductivity results. The values ranged between 230 – 310 µS/cm. The *perm* had, on average, a conductivity 10 µS/cm higher than in the *source*.

4. Results and Discussions

Studied parameters are presented over six periods from sections 4.1 – 4.6. The parameters studied are coagulant dosage, flux, RT, operation without coagulant, CEB adjustment, performance recovery, and seasonal changes. Each section separately describes changes in TMP, permeability, UV_{254}, TOC, and aluminium residue in *perm* for L1 and L2. Conclusive remarks on the results are presented in the main finding. Section 4.7 is auxiliary results and includes seasonal changes, PDT, and challenges during operation.

4.1. Period 1: Optimal Coagulant Dosage

Various coagulant dosages were tested in period 1, between 2022-10-10 and 2022-12-15, and the first two weeks of period 1 included the commissioning of the pilot plant. The flux was set to 70 lmh, the RT was 21 s, the filtration cycle was 60 min, and the CEB interval was 48 h without chlorine. Furthermore, the *source* used during commissioning for both membrane lines was carbon filtrate from KF4, which later changed to filtrate KF2. Two different carbon filtrates were used to compare the operation of the pilot unit when using a new carbon in contrast to saturated carbon. During the period, raw water temperature decreased from 10,8 to 5,1 °C.

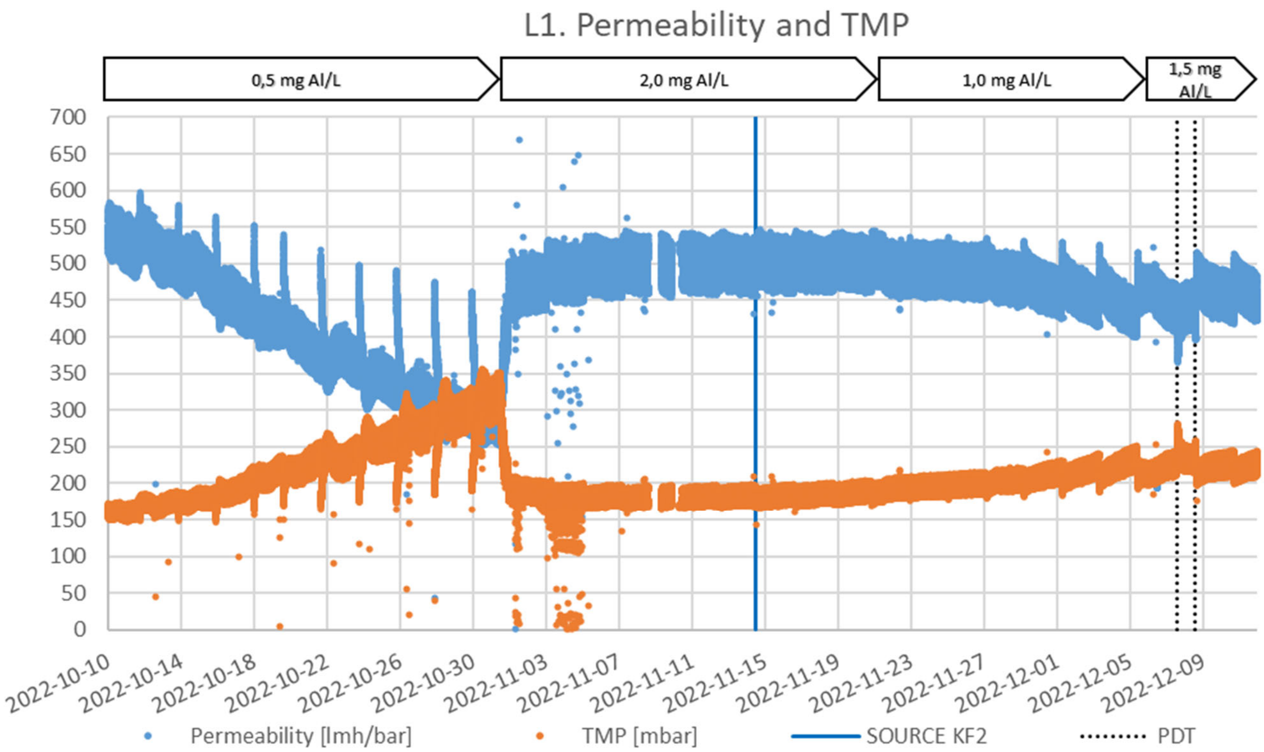

Figure 5. Permeability (blue) and TMP (orange) during period 1 for L1. The blue line represents when the source was changed from KF4 to KF2. The dotted lines denote when a PDT was performed. The arrows show the aluminium dosage during the period.

For L1, four different aluminium dosages were tested, as seen in Figure 5. At 0,5 mg Al/L, the permeability decreased from 535 – 275 lmh/bar with no sign of stabilising. The decrease was expected due to the commissioning of new membranes, but it continued after the first two weeks, which suggests that the dosage was insufficient. In addition, the mPermeability after a CEB was considerably lower than the peak after each cycle. At 2,0 mg Al/L, the permeability increased with scattered values during the first two CEB cycles, corresponding to four days, indicating that an increase in aluminium dosage could restore the permeability without initiating chlorine in CEB. On 2022-11-03, the mPermeability stabilised at 496 lmh/bar and the mTMP at 183 mbar, which shows that 2,0 mg Al/L is enough for stable operation. However, there are no peaks in permeability after a CEB, which indicates that the dosage was excessive. When 1,0 mg Al/L was dosed, the permeability started decreasing, which was first visible after three CEB cycles. The CEB cycle had an exponentially steeper trend at the beginning of each permeability curve. Finally, 1,5 mg Al/L resulted in the optimal mPermeability, which was decided by narrowing down previously tested aluminium concentrations. The permeability was approximately 458 lmh/bar and mTMP 222 mbar.

On 2022-11-14, the *source* was changed from KF4 to KF2. KF2 had recently been filled with new carbon, giving the *source* a lower NOM concentration and potentially a higher load of fine carbon particles. However, no noticeable effect on the operation was shown.

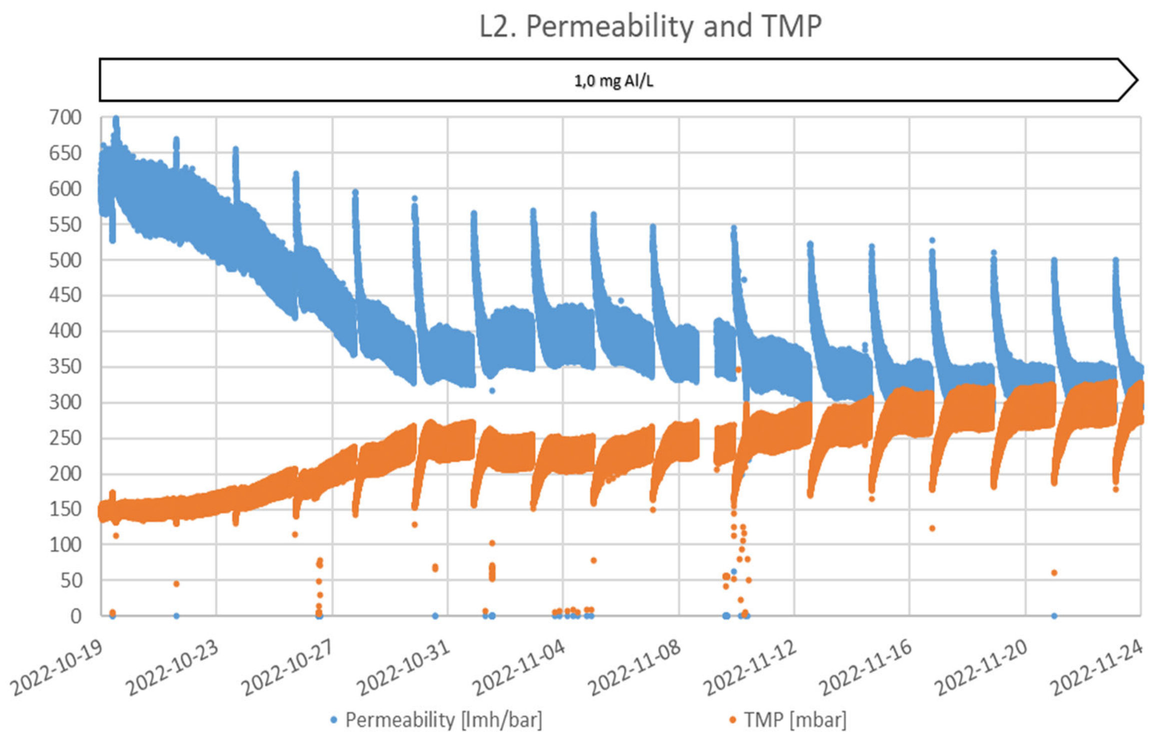

Figure 6. Permeability (blue) and TMP (orange) during period 1 for L2.

The operation for L2, shown in Figure 6, had a constant aluminium dosage at 1,0 mg Al/L during the whole period and showed a sharp decrease during commissioning, as expected. On 2022-10-31, the permeability levelled out, but without a stable trend. The pattern shows a high top after each CEB cycle over 500 lmh/bar, stabilising after approximately nine filtration cycles with, on average, a drop down to 350 lmh/bar permeability. The trend suggests that the dosage was insufficient to attain a stable permeability.

For both lines, the total aluminium residue in *perm* was between 85 – 100 % in dissolved form. This suggests that no solid aluminium passed the membranes.

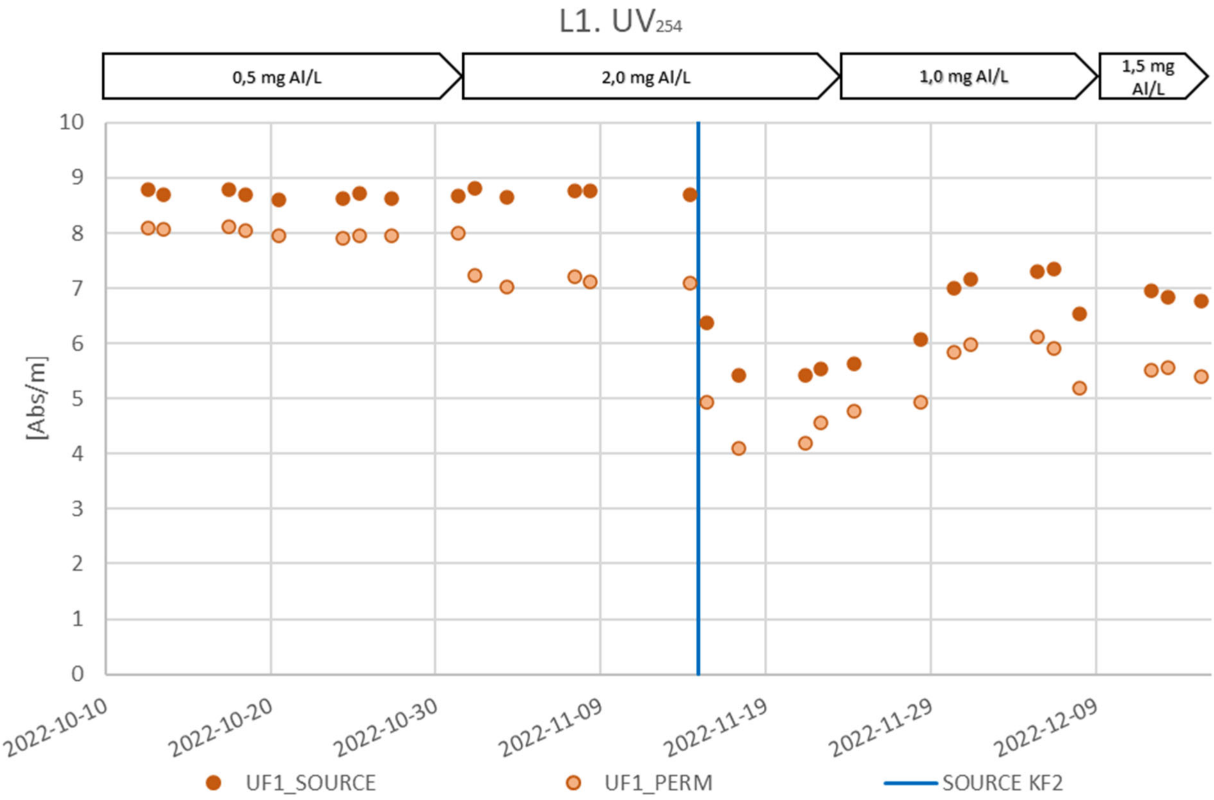

Figure 7. Results of reduction in UV_{254} and TOC and aluminium dosing for L1. The blue line represents when the source was changed from KF4 to KF2.

UV_{254} at different aluminium dosages for L1 showed the NOM reduction in Figure 7. UV_{254} is 8,7 abs/m when KF4 is used as the *source*, and the reduction is 7,8 % with 8,0 abs/m in the *perm* at 0,5 mg Al/L. The reduction is almost double at 18,3 % for 2,0 mg Al/L and 7,1 abs/m in the *perm*. The *source* is then reduced to 6,0 abs/m when changed from KF4 to KF2. It should be noted that the reduction of UV_{254} is difficult to determine for 1,0 mg Al/L as the quality of the *source* is decreasing. It appears to be removing the same fraction but there is a fraction in the source that is varying, which the UF can't remove. The *source* stabilises at 6,9 abs/m and the dosage at 1,5 mg Al/L. The 1,5 mg Al/L dosage shows the highest reduction of UV_{254} at 20 % with 5,5 abs/m in *perm*. Comparing UV_{254} and TOC in *source* and *perm*, the parameters have a proportional correlation and are equally sufficient to represent the reduction of NOM.

The separation of NOM for L2, with a constant aluminium dosage of 1,0 mg Al/L, showed that the UV_{254} was reduced from 8,7 to 7,7 Abs/m, an 11,2 % UV_{254} reduction. The TOC was reduced from 4,5 to 4,1 mg/L, a decrease of 9,1 %. The results of NOM reduction from L2 cannot be compared with L1, as L2 still had *source* KF4 and, therefore, a higher UV_{254} and TOC than L1 at a dosage of 1,0 mg Al/L.

4.1.1. Main Findings

Table 2. Period 1 operational parameters for L1. Including average TMP, average permeability, and actual aluminium concentration in the feed and aluminium residue in perm.

Membrane line 1				
Test parameter	**mTMP**	**mPermeability**	**Al. *feed***	**Al. *perm***
[mg Al/L]	**[mbar]**	**[lmh/bar]**	**[mg Al/L]**	**[mg Al/L]**
0,5	282	308	0,54	0,03
1,0	208	478	0,97	0,02
1,5	222	458	1,83	0,02
2,0	183	496	2,29	0,02

For L1 in Table 2, coagulant dosing at 1,5 mg Al/L was the lowest dosage where a stable operation could be achieved, making it the most suitable. The actual values exceeded the setpoint slightly for the tested aluminium dosages. However, all tested dosages gave an aluminium residue in *perm* below the internal limit, 0,03 mg Al/L. Changing the source to a filter with fresh activated carbon media at given parameter settings did not affect the permeability. By increasing the coagulant dose to 2,0 mg Al/L, the permeability can be restored to a starting position of approximately 500 lmh/bar after the permeability dropped below 250 lmh/bar without dosing NaOCl in the CEB.

Table 3. Period 1 operational parameters for L2. Including average TMP, average permeability, and actual aluminium concentration in the feed and aluminium residue in perm.

Membrane line 2				
Test parameter	**mTMP**	**mPermeability**	**Al. *feed***	**Al. *perm***
[mg Al/L]	**[mbar]**	**[lmh/bar]**	**[mg Al/L]**	**[mg Al/L]**
1,0	292	332	0,81	0,03

The results of L2 in Table 3 resulted in a mPermeability of 332 lmh/bar. Compared with 1,0 mg Al/L for L1, the mPermeability was 478 lmh/bar. L1 at the exact dosage as L2 displayed better performance in all parameters. The cause might be a result of the previous high aluminium dosage of 2,0 mg Al/L, which increased its starting position. Furthermore, from the trend in Figure 6, the dosage of 1,0 mg Al/L was not optimal, which led to a fast drop in permeability after each CEB, which was caused by fouling that BW could not remove.

4.2. Period 2: Alternating Flux and Retention Time during Lower Temperatures

Between 2022-12-20 and 2023-02-02, the second period was conducted with parameters set to 70 lmh, RT 21 s, the filtration cycle was 60 min, and the CEB interval was 48 h without chlorine. The RT was changed as a variable of a changing flux. During the period, the aluminium dosage was altered as a controlled variable due to decreases in permeability. Furthermore, *sources* 1 and 2 were taken from carbon filter 2. Raw water temperature decreased from 3,4 to 1.1 °C during the period.

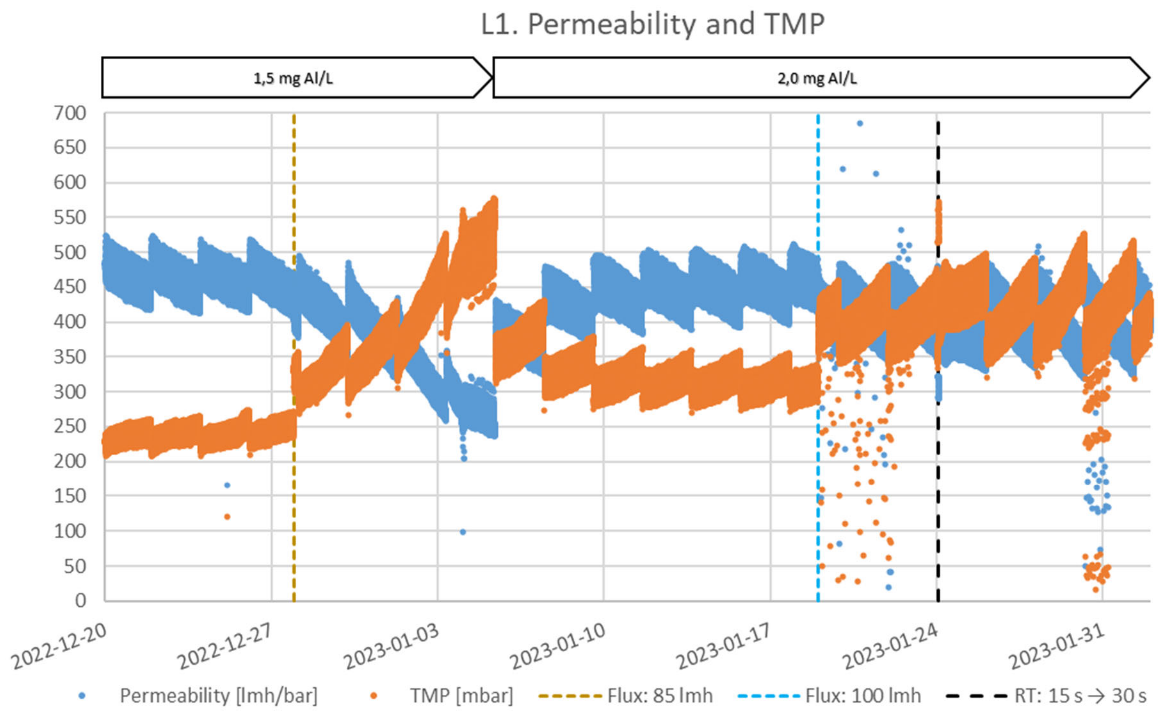

Figure 8. Permeability (blue) and TMP (orange) during period 2 for L1. The yellow (85 lmh) and blue (100 lmh) dotted line denotes when flux was changed. The black dotted line represents when RT was increased from 15 to 30 s. The arrows show the aluminium dosage.

When flux was increased to 85 lmh and indirectly reduced the RT to 18 s, the permeability was decreased, which is presented in Figure 8. It dropped from a mPermeability of 463 lmh/bar to below 250 lmh/bar. To counter the downward trend, the aluminium dosage was increased to 2,0 mg Al/L, and the permeability recovered to 445 lmh/bar after 3 CEB cycles. This concludes that 2,0 mg Al/L is needed to maintain stable permeability at a flux of 85 lmh.

On 2023-01-19, the flux was increased to 100 lmh, and the permeability decreased to 414 lmh/bar. The TMP at 100 lmh was considerably higher at 401 mbar, compared to flux 70, with a TMP of 241 mbar. Interference emerged in the TMP during the two first CEB cycles, where it momentarily dropped at scattered pressures. Still, the operation was generally functional at a new steady state despite a scattered decline in TMP interference. Another trend was that the permeability decreased with a steeper slope during each CEB cycle, dropping approximately 150 lmh/bar.

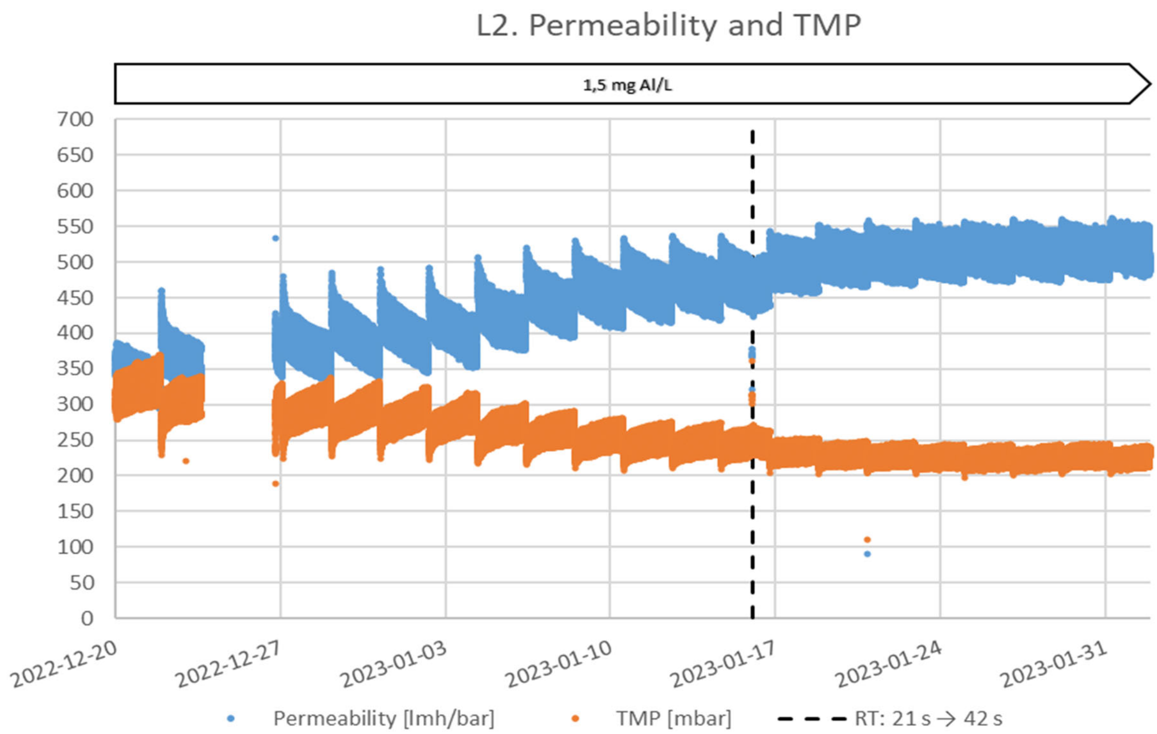

Figure 9. Permeability (blue) and TMP (orange) during period 1 for L1. The dotted line denotes when RT was increased.

In Figure 9, L2 increased permeability between 2022-12-20 and 2023-01-15 when the coagulant dosage was set to 1,5 mg Al/L. The value increased from 360 to 473 lmh/bar. The decrease between the peaks for each CEB cycle and the mPermeability decreased equivalent. This concludes that an increase from 1,0 to 1,5 mg Al/L prolongs the recovery of the permeability to 24 days (twelve CEB cycles). Compared with L1 in period 1, when the dose was increased to 2,0 mg Al/L, it took only four days (two CEB cycles) to recover permeability. This shows that increased aluminium dosage to recover permeability is much more effective at 2,0 compared to 1,5 mg Al/L.

On 2023-01-16, the RT was doubled from 21 to 42 s to reduce an increased aluminium concentration in the *perm*. The increased aluminium concentration in the *perm* is an effect of decreased temperatures in the *source*. However, a correlation between the increased RT and aluminium residue in *perm* could not be concluded.

It was difficult to see a correlation between permeability and RT when RT was increased for L1 and L2. Nevertheless, increased RT leads to more optimal coagulation, and less fouling on the membrane, this is seen by a reduction in the TMP rise between CEB.

Table 4. Period 2 operational parameters and water quality for L1 and L2. Including flux, RT, set point aluminium dosage in the feed, UV_{254} and TOC for source and perm.

Membrane Line	Flux	Retention time	Aluminium dosage	UV_{254} *source*	UV_{254} *perm*	TOC *source*	TOC *perm*
	[lmh]	[s]	[mg Al/L]	[abs/m]		[mg/L]	
1	70	21	1,5	7,0	5,6	3,99	3,43
	85	18	1,5	7,4	5,7	4,13	3,44
	85	18	2,0	7,5	6,2	4,19	3,65
	100	15	2,0	7,5	6,5	4,10	3,81
	100	30	2,0	7,7	6,7	4,20	3,78
2	70	21	1,5	7,3	6,3	4,14	3,69
	70	42	1,5	7,6	6,8	4,19	3,83

Table 4 shows that L1 NOM concentration in the source increases during the tested period from 7,0 to 7,7 abs/m of UV_{254} and from 3,99 to 4,20 mg/L of TOC. The reduction in both UV_{254} and TOC decreased with higher flux. This was especially noticeable during flux 85 lmh when the aluminium dosage increased from 1,5 to 2,0 mg Al/L, which decreased UV_{254} reduction from 22 to 17 % and TOC reduction from 17 to 13 %. When RT was increased from 15 s to 30 s, UV_{254} and TOC reduction decreased slightly but without a significant certainty.

L2 showed lowering UV_{254} and TOC values in the source. The average UV_{254} and TOC reduction was 12,4 % and 9,9 %, respectively.

4.2.1. Main Findings

Operating the membranes at flux up to 100 lmh during lower raw water temperatures is possible. It is, however, necessary to increase the aluminium dosage to maintain stable permeability, where 2,0 mg Al/L was enough for both 85 and 100 lmh to keep permeability over 250 lmh/bar. The removal of NOM is reduced when flux increases and even more when the aluminium dosage is increased as a measure of operational stability.

The increased RT for L1 showed no noticeable effect on the permeability. Still, when RT was increased to 42 s in L2, it showed increased permeability. Therefore, an RT of 21 s is considered insufficient during colder temperatures and needs to exceed 42 s. The effect of an upper limit of the RT is unknown.

In L2, permeability recovered after being reduced to 350 lmh/bar. However, it required almost four weeks before the permeability reached over 500 lmh/bar when the aluminium dosage was increased from 1,0 to 1,5 mg Al/L. Alternatively, temporarily coagulant dosing with higher aluminium concentration is required to achieve faster permeability recovery without chlorine.

4.3. Period 3: Filtration without Coagulant

Period 3 was conducted between 2023-02-08 and 2023-03-20. L1 was operated without coagulant dosage. On 2023-02-13, a CEB was initiated on both lines with 200 mg/L chlorine was added to the alkaline part of the CEB to achieve better recovery of the membranes before the start of period 3. Both lines had a starting point over 500 lmh/bar and were operated with a flux of 70 lmh, an RT of 42 s, a filtration cycle of 60 min, and a CEB interval of 48 h without chlorine. The raw water was at an average of 0,9 °C.

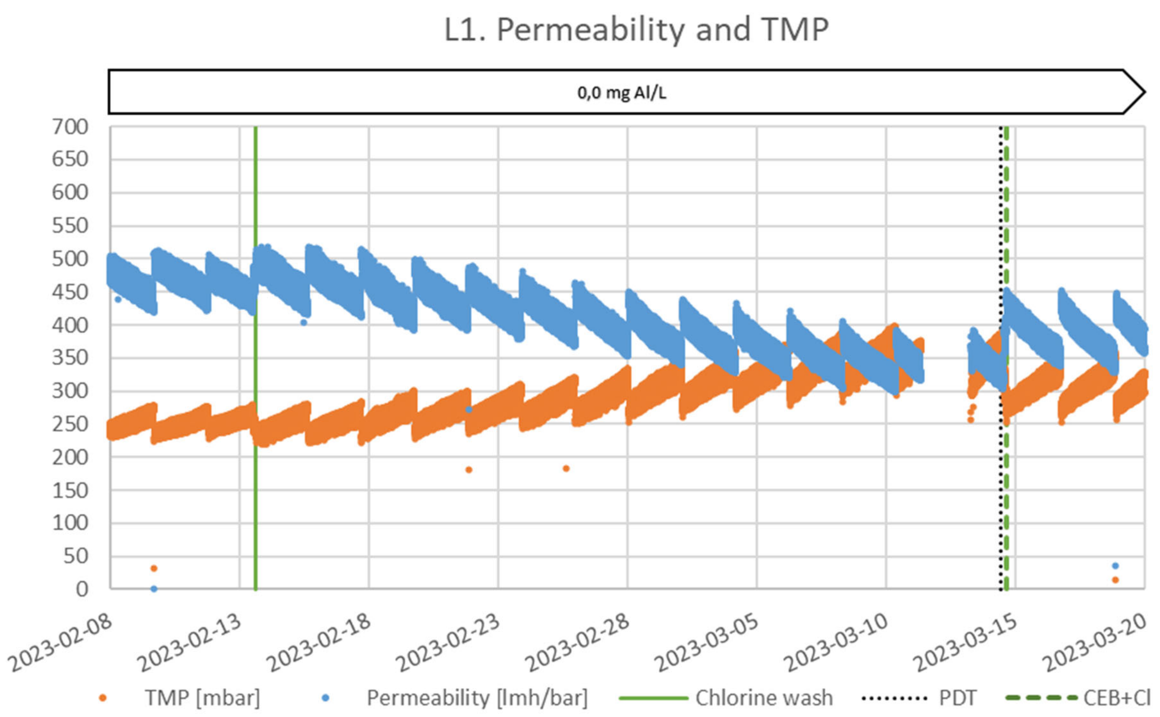

Figure 10. Permeability (blue) and TMP (orange) during period 3 for L1. The green line is when chlorine is present during a manual CEB. The black dotted line denotes when a PDT was performed, and the green dotted line denotes when a chlorine was activated continuously for all upcoming CEB.

From 2023-02-13, the permeability in L1 dropped from an average of 471 lmh/bar to 332 lmh/bar after 13 CEB cycles, resulting in a permeability drop rate of 4,1 lmh/bar per day. On 2023-03-15, chlorine at 200 mg/L was activated on the alkaline part of the CEB. As a result, the downward trend of the permeability stopped at 452 lmh/bar after each CEB but never recovered. The permeability was stable for three consecutive CEB at a mPermeability of 390 lmh/bar.

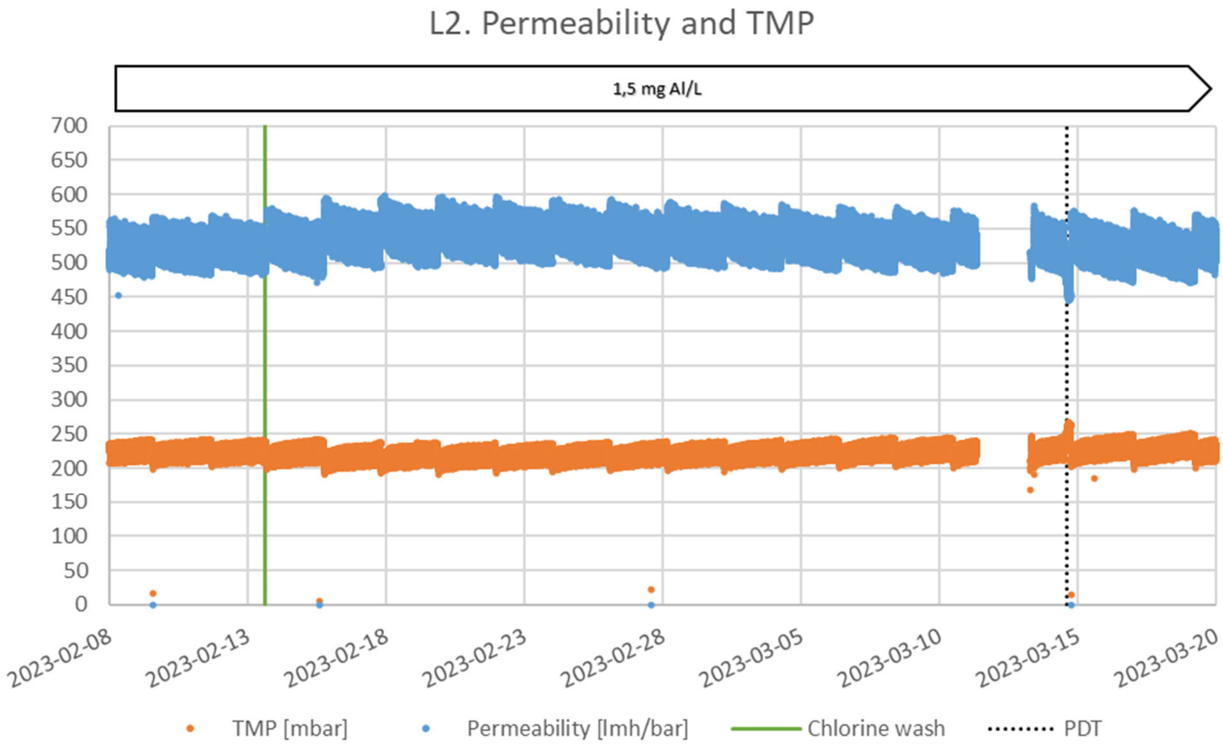

Figure 11. Permeability (blue) and TMP (orange) during period 3 for L1. The green line is when chlorine is present during a manual CEB. The black dotted line denotes when a PDT was performed.

L2 was stable with an average permeability of 528 lmh/bar. After the first chlorine wash in the CEB, the permeability increased marginally, up to 597 lmh/bar. It then slowly decreased to a more stable position at 524 lmh/bar for the given coagulant dosage. The TMP was, on average, 222 mbar.

Table 5. Reduction of NOM for period 3. Including dosage in the feed, UV_{254} and TOC for source and perm.

Membrane Line	CEB phase	Aluminium dosage	UV_{254} *source*	UV_{254} *perm*	TOC *source*	TOC *perm*
	[-]	[mg Al/L]	[abs/m]		[mg/L]	
1	Operation without coagulant	0,0	8,0	8,0	4,19	4,12
	Chlorine dosing of 200 mg/L	0,0	8,0	7,9	4,28	4,18
	Chlorine is activated during CEB	0,0	-	-	4,04	3,96
2	Uniform operation	1,5	7,8	7,2	4,17	3,88

By comparing L1 and L2, operation without coagulation almost completely takes away the ability to remove NOM, as seen in Table 5. L1 removed 1,1 % of UV_{254}, while L2 removed 9,4 %. The reduction of TOC was 2,1 % for L1 and 6,9 % for L2.

4.3.1. Main Findings

According to L1, operation without coagulant decreases the permeability to a critical point with no sign of stabilisation, see Table 6. The activation of chlorine in the alkaline part of the CEB stabilises the permeability but cannot recover it to its starting position, as when the coagulant at 2,0 mg Al/L is temporarily dosed. To achieve a significant reduction of NOM, a coagulant dosage is required.

Table 6. Operational parameters for period 3 for both lines. Including average TMP, average permeability, and actual aluminium concentration in the feed and aluminium residue in perm.

Membrane Line	**Test parameter**	**mTMP**	**mPermeability**	**Al. *feed***	**Al. *perm***
	[-]	**[mbar]**	**[lmh/bar]**	**[mg Al/L]**	**[mg Al/L]**
1	Operation without coagulant	247	471	0,03	0,03
	Chlorine dosing of 200 mg/L	294	399	0,03	0,03
	Chlorine is activated during CEB	301	390	0,03	0,03
2	Uniform operation	222	528	1,29	0,03

4.4. Period 4: Evaluation of CEB Effluent

During period 4, from 2023-03-20 to 2023-04-09, both lines were kept in a steady state with a coagulant dosage of 1,5 mg Al/L, flux 70 lmh, RT 42 s, 60 min filtration cycle, and a CEB interval 48 h without chlorine. The period aimed to evaluate the neutralisation step of the CEB.

When L1 was operated with coagulant again, the permeability recovered with a lower increase after each CEB. mPermeability between 2023-03-20 and 2023-03-29 rose from 393 to 422 lmh/bar. At the end of the period, the permeability was, on average, 431 lmh/bar, and the TMP was 286 mbar after eight CEB cycles. L2 kept stable operation during the period with a mPermeability of 513 lmh/bar and a TMP of 228 mbar.

The characterisation of the CEB effluent has, on average, a pH of 6,5 after the neutralisation cycles have been conducted, as seen in Table 15 in Appendix 5. The dissolved aluminium stays on average at 11,6 mg Al/L. The mean turbidity is 4,3 FNU, and the suspended solids concentration is 36,8 mg /L. Samples with the highest suspended solids had values of 50,3 mg/L, which exceeds the discharge limit of 40 mg/L (Heldt, 2022). Then, after implementing a regular BW before the CEB sequence, the turbidity was reduced to 1,84 FNU, and the suspended solids concentration decreased to 7,6 mg/L.

A jar test of the neutralised CEB effluent was carried out, where different pH values were tested to compare the aluminium concentration. Total aluminium concentration ranged between 12,0-13,1 mg Al/L in the CEB, presented in Figure 30 in Appendix 5. Based on values from the jar test, dissolved aluminium is kept under 0,03 mg Al/L when the pH is between 6,5 and 7,0. A pH over seven shows an exponential increase in dissolved aluminium; at pH 8,0, the value is 0,16 mg/L. The test was later repeated; unfortunately, the result of the second jar test was inconclusive.

Analysis of chlorinated compounds (THM and HAA) in the neutralised CEB effluent showed that chlorate was the only substance that exceeded the limits at 3,06 mg/L, which is presented in Table 16 in Appendix 5. The dosage of sodium metabisulfite was afterwards increased to counteract the chlorate concentration in the effluent. Nevertheless, the measures to reduce the chlorate concentration were ineffective, and the chlorate concentration persisted. Furthermore, the bromate concentration was just at the 10 mg/L limit. Further actions need to be taken to reduce the chlorate and bromate concentrations.

The concentration of heavy metals in the CEB effluent was below the limit, as seen in Tables 17 and 18 in Appendix 5. Additionally, all parameters in the extended analysis were below the limit according to revised guidelines in Table 19 in Appendix 6. (Heldt, 2022)

4.5. Period 5: CEB Adjustment

L1 was operated without coagulant during Period 5 and had CEB with chlorine at different intervals. Three intervals were tested in three phases with a constant CEB interval of 48 h and a 200 mg Cl/L dosage in the alkaline CEB part. Phase 1 was operated with a chlorine wash during each CEB. Phase two was planned with chlorine every third CEB, and phase three had a chlorine wash every second CEB. The phases had a starting permeability between 470 and 510 lmh/bar, and a limit at 200 lmh/bar was set when the coagulant would be activated to recover permeability drop. Flux was set to 70 lmh, RT 21 s, and the filtration cycle at 60 min.

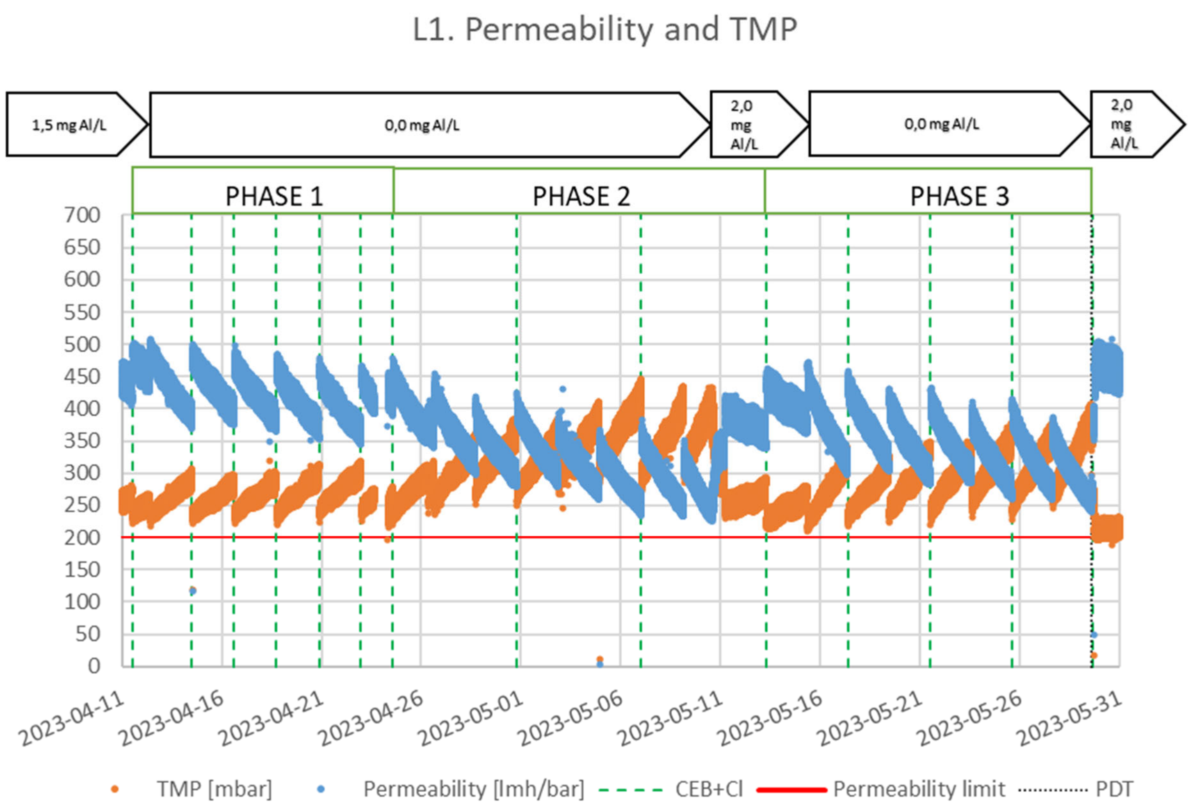

Figure 12. Permeability (blue) and TMP (orange) during period 5 for L1. The green dotted line is when chlorine was activated continuously for all upcoming CEBs. The black dotted line denotes when a PDT was performed. The red line is the permeability limit.

All phases show a decrease in permeability between CEB cycles, as shown in Figure 12. Overall, the permeability keeps decreasing during operation without coagulation and chlorine at every CEB. In some cycles, it can reduce the drop. However, when the permeability after a CEB is close to 400 lmh/bar, the chlorine in CEB increases the permeability as slightly as 10 lmh/bar higher than the previous cycle. This can be seen when the chlorine is turned on for phases two and three.

During phase 2, the permeability dropped to a critically low level, and as an act to recover the permeability, coagulation was activated temporarily at 2,0 mg Al/L. The permeability increased up to 473 lmh/bar during 2,5 CEB cycles. It recovered at a rate of 21 lmh/bar per CEB.

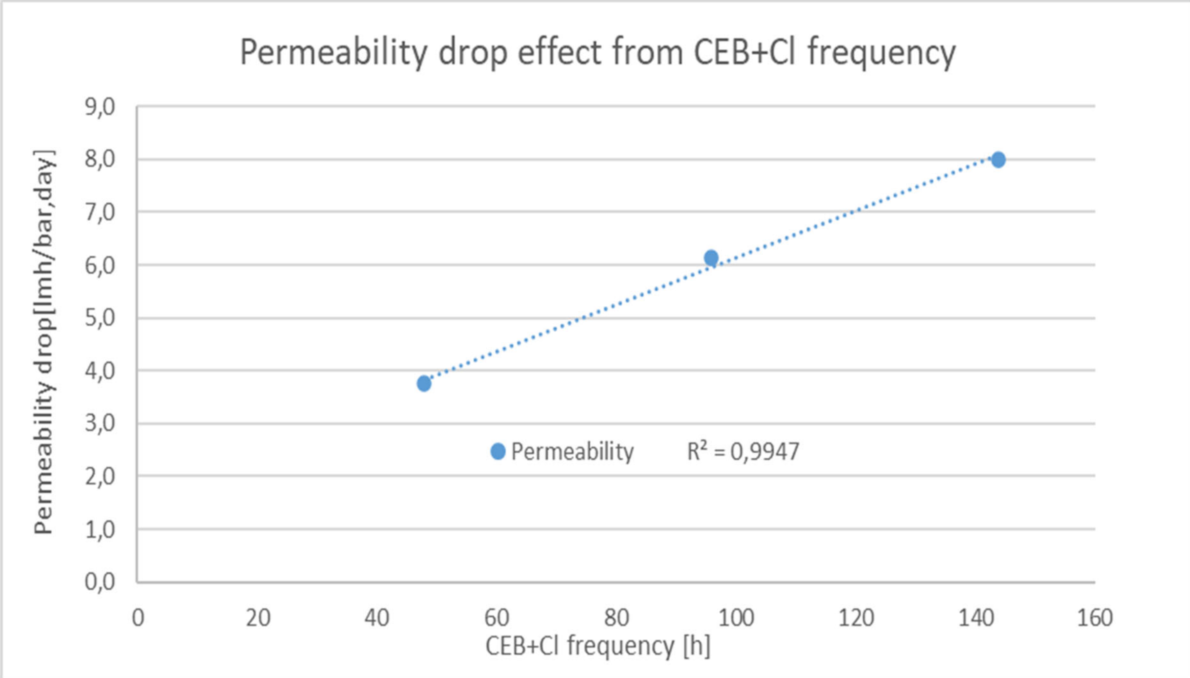

Figure 13. Correlation between the average drop in permeability and the frequency of chlorine activation during a CEB.

The drop during one filtration was, on average, between 39 and 42 lmh/bar. This consistency shows that chlorine frequency in CEB did not affect permeability drop over the filtration sequence. In contrast, there is a clear difference in the permeability drop per CEB between the phases, see Figure 13. Performing a chlorine wash with a 48-h interval resulted in a permeability drop of 3,8 lmh/bar per day. The rate of permeability drop per CEB shows a linear correlation with the frequency of chlorine in CEB. In phase two, at a chlorine frequency of 144 h, the permeability drop was doubled the one in phase one, at 8,0 lmh/bar per day. The third phase at a chlorine frequency of 96 h gives a drop of 6,1 lmh/bar per day. The correlation between permeability drop rate and chlorine frequency in CEB has a 99 % accuracy.

L2 has had a stable operation but with a slight downward trend in permeability. It has decreased by approximately 1,6 lmh/bar day in two months. The coagulant dosage has been constant at 1,5 mg Al/L, and the CEB setting has not been changed. However, the raw water temperature has increased from 1,6 to 7,1 °C and may shift the steady-state permeability of the operation. During the last period, the decrease in permeability slowed down marginally.

The difference in chlorine frequency was irrelevant, and the reduction was approximately 0 abs/m, shown in table 7. Measured as TOC, a slight difference was noticed with better reduction at a higher frequency, but the difference was insignificant. Compared with L2 and a coagulant dosage of 1,5 mg Al/L, the reduction of UV_{254} was 10 %, and TOC reduction was 8 %. Still, it should be noted that the water quality decreased during the period regarding UV_{254} and TOC.

Table 7. Reduction of NOM for period 5. Including chlorine frequency, aluminium dosage, UV_{254} and TOC for source and perm.

Membrane Line	Chlorine frequency	Aluminium dosage	UV_{254} *source*	UV_{254} *perm*	TOC *source*	TOC *perm*
	[h]	[mg Al/L]	[abs/m]		[mg/L]	
1	48	0,0	7,9	7,9	4,11	4,04
	96	0,0	8,1	8,1	4,32	4,28
	144	0,0	7,6	7,6	4,19	4,15
2	-	1,5	7,7	6,9	4,17	3,85

4.5.1. Main Findings

Operation without coagulant shows an apparent decrease in permeability, which cannot be recovered by adding chlorine in the CEB unless the mPermeability is below 300 lmh/bar. Still, by adding chlorine to the CEB, the drop in permeability can be delayed. The frequency of chlorine in CEB shows that the drop rate of permeability is approximately 4 lmh/bar higher for each CEB without chlorine.

Table 8. Operational parameters for period 5 for both lines. Including average TMP, average permeability, permeability drop rate, actual aluminium concentration in the feed and aluminium residue in perm.

Membrane Line	Chlorine frequency	mTMP	mPermeability	Permeability drop rate	Aluminium dosage	Al. *feed*	Al. *perm*
	[-]	[mbar]	[lmh/bar]	[lmh/bar, day]	[mg Al/L]	[mg Al/L]	
1	48	262	424	3,8	0,0	0,02	0,02
	96	291	393	6,1	0,0	-	-
	144	329	324	8,0	0,0	0,02	0,02
2	-	227	456	1,6	1,5	1,31	0,02

4.6. Period 6: Alternating Flux during Lower Water Quality

Between 2022-06-01 and 2023-07-10, alternating flux was operated with start parameters set to 70 lmh, RT 42 s, filtration cycle was 60 min, and CEB interval was 48 h without chlorine. The RT was changed as a dependent variable of flux. Staring at flux 70 lmh, the aluminium dosage was set at 2,0 mg Al/L to recover the permeability before increasing the flux to 85 and 100 lmh, with an aluminium dosage of 1,7 mg Al/L.

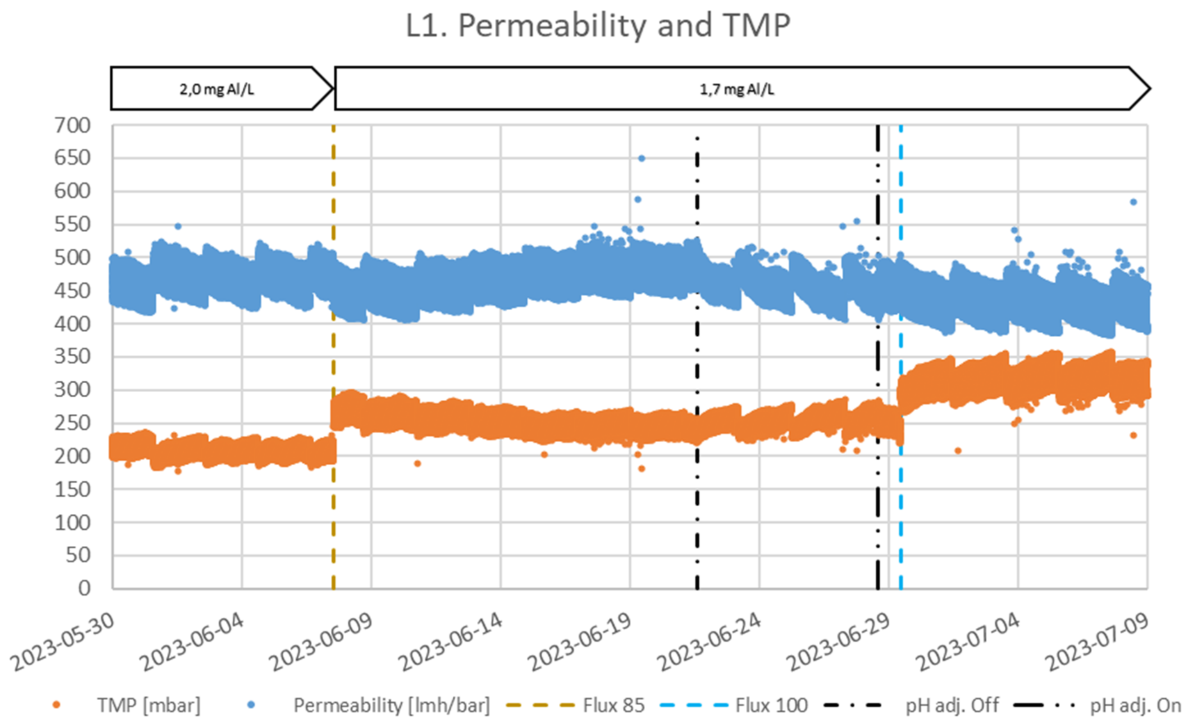

Figure 14. Permeability (blue) and TMP (orange) during period 6 for L1. The yellow (85 lmh) and blue (100 lmh) dotted line denotes when flux was changed. The black striped and dotted lines represent when the pH adjustment was switched off and on.

At flux 70 with 2,0 mg Al/L, permeability was stable and showed no downward trend. The TMP was approximately 210 mbar on average. When flux was increased to 85 lmh (RT 36 s), and the aluminium dosage was decreased to 1,7 mg Al/L, the permeability instantly dropped approximately 20 lmh/bar. Still, it recovered quickly up to a permeability over 500 lmh/bar in 4 CEB cycles. Then, the permeability was kept constant for two CEB cycles. On 2023-06-21, chemicals for the pH adjustment ran out. The adjustment was then turned off, and the permeability decreased with a drop rate of 6,5 lmh/bar per day. The fast decrease in permeability is an effect of reduced floc formation at lower pH, which results in faster fouling of membrane pores.

At flux 100 lmh (RT 30 s) and when the pH adjustment was turned back on again, the permeability drop rate was 2,6 lmh/bar per day. This shows that, with the current aluminium dosage, the permeability is stable at flux 85 lmh but not 100 lmh. Then again, without pH adjustment, the drop rate is faster at flux 85 lmh.

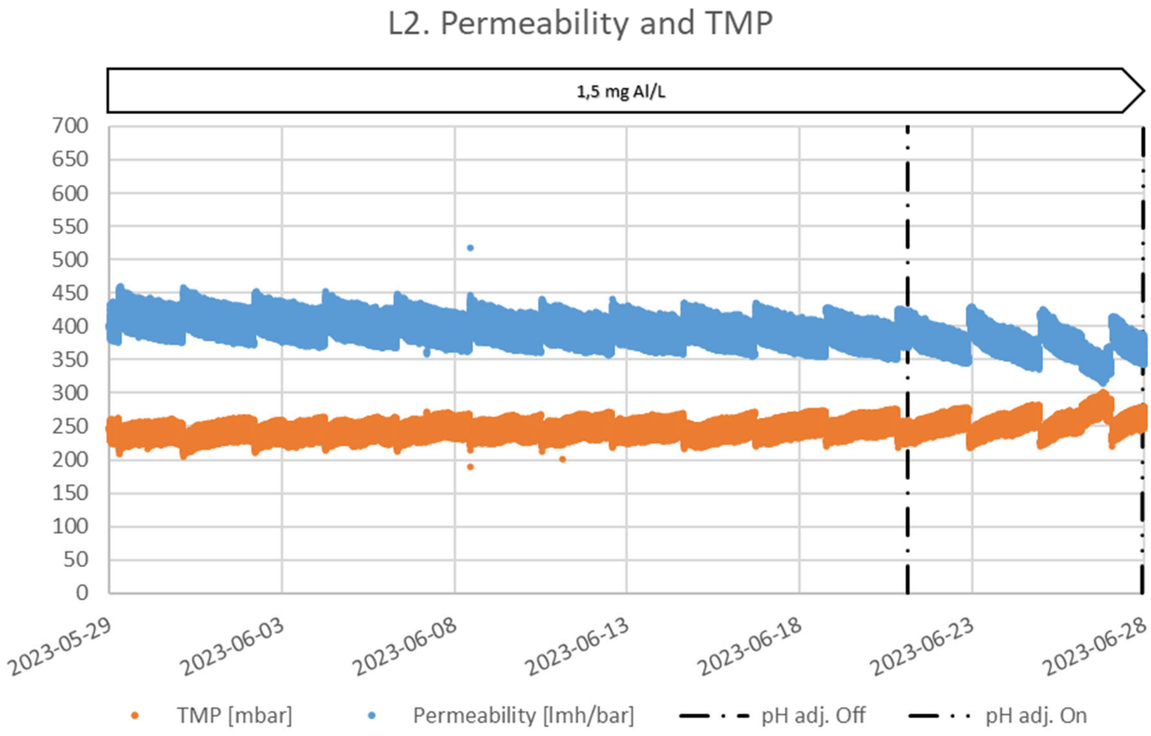

Figure 15. Permeability (blue) and TMP (orange) during period 6 for L2. The black striped and dotted lines represent when the pH adjustment was switched off and on.

At flux 70 lmh and aluminium dosage of 1,5 mg Al/L, presented in Figure 15, the mPermeability was 398 lmh/bar and had a drop rate of 1,5 lmh/bar per day, and the TMP was 245. When the pH adjustment was turned off, the drop rate stayed at 1,5 lmh/bar per day. When the pH adjustment was turned off, the decline in permeability was higher during the CEB cycle. Nevertheless, this result is more uncertain, as L2 only operated without pH adjustment for one week.

Table 9. Reduction of NOM for period 6. Including flux, aluminium dosage, UV_{254} and TOC for source and perm.

Membrane Line	Flux	Aluminium dosage	pH adjustment	UV_{254} *source*	UV_{254} *perm*	TOC *source*	TOC *perm*
	[lmh]	[mg Al/L]	-	[abs/m]		[mg/L]	
1	70	2,0	On	7,8	6,9	4,33	3,95
	85	1,7	On	8,2	7,4	4,14	3,87
	85	1,7	Off	8,4	7,5	4,12	3,76
	100	1,7	On	8,3	7,5	4,30	3,99
2	70	1,5	On	8,3	7,5	4,33	3,93

The results on the reduction of NOM in Figure 9 were difficult to evaluate as the UV_{254} and TOC in *source* varied during period 6. For L1, the NOM reduction was insignificant between different flux and aluminium dosages tested. It had a UV_{254} reduction between 10 - 12 % and a TOC reduction between 7 - 9 %. For L2, the UV_{254} reduction was 10 %, and the TOC reduction was 8 %.

4.6.1. Main Findings

At L1, when the flux is increased to 85 lmh and a dosage of 1,7 mg Al/L, the average permeability is stable at 472 lmh/bar. When pH adjustment is deactivated, the permeability decreases with a drop rate of 1,1 lmh/bar per day. During those settings, *perm* residue exceeds the aluminium limit at 0,04 mg Al/L. When flux was increased to 100 lmh, with pH adjustment turned on, the drop rate increased to 2,6 lmh/bar per day. The performance of L2 with reference parameters decreased with a drop rate of 1,0 lmh/bar per day.

Table 10. Operational parameters for period 6 for both lines. Including average TMP, average permeability, permeability drop rate, actual aluminium concentration in the feed and aluminium residue in perm.

Membrane Line	**Flux**	**mTMP**	**mPermeability**	**Permeability drop rate**	**Aluminium dosage**	**pH adjustment**	**Al. *feed***	**Al. *perm***
	[lmh]	[mbar]	[lmh/bar]	[lmh/bar, day]	[mg Al/L]	-	[mg Al/L]	
1	70	206	473	0,0	2,0	On	1,95	0,02
	85	248	472	-1,4	1,7	On	1,84	0,02
	85	257	451	1,1	1,7	Off	1,70	0,04
	100	313	433	2,6	1,7	On	1,50	0,03
2	70	247	391	1,0	1,5	On	1,39	0,02

4.7. Auxiliary Results

4.7.1. Seasonal Effect on Performance

L2 was kept with constant parameters for extended periods between 2023-02-13 and 20-06-26. The coagulant dosage was 1,5 mg Al/L, the flux was set to 70 lmh, the RT was 21 s, the filtration cycle was 60 min, and the CEB interval was 48 h without chlorine. For L2, the aluminium dosage setpoint was 1,5 mg Al/L. Still, according to lab results, the actual dosage was approximately 1,4 mg Al/L, as seen in Figure 18 in Appendix 1. Furthermore, two PDTs were performed during the period but had no noticeable effect on the operation.

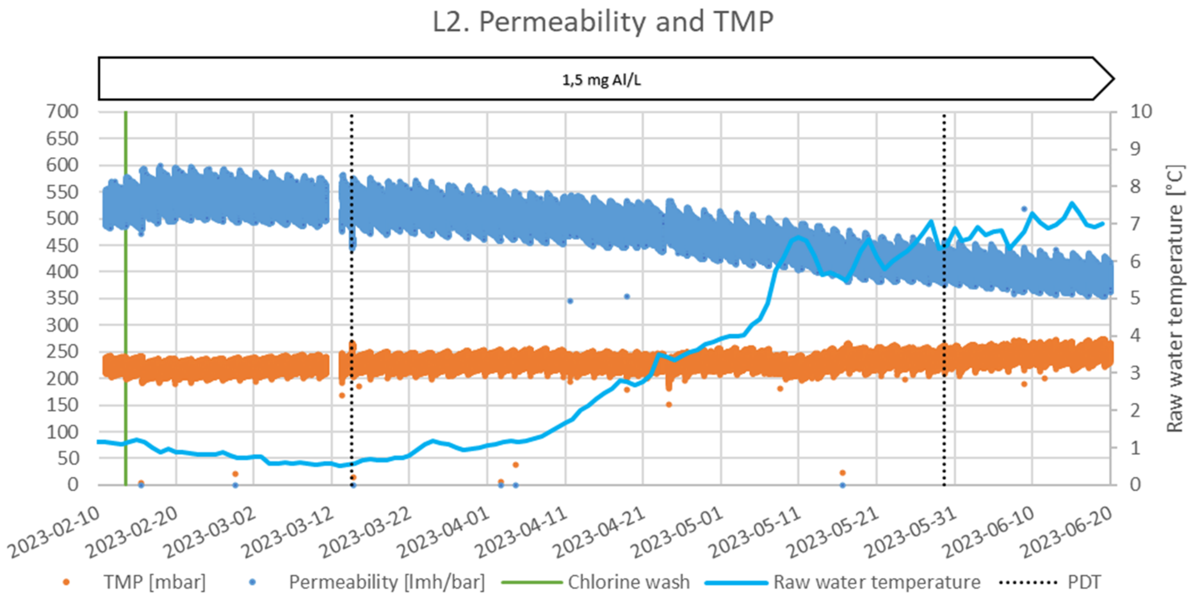

Figure 16. Permeability (blue) and TMP (orange) for L2. The blue line shows the raw water temperature during the period. The green line is when chlorine is present during a manual CEB. The black dotted line denotes when a PDT was performed.

Figure 15 shows how the operation has been affected by seasonal changes over four months. The performance recovered up to 598 lmh/bar at the beginning of the period after a manual chlorine wash was activated in the CEB. The raw water was, on average, 0,7 °C during 2023-02-15 and 2023-03-21, in which top permeability dropped from 598 to 569 lmh/bar. This is an average permeability drop rate of 1,5 lmh/bar per day. When the raw water temperature started rising from 0,9 to 6,6 °C between 2023-03-23 and 2023-05-09, the permeability drop rate doubled to 3,0 lmh/bar per day. After 2023-05-10, the raw water temperature increased at a lower rate; however, the permeability drop rate remained over 3 lmh/bar per day. As the raw water temperature rises to achieve operation with a permeability drop rate lower than 1,5 lmh/bar per day, the aluminium dosage must be higher than 1,5 mg Al/L, especially when the raw water temperature increases.

4.7.2. PDT

A PDT was performed at the end of Period 1 for L1. The first test failed due to positioned incorrectly in the filtration cycle. Subsequently, a PDT was conducted again after adjusting the limit and passing the test. The first PDT showed a sharp decrease in permeability caused by coagulant fouled into the membrane pores. Therefore, a PDT must be planned at the beginning of a filtration cycle and before a scheduled CEB to avoid fouling.

A PDT was also performed for L2 in Period 1, which passed the test. Nevertheless, a severe increase in TMP occurred due to coagulant fouling the membrane pores. The permeability and TMP then stabilised after a manually performed CEB.

The following PDTs showed a passed test for both lines, which indicates that the membranes are holding and are without fibre breakage. Furthermore, As the PDT was performed in junction with an upcoming CEB and at the beginning of a filtration cycle, the permeability was not negatively affected by the PDT.

4.7.3. Operational Challenges

Both planned and unplanned downtime occurred during the pilot operation. The causes of the unexpected stop varied, but recurringly, it was caused by stagnant water during cold temperatures, which led to freezing pipes and other equipment damage. Most downtimes were less than two days. There was one exception, with a stop of eleven days, as spare parts were missing. Some of the downtimes have had a slightly negative effect on the permeability and showed a CEB slope becoming steeper. Overall, the permeability trend showed no adverse impact from downtime over an extended period.

The setpoint of coagulant dosage and pH adjustment were challenging to keep precise. As L1 and L2 had separate pumps for the aluminium dosage, consistent pumping often resulted in inadequate aluminium dosage concentration, making comparisons harder. Usually, the aluminium concentration for L1 was higher than the setpoint and had to be adjusted. The pH adjustment is critical to keep accurate as the pH adjustment regulates the floc formation. Setpoint and actual dosages are presented in Figures 17, 18, and 19 in Appendix 1.

5. Conclusion and Recommendations for the Future Plant

The results from the UF pilot project gave valuable information on the operation of a UF with direct coagulant dosage. The placement of the UF step is shown to be suitable after the activated carbon filter step as the pilot was exposed to a wide range of tested parameters and were and showed sufficient operational results.

The lowest aluminium dosage for stable operation was 1,5 mg Al/L. A higher coagulant dosage than 1,5 mg Al/L may be needed at seasonal variations affecting the operation. Temporarily increasing the coagulant dosage to 2,0 mg Al/L was effective in recovering membrane performance quickly and an appropriate alternative to chlorine in the caustic step of the CEB. pH 6,9 in the *feed* was enough for a continuous operation with sufficient floc formation. At a dosage of 1,5 mg Al/L, aluminium residue in the permeate was consistently between 0,02 – 0,03 mg Al/L. The future WTP should be designed for an average dosing of 2,0 mg Al/L.

The initial coagulant retention time was 21 s (flux of 70 lmh) and this was found to be insufficient during water temperatures between 1–7 °C. It was therefore increased to 42 s to ensure optimal floc formation on the membrane and aluminium concentrations in the permeate below the internal limit. No adverse effect on the operation has been caused by increasing the RT.

At higher flux (85 and 100 lmh), the performance was acceptable in short-term results. The operation was functional with a higher flux at 85 (RT 36 s) lmh. However, the dosage needed to be increased, and 2,0 mg Al/L was considered to be sufficient. At flux 100 (RT 30 s) lmh, the permeability did not stabilise even with an increased dosage of 2,0 mg Al/L.

Operation without coagulant shows an apparent decrease in permeability, which cannot be recovered by adding chlorine in the CEB unless the mean permeability is below 300 lmh/bar. However, the chlorine in CEB could stabilise the permeability drop and show a linear correlation between chlorine frequency in CEB and permeability drop rate.

A CEB sequence with 8,5 L/min caustic dosage and 15,5 L/min acidic dosage was suitable to reach the required pH level of 11,95 during the caustic step and 2,25 during the acidic step in a chemical backwash. It also neutralises the pH in the effluent CEB, which is between 6,5 and 7,7 at specific settings. A regular BW should also be implemented prior to a CEB, ensuring no suspended solids exceed the 40 mg/L limit.

At reference settings, with 1,5 mg Al/L, the NOM reduction varied between 10 – 20 % reduction in UV_{254}, with a higher removal during higher temperatures. Operating the pilot without coagulant decreases the permeability and increases the TMP without stabilisation. The Removal of NOM is also almost diminished completely. With approximately a 1 – 2 % reduction of UV_{254}.

6. Appendices

Appendix 1: Aluminium Concentration and pH Adjustment

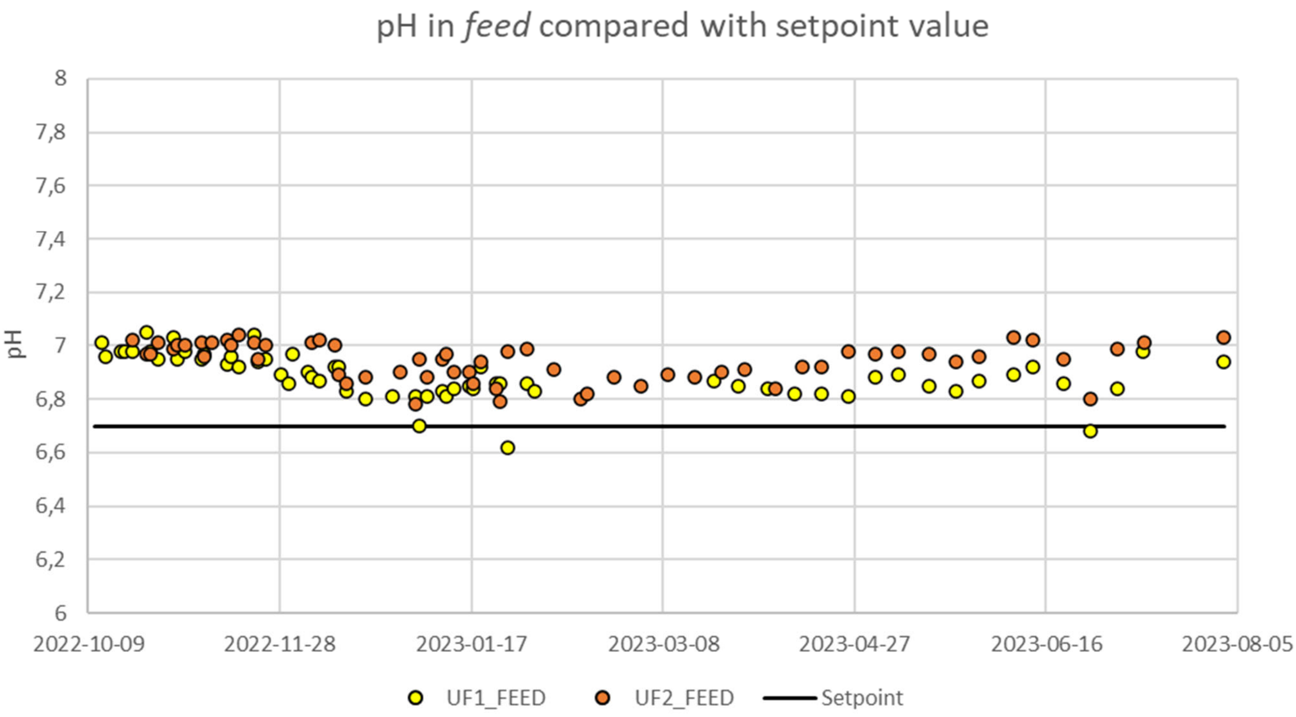

Figure 17. pH value in feed compared to the setpoint.

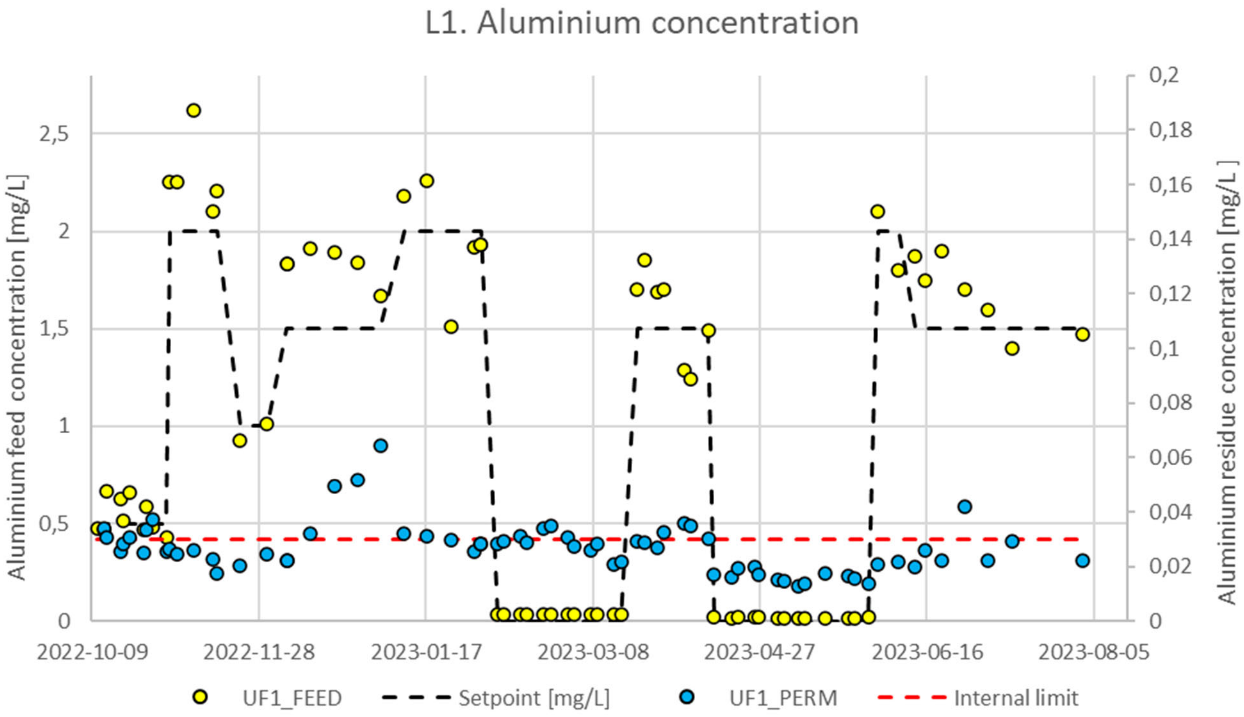

Figure 18. Aluminium concentration in feed and perm for L1.

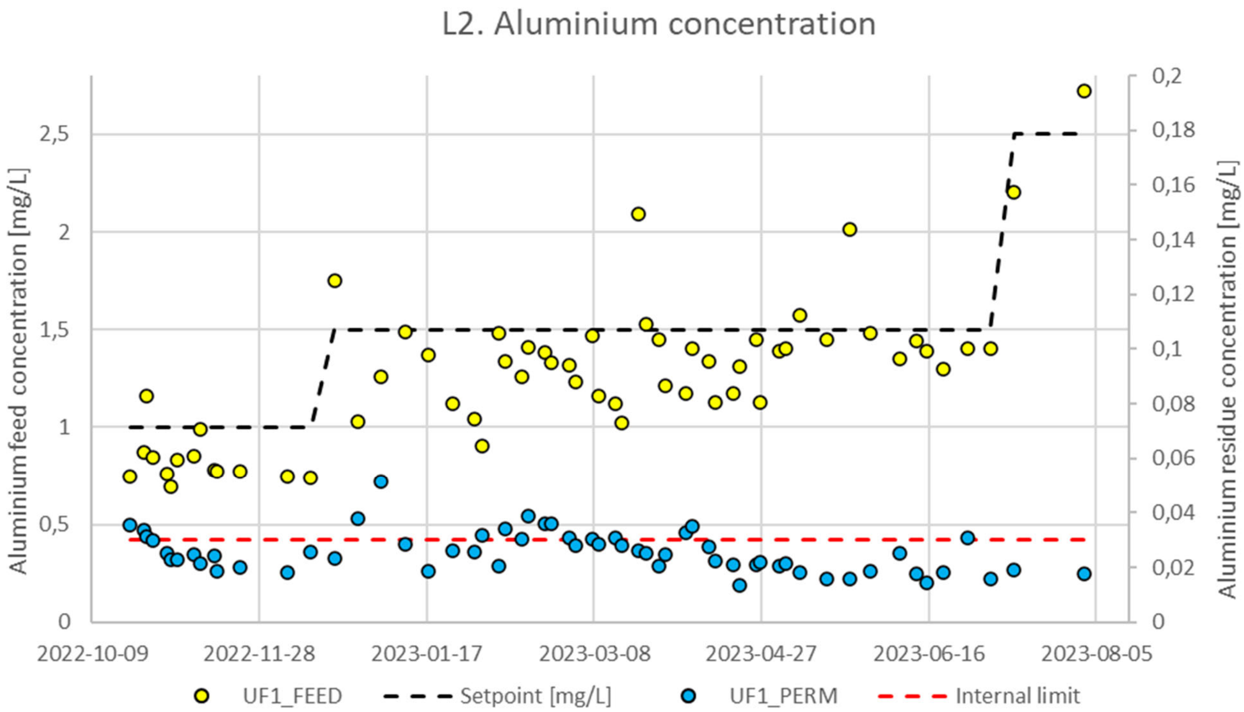

Figure 19. Aluminium concentration in feed and perm for L2.

Appendix 2: Dosage Setting in CEB and Neutralisation Cycle

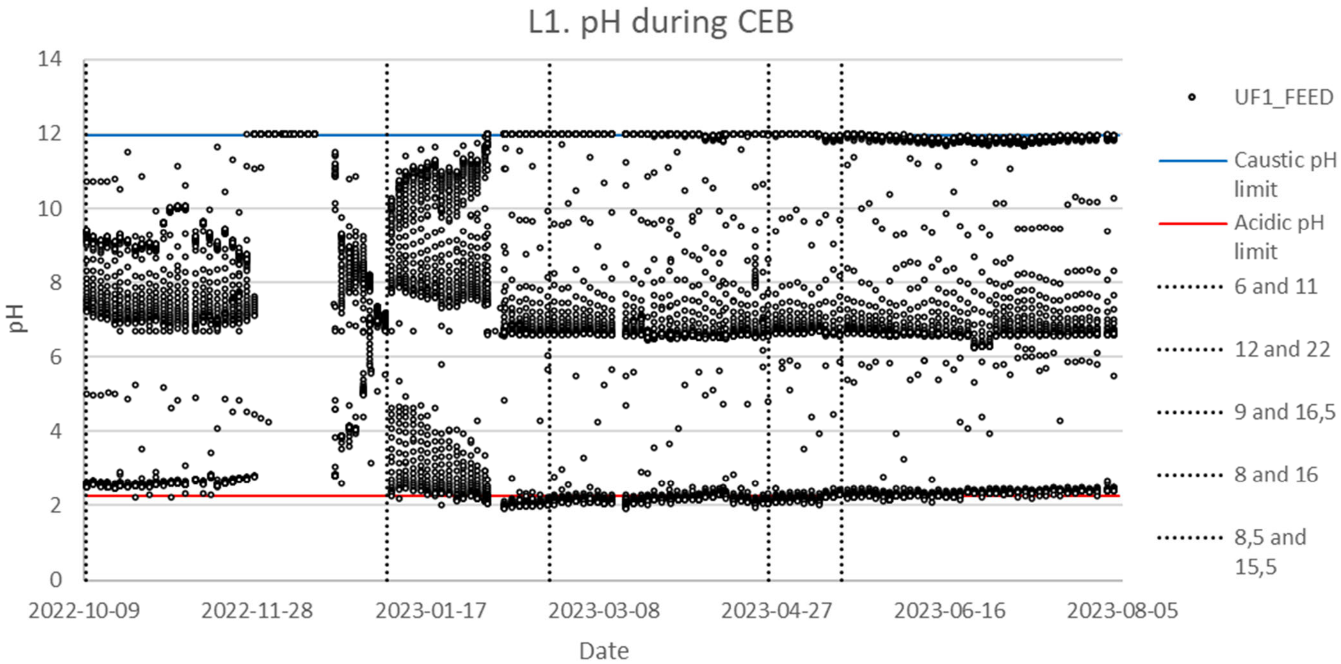

Figure 20. pH in feed during CEB for L1.

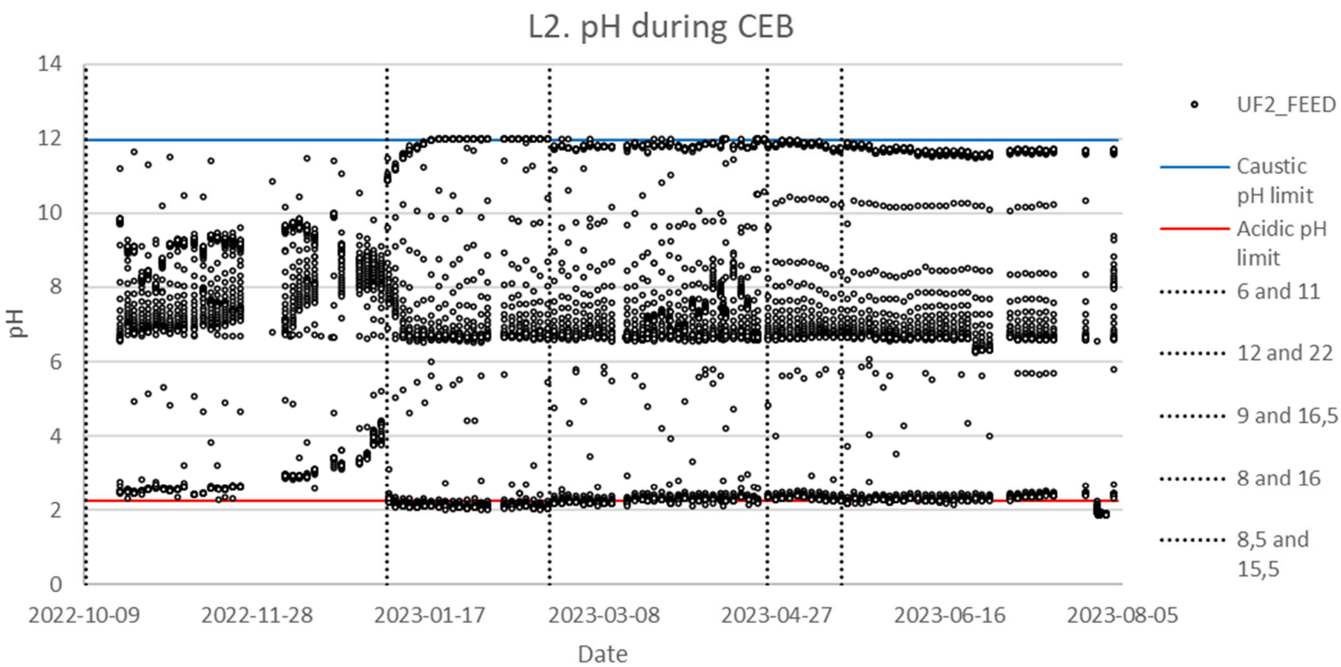

Figure 21. pH in feed during CEB for L2.

Table 11. Settings for neutralisation cycle.

Neutralisation cycle setting	**Unit**	**Value**
Start neutralisation	%	30
Mixing time (pH)	s	60
Chemical dosing time	s	90
pH lower setpoint	-	6,5
pH higher setpoint	-	7,5
Mixing time (redox)	s	60
Chemical dosing time (redox)	s	90
Redox lower setpoint	mV	0
Redox higher setpoint	mV	300
Stop emptying	%	15

Appendix 3: Measured Parameters

Table 12. Inline measurements for the UF pilot plant.

Inline measurement	Unit
Permeability	Lmh/bar
TMP	mbar
pH feed	-

Table 13. Measured parameters from chemical analysis for the UF pilot plant.

Chemical analysis	Unit	UF1 source	UF1 feed	UF1 perm	UF1 BW	UF2 source	UF2 feed	UF2 perm	UF2 BW	UF CEB
Turbidity	FNU	x	x	x	x	x	x	x	x	x
UV_{254}	Abs/m	x	x	x	x	x	x	x	x	
pH	-	x	x	x	x	x	x	x	x	x
Temperature	°C	x	x	x	x	x	x	x	x	x
Conductivity	mS/cm	x	x	x	x	x	x	x	x	
Alkalinity	mg HCO_3/L	x	x	x	x	x	x	x	x	
TOC	mg/L	x	x	x	x	x	x	x	x	
DOC	mg/L		x				x			
Total aluminium	mg/L	x	x	x	x	x	x	x	x	x
Dissolved aluminium	mg/L	x	x	x	x	x	x	x	x	x
Chloride	mg/L	x	x	x	x	x	x	x	x	
Sulphate	mg/L	x	x	x	x	x	x	x	x	
Calcium	mg/L	x	x	x	x	x	x	x	x	
Magnesium	mg/L	x	x	x	x	x	x	x	x	
Water hardness	mg/L	x	x	x	x	x	x	x	x	
Total chloride	mg Cl_2/L	x	x	x	x	x	x	x	x	
SS	mg/L									x

Table 14. Measured parameters from microbiological analysis for the UF pilot plant.

Microbiological analysis	Unit	UF1 source	UF1 feed	UF1 perm	UF1 BW	UF2 source	UF2 feed
Coliform bacteria	mpn/100 ml	x	x	x	x	x	x
E. coli	mpn/100 ml	x	x	x	x	x	x
Microorganisms, 3 days	cfu/ml	x	x	x	x	x	x
Microorganisms, 7 days	cfu/ml	x	x	x	x	x	x
Yeast	cfu/100 ml	x	x	x	x	x	x
Mold	cfu/100 ml	x	x	x	x	x	x
Micro fungus	cfu/100 ml	x	x	x	x	x	x

Appendix 4: Measured Water Quality

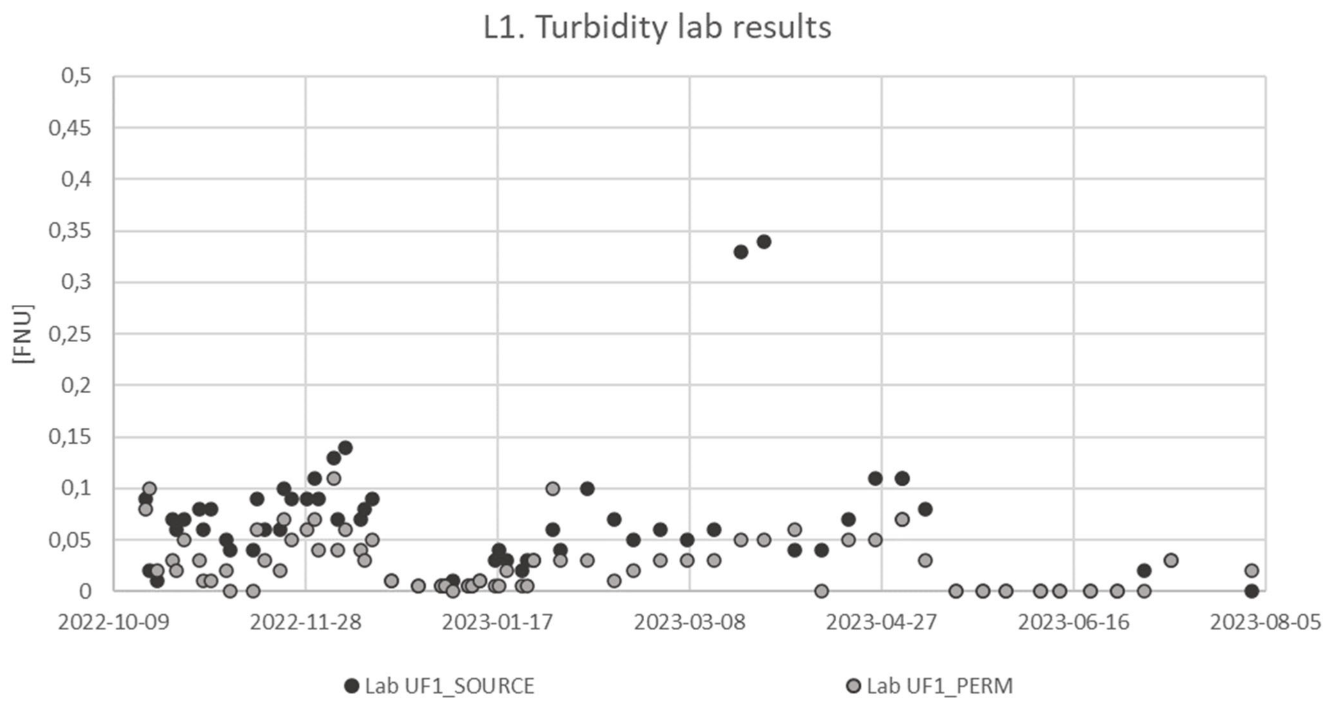

Figure 22. Turbidity lab results for L1.

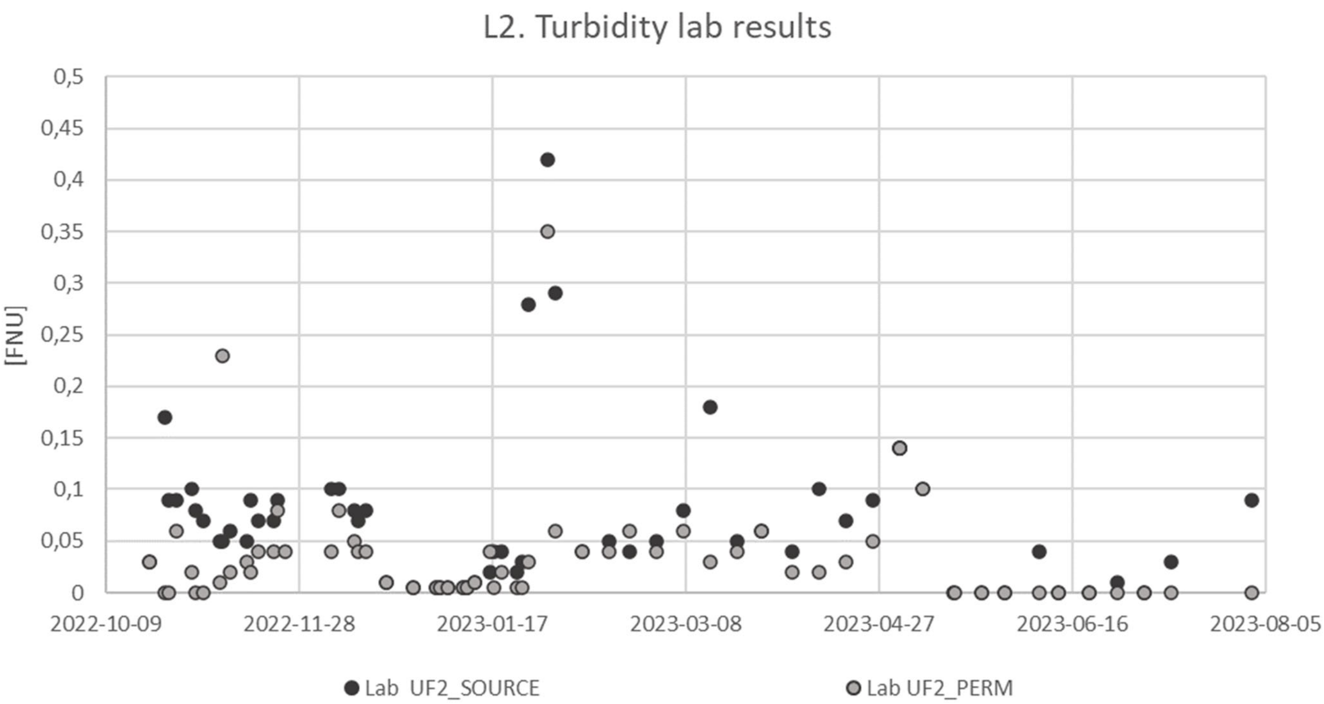

Figure 23. Turbidity lab results for L2.

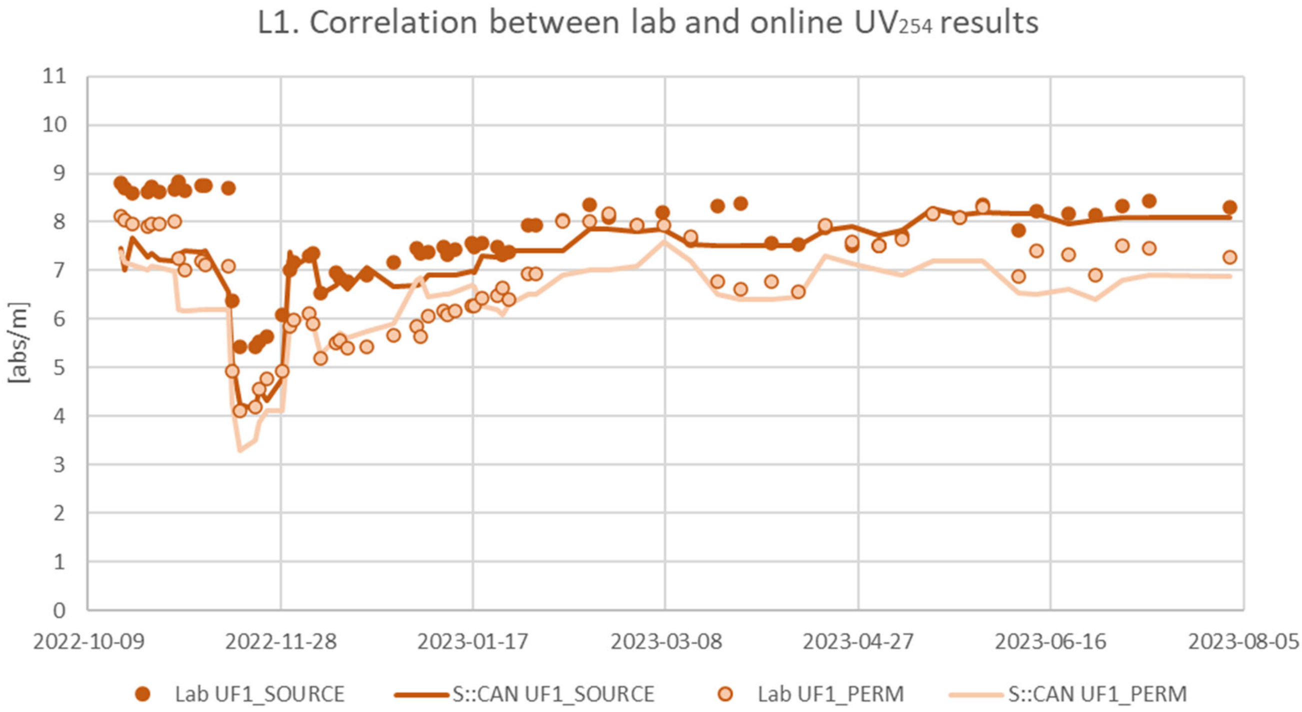

Figure 24 Lab and online UV_{254} results for L1.

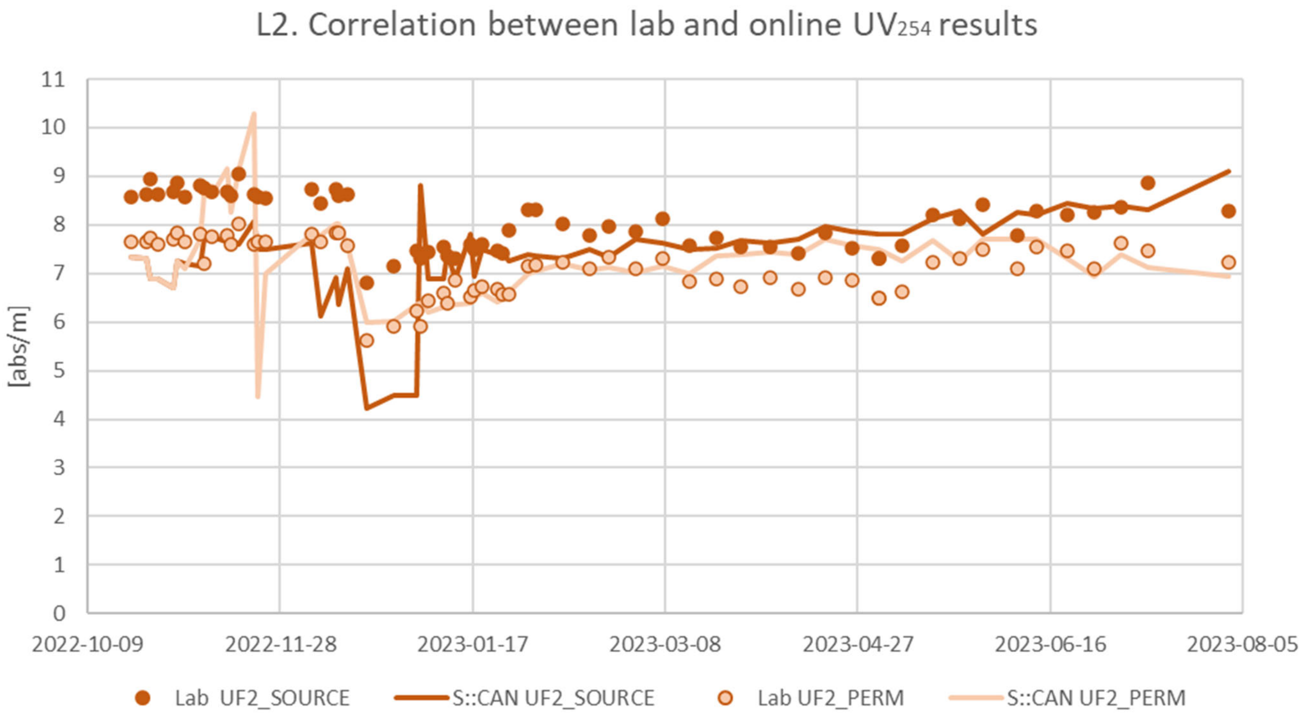

Figure 25. Lab and online UV_{254} results for L2.

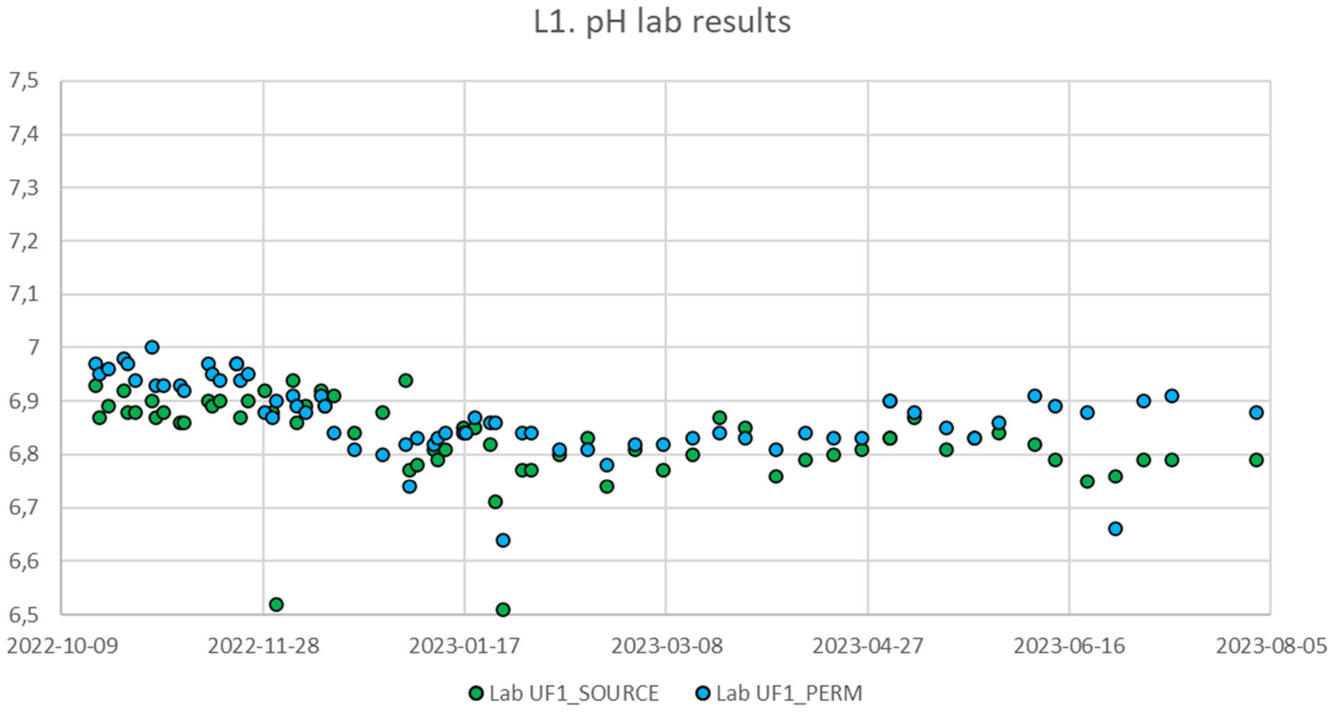

Figure 26. pH lab results for L1.

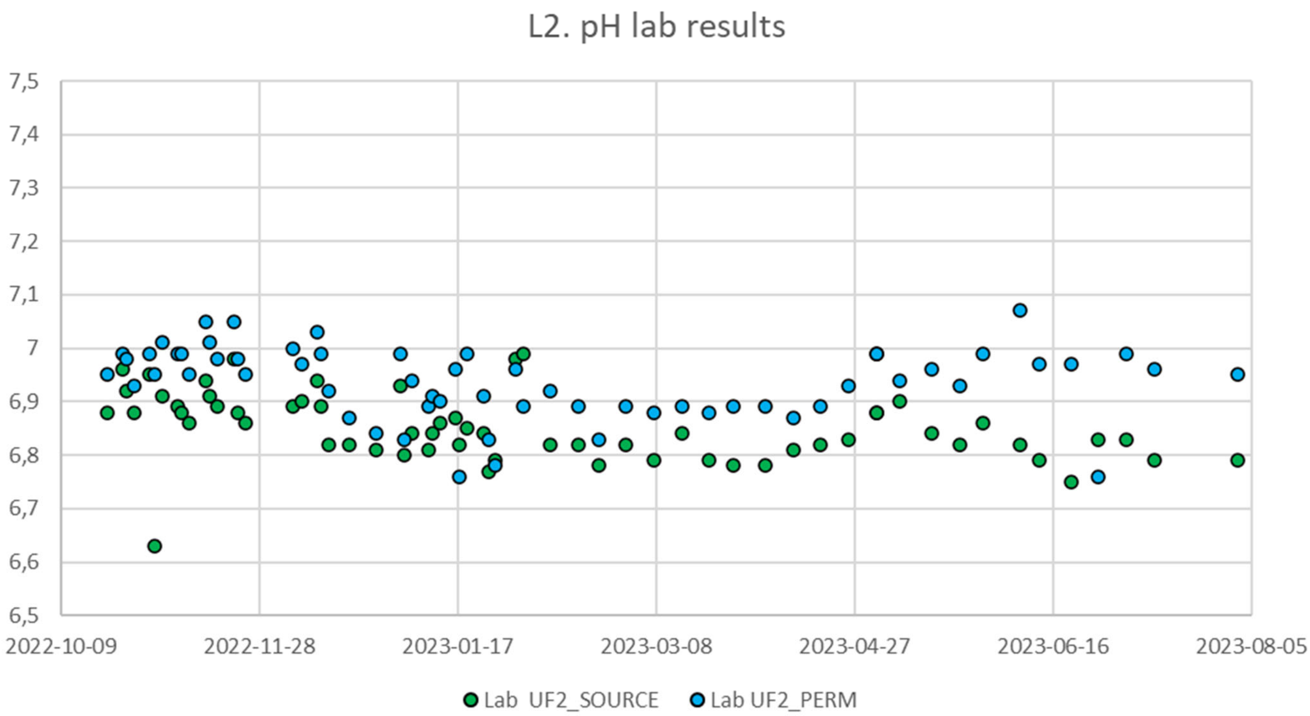

Figure 27. pH lab results for L2.

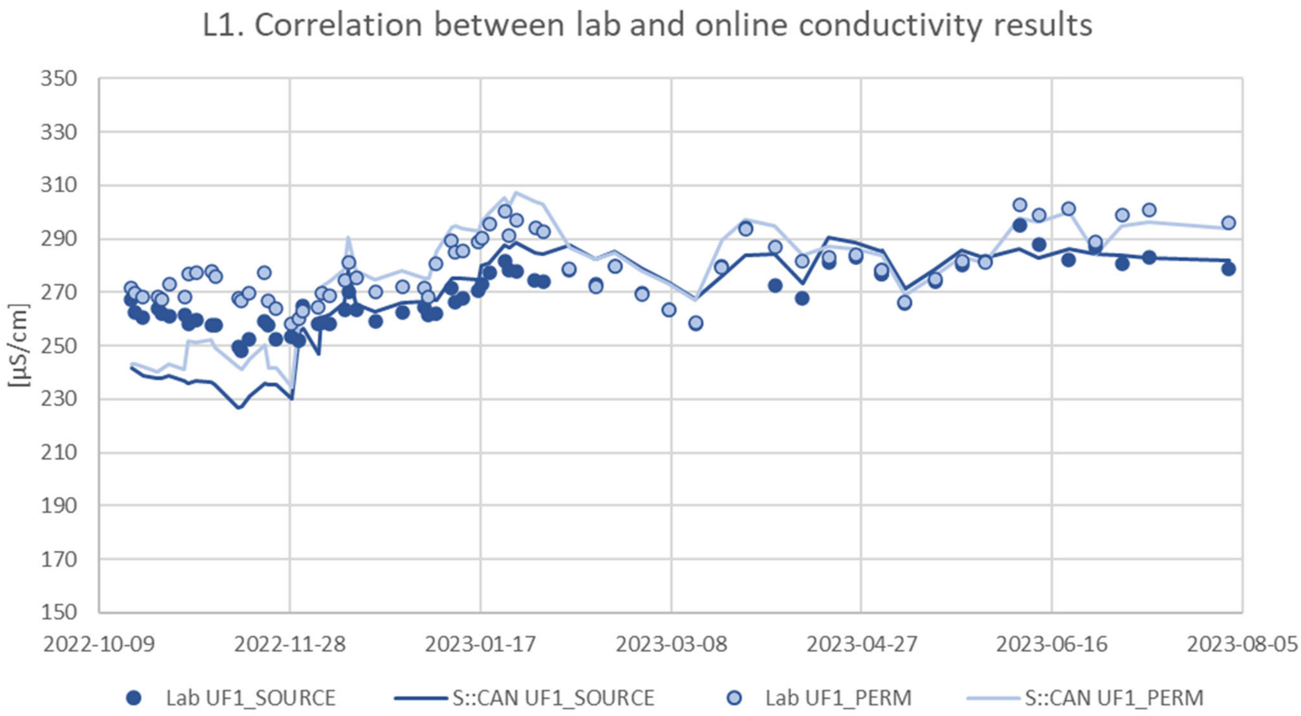

Figure 28. Lab and online conductivity results for L1.

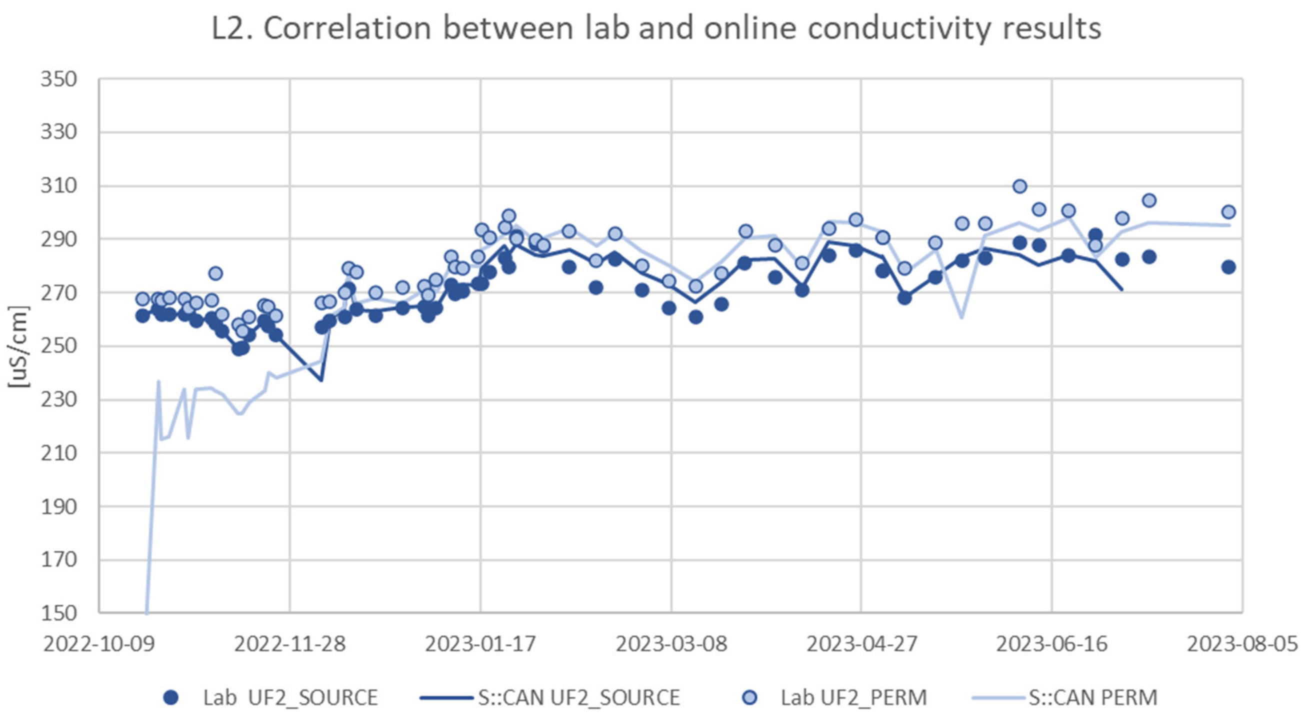

Figure 29. Lab and online conductivity results for L2.

Appendix 5: Water Quality of Neutralised CEB

Table 15. Characterisation of neutralised CEB effluent. Measured parameters are turbidity, pH temperature, total aluminium, dissolved aluminium, and suspended solids. The mean values are over the first four samples taken.

Date	Turbidity [FNU]	pH [-]	Temperature [°C]	Total aluminium [mg Al/L]	Dissolved aluminium [mg Al/L]	Suspended solids [mg/L]
2023-03-27	5,02	6,53	20,5	12,8	0,213	50,3
2023-03-29	-	6,55	14,9	10,8	0,018	34,4
2023-04-04	4,17	6,38	13,4	11,2	0,249	44,5
2023-04-06	3,74	6,43	14,8	11,7	0,326	17,8
2023-04-26	1,84	6,63	13,6	5,34	0,044	7,6
Mean	**4,3**	**6,5**	**15,9**	**11,6**	**0,2**	**36,8**

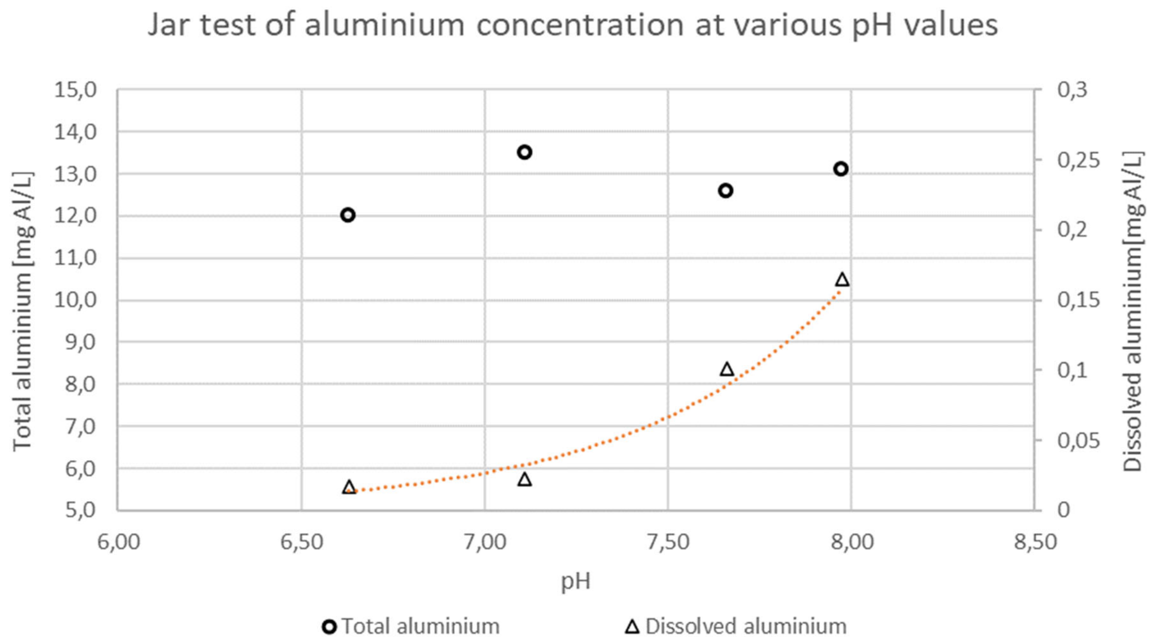

Figure 30. Total and dissolved aluminium concentration at different pH. The aluminium concentrations are taken on neutralised CEB effluent in a Jar test 2023-03-23.

Table 16. Chlorine compounds, THA and HAA in CEB effluent.

Analysis	**Unit**	**2023-03-15**	**2023-05-17**
Bromate	µg/L	10	11
Chlorate	mg/L	3,06	4,95
Chlorite	mg/L	<0,02	<0,03
Trichloromethane	µg/L	24	28
Bromine dichloromethane	µg/L	10	9,5
Bromochloromethane	µg/L	2,8	3,2
Methyl tribromide	µg/L	<1,0	<1.0
Total THM	µg/L	38	41
1,1,2-Trichloro ethene	µg/L	<1,0	<1,0
Tetrachloroethylene	µg/L	<1,0	<1,0
Benzene	µg/L	<0,2	<0,2
1,2-Dichloroethane	µg/L	<1,0	<1,0
Bromine dichloroacetic acid (BDCAA)	µg/L	<10	<10
Bromine chloroacetic acid (BCAA)	µg/L	<10	<10
2,2-Dichloro propionic acid	µg/L	<10	<10
Dibromo chloroacetic acid (DBCAA)	µg/L	<10	<10
Dibromo acetic acid (DBAA)	µg/L	<10	<10
Dichloroacetic acid (DCAA)	µg/L	<10	<10
Bromine acetic acid (MBAA)	µg/L	<10	<10
Chlorine acetic acid (MCAA)	µg/L	<10	<10
Tribromo acetic acid (TBAA)	µg/L	<10	<10
Trichloroacetic acid (TCAA)	µg/L	<10	<10

Table 17. Heavy metals in the CEB effluent.

Analysis	**Unit**	**2023-03-20**	**2023-03-22**	**Mean**
pH	-	6,6	6,62	6,6
TOC	mg/L	7,0	6,92	7,0
DOC	mg/L	4,3	4,13	4,2
Calcium	mg/L	25,0	27,32	26,2
Magnesium	mg/L	5,0	5,24	5,1
Total phosphor	mg/L	0,01	0,014	0,01
Oil index	mg/L	0,51	0,10	0,3
Potassium	mg/L	2,70		2,7
Arsenic	µg/l	0,29	0,32	0,3
Barium	µg/l	8,80	8,40	8,6
Lead	µg/l	0,18	0,12	0,2
Cadmium	µg/l	<0,004	<0,004	<0,004
Cobalt	µg/l	0,044	0,038	0,04
Copper	µg/l	2,80	1,80	2,3
Chromium	µg/l	0,41	0,43	0,4
Mercury	µg/l	<0,1	<0,1	<0,1
Nickel	µg/l	1,90	1,90	1,9
Vanadium	µg/l	0,42	0,46	0,4
Zink	µg/l	9,30	2,50	5,9

Table 18. Extended analysis of the CEB effluent.

Analysis	Unit	2023-03-27
Benzo (b, k) fluoranthene	µg/l	<0,050
Benzo (g, h, i) perylene	µg/l	<0,025
Indeno(1,2,3-cd) pyrene	µg/l	<0,025
Sum of PAH:er	µg/l	<0,10
Benzo(a)pyrene	µg/l	<0,010
Trichloromethane	µg/l	<1,0
Bromodichloromethane	µg/l	<1,0
Dibromochloromethane	µg/l	<1,0
Tribromomethane	µg/l	<1,0
THM	µg/l	<4,0
1,1,2-Trichloroethene	µg/l	<1,0
Tetrachloroethene	µg/l	<1,0
Sum	µg/l	<2,0
Benzene	µg/l	<0,20
1,2-Dichloroethane	µg/l	<1,0
Smell, strength		.
Smell, type,		.
Turbidity	FNU	1,5
Colour (410 nm)	mg	5,7
pH		6,7
Temperature	°C	22,9
Alkalinity	mg	32
Conductivity	mS/m	48
Chloride	mg/l	4,3
Sulphate	mg/l	160
Fluoride	mg/l	<0,20
Cyanide,	µg/l	<0,50
Bromat/BrO^{3-}	µg/l	<2,0
COD-Mn	mg	4,4
Ammonium	mg/l	0,27
Ammonium nitrogen	mg/l	0,21
Nitrate	mg/l	1,2
Nitrate nitrogen	mg/l	0,28
Nitrite	mg/l	<0,0070
Nitrite-nitrogen	mg/l	<0,0020
$NO_3/50+NO_2/0,5$	mg/l	<1,0
Water hardness	°dH	5,1
Sodium	mg/l	59
Potassium	mg/l	3
Calcium	mg/l	28
Iron	µg/l	11
Magnesium	mg/l	5,3
Manganese	µg/l	1,8
Aluminium	µg/l	9900
Antimony	µg/l	0,13
Arsenic	µg/l	0,3
Lead	µg/l	0,074
Boron	µg/l	20
Cadmium	µg/l	<0,0040
Copper	µg/l	1,5
Chrome	µg/l	0,46
Mercury	µg/l	<0,10
Nickel	µg/l	1,8
Selenium	µg/l	<0,50
Uranium	µg/l	0,4

Appendix 6: Guidelines for Effluent Discharge to Mälaren

The guidelines are reference limits for substances that can be released back into effluent streams to Mälaren. The regulated values are revised from limits produced by Järfälla Municipality.

Table 19. Limits for substances that are in the effluent stream back to Mälaren.

Substance/parameter	Value	Unit
Lead (Pb)	3,0	µg/L
Cadmium (Cd)	0,3	µg/L
Copper (Cu)	9,0	µg/L
Chromium (Cr)	8	µg/L
Mercury (Hg)	0,04	µg/L
Nickel (Ni)	6	µg/L
Oil index	0,5	mg/L
pH	≥ 6,5 and ≤ 9,5	pH-unit
Suspended solids	40	mg/L
Total phosphorus (P)	100	µg/L
Zink (Z)	15	µg/L

Appendix 7: Original Experimental Plan for the UF Pilot Project 2022-2023

In Table 20, the initial experimental plan is explained. It includes the schedule for the different periods and their purposes, with planned parameter settings. Specific goals in the project were either changed or adjusted from the original design. Also, the implementation was changed to better adapt to new findings from the results and unexpected events. This forced the project in a different direction for some of the periods. Period 9 was planned to investigate iron coagulant for L1 and use UF2 BW as feed water in L2. However, both goals were removed, and more focus was put into evaluating the neutralisation of CEB effluent and giving more time to follow the operation of the other purposes.

Table 20. Original experimental plan.

Period	Weeks	Membrane 1 goal	Membrane 1 operation	Membrane 2 goal	Membrane 2 operation
P1.	42-48	The membrane uses feed water from KF4 until new carbon packing arrives. Variable aluminium dosing is between 0,5 – 2,0 mg Al/L. The purpose is to find the optimal coagulant dosage for TMP with as low a dosage as possible. Higher dosage to separate NOM.	Al dosage 0,5 mg/L RT: 21 s Flux: 70 lmh pH: pH 6,7 (+/-0,1) CEB interval: 48 h Without chlorine (operation without chlorine in CEB if it is not needed)	The fixed aluminium dosage is used as a reference line. The purpose is to map performance over time to ensure TMP for a given dosage.	Al dosage: 1.0 mg/L The remaining parameter settings are the same as in L1.
		New carbon packing (KF2) and the same settings as before. How does new carbo affect the membrane, and can fines affect TMP?	-	-	
P2.	49-5	When the carbon is saturated, the variable dosage of aluminium continues, and then the flux will be increased to 85 and 100 lmh. Retention time 1-2 weeks 60 s	Loading is tested with flux 70-100 lmh and constant aluminium dosage. A difference in TMP is expected.	Change feed water from KF4 to KF2—Analyse performance when new carbon packing is used.	Aluminium dosage is changed after the trend in TMP. Based on results during October and November.
P3.	6-10	No coagulant dosage during five weeks at low temperatures. The purpose is to see how direct coagulation with UF affects filtration.	Aluminium dosage 0 mg/l The remaining settings are as standard. *Chlorine may be added if needed.*	Settings are as standard.	-

P4.	11-14	CEB interval adjustment is tested Buffer time	-	Settings are as standard.	-
P6.	15-19	No aluminium dosage for five weeks during the eutrophication period. During this period, it is tested if chlorine is needed in the CEB. Evaluate the steady state and the breaking point of the performance without coagulant.	Eutrophication without coagulant dosing.	Fixed aluminium dosage and should only be adjusted if needed.	-
P7.	20-25	Varied flux as raw water quality is lower, and the production is as highest.	85 lmh 100 lmh The remaining settings are as standard.	Analyse how the membrane operates during the summer season.	-
P8.	26-28	The purpose is to investigate various dosages for NOM reduction	-	Varied aluminium dosage to evaluate optimal NOM reduction.	Various aluminium dosages to consider optimal NOM reduction.
P9.	*29-38*	Varied dosage iron as coagulant. Micro pilot experimental design is conducted to have a basis for dosage interval and pH adjustment. Extra laboratory analysis for UV, iron, and TOC.	-	BW sand filtrate as feed water. OBS! Investigate if sand particles get stuck in the membrane. Last week should have settings as in P1.	-

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